Alaska Department of Transportation and Public Facilities

RESEARCH

A Hydraulic Evaluation of Fish Passage Through Roadway Culverts in Alaska

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A HYDRAULIC EVALUATION OF FISH PASSAGE THROUGH ROADWAY CULVERTS IN ALASKA

FINAL REPORT

by

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16. Abstract

Culverts are a very simple hydraulic structure. However, because the engineer must design for peak flows passing through the culvert while fish are trying to move upstream serious problems arise. Almost all culvert installations in interior and northern Alaska were casually examined, with approximately 100 examined in detail where hydraulic problems existed that may retard fish passage. Data from the field program are included in an appendix to this report. The two major hydraulic problems in regard to fish passage were high velocities and perching; inlet drops caused by deposited sediment, aufeis, alignment of culvert with stream, and non-uniform culvert slopes are some of the other fish passage deterents that were observed. Also, all known baffled structures were evaluated. Numerous recommendations were made that should improve the hydraulic conditions that exist at a culvert relative to fish passage. Also, it is recommended that further studies be carried out to evaluate the swimming performance of the native fish. Present design criteria are based on very limited studies. Lastly, it is recommended that the concept of the velocity in the occupied zone (area in culvert where fish swim) be considered as the culvert design velocity for fish passage in place of the presently used average cross-sectional velocity.

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IMPLEMENTATION STATEMENT

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Because this was the first major project undertaken on fish passage, one of the primary goals of the work was to point out problem areas that have to be solved before significant progress can be made in culvert design to enhance fish passage. The work has pointed to the need for biological research on fish swimming ability, which is now underway. It has also indicated another major need, research on elevated or "perched" culverts.

A research project entitled "Design of Depressed Invert Culverts" will soon be underway. While its main focus is examination of the reduction in water velocity realized from burial of the culvert invert below the stream bottom, an effort will also be made to determine the impact of this type of installation on perching. Additional research on culvert perching should be a high priority for future studies in this area.

The findings of this report will be implemented further by application of the recommendations and conclusions to future culvert designs made by DOT&PF engineers and hydrologists. The report will enhance the knowledge of the designers by showing what problems and successes have resulted in the field from previous designs. It represents a starting point from which modifications can be considered.

The recommendation regarding use of the "occupied zone" water velocity concept will be pursued with Alaska Department of Fish & Game. If a method can be devised that is mutually agreeable, DOT&PF designers will be able to use the full benefit of channel roughness to obtain more realistic (and less expensive) culvert designs.

The Data Report (Appendix) will be useful to design, operations and research people for documenting conditions that existed at each culvert examined during the study period. It should be particularly valuable for future studies on the causes and rates of culvert perching.

Finally, plans have been made by Statewide Standards and Technical Services to incorporate the findings of this report in the State Hydraulics Manual which is currently being revised. This document will provide designers with a practical guide to use of this and other fish passage research.

Stephen H. Kailing, P.E.
Project Manager
Statewide Research

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INTRODUCTION

Fish passage through culverts in Alaska is a very real and important problem. In the design of a culvert, one is interested in passing the required quantity of the design flow and, at the same time, not significantly retarding the passage of fish. It is much easier to make this general statement on design criteria than it is to actually develop the specific criteria that leads to both successful passage of the fish and an economical structure.

This publication reports on the results of a research project entitled, "Evaluation of Fish Passage Through Roadway Drainage Structures." The overall research objective of this project was to begin a preliminary investigation on improving the design of roadway drainage structures to better accommodate fish passage for least cost. Three specific sub-objectives were identified:

1. review and assess the current knowledge and design practice of fish passage through drainage structures with particular regard to conditions in Alaska;

2. study the performance of in-place culverts with emphasis on fish passage and hydraulic design criteria; and

3. design conceptual improvements on modifications of culverts for fish passage.

The above three sub-objectives will be addressed in the order as given. Three major topics will be presented under the first objective. They are criteria for passing the design flood, design criteria for fish passage and swimming capability, and behavior related to fish passage through culverts. The last subject is not an area that was examined in this project, however, results from other researchers will be presented here when they are relevant to the general theme of this report.

The second objective of this study (performance of in-place culverts) was accomplished by a major field program. Numerous culverts were visually examined with well over 100 being examined in detail.

Results of this field data collection program are published in the attached appendix.

The third objective will be numerous recommendations or suggestions for improving the design of culverts for enhanced fish passage. These recommendations will be based both on the field examination programs and results from other researchers.

EXISTING DESIGN CRITERIA

Design Flow

The selection of the flood design frequency for culverts depends upon the type of structure (Table 1) as well as economic and safety considerations. Obviously, the loss or damage to major and sole access highways because of flooding is more critical than the same damage to a secondary access route.

TABLE 1. Design flood frequency.

Type of structure	Design frequency
Culverts on primary highways	50 years
Culverts on secondary highways with high volumes or providing sole area access	50 years
Culverts on secondary highways of less importance	10 years

Source: State of Alaska, Department of Transportation and Public Facilities, Hydraulics Manual.

The determination of design flows for given return periods from various sources is quite simple. The DOT&PF personnel can use a series of graphs for the state to determine either the 10 year or 50 year floods based solely on the drainage area. The state is broken up into three hydrologic regions. By entering the correct graph based on the geographical region and using the drainage area, the required design discharge can be obtained. Other methods may also be used by design engineers.

Estimates of design floods can also be determined by using a technique developed by Lamke (1979). After dividing the state into two hydrologic regions, he developed multiple regression equations to relate the magnitude of a design discharge for a given frequency to climatic and physical characteristics of the drainage basin. Physical characteristics include amount of storage in lakes and ponds, drainage area, and quantity of forested land and climatic characteristics that include annual precipitation and mean minimum January temperature.

Both of the above described methods give exact values of a design flow for a given return period. The question is how well do these methods predict the true flood magnitude? Kane and Janowicz (1985) investigated the variability of predicted flood flows within three hydrologic regions of Alaska. The three regions are the southern coast, south central and, basically, north of the Alaska Range. Estimates of the 2-year flood are shown in Figures 1, 2 and 3 for all drainage areas where flow has been gaged at least for five years.

The discharges for a 2-year return period are presented because they are very close to the mean annual flood that is used in the fish passage design. Use of the mean annual flood will be discussed in the next section on fish passage design criteria. The predicted values of Kane and Janowicz were obtained by using four different probability distributions. By using a statistical test of best fit, they concluded that overall the two parameter log normal distribution more accurately fit the distribution of the annual floods in Alaska than either the three parameter log normal, Gumbel extreme value or log Pearson III methods.

The important message indicated by the three figures is that it is very difficult to fit one curve to an entire hydrologic area and expect good results each time. This same general conclusion was made by the Inland Waters Directorate (1975) for the MacKenzie Highway project. The

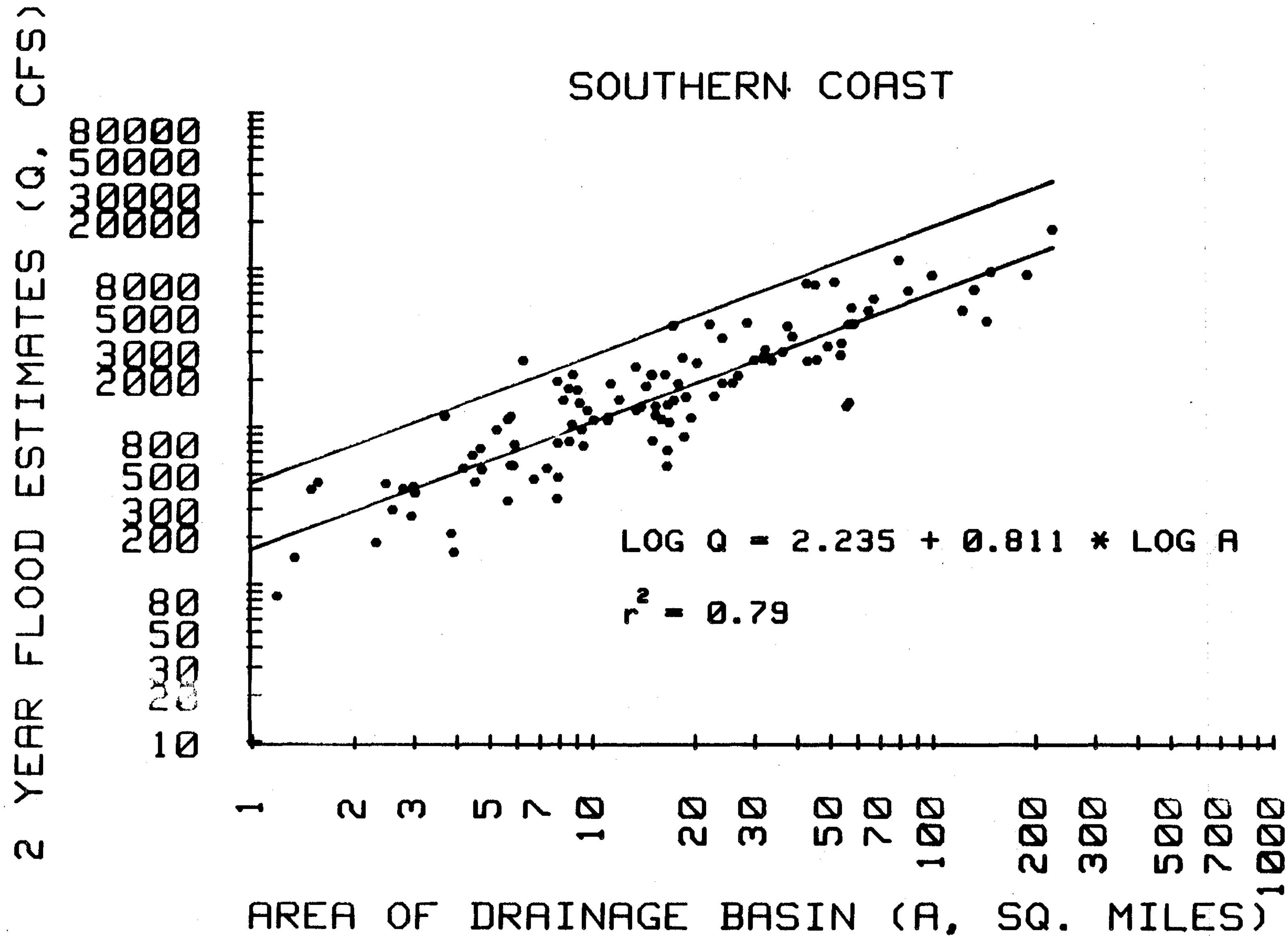


Figure 1. Two-year flood estimates for the Southern Coast of Alaska showing the variation as a function of drainage area (Kane and Janowicz, 1985).

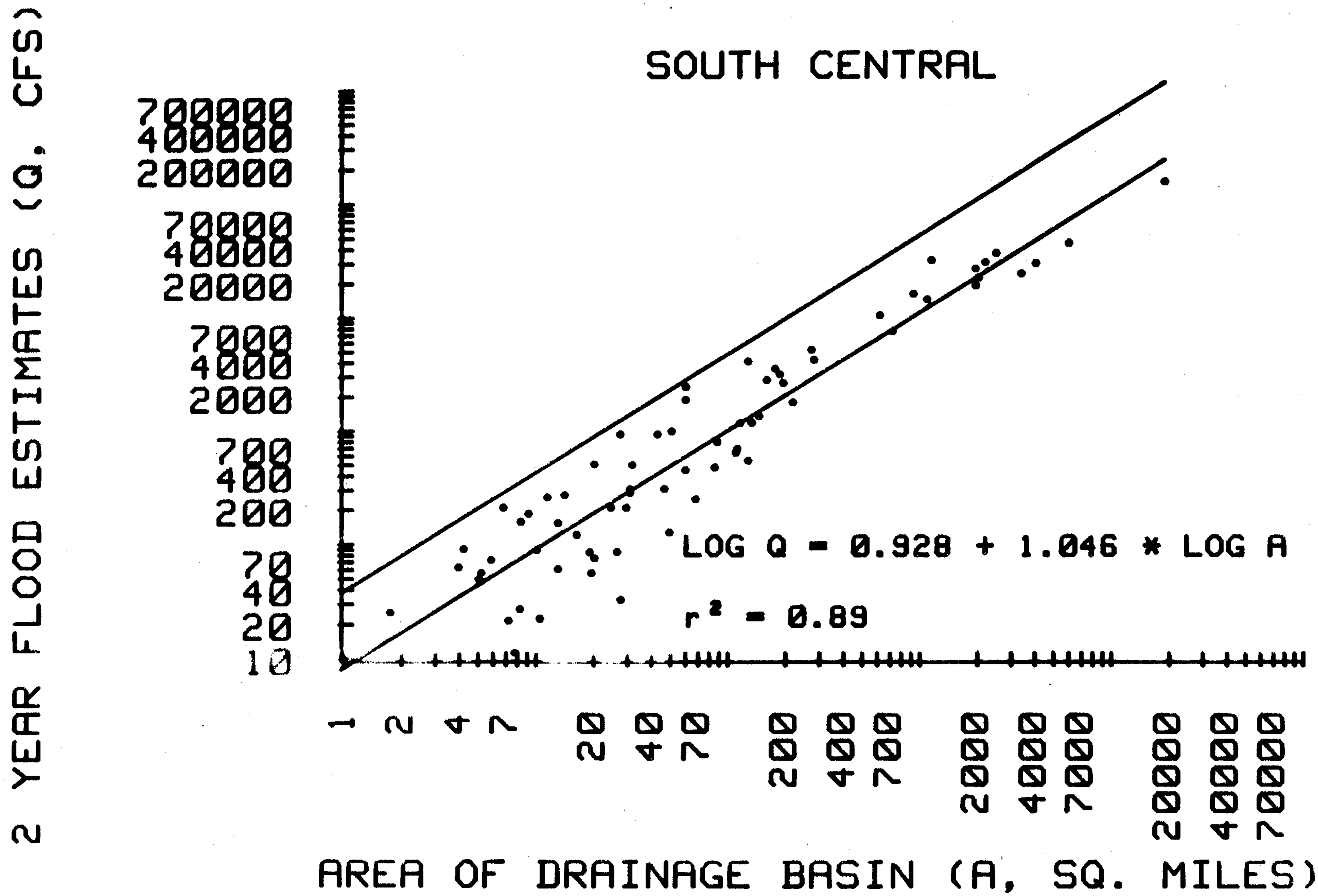


Figure 2. Two-year flood estimate for South Central Alaska showing variations as a function of drainage area (Kane and Janowicz, 1985).

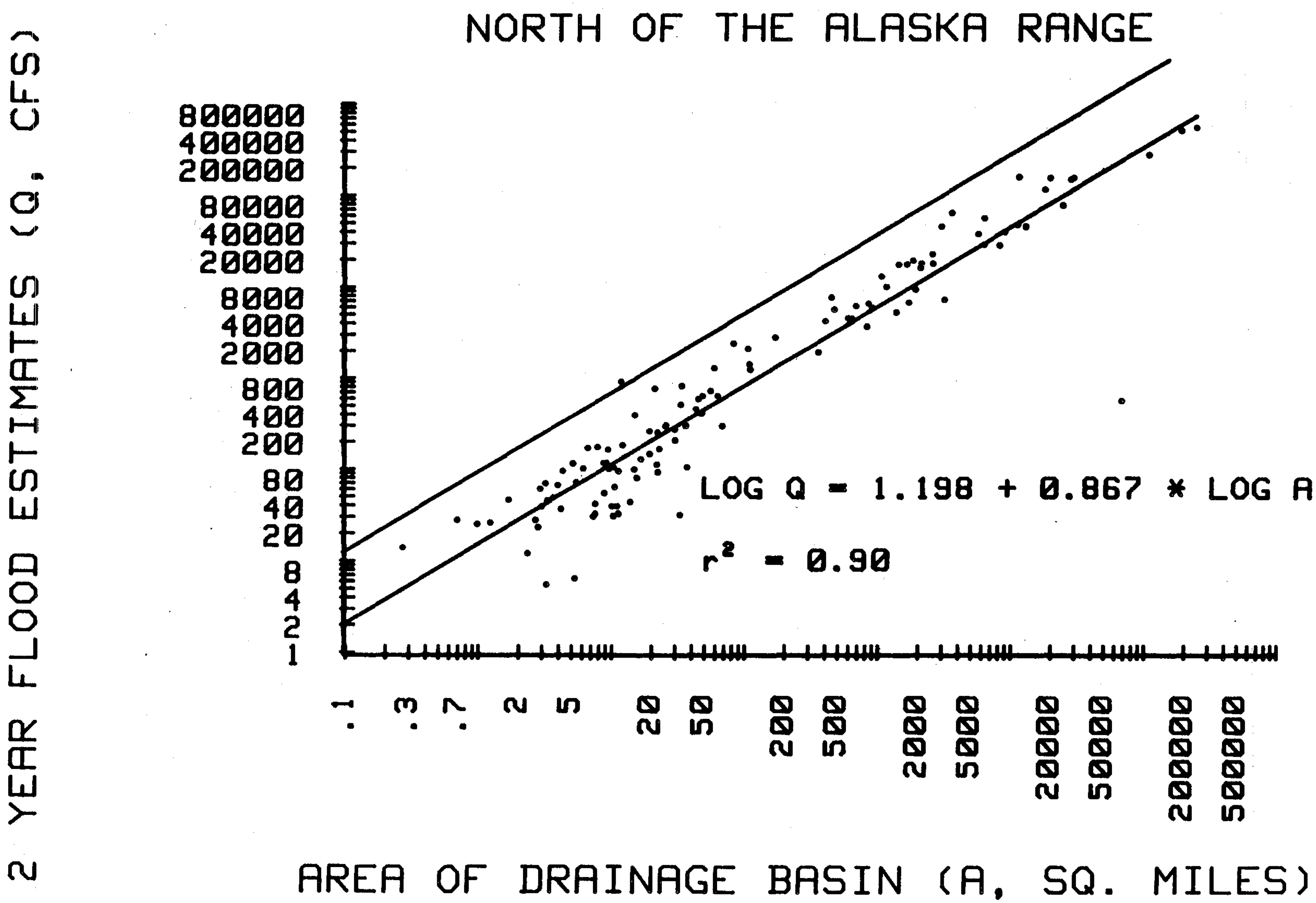


Figure 3. Two-year flood estimates for North of the Alaska Range (including Glenallen area) showing variation as a function of drainage area (Kane and Janowicz, 1985).

lower curve in these figures (1, 2 and 3) is the curve of best fit while the upper curve is the 95% upper confidence limit.

An examination of predicted floods using various return periods for a selected interior Alaska stream are shown in Table 2.

TABLE 2. Predicted floods for return periods of 2, 10 and 50 years for Globe Creek near Livengood (Area = 23 mi^2, N = 16 years, where n = number of years of record).

Method	P_2 (CFS)	P_{10} (CFS)	P_{50} (CFS)
2 parameter log normal	271	803	1,545
3 parameter log normal	236	930	2,340
Gumbel extreme value	318	702	1,040
Log-Pearson III	240	858	2,316
Lamke	246	811	1,810
Kane and Janowicz	239	635	1,138
Kane and Janowicz (upper 95%)	1,476	3,836	8,238

The point of presenting Table 2 is to show that considerable variation can occur in making design flow estimates depending upon the technique used. The reason for these variations are numerous. Flow records in Alaska are of a short length and data stations are very sparse. However, the most important factor as far as culvert design is concerned is that few stations are located on small streams where culverts are usually placed. Therefore, design flow estimates and, therefore, velocity estimates are not very accurate and considerable uncertainty is introduced in the first stage of culvert design. It should be noted that this uncertainty is greater for that area north of the Alaska Range.

Design Criteria for Fish Passage

In Alaska, it has been a general practice to determine the mean annual flood for a drainage area above a proposed culvert and determine what mean velocity would result due to this flood for various culvert design possibilities. Acceptable velocities for fish passage through culverts are derived from relatively few field studies. Although numerous reports are available related to fish swimming performance, a review of these papers reveals that a small core of papers are repeatedly cited. The reasons for this are that such studies are very difficult to perform, costly, labor intensive and open to criticism because of the need to handle the fish.

Most of the work related to swimming capability has been directed at anadromous fish with commercial value such as salmon (Johnson, 1960; Becker, 1962; Brett, 1965 a,b; Ellis, 1966; and Brett and Glass, 1973). More recently with accelerated resource development in cold regions the swimming performance of sport fish found in northwest Canada and Alaska has been studied (Jones, 1973; Jones et al., 1974; and MacPhee and Watts, 1976).

Ideally then, if one uses the results from the fish passage performance studies and a design discharge for the culvert, an acceptable design can be achieved. The first major difficulty here is that if a culvert is designed to handle a flood for a 50-year return period and the fish design is based on the mean annual flood (return period approximately 2.33 years), then, anytime the streamflow exceeds the magnitude of the mean annual flood, the velocity in the culvert will exceed that value used in the design and some of the fish may be delayed in their migration. In reality, some of the larger, more mature, and stronger swimming fish will be delayed less than younger fish. MacPhee and Watts (1976) observed many sexually immature grayling moving upstream with the adult grayling. The importance of this behavior is not clear. Many of the immature grayling also migrated downstream with the outflow of the adults.

The question here is whether or not fish can stand a delay in the migration when spawning. If the answer is yes, then how long? One can get an appreciation for this problem by examining the timing of various flood events for a particular region and comparing this to the pattern of fish movement in the same area (Ashton and Carlson, 1984). In most of Alaska, the spring snowmelt period usually produces fairly high flows and an examination of the flood series will reveal that many of the major floods are generated from snowmelt events. This corresponds with the upstream movement of grayling.

Another major problem in cold regions is that conditions used in the design of a culvert may not be those found in the field. A majority of small streams in Alaska have extensive ice deposits that develop during the winter months both in channels and drainage structures. Also, the capacity of culverts can be reduced by deposited sediment and debris. All these problems result in higher velocities within the culvert for a given discharge.

Finally, the installation of culverts may deviate from the actually design. For example, the culvert may not be installed at the proper slope or in some ice-rich areas where permafrost is located, settling of the culvert may change the characteristics of flow through the culvert.

FISH BEHAVIOR RELATIVE TO CULVERTS

Concern for fish passage through culverts is not a local problem. Resource development and its associated impact on the environment has induced engineers and biologists to address the problems of fish passage through culverts. Generally, for the northwestern states, British Columbia, Yukon and Northwest Territories and Alaska, road density has been low and, even more importantly, development has been minimal in the headwater streams where culverts are generally installed. Timber harvesting in these areas provided the first impetus for studying the impact of culverts on fish migration.

Many of the first studies were not directed at fish swimming capabilities; but rather, they defined the major problems with culvert installation that might hinder fish passage (Metsker, 1970; Evans and Johnston, 1972; Gebhards and Fisher, 1972; and USDA Forest Service, 1979). Slowly other reports started to appear where the swimming capability of the fish was compared with the hydraulic behavior of the culvert. Although this is the correct approach to take, little data existed that quantified the ability of the fish. The early work cited previously for salmon was first used; later, data for other fish types were gathered and more generalized relationships were developed.

Culverts can block or delay fish from migrating upstream for the purpose of spawning or utilizing the habitat. Obviously the complete blocking of spawning fish is more detrimental than the loss of habitat. The temporary delay of spawning fish can have a very important impact on fish passage because higher energy expenditures by the fish may preclude spawning. Delays may lead to predation by animals. Also, heavy fishing pressure exists along all highways in Alaska and since this is where culverts may delay migration, fish are quite vulnerable to capture.

In the literature, several researchers have accepted the concept that the swimming performance of fish can be divided into three categories. They are:

Burst speed - a speed which fish can maintain for only a very short period of time without substantial deviation or reduction. The time is generally only a few seconds and in reality varies depending upon fish species. Bell (1973) used 5-10 seconds, Blaxter (1969) 1-5 seconds and Bainbridge (1960) 1 minute. This is the velocity at which the fish may need to swim to pass a slotway in a baffled culvert or to enter a perched culvert.

Sustained speed - a speed which fish can maintain for a considerable length of time but ultimately results in fatigue. Again, various time frames have been used for this definition from 10 minutes (Jones et al., 1974) to 500 minutes (Brett, 1967). Generally it is felt that fish swimming at this speed are stressed and it is this velocity that is generally used in culvert design.

Cruising speed - a speed which fish can maintain for an extended period of time without fatigue.

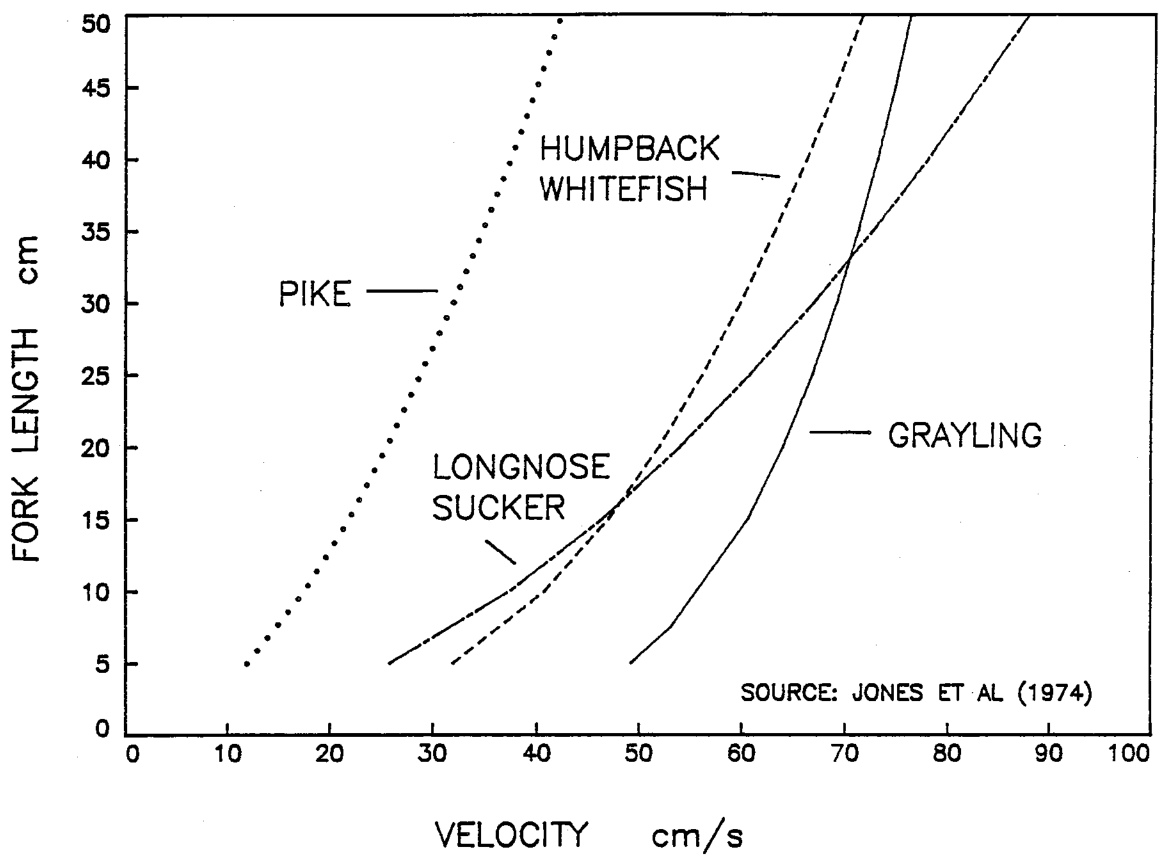


Figure 4. Swimming capability of selected fish versus for length.

Two major studies have been carried out to examine the swimming capability of several fish species that are found in Alaska. The first study by Jones et al. (1974) was performed on 17 species of fish found in the northern portion of the MacKenzie River drainage. Their general conclusions were:

1. The swimming capability of fish found in this region could be quantified using an equation of the form $V = KL^x$, where V is the water velocity (cm/s), K = constant, L = fork length (cm) and x is an exponent. A table of K and x values is presented for 10 species of fish. The results for grayling, longnose sucker, northern pike and humpback whitefish are shown in figure 4.

2. A weak relationship between swimming capability and water temperature was found for some large species of fish (northern pike, yellow walleye and arctic grayling).

The second study was that of MacPhee and Watts (1976) where they studied the swimming performance of arctic grayling and longnose sucker both in the laboratory and field at velocities ranging from 0.6 to 1.9 m/s. Tremendous quantities of data were collected in this study. The most important results were:

1. graphs for three years showing the numbers of grayling migrating upstream versus time for various size classes;

2. graphs of fork length versus water velocity that permitted 25, 50 and 75% of arctic grayling and longnose suckers to ascend either a 18.3 m or 30.5 m long culvert; and

3. graphs showing the cruising and sustained speed of arctic grayling that were tested in a circular flume as a function of fork length.

MacPhee and Watts also concluded that swimming performance of arctic grayling (141-172 mm) increased by 80% with a temperature change from 0°C to 14°C.

Both of these studies provide an enormous amount of data and knowledge about fish swimming performance, but they also raise several questions. When one compares the data of MacPhee and Watts to Jones et al. for the same fish, arctic grayling, substantially different conclusions are reached.

First, a plot of swimming performance versus fork length (Figure 5) shows that a large discrepancy exists in the swimming performance of arctic grayling. Part of this difference can be explained by the research methods used. Jones et al. (1974) were interested in establishing the critical velocity (a velocity that fish could maintain for 10 minutes). Their procedure was to allow the fish to swim at 10 cm/sec for one hour to acclimate themselves; thereafter, the velocity was increased by 10 cm/s for a time period of 10 minutes. The velocity was continually increased by the same velocity increments for each subsequent 10 minute period until the fish could no longer maintain this velocity.

MacPhee and Watts (1976) monitored the passage of spawning fish through two culverts (18.3 and 30.5 m long). Knowing the velocity through the culvert, they measured the percent success rate as a function of fork length.

Both of the previous research groups followed their field study with laboratory-type studies. The major differences in the results were that Jones et al. (1974) could not verify any relationship between swimming performance and water temperature (for arctic grayling); whereas, MacPhee and Watts (1976) felt there was a very significant effect.

Jones et al. came up with a relationship for the critical swimming velocity of:

$$V_{cr} = KL^{x} \tag{1}$$

where

V_{cr} = critical velocity - cm/s
K = constant
L = fork length - cm
x = exponent

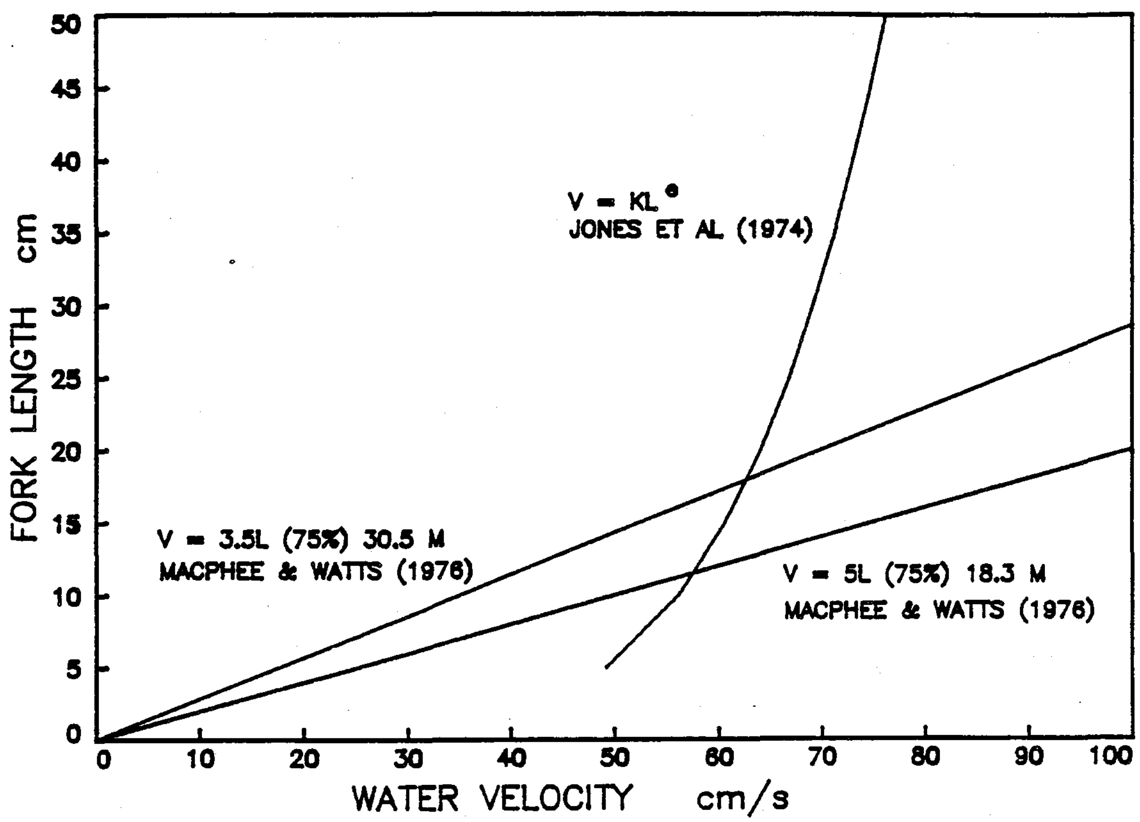


Figure 5. Swimming capability of Arctic Grayling versus for length from two different studies.

The curve in Figure 5 was plotted using the constant and exponent that they developed for arctic grayling. MacPhee and Watts came up with a linear equation, relating the water velocity with 75% success of passing for two culvert lengths:

$$V_w = 3.5L \qquad (30.5 \text{ m culvert}) \tag{2}$$

$$V_w = 5.0L \qquad (18.3 \text{ m culvert}) \tag{3}$$

where

V_w = water velocity for a particular culvert length, cm/s
L = fork length, cm

It is readily obvious from the results that if one is willing to accept that if 75% passing is acceptable, much higher allowable velocities would be predicted by MacPhee and Watt's data. It should be noted for MacPhee and Watt's study that the fish were able to rest before attempting to pass through the culvert. In the Jones et al. study, the fish were not resting prior to the critical velocity, but had been swimming at increasingly higher velocities for 10 minutes at 10 cm/s velocity increments before attaining the critical velocity.

Several questions can be raised concerning these studies:

(a) How important is the motivational factor on fish swimming performance?

MacPhee and Watts alluded to this point and tended to imply that spawning fish show higher swimming performance than nonspawning fish. It does not appear that the fish used by Jones et al. were studied during a spawning period. This may explain why some of the larger fish show a much poorer performance than those of MacPhee and Watts. MacPhee and Watts did clearly state that grayling migrating downstream were less motivated to swim vigorously than those migrating upstream.

(b) In MacPhee and Watt's study, numerous immature fish (generally less than 230 mm) were observed moving with spawners. Is it necessary that the culvert be designed to pass these weaker swimming fish or could they withstand a delay of several days without harm?

In the MacPhee and Watt's 1974 field observations, many of these fish (fork length 160-240 mm) returned downstream within three weeks of migrating upstream. Possibly this behavior was in response to decreasing stream flows. They did not collect downstream migration data for other years when different flow conditions may have prevailed.

(c) How critical is the timing of the fish migration relative to floods?

For arctic grayling this could be quite important. MacPhee and Watts' data showed that most arctic grayling arrived at their experiment culvert on the receding portion of the streamflow. Since these fish are moving upsteam while the flood wave is traveling downstream, they must meet. If a culvert is positioned along a stream where peaks of both the flood and the arctic grayling migration coincide, then the fish may be delayed for a considerable period of time until the flow rate declines.

(d) This discussion raises another point. How long can arctic grayling (or any other type of fish) be delayed in their migration for the purpose of spawning?

Dryden and Stein (1975) state that three days is the maximum amount of time that annual spawning migrations can be blocked. They also conclude that delays are more critical as fish approach the spawning areas. Lastly, they point out that delays up to seven days would be acceptable once in 50 years when the floods coincide with fish migration. While these guidelines are useful, there is very little scientific evidence of the physiological effects due to forced delays on spawning fish.

(e) Finally, do arctic grayling (or any other fish type) in one area have the same swimming capabilities as fish in another area?

For example, do arctic grayling in the interior of Alaska that overwinter for shorter periods of time have the same swimming capability as the same fish on the North Slope of Alaska that overwinter for longer periods of time? This is important, particularly for those fish that are spring spawners.

FIELD CULVERT PERFORMANCE

The major program of this research project was to evaluate the in situ performance of culverts along highways in Alaska in terms of hydraulic behavior and fish passage. Data collected in this effort is provided in a separate appendix to this report. Since the number of culverts is far too numerous to allow detailed evaluation of all and because the evaluation of those culverts performing adequately would not identify any type of problems, culverts selected for detailed observations generally had some deficiency that would result in fish being stressed in their upstream migration. Approximately 100 culverts were examined in detail and another 100 were casually observed. Every culvert was at least briefly examined along the Alaska Highway in Alaska, Dalton Highway, Denali Highway, Elliot Highway, Parks Highway, Richardson Highway and Steese Highway (Figure 6). In addition, select culverts were examined both in the Anchorage area where some type of baffle had been used to enhance fish passage and on local roads near Fairbanks.

In the transition from a natural stream into a culvert, the flow generally becomes more ordered. This is caused by the concentration of flow into a relatively smooth pipe that lacks the normal meandering patterns and boundary roughness of streams. In regards to fish, the water velocity is generally increased throughout the culvert cross

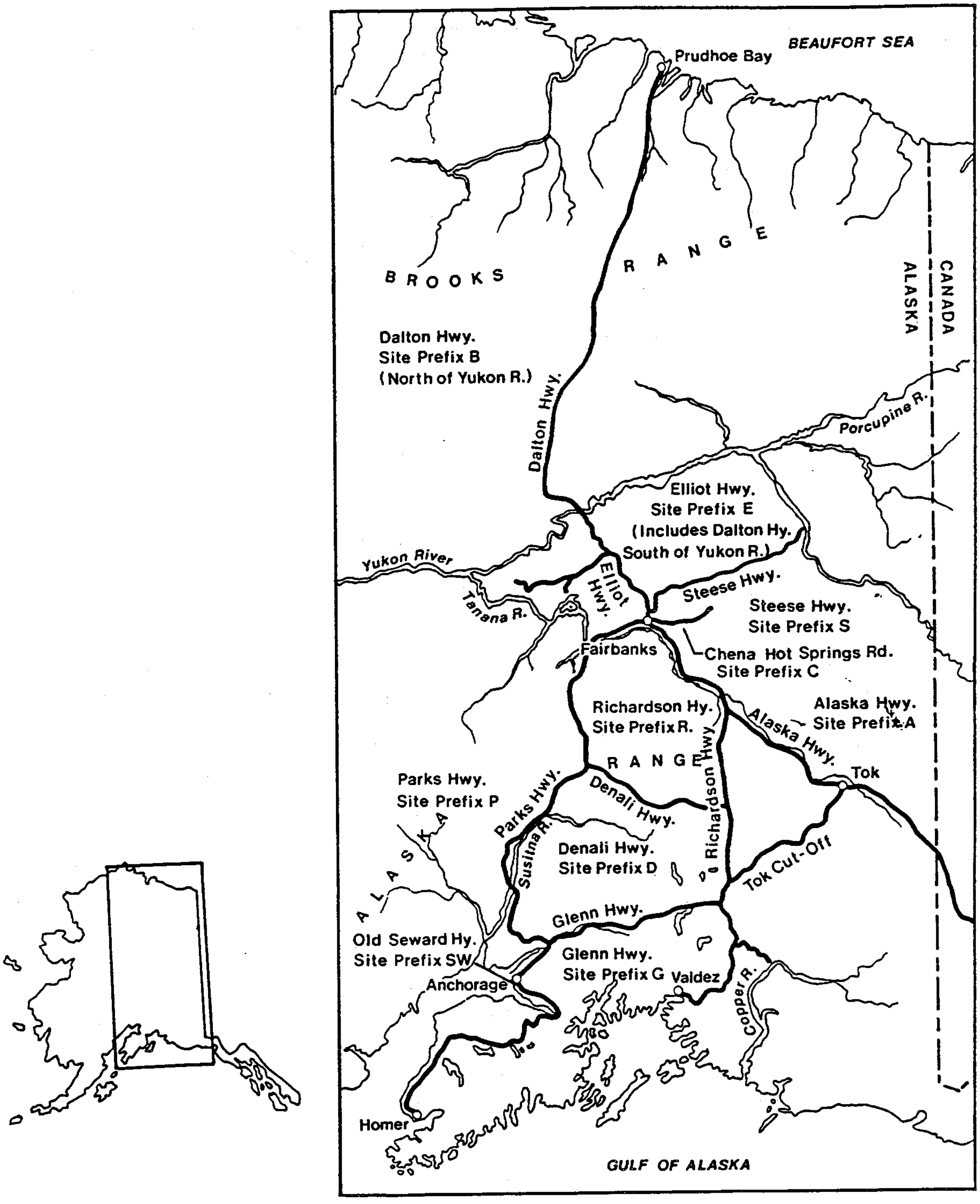


Figure 6. Location map showing both highways and site prefixes for culverts examined.

section. Increases of the velocity in the culvert can be due to many other reasons than roughness: increased slope, backwater effect upstream of culvert, obstacles within the culvert that produce supercritical flow, and free-fall or perched outlets. Since high velocities can be due to many factors, one goal of the field evaluation was to identify specifically why certain culverts would be an obstacle for fish passage.

The field program consisted of the following field measurements and observations:

1. culvert cross-sectional dimensions, length and slope;
2. slope of water surface 200 ft upstream of culvert, 200 ft downstream of culvert and through culvert;
3. velocity profile(s) within culvert;
4. discharge measurement;
5. photographs looking both upstream and downstream and at culvert inlet and outlet;
6. culvert condition (debris, perched, bed load size, distortion of barrel alignment, high water marks, aufeis, etc.); and
7. transition from stream to culvert and culvert to stream (debris, fish resting areas, alignment, etc.).

Some of the measurements are illustrated in Figure 7. The drainage area was determined from USGS topographic maps for all watersheds above culverts that were examined in detail.

Upon arrival at a culvert two questions were first addressed. Does this stream appear to represent fish habitat and, secondly, does the culvert appear to be a barrier (temporary or permanent) to upstream fish passage? The answer to the first part of this question was generally yes unless the stream crossed was at the head of the watershed and was a small first-order intermittent stream. The conditions that prevailed at the culvert depended upon the timing of the visit. Since it was physically impossible to visit all of the culvert sites during high flow, some sites were visited at low flow when the velocities would be more amenable to fish passage. Also, many streams exhibit extensive aufeis deposits that could be detrimental to fish passage. We recorded

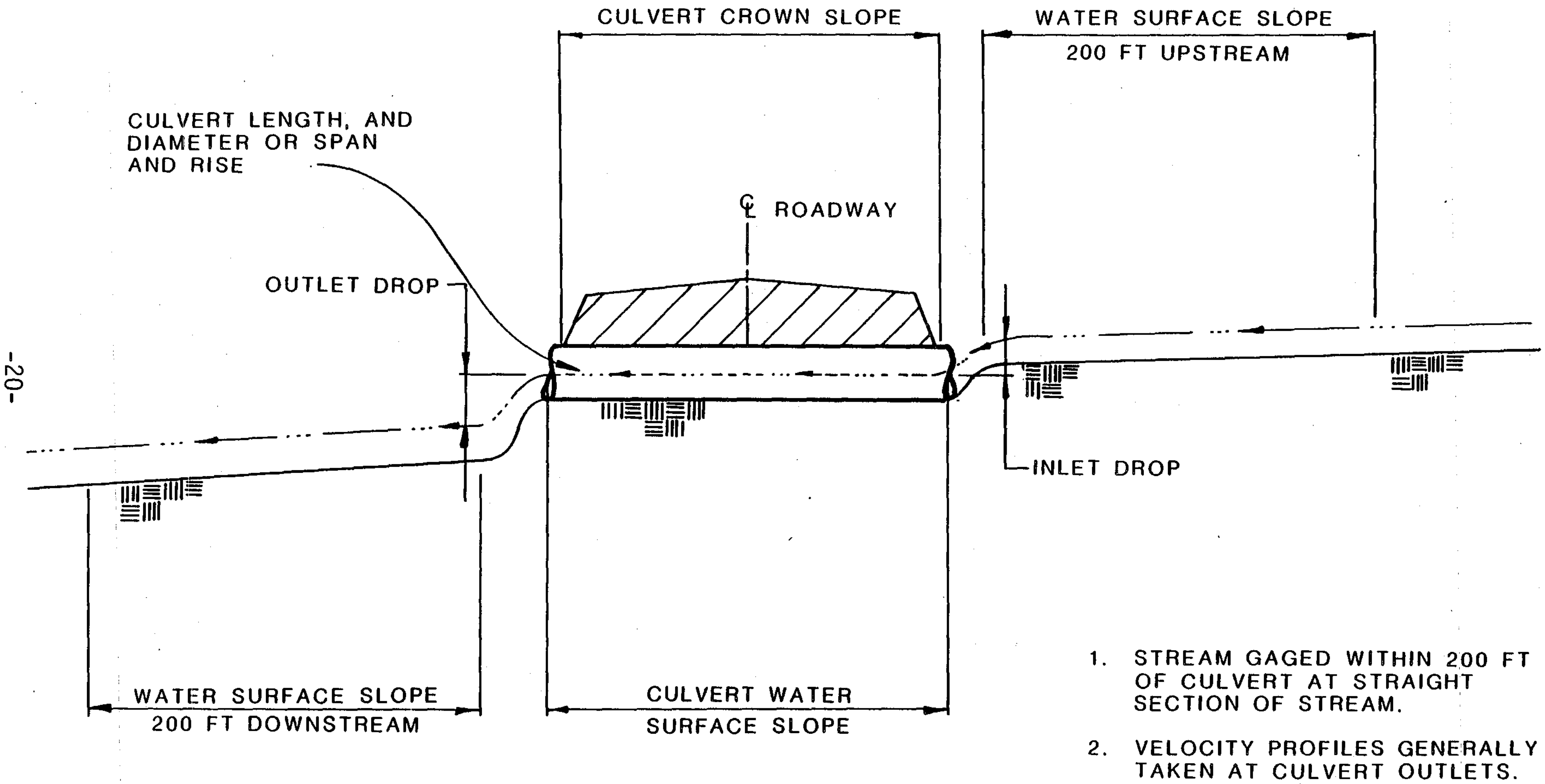


Figure 7. Typical site data collected. Schematic shows types and locations of data collected at a typical field location.

this information from sites visited in May and June, but later in the summer most of the ice had ablated and this problem was not evident.

High Velocity

The two most significant hydraulic deterents to fish passage are high velocities within the culvert and perched culverts. In some cases, high velocities existed in culverts because of the nature of the installation, while other cases of high velocity were due to changes or circumstances that were beyond the designer's control. Realistically, the problems of perching and high velocities cannot be considered as unrelated.

Over 25% of the culverts presented in the data report (Wellen and Kane, 1985) exhibited velocities that would likely deter upstream fish migration (Figure 8). The criteria used here was that velocities in excess of 4.0 fps would be detrimental to fish. This was based on present design criteria used in the state. In some culverts that we tagged as having velocities detrimental to fish, we did visually observe fish upstream of the structure. This could be due to lower velocities existing prior to our visit, lower velocities occurring near the water-culvert interface where fish would naturally swim, or fish having the capability of swimming against this arbitrarily assumed velocity. It is possible that lower velocities could occur at an installation than we observed; however, it is much more likely that higher velocities occurred, particularly during the snowmelt period. Since some types of fish spawn immediately after snowmelt, it is critical that the designer consider the flow regime at the time of migration. Because of these reasons it is certain that many more culverts had higher velocities than we observed because we only visited a small fraction of the sites during the period of high flow.

Steep slope in combination with the relatively low roughness of the culvert produces high mean velocity. Manning's equation can be used to determine the mean velocity.

$$Q = \frac{C}{n} R^{2/3} S^{1/2} A \qquad (4)$$

where

Q = discharge $[L^3/T]$

C = constant (C = 1.49 for English units and 1.0 for metric units)

n = Manning's roughness coefficient

R = hydraulic radius = A/P $[L]$

P = wetted perimeter $[L]$

S = slope

A = cross-sectional area $[L^2]$

This equation can be modified to determine the mean velocity by dividing each side of the equation by A:

$$V = \frac{C}{n} R^{2/3} S^{1/2} \tag{5}$$

It can be seen in this equation that as the slope increases the velocity increases; doubling the slope increases the mean velocity by a factor of 1.41. In contrast, increasing the roughness coefficient decreases the velocity; in this case, doubling the roughness coefficient decreases the velocity by a factor of 2. Natural streams have roughnesses that vary from 0.024 to 0.075 (Barnes, 1967). The same roughness factor for corrugated metal culverts vary from 0.022 to 0.038 depending primarily upon culvert diameter, flow conditions (whether full flow or partly full) and size of corrugations (U.S. Department of Transportation, 1980). Most of the culverts we observed typically have a roughness coefficient of about 0.026, whereas the roughness coefficient of most of the streams that we observed was greater than 0.04. Although we did not directly make the measurements to compute the roughness coefficient of the streams we visited, it can be estimated by using the color photographs presented by Barnes (1967).

To control velocity in culverts most designers suggest that a minimum gradient be used.

Evans and Johnston (1972)	at or near zero
U.S. Department of Agriculture Forest Service (1979)	3% less than actual grade

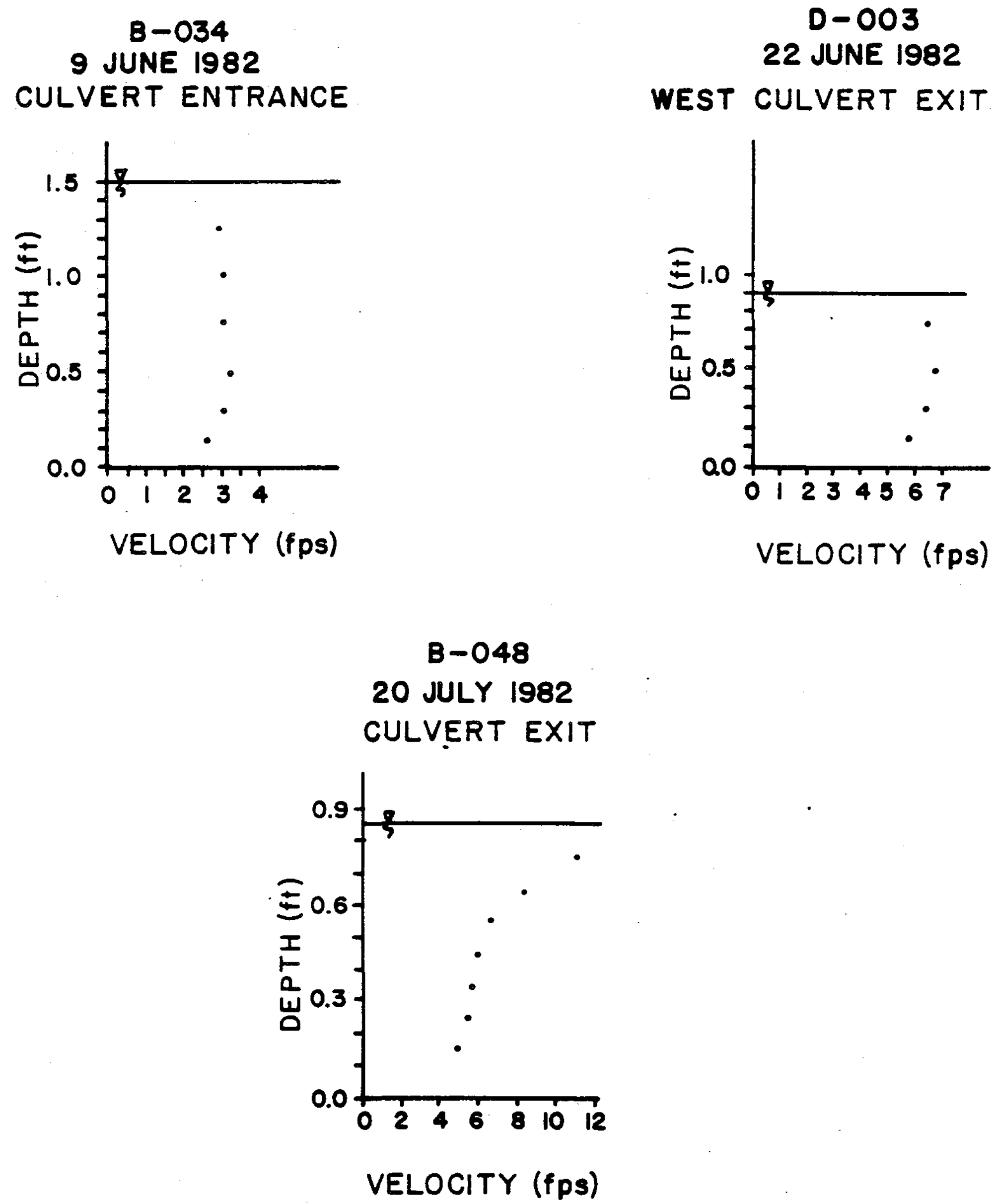


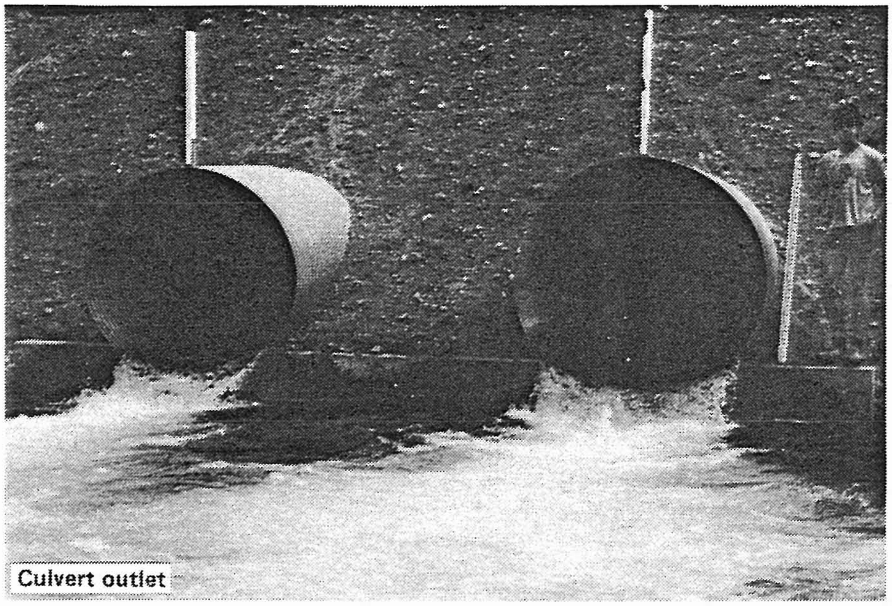
Figure 8. Typical profiles for low, medium and high velocities in culverts.

State of Alaska, DOT&PF, Hydraulics Manual	flat grade
Morsell et al. (1981)	0.5%
Dane (1978)	less than 0.5% without baffles; less than 5.0% with baffles
Dryden and Stein (1975)	prefer 0% gradient; less than 5.0% with baffles
Gebhards and Fisher (1972)	less than 0.5%

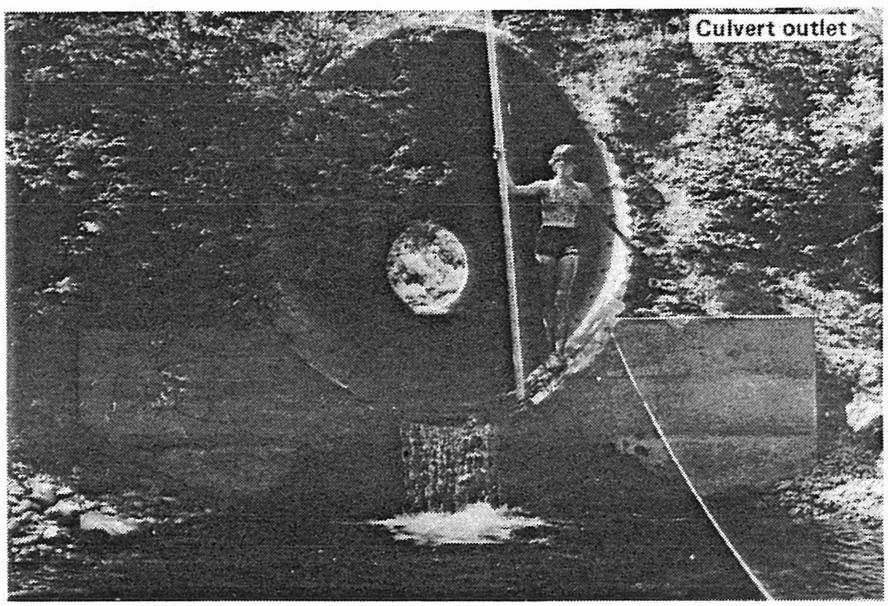
This approach results in the hydraulic structure being installed at a slope less than the stream gradient in many cases. Also, it results in a lower velocity only if the culvert is enlarged to handle the same design discharge. This approach does have its negative aspects, the major one being that the sediment carrying capacity may be reduced and debris is deposited at the upstream end of the culvert (USDA, Forest Service, 1979). Significant deposition at the culvert inlet can produce supercritical flow conditions near the inlet which are definitely not beneficial to fish.

Perching

Our classification of a perched culvert was based upon whether a drop in the water surface at the culvert outlet was apparent. Therefore, culverts perched at low flows may not appear to be perched at high flows. Over 40% of the culverts examined in detail were perched to some extent (Figure 9). The problem of perching was more prevalent for steep gradient streams. Also, the generalization can be made that greater heights of perching occurred for the steeper gradient streams (Table 3). All of the perched culverts encountered were observed in detail to assess whether some characteristic could be identified that would indicate the potential for perching. Except for the two generalizations above there was no identifiable reason for each case of perching. Possibly, if conditions during high flow were observed and the conditions prior to construction were known, reasons for the perching problem could have been identified.



(a) Slime Creek, Parks Highway (P-016) drop for north culvert 0.95', south culvert 1.54' (diameter 6 ft).



(b) Little Panguingue Creek, Parks Highway (P-014), drop 2.4' (diameter 10 ft).

Figure 9. Typical perched culverts found along Alaskan highways.

TABLE 3. Characteristics of perched culverts.

Site	Outlet drop (ft)	Inlet drop (ft)	Upstream slope	Downstream slope	Culvert slope	Water surface slope
			Alaska Highway			
A-001	0.7	1.0	.008	0	.035	---
			Chena Hot Spring Road			
C-001	0.7	---	.003	.011	.008	.009
			Dalton Highway			
B-016	0.47	---	.034	.031	.024	.038
B-035	1.10	.91	.025	.023	.035	.023
B-036	0.6	---	.025	.018	.020	.029
B-037	0.9	---	.029	.049	.035	.039
B-038	0.55	---	.022	.018	.006	.027
B-040A	1.11	---	.036	.036	.029	.035
B-042A	2.63	---	.025	.011	.022	.029
B-042	1.78	---	.010	.012	.012	.048
B-044A	---	1.59	.031	.031	.017	.023
B-045*	S 1.0	---	N 0.011	N 0.011	N 0.007	N 0.060
			S 0.021	S 0.010	S 0.014	S 0.028
B-048	0.62	---	.054	.032	.044	.061
B-050*	N 0.53	---	.008	.024	N .021	N 0.49
					M .024	
					S .027	
B-051*	1) 0.87	---	.044	.032	1) .022	.044
	2) 0.56	---			2) .021	
	3) 0.32	---			3) .024	
	4) 0.95	---			4) .022	
			Denali Highway			
D-002	1.01	---	.013	.020	.015	.016
D-003*	E 1.12	0.11	.001	.003	E 0.010	E 0.021
	W 1.08				W 0.012	W 0.022
D-007	.89	---	.015	.014	.025	.029
D-013	0.80	---	.027	.018	.022	.042
D-014*	E 2.98	---	.050	.071	E .076	E .078
	W 2.96	---			W .063	W .077
D-015	2.50	---	.011	.060	.027	.042
D-017*	E 0.68	---	.022	.025	E .040	.056
					W .039	
D-018	1.47	---	.011	.031	.033	.050
D-019	2.98	---	.028	.052	.033	.044

TABLE 3 (Continued)

Site	Outlet drop (ft)	Inlet drop (ft)	Upstream slope	Downstream slope	Culvert slope	Water surface slope
			Denali Highway (Continued)			
D-020	0.94	---	.052	.054	.035	.057
D-021	3.59	---	.036	.054	.035	.061
D-022	1.12	---	.050	.057	.049	.065
D-023	0.93	---	0	.042	.025	.039
			Elliot Highway			
E-001	3.01	---	.002	.008	.003	.015
E-008A*	N 0.49	---	.002	.011	N .011	N .016
	S 0.39	---			S .012	S .017
			Old Seward Highway			
SW-001*	N 7.84	---	.031	.054	N .023	N .023
					S .022	S .023
			Parks Highway			
P-008	---	.52	.015	.023	.026	.038
P-011*	---	S 1.23	.032	.022	N .024	N .026
					S .023	S .031
P-014	2.38	---	.037	.026	.032	.031
P-016*	N 0.95	---	.016	.024	N .021	N .036
	S 1.54	---			S .018	S .030
			Richardson Highway			
R-009	0.12	0.68	.038	.047	.027	.029
R-010	0.44	0.84	.013	.015	.019	.023
R-011	0.78	0.78	.001	.003	.007	.034
			Steese Highway			
S-005	0.42	1.38	.006	.010	.014	.026
S-006	0.90	1.56	.007	.018	.016	.021
S-029	4.34	---	.022	.038	.032	.035

* Multiple culverts.

Very little information was found in the available literature of fish's jumping ability or the ability to pass vertical obstacles. Where it has been determined that salmon fry move upstream for better habitat conditions, it has been assumed that they have no jumping ability. In general, as fish grow their jumping ability increases. This presents the situation where some adult spawners may pass a perched culvert but not the smaller fish that may wish to utilize the habitat. On many of the streams where perched culverts existed, we observed grayling upsteam of the culvert. For example, an unnamed creek on the Denali Highway (site D-013, mile 83) was perched at the outlet 0.8' and upstream of the culvert there was a natural vertical drop of 1.5'; grayling approximately 9 in (230 mm) in length were seen below and immediately above the culvert, as well as above the natural drop. Apparently these drops would not limit adult spawning grayling from migrating upstream but may have limited younger grayling.

There is also the joint problem of perched culverts and high velocities occurring together. We observed some perched culverts where the fish would have been stopped because of the amount of perching; however, there were many streams where we felt that the combination of perching and high velocities together may have prevented upstream migration of fish.

It is doubtful that culverts are perched at the time of installation. The process of scouring at a culvert outlet is quite complex. An ideal design would result in material that is eroded below a culvert being replaced by upstream material. What is more commonly seen is that low velocities are produced upstream of a culvert and the transport capability of the stream is reduced. This results in upstream deposition; then as the water flows through the culvert, it accelerates and erodes new material at the downstream end. This material may be carried only a short distance before the velocities again decrease and the eroded material is redeposited.

The point that we are trying to make here is that by flattening the slope the velocity is reduced; but this may result in the development of another condition at the culvert that is detrimental to fish. This is the problem of perching. When considering the velocity in a culvert, one should not ignore the effect that the installation of a culvert has on the sediment carrying capacity of a stream.

Inlet Drops

On about 10% of the culverts examined in detail, we observed a drop at the upstream inlet (Figure 10). Obviously this might be a deterrent to fish that have successfully moved upstream through a culvert against high or even moderate velocities. In all cases this drop was due to the deposition of material that was either from the natural stream channel or from the roadway embankment itself. When it was from the stream channel, the deposition was due to lower velocities at the upstream end of the culvert because the culvert was at a flatter gradient than the stream. If the material was from the roadway embankment then the material was riprap deposited at the culvert entrance because the finer underlying material had been eroded away and the heavier riprap rolled down the embankment to rest in front of the culvert.

At several sites during low to moderate flows, debris at the culvert inlet was responsible for the formation of supercritical flow. Supercritical flow can be defined by the Froude number:

$$F = \frac{V}{(gd)^{1/2}} \tag{6}$$

where

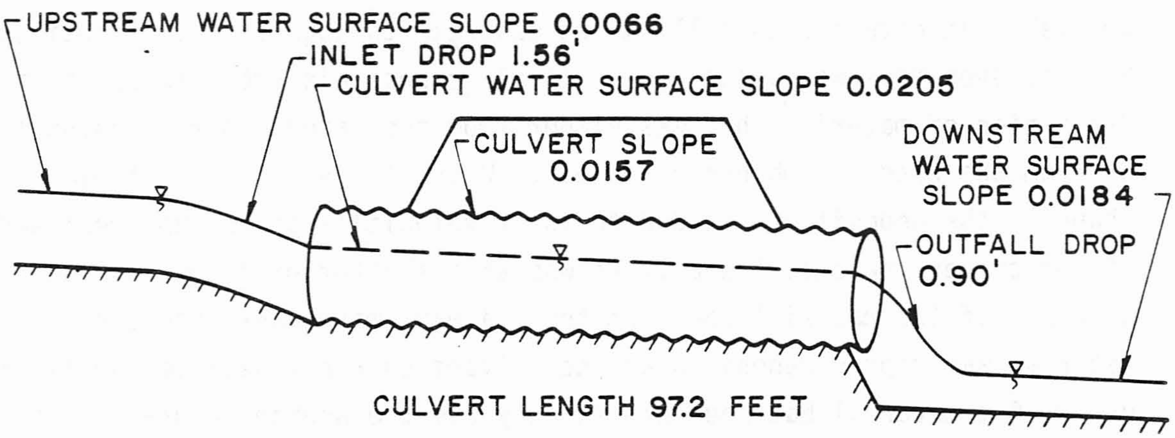
F = Froude number, dimensionless

V = velocity [L/T]

g = gravitational acceleration [L/T^2]

d = depth [L]

The Froude number is either a ratio of the inertial force to the gravitational force or a ratio of the velocity of the water to velocity of an elementary wave. Froude numbers in excess of 1 describe supercritical (rapid) flow and numbers less than 1 indicate subcritical (tranquil) flow. Either flow regime can occur at the same level of specific energy; however, the flow regimes are quite different because



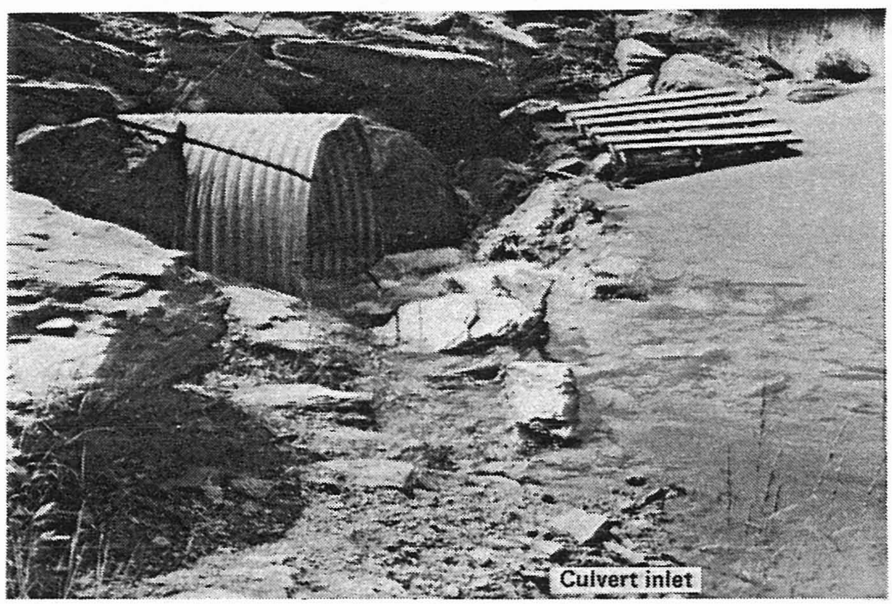


Figure 10. Photograph and profile of a culvert on Boston Creek (site S-006) with an inlet drop (Diameter 4 ft 6 in).

supercritical flow is associated with high velocities and shallow depths and subcritical flow is associated with low velocities and deeper depths. A common field experiment is to throw a rock in a stream; if the wave produced travels upstream the flow is subcritical ($F < 1$).

Supercritical flow even over short distances is a definite obstacle to fish migration. In all the cases of inlet drops where supercritical flow developed there was a transition from supercritical flow to subcritical flow within the culvert. This transition is achieved through a hydraulic jump which is quite evident because of a rapid increase in depth and a reduction in the water velocity.

This condition of an inlet drop is due to the fact that the installation of the culvert has modified the sediment carrying capacity of the stream. Reducing the culvert slope to minimize the culvert velocity will produce this condition. This raises the same point as made in the previous section; one should not alter the stream slope by placing a culvert at a flatter slope without considering the consequences of this action on the sediment carrying capacity.

Aufeis

One of the most difficult phenomena to assess in terms of fish passage is that of aufeis. Aufeis can be described as the build-up of ice in the channel that occurs throughout the winter season as water flows from beneath the ice to the surface through cracks in the ice cover (Figures 11, 12 and 13). This water freezes when exposed to the ambient air and this produces over the winter several layers of ice that can completely fill the stream channel and extend over the banks and into the flood plain. Nearly 25% of the culverts visited had extensive aufeis deposits; this value would have been considerably higher had all of the installations been visited immediately after breakup.

The problem of aufeis is a large maintenance problem for DOT&PF. This ice can completely fill culverts and when this occurs, unless steam equipment is used to initiate flow through the culvert, water will run over the roadway. From a fishery and hydraulic viewpoint, this ice reduces the cross-sectional area of flow so that during periods of peak flow high headwater conditions are produced. This high headwater,

Figure 11. Aufeis accumulation at Douglas Creek (B-012), Dalton Highway prior to bridge construction (span 12 ft 4 in, rise 7 ft 9 in).

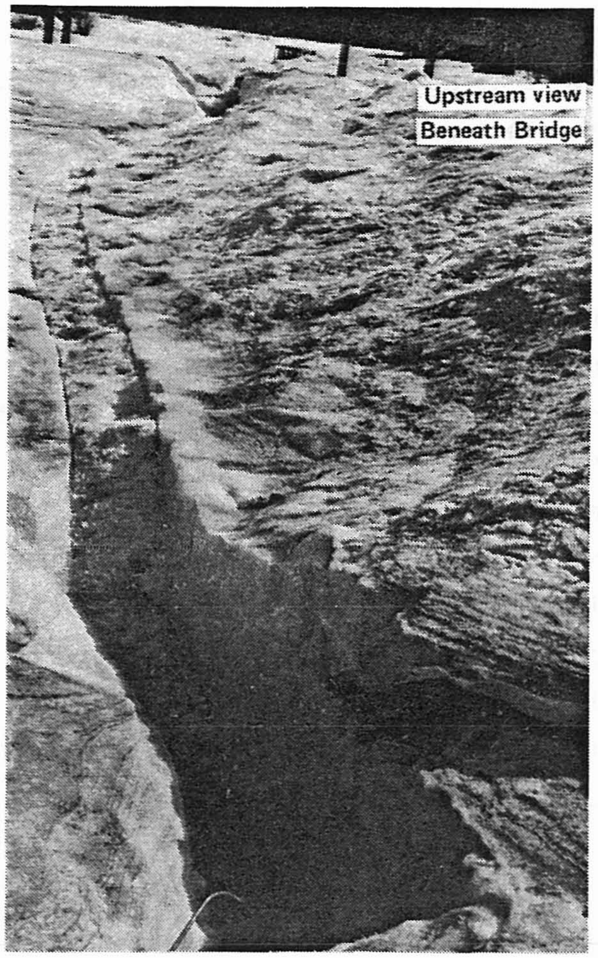


Figure 12. Aufeis accumulation at Douglas Creek (B-012), Dalton Highway after bridge construction.

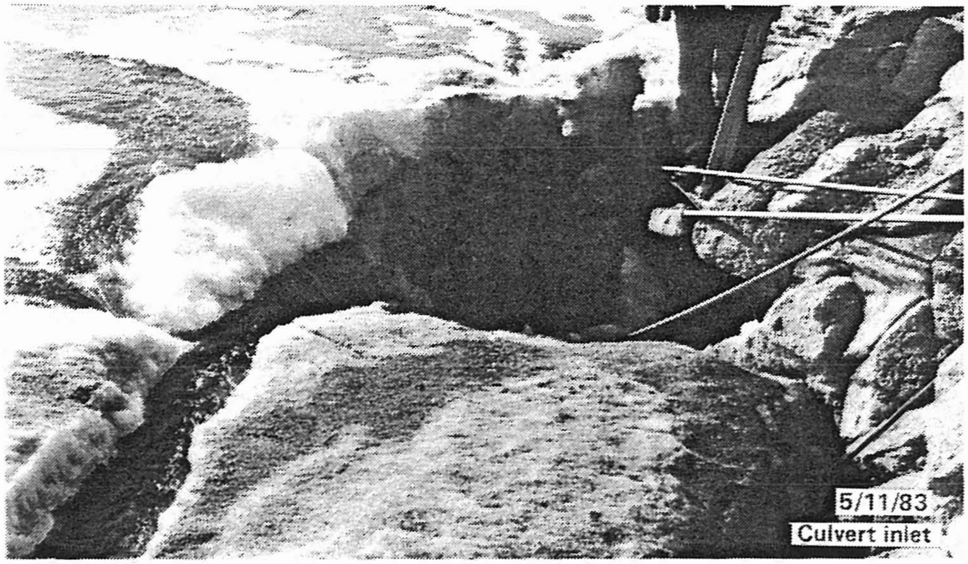


Figure 13. Extreme aufeis accumulation at inlet of a culvert at Alder Mountain Creek (B-007), Dalton Highway (span 9 ft 6 in, rise 6 ft 5 in).

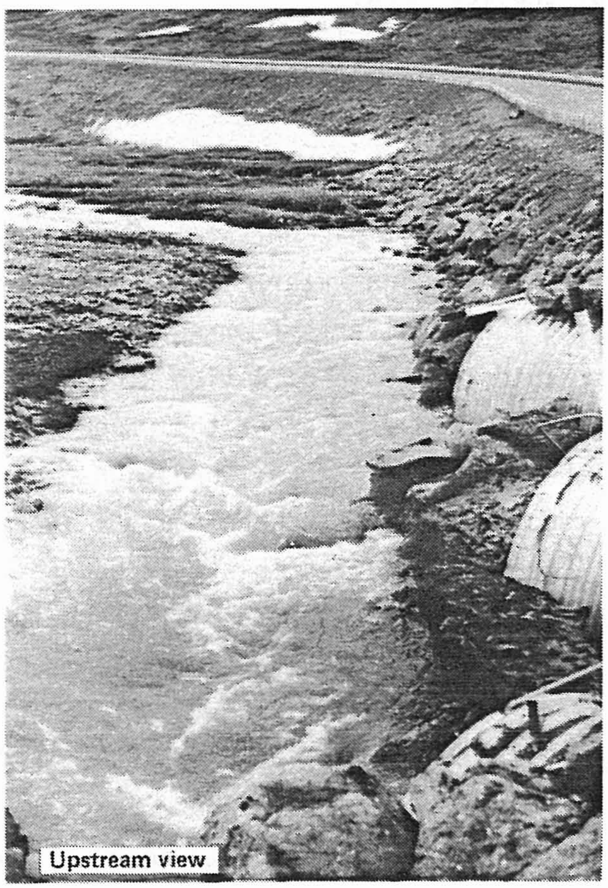


Figure 14. Typical problem where culverts are not aligned with stream flow, WF of the NF of the Chandalar River (B-043), Dalton Highway (span 10 ft 8 in, rise 6 ft 11 in).

combined with the low roughness of ice, produces much higher velocities than indicated by the design. Most of the ice in the culvert is removed during the snowmelt runoff period; in come cases considerable ice remains after the breakup period, particularly upstream of the culvert in the channel and flood plain.

This is not a problem that can always be solved by replacing the culvert with a bridge. An example of this is Douglas Creek (site B-012) on the Dalton Highway. During the first year of the study a culvert was in place; during late summer it was replaced with a bridge. At the time of breakup, ice extended up to the bottom supports of the bridge and maintenance crews were busy cutting a channel in the ice (see Appendix). It should be noted that while culverts may increase the severity of the aufeis problem, this process occurs naturally in small shallow headwater streams as well as in much larger braided streams and rivers that are characterized by shallow flow.

Alignment

In eight streams, serious maintenance problems existed because when the culvert was installed it was not aligned with the natural stream channel (Figure 14). Flowing water changed direction up to 90° when either approaching these culverts from upstream or exiting these culverts. This rapid change in direction of the water produced substantial turbulence and erosion of the roadway embankment.

In the DOT&PF Hydraulics Manual, under Chapter 7 on spawning streams, it is recommended that sudden changes in alignment be avoided. It was obvious that at some sites this rule had not been adhered. When steep gradients stream meander substantially and these meanders are cutoff by the positioning of a culvert, the slope of the culvert will be greater than the stream slope if the ends of the culvert match the original stream elevations. This condition will definitely result in culvert velocities being much greater than the actual stream velocities. Also, this condition may be conducive to scour at the culvert outlet.

Nonuniform Slopes

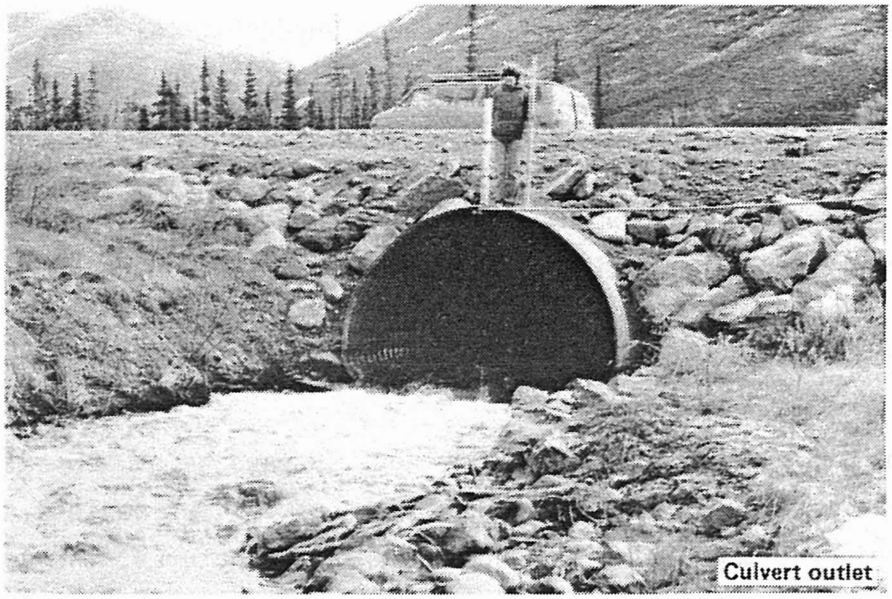
During low flows it was easy to observe that the slope of some culverts were not uniform. Five culverts were observed to have sufficient variation in slope to produce supercritical flow. Generally, the upper half of the slope would have a steep slope and the lower half would have a horizontal or adverse slope; this condition appeared to result from settling of the culvert. This could be caused by the culvert being situated on ice-rich permafrost that had partially thawed or a poorly prepared base for the culvert.

Baffled Structures

For the sole purpose of enhancing fish passage, a few culverts in the state have been modified with baffles of various designs. Although some engineers and biologists knew of these structures, there had been no apparent attempts to evaluate the performance of these baffles after the installation.

On Abba Dabba Creek (Figure 15, site B-016, Dalton Highway) an arch-type culvert with a span of 9 feet 6 inches and a rise of 6 feet 5 inches was fitted with baffles. Metal plates 6 inches high and 4 foot wide were irregularly spaced at intervals of 3 and 6 feet. The plates were connected with chains that were fastened to the upstream lip of the culvert. This culvert was perched (approximately 0.5 feet) and was placed at a 2.4% slope. Velocity profiles downstream of a baffle near the culvert exit and another profile 20 feet upstream of the culvert exit show that very low velocities exist in the area surrounding the baffles. Some sediment was trapped behind the upstream baffles, in addition a few of the baffles on the lower part of the culvert had been damaged. Overall it appeared that this baffled culvert was functioning quite well and serving its purpose.

Rabbit Creek (Figure 16) on the Old Seward Highway south of Anchorage had concrete baffles installed in two parallel culverts (span 9 feet 6 inches and rise 10 feet 8 inches). The right culvert (looking downstream) had most of the baffles destroyed or missing and most of the flow was through this culvert. The baffles in the left culvert were not



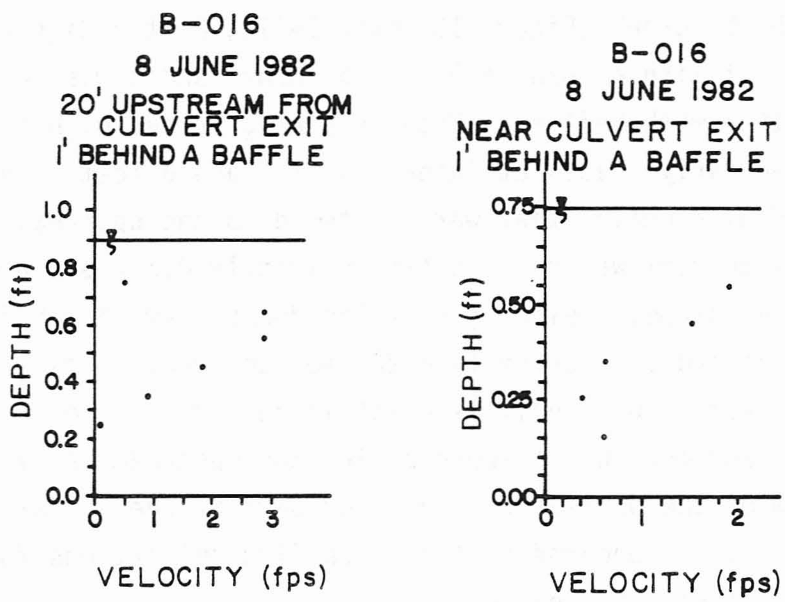
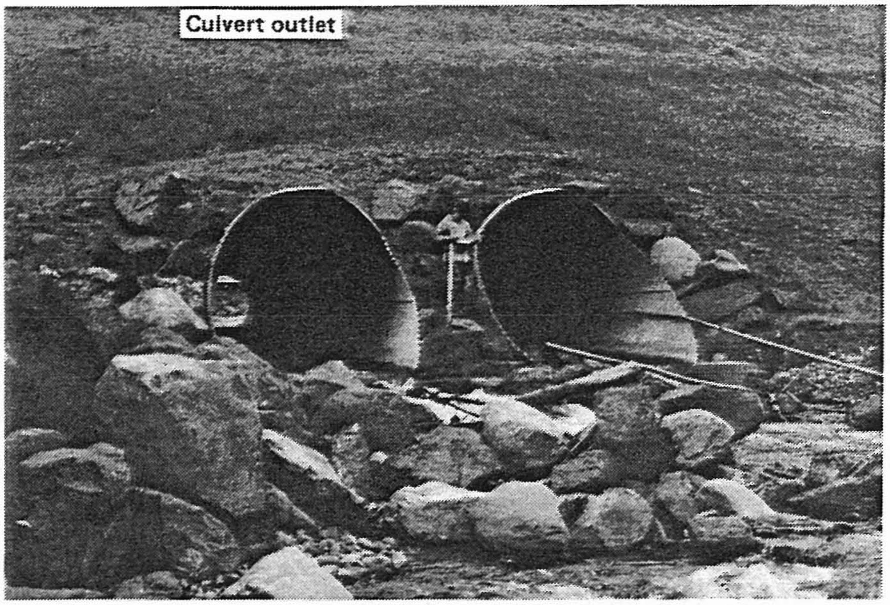


Figure 15. Photo of baffled culvert outlet at Abba Dabba Creek (B-016), Dalton Highway with two velocity profiles (span 9 ft 6 in, rise 6 ft 5 in).



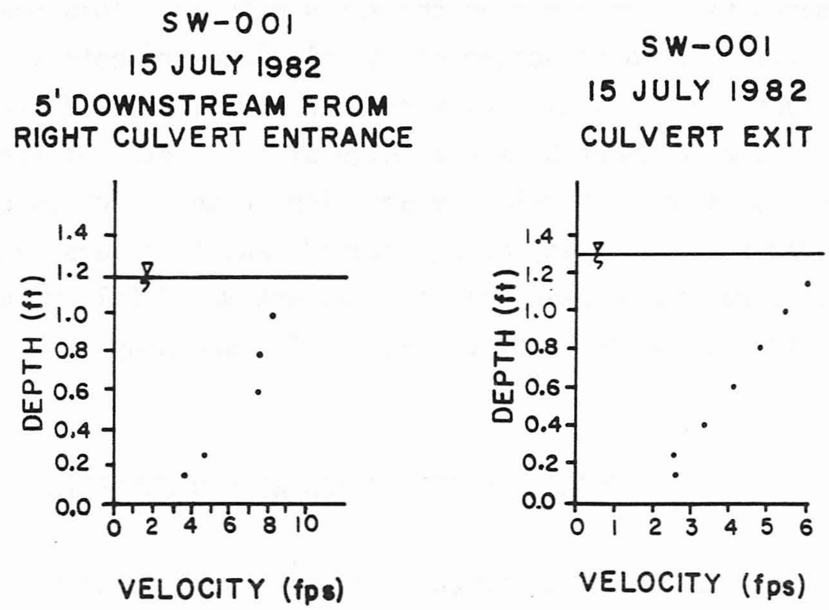


Figure 16. Photographs of baffled culvert outlet on Rabbit Creek (SW-001), Old Seward Highway with two measured velocity profiles (span 9 ft 6 in, rise 10 ft 8 in).

visible because they were buried in approximately 1.4 feet of sediment that had accumulated in the culvert. The slope of the culverts was about 2.3%; however, there was a drop of 7.8 feet just downstream of culvert outlet. At the flow conditions that prevailed at the time of the visit, it was obvious that these baffles were no longer effective. Velocity profiles in the right culvert show that the baffles influence the velocity some, but not as effectively as they should because of the damage and sediment.

A 7 feet 6 inch circular culvert in Meadow Creek (Figure 17) on Eagle River Loop Road off the Glenn Highway was also installed with baffles. Steel plating 6 inches high had been welded in place at 6 feet spacing. The baffles had been notched on alternating sides to channel the flow from side to side in the culvert; this technique did not appear to be effective as the flow went straight through the culvert. Velocity profiles taken in the culvert illustrate that the baffles are working properly in that the velocity is reduced.

The last baffled culvert to be visited was Wasilla Creek (Figure 18) on Palmer-Wasilla Road off of the Parks Highway. This road was in the midst of major reconstruction so detailed measurements were not made. Two identical arch-type culverts had been installed with four concrete sills, each about 30 inches high at the center of the culvert. Neither the slopes nor the velocity are high in this section of the stream. Sediment was already being trapped behind the upstream sills. Eventually, it was forecasted that the culvert would fill with sediment over the entire length and provide habitat for spawning fish.

VELOCITY DISTRIBUTION WITHIN CULVERTS

Present design criteria for culverts in Alaska makes use of the mean velocity in the cross-section for the mean annual flood. However, it is common knowledge that fish do not seek areas where the mean velocity exists when migrating, but instead they seek the path of least resistance. This is where the velocities are the lowest which is near the banks and bottom of natural streams and along culvert boundaries.

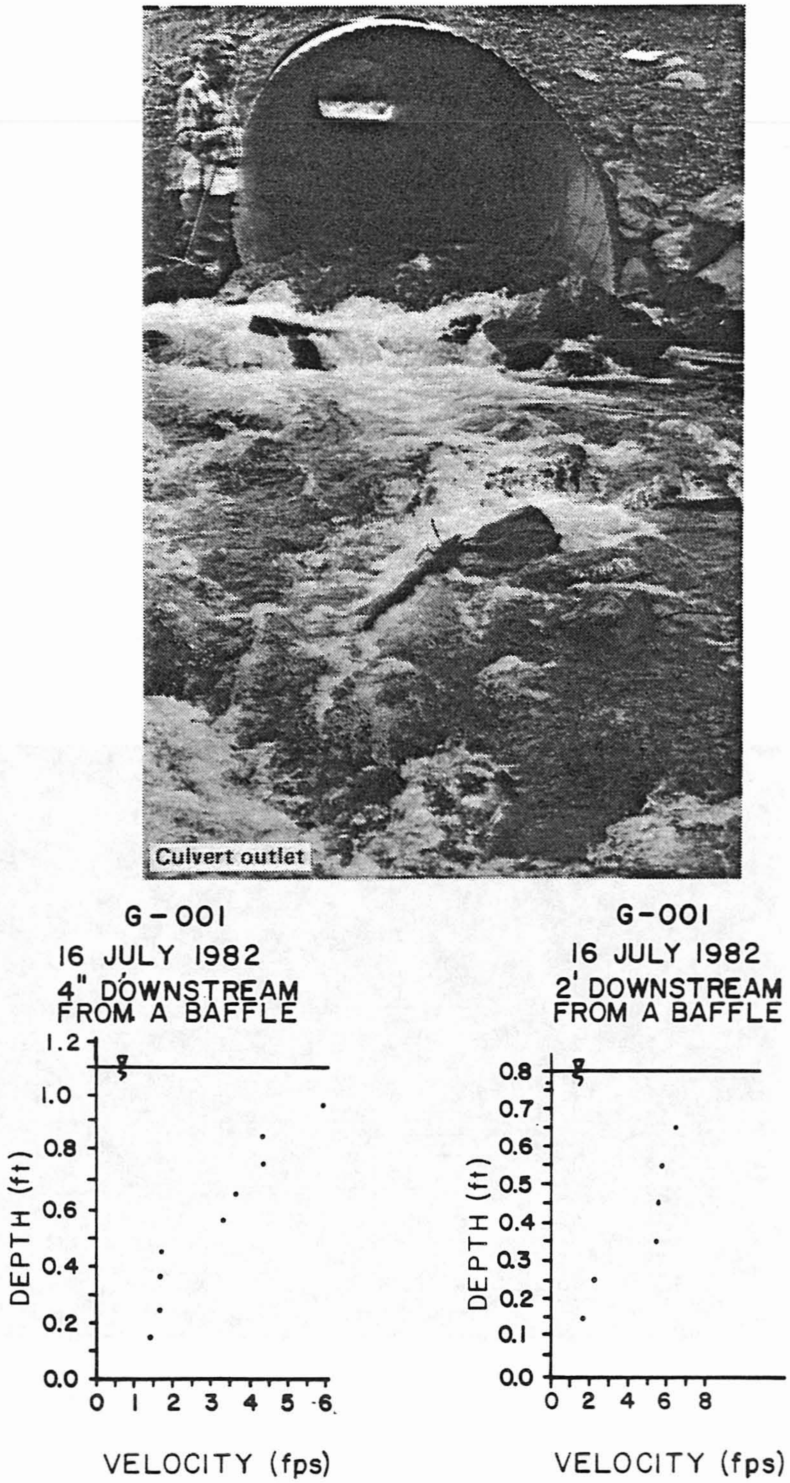


Figure 17. Photograph of baffled culvert outlet on Meadow Creek (G-001) of the Glenn Highway on Eagle River Loop Road with two measured velocity profiles (diameter 7 ft 6 in).

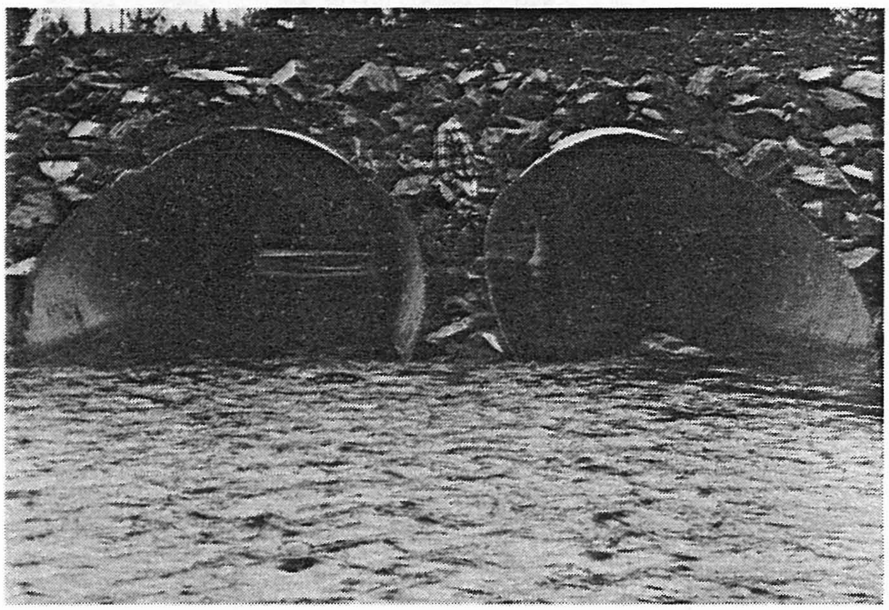


Figure 18. Photograph of baffled structure on Wasilla Creek (P-050) on Palmer-Wasilla Road off the Parks Highway (span 9 ft 6 in, rise 6 ft 5 in).

In this study we wanted to examine in detail the velocity profiles in culverts for various field conditions and also propose the concept that for fish passage design, velocities near the boundary be used instead of the mean velocity. The rationale for this approach is that first, this is where fish swim and second, by altering the roughness of the culvert the velocity can be modified in the near vicinity of the boundary.

The concept of using some measure of the velocity near the boundary is not new. Morsell et al. (1981) proposed the concept of the velocity in what they call the occupied zone. We will continue to use their notation of $V_{occupied}$. The size of the occupied zone has to be defined for each type of fish and then some technique developed to predict what the velocity is in this zone.

Morsell et al. (1981) defined the velocity in the occupied zone as:

$$V_{occ} = V_{skin} + 0.25(V_{ave} - V_{skin}) \tag{7}$$

where

V_{skin} = water velocity adjacent to sides of culvert [L/T]
V_{ave} = average water velocity within culvert [L/T]

They arbitrarily define:

$$V_{skin} = 0.4\ V_{max} \tag{8}$$
$$V_{ave} = 0.8\ V_{max} \tag{9}$$

This means that

$$V_{skin} = 0.5\ V_{ave} \tag{10}$$

Substituting these equations back into Equation 7 yields:

$$V_{occ} = 1.25\ V_{skin} = 0.625\ V_{ave} = 0.5\ V_{max} \tag{11}$$

This is a simpler expression than they present in their paper. Generally the average velocity (V_{ave}) is determined from Manning's equation and using Equation 11 the velocity in the occupied zone can be determined. There is no need to determine the skin velocity before determining the velocity in the occupied zone.

We have some reservations about the form of the equations used to determine the velocity in the occupied zone, but we do strongly support the concept of using the velocity in the occupied zone when designing culverts.

Our suggestion is that first the size of the occupied zone be defined by the type of design fish in the stream and then the velocity in this zone be determined by using established equations. Chow (1964) presents an equation to predict velocity profiles incorporating three variables: average velocity, relative depth and a roughness coefficient:

$$\frac{(V - V_{ave})C}{V_{ave}(8g)^{1/2}} = 2 \log_{10} Y/Y_o + 0.88 \qquad (12)$$

where

- V = velocity at any point (fps)
- V_{ave} = average velocity in cross-section (fps)
- Y = depth at any point (ft)
- Y_o = total depth (ft)
- C = Chezy's roughness coefficient

Earlier we used Manning's roughness coefficient (n) and this can be equated to Chezy's roughness coefficient:

$$C = \frac{1.49}{n} R^{1/6} \qquad (13)$$

If Equation 13 is substituted into Equation 12 and rearranged:

$$V = \frac{(32g)^{1/2}}{1.49} V_{ave} nR^{-1/6} \log_{10} (Y/Y_o) + \frac{0.88(8g)^{1/2}}{1.49} V_{ave} nR^{1/6} + V_{ave} \qquad (14)$$

Predictions of velocity were made for many (47) of the culverts where velocity profile measurements were taken. In 34 cases the predicted velocity profiles conform quite well with those measured, while in 13 cases the comparison is not very good.

Substantial variation exists in Manning's roughness coefficient for the culverts observed. The main reason for this is that sediment and large riprap was found in the bottom of the culverts, in some cases for the entire length and for other cases only in part of the culvert. This could often be observed in the measured velocity profiles. Instead of the velocity profile being uniform as depicted in many publications, it was often irregularly shaped. It must be recalled that many of these culverts have been in place for a considerable time, so conditions have changed at the site. This could be due to debris within the culvert barrel, but also the culvert could have been deformed, slope changed, or culvert perched. Perched culverts typically result in the flowing water accelerating at the outlet of the culvert and many of the measured profiles were taken here.

Our estimate of the average Manning's n over the entire length of the culvert was determined by the slope (from elevation measurements at each end of culvert), discharge measurement (made in the stream), and hydraulic radius and area determinations (made at point of velocity profile measurements). Because it was difficult to make water surface measurements in many cases inside the culvert, entrance and exist losses are also reflected in our estimate of n.

In our predictions for the velocity profiles we used an average Manning's n for the entire culvert length; technically we should have used a value for that section of the culvert where the velocity measurement was made. But since we did not have water surface elevations throughout the culvert, we could not generate an n value for just a section of the culvert.

RECOMMENDATIONS

Our recommendations fall into two classes: design recommendations that are known to enhance fish passage and research recommendations that may lead to enhanced fish passage.

A. More design consideration should be given to the location of stream crossings. Instead of the roadway alignment being dictated solely by geotechnical criteria away from the stream, hydraulic criteria of the stream should also be used. For example, hydraulic structures should be placed in stream segments where the channel is straightest so that the slope of the channel is not greatly increased because natural meanders were eliminated. In many cases, such as roadway upgrades, implementation of this recommendation may not be possible because of the existing right-of-way agreements.

If the slope of the stream can be maintained in the hydraulic structure, the velocities should be closer to actual channel velocities. More careful selection of a site should help minimize alignment problems where erosion of the embankment occurs and riprap material ends up in either the channel or culvert.

Present DOT&PF design criteria already makes this suggestion, but it appeared in many cases that no effort was made to adhere to this guideline. It was also alluded to earlier that considerable erosion had occurred around both inlet and outlet when the culvert structure was not aligned with the stream; so, maintenance cost would also be reduced by following this guideline closer when possible.

B. More careful placement of riprap at the upstream end of culverts should be attempted. Supercritical flow in culverts could be attributed to riprap that was dislodged from the embankment slope to the stream channel or culvert. Most riprap appears to have been placed directly on the face of the embankment. While extending the culvert length would reduce this problem, it would also make it more difficult for fish passage because of the added length. In many of the cases where riprap had been installed it was for the purpose of alleviating erosion caused by the culvert not being aligned with the stream.

C. In every observation where aprons existed, they made the passage of fish more difficult, if not impossible. We recommend that aprons be used sparingly in the future. The aprons resulted in increased velocities at the outlet because they were installed at a steeper slope than the culvert itself. Plus, the roughness of the apron is much lower than corrugated metal culverts. Where the apron is short, fish should have less difficulty passing at high flows than at low flows (the latter was the condition when most culverts were observed).

D. In streams that have low base flows but high peak flows, culvert design should ensure that a proper depth of flow is maintained for fish passage. This is particularly true for areas north of the Brooks Range, where the mean annual floods are higher than the rest of the state but the summer baseflow is lower. For most streams, arch-type culverts with a wider bottom width and greater resistance offer lower velocities and are recommended for use to enhance fish passage. This is not a logical solution for many of the northern streams with low base flows. The beaded pattern of drainage (small ponds connected by narrow channels) of arctic watersheds derive all of their summer baseflow from the active layer (that layer above the permafrost that thaws every year) and during periods of low precipitation in the summer the contribution to runoff is quite low. For these streams, circular culverts are preferred over arch-type culverts because of the added depth for fish passage. Some arch-type culverts observed along the Dalton Highway north of the Brooks Range appeared to be functioning all right. The reason was either they had been intentionally set below the streambed or they had settled as permafrost thawed. This allowed water to stand in the culverts which was in many cases deep enough for the fish to swim.

E. Excessive settlement of culverts appeared to be the cause of nonuniform slopes for a few culverts. The upstream half of the culvert generally had the greatest slope, with the bottom or downstream half being essentially horizontal or in some cases having an adverse slope. This condition generally produced high velocities in that section of the culvert with the steepest slope; in come cases supercritical flow existed. It was not evident from our investigation if this was caused by settlement of the roadway embankment or if ice-rich permafrost had thawed and consolidated to produce the settlement. The distribution of ice lenses and massive ice along and under streams is not well documented. Excessive settlement is not a serious problem, as only about 2% of the culverts had this problem. However, it is recommended that greater care be exercised when placing culverts at the design slope.

F. The transient problem of aufeis accumulation in culverts and particularly in stream channels and floodplains above roadways is a serious maintenance problem. Replacing culverts with bridges does not always solve this problem. Presently the ability does not exist to predict when, where and how much aufeis will develop. It is generally accepted that roadways enhance aufeis accumulation upstream; but also there are natural areas that are relatively undisturbed where deposits of comparable magnitude develop. Most culverts where aufeis occurs have been fitted with thaw pipes to facilitate melting in the spring. It is recommended that undisturbed streams where aufeis appears naturally be studied to see if they are utilized at all by spring spawning fish. The interaction of fish and streams having a high frequency occurrance of aufeis is an area where very little is known.

G. It is recommended that DOT&PF start a monitoring program to evaluate some existing culverts. The two major problems associated with fish passage are perching and excessive velocities. At the insistence of the State of Alaska, Department of Fish and Game, some baffled culverts have been installed. Since these culverts have been installed, there have been no site visits to our knowledge to evaluate these culverts by either fish biologists or hydraulic engineers. More recently, some arch-type and circular culverts have been installed with riprap in the bottom of the culverts. Sandahl (1972) commented on the advantages of riprap in the bottom of a reinforced concrete arch shaped pipe to control velocity. Manning's equation shows that if you decrease the slope or increase the roughness coefficient you similarly decrease the velocity. In the past most attempts at controlling the velocity have been accomplished by decreasing the slope. As alluded to earlier in the paper, this may upset the natural erosional processes and result in deposition above the culvert and erosion at the outlet.

H. It is recommended that additional circular or arch-type culverts, with riprap placed in the bottom, be installed by DOT&PF and that these be monitored from the time of installation. It is also recommended that they be installed on steep gradient streams (>2% slope) where the problem of perching is more prevalent. Most publications state that the culvert should be installed at slopes less than 0.5%, mainly to control the velocity. We suggest that the culvert be installed at the same gradient as the stream so that the natural processes of erosion are not altered. In Alaska, few culverts are now installed at slopes less than 0.5% (Table 3). Various designs should be used for placing material in the culvert bottom and retaining it. One visit after spring breakup and one late in the fall should be sufficient to monitor the behavior of these culverts.

I. It is recommended that the concept of the occupied velocity as presented by Morsell et al. (1981) be considered for culvert design. This is a more realistic approach because the design velocity used is that which the fish encounter when passing through the culvert. If riprap is placed in the bottom of a culvert to increase the effective roughness, this effect will be greater in the occupied zone than where the average velocity exists. The approach used by Morsell et al. (1981) to determine the velocity in the occupied zone should be evaluated. It is our suggestion that first the occupied zone be defined based on the design fish (weakest swimming upstream migrant) and then the velocity across this zone be determined using an equation that reflects the boundary conditions in the culvert.

J. It is recommended that further studies be carried out on the swimming capabilities of native Alaskan fish. Considerable discrepancy exists between the results of MacPhee and Watts (1976) and Jones et al. (1974). In doing such a study, the researchers should examine whether there are regional differences in performance for arctic and subarctic fish and how motivation impacts the swimming capability or performance of spawning fish.

K. While completed research on fish performance has been quite useful, these studies have been also the source of new unanswered questions. MacPhee and Watts (1976) examined the behavior of spawning arctic grayling in the near vicinity of culverts and reported on the percent passing the culvert of a size class in a specific period of time. However, what was the activity of this fish prior to reaching the culvert? Had they just rested before approaching the culvert or had they been swimming upstream for some time? It is recommended that the behavior of spawning fish be studied both in the stream channel prior to approaching a culvert and at the culvert.

L. On many Alaskan streams, snowmelt generated floods exist every spring. It is recommended that the effect that the floods have in terms of delay on spring spawning fish be studied. Dryden and Stein (1975) suggest that three days should be the maximum delay that fish must endure. However, there doesn't appear to be any scientific evidence that supports this conclusion.

M. The most prevalent culvert problem observed was their tendency to become perched. Again, this is an area where little scientific data exist on the jumping ability of fish. For arctic grayling, we observed that where perching was as much as 1.0 foot fish were observed upstream. However, fish observations were only casual and not systematically performed, so no definite conclusions could be reached in regards to jumping ability relative to fish size and discharge velocities. It is a certainty that some of the perched culverts are a complete blockage to fish; it is recommended that some remedial measures be attempted to alleviate perching at existing culverts.

CONCLUSIONS

The success of fish migrating upstream through a culvert depends both upon the swimming ability of the fish and the hydraulic conditions that exist at the culvert. It is known that under certain conditions culverts are deterrents to fish passage. However, it is also known that culverts are much more economical to use than bridges. The difficulty comes in trying to determine when a culvert is appropriate and when it is not. Because of the large financial savings of culverts relative to bridges, it makes economical sense to study this problem both from hydraulic and fish performance viewpoints. This study has attempted to examine the hydraulic aspects of culvert design and operation relative to the information that has been garnered in previous fish performance studies.

The main limitation of this study is that only one visit (with a few exceptions) was made at each culvert site. Many of these culverts have been in existence for many years and the original conditions have changed. Also, the greatest change occurs during high flow when the sediment transporting capacity of a stream is greatly enhanced; only a few culverts were visited when this condition existed. Seasonal changes also occur at a culvert site because of the presence of ice in the spring.

Ideally a hydraulic structure should not change the conditions that exist at a site. This means that the cross-sectional area should not be restricted by the structure, the slope should not change, and the boundary roughness should remain the same. Altering these conditions changes the velocity distribution and consequently sediment carrying capacity of the stream. Changing the slope to reduce velocities will definitely alter the sediment transporting capacity of the stream both upstream and downstream of the culvert.

A more realistic design of culverts should be made by matching the velocities in the occupied zone where the fish will naturally swim to the swimming ability of the design fish. This approach is preferred because velocities in the occupied zone can more readily be reduced by increasing the boundary roughness than can the mean velocity which is presently used in the design of culverts.

Methods to minimize perching on newly designed culverts should be investigated, as well as remedial methods to alleviate perching at existing culverts.

Additional data is needed on the swimming ability and behavior of numerous native Alaskan fish. And, do these variables change for different climatic regions of the state? Also, the motivational factor during spawning may be very important in the swimming performance of the fish.

There are many sites where culverts can be installed to pass the design flood and still allow upstream migrating fish to pass. There are also certain situations where culverts obviously should not be used.

The line between these two conditions is not well-defined at this time. For some of the cases on this boundary, the traditional culvert can be modified, usually at some additional cost, to achieve a structure that functions in a manner acceptable to both the engineer and fishery biologist.

While there are some fish data available to aid in culvert design, much more is needed. Considerable time and money will be needed to perform the required research that will produce designs that are acceptable to both engineers and biologists. This problem will not be solved by a single study, but in steps as numerous studies are completed.

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