Spawning Migration of Arctic Grayling Through Poplar Grove Creek Culvert, Glennallen, Alaska, 1986

Final Report

by

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16. Abstract

Specification of appropriate culvert design criteria for fish passage has been a source of considerable, long-standing controversy within the State of Alaska. In an effort to resolve this issue, the Alaska Departments of Fish and Game and Transportation and Public Facilities chose the Poplar Grove Creek culvert crossing of the Richardson Highway located near Glennallen, Alaska, as a study site for a joint interagency fish passage study. During May 1986, the migration of Arctic grayling (*Thymallus arcticus*) through the Poplar Grove Creek culvert was studied. The highway culvert is 33.5 m (110 ft) long and 1.5 m (5 ft) in diameter. Under some flow conditions, the culvert's water velocities (particularly at the culvert inlet and outlet) have exceeded that reported as the sustained swimming speed of Arctic grayling. The purpose of the study was to document the conditions that permitted or prevented Arctic grayling passage through the culvert and to recommend guidelines for fish passage through this and other culverts.

Successful fish passage through the culvert ranged from 12% to 79% at mean culvert outlet velocities of 1.94 m/s to 1.81 m/s (6.35 fps to 5.94 fps) and water temperatures of 2.4°C to 7.1°C, respectively. Weighted average water velocities for the entire length of the culvert barrel ranged from 0.91 m/s to 0.79 m/s (2.98 fps to 2.59 fps), respectively, during this period. Water velocities near the culvert wall (the area actually utilized by fish while ascending the culvert barrel) ranged from 0.77 m/s to 0.73 m/s (2.53 fps to 2.4 fps), respectively, during this period. Radio telemetry techniques for monitoring fish movements through culverts were assessed and proved useful. Stream hydrology, culvert hydraulics, water quality, and temperature and fish sexual maturity data were collected and related to observed swimming performance. Velocity distribution profiles were measured to further evaluate the "V-occupied zone" concept (the zone used by fish during culvert passage.)

Previous fish passage studies have largely recognized only a fish's profile drag as a deterrent to its passage through a hydraulic structure. Accordingly, previous investigations have focused on the water velocities that fish may successfully ascend for fixed time periods. As a departure from most previous fish passage studies, this investigation considers the concept that fish may successfully ascend for fixed time periods. As a departure from most previous fish passage studies, this investigation considers the concept that fish may also have to contend with adverse horizontal pressure gradient and virtual mass forces. Such adverse forces at the culvert inlet ot outlet may restrict or block fish passage, even in the presence of otherwise acceptable water velocities in the culvert barrel. This study thus recommends that future design criteria specifically consider and address the distinctly different power and energy requirements for fish in the culvert inlet, outlet, and barrel. A preliminary evaluation of the power and energy requirements for selected fish which successfully negotiated the Poplar Grove Creek culvert in 1986 is presented.

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ABSTRACT

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Successful fish passage through the culvert ranged from 12% to 79% at mean culvert outlet velocities of 1.94 m/s to 1.81 m/s (6.35 fps to 5.94 fps) and water temperatures of 2.4°C to 7.1°C, respectively. Weighted average water velocities for the entire length of the culvert barrel ranged from 0.91 m/s to 0.79 m/s (2.98 fps to 2.59 fps), respectively, during this period. Water velocities near the culvert wall (the area actually utilized by fish while ascending the culvert barrel) ranged from 0.77 m/s to 0.73 m/s (2.53 fps to 2.4 fps), respectively, during this period. Radio telemetry techniques for monitoring fish movements through culverts were assessed and proved useful. Stream hydrology, culvert hydraulics, water quality, and temperature and fish sexual maturity data were collected and related to observed swimming performance. Velocity distribution profiles were measured to further evaluate the "V-occupied zone" concept (the zone used by fish during culvert passage.)

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criteria specifically consider and address the distinctly different power and energy requirements for fish in the culvert inlet, outlet and barrel. A preliminary evaluation of the power and energy requirements for selected fish which successfully negotiated the Poplar Grove Creek culvert in 1986 is presented.

ACKNOWLEDGEMENTS

Sincere appreciation is extended to the U.S. Federal Highway Administration (FHWA) for their foresight, encouragement and ultimate funding of this interagency investigation. In large part, the success of this joint interagency fish passage investigation and the open dialog it has fostered between agencies are due to FHWA's encouragement.

Appreciation is also extended to the Alaska Department of Transportation and Public Facilities (DOT&PF) and the Alaska Department of Fish and Game (ADF&G) for their personnel and fiscal support and their committment to the successful resolution of long-standing interagency disagreements regarding fish passage design criteria. Particular appreciation is extended to Nathan Johnson of DOT&PF and to John Clark, Rocky Holmes, Roger Post, and Butch Potterville of ADF&G for providing field assistance and manpower.

Further appreciation is extended to the University of Alaska's Institute of Northern Engineering and the Alaska Cooperative Fisheries Research Unit for their assistance in the development of the study design, procurement of field supplies and equipment and hiring of field support personnel. Thanks is extended to David Bjerklie, Jeffery Chapman, Robert Gieck, and Kathleen McCullom, who most ably assisted as field support technicians for the Institute of Northern Engineering. Robert Gieck's continued support, analysis of field data and preparation of the final report graphics are particularly acknowledged.

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INTRODUCTION

Arctic grayling (*Thymallus arcticus*), as well as other fish with slow-to-moderate swimming performance, are widely distributed throughout Alaska and must often pass through highway culverts. Culvert design without adequate consideration of fish passage criteria, or the incorrect placement or maintenance of highway culverts may selectively or totally block the movement of fish, thereby hindering or prohibiting fish access to rearing or spawning habitat, or creating delays during the spawning migration. Blocked or even delayed fish migration may adversely impact their reproductive success. Historically, a lack of adequate information has hampered the development of appropriate design criteria to assure efficient fish passage to minimize adverse environmental impacts, and to simultaneously minimize the overall cost of road construction and maintenance. Further knowledge was needed on local hydrology, hydraulics of culvert drainage structures, and physical and biological factors affecting fish migration behavior and swimming performance.

In 1985, the Alaska Department of Fish and Game (ADF&G) and the Alaska Department of Transportation and Public Facilities (DOT&PF) established a cooperative State Fish Passage Task Force. This task force, with technical assistance from the University of Alaska Fairbanks, was established to expand the available data base and resolve long-standing interagency disagreements regarding fish passage design criteria. The 1986 Poplar Grove Creek study is the first joint ADF&G and DOT&PF fish passage investigation. This report thus is intended not only as a contribution to fish passage research, but also as an effective example of interagency cooperation and open dialog toward problem solution.

BACKGROUND

A review of the literature relating to fish passage through drainage structures revealed that the engineering and, quite frequently, the biological communities have erroneously accepted the concept that fish are capable of negotiating any man-made barriers to their passage so long as given swimming velocities can be maintained for defined, fixed time periods (Brett, 1963; Beamish, 1978; and Bell, 1986). Thus, engineers and biologists have recognized only the fish's profile drag as a deterrent to its passage through a hydraulic structure. However, Ziemer and Behlke (1966) showed that, if horizontal pressure gradients exist in a fish passage structure, fish must also contend with an additional adverse force that may restrict velocities.

Behlke (1987) described the forces that a fish must overcome to pass through pressure gradients having horizontal components and to pass through hydraulic structures exhibiting sloping hydraulic grade lines. Behlke determined, by integrating the forces acting on a swimming fish, the net energy and power levels necessary for fish to deliver if they are to negotiate successfully uniform, steady flow in sloping open channels or steady flow in pipe type facilities. The concepts set forth by Behlke have been integrated as an underlying component of this study. The implications of these concepts to the design of fish passage structures are further expanded later.

OBJECTIVES

The primary purpose of this interdisciplinary study was to gather information on the effects of fish size, water temperature, measurable hydraulic conditions and their relationship to the passage rate of Arctic grayling through the Poplar Grove Creek culvert. Specific objectives included:

(1) a reexamination of a new visual technique (Tilsworth and Travis, 1987) for the study of fish passage through existing culvert structures;

(2) a comparison of observed swimming abilities of various size classes of Arctic grayling with the experimental results originally obtained by MacPhee and Watts (1976) (presently, these results form an integral component of the state's fish passage culvert velocity criteria for Arctic grayling);

(3) collection of more detailed data on culvert hydraulic and installation variables, including adverse horizontal pressure gradients, that may affect successful fish passage;

(4) preliminary field assessment of the culvert velocity known as the "Velocity Occupied Zone" (V-occupied) cited by Morsell et al. (1981) and Kane and Wellen (1985); and

(5) preliminary evaluation of the applicability and usefulness of radio telemetry for culvert/fish passage studies.

PROJECT ORGANIZATION

Personnel and Agencies

Project personnel came from DOT&PF, ADF&G and the University of Alaska Fairbanks' (UAF) Institute of Northern Engineering (INE) and the Alaska Cooperative Fishery Research Unit (ACRFU). DOT&PF and ADF&G provided professional resource personnel and overall project management. UAF provided fishery, hydrology and hydraulic engineering personnel, graduate students and technicians to assist in the field work and data analysis. The senior writer, Dr. Charles Behlke, was selected jointly by DOT&PF and ADF&G to function as the overall project coordinator.

Project Planning

The interdisciplinary team met weekly during the initial phases of the project. These meetings provided the strategic and tactical directions for the project. Many of the interdisciplinary discussions resulted in a much better understanding by the entire team of the methods, problems and expectations of the various disciplines involved.

SITE DESCRIPTION

Stream Basin

Poplar Grove Creek is a small drainage basin of approximately 31 km^2 (12 mi^2) that empties into the Gulkana River near Gulkana Junction, Alaska. The drainage area is almost totally underlain by permafrost and contains extensive muskeg and marsh areas. The elevations of the drainage basin vary from 540 m (1,650 ft) at the outlet to about 660 m (2,000 ft) at the headwaters. The stream channel is typically 3.6 to 4.6 m (12 to 15 ft) wide with varying slopes. Considerable amounts of debris (i.e., fallen trees and bushes) exist in the stream channel and, in some cases, substantial backwater results from this debris.

Climate

Poplar Grove Creek experiences long, cold winters and short, warm summers. The average January air temperature is -11°C (+12°F), and the average July temperature is 14.4°C (58°F). The drainage basin receives an average yearly precipitation of 38.1 cm (15 in). During the field investigation, the air temperature ranged from minus 6.7 to 15°C (20 to

59°F) and only trace amounts of precipitation fell (Gulkana FAA Flight Service Station, 1986).

Drainage Structure

The Poplar Grove Creek culvert is located at Mile 138.1 of the Richardson Highway (Figure 1). The culvert was originally installed in 1953 during
reconstruction of the original highway. The culvert is 33.5 m (110 ft) long, 1.5 m (5 ft) in diameter, and is constructed of 7.6 cm by 2.5 cm (3 by 1 in) corrugated steel. A plan view of the culvert is presented in Figure 2. The elevation sketch with an exaggerated vertical scale presented in Figure 3 shows that, since the original installation, the culvert has settled differentially and at some points has been deformed from its original circular shape.

Habitat

From its mouth to a distance approximately 3.2 km (2 mi) upstream of the Richardson Highway crossing, Poplar Grove Creek has an incised, confined stream channel. Above this reach, Poplar Grove Creek is a typical tundra beaded stream with relatively slow water velocities. The water is typically humic stained, particularly during spring breakup and other high-water flows. The spawning habitat for Arctic grayling is located in a series of shallow lakes and ponds at the headwaters located approximately 4.8 km (3 mi) upstream of the highway crossing. The interconnected lakes and ponds provide excellent spawning and rearing habitat for Arctic grayling. Fry grow rapidly during the summer and migrate downstream, typically in late summer, to overwinter in the Gulkana River and Copper River drainages.

METHODOLOGY

This field project was organized to gather information about culvert hydraulics, stream water quality, fish population and life history, and the behavioral patterns and passage rates of Arctic grayling passing through the culvert drainage structure during their spawning migration. Each of these topics is covered in the following sections of this report.

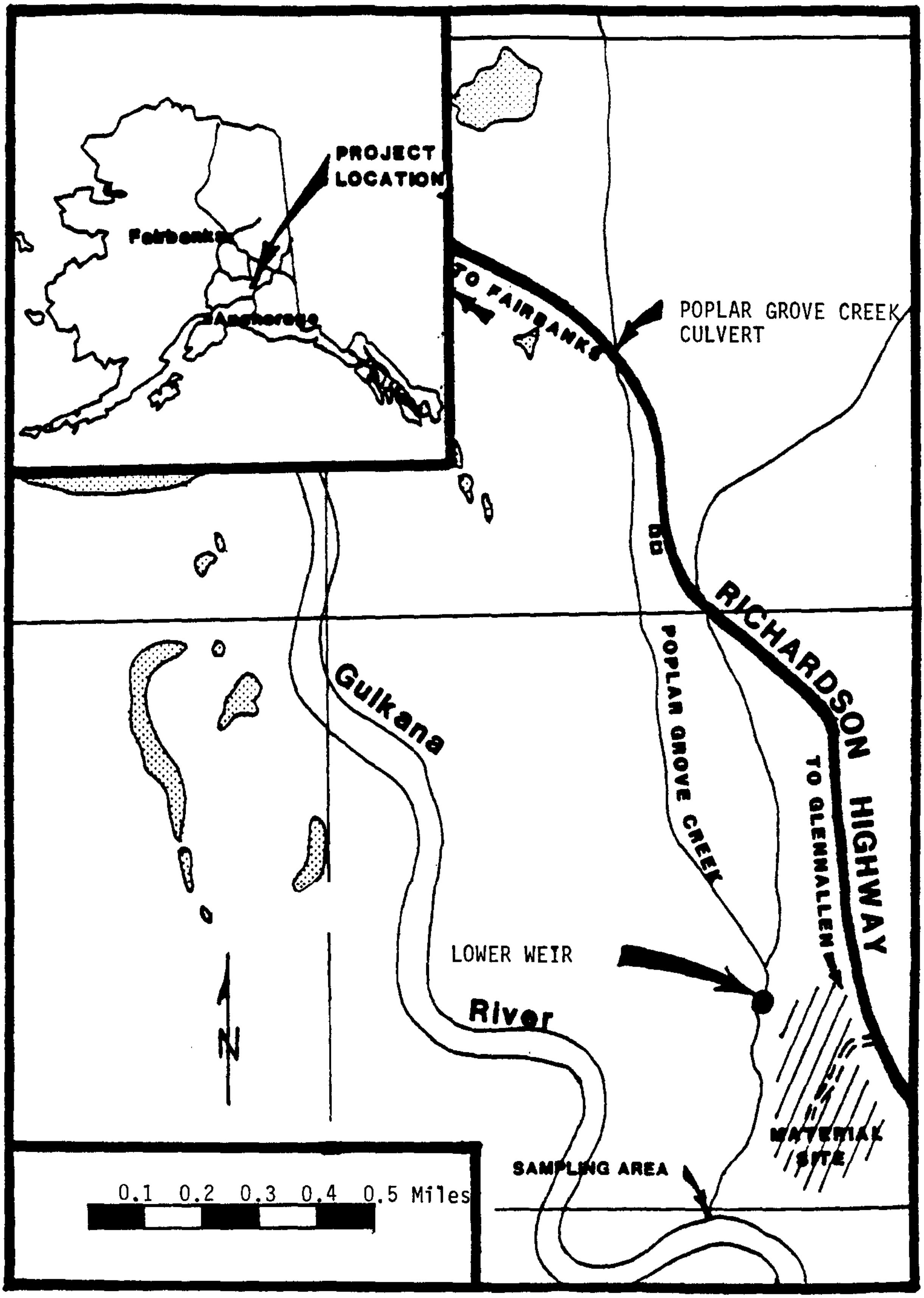

Figure 1. Locational site map, Poplar Grove Creek culvert.

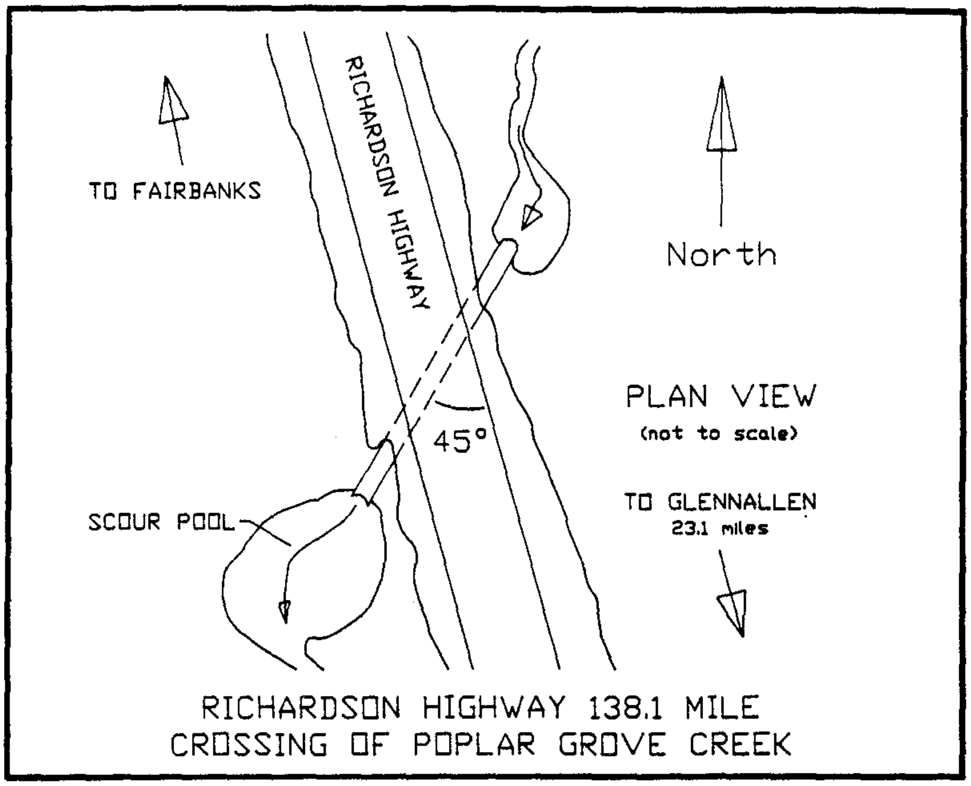

Figure 2. Plan view and typical section, Poplar Grove Creek culvert.

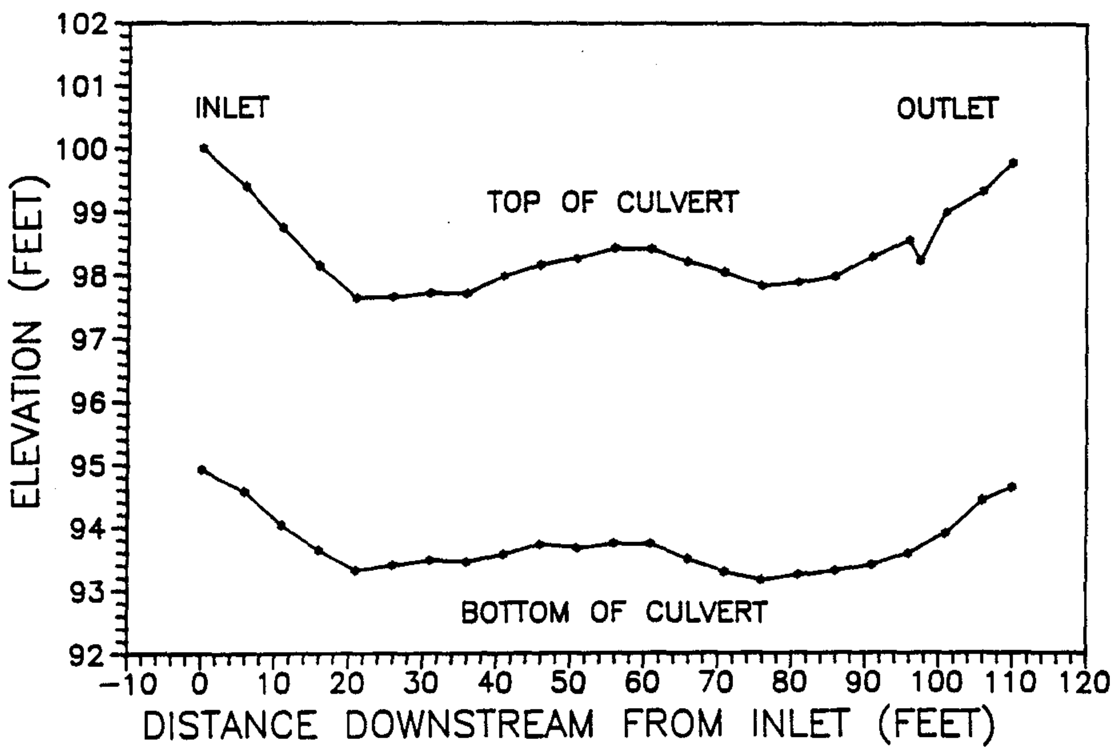

Figure 3. Profile of Poplar Grove Creek culvert.

Stream Gaging

Stream discharge was measured daily at various stream locations and was correlated with the continuous measurement of water stage at a natural pool located 300 m (1000 ft) downstream of the culvert outlet. A recording pressure transducer was installed in the downstream control pool to record water stages. We used three current meters during this study to measure water velocities and estimate discharge: the pygmy current meter, the Gurley current meter, and the Montedoro-Whitney electromagnetic current meter.

Initial discharge measurements were made approximately 1.5 km (1 mi) from the culvert at a downstream weir site originally used in studies by MacPhee and Watts (1976). One small tributary enters Poplar Grove Creek on the southeast side just above this weir site. Good locations for stream gaging on this tributary were difficult to locate, so it was gaged just below a culvert where it crosses the Richardson Highway. Later, when all of the ice was out of the channel, a gage was installed in a steep section near its confluence with Poplar Grove Creek.

As May progressed, all of the winter ice melted from Poplar Grove Creek, and a suitable gaging site was found close to the location where the water temperatures and stage measurements were taken. During the major fish migration period through the Poplar Grove Creek culvert (May 18 to 20), stream gaging was performed at a site approximately 300 m (1000 ft) downstream from the study culvert.

Water Temperature and Quality

After the ice melted from the stream, two YSI thermistors were installed in the same pool as the recording pressure transducer. These thermistors were connected to a Campbell Scientific data logger. One thermistor was located near the bottom of the pool and the other was located 15 cm (6 in) above the first. Initially, the water depth in the pool was 1 m (3 ft); this depth decreased continuously during the study. Readings from the two thermistors were stored every minute; hourly averages were calculated and stored in the data logger. Water quality parameters were measured daily in the culvert outlet scour pool. Dissolved oxygen and apparent color were determined with a Hach DR-EL/4 water testing kit. Turbidity was measured with a Hach 16800 portable turbidimeter. Water temperature to the nearest degree C was measured with a pocket thermometer.

Culvert Hydraulics

Vertical water velocity profiles (from just above the culvert invert to the water surface) were measured at the culvert outlet, at 1.5 m (5 ft) upstream from the culvert outlet within the culvert barrel (through a hole cut in the culvert crown), at 1.2 m (4 ft) downstream from the culvert inlet, at the culvert inlet (through another hole cut in the culvert crown), and on the centerline of a flashboard which extended approximately 1.2 m (4 ft) downstream from the culvert outlet. These water velocities were measured with the Montedoro-Whitney electromagnetic current meter. Water surface elevations, referenced to a project-established bench mark, were taken 61 m (200 ft) upstream from the culvert inlet, in the pool immediately upstream of the culvert inlet, at the culvert inlet, 1.2 m (4 ft) downstream of the culvert inlet, 1.5 m (5 ft) upstream of the culvert outlet, at the culvert outlet, in the pool immediately downstream of the culvert outlet, and 61 m (200 ft) downstream of the culvert outlet.

Fish Tagging

We captured 850 fish by dipnetting at the mouth of Poplar Grove Creek, immediately below the downstream weir, and at the culvert outlet scour pool. Captured fish were measured to the nearest 1 mm (0.04 in), sexed, checked for the degree of ripeness and tagged with a numbered "streamer" tag (FLOY Tag Model FSTL-73) inserted through the posterior base of the dorsal fin. Forty fish captured at the lower weir site were also weighed to the nearest 1 g.

Radio Telemetry

Fish were captured for radio telemetry by dipnetting in the culvert outlet scour pool and were processed in the same manner as tagged fish. With the aid of forceps, radio tags were implanted in four fish by sliding the transmitter through the esophagus into the stomach. A loop of surgical nylon thread connected the transmitter to the lower jaw; it was used, upon recapture, to remove the transmitter without probing the stomach. Implanted fish were held for a 15-minute recovery period. Upon release, their movements were monitored, and the actual time required for culvert passage was recorded.

The radio tag transmitters were procurred from Custom Telemetry and Consulting, Athens, Georgia. The transmitters weighed approximately 3 grams each, were tear-drop shaped (about 30 by 10 mm), and were covered with beeswax. The transmitters operated at 164 MHz and, when submerged in Poplar Grove Creek, could be monitored at a distance of 20 m (65 ft).

Observations of Fish Passage

Arctic grayling attempting to migrate through the culvert were observed using the methods outlined by Tilsworth and Travis (1987). It was originally intended to position observers at both the inlet and outlet of the culvert; however, turbidity during the 1986 spawning migration precluded visual observation at the culvert inlet. Nearly continuous observations were made at the culvert outlet between 10:00 a.m. and 11:00 p.m. ADT during peak days of the spawning run. Hourly totals of all fish (tagged and untagged) entering the culvert were recorded. In addition, hourly totals were recorded for all fish unsuccessfully attempting to enter the culvert (defined as fish that ascended up to or within 0.6 m (2 ft) of the culvert outlet lip but which subsequently washed or turned back downstream) and for fish that successfully ascended into the culvert barrel but which subsequently washed downstream back out of the culvert barrel past the observer. To enhance observability, white-painted, plywood "flashboards", 1.2 by 2.4 m (4 by 8 ft) were positioned on the stream bottom at the inlet and at the outlet of the culvert. The total success rate(s) for each hourly period was calculated by the following formula:

$$S = (T-W) / (T+U)$$

where: T = number of fish entering the culvert
W = number of washouts
U = number of unsuccessful attempts at entering culvert.

RESULTS

Basin and Stream Hydrology

Snowpack conditions in the Copper River basin during the spring of 1986 were near normal levels. At the beginning of April, the basin-wide average was near 12 cm (4.7 in). By the beginning of May, the basin-wide average was approximately 16.5 cm (6.5 in). This was similar to the historical average of 14 cm (5.5 in). At an elevation of 661 m (2,170 ft) near Chistochina, the water content of the snowpack was 6.6 cm (2.6 in) on March 26 and 4.3 cm (1.7 in) on May 2. The Chistochina site is 40 km (25 mi) northeast of the Poplar Grove study site. At Haggard Creek 35 km (22 mi) north of the Poplar Grove study site, the water content of the snowpack was 10 cm (3.9 in) on March 26 and 14 cm (5.5 in) on May 2 at 774 m (2,540 ft) elevation. In contrast, the elevations in the Poplar Grove Creek watershed vary from 550 m to 610 m (1,800 ft to 2,000 ft). Some late winter storms brought the snowpack up to average conditions.

Stream discharge in Poplar Grove Creek was measured from May 6 to May 21, 1986. Figures 4, 5 and 6 depict the discharge hydrograph for Poplar Grove Creek at the culvert outlet scour pool, for an adjacent unnamed tributary, and for Poplar Grove Creek at the MacPhee and Watts lower weir site, respectively. Nearly all of the spring runoff was generated from snowmelt. Rainfall during this period was negligible. The size of the drainage basin that potentially contributes to the runoff is about as 31.2 km^2 (12 mi^2); however, this estimate of drainage area is probably not very accurate. The portion of the watershed located upstream of the Richardson Highway crossing is relatively flat and dominated by numerous small lakes that are connected by small waterways. We estimated the drainage area using a U.S. Geological Survey topographic map (scale 1:63,360). In addition, the mapped estimates had previously been field checked in 1985 by flying over the upper reaches of the watershed (Tilsworth and Travis, 1987). A subjective estimate of the error range for the drainage area estimate is plus or minus 10.4 km^2 (4 mi^2).

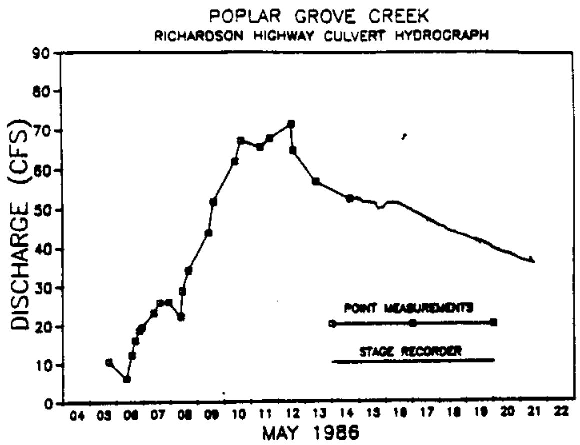

Figure 4. Discharge hydrograph at Poplar Grove Creek culvert.

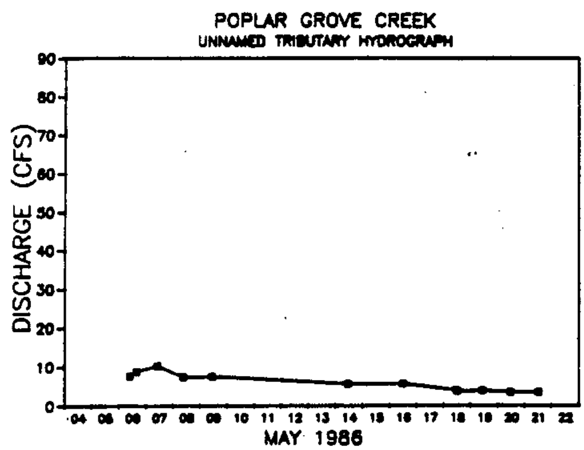

Figure 5. Discharge hydrograph at unnamed tributary.

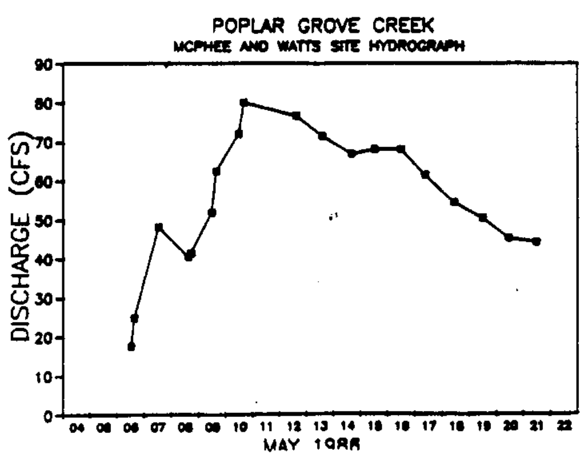

Figure 6. Discharge hydrograph at MacPhee and Watts site.

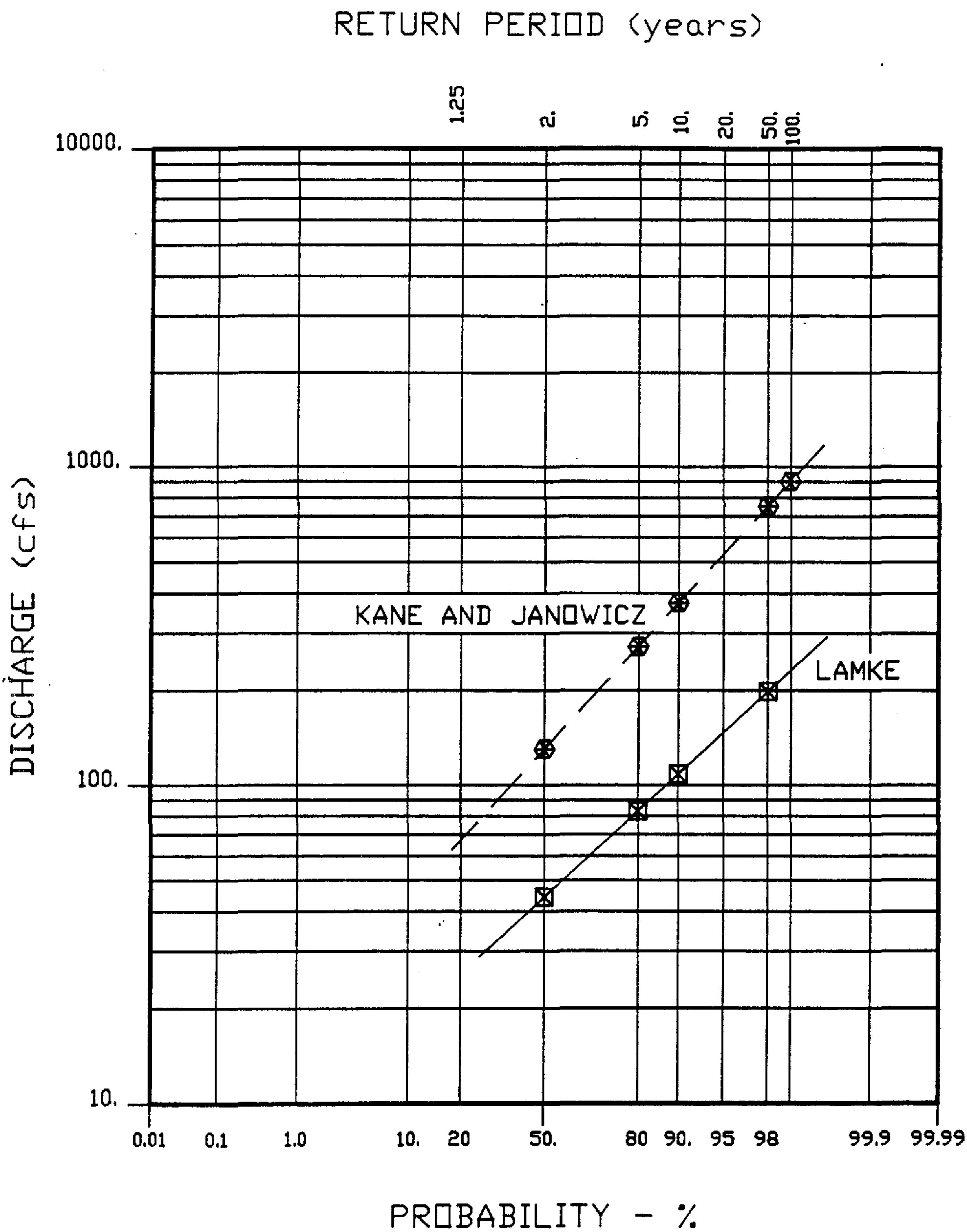

Figure 7. Flood frequency estimates.

Flood Frequency

Figure 7 shows the estimates of flood frequency as a function of the return period utilizing both the Lamke (1979) and Kane and Janowicz (1987) methodologies. For comparative purposes, similar results are shown for the 29.5 km^2 (11.4 mi^2) Dry Creek watershed located approximately 32 km (20 mi) from the Poplar Grove Creek study site (Table 1). Additionally, results of the flood frequency analysis of Dry Creek using 18 years of data are shown. It should be recognized that estimating flood of various return periods for small watersheds is difficult, as shown by the significant variation among estimates in Table 1.

TABLE 1. Flood discharge estimates for Poplar Grove Creek and nearby Dry Creek for selected return periods.

	FLOOD MAGNITUDE (m^3/s)				
Return Period (Yrs)	Poplar Grove Creek		Dry Creek		
	Lamke	Kane & Janowicz	Lamke	Kane & Janowicz	Flood Est. Log-Normal
2	1.3	3.9	2.0	3.7	1.2
5	2.3	7.7	4.5	7.3	7.2
10	3.1	10.9	7.0	10.5	18.6
20		14.6		14.0	40.3
25	3.9		7.5		
50	5.3	20.2		19.5	96.4

The peak flow during the 1986 snowmelt period for Poplar Grove Creek was 2.04 m^3/s (72 cfs) on May 12. Based on Lamke's methodology, the return period for this flood event would be slightly less than 5 years. Based on the methodology of Kane and Janowicz, the return period for this flood event would be 1.25 years (Figure 7). The Poplar Grove Creek watershed contains approximately 20 percent lake area (storage), while the Dry Creek watershed contains only 1 percent lake (storage) area. Accordingly, Dry Creek should have much higher predicted flood magnitudes for the same return period than does Poplar Grove Creek.

Water Quality and Temperature

Results of the water quality and temperature monitoring within the culvert scour pool are presented in Table 2 and in Figures 8 to 10 for the study period (May 5-20, 1986). Water temperatures from the installed thermistors are presented in Table 3. The maximum daily water temperature from May 15 to 21 (thermistor readings) ranged from 3.13 to 7.07°C; the minimum daily water temperature during this period ranged from 1.50 to 5.03°C. Dissolved oxygen varied from 11.2 mg/l at a water temperature of 2.0°C to 12.4 mg/l at a water temperature of 4.9°C. Apparent color fluctuated from 110 to 325 units, and turbidity ranged from 2.1 to 31.0 NTU.

TABLE 2. Water quality data, Poplar Grove Creek, May 1986.

Date	Time ADT (HHMM)	Turbidity (NTU)	Apparent Color Units	D.O. (mg/l)	Water Temp (°C)
5	1750	14.0	150		0.00
6	1744	2.1	205		0.00
7	1440	2.5	250		0.75
8	1638	3.8	290		0.00
10	1600	6.8	250		0.20
11	1700	9.4	300		0.00
12	1620	10.0	325		0.00
13	1715	29.0	260		0.50
14	1310	31.0	265		1.50
15	1140	26.0	270	11.2	2.00
16	1520	23.5	200	12.1	3.80
17	1500	22.0	110	11.9	3.80
18	1255	18.0	175	12.1	3.80
19	1230	7.3	250	12.1	N.A.
20	1130	20.0	190	12.4	4.90

Culvert Hydraulics

By May 17, the culvert was free of ice and exhibited outlet control (i.e., depth everywhere in the barrel was greater than critical depth) throughout the study period. Figure 3 depicts a profile view of the Poplar Grove Creek culvert invert and crown. This figure illustrates the settlement that has occurred since installation of the structure. This created a somewhat eliptical shape at some barrel locations.

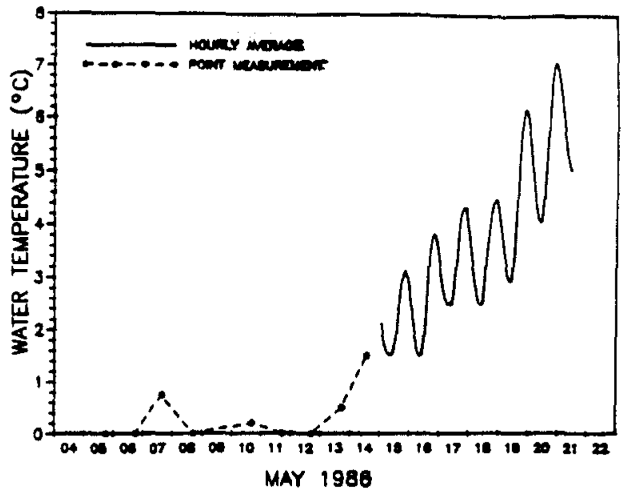

Figure 8. Water temperatures, Poplar Grove Creek.

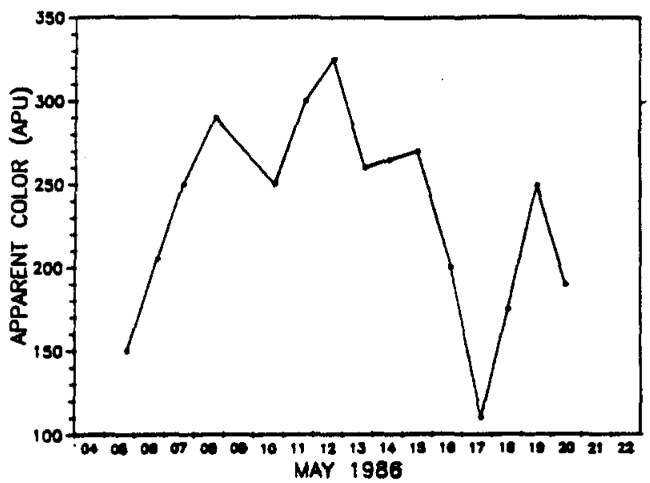

Figure 9. Apparent color units, Poplar Grove Creek.

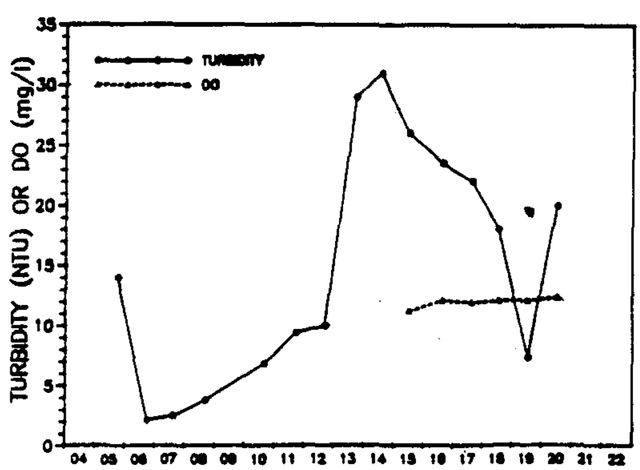

Figure 10. Turbidity and dissolved oxygen, Poplar Grove Creek at scour pool.

TABLE 3. Water temperature data (°C), thermistor readings, Poplar Grove Creek, May 15-21, 1986.

	DATE MAY 1986						
Time (hrs)	15	16	17	18	19	20	21
00	2.12	2.60	3.18	3.74	4.19	5.76	6.79
01	1.96	2.36	2.98	3.52	4.02	5.51	6.59
02	1.80	2.16	2.83	3.31	3.84	5.25	6.37
03	1.70	1.96	2.72	3.11	3.66	5.00	6.13
04	1.62	1.80	2.62	2.94	3.47	4.74	5.89
05	1.56	1.64	2.55	2.79	3.30	4.54	5.66
06	1.54	1.55	2.49	2.65	3.14	4.37	5.45
07	1.51	1.50	2.48	2.53	3.01	4.22	5.29
08	1.51	1.50	2.53	2.48	2.96	4.11	5.16
09	1.54	1.55	2.49	2.48	2.93	4.07	5.06
10	1.59	1.66	2.59	2.51	2.97	4.07	5.03
11	1.70	1.85	2.73	2.65	3.13	4.19	N.A.
12	1.83	2.11	2.93	2.87	3.40	4.43	N.A.
13	2.04	2.44	3.17	3.18	3.78	4.79	N.A.
14	2.31	2.87	3.40	3.50	4.20	5.24	N.A.
15	2.56	3.28	3.74	3.68	4.60	5.56	N.A.
16	2.79	3.55	4.02	3.90	5.13	5.96	N.A.
17	2.93	3.69	4.19	4.08	5.56	6.30	N.A.
18	3.01	3.80	4.25	4.25	5.86	6.63	N.A.
19	3.10	3.83	4.31	4.36	6.05	6.84	N.A.
20	3.13	3.78	4.31	4.42	6.15	7.00	N.A.
21	3.03	3.69	4.31	4.46	6.16	7.07	N.A.
22	3.00	3.56	4.08	4.45	6.06	7.03	N.A.
23	2.84	3.39	3.92	4.34	5.93	6.94	N.A.

Water Velocity Distribution Curves: Vertical water velocity profiles were measured May 16, 18, 19, 20 and 21 along the culvert centerline at five locations between the culvert inlet and the culvert outlet flash board (Figures 11 through 34). Water velocity information at other points within the culvert barrel was not obtained because of inaccessibility.

It should be noted that the velocity profiles depicted in Figures 11 through 34 are measurements taken at or close to the ends of the culvert. At the inlet end locations (Figures 11, 15, 20, 25 and 30), the flow was entering the culvert and was accelerating. Close to the culvert invert, a region of separation was observed along the culvert sidewalls. We believe that this region of separation extended

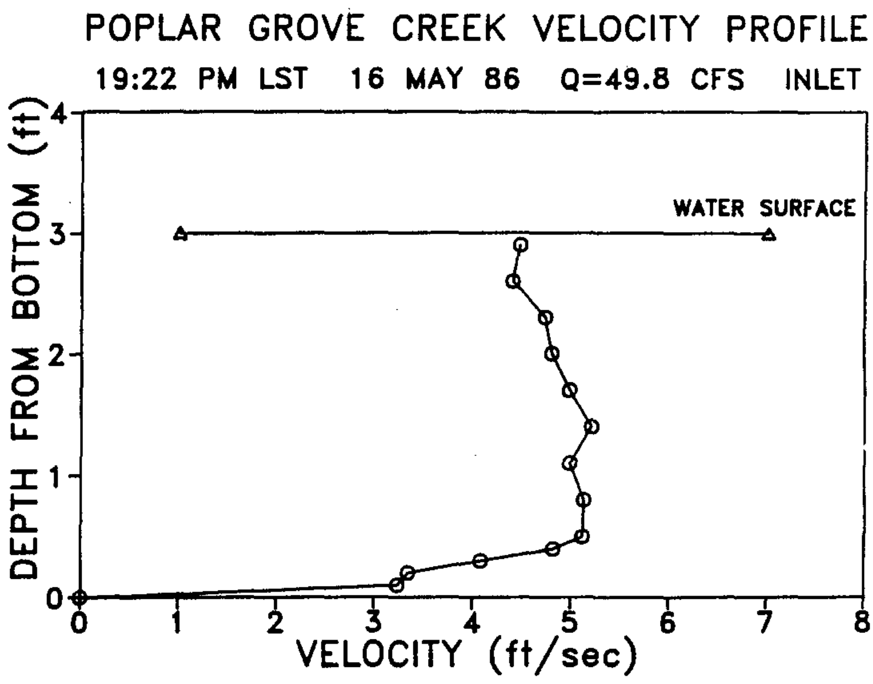

Figure 11. Water velocity profile, culvert inlet, 16 May 1986.

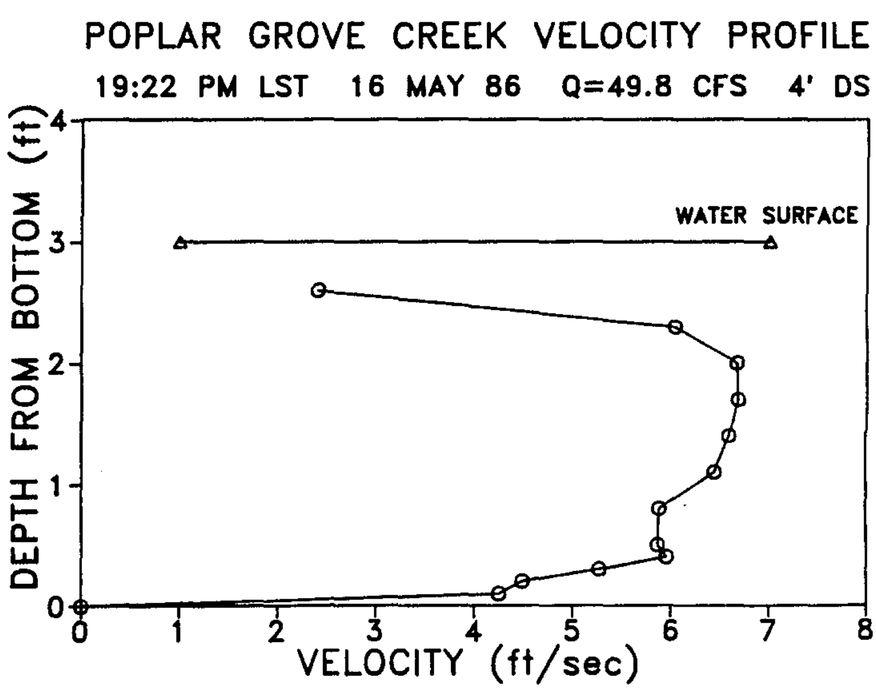

Figure 12. Water velocity profile, 1.2 m downstream culvert inlet, 16 May 1986.

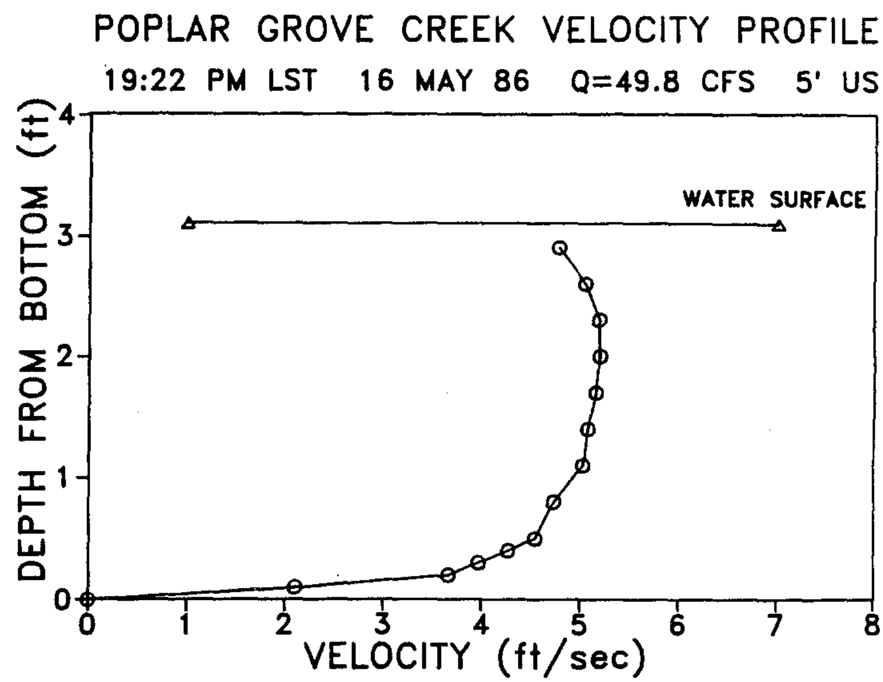

Figure 13. Water velocity profile, 1.5 m upstream culvert outlet, 16 May 1986.

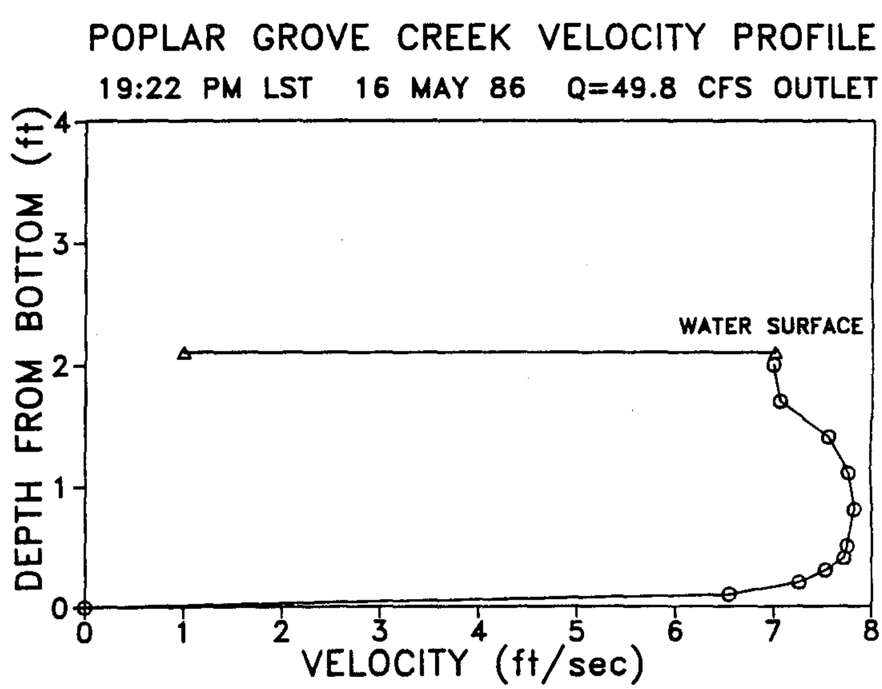

Figure 14. Water velocity profile, culvert outlet, 16 May 1986.

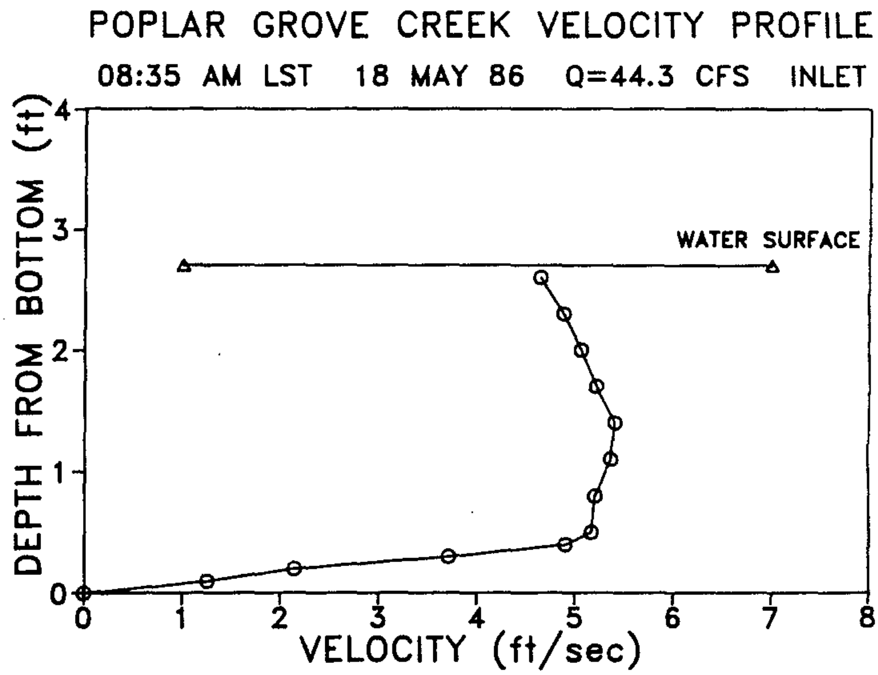

Figure 15. Water velocity profile, culvert inlet, 18 May 1986.

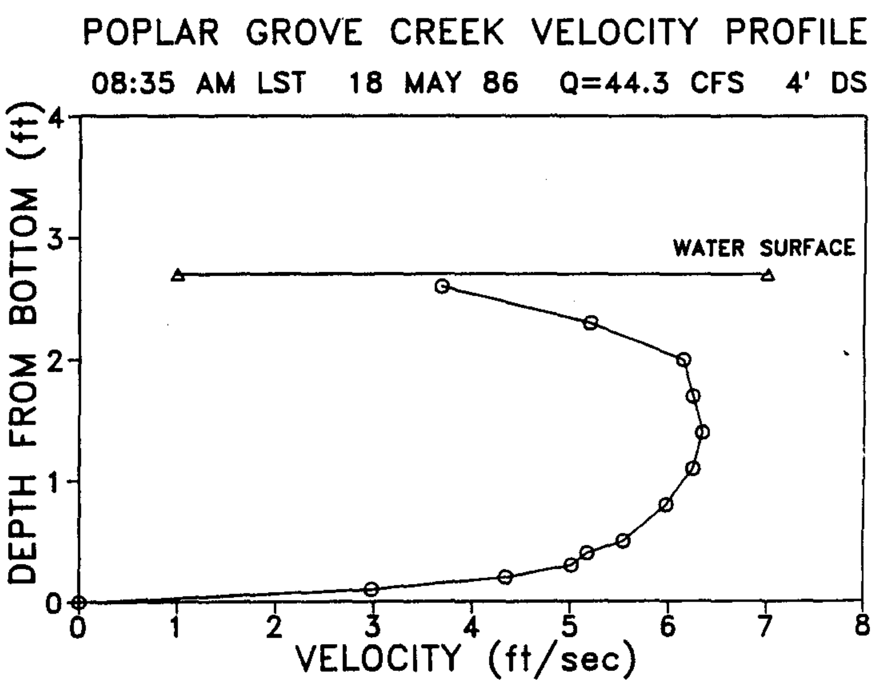

Figure 16. Water velocity profile, 1.2 m downstream culvert inlet, 18 May 1986.

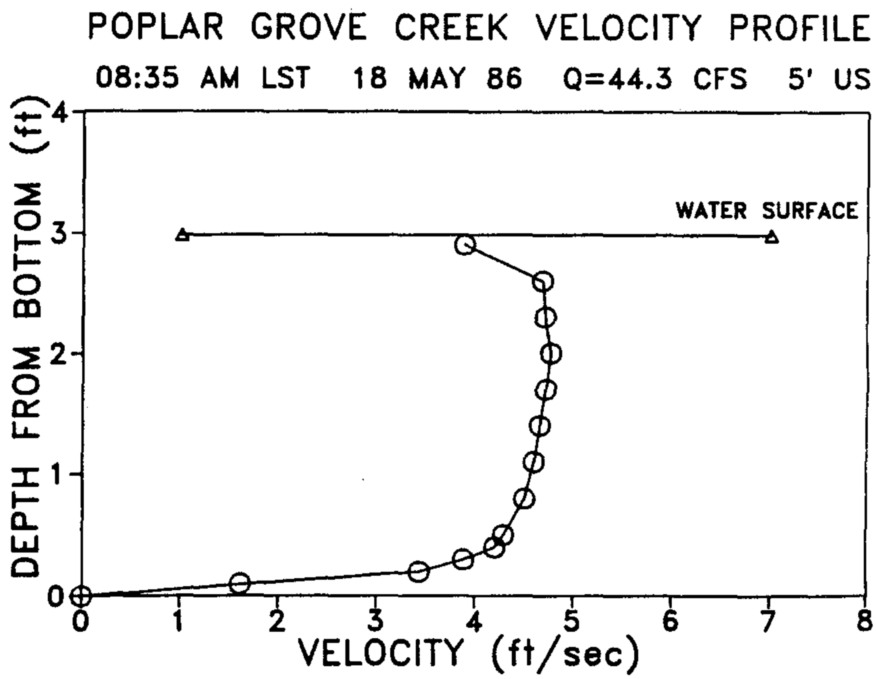

Figure 17. Water velocity profile, 1.5 m upstream culvert outlet, 18 May 1986.

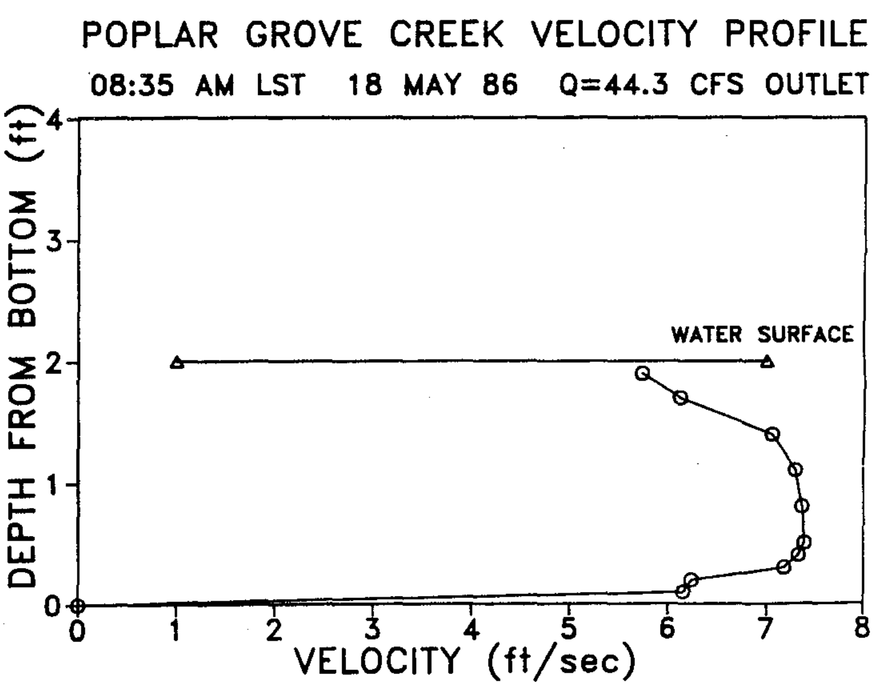

Figure 18. Water velocity profile, culvert outlet, 18 May 1986.

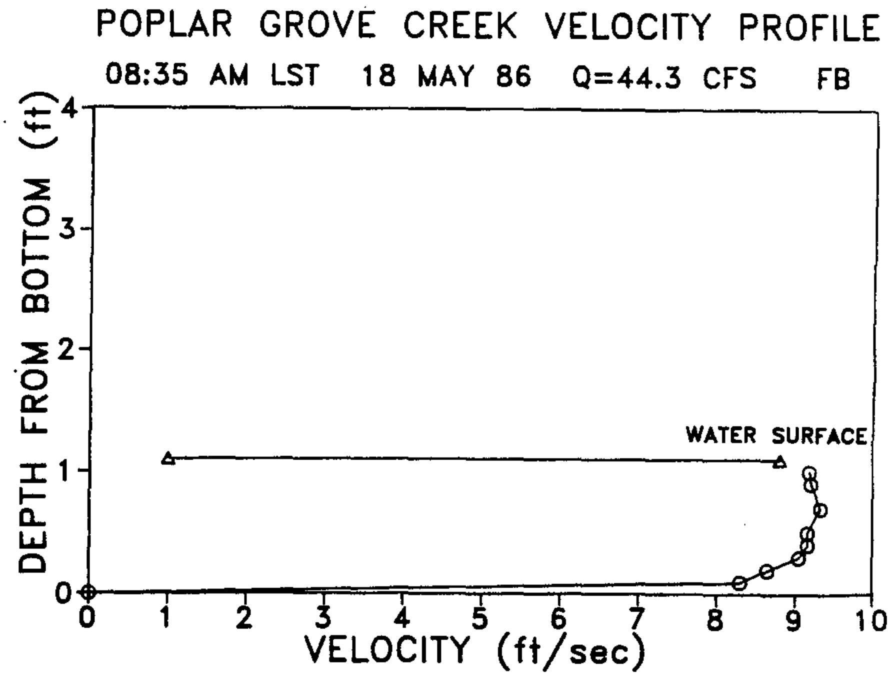

Figure 19. Water velocity profile, outlet flash board, 18 May 1986.

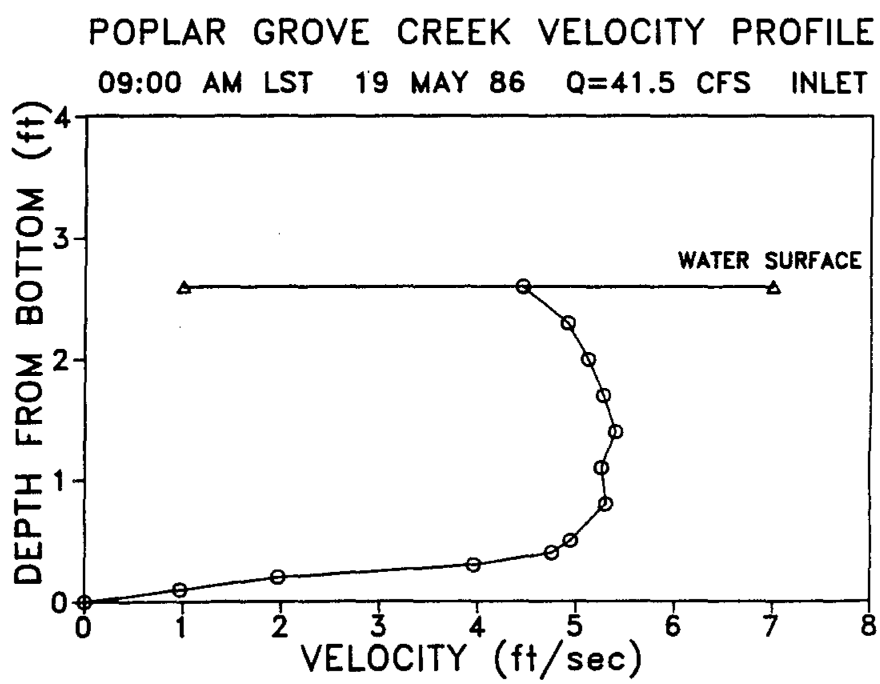

Figure 20. Water velocity profile, culvert inlet, 19 May 1986.

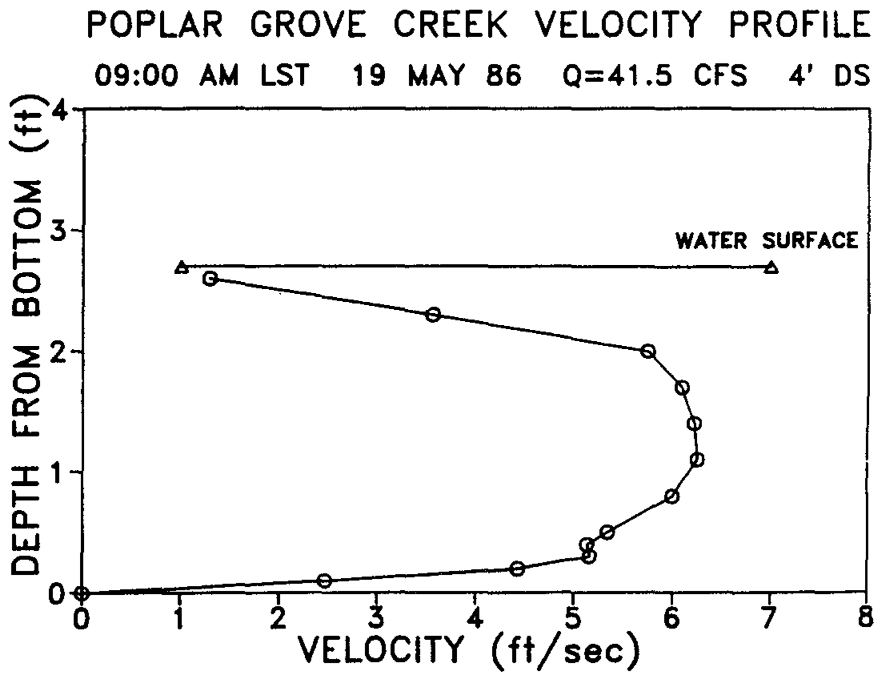

Figure 21. Water velocity profile, 1.2 m downstream culvert inlet, 19 May 1986.

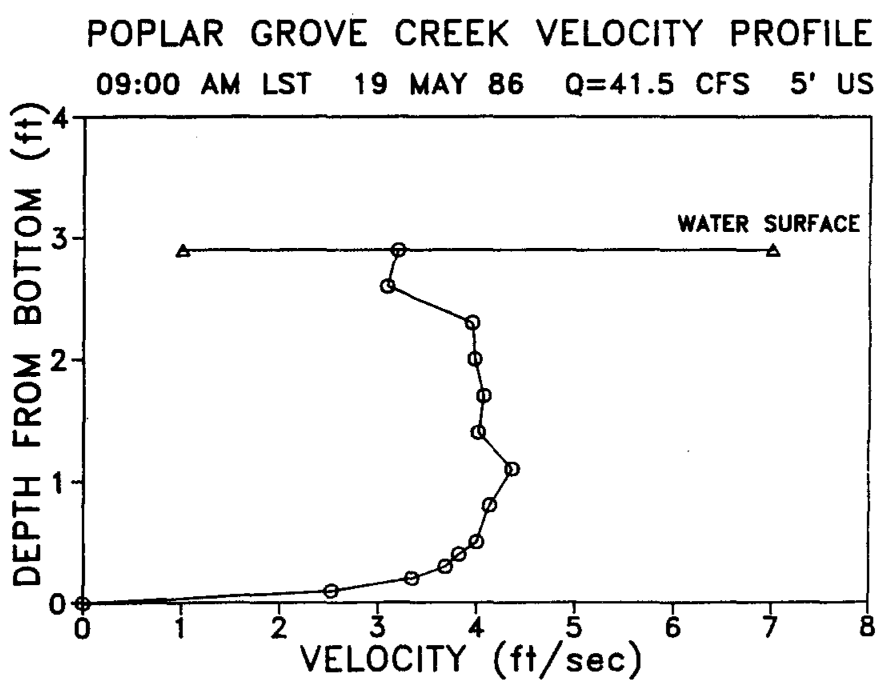

Figure 22. Water velocity profile, 1.5 m upstream culvert outlet, 19 May 1986.

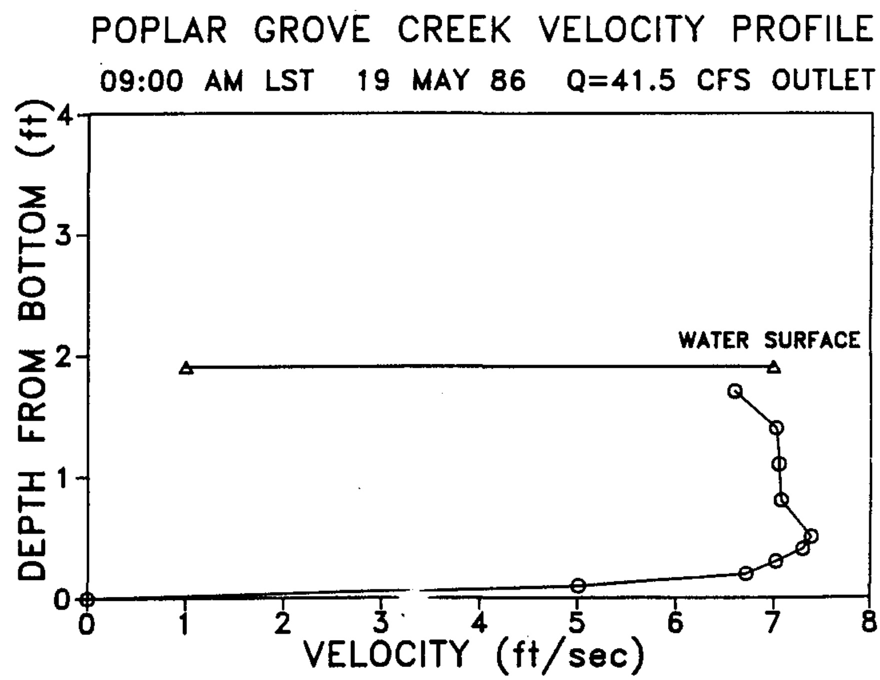

Figure 23. Water velocity profile, culvert outlet, 19 May 1986.

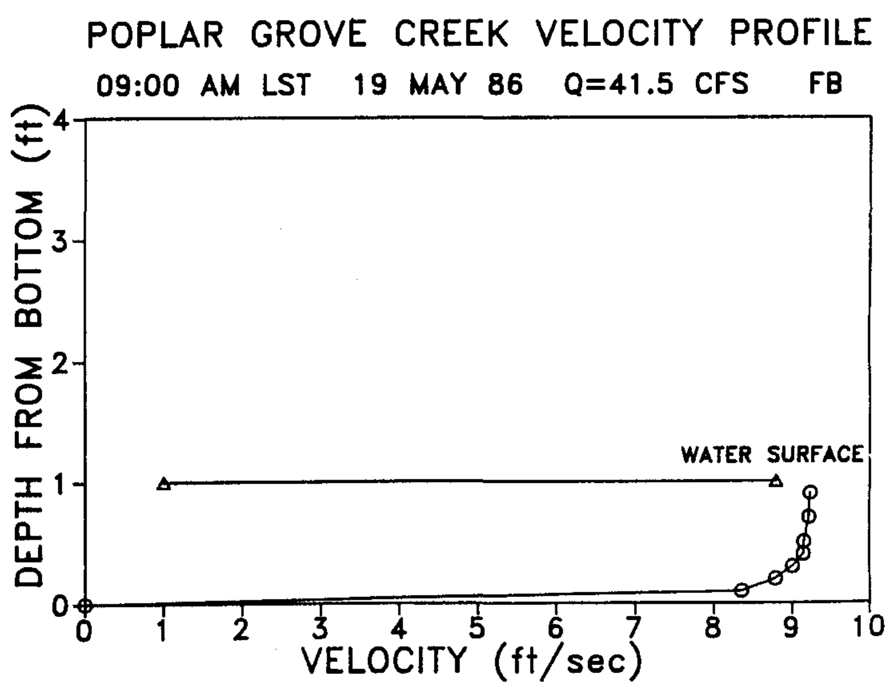

Figure 24. Water velocity profile, outlet flash board, 19 May 1986.

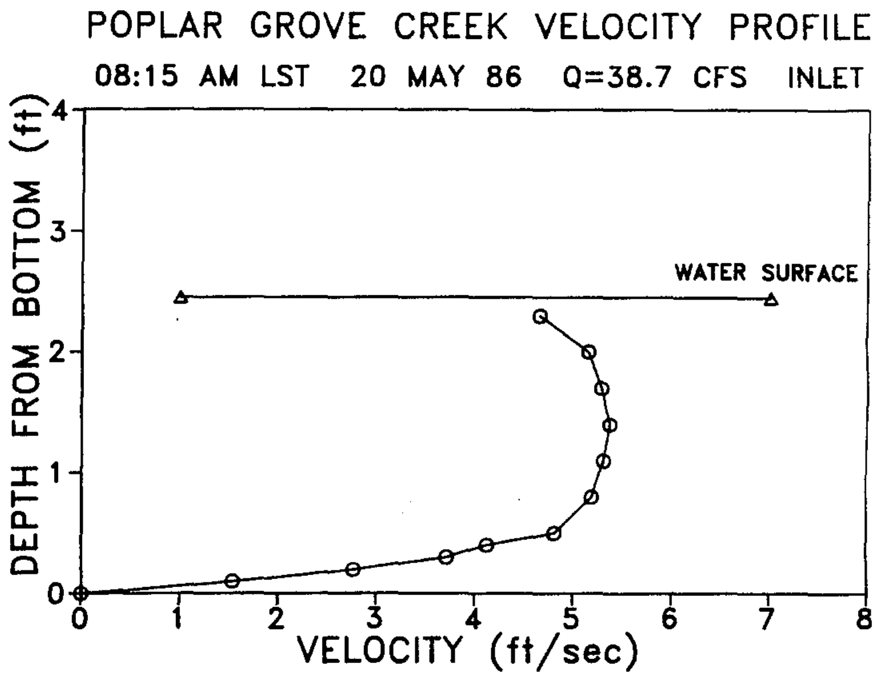

Figure 25. Water velocity profile, culvert inlet, 20 May 1986.

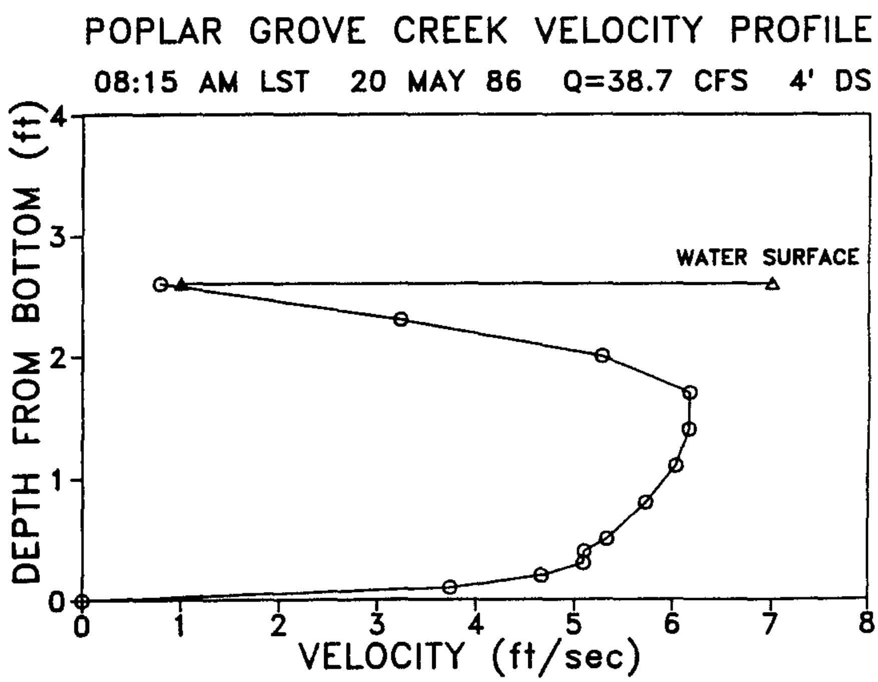

Figure 26. Water velocity profile, 1.2 m downstream culvert inlet, 20 May 1986.

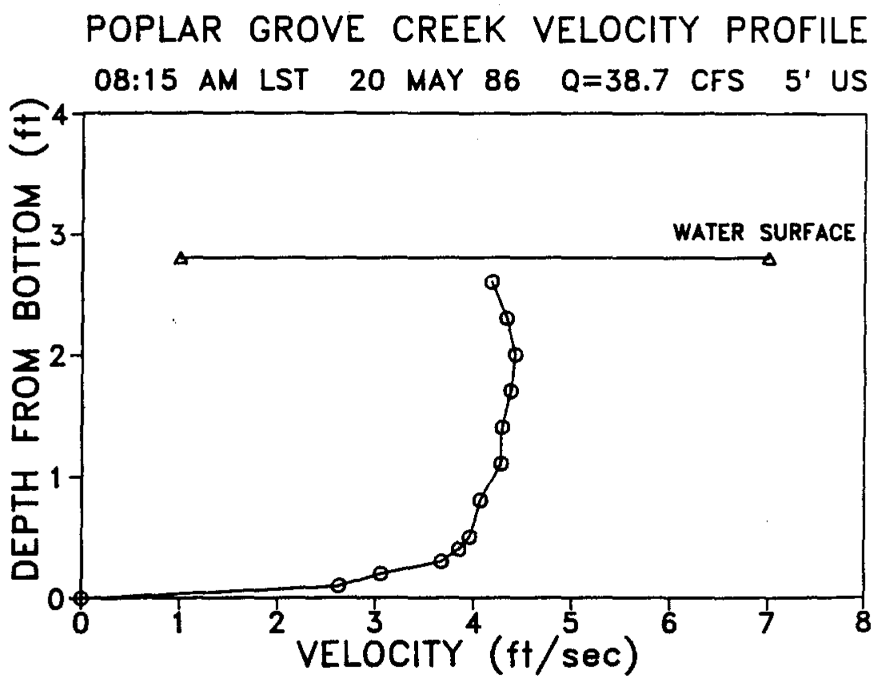

Figure 27. Water velocity profile, 1.5 m upstream culvert outlet, 20 May 1986.

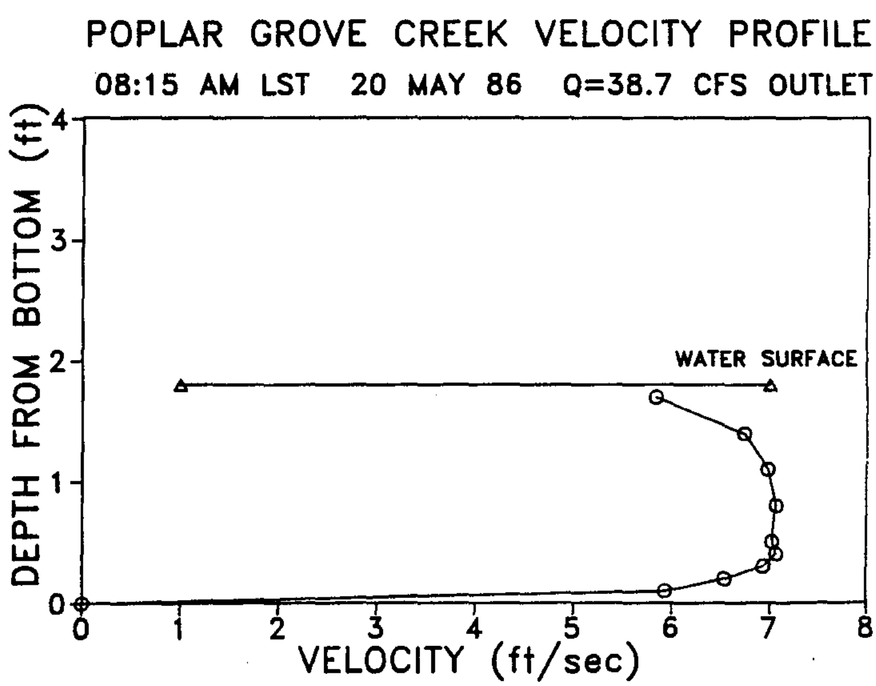

Figure 28. Water velocity profile, culvert outlet, 20 May 1986.

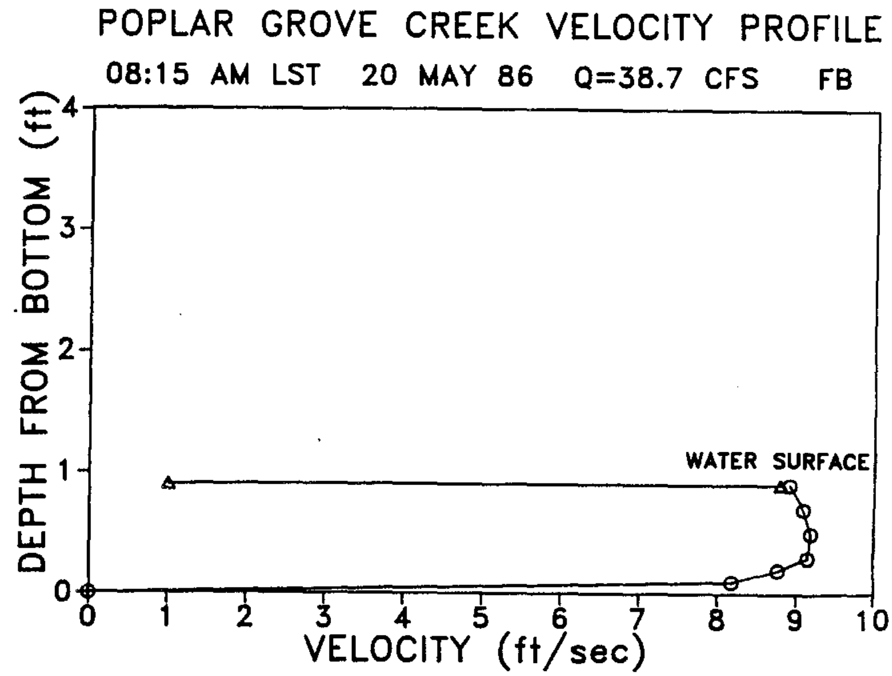

Figure 29. Water velocity profile, outlet flash board, 20 May 1986.

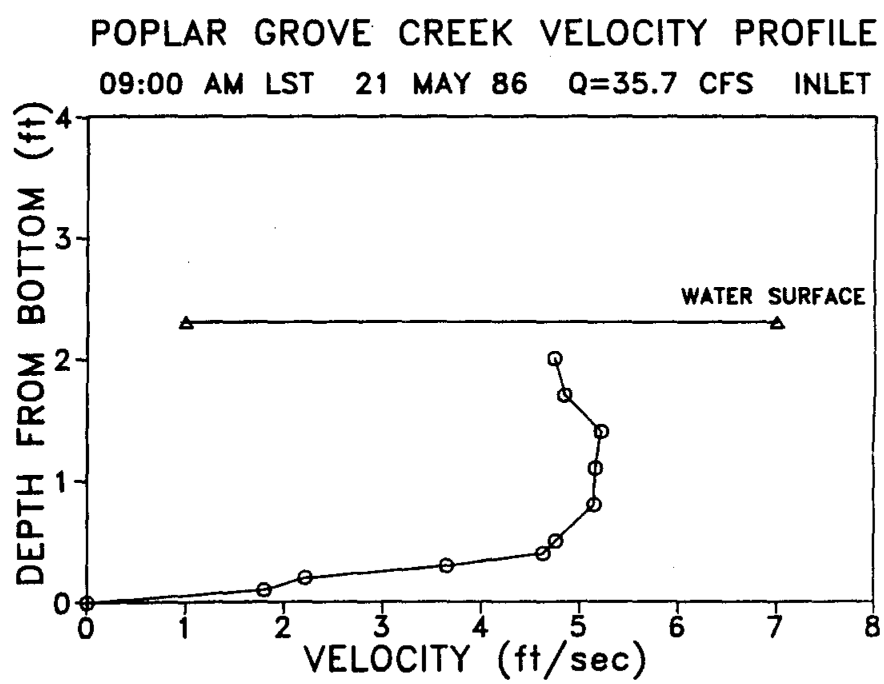

Figure 30. Water velocity profile, culvert inlet, 21 May 1986.

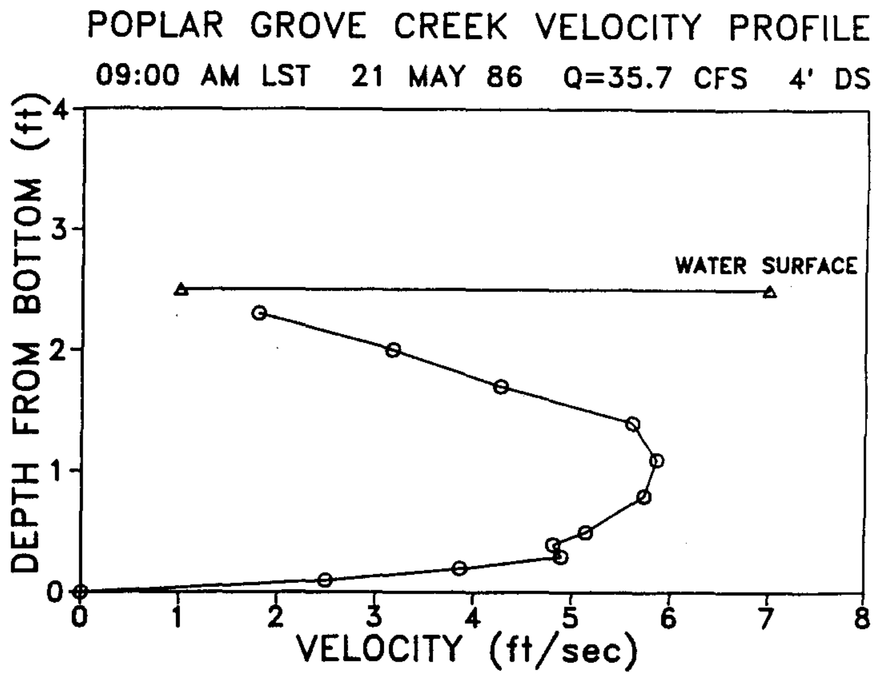

Figure 31. Water velocity profile, 1.2 m downstream culvert inlet, 21 May 1986.

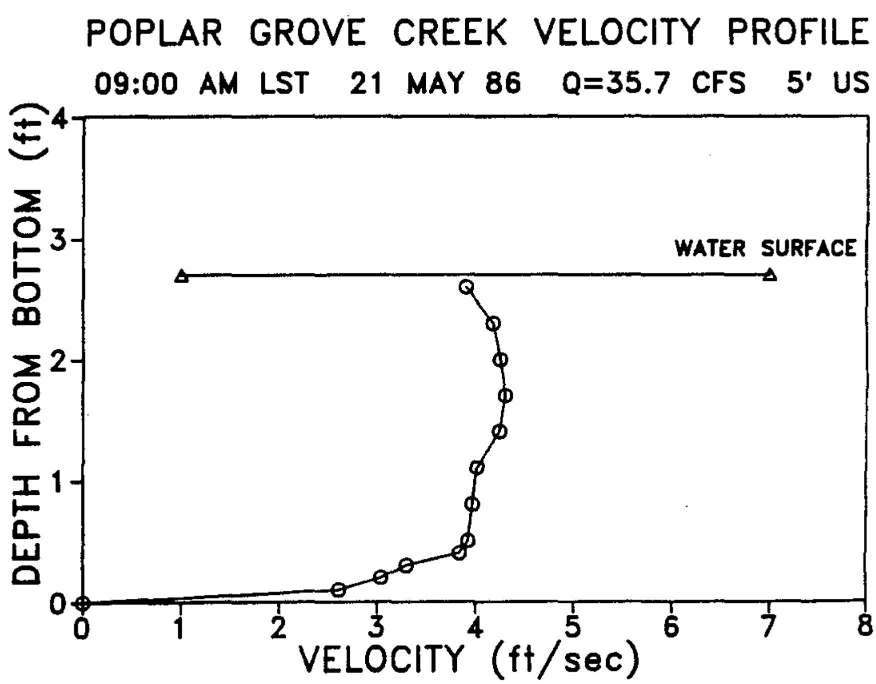

Figure 32. Water velocity profile, 1.5 m upstream culvert outlet, 21 May 1986.

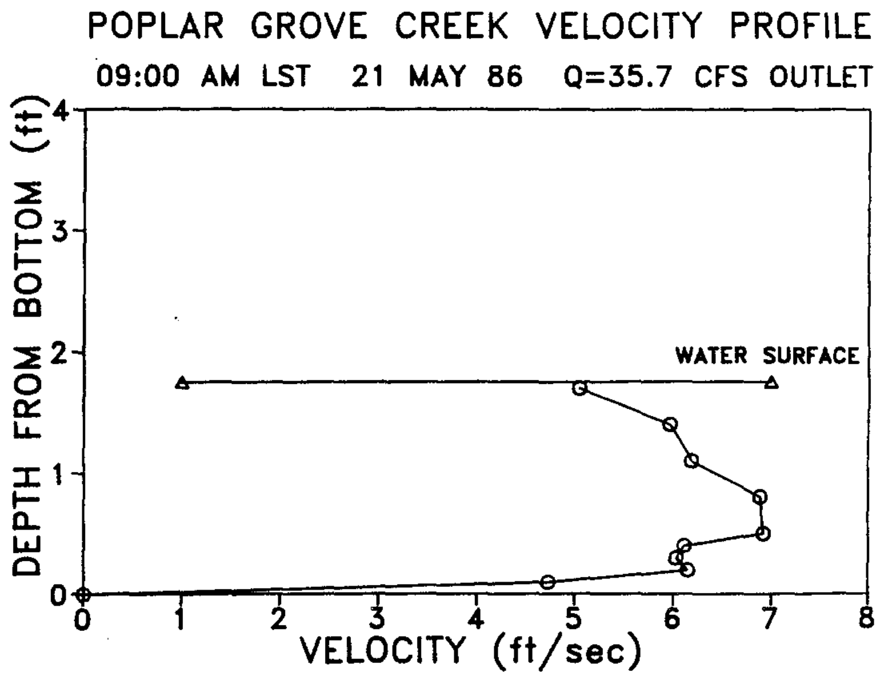

Figure 33. Water velocity profile, culvert outlet, 21 May 1986.

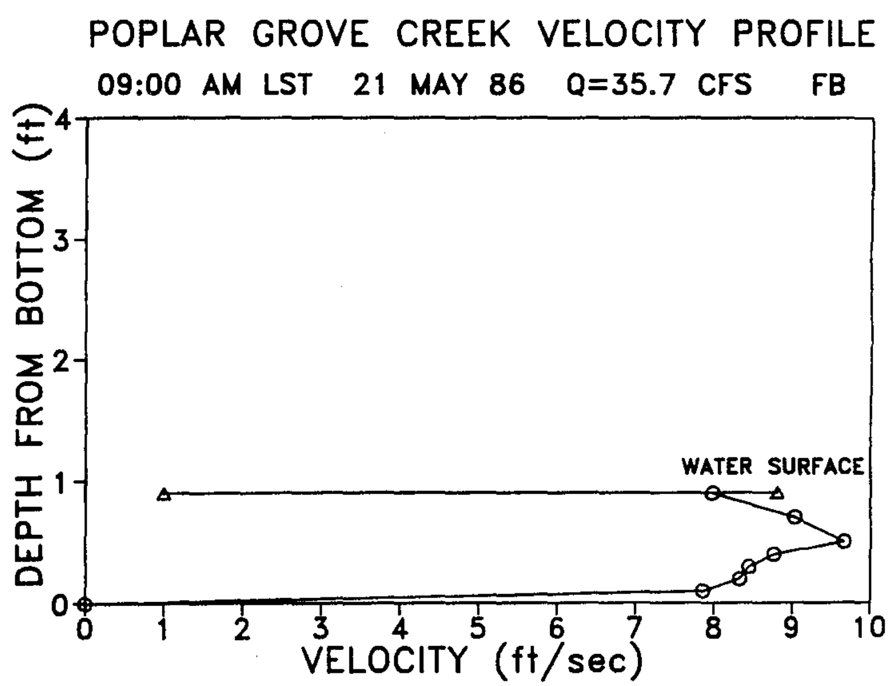

Figure 34. Water velocity profile, outlet flash board, 21 May 1986.

throughout the entire water profile at this location, but this view cannot be verified by observation. Flow was entering from below the culvert lip which protruded into the upstream pool and was not set flush with the stream bottom. The water flow at the culvert inlet was thus experiencing considerable contraction from the sides and bottom of the culvert. Since the flow cross section was constricted at this location, culvert water velocities were accelerating and velocity distribution curves were rather uniform for the area directly above the invert area of separation. It should be further noted that a white, half-culvert insert had been located in the bottom half of the culvert to improve potential visibility for observing fish as they swam over the insert. The insert consisted of a 0.61 m (2 ft) long half-section of culvert. Because of installation difficulties, the insert protruded outward approximately 20.3 cm (8 in) from the upstream end of the culvert. Water velocities, however, were measured at points vertically downward from the top end of the culvert. Thus, the water velocities measured within 5 cm (2 in) of the culvert invert probably were taken in a zone of separation and therefore probably do not accurately represent the effects of normal culvert wall contractions.

Velocity profiles were measured 1.2 m (4 ft) downstream from the culvert inlet where the contracted entrance jet from upstream was beginning to break down. However, the velocities toward the midpoints of the vertical profile were high as would be expected just downstream from an entrance contraction. This velocity distribution was probably much more affected by the upstream contraction and the beginning of dissipation of the contracted water jet than by wall friction effects. Relative to the much slower velocities (which are produced by wall friction effects) in the culvert barrel, the velocity distribution curves in this zone of kinetic energy dissipation better describe the actual water velocities fish encounter while swimming out through the culvert inlet.

The final 3 m (10 ft) of the culvert at its outlet end exhibited an adverse slope (sloped upward in the downstream direction because of differential settling). Thus, the acceleration of flow as it approached the downstream end of the culvert was more dominant than it would have been in the absence of an adverse slope. It was impossible to obtain velocity profiles within the culvert barrel, except as previously noted near the culvert ends. Regardless, the velocity distributions close to the invert at the point measured 1.5 m (5 ft) upstream from the culvert outlet lip are expected to be quite different from those predicted within the culvert barrel. This is to be expected because the water was accelerating in the lower 3.0 m (10 ft) of the culvert. This would not have occurred at depths closer to the hydraulically normal depth of the existing flows in this culvert, if it were set at its average slope. Thus, the measured velocity profiles at the culvert outlet are not what would be expected under normal flow conditions with normal wall friction effects. Instead, the velocity distribution curves for the culvert outlet are much more uniform than they would be otherwise under hydraulically normal flow conditions (Figures 14, 18, 23, 28 and 33).

Calculating Backwater Curves in the Culvert Barrel: In order to determine the flow depths and mean velocities at various points within the culvert barrel, backwater curves were computed from the measured water surface elevation at a point 1.5 m (5 ft) upstream from the downstream end of the culvert to a point 1.8 m (6 ft) downstream from the culvert inlet. A Manning n of 0.024 and a partially full, circular cross section was assumed for the backwater calculations. The latter assumption was adopted after preliminary computations indicated virtually no difference between curves for circular or elliptical culverts (geometrically, an elliptical cross section would more accurately reflect the degree of distortion exhibited by the Poplar Grove Creek culvert). This was because hydraulic controls downstream from the distorted portion of the culvert determined the shape of the backwater curve to a much greater degree than did small changes in the culvert's cross-sectional shape.

Figures 35 through 38 (plots of the calculated water surface profiles and average water velocities at grade-breaks in the culvert) depict the water surface profiles in the culvert barrel at approximately noon of each day between May 17 and May 20. Water surface elevations in the

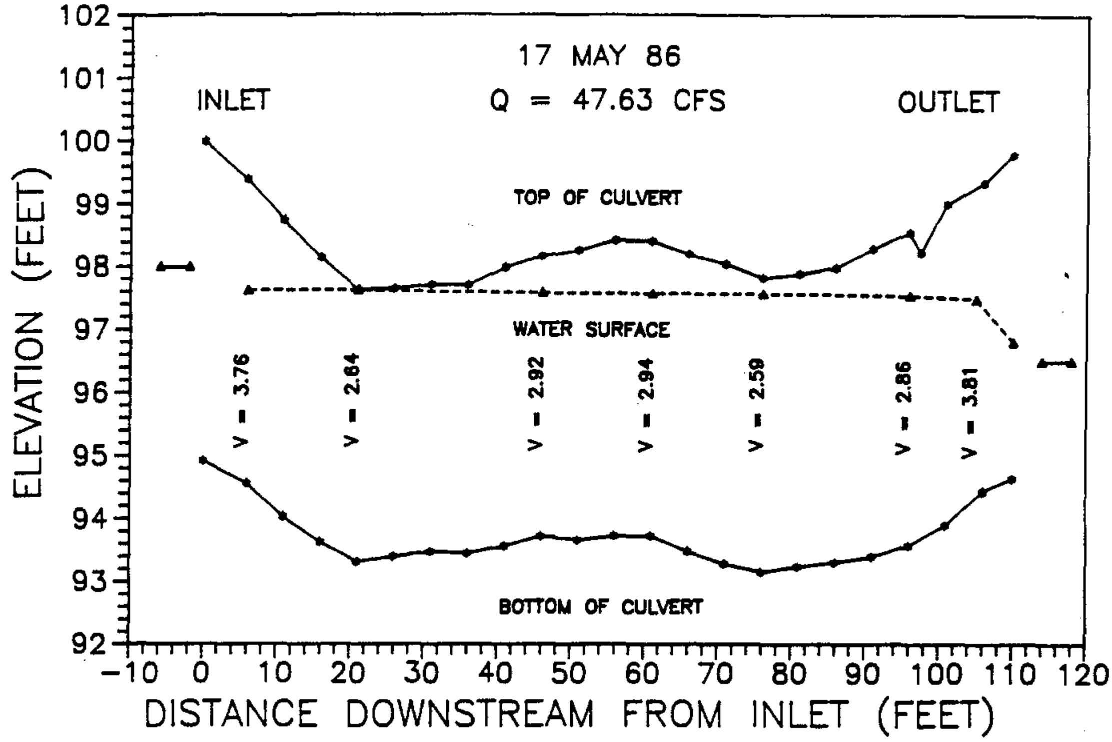

Figure 35. Calculated culvert water surface profiles, 17 May 1986.

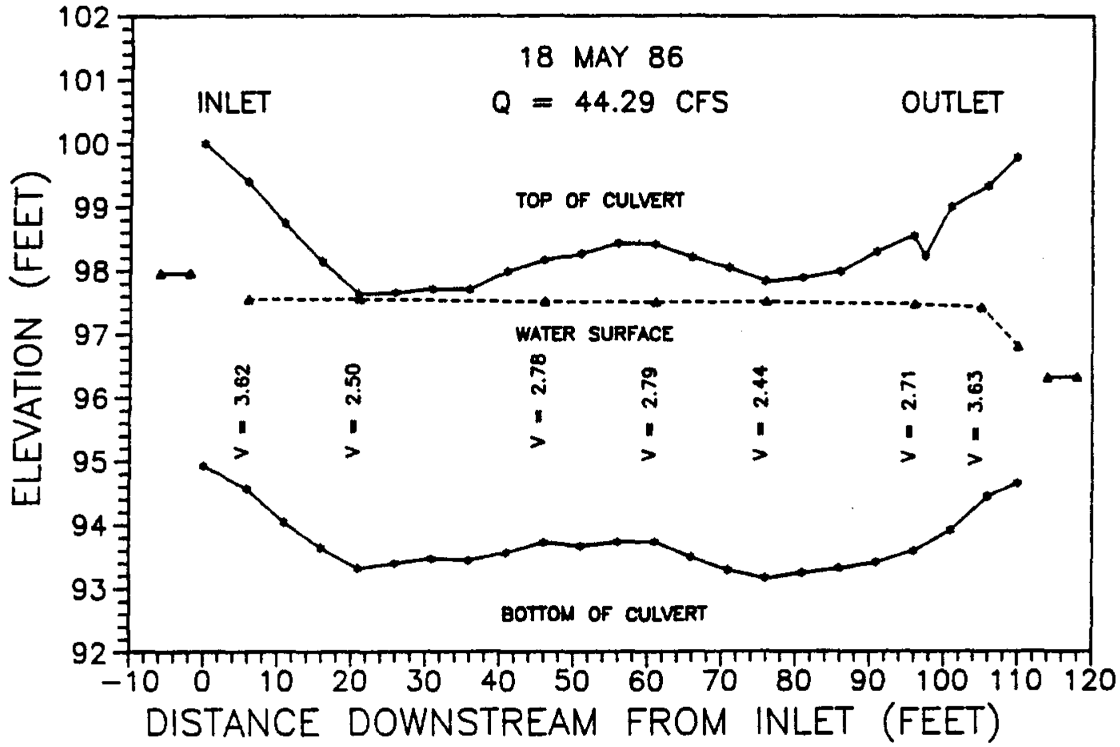

Figure 36. Calculated culvert water surface profiles, 18 May 1986.

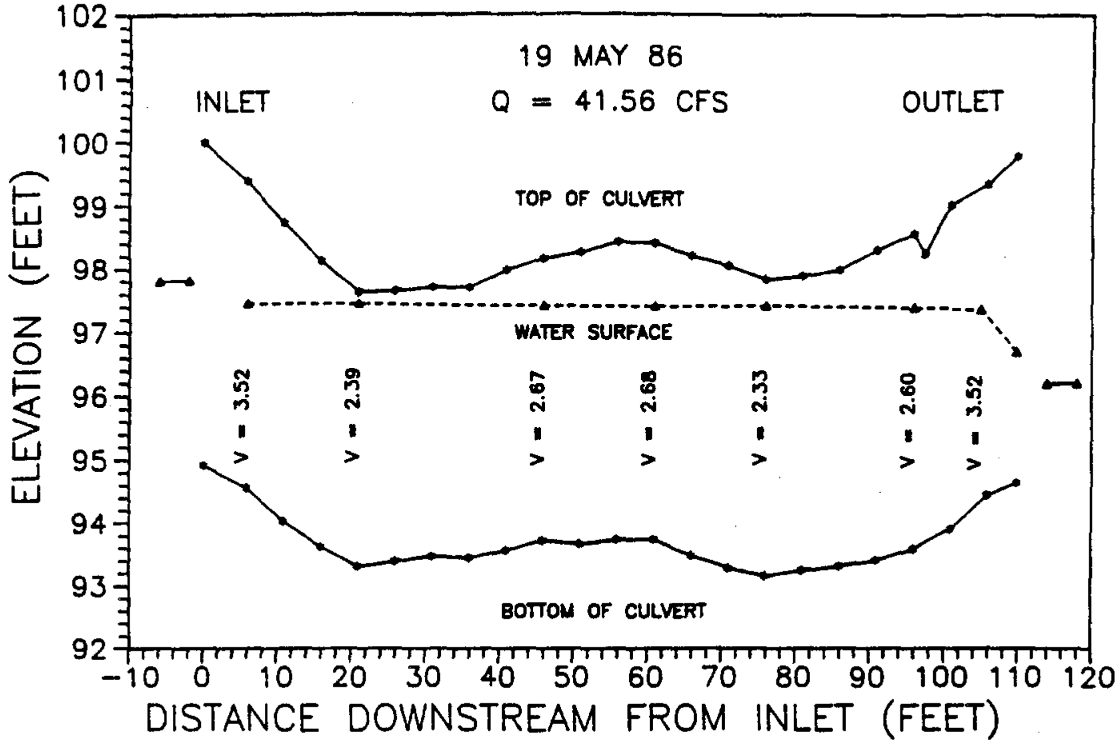

Figure 37. Calculated culvert water surface profiles, 19 May 1986.

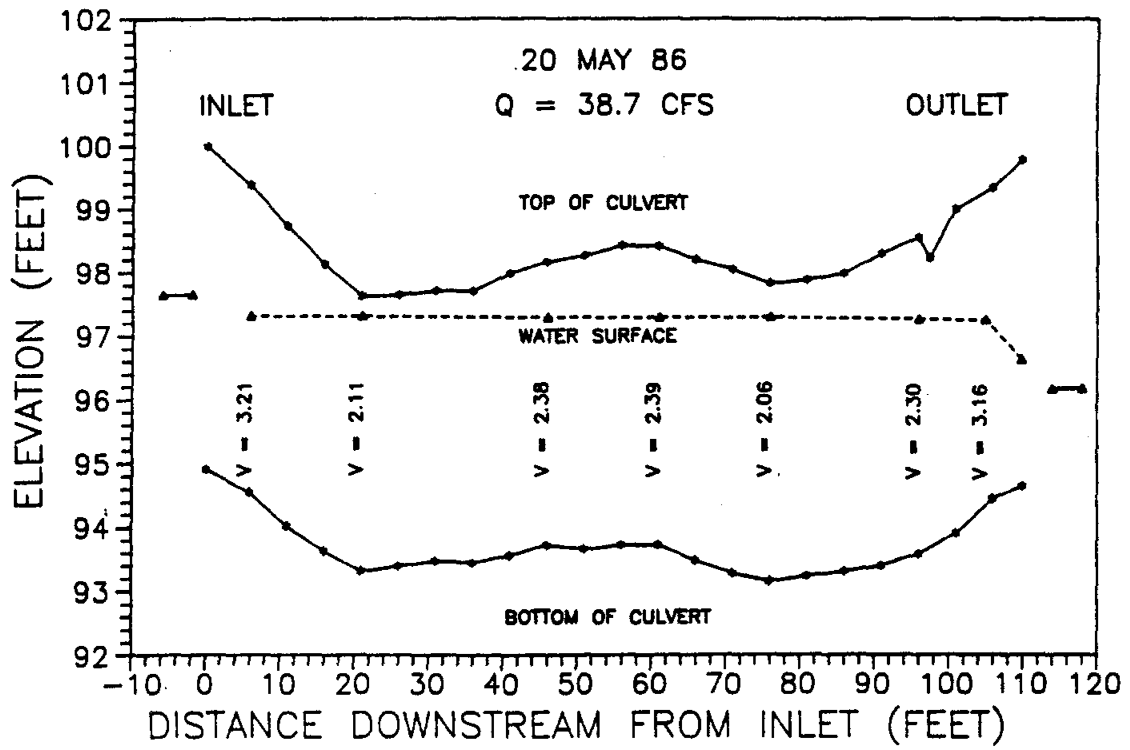

Figure 38. Calculated culvert water surface profiles, 20 May 1986.

pools upstream and downstream from the culvert are shown by tic marks at the edge of these figures.

Using Regressions to Predict Culvert Water Velocities: In order to determine the correlation between the observed passage rates of Arctic grayling through the culvert and actual culvert water velocities, it was necessary to develop equations that would predict water velocities at various points in the culvert for each period of fish passage observation. Linear regressions equations were developed based on: (1) calculated average culvert outlet velocity (defined as discharge divided by the culvert cross-sectional area at the outlet), (2) measured $V_{occupied}$ culvert outlet velocity (defined as the average velocity for the lowest 91 mm (0.3 ft) above the culvert invert centerline), and (3) calculated $V_{weighted}$ culvert barrel velocity (defined as the weighted average of the mean velocity for the entire culvert as derived from the backwater curve calculations). In addition, a linear regression was developed for the inferred $V_{occupied}$ culvert barrel velocity (defined as the lowest 91 mm (0.3 ft) above the culvert invert) based on the observed relationship between the weighted mean culvert water velocity and the $V_{occupied}$ water velocity at a point 1.5 m (5 ft) upstream of the culvert outlet. The derived inferrential relationship was then extended to the weighted mean culvert velocity to predict the $V_{occupied}$ culvert barrel velocity.

Measured water velocities and the derived linear regression values by hourly period between May 16 to 21 are presented in Table 4. The coefficients of determination (R^2) and the standard error of the estimates (SEE) for each linear regression equation are presented below.

$V_{average}$ Culvert Outlet Water Velocity:	R^2 = 0.77 SEE = 0.14 fps
$V_{occupied}$ Culvert Outlet Water Velocity:	R^2 = 0.81 SEE = 0.25 fps
$V_{weighted}$ Culvert Barrel Water Velocity:	R^2 = 0.95 SEE = 0.06 fps

$V_{occupied}$ Culvert Barrel Water Velocity: $R^2 = 0.83$
SEE = 0.06 fps

Hydraulic Considerations Affecting Fish Passage: Arctic grayling entering the culvert outlet usually swam close to the culvert invert. Most of the grayling exhibited relative difficulty in the immediate vicinity of the outflow lip of the culvert, swimming with a short, rapid body flutter until they had passed a point approximately 0.6 m (2 ft) upstream from the culvert outlet lip. Fish which were able to get to that point generally appeared to begin to swim more easily (less vigorous body movement) as they passed further upstream. Culvert outlet mean velocities during the fish migration period (May 17 to 20) ranged from 6.35 to 5.94 fps (Table 4). Clearly, although the culvert could be classified as only partially perched, fish were experiencing relative difficulty entering the outlet lip of the culvert.

It should be pointed out that because the culvert sloped adversely at this point, horizontal pressure gradients close to the culvert outlet lip and rapidly increasing water depths in the upstream direction (with rapidly increased cross-sectional area and decreased water velocities) both combined to ease the passage of those fish that successfully entered the culvert. In contrast, if the culvert had been situated at a constant grade from one end to the other, and if the downstream invert lip had been at the same elevation as the study culvert, the horizontal pressure gradient near the outlet lip would probably have been somewhat reduced, but the flow velocity would not have decreased as rapidly for the fish as it moved upstream. Thus, fish would have found the entrance conditions at the culvert outlet lip easier but would have experienced more difficulty in swimming upstream through the lower portion of the culvert.

It is clear from Figures 35 through 38 and the velocity profiles measured on the downstream flashboard and at the culvert outlet lip, that water velocities were much slower in the barrel of the culvert (not including the culvert inlet) than they were at the location where fish entered the culvert.

TABLE 4. Water velocities (fps) in Poplar Grove Creek culvert, 16-21 May 1986.

Date	Hrs (ADT)	Obs V-Ave Out	Regrs V-Ave Out	Obs V-Occ Out	Regrs V-Occ Out	Obs V-Wgh Culv	Regrs V-Wgh Culv	Infer V-Occ Culv	Regrs V-Occ Culv
May 16	1606	6.43	6.37		7.10		3.08		2.62
	2022		6.35	7.14	7.05	3.12	3.05	2.66	2.61
May 17	0906		6.28		6.92	2.98	2.98	2.53	2.58
	1300-1400		6.26		6.87		2.96		2.56
	1400-1530		6.25		6.86		2.95		2.56
	1530	6.35	6.25		6.86		2.95		2.56
	1530-1600		6.25		6.85		2.95		2.56
	1600-1650		6.24		6.84		2.95		2.56
May 18	0920		6.15	6.45	6.67	2.86	2.85	2.45	2.51
	1000-1100		6.15		6.66		2.85		2.51
	1100-1230		6.14		6.64		2.84		2.51
	1230-1330		6.13		6.63		2.83		2.50
	1330-1500		6.13		6.62		2.83		2.50
	1500-1600		6.12		6.60		2.82		2.50
	1600-1700		6.12		6.59		2.82		2.49
	1718	5.88	6.11		6.58		2.81		2.49
	1700-1800		6.11		6.58		2.81		2.49
	1800-1900		6.11		6.57		2.81		2.49
	1900-2000		6.10		6.56		2.80		2.48
	2000-2100		6.09		6.55		2.79		2.48
	2100-2200		6.09		6.54		2.79		2.48
	2200-2240		6.09		6.53		2.78		2.48
May 19	0900		6.03	6.39	6.42	2.70	2.73	2.51	2.45
	1040-1320		6.01		6.39		2.71		2.44
	1320-1430		6.00		6.37		2.70		2.44
	1430-1500		6.00		6.36		2.70		2.43
	1500-1600		6.00		6.35		2.69		2.43
	1554	5.94	5.99		6.35		2.69		2.43
	1600-1700		5.99		6.34		2.69		2.43
	1700-1800		5.98		6.33		2.68		2.43
	1800-1900		5.98		6.32		2.68		2.42
	1900-2000		5.97		6.31		2.67		2.42
May 20	0915		5.90	6.49	6.17	2.59	2.60	2.40	2.38
	1100-1345		5.89		6.14		2.58		2.38
	1345-1500		5.88		6.12		2.57		2.37
	1500-1620		5.87		6.10		2.56		2.37
	1620-1715		5.86		6.09		2.56		2.36
	1754	5.94	5.86		6.08		2.55		2.36
May 21	1000		5.77	5.76	5.91	2.51	2.46	2.30	2.32
	1230	5.80	5.76		5.89	2.45		2.31	

Notes: Observed average culvert outlet velocity equals the discharge divided by the culvert cross-sectional area at the outlet. Observed V-occupied culvert outlet velocity is calculated as the average velocity for the lowest 91 mm (0.3 ft) above the culvert invert centerline.

Table 4 Footnotes (Continued):

Observed V-weighted culvert velocity is calculated as the weighted mean velocity for the entire culvert. Inferred V-occupied culvert barrel velocity is calculated as the inferred mean value for the lowest 91 mm (0.3 ft) above the culvert invert and is based upon the observed relationship between weighted mean culvert velocity and the V-occupied velocity at a point 1.5 m (5 ft) upstream of the culvert outlet. The inferential relationship was extended to the weighted mean culvert velocity to generate a V-occupied velocity for the culvert barrel. Inferrential relationships were 85% of V_{ave} on 5/16/86; 85% on 5/17/86; 88% on 5/18/86; 93% on 5/19/86; 93% on 5/20/86; and 91% on 5/21/86.

Regressions: V-ave. Outlet (R-Square = 0.77, SEE = 0.14); V-occupied Outlet (R-Square = 0.81, SEE = 0.25); V-weighted Culvert (R-Square = 0.95, SEE = 0.06); V-occupied Culvert (R-Square = 0.83, SEE = 0.06)

The survey of the barrel of the culvert indicated no abrupt depressions or other places where fish could stop swimming to rest in the culvert. Thus, since observers were unable to observe fish all the way through the culvert barrel, it is presumed that fish had to swim continuously while they were in the culvert (although it is possible that they could have darted forward and then drifted back downstream some distance). Nonetheless, it is not known whether the fish maintained forward movement or, at times, just maintained their positions in the culvert barrel.

Fisheries

Upstream Spawning Migration: Arctic grayling were observed migrating up Poplar Grove Creek between May 12 and May 20. Observations were terminated on May 20 when data collection efforts were completed. Arctic grayling were observed at the mouth of the creek on May 12 at 1445 hours (ADT). The water temperature in Poplar Grove Creek was 0.5°C and some ice was still anchored to the creek bottom. The water temperature in the Gulkana River was 1.0°C. Although several attempts were made to dipnet fish along the cut banks of the creek, no fish were captured. The first Arctic grayling was captured by dip net at the mouth at 1700 hours (AST) on May 13. The water temperature at that time continued to hover around 0.5°C. By the afternoon of May 14, stream water temperature had risen to 2.0°C and the spawning migration appeared to begin in earnest. Large numbers of Arctic grayling were observed well within the creek mouth; 100 were captured by dip net approximately 200 yards upstream of the mouth and tagged for later recovery. The first fish arrived at the lower weir site (located approximately 0.7 km upstream from the mouth) during the afternoon of May 15. Water temperature was 2.8°C at 1800 hours ADT. A single Arctic grayling was first observed at the culvert outlet scour pool (located approximately 2.5 km upstream of the mouth) on May 16 at 1400 hours ADT. The water temperature in the scour pool was 3.8°C. The first fish was observed at the upstream weir (located approximately 91 m upstream from the culvert) at 1800 hours on May 17. Water temperature was 4.0°C.

Length, Weight and Condition Factor Relationships: Length frequency distributions by day and sample location are depicted in Figures 39 through 45 and in Appendix Table 1.

The mean fork length for all Arctic grayling sampled at the upstream weir between May 18 and May 20 was 235 mm (9.25 in) (range 170 mm to 349 mm). Daily mean fork length declined from a maximum of 251 mm (9.9 in) on May 18 to 229 mm (9.0 in) on May 20 at the upper weir sample location (Figure 46).

Figure 47 depicts the fork length versus weight relationship for 40 Arctic grayling captured at the downstream weir on May 16, 1986. These data plus condition factors are presented in Table 5. The average condition factor for these fish was 0.92 (range 0.8 to 1.08).

Sex Composition and Maturation: Figure 48 depicts the proportion of Arctic grayling, by day, in the spawning migration that were sexually ripe. On May 14, at the onset of the spawning migration (fish sampled at creek mouth), 26 percent of the run were ripe males, 1 percent ripe females, and 73 percent nonripe males and females, or immatures. By May 17 at the culvert outlet scour pool, 42 percent of the run consisted of sexually ripe males, 2 percent were ripe females, and 56 percent were nonripe males and females, or immatures. Three days later on May 20 (at the upstream weir), 54 percent of the run consisted of sexually ripe males, 45 percent were ripe females, and 1 percent were nonripe males and females, or immatures. Water temperatures during this interval ranged between 1.5°C on May 14 to 7.1°C on May 20.

Diel Movements: Figures 49 through 52 depict the diel variation in culvert fish passage rates for May 17 through May 20. Active fish movements predominately occurred between 1000 hours and 2300 hours ADT. Maximum fish activity was most pronounced between 1300 hours and 2100 hours ADT. Peak hourly activity varied from 1600-1700 hours ADT on May 17 and 19, 2100-2200 hours ADT on May 18, and 1500 to 1600 hours ADT on May 20. Peak activity appeared to correlate with the peak or prepeak water temperatures for the day.

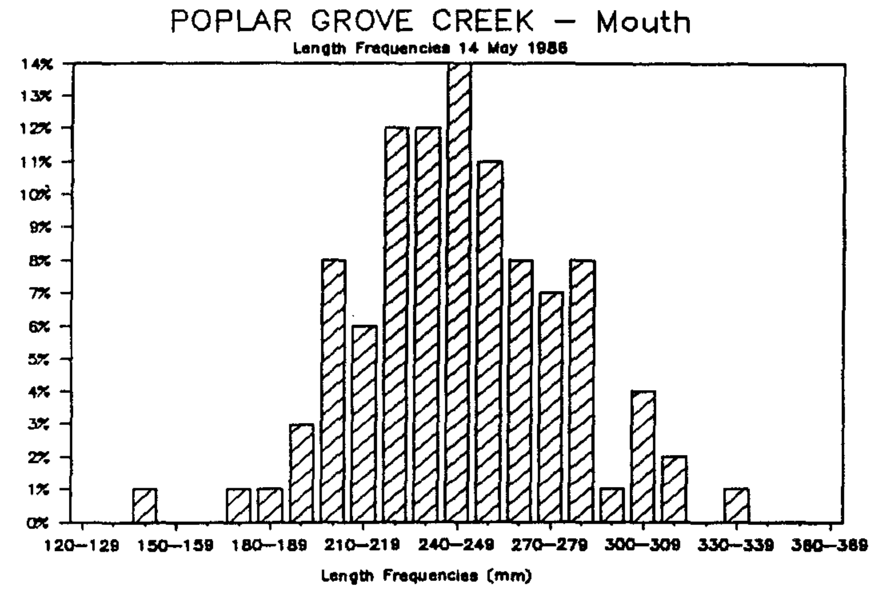

Figure 39. Length frequency distribution for Arctic grayling tagged at stream mouth, 14 May 1986.

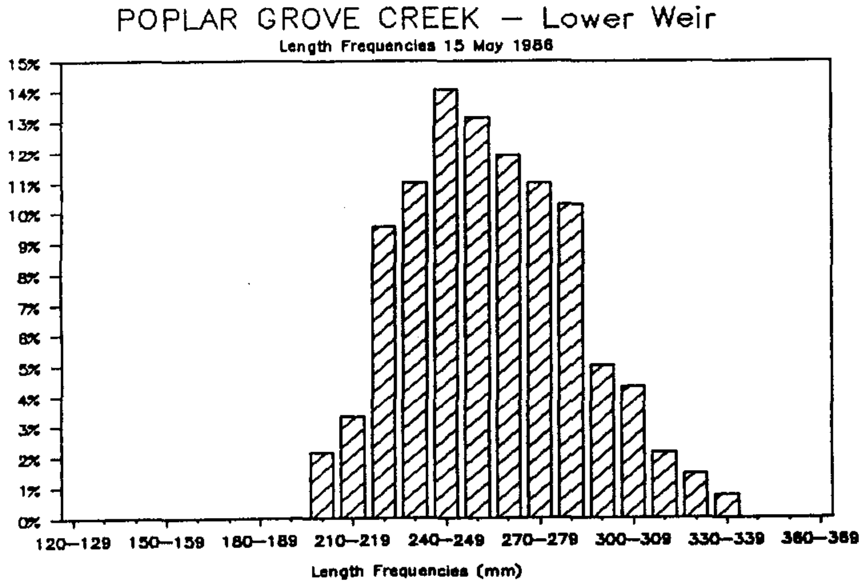

Figure 40. Length frequency distribution for Arctic grayling tagged at lower weir site, 15 May 1986.

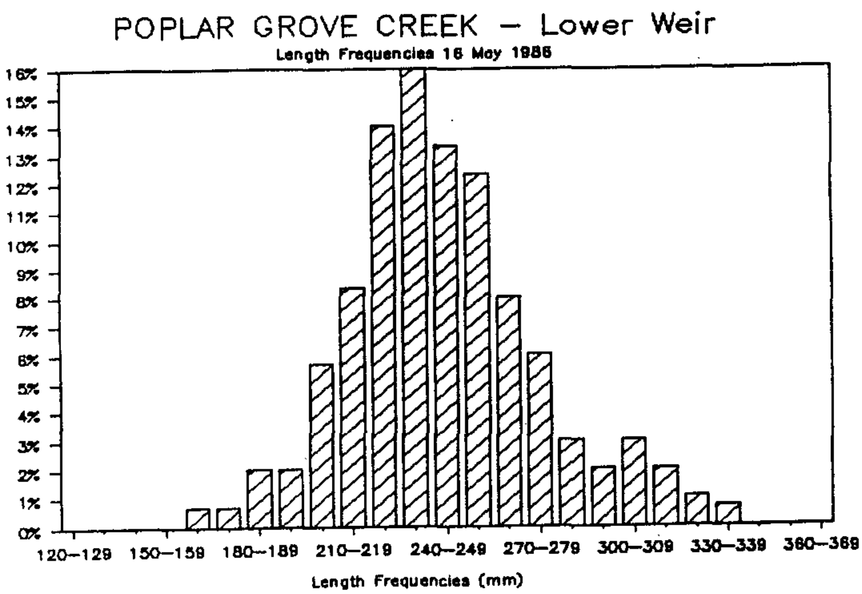

Figure 41. Length frequency distribution for Arctic grayling tagged at lower weir site, 16 May 1986.

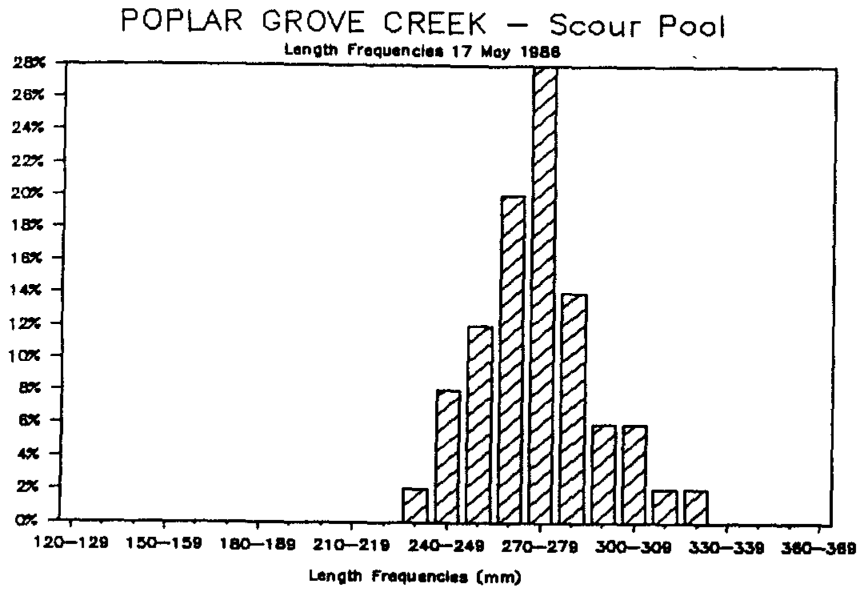

Figure 42. Length frequency distribution for Arctic grayling tagged at culvert scour pool, 17 May 1986.

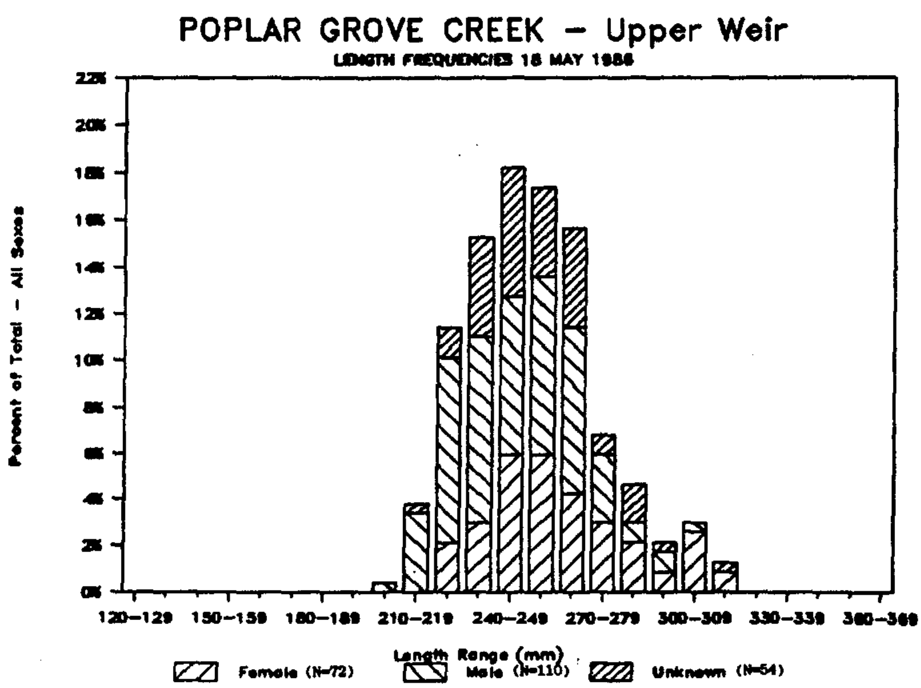

Figure 43. Length frequency distribution by sex for Arctic grayling recovered at the upper weir site, 18 May 1986.

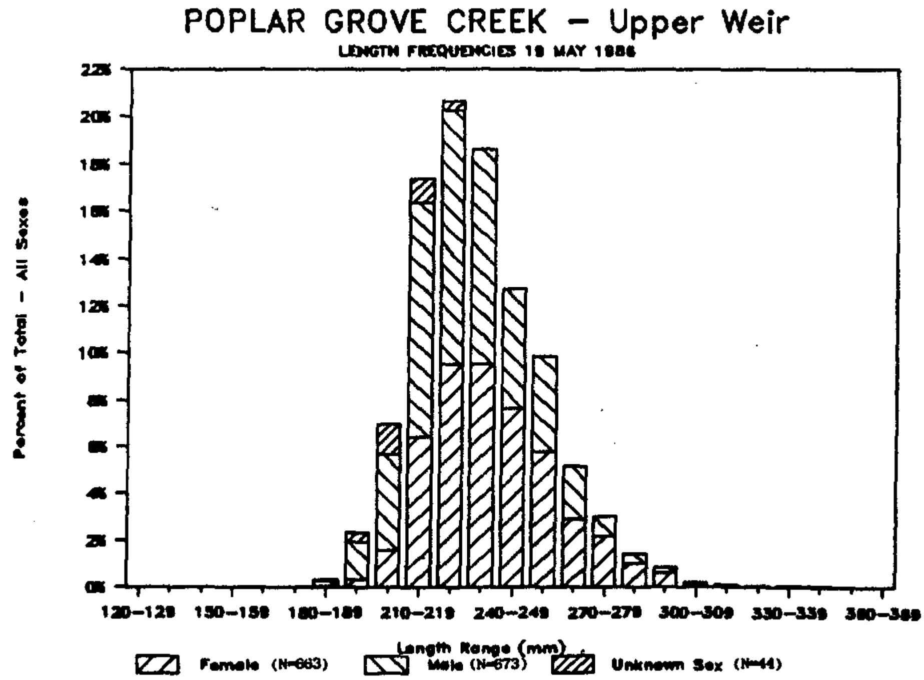

Figure 44. Length frequency distribution by sex for Arctic grayling recovered at the upper weir site, 19 May 1986.

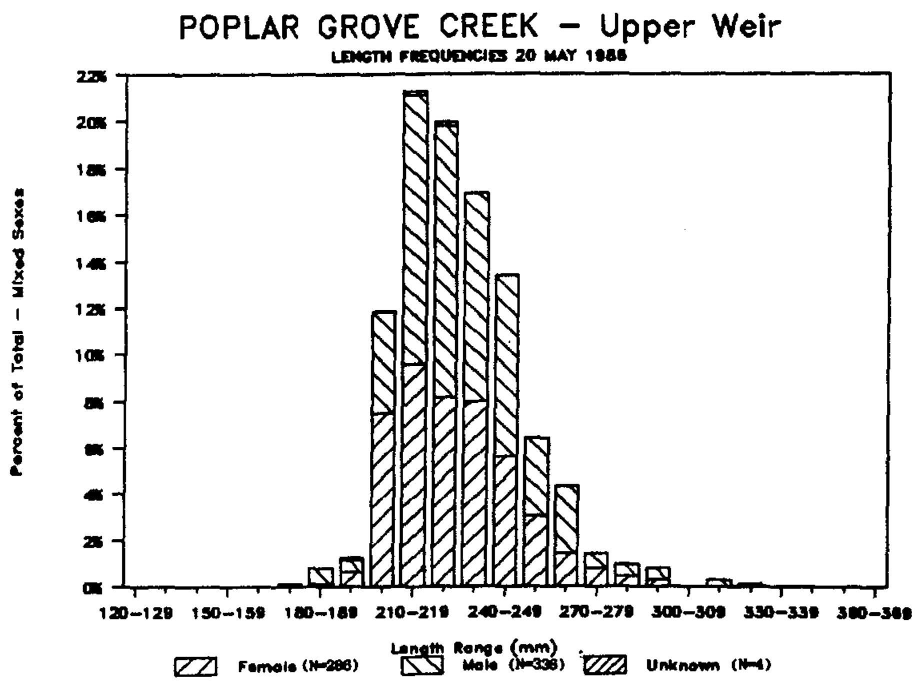

Figure 45. Length frequency distribution by sex for Arctic grayling recovered at the upper weir site, 20 May 1986.

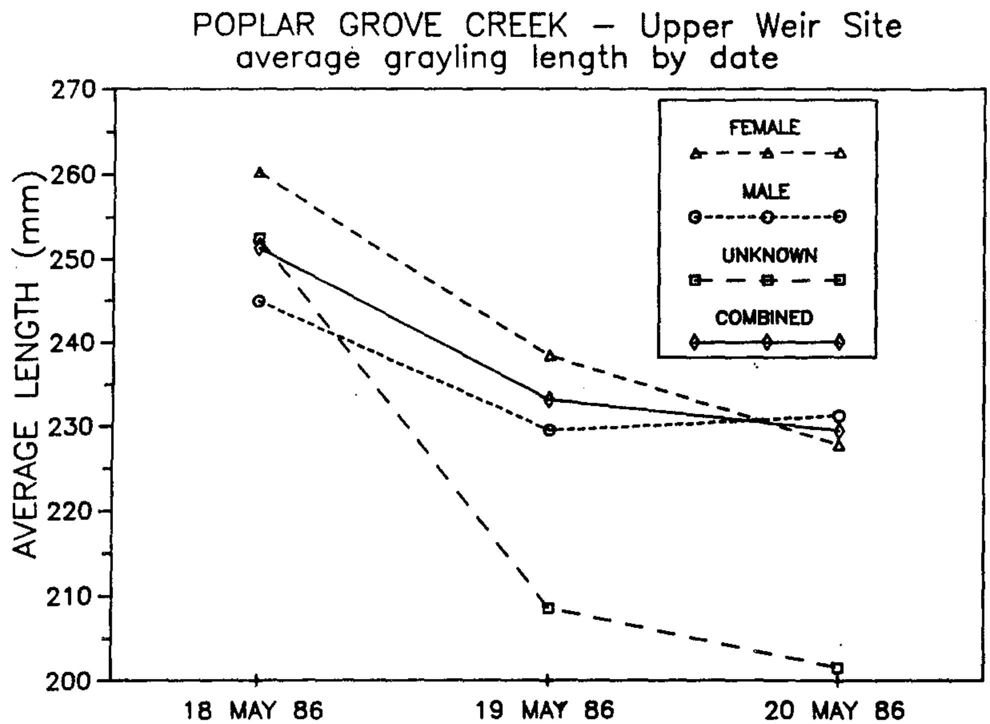

Figure 46. Arctic grayling fork length (mm) versus date of capture.

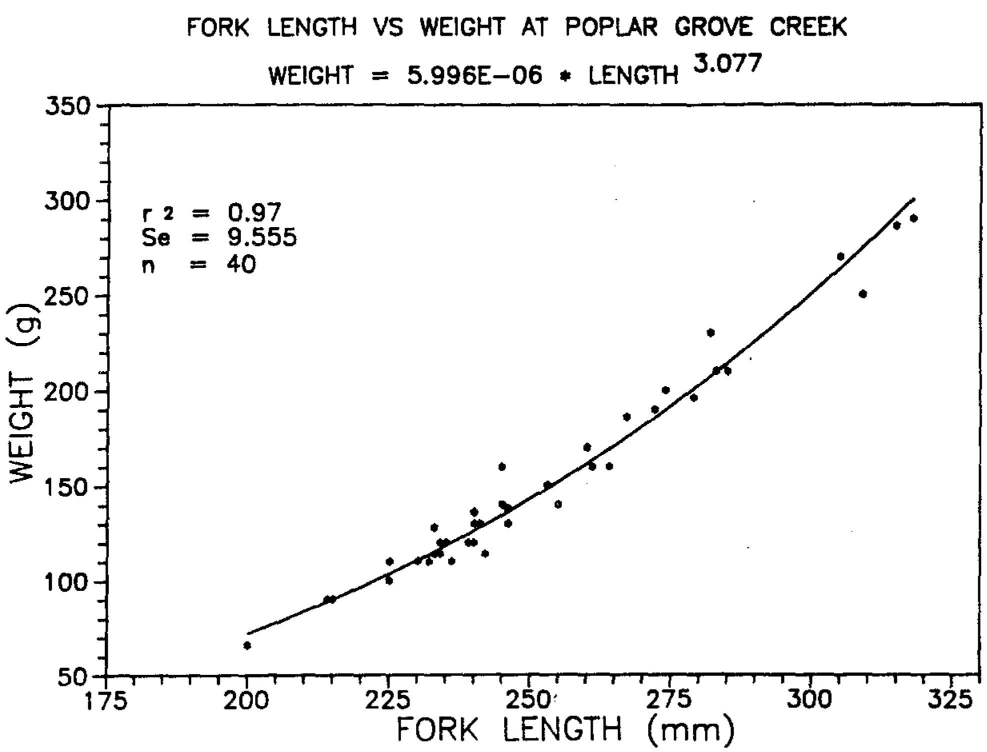

Figure 47. Arctic grayling fork length (mm) versus weight (g).

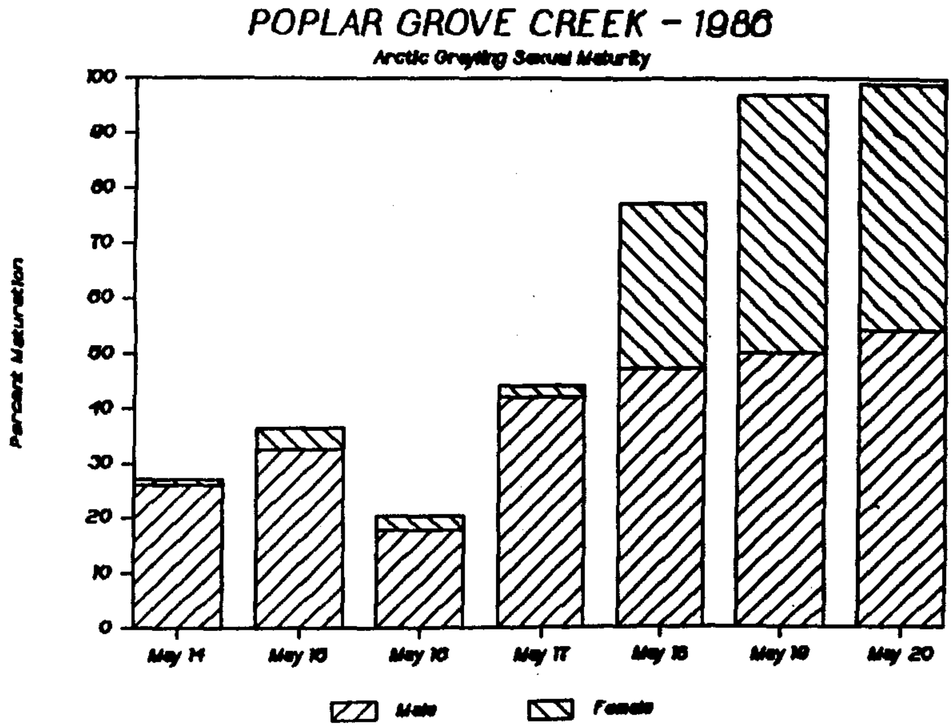

Figure 48. Proportion of Arctic grayling sexually ripe, by date of capture.

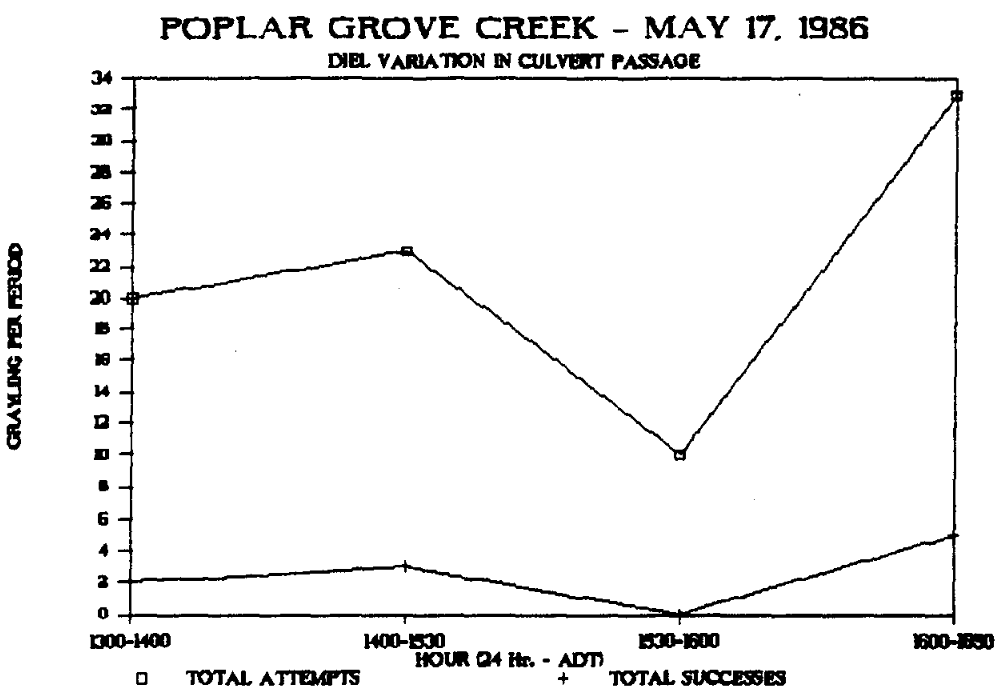

Figure 49. Diel variation in fish migration through culvert, 17 May 1986.

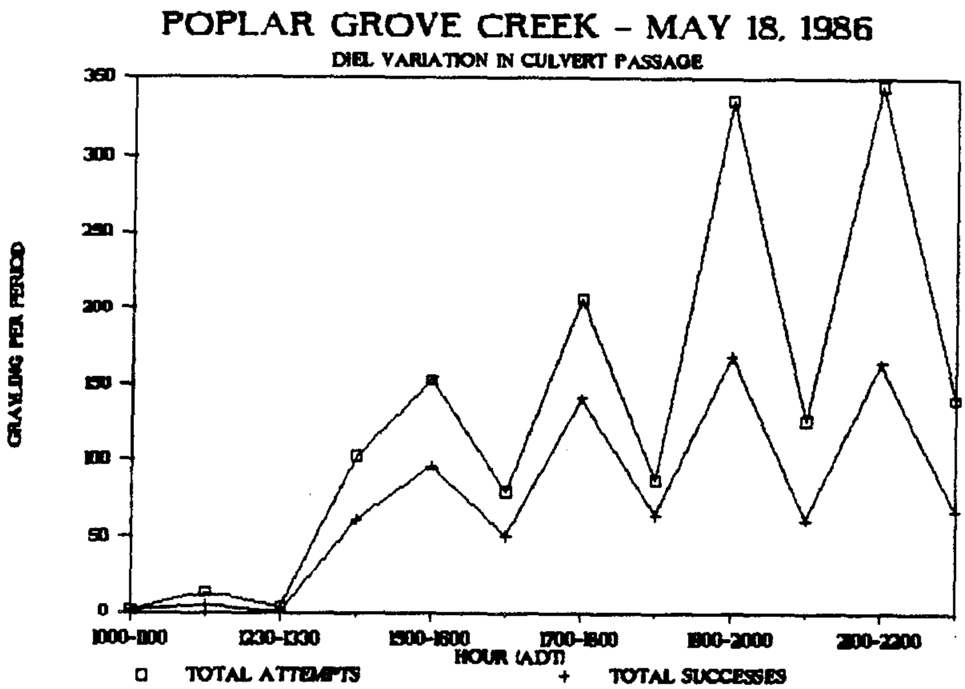

Figure 50. Diel variation in fish migration through culvert, 18 May 1986.

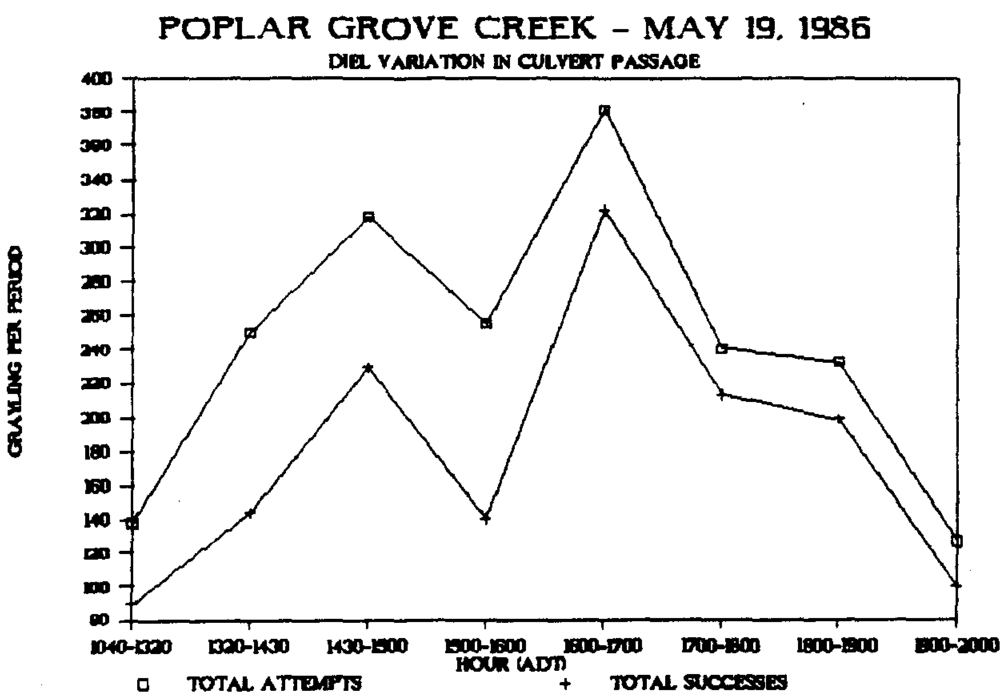

Figure 51. Diel variation in fish migration through culvert, 19 May 1986.

TABLE 5. Arctic grayling fork length, weight and condition factor, Poplar Grove Creek, 16 May 1986.

Tag No.	Sex	Length (mm)	Weight (grams)	Condition Factor
529	M	285	210	0.9072
530	X	315	286	0.9150
531	M	253	150	0.9263
532	X	246	130	0.8732
533	M	245	140	0.9520
534	X	225	110	0.9657
535	X	274	200	0.9723
536	X	236	110	0.8369
537	X	233	128	1.0119
538	X	240	120	0.8681
539	X	272	190	0.9442
540	X	234	114	0.8897
541	X	246	138	0.9270
542	X	240	130	0.9404
543	X	241	130	0.9287
544	X	267	186	0.9772
546	X	239	120	0.8790
547	X	318	290	0.9018
548	X	309	250	0.8474
549	X	214	90	0.9183
550	X	245	160	1.0880
551	M	230	110	0.9041
552	X	282	230	1.0256
553	X	240	136	0.9838
554	X	215	90	0.9056
555	X	234	120	0.9366
556	X	232	110	0.8809
557	F	255	140	0.8443
558	X	261	160	0.8999
559	X	200	66	0.8250
560	M	264	160	0.8696
561	M	235	120	0.9247
562	X	305	270	0.9516
563	X	260	170	0.9672
564	X	225	100	0.8779
565	X	233	114	0.9012
566	M	279	196	0.9025
567	X	242	114	0.8044
568	X	235	120	0.9247
569	X	283	210	0.9265
N = 40	AVERAGES	252	153	0.9182

NOTES: Condition factor = 100W/L^3; where W=weight(grams) and L=length(cm). Sex: M=Male; F=Female; and X=Unknown

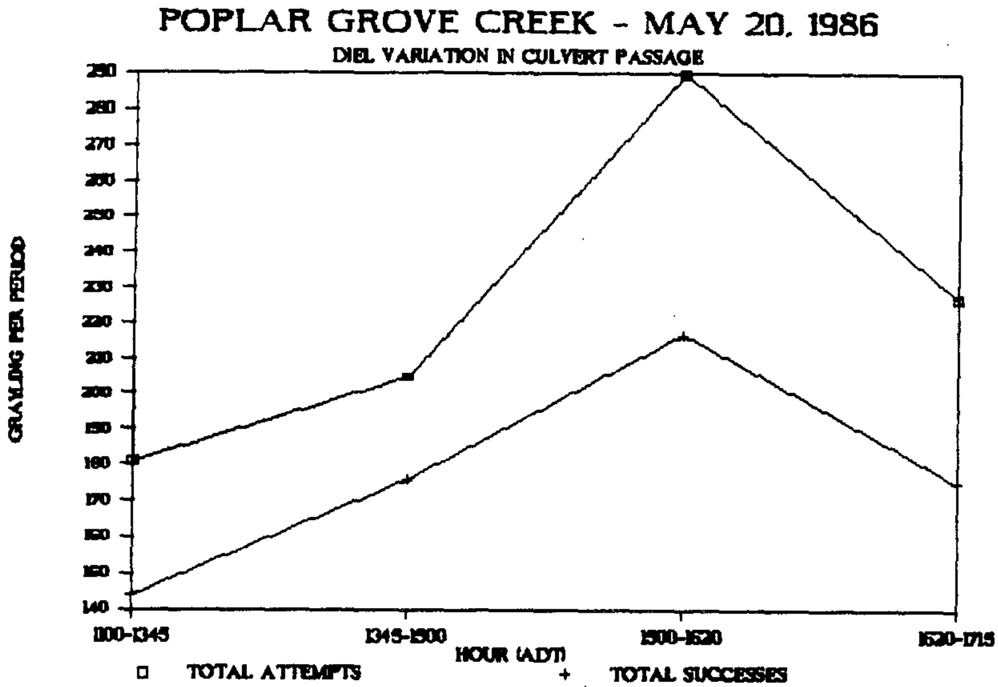

Figure 52. Diel variation in fish migration through culvert, 20 May 1986.

Fish Population Estimates: A total of 3,031 grayling were counted as they passed through the culvert between May 17 and May 20. We subsequently recovered 2,246 fish at the upstream weir. Based on a Peterson Index derived from tag recoveries at the upstream weir, however, we estimate a migration of 10,972 fish (including immatures). We believe that the Peterson Index estimate closely approximates the actual run strength since length frequency compositions at the mouth and lower weir tagging sites suggest that the initial tagging operation successfully encompassed the early, middle and late components of the migration. Nonetheless, the upstream weir was pulled on May 20; hence, fish that arrived at the scour pool on May 18 and 19 may not have been available for recovery at the upstream weir by May 20 (due to the mean 37.9 hour delay). In addition, the recognized but unquantified tag loss factor (see Fish Migration Tagging Program) may have reduced potential tag recoveries, thereby inflating the Peterson Index population estimates.

Fish Migration Tagging Program: A total of 850 Arctic grayling were tagged with a numbered, colored coded "streamer" tag (Floy Tag Model FSTL-73) between May 14 and May 17. Subsequent tag recoveries occurred between May 15 and May 20 at a variable distance upstream from the initial tagging site ranging from 183 m (200 yards) to 2.9 km (1.8 miles).

Based on tag recovery information, the average fish took approximately 114.6 hours (S.D. = 17.3 hr; n=17) to ascend 2.9 km (1.8 miles) of stream to the culvert outlet, successfully transit the culvert and further ascend an additional 91 m to the upstream weir (Figure 53 and Appendix Tables 2 through 6). Ripe male fish averaged 126.1 hours (S.D. = 15.6 hr; n=8); ripe female fish averaged 105.8 hours (S.D. = 11.6 hr; n=5); and nonripe or immature fish averaged 102.4 hours (S.D. = 10.6 hr; n=4).

The average delay duration between the culvert outlet scour pool and the upstream weir was 37.9 hours (S.D. = 17.4 hr; n=7). Ripe male fish averaged 47.9 hours (S.D. = 17.0 hr; n=4); a single ripe female fish required 27.3 hours (n=1); and nonripe or immature fish averaged 23.2 hours (S.D. = 1.2 hr; n=2). Subtracting the average scour pool delay time from the aggregate migration time from the mouth to the upper weir suggests a migration time from the mouth to the culvert outlet scour pool of 76.7 hours. The overall stream gradient for this reach is approximately 1.84 percent (derived from USGS 1:63,360 map).

Based on the inferred migration time between the stream mouth and the culvert outlet scour pool (76.7 hr), the mean forward velocity of the fish with respect to the ground (not be confused with swimming velocity with respect to the water) was 1.05 cm/sec (0.034 ft/sec).

Between the stream mouth and the lower weir, the average fish took approximately 29.7 hours (S.D. = 9.2 hr; n=10) to ascend approximately 0.8 km (1/2 mile) of stream. Ripe male fish averaged 32.8 hours (S.D. = 10.8 hr; n=6); and nonripe or immature fish averaged 25.0 hours (S.D. =

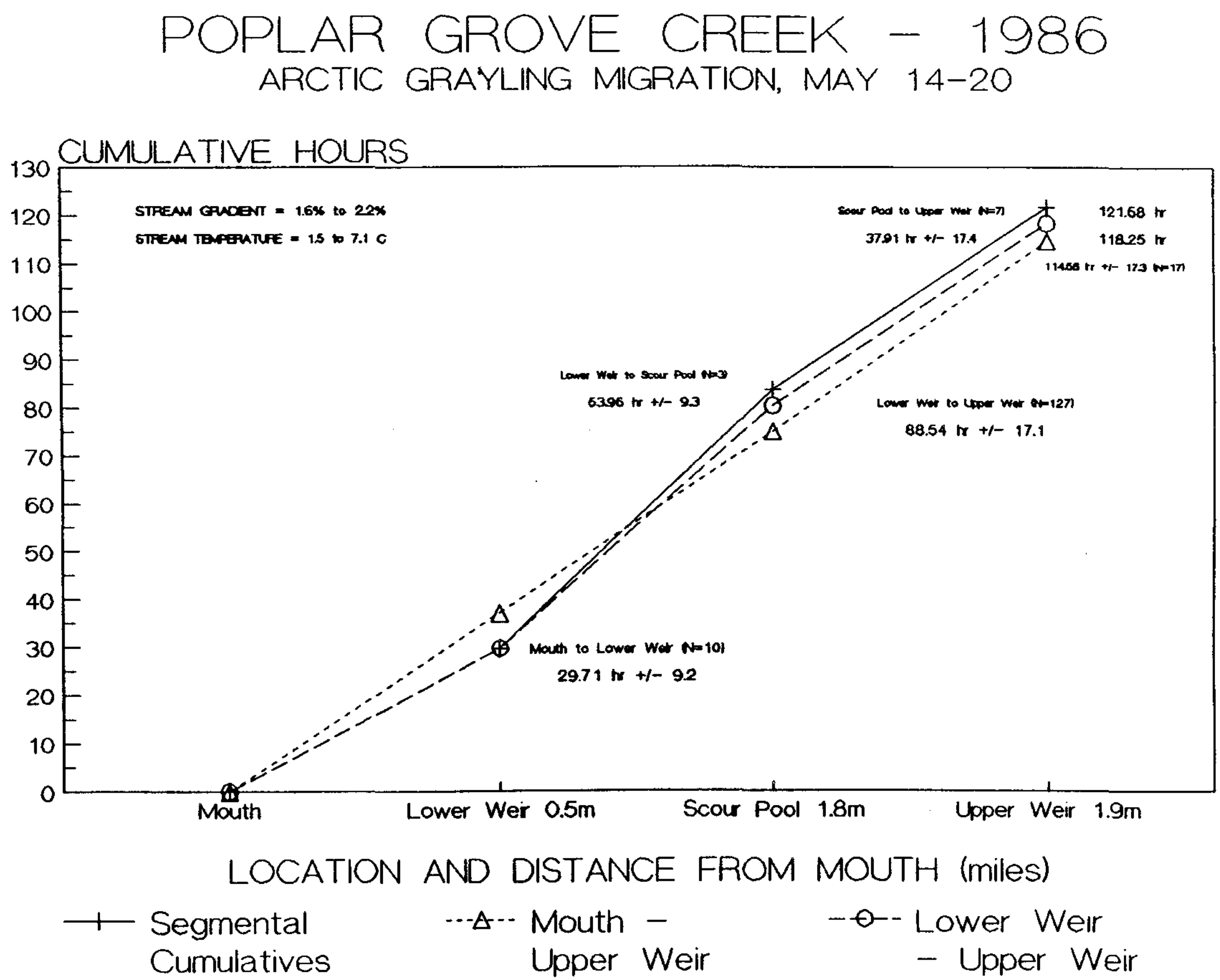

Figure 53. Timing of Arctic grayling migration, 14 to 20 May 1986.

0.5 hr; n=4). The approximate stream gradient for this reach was 2.27 percent (from USGS 1:63,360 map). Mean forward velocity of the average fish with respect to the ground for this stream segment was 0.753 cm/sec (0.0247 ft/sec).

Relative daily tag recovery was determined by comparing subsequent percent recovery rates for each day's tagging operation. On May 14, 100 Arctic grayling were tagged at the stream mouth. Total recovery for this batch of tags for all subsequent upstream recovery locations was 17 percent. On May 15, 400 fish were tagged at the lower weir site. Total recovery for this batch of tags on all subsequent upstream recovery locations was 18 percent. On May 16, 300 fish were tagged at the lower weir site. Total recovery for this batch of tags was 18 percent. On May 17, a final batch of 50 fish were tagged at the culvert outlet scour pool. Total recovery for this batch of tags was 14 percent.

Fish Radio Telemetry Tagging Program: Each of the two available transmitters were used in two fish (Table 6). The air weight of the transmitters, relative to the fish body weight, ranged from 0.98 to 1.61%. All fish were adult sized. Fish No. 1 moved about the scour pool for approximately 4 hours during which it seemed to make three attempts to enter the culvert. After the unsuccessful attempts, it slowly moved out of the scour pool and moved downstream. This fish was recaptured about 40 m downstream for fear that it would not return upstream. The transmitter was removed, and the fish was released. Fish No. 2 exhibited a similar movement pattern, but was allowed to move without interference. This fish moved back and forth between the scour pool and the next pool located approximately 100 m downstream for about 24 hours before passing through the culvert in just 5 minutes; water temperature was 5°C. After transitting the culvert, Fish No. 2 moved quickly until it reached the upstream weir where it was recaptured.

Fish No. 3 moved between the scour pool and the downstream pool for approximately 6.5 hours after implantation; then it took approximately 12 minutes to transit the culvert barrel. Water temperature was 6.5°C.

However, after leaving the culvert, it stopped several times before arriving at the upstream weir where it was subsequently recaptured.

After implantation, Fish No. 4 moved from the scour pool to the pool located 100 m downstream and remained there for at least 27 hours. It was not recaptured before the study ended, resulting in a lost transmitter.

TABLE 6. Telemetry data, Arctic grayling, Poplar Grove Creek, May 1986.

Characteristic	Fish No 1	Fish No 2	Fish No 3	Fish No 4
Fork Length (mm)	356	308	282	317
Weight (g)	315	278	210	330
Sex	male	male	male	female
Transmitter Weight (g)	3.38	3.24	3.38	3.24
Transmitter Burden (%)	1.07	1.16	1.61	0.98
Time between implantation and recapture (hr:min)	3:50	24:12	6:27	27:00
Time required to transit culvert barrel (min:sec)	*	5:20	12:04	*
Time of culvert entry (May 19, 1986, ADT)	*	1442	2042	*
Water temperature at culvert entry (°C)	*	5.0	6.5	*
Estimated total length (to tip of tail in mm)	*	330	300	*
Sustained swimming speed (body lengths/sec)**	*	2.5	2.7	*
Burst swimming speed (body lengths/sec)**	*	7.5	8.3	*

* Did not enter culvert.
** See Discussion for explanation

Observations of Fish Passage : The first pulse of Arctic grayling was observed at the culvert outlet scour pool during the late morning hours on May 17. Water temperature at this time ranged between 2.4 to 4.4°C. The culvert outlet was periodically monitored for fish activity between 1000 and 1300 hours ADT; however, no active attempts to ascend the culvert were observed during this period. At 1300 hours, several fish were observed attempting to ascend past the culvert outlet flash board. An observer was subsequently positioned at the culvert outlet, and continuous fish passage observations were obtained between 1300 and 1650 hours. Observations were terminated at 1650 hours due to low levels of fish activity, minimal successful culvert fish passages, and competing manpower requirements.

A total of 88 attempts and 10 successes were observed between 1300 and 1650 hours ADT on May 17. The hourly passage success, expressed as the percent of total passages to total attempts each hour, ranged between 0 and 15 percent, with a daily mean of 11 percent. Of the observed total failures, 94 percent were at the outlet, and 6 percent were within the culvert barrel. Mean culvert outlet water velocity (Q/A) was 1.94 m/s (6.35 fps); weighted average culvert barrel water velocity was 0.91 m/s (2.98 fps); and the inferred culvert barrel V-occupied water velocity was 0.77 m/s (2.53 fps).

On May 18, active fish movement was first observed by midmorning. This was substantially earlier than on May 17 but consistent with later observations on May 19 and 20. Since ambient air temperatures and water temperatures were not significantly different between May 17 and 18, we are not certain why fish activity commenced so late on May 17. It may be related to the late morning arrival of fish in the scour pool on May 17 with an associated resting period prior to attempting culvert passage.

Observations on May 18 commenced at the culvert outlet at 1000 hours ADT and continued until 2240 hours, when they were terminated due to poor lighting conditions. A daily total of 1,593 attempts and 877 successes were observed between 1000 and 2240 hours. The hourly passage success ranged between 0 and 74 percent, with a daily mean of 55 percent. Of the observed total failures, 97 percent were at the outlet, and 3 percent were within the culvert barrel. Water temperatures ranged between 2.5 and 4.5°C; mean culvert outlet water velocity (Q/A) was 1.79 m/s (5.88 fps); weighted average culvert barrel water velocity was 0.85 m/s (2.78 fps); and the inferred culvert barrel V-occupied water velocity was 0.75 m/s (2.45 fps).

The initial period of fish activity on May 19 was similiar to that observed on May 18. Observations on May 19 commenced at the culvert outlet at 1040 hours ADT and continued until 2000 hours, when they were terminated due to poor visibility. A daily total of 1,941 attempts and 1,432 successes was observed. The hourly passage success ranged between 55 and 89 percent, with a daily mean of 74 percent. Of the observed total failures, 98 percent were at the outlet, and 2 percent were within the culvert barrel. Water temperatures ranged between 2.9 and 6.2°C; mean culvert outlet water velocity (Q/A) was 1.81 m/s (5.94 fps); weighted average culvert barrel water velocity was 0.82 m/s (2.70 fps); and the inferred culvert barrel V-occupied water velocity was 0.77 m/s (2.51 fps).

Our observations on May 20 were between 1100 hours ADT and 1715 hours. By 1715 hours, fish activity had dropped off considerably, suggesting that the primary spawning run was coming to an end. At that time, manpower was diverted to begin camp demobilization. A daily total of 903 attempts and 712 successes were observed. The hourly passage success ranged between 75 and 86 percent, with a daily mean of 79 percent. Of the observed failures, 98 percent were at the outlet, and 2 percent were within the culvert barrel. Water temperatures ranged between 4.1 and 7.1°C; mean culvert outlet water velocity (Q/A) was 1.81 m/s (5.94 fps); weighted average culvert barrel water velocity was 0.79 m/s (2.59 fps); and the inferred culvert barrel V-occupied water velocity was 0.73 m/s (2.40 fps).

Tables 7 through 10 present the total culvert fish passage attempts, failures, and successes by hour for May 17 through May 20.

Several problems were encountered with the observation procedures. First, because of the unexpected turbidity and coloration of Poplar Grove Creek in 1986, it was not possible to observe culvert barrel passage times for large numbers of Arctic grayling. Poor visual conditions precluded direct observation at the culvert inlet as called

TABLE 7. Observations of fish passage by hour through Poplar Grove Creek culvert, May 17, 1986

Hourly Period (ADT)	Total Attempts		Total Failures		Outlet Failures		Barrel Failures		Successes	
	No.	% Daily Total	No.	% Hourly Total Attempts	No.	% Hourly Total Attempts	No.	% Hourly Total Attempts	No.	% Hourly Total Attempts
1000-1100	N/O		N/O		N/O		N/O		N/O	
1100-1200	N/O		N/O		N/O		N/O		N/O	
1200-1300	N/O		N/O		N/O		N/O		N/O	
1300-1400	20	23%	18	90%	18	90%	0	0%	2	10%
1400-1530	23	26%	20	87%	17	74%	3	50%	3	13%
1530-1600	10	11%	10	100%	10	100%	0	0%	0	0%
1600-1650	35	40%	30	86%	28	80%	2	29%	5	15%
TOTALS	88		78	89%	73	83%	5	33%	10	11%

Mean discharge = 46.6 CFS
Water temp. = 2.4 to 4.4°C
Mean fork length of grayling in downstream scour pool below culvert = 274 mm

Mean outlet velocity (Q/A) = 1.94 m/s (6.35 fps)
Weighted avg. barrel velocity = 0.91 m/s (2.98 fps)
Inferred V-occupied barrel velocity = 0.77 m/s (2.53 fps)

1. Total attempts are defined as Arctic grayling that approached and ascended within 0.61 m (2 ft) or beyond the culvert outlet lip during an hourly period.

2. Failures are defined as Arctic grayling that ascended within 0.61 m (2 ft) or beyond the culvert outlet lip but either did not make it all the way into the CMP barrel (outlet failures; 94% of total failures) or were subsequently washed back downstream after fully entering the culvert barrel (barrel failures; 6% of total failures).

N/O = No observations.

* Observations terminated at 1650 hours.

TABLE 8. Observations of fish passage by hour through Poplar Grove Creek culvert, May 18, 1986

Hourly Period (ADT)	Total Attempts		Total Failures		Outlet Failures		Barrel Failures		Successes	
	No.	% Daily Total	No.	% Hourly Total Attempts	No.	% Hourly Total Attempts	No.	% Hourly Total Attempts	No.	% Hourly Total Attempts
1000-1100	2	<1%	0	0%	0	0%	1*	50%	1	50%
1100-1230	13	<1%	8	62%	5	38%	3*	37%	5	38%
1230-1330	3	<1%	3	100%	3	100%	0	0%	0	0%
1330-1500	102	6%	41	40%	37	36%	4	6%	61	60%
1500-1600	153	10%	57	37%	49	32%	8	8%	96	63%
1600-1700	79	5%	29	37%	26	33%	3	6%	50	63%
1700-1800	206	13%	66	32%	60	29%	6	4%	140	68%
1800-1900	87	5%	23	26%	22	25%	1	2%	64	74%
1900-2000	336	21%	167	50%	167	50%	0	0%	169	50%
2000-2100	126	8%	65	52%	65	52%	0	0%	61	48%
2100-2200	346	22%	182	53%	182	53%	0	0%	164	47%
2200-2240**	140	9%	74	53%	74	53%	0	0%	66	47%
TOTALS	1,593		715	45%	690	43%	23	3%	877	55%

Mean discharge = 43.1 CFS
Water temp. = 2.5 to 4.5°C
Mean fork length of successful attempts = 251 mm

Mean outlet velocity (Q/A) = 1.79 m/s (5.88 fps)
Weighted avg. barrel velocity = 0.85 m/s (2.78 fps)
Inferred V-occupied barrel velocity = 0.75 m/s (2.45 fps)

1. Total attempts are defined as Arctic grayling that approached and ascended within 0.61 m (2 ft) or beyond the culvert outlet lip during an hourly period

2. Failures are defined as Arctic grayling that ascended within 0.61 m (2 ft) or beyond the culvert outlet lip but either did not make it all the way into the CMP barrel (outlet failures; 97% of total failures) or were subsequently washed back downstream after fully entering the culvert barrel (barrel failures; 3% of total failures).

* Four barrel failures occurred between 1100 and 1230. However, since one failure occurred before any fish had entered the culvert barrel during that observation period, it was apportioned as though it was a fish that had entered the culvert barrel between 1000 to 1100 hours.

** Observations terminated at 2240 hours.

TABLE 9. Observations of fish passage by hour through Poplar Grove Creek culvert, May 19, 1986

Hourly Period (ADT)	Total Attempts		Total Failures		Outlet Failures		Barrel Failures		Successes	
	No.	% Daily Total	No.	% Hourly Total Attempts	No.	% Hourly Total Attempts	No.	% Hourly Total Attempts	No.	% Hourly Total Attempts
1040-1320	138	7%	49	36%	47	34%	2*	2%	89	64%
1320-1430*	250	13%	106	42%	105	42%	1	<1%	144	58%
1430-1500	318	16%	89	28%	88	28%	1	<1%	229	72%
1500-1600	255	13%	115	45%	115	45%	0	0%	140	55%
1600-1700	382	20%	60	16%	59	15%	1	<1%	322	84%
1700-1800	240	12%	27	11%	26	11%	1	<1%	213	89%
1800-1900	232	12%	34	15%	32	14%	2	1%	198	85%
1900-2000**	126	6%	27	21%	27	21%	0	0%	99	79%
TOTALS	1,941		507	26%	499	26%	8	<1%	1,432	74%

Mean discharge = 40.7 CFS
Water Temp. = 2.9 to 6.2°C
Mean fork length of successful attempts = 233 mm

Mean outlet velocity (Q/A) = 1.81 m/s (5.94 fps)
Weighted avg. barrel velocity = 0.82 m/s (2.70 fps)
Inferred V-occupied barrel velocity = 0.77 m/s (2.51 fps)

1. Total attempts are defined as Arctic grayling that approached and ascended within 0.61 m (2 ft) or beyond the culvert outlet lip during an hourly period.

2. Failures are defined as Arctic grayling that ascended within 0.61 mm (2 ft) or beyond the culvert outlet lip but either did not make it all the way into the CMP barrel (outlet failures; 98% of total failures) or were subsequently washed back downstream after fully entering the culvert barrel (barrel failures; 2% of total failures).

* Number of total attempts dropped off noticeably for approximately one-half hour while tagged fish were recovered with dip nets near culvert outlet.

** Observations terminated at 2000 hours due to poor visability.

TABLE 10. Observations of fish passage by hour through Poplar Grove Creek culvert, May 20,1986

Hourly Period (ADT)	Total Attempts No.	Total Attempts % Daily Total	Total Failures No.	Total Failures % Hourly Total Attempts	Outlet Failures No.	Outlet Failures % Hourly Total Attempts	Barrel Failures No.	Barrel Failures % Hourly Total Attempts	Successes No.	Successes % Hourly Total Attempts
1000-1100	N/O		N/O		N/O		N/O		N/O	
1100-1345	181	20%	37	20%	37	20%	0	0%	144	80%
1345-1500	205	23%	29	14%	27	13%	2	1%	176	86%
1500-1620	290	32%	73	25%	72	25%	1	<1%	217	75%
1620-1715*	227	25%	52	23%	51	22%	1	<1%	175	77%
TOTALS	903		191	21%	187	21%	4	<1%	712	79%

Mean discharge = 37.8 CFS
Water Temp. = 4.1 to 7.1°C
Mean fork length of successful attempts = 229 mm

Mean outlet velocity (Q/A) = 1.81 m/s (5.94 fps)
Weighted avg. barrel velocity = 0.79 m/s (2.59 fps)
Inferred V-occupied barrel velocity = 0.73 m/s (2.40 fps)

1. Total Attempts are defined as Arctic grayling that approached and ascended within 0.61 m (2 ft) or beyond the culvert outlet lip during an hourly period.

2. Failures are defined as Arctic grayling that ascended within 0.61 m (2 ft) or beyond the culvert outlet lip but either did not make it all the way into the CMP barrel (outlet failures; 98% of total failures) or were subsequently washed back downstream after fully entering the culvert barrel (barrel failures; 2% of total failures)

N/O = No observations.

* Observations terminated at 1715 hours.

for in the experimental design. Consequently, confirmed visual counts of successful culvert passages were not obtained. However, the culvert passage times for two radio-tagged fish were obtained.

Nonetheless, the white background of the flashboard coupled with optimal lighting angles at the culvert outlet permitted reasonably good visual observation of culvert barrel failures (fish that successfully ascended into the culvert barrel but subsequently washed back downstream out of the culvert) and "outlet failures" (fish that approached and ascended within two feet of the culvert outlet lip but did not make it all the way into the culvert barrel). An inferred hourly estimate of successful culvert fish passages was therefore determined by subtracting the total number of "washouts" and "outlet failures" from the number of "total attempts."

Finally, the poor visual conditions greatly hampered direct observation of fish movements and behavior within the culvert outlet scour pool. We were thus unable to observe the behavior of fish as they approached the culvert outlet to determine whether additional, uncounted culvert "outlet failures" were occuring in the decelerating outlet flow beyond the observable area over the flash board [measured maximum water velocities at the downstream edge of the flash board approached 3 m/s (10 fps)] or whether the observed "total attempts" actually included multiple attempts by the same fish.

Miscellaneous Observations of Swimming Performance : Several miscellaneous measurements of Arctic grayling swimming performance were obtained at the lower weir site and the culvert outlet between May 15 and May 19 (Table 11). Maximum sustained (possibly low burst - see Discussion) swimming performance was determined at the culvert outlet by timing the observed forward progression of individual fish for known distances across the culvert outlet flashboard. Estimated sustained swimming velocities with respect to the water (V_{fw}) were then calculated by adding the observed forward velocity of the fish with respect to the ground to the known culvert water velocities at the time of observation. These ranged between 2.13 m/s to 2.53 m/s (7.0 fps to 8.3 fps). The duration of time that eight Arctic grayling were able to hold stationary against known culvert outlet water velocities (before either giving up and washing back downstream or being unable to continue such levels of energy expenditure -- a distinction was not possible to determine) was also recorded and ranged between 0.7 and 4.9 seconds at culvert water velocities of 1.83 to 2.44 m/s (6 to 8 fps) and water temperatures between 4.5 and 6.2°C. For several fish that jumped out of the water, calculations for a range of burst swimming performance were also made by observing the height above the water surface that they reached and later calculating the required exit velocity to have attained that height, using the formula $V = (2gh)^{1/2}$. These calculated burst swimming velocities were 2.44 and 3.87 m/s (8.0 and 12.7 fps) for medium (240 to 260 mm) and large (greater than 280 mm) fish, respectively.

TABLE 11. Miscellaneous observations of Arctic grayling swimming performance, Poplar Grove Creek, 1986.

5/15/86: Several large (>280 mm) untagged Arctic grayling noted upstream of lower weir. Fish presummed to have bypassed the weir via a 5 inch gap at bottom of weir which was intentionally created to relieve excessive hydraulic head on weir structure. The velocity jet through the weir gap was about 12.5 feet per second.

5/15/86: Two large (?) untagged Arctic grayling observed leaping out of the downstream weir tailrace and striking the top weir rail located approximately 2.5 feet above downstream water elevation.

5/18/86: One 8 to 10 inch (200 to 250 mm) Arctic grayling ascended up flashboard 2 feet in 1.6 seconds at a water velocity of 7 feet per second.

5/18/86: One 8 to 10 inch (200 to 250 mm) Arctic grayling ascended up flashboard 2.2 feet in 1.7 seconds at a water velocity of 7 feet per second.

5/18/86: Seven 8 to 10 inch (200 to 250 mm) Arctic grayling observed holding a relative position at culvert outlet lip (water velocity 8 feet per second) for the following durations:

1. 1.5 seconds	5. 2.3 seconds
2. 1.3 seconds	6. 2.0 seconds
3. 1.1 seconds	7. 1.0 seconds
4. 0.7 seconds	Ave. 1.41 seconds

5/18/86: One medium (240 to 280 mm) sized Arctic grayling observed leaping out of the upper weir tailrace and striking the top weir rail located approximately 1 foot above the downstream water elevation.

5/19/86: One 8 to 10 inch (200 to 250 mm) Arctic grayling observed holding relative position at culvert outlet lip for 4.9 seconds at a water velocity of 6 feet per second.

5/19/86: One 8 to 10 inch (200 to 250 mm) Arctic grayling ascended 1 linear foot upstream from culvert outlet lip in 1.0 seconds at a water velocity of 6 feet per second.

DISCUSSION

Overview of Fish Passage Concerns

Typically, a culvert contains three different hydraulic situations that a fish must negotiate to pass through the structure. These occur at the culvert outlet, in the culvert barrel, and at the culvert inlet. If hydraulic conditions in any of these three locations are too difficult for the fish to negotiate, or if part of the culvert has tired the fish too much to allow it to complete the next step in its passage through the culvert, it cannot negotiate the structure. Thus, it is necessary to identify the hydraulic conditions at the culvert outlet, in the barrel and at the inlet, and to determine if these individually and cumulatively allow the design fish to pass through the culvert.

Three major data gaps have hindered the development of culvert design criteria that adequately address passage concerns for Arctic grayling. First, the spring spawning run of Arctic grayling generally occurs at the same time as snow runoff from most basins. Consequently, the flood event often creates flow conditions at a culvert that conflict with the fish spawning run. If fish passage could be delayed for a few days without harm to the fish stock, culverts would not have to be designed to simultaneously pass spring floods and fish migrating upstream. This would allow the use of smaller culverts which pass peak floods with higher water velocities than fish could negotiate. Unfortunately, it does not appear that any quantitative investigations have ever been conducted on the impacts of delayed spawning migration to fish reproductive success and population dynamics. Accordingly, a study to determine the effects of delay on a spawning run of Arctic grayling at Fish Creek near Cantwell, Alaska, has been initiated by the Inter-agency Fish Passage Task Force. The results of this study are anticipated in late 1988 and may have an effect on any subsequent development of culvert design criteria.

A second data deficiency is the determination of the appropriate point to measure culvert water velocities as they relate to fish passage. Some recent literature recommends that the appropriate design velocities

velocities should reflect the area of the culvert that fish actually swim in and not necessarily some average cross-sectional velocity at any given point in the culvert barrel or at the culvert outlet. However, very few quantitative studies report the behavioral movements of fish through culvert structures or accurately predict the water velocities at particular points within culverts flowing partially full.

This study at Poplar Grove Creek culvert suggests that Arctic grayling hug the culvert invert because of lower water velocities there than elsewhere in the culvert. Water velocity profiles above culvert inverts (principally at the inlets and outlets) were studied at many culvert locations in Alaska by Kane and Wellen (1985). However, their methods did not properly predict water velocities measured at a few accessible points in the Poplar Grove Creek culvert in 1986.

A third data gap relates to the calculation of the total energy and power requirements of fish that successfully ascend through culvert structures. As the hydraulic analysis segment of this discussion will show, the absolute velocities at which Arctic grayling move through different points (inlet, outlet and barrel of the culvert) have a profound effect on total energy and power requirements. These absolute velocities (velocities with respect to the culvert, not with respect to the moving water) have proved difficult to ascertain, but this project sheds some light on culvert design criteria.

Fish Radio Telemetry Tagging Program

No adverse effects from implantation were observed. The relative weight of the transmitters was quite low and appeared to have little burden, if any, on swimming performance. Since all fish moved downstream after implantation, thus delaying their culvert passage, a question arises. Was this behavior normal, or was it caused by handling and implantation? We believe it is normal behavior (at least for Poplar Grove Creek) because numerous nontagged fish were observed milling about in the scour pool and the next pool downstream. The three recaptured fish were all in good condition, and their transmitters were easily removed with the string. No regurgitation was evident.

Relative swimming performance (body length/sec) was estimated for both radio-tagged fish that successfully passed through the culvert. The total length of the fish (as opposed to fork length) was used and was estimated by dividing fork length by an isometric conversion factor of 0.92 (Grabacki, 1981). Sustained swimming speed was estimated by adding 75 cm/sec (the approximate water velocity near the culvert invert where the fish actually swam) to the average velocity of passage (3,300 cm culvert length divided by 522 seconds average fish transit time through the culvert= 6.4 cm/sec). This procedure estimated sustained swimming speeds (V_{fw}) of 2.5 to 2.7 body lengths/sec and assumes that fish were swimming steadily against a water velocity of 75 cm/sec. The estimated sustained swimming speed may be invalid because the culvert is known to contain highly variable velocities. Bell (1986) indicates that "pulsing velocities can increase the instantaneous energy requirements by four times throughout the darting speed range." This may account for much of the variations in indicated swimming performance noted by previous investigators. Nonetheless, the indicated 2.5 to 2.7 body lengths/sec sustained swimming speed estimate is similar to that reported by Ziemer (1961), MacPhee and Watts (1976), Dane (1978), and Bell (1986). In contrast, Beamish (1978) reports that the sustained swimming speed of most fish species is 1 body length/sec or less.

If passage is assumed to consist of negotiating a high velocity zone and an adverse pressure gradient at each end of the culvert, and a lower velocity zone in the culvert barrel, then passage consists of a "burst" of swimming at each end and a slower sustained swimming speed in the culvert barrel. If an average outlet velocity (across the downstream flashboard) of 250 cm/sec (approx. 8 fps) is assumed for the Poplar Grove Creek culvert (which is within the range of observed values), then the radio-tagged fish (and fish that successfully entered the culvert) required a minimum burst swimming speed of 7.5 to 8.3 body lengths/sec (plus an additional power expenditure to overcome the adverse pressure gradient) in order to enter successfully the culvert barrel. This burst speed estimate is similar to the darting swimming speeds reported by Calhoun (1966), Watts (1974) and Bell (1986). Beamish (1978), however, indicates that burst speeds of 10 to 20 body lengths/sec are possible for a few seconds.

Based on other observations we made of leaping Arctic grayling (see RESULTS - Miscellaneous Observations of Swimming Performance), we also observed burst swimming velocities in the range of 8.0 to 12.7 fps (9.7 to 12.9 body lengths/sec). Thus, the inferred burst swimming speeds noted for the radio-tagged fish suggest that the two radio-tagged fish were swimming at a burst velocity slightly slower than that observed by other investigators for fish of comparable length. This suggests that the culvert outlet velocities may have approached, but not necessarily exceeded, the maximum, critical burst swimming speed for Arctic grayling.

Radio telemetry was determined to be a potential, cost-effective method for analyzing culvert fish passage problems, particularly in instances where turbidity or other obscuring conditions prevent direct observations. However, transmitter burdens should not exceed 2%. In this study, fish lighter than 150 g (fish approximately 250 mm long) could not have been utilized. Lighter transmitters (approx. 1 gram) would be necessary to study effectively fish in the design length range of 200 to 250 mm.

Comparison of Observations with Other Investigations at Poplar Grove

Observed passage rates of Arctic grayling through the Poplar Grove Creek culvert were correlated with measured culvert water velocities at various locations within the culvert and with water temperature. Linear regressions were developed to predict the anticipated fish passage rates through the Poplar Grove Creek culvert at various water velocities and points of measurement. Culvert water velocity and water temperature were designated as the independent variables. Percent passage was designated as the dependent variable. Although fish length should have been incorporated as an independent variable (and was so intended in the sample design), poor water visibility precluded the identification and recapture of tagged Arctic grayling of known length upon successful passage through the culvert at known velocities.

Both linear and log-linear regressions were developed. Based on a comparison of the "fit" and standard error that each analysis generated, we determined that a log-linear regression equation best fit the fish passage observations. Due to a relatively small statistical sample (n=28), it should be recognized that the coefficients of determination (R^2) for these regressions are only 0.66. Nonetheless, the coefficients of determination are similar, and in some cases better than those derived for previous studies (MacPhee and Watts, 1976; Arctic Hydrologic Consultants, 1985; and Tilsworth and Travis, 1987) which independently evaluated the swimming performance and percent passage of Arctic grayling through the Poplar Grove Creek culvert. The individual regressions follow.

Mean Outlet Velocity
Predicted % passage = 1065.3 - 1211.98 (log of mean outlet velocity, fps) + 31.14 (log of temperature in degrees C)
$R^2 = 0.66$; standard error of the estimate = 16

Average Outlet Velocity
Predicted % passage = 1865.09 - 2335.92 (log of average outlet velocity, fps) + 29.51 (log of temperature in degrees C)
$R^2 = 0.66$; standard error of the estimate = 16

Weighted Culvert Barrel Velocity
Predicted % passage = 268.77 - 527.36 (log of weighted culvert barrel velocity, fps) + 31.45 (log of temperature in degrees C)
$R^2 = 0.65$; standard error of the estimate = 16

(NOTE: All logs are to base 10)

Table 12 compares of the predicted culvert water velocities at various design percent passage levels derived from these studies and the log-linear regressions developed for this study.

Table 13 compares the culvert water velocity design recommendations for Arctic grayling inferred from this study with the literature recommendations and the existing ADF&G culvert design guidelines for a hypothetical 30 m (+/- 3 m) culvert. For comparative purposes, the design recommendations presented in Table 13 for low performance category fish have been normalized to the extent possible to reflect equivalent water temperatures, fish length, and design passage rate (e.g., 75% passage).

Hydraulic Analysis of Fish Passage Observations

The hydraulic discussion that follows attempts to set forth the problems which a fish faces in passing through the Poplar Grove Creek culvert. The discussion relates to a wide variety of culverts, but the numerical results are for the Poplar Grove Creek culvert for the days when the research group measured fish passage through the culvert in 1986.

The analytical discussion that follows is directed toward defining what fish, ranging in fork lengths from 200 to 300 mm, must be capable of doing to pass through the culvert outlet, barrel and inlet. This segment of the report relies on fish movement velocities and water velocities observed at Poplar Grove Creek Culvert as input into fluid flow equations. In general, however, this segment of the report does not suggest whether or not various sizes of grayling are capable of passing successfully through each segment of the culvert. Attempts to match what fish must do with what they appear to be capable of doing are discussed later in this section of the report and under **Conclusions**. Without first understanding the fluid mechanic/hydraulic interactions of fish and the surrounding water, an understanding of what is possible and what is impossible for differing sizes of fish at specific locations is not attainable.

Culvert Outlet Hydraulics: Since the elevation of the scour pool's water surface is greater than that of the outlet invert, but less than that of the hydraulic normal depth at the outlet, we define this culvert as a partially perched culvert. Although the flowing water surface profile drops somewhat into the pool at the culvert outlet (see Figures 35-38), some backwater effects from the receiving pool do not allow the complete, freefall conditions of a perched culvert to exist. Measurements of water depths at the culvert outlet indicate that the hydraulic critical depth, dc, (that depth at which $Q^2b/gA^3 = 1.0$, where

TABLE 12. Comparison of the predicted culvert water velocities in feet per second at various design percent passage levels for Arctic grayling in Poplar Grove Creek as derived by Tilsworth and Travis (1987), MacPhee and Watts (1976), Arctic Hydrologic Consultants (1985) and this study.

Design Percent Passage	This Study Mean Outlet Vel.	This Study Avg. Outlet Vel.	This Study Weight Culvert Vel.	Tilsworth & Travis Mean Outlet Vel.	MacPhee & Watts Weight Culvert Vel.	Arctic Hydro. Weight Culvert Vel.
0	7.86	6.41	3.53			4.42
5	7.79	6.37	3.45			3.54
10	7.71	6.34	3.38			3.24
15	7.64	6.31	3.31			3.05
20	7.57	6.28	3.24			2.92
25	7.50	6.25	3.17		3.09	2.82
30	7.43	6.22	3.10			2.73
35	7.36	6.19	3.03			2.66
40	7.29	6.16	2.96			2.59
45	7.22	6.13	2.90			2.54
50	7.15	6.10	2.84		2.93	2.49
55	7.08	6.07	2.78			2.44
60	7.01	6.04	2.72			2.40
65	6.95	6.01	2.66			2.36
70	6.88	5.98	2.61			2.32
75	6.81	5.95	2.55		2.70	2.29
80	6.75	5.92	2.49	7.30		2.26
85	6.69	5.89	2.44			2.23
90	6.63	5.86	2.38			2.20
95	6.56	5.83	2.33	6.90		2.18
10	6.50	5.80	2.28			2.15

This Study - Water temperature = 2.4 to 7.1°C (mean 4.4°C); avg. grayling fork length 235 mm (range 170 to 349 mm); culvert length = 33.5 m.

%Passage=1065.295-1211.985log(V-mean outlet)+31.136log(temp°C); R^2 = 0.66, SEE = 16.
%Passage=1865.09-2335.915log(V-avg outlet)+29.505log(temp°C); R^2 = 0.66, SEE = 16.
%Passage=268.768-527.356log(V-weight barrel)+31.446log(temp°C); R^2 = 0.65, SEE = 16.

Tilsworth and Travis (1987) - Cumulative aggregate daily observations for two days. 78% passage observed at a water temperature of 7.7°C. 95% passage observed at a water temperature of 9.5°C. Actual grayling fork lengths unknown but believed greater than or equal to 230 mm. Culvert length = 33.5 m. Observations occurred after grayling were delayed by velocity barrier for approx. eight days.

MacPhee and Watts (1976) - water temperatures ranged between 5 to 8°C; grayling fork length = 235 mm; culvert length = 30 m. At water temperatures ranging between 9 to 12°C, the predicted culvert velocities at the 25%, 50% and 75% passage occurred at 3.63 fps, 3.24 fps and 2.93 fps, respectively.

Arctic Hydro. Consultants (1985) - Multiple linear regression model based on data collected by MacPhee and Watts (1976). For comparative purposes, average water temperature = 4.4°C; grayling fork length = 235 mm; culvert length = 33.5 m. V_{weight} = 0.541 - 4.97log(culvert length in feet) + 5.7log(fork length in mm) + 0.786log (temp.°C)-1.13log(%Passage + 1) (R^2 = 0.550; SEE = 0.7)

TABLE 13. Comparison of the Poplar Grove Study Inferred Group I (low performance swimmers) fish passage culvert velocity design guidelines with the literature recommendations and the existing ADF&G fish passage guidelines for a hypothetical 30 m (100 ft) culvert (plus/minus 3 m), in meters per second (bracketed figures in feet per second).

Source	Culvert Water Velocity	Comments
This Study	0.78 (2.55)	Inferred weighted culvert barrel design velocity for grayling; 75% design passage. Water temp. 2.4 to 7.1°C (mean = 4.4°C). Average fork length = 235 mm (range 170 to 349 mm).
This Study	1.80 (5.95)	Inferred average culvert outlet design velocity for grayling at 75% design passage (outlet control, velocities approx. 60% lower in culvert barrel). Water temp. 2.4 to 7.1°C (mean = 4.4°C).Average fork length = 235 mm (range 170 to 349 mm).
MacPhee and Watts (1976)	0.82 (2.70)	Weighted culvert barrel velocity; 75% design passage. Water temp. 5 to 8°C. Fork length = 235 mm for comparison.
MacPhee and Watts (1976)	0.89 (2.93)	Weighted culvert barrel velocity; 75% design passage. Water temp. 9 to 12°C. Fork length = 235 mm for comparison.
Jones et al. (1974)	0.59 (1.93)	Laboratory trials for critical velocities for grayling. Fork length 210 to 340 mm.
Dane (1978)	0.90 (2.95)	Generalized weighted culvert barrel velocity recommendation for all fish species in culverts over 24.5 m. Water temp. and fork length not specified.
Bell (1986)	0.76–2.13 (2.5–7.0)	Generalized estimate of sustained grayling swimming ability for long and short culverts, respectively. Water temp. and fork length not specified.
Evans and Johnson (1977)	0.61 (2.0)	Generalized weighted culvert barrel velocity recommendation for trout. Adapted from Ziemer (1961). Water temp. and fork length not specified.
Ziemer (1961)	0.7–0.79 (2.3–2.6)	Generalized weighted culvert barrel velocity recommendation for trout 3 to 3.4 times fork length; fork length = 235 mm for comparison. Water temp. not specified.
Derksen (1980)	0.6 (1.97)	Generalized weighted culvert barrel velocity. Adapted from Jones (1974).
Salzman and Koski (1971)	0.61–1.22 (2.0–4.0)	Generalized weighted culvert barrel velocity recommendation for trout in long to short culverts, respectively. Water temp. and fork length not specified.
Dryden and Jessop (1974)	0.94–1.58 (3.1–5.2)	Generalized centerline culvert barrel velocity recommendation for northern pike.
Schultz (1973)	0.9 (2.95)	Generalized average cross-sectional culvert velocity recommendation. Water temp. and fork length not specified.
ADF&G Guidelines	0.7 (2.29)	Weighted culvert barrel velocity. 75% design passage. Water temp. and fork length set at 4.4°C and 235 mm, respectively, for comparative purposes.

Q is the water discharge, b is the distance across the culvert at the water surface, g is the gravitational acceleration constant, and A is the cross-sectional area of flow) exists close to the outlet lip. Additional measurements of water surface depths five feet upstream from the outlet lip indicated subcritical flow at that point.

Since the flow was at greater than the critical depth upstream from the immediate vicinity of the outlet lip of the culvert, it can reasonably be assumed that horizontal pressure gradient components upstream from this culvert lip were not strong enough to impact noticeably fish migrating upstream after they had cleared the culvert lip. The culvert's final 3 m (10 feet) at the downstream end sloped upward in the downstream direction (Figure 3), and the flow in this zone was hydraulically subcritical. Thus, the water surface profiles over the downstream, final 3 m (10 ft) of the culvert were hydraulically A-2 curves (because of the adverse slope) on each of the days when we measured fish and hydraulic properties. (A-2 curves exhibit water depths greater than the critical depth and increasing in the upstream direction.)

Analysis of Entrance to Culvert Outlet: The water surface profile dropped quickly from the downstream culvert lip to the water surface elevation in the downstream pool (Figure 54). This drop was over a horizontal distance of approximately 0.6 m (2 ft). Because of the presence of the downstream flashboard, the flow exiting the culvert quickly attained a horizontal direction. The resulting pressure distribution in the water flow became hydrostatic approximately 60 cm (2 ft) downstream from the culvert lip. For computational purposes, it is assumed that the hydraulic grade line (HGL)--i.e., the locus of the piezometric head in the zone of flow--dropped linearly from its location on the water surface above the outlet lip of the culvert to its approximate location at the pool elevation 0.6 m (2 ft) downstream from the culvert lip (Figure 54). Thus, the angle (θ) at which the HGL slopes with the horizontal is assumed to be given by the arctan of $\Delta WS/0.6$. Admittedly, this is a linear approximation to a more complicated hydraulic grade line. Nonetheless, it is a reasonable approximation for the computations that follow. We also assume that the fish ascended from 0.6 m (2 ft) out on the flashboard along a sloping straight line to the culvert's downstream invert lip. This is shown in Figure 54. Arctan ($\Delta z/0.6$) is thus the angle (θ) at which the fish is assumed to swim with respect to the horizontal while passing from the flashboard to the culvert invert. Δz at the culvert outlet was 0.06 m (0.2 ft), so angle (ϕ) had a value of 6 degrees.

Behlke (1987) has shown for a fish, whose specific weight (density) is the same as that for water, swimming in uniform, steady flow at an angle (ϕ) with the horizontal where the hydraulic grade line slopes at an angle (θ) with the horizontal the force necessary for the fish to overcome is given by

$$P = D + W(\sin \phi + \cos \phi(\tan (\theta - \phi)), \qquad \text{Eq. 1.}$$

where P is the propulsive force necessary for the fish to generate in order to overcome its profile drag and to increase its potential energy, D is the fish's profile drag, and W is the fish's weight. The second term in the right side of Equation 1 will be termed the gradient force. Profile drag, D, in equation form is

$$D = C_d \ \rho \ S \ L^2 V_{fw}{}^2/2 \qquad \text{Eq. 2.}$$

where (ρ) is the mass density of the water, L is the fish's length, V_{fw} is the velocity of the fish with respect to the water, S (taken here to be 0.4) is a factor to convert L^2 to the wetted surface area of the fish, and C_d is a drag coefficient which depends on the fish's Reynolds Number, N_R and other factors. ($N_R = V_{fw}L/\nu$, where (ν) is the kinematic viscosity of the water.)

To determine C_d, Webb (personal communication, 1988) observes that bio-hydrodynamicists have adopted, as a reference, the drag of a turbulent boundary layer on a rigid, flat plate of length L and the same area as that of the fish's surface. Analysis and experience yield a correction factor, k, which is applied to the reference in order to obtain a drag coefficient for swimming fish. Thus,

$$C_d = k\ (.072)/N_R^{.2} \qquad \text{Eq. 3.}$$

Webb indicates it is generally believed that k lies between 3 and 5 (k = 4 is adopted here). The term $(.072)N_R^{.2}$, being the approximate drag of a boundary layer on a rigid, flat plate (Streeter, 1958), is the reference.

The Poplar Grove Creek culvert was partially perched, and water accelerated as it exited the culvert and entered the flashboard. This creates at the culvert outlet an additional drag force on the fish because of its virtual mass (Daily and Harleman, 1966). It is assumed that the water accelerated over a distance of 0.6 m (2 ft) from its velocity at the culvert outlet to its flashboard velocity. The mass of the fish is assumed to be equal to the mass of the fluid which it displaces, and 0.2 is selected as the added mass coefficient (Harleman and Daily). Thus, the virtual mass force that the fish must overcome if it is to move ahead (or even remain stationary) in the zone between the flashboard and the culvert is:

$$\begin{aligned} F_{VM} &= 1.2\ (\text{mass of fish})\ (\text{acceleration of water}) \\ &= 1.2\ (M_f)\ (a_w) \qquad \text{Eq. 4} \\ &= 1.2\ (W_f\ /g)(V_o\ \text{flashboard}-V_o\ \text{outlet})\ /\ (t_{out-fb}) \end{aligned}$$

where t_{out-fb} is the time required for the average small element of water to move in the fish-occupied zone from the culvert outlet lip to a point 0.6 m (2 ft) downstream on the flashboard. t_{out-fb} is calculated by dividing this distance by the average of V_o at the outlet lip and V_o on the flashboard. The calculated acceleration, a_w, is thus an average acceleration of the water in this zone.

The virtual mass force calculated by Equation 4 is added to the drag force (Eq. 1) to yield the total force that the fish must overcome if it is to move upstream through this zone of accelerated water flow. A

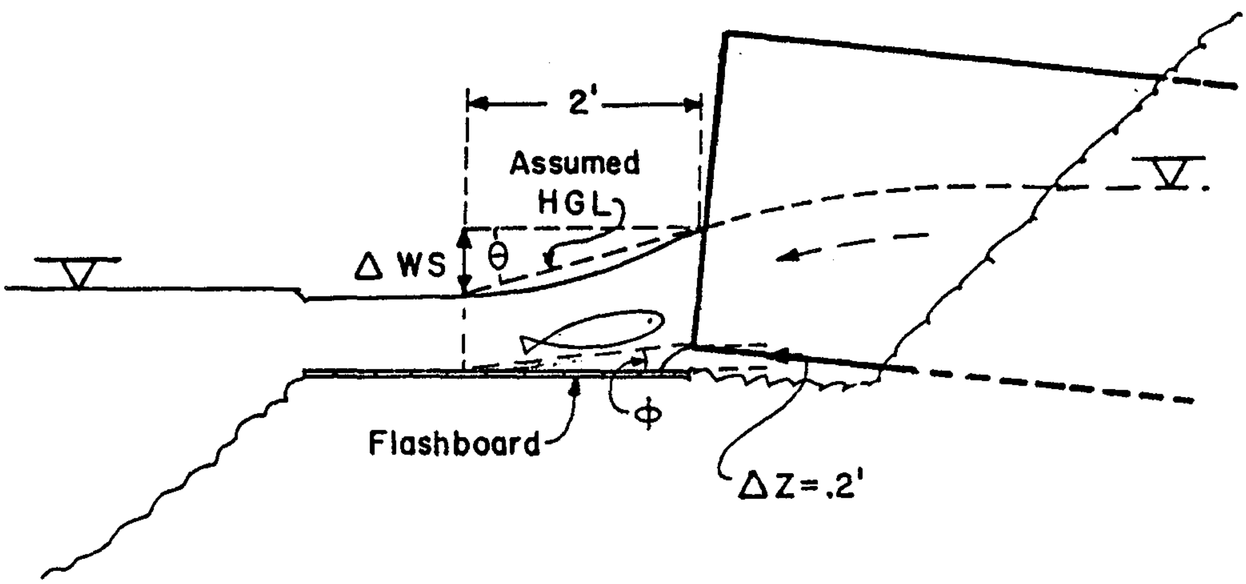

Figure 54. Culvert outlet conditions encountered by fish migrating upstream.

similar procedure must also be followed to calculate the total drag force affecting the fish at the culvert inlet as it exits the culvert. The propulsive force, P, necessary for the fish to generate in both inlet and outlet zones of the culvert is given by,

$$P = (D + F_{VM} + W(\sin \phi + \cos \phi(\tan (\theta - \phi))) \qquad \text{Eq. 5.}$$

Behlke (1987) shows the net power necessary for a swimming fish to deliver to its surroundings is equal to the product of the velocity of the fish with respect to its surrounding medium (V_{fw}) and its propulsive force, P. Observations indicated that the velocity of the fish with respect to a fixed reference frame (V_f) for a grayling in the approximately 200-240 mm size range was approximately 0.3 m/sec (1 ft/sec) in this very short but difficult location. Water velocity profiles were measured on the flashboard and at the culvert outlet. These were shown in Figures 14, 18, 19, 23, 24, 28, 29, 33 and 34. For computations, the water velocity very close to the bottom where the fish swam in this zone is assumed to be the average of the measured velocities in the zone from the flashboard surface upward to an elevation of 9 cm (3.6 in) above the board and the measured velocities from the lip of the culvert to an elevation of 9 cm (3.6 in) above the lip.

Thus, the mean water velocity (V_w) in this fish-swimming zone is assumed to be the average of the water velocities in the fish-occupied zone at the culvert lip and the water velocities in the fish-occupied zone on the flashboard. Since $V_{fw} = V_f + V_w$, $V_{fw} = (0.3 \text{ m/sec} + V_w)$, the net power (Pwr) which the fish delivers at this location of the Poplar Grove Creek culvert can then be expressed in equation form as,

$$\begin{aligned} Pwr &= P\ (V_{fw}) && \text{Eq. 6} \\ &= P\ (0.3 \text{ m/sec} + V_w). && \text{(N-m/sec)} \\ &= P\ (1.0 \text{ ft/sec} + V_w). && \text{(ft-lb/sec)} \end{aligned}$$

While fish in the 200-240 mm size zone were observed to swim with V_f of approximately 0.3 m/sec (1 ft/sec) when passing upstream from the flashboard through the downstream lip of the culvert, larger fish swam with greater values of V_f. The approximate velocities at which the larger fish swam on entering the culvert were not measured, so the estimated values for Pwr given in Table 14 for fish larger than 240 mm are, in all probability, smaller than was the actual case, since we also assumed that V_f for these larger fish also was 0.3 m/sec (1 ft/sec). Ziemer and Behlke (1966) defined the net mechanical energy (net energy) delivered by a fish to its surroundings in passing through a discrete segment of a fish passage structure as its "total energy." Here energies, E, will be calculated for the fish's entrance to the culvert, for its passage through the barrel, and for its exit from the culvert. A summation of these individual E's would be the true total net energy delivered by the fish to its surroundings in entering, passing through, and exiting the culvert. A summation of E's could be compared with that of a fish swimming through an equivalent length of the replaced streambed to determine the effects of the culvert.

By definition, the net total energy delivered by the fish to its surroundings for any segment of its passage through the culvert is,

$$E = \int_0^{t_p} (Pwr)\,dt \qquad \text{Eq. 7}$$

where t_p is the time required for the fish to pass through that segment of the structure. t_p is equal to the distance travelled in passing through that segment of the structure (Δs), divided by the fish's average velocity, relative to the culvert, in passing through that segment. Thus, if the fish's velocity, V_f, is constant through that portion of the structure,

$$t_p = \Delta s / V_f \qquad \text{Eq. 8}$$

At the culvert outlet, the energy is assumed to be the product of the fish's average net power delivered to its surroundings and the time spent entering the culvert. The entrance time was approximately two seconds for those smaller fish that successfully entered the culvert directly from the flashboard, as opposed to entering from the sides of the downstream lip of the culvert. Thus, for the fish entering the culvert from the flashboard, E for the culvert outlet is,

$$E = t_p\ (Pwr) = (2\ sec)\ (Pwr). \qquad \text{Eq. 9}$$

The time spent in entering the culvert varied from fish to fish. Therefore, the assumptions made here, for computational purposes, are those which an "average, 200-240 mm fish"--the smaller fork length limits of spawning grayling--would exhibit. E's for 200-300 mm fish entering the culvert on May 18-20 are also given in Table 14. Values for the profile drag forces, for added mass and for the force necessary to overcome the sloping hydraulic grade line (gradient forces) are also shown in Table 14.

Culvert Barrel Hydraulics: Figure 3 shows the complicated nature of the Poplar Grove Creek culvert's grade. The water surface profile for the afternoon (corresponding to the time of most fish passage activity) of each study day has been calculated utilizing standard backwater calculation procedures. Computations were initiated from a point 1.5 m (5 ft) upstream from the culvert outlet and were carried to a point 1.5 m (5 ft) downstream from the culvert entrance. This segment of the culvert was consider to be the culvert "barrel" for the purposes of this study. At both of these points, water surface elevations and water depths were known from measured values. Because the downstream, final three meters (10 ft) of the culvert invert sloped upward in the downstream direction, water velocities in most of the barrel of the culvert were less than 1 m/sec (3.3 ft/sec). Thus, the friction losses in the culvert, with the exception of the entrance loss, were very small. Hence, the water surface profiles through most of the culvert were almost flat. Figures 35 through 38 show computed water surface profiles through most of the culvert for the study days. Average water velocities at critical points (points where significant invert grade changes occur) along the culvert barrel are also shown on these figures.

A distance-weighted-average water velocity (V_{ave}) was calculated for each day. This water velocity was calculated by averaging distance-weighted velocities of critical points shown in Figures 35 through 38. These figures clearly indicate the variations in average cross-sectional velocities that occurred in the culvert barrel. Thus, the calculated distance-weighted-average velocity, V_{ave}, for any day was not a constant velocity which fish were forced to contend with throughout the culvert. Greater and lesser velocities occurred at shallower and deeper locations, respectively, in the culvert, so some parts of the culvert barrel were easier for the fish than were others.

Though it was not possible to observe fish as they moved upstream from the cut-out in the top of the culvert located 1.2-1.8 m (4-6 ft) upstream from the culvert outlet or downstream from the similarly located cutout near the culvert inlet, virtually all fish seen in observable sections of the culvert swam very close to the culvert invert. Measurements were not made of how far from the bottom the fish swam, but they appeared to swim as close to the invert as possible. Because the fish appeared to swim so close to the invert, mean velocities for a point 1.5 m (5 ft) upstream from the outlet lip of the culvert have been determined for a fish-occupied, vertical zone close to the culvert invert. This vertically occupied zone was also defined as extending from the invert boundary to a vertical height of 9 cm (3.6 in). This vertical height was selected as best representing the area that an Arctic grayling would occupy if it were to swim with its belly parallel to the culvert invert. The mean velocity in this zone, determined from measured velocity profiles at this location, is defined as $V_{occupied}$ for this location.

A "mean apparent $V_{occupied}$" (V_o) for all but the first two feet downstream from the culvert inlet is defined as the product of the distance-weighted-average water velocity, V_{ave}, and the ratio of $V_{occupied}$ at the location 1.5 m (5 ft) upstream from the culvert outlet to the average cross-sectional water velocity at that point. For the calculation of V_{ave}, mean cross-sectional water velocities were determined for points of culvert invert grade change from the calculated backwater curves through the culvert. The calculated average water

TABLE 14. Calculated power (Pwr) and energy (E) for fish entering the culvert outlet from the flashboard on May 18-20, 1986.

Date: 5/18/86 $Q = 1.22\ m^3/sec$

Fish length, mm	Profile drag force, N	Virt. mass force, N	Gradient force, N	Power watts	Outlet TE, joules
200	1.06	0.15	0.17	3.03	6.06
220	1.25	0.20	0.22	3.70	7.40
240	1.47	0.26	0.29	4.45	8.90
260	1.69	0.33	0.37	5.28	10.56
280	1.93	0.41	0.46	6.20	12.39
300	2.19	0.50	0.57	7.20	14.41

Date: 5/19/86 $Q = 1.15\ m^3/sec$

Fish length, mm	Profile drag force, N	Virt. mass force, N	Gradient force, N	Power watts	Outlet TE, joules
200	1.03	0.17	0.17	2.99	5.97
220	1.22	0.23	0.22	3.65	7.30
240	1.43	0.30	0.29	4.40	8.80
260	1.65	0.38	0.37	5.23	10.46
280	1.89	0.47	0.46	6.15	12.30
300	2.14	0.58	0.57	7.16	14.32

Date: 5/20/86 $Q = 1.07\ m^3/sec$

Fish length, mm	Profile drag force, N	Virt. mass force, N	Gradient force, N	Power watts	Outlet TE, joules
200	1.06	0.18	0.16	3.07	6.14
220	1.25	0.20	0.21	3.68	7.36
240	1.47	0.26	0.27	4.42	8.84
260	1.69	0.33	0.35	5.25	10.49
280	1.94	0.42	0.44	6.15	12.31
300	2.19	0.51	0.54	7.15	14.30

velocity, V, at a point of invert grade change was assumed to represent the culvert's water velocity for half the distance to the next invert grade change upstream and half the distance to the next invert change downstream. These distance-weighted products were then summed, and the sum was divided by the distance from the outlet lip of the culvert to two feet downstream from the inlet lip of the culvert (where the inlet zone of the culvert began) to obtain V_{ave}. The total barrel length of the culvert for barrel computations was considered to be 32.9 m (108 ft). Calculated values of V_o for the study days are given in Table 15.

TABLE 15. Average cross-sectional velocities (V_{ave}) and mean apparent $V_{occupied}$ (V_o) for Poplar Grove Creek Culvert for May 18-20, 1986.

Date	V_{ave} (m/sec)	V_{ave} (ft/sec)	V_o (m/sec)	V_o (ft/sec)
May 18	0.85	2.78	0.75	2.45
May 19	0.82	2.70	0.77	2.51
May 20	0.79	2.59	0.73	2.40

If the culvert had exhibited a constant grade from end to end, the value of V_o would be much more uniform and meaningful. However, the computational method of determining V_o is important when attempting to apply the hydraulic concepts and the computational method to other situations. The values of V_o calculated for this report were not those locally exhibited throughout the barrel of the study culvert and may not be too meaningful because of probable lesser values for the local $V_{occupied}$ near low points in the culvert invert.

Behlke (1987) has shown that the net power which a fish must deliver to its surroundings while swimming in the barrel of a culvert flowing as an open channel and exhibiting uniform, steady flow is

$$Pwr = (W(\sin \theta) + C_d(\rho)\ (L^2)(V_{fw}{}^2/2))V_{fw} \qquad \text{Eq. } 10$$

Behlke has also shown that the net energy delivered by the fish to its surroundings in passing through the aforementioned culvert barrel is

$$E = L_c(1 + (V_w/V_f)(W(\sin \theta) + D) \qquad \text{Eq. } 11$$

where L_c is the length of the culvert barrel, and the other terms are as before. Since V_w of this equation is the water velocity where the fish swims, it can be replaced by V_o. Both we and Travis (1987) found that fish velocities, V_f, in the barrel of the Poplar Grove Creek culvert were quite slow, ranging from less than 3 cm/sec (0.1 ft/sec) to 11 cm/sec (0.37 ft/sec). Thus, the ratio V_w/V_f ($=V_o/V_f$) can reach a value of 20 or more. As Behlke (1987) has shown, this is essentially a multiplying factor which results from the fact that the fish swims through moving water in the culvert, somewhat like a person walking up a tilted treadmill or walking up a down-bound escalator. In essence, the culvert length which the fish experiences in its swimming activities appears to it to be $L_c(1 + (V_o/V_f))$. It is interesting to note that stronger fish, usually the larger ones, swim with greater values of V_f, so the "apparent length" of the culvert for them is less than the apparent length of the culvert for slower, usually smaller, fish. (This apparent length concept also applies to streams.)

Though present practice requires rather small slopes for culverts, usually less than 2%, it is conceivable that this and other studies may lead to culvert baffling systems which may allow much steeper culvert settings. Also, Equations 10 and 11 can be used for any open channel situation. Therefore, it is worthwhile to note that for slopes of less than about 10% the value of sin (θ) is very small, so W(sin θ)is usually small compared to the fish's profile drag (D) and may be neglected in both Equations 10 and 11. However, for steep, baffled culverts or other open channels, this term (which represents the fish's increasing potential energy as it climbs through the structure) is present and adds to the fish's difficulty presented by the profile drag force. This term becomes significant in the discussions of the culvert entrance and outlet, and it should always be considered in initial computations until it can be shown to be inconsequential.

Examination of Equation 11 shows that a value for V_f must be known or selected to determine E for known hydraulic conditions and size of fish. Examination of Equation 8 reveals that V_{fw} must be determined. Since $V_{fw} = V_f + V_o$, V_f must also be known for calculations of Pwr by Equation 10. V_f is the only parameter of either Equations 10 or 11 which probably could not be determined with reasonable accuracy from laboratory studies of small-scale hydraulic models. Thus, a principal reason for field studies of actual fish movement through existing culverts is to gain insights into the velocities at which fish move into, through, and out of culverts of differing hydraulic characteristics and to learn where fish actually swim within the culvert.

Because of the unexpected turbidity of the water passing through the Poplar Grove Creek culvert during the 1986 migration of Arctic grayling, we could not observe times of passage for large numbers of tagged fish, as we had planned based on observations by Tilsworth and Travis (1987) in 1985. However, the passage time of two fish tagged with radio transmitters was measured. In addition, Travis (1986) measured passage times of 18 fish at the same culvert. These fish were tagged by two length categories, greater or less than a fork length of 229 mm (9 in). Utilizing Travis' data and the passage time for the two radio-tagged fish of this study, we calculated several regression curves relating V_f to hydraulic parameters and to physical measurements of fish weight and length. The best of these related V_f to only the fish's length, L, as follows,

$$V_f = 11.76\ L^4 - 0.0168\ \text{(m/sec)} \qquad \text{Eq. 12}$$
$$= 38.53\ L^4 - 0.0552\ \text{(ft/sec)}$$

where L is the fork length of the fish, in meters, for either equation ($R = 0.95$ and $R^2 = 0.91$).

Water velocity, V_o, is not a parameter for Equation 12. Clearly, at some value of V_o, a specific size of fish could not make any headway in the culvert. Additional data on the travel times of fish through culverts is needed, and Equation 12 should be considered reasonably valid only for fish movement through the Poplar Grove Creek culvert at water velocities measured during the spawning migrations of 1985 and 1986. This statistically derived "formula" must be tested at other culverts having different hydraulic characteristics, and it must be tested with other runs of fish.

Recognizing the limitations of Equation 12, but also recognizing that it probably is close to reality for fish-negotiable velocities in the

Poplar Grove Creek culvert, V_f from that equation can be substituted into Equation 11. Also, values for the apparent V_o taken from Table 15 can be substituted into Equation 11, and E values can be calculated for a specific size of fish swimming through the culvert barrel (Table 16).

Knowing measured or calculated values of W, calculating C_d from Equation 3, and noting again that $V_f = V_o + V_f$, the average net power delivered to its surroundings by a specific size of fish, in order to swim through the barrel of the culvert, is found from Equation 10. Calculated values for net power delivered by the fish if it swims through the culvert barrel are also tabulated in Table 16.

The apparent anomaly of a greater value for V_o on May 19 than on May 18 resulted from actual, measured velocity profiles at the point 1.5 m upstream from the outlet. We have no explanation for this; however, it may have been due to a measuring error (a slight variation in the exact placement of the flow meter). Since the inferred V_o for the entire culvert barrel is dependent on V_o at that point, the anomaly is reflected in Table 16.

Culvert Inlet Hydraulics: The water inlet to the Poplar Grove Creek culvert consisted of a simple, circular opening which extended from the embankment into the upstream pool less than 0.15 m (6 in) at the invert. The invert lip was located approximately 0.3 m (1 ft) above the bottom of the upstream pool. We had planned to observe passage times of tagged fish. In an attempt to enhance observations, we bolted white culvert segments to the bottom of the culvert at both the upstream and downstream ends of the culvert. These sections of matching, corrugated metal were almost flush with the bottom of the culvert, but they extended somewhat beyond the actual entrance and exit culvert invert lips. At the upstream end of the culvert, the insert extended approximately 0.2 m (8 in) into the pool beyond the culvert lip. In essence, the lip of the insert became the invert lip of the culvert at the entrance. Though the inserts probably affected the water flow patterns somewhat, this did not appear to be significant.

The velocity profiles of Figures 11, 12, 15, 16, 20, 21, 25, 26, 30 and 31 for the culvert inlet and for 1.25 m (4 ft) downstream from the inlet indicate that water velocities in the 9 cm deep, $V_{occupied}$ zone immediately above the invert were greater than those measured 1.5 m (5 ft) upstream from the outlet end of the culvert. Observations of flow in the culvert from its inlet downstream for approximately 2 m (7 ft) indicate a high-velocity flow down the center of the culvert, with lower velocities toward the sides of the culvert. This is because of the entrance contraction resulting from the sharp edge of the culvert and its extension into the upstream pool.

In the zone between the culvert inlet and the point at which the center contracted flow decelerated and dispersed to a more uniformly distributed flow in the cross section, fish apparently elected to swim close to the sides of the culvert -- as close to the sides as possible to take advantage of the lower velocities in that area. Since we didn't know the water velocities in this zone and precisely where each fish was swimming as it approached the upstream end of the culvert, we assumed for computational purposes that the fish was subjected to the same apparent $V_{occupied}$ (V_o) here as elsewhere in the barrel of the culvert. The computations shown in Table 16, therefore, include the Pwr and E of the fish swimming in the barrel up to within 0.6 m (2 ft) of the culvert inlet.

As fish exit the culvert, they are subjected to the same pressure gradients which produce the acceleration of water as it enters the culvert from its almost negligible velocity in the pool to its rather significant velocity just inside the culvert. Most of this acceleration appeared to occur in a zone which extended from approximately 0.3 m (1 ft) outside the culvert mouth to approximately 0.6 m (2 ft) inside the culvert entrance. The suddenly accelerated water gains its kinetic energy, and velocity, from losses of flow work, p/γ, and/or potential energy of elevation (z of the energy equation), where Energy = $V^2/2g + p/\gamma + z$, where (γ) is the specific weight of water. Thus, a fish swimming in this zone is subjected to pressure and/or slope gradient effects as well as its profile drag and virtual mass effects due to the water's velocity and acceleration, respectively.

In order to make an approximate calculation of the net power and total energy necessary for the fish to deliver in order to pass outward through the culvert inlet, we assumed that the exit zone is 0.9 m (3 ft) in length, and that the hydraulic grade line drops linearly in the distance from the upstream pool elevation to the water surface elevation just inside the culvert. The water velocity at the culvert entrance used to calculate the profile drag on the fish exiting the culvert is the mean of the vertical velocity profile measured at 3 cm (0.1 ft) increments for the bottom 9 cm (0.3 ft) upward from the invert at the culvert entrance lip. We assumed that the fish recognizes this 0.9 m (3 ft) zone as one requiring a high level of power output for a short distance and short time, so we assume that the fish's velocity, V_f, is 0.3 m/sec (1 ft/sec). This assumption is not based on observation at this culvert inlet and is certainly a subject for future work, but it is probably reasonable based on observations at the culvert outlet.

At the culvert inlet, where the fish exits the culvert, it swims through accelerating water so the propulsive force, P, necessary for it to generate in order to exit the culvert is assumed to be that given in Equation 5. Since it was not possible to observe fish exiting the Poplar Grove Creek culvert, we simply assumed that the fish moved horizontally upstream through this segment of its passage. Thus, in Equation 5 the angle (ϕ) is assumed to be zero and tan (θ) is assumed to be the difference in water surface elevations in the upstream pool and just inside the culvert, divided by the observed approximate 0.9 m (3 ft) length of this zone. This is illustrated in Figure 55.

P just calculated by Equation 5 can now be substituted into Equation 6 to calculate the net power (Pwr) delivered by the fish as it exits the culvert. The value of Pwr thus calculated can then be substituted into Equation 7 to determine the approximate inlet E expended by the fish exiting the culvert. The upper limit of the integral of Equation 7 is simply obtained by dividing the distance the fish travels, 0.9 m (3 ft),

TABLE 16. Calculated energy (E) and power (Pwr) for fish swimming through only the barrel of the Poplar Grove Creek culvert, May 18-20, 1986.

Date: 5/18/86
$Q = 1.221\ m^3/sec$
Apparent mean $V_{occupied} = 0.747$ m/s

Length mm	V_f m/sec	V_{fw} m/sec	Profile drag, N	Power watts	Barrel E joules
200	0.002	0.749	0.151	0.113	1893.3
220	0.011	0.758	0.183	0.139	427.0
240	0.022	0.769	0.220	0.169	251.4
260	0.037	0.784	0.263	0.206	184.0
280	0.055	0.802	0.313	0.251	149.4
300	0.078	0.825	0.373	0.308	129.4

Date: 5/19/86
$Q = 1.153\ m^3/sec$
Apparent mean $V_{occupied} = 0.765$ m/s

Length mm	V_f m/sec	V_{fw} m/sec	Profile drag, N	Power watts	Barrel E joules
200	0.002	0.767	0.158	0.121	2025.6
220	0.011	0.776	0.191	0.148	456.5
240	0.022	0.787	0.229	0.181	268.5
260	0.037	0.802	0.274	0.220	196.3
280	0.055	0.821	0.326	0.268	159.1
300	0.078	0.844	0.388	0.327	137.6

Date: 5/20/86
$Q = 1.070\ m^3/sec$
Apparent mean $V_{occupied} = 0.732$ m/s

Length mm	Vf m/sec	V_{fw} m/sec	Profile drag,N	Power watts	Barrel E joules
200	0.002	0.734	0.145	0.107	1787.3
220	0.011	0.742	0.176	0.131	403.4
240	0.022	0.754	0.212	0.160	237.7
260	0.037	0.769	0.254	0.195	174.1
280	0.055	0.787	0.302	0.238	141.6
300	0.078	0.810	0.361	0.292	122.8

by the value of V_f just assumed, 0.3 m/sec (1 ft/sec). Values for E and Pwr calculated by these methods, the profile drag, virtual mass force, and the additional drag associated with the sloping HGL (Gradient Force) for various lengths of grayling are shown in Table 17.

Power and Energy Expenditures

The preceding developments of Pwr and E for fish passing through the Poplar Grove Creek culvert are probably the first time that anyone has properly quantified the change that occurs in a fish's potential energy as it passes through a culvert (or any other structure). It should be noted that this change in potential energy--represented by $W(\sin \phi + \cos \phi (\tan(\theta - \phi))$ in Equations 1 and 5, and subsequently utilized to calculate Pwr and E as the fish enters and exits the culvert--has some significance at any location where the HGL has a slope greater than about 10%. Clearly, this often occurs at inlets and outlets of culverts. Recognition of this term now makes it possible to analyze fish passage through rather steep, baffled culverts (baffled to keep water velocities small enough so that profile drag does not in itself become insurmountable for the fish). This means that the effects of culvert slope and short, steep HGLs at inlet and outlet of culverts can be quantified together with the effects of profile drag.

We only mention swimming efficiencies to indicate that they have not been overlooked. What really matters to the protection of fish passage is what fish are capable of achieving: i.e., the net effects. The preceding effort has been directed toward understanding what the fish really is doing when it ascends a culvert and how much net power and energy it must deliver to enter, pass through, and exit the culvert. This report and subsequent proposed studies involve field research to attempt to determine the maximum net energy and power levels that a satisfactory percentage of spawning-size grayling can deliver. When the Arctic grayling's net capabilities and swimming characteristics are understood, the hydraulic methods of this report can be used to determine if proposed culverts will allow the fish to pass.

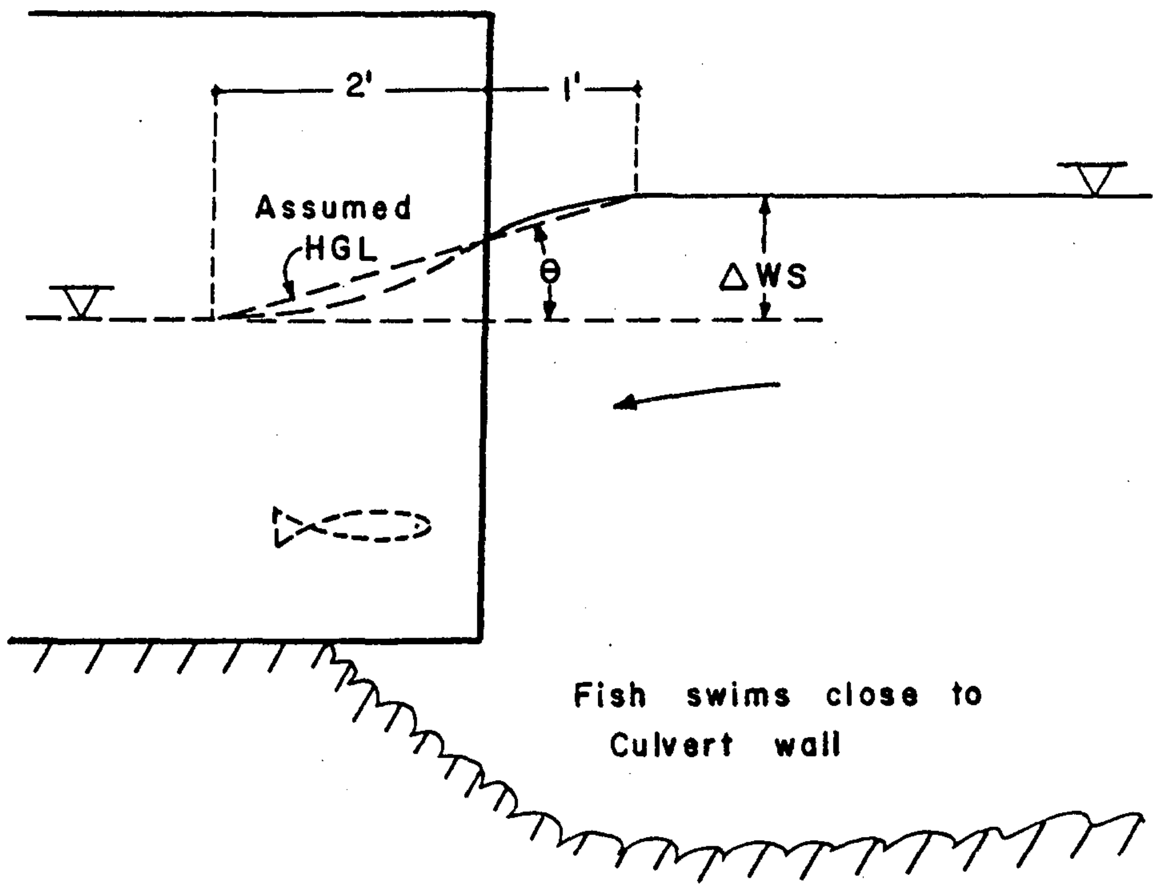

Figure 55. Culvert inlet conditions encountered by fish migrating upstream.

TABLE 17. Calculated energy (E) and power (Pwr) for fish exiting the Poplar Grove Creek culvert, May 18-20, 1986.

Date: 5/18/86; Q = 1.221 m^3/sec; V-Occ. = 0.534 m/s

Length (mm)	Drag force, N	Virt. mass force, N	Gradient force, N	Power watts	Inlet TE joules
200	0.18	0.01	0.16	1.31	3.94
220	0.22	0.02	0.21	1.65	4.95
240	0.26	0.02	0.27	2.04	6.11
260	0.30	0.03	0.34	2.48	7.43
280	0.34	0.03	0.43	2.98	8.93
300	0.38	0.04	0.52	3.54	10.61

Date: 5/19/86; Q = 1.153 m^3/sec; V-Occ. = 0.500 m/s

Length (mm)	Drag force, N	Virt. mass force, N	Gradient force, N	Power watts	Inlet TE joules
200	0.17	0.01	0.16	1.23	3.69
220	0.20	0.02	0.21	1.55	4.65
240	0.24	0.02	0.28	1.92	5.75
260	0.28	0.03	0.35	2.34	7.01
280	0.31	0.03	0.44	2.81	8.44
300	0.36	0.04	0.54	3.35	10.06

Date: 5/20/86; Q = 1.070 m^3/sec; V-Occ. = 0.628 m/s

Length (mm)	Drag force, N	Virt. mass force, N	Gradient force, N	Power watts	Inlet TE joules
200	0.22	0.01	0.12	1.50	4.49
220	0.27	0.02	0.21	2.07	6.22
240	0.31	0.03	0.28	2.55	7.65
260	0.36	0.03	0.35	3.09	9.27
280	0.41	0.04	0.44	3.70	11.10
300	0.47	0.05	0.54	4.39	13.16

The Poplar Grove Creek culvert exhibits a pronounced drop in water surface profile at both its inlet and outlet. Not all culverts exhibit these characteristics, though in order to generate additional kinetic energy in the culvert, the hydraulic grade line must drop some at the inlet of any culvert which exhibits larger water velocities than the approaching stream. Tables 14, 16 and 17 clearly show that the inlet and outlet of the culvert are points of greater, time-average difficulty for the fish than are any other individual points in the culvert barrel. This is exhibited by the fact that Pwr levels to pass through either the inlet or outlet are an order of magnitude greater than are those necessary to pass through the barrel. Though observations at Poplar Grove Creek culvert were not possible at the inlet, observations at the outlet clearly showed that the fish entering the culvert were swimming much harder to enter the culvert than they were immediately after passing over the culvert outlet lip.

Tables 14, 16 and 17 also clearly show that E is much greater for fish swimming through the barrel of the Poplar Grove Creek culvert than it is for fish entering or exiting the culvert. For small fish, E through the barrel of the culvert is 2.5 times greater than it is for either the inlet or outlet. For larger fish, this difference is one order of magnitude. However, for large or small fish, the problem shifts from one of having to be able to generate enough power to enter the culvert, then to be able to generate enough energy to negotiate the barrel, and, finally, to generate enough power to exit the culvert. Tables 14 and 17 clearly indicate that the outlet of this culvert required more power from the fish than the inlet. The experienced hydraulic engineers of the research team agree that culvert passage appeared more difficult at the outlet than at the inlet. Table 16 indicates, subject to the correctness of the analysis, that small fish would have to generate a tremendous amount of energy to pass through the culvert barrel on any of the three days covered by that table. It must be recalled that V_f was estimated from the regression Equation 12. On each of the three days studied, some 200 mm grayling passed through the culvert. It does not appear possible for any of the grayling to generate the E postulated for 200 and 220 mm grayling by Table 16. Thus, fish in these size categories, and perhaps some larger size categories, probably had to swim with V_f greater than those postulated for the "average fish" of any size category presented in Equation 12 if they were to negotiate the culvert barrel. Since many of the observed fish did successfully negotiate the culvert, many fish probably produced a V_f greater than predicted by Eq. 12.

This illustrates the uncertainties of Equation 12 and the broad confidence limits of that equation when applied to small fish. Of course, even if the equation does well as an estimator of V_f for the "average fish," some of the fish in each size category are strong enough to make a mockery of the equation, so they get through the culvert. Equation 12 predicts that an "average 200 mm fish" would require 4.7 hours to pass through the culvert. It is doubtful that such a long time is realistic. Whether the accuracy of Equation 12 for small fish is highly questionable or whether the culvert outlet pond loaded up with small fish during the three days of the study is not known. However, on May 20, a significant number of 200 and 220 mm fish passed through the culvert. It is doubtful that these fish were only those of the small fish which were unusually strong, so this too probably indicates that the lower end of Equation 12 may be in error. As an alternative explanation, it is possible that these smaller fish successfully ascended through the culvert within a smaller V-occupied zone than that occupied by a larger fish. Since the weighted water velocity within a smaller V-occupied zone would be less than that in a larger zone (as one moved away from the boundary layer), it would be reasonable to anticipate a higher passage rate.

It is plain from a study of Tables 14, 16 and 17 that, while the body weight of fish increases roughly as L^3, the power necessary for a fish to pass through any point in a culvert increases as a lesser power of fish length. The power and energy requirements relative to size are greater for small fish than for large fish. Indeed, because they cannot swim as fast as large fish, small fish often require a greater energy commitment than do larger fish. This is illustrated forcefully for the barrel of the culvert by Table 16 which shows that E may be much greater for average small fish than for average large fish.

It appears reasonable to assume that grayling successfully attempting a short, difficult segment of a culvert swim with a V_f = 1.0 ft/sec, so the methods outlined in this report for the calculation of Pwr and E for inlet and outlet conditions appear to yield reasonable results. At the outlet of the Poplar Grove Creek culvert, fish appeared to swim close to their maximum power capabilities on entering the culvert. Some, of course, simply could not or would not develop the power necessary to enter the culvert. It did appear from the field studies that the numbers given in Table 14 for 220-260 mm fish are close to the maximum capabilities of these sizes of grayling for a short time period -- 1 to 3 seconds.

Although some 200 mm fish passed through the culvert on each day of the study, more passed through later in the study than on May 18. Some of this could be because few 200 mm fish had arrived in the scour pool by May 18, as was evidenced by the scour pool catches on May 17. To the extent that Tables 14, 16 and 17 properly reflect the energy and power requirements for fish, neither energy nor power requirements changed greatly over the three days studied. This is because water velocities did not change appreciably with changes in discharge and depth in the culvert. Thus, it appears the probable greater availability of small fish in the scour pool late in the study, warmer water later in the study, and a possibly greater biological stimulus later in the study could have combined with slightly smaller hydraulic difficulties to account for greater numbers of smaller fish passing through the culvert on May 20, than on May 18. In this context, it should be noted that for culvert barrels exhibiting small HGL slopes, Equation 10 shows that Pwr increases as $V_{fw}^{2.58}$, so small decreases in V_w can have a considerable effect on Pwr and E, especially for small fish.

Limitations and Explanations Relevant to the 1986 Poplar Grove Creek Study: *Several assumptions are critical to the preceding discussion and warrant further explanation.* A comparison of Figure 39 with Figure 40 indicates that the population sampled at the stream mouth on May 14 had moved to the lower weir site by May 15. It appears the size distribution of fish found at the lower weir site on May 15 was virtually the same size distribution as sampled the previous day at the stream mouth. Since the lower weir trapped fish only while it was in operation and fish were not sampled continuously at the lower weir during the 24 hours between the afternoon of May 14 and the afternoon of May 15, it is not known whether larger fish arrived at the lower weir earlier than smaller fish. Thus the size filtering effects of this reach of stream are not known. However, during sampling at the lower weir on May 15, larger fish were caught earlier in the afternoon. As the afternoon progressed, the sampling pool immediately downstream from the weir became depleted of large fish, and the sampling population shifted to smaller fish as the afternoon progressed. Thus, it appears the fish in the smaller size intervals, 160-230 mm, probably required 24 hours to travel approximately 0.8 km (0.5 miles) from the stream mouth to the lower weir. This would give those fish an average stream V_f of 0.0093 m/sec (0.031 ft/sec) for this segment of the stream. If that stream V_f were continued upstream to the culvert, it would require an average of 3.6 days for the fish smaller than 230 mm to get from the lower weir to the culvert scour pool. Therefore, since small fish may not have been present in the culvert outlet scour pool prior to May 19, this factor instead of hydraulic difficulties at the culvert entrance may explain why small fish did not appear at the upper weir in large numbers until May 19-20.

A comparison of Figure 42 with Figure 41 appears to reveal the size filtering effects of the stream between the lower weir and the culvert outlet scour pool between the afternoon of May 16 and the afternoon of May 17. While some fish, probably medium size fish (230-280 mm), could have been accumulating in the scour pool unable to enter the culvert and other larger fish (280 mm plus), and while stronger medium size fish could have passed through the culvert before sampling began the afternoon of May 17, it is virtually certain that fish smaller than 230 mm had not yet been able to swim the 2.9 km (1.8 miles) from the lower weir to the culvert outlet scour pool. Any fish swimming this distance in exactly a 24 hour period would have to travel with a velocity of 0.0334 m/sec (0.11 ft/sec) with respect to the stream bed (V_f). If fish swam through the culvert with this same relative velocity, they would pass through the culvert in 16.7 minutes. This inferred culvert barrel transit time is of the right order of magnitude for V_f through the culvert observations of Travis (1986) and for the two radio transmitter observations of our study for fish longer than 230 mm. Thus in our study, it is possible that fish longer than 230 mm may not have been noticeably more affected by the culvert than they were by the natural stream. Confirmation of this hypothesis will require additional study.

Measurements of water velocity profiles at the culvert outlet and on the flashboard indicate that the water velocities in the fish-occupied zones did not change noticeably from May 18 through May 20. Table 14 indicates virtually no change in the power or total energy requirements for fish entering the culvert on these days. Thus, it appears that small fish (less than 230 mm) that passed through the culvert in large numbers on May 20 had the capability of passing through the culvert earlier, but either they had not arrived at the scour pool yet in significant numbers, or they were unmotivated to attempt to transit the culvert. The shift at the upper weir toward smaller fish on May 19 and 20 may be directly related to the size filtering effect of the stream distance which appears to have allowed the larger fish to ascend to the culvert and move through it to the upper weir at least a day or two before the smaller fish arrived at the culvert outlet scour pool. Shedding further light on this conclusion is the fact that Travis (1986) noted in 1985 that a great number of fish, when unable to swim through the fast-moving water flowing from the culvert outlet, leaped in their attempts to enter the top of that jet. Similar leaping behavior was noted at the upper and lower weirs in 1986 but was not noted at the culvert outlet. Hence, it inferentially appears that the culvert outlet conditions in 1986 were not adverse enough to induce fish to engage in leaping attempts to transit a high velocity barrier.

Table 15 predicts that 200 mm fish would spend approximately 4.7 hours in passing through the culvert barrel if they moved at V_f predicted by Equation 12. Also, Table 16 predicts that these small fish would have to release a tremendous amount of energy - approximately 3,000 Joules - to move through the culvert. Observations by Travis (1986) in 1985 indicated that some fish required almost 3/4 of an hour to pass through the culvert; however, no fish observed in 1985 or 1986 required anywhere near 4.7 hours. Thus, it is relatively certain that Equation 12 is not accurate for the "average" small fish around 200 mm (although certainly a subset of these smaller fish are individually capable of negotiating the culvert at V_f values approximating those of larger fish). Equation 12 does appear reasonably accurate for fish 240 mm and larger for the inferred 1986 V-occupied water velocity of approximately 0.75 m/sec (2.45 ft/sec) and the 33.5 m (110 ft) length of the Poplar Grove Creek culvert.

Previous studies by Kane and Wellen (1985) generally predicted slower water velocities in the fish-occupied zones than have been measured in our study. However, it should be recognized that all velocity profiles taken for our study were in areas of accelerating flow; hence, the water velocities in the fish-occupied zones should be higher than in areas without acceleration. In addition, Kane and Wellen's predictive method does not apply to water velocities close to the side boundaries of culverts. Perhaps literature can be found that will shed light on this, although few investigators have cared about this topic for partially full, flowing culverts.

It is important to note that the average water velocity at the mouth of Poplar Grove Creek culvert was over twice that in the barrel of the culvert. While it is convenient to measure water velocities at outlets of culverts, the water velocity in the barrel of a culvert often is less than that at the outlet. Thus, if the water surface contracts from the barrel to the outlet, outlet velocities mean little in attempting to assess the possibilities of fish being able to pass through a culvert barrel. Since power requirements for fish passing through the barrel of a culvert increase approximately to the third power (2.58) of the relative velocity of the fish to the water, misjudgements of barrel water velocity can have very considerable effects on estimated fish capabilities to negotiate successfully a culvert barrel.

Because the receiving scour pool's water surface elevation was considerably lower than the water surface elevation measured 1.6 m upstream from the culvert outlet, the water accelerated and the cross-sectional area of flow was less at the outlet lip than it would have been if the scour pool's water surface elevation had approximated that 1.6 m upstream from the culvert outlet. If the water surface elevation of the scour pool had been only slightly less than that 1.6 m upstream, the water velocity (V_w) would have been only 75 percent of what was actually measured. Thus, the drag forces shown in Table 14 would have been reduced to approximately 60 percent of those shown; the pressure gradient forces would have become negligible; and the power necessary for the fish to enter the culvert would have been reduced to approximately 45 percent of that shown in Table 14. Entrance to the culvert would have been made much easier than it actually was.

The Poplar Grove Creek culvert sloped adversely upward for the final 3 m of the culvert at the outlet end. However, for a normal culvert with outlet control supporting subcritical flow in the barrel, if the water surface elevation in the scour pool matched the hydraulic normal depth of flow at the outlet lip, the drag force and the power generated by the fish entering the culvert would be identical with that in the barrel of the culvert upstream from the outlet, and the gradient force would become negligible. Thus, outlet effects as identified earlier in this report would disappear, and the culvert would function (relative to a fish's perspective) as though it consisted of a barrel and an inlet. Total energy requirements would be reduced.

CONCLUSIONS

Alaska's current culvert water velocity design guidelines for fish passage are predicated predominantly on the hypothesis that a fish's profile drag is the sole deterrent to its passage through a hydraulic structure. While this approach is appropriate for full outlet controlled (completely backwatered) culverts, it does not adequately address culverts with a pronounced hydraulic gradient at either the inlet or outlet, or with zones of pronounced water velocity acceleration (as is typical of most existing culverts installed to date). Under such typical conditions, fish must also contend with highly variable culvert outlet, inlet and barrel hydraulic conditions, including adverse horizontal pressure gradients and virtual mass forces, which may restrict or block fish passage, even in the presence of otherwise acceptable water velocities in the culvert barrel.

The power and energy calculations for passage of Arctic grayling through the Poplar Grove Creek culvert during the 1986 study indicate that the fish had to develop extremely high power outputs to get past the partially perched culvert outlet. However, the predicted energy expenditures for passage of 200-240 mm design fish past the culvert outlet were not substantial. These predictive calculations are consistent with the visual observations of vigorous swimming performance at the culvert outlet noted during the 1986 study. The analysis of fish swimming performance within the barrel of the culvert indicates that those fish swam rather slowly through the culvert barrel such that their total power capabilities were not taxed (the fish seemed to minimize total power output for the long haul ahead). Thus, application of the power and energy equations to culvert fish passage situations points out a complex fish passage paradox: by passing slowly through the barrel of the culvert, fish may minimize their power output; however, this strategy maximizes the energy (not to be confused with power) output necessary to pass through the culvert.

In short, the analysis completed to date suggests that culvert entry may tax a fish's short-term (one to three seconds) power development. In contrast, passage through the barrel of a culvert appears to predominantly tax a fish's long-term energy production. Typical conditions at a culvert entrance (culvert exit for the fish) do not appear to severely tax either the power or energy capabilities of most fish, although a fish that is running out of available energy may be swept back downstream when it reaches this final transition.

Since Arctic grayling did not appear to be appreciably delayed by the culvert on May 19 and 20, it appears that the values for power (Pwr) and energy (E) in Tables 14 and 17 are "safe" values for spawning Arctic grayling entering and exiting culverts. Based on the V_f predicted by Equation 12, 240 mm Arctic grayling successfully swam through the Poplar Grove Creek culvert barrel on May 20 with an inferred V_f of 0.022 m/sec

(0.073 ft/sec), a power requirement of 0.160 watts (0.118 ft-lb/sec), and a total energy expenditure of 237.7 joules (176 ft-lb). Although it is not known what the upper limiting hydraulic factors would have been to "just allow" 240 mm fish to swim through the culvert, these simultaneous values are apparently "safe" for the efficient passage of Arctic grayling 220 mm or longer in fork length.

Additional study and refinement of the energy and power equations for culvert inlets, outlets and barrels under different hydrologic and hydraulic conditions is needed to fully develop culvert design specifications that will enhance fish passage in a cost-effective manner. A partial analysis of power and energy requirements was incorporated in a subsequent 1987 Inter-Agency Fish Passage Task Force fish passage study at Fish Creek near Cantwell, Alaska. Additional observations of fish passage and refinement of the equations are proposed at several interior Alaska culverts in spring 1988. Final design recommendations based on these power and energy equations will be incorporated in the revised culvert design criteria currently under development by the Inter-Agency Fish Passage Task Force.

The performance regressions derived from the 1986 observations of fish passage observations predict that the 75 percent design passage level (plus or minus 16%) for all attempts by Arctic grayling to pass successfully through the entire 33.5 m (110 ft) culvert (outlet, barrel and inlet) occurred at an average outlet velocity (Q divided by the cross-sectional area) of 1.80 m/s (5.95 fps) at a mean water temperature of 4.4°C. The corresponding mean culvert barrel velocity was 0.78 m/s (2.55 fps).

By comparison, the State's existing fish passage criteria predict that the 75% design fish passage will occur at 0.70 m/s (2.29 fps) under identical culvert length and water temperature conditions. The State's existing criteria, however, stipulate the mean cross-sectional culvert outlet velocity, rather than the mean weighted culvert barrel velocity, as the design velocity. However, a review of the underlying studies which have heretofore formed the principle basis for the State's current guidelines (MacPhee and Watts, 1976; and Arctic Hydrological Consultants, 1985) and the results from the present Poplar Grove Creek study, the specification of mean cross-sectional outlet velocity as the design parameter is *only* appropriate for full outlet controlled culverts (where mean weighted culvert barrel velocity equals outlet velocity). In all other situations, the State's existing culvert velocity guidelines are only applicable to the mean weighted culvert barrel velocity. In this regard, it is noteworthy that the design velocity regressions independently developed by MacPhee and Watts (1976), Arctic Hydrological Consultants (1985) and the 1986 Poplar Grove Creek study <u>all</u> closely predicted the 75% passage design velocities (see Table 12).

Based on these findings, we recommend that the State consider the following *interim* revisions to the existing culvert design criteria for fish passage. *Final design guidelines based on power and energy calculations for form drag, adverse pressure gradient and virtual mass forces will be released at a later date upon completion of the "Design Manual" currently under development by the Inter-Agency Fish Passage Task Force.*

1. Optimally, the culvert design specifications should separately and cumulatively consider whether the water velocities (profile drag), pressure gradient forces, and virtual mass forces at the culvert inlet, outlet and barrel exceed the power and energy capabilities of the design fish. However, until accepted power and energy equations are developed, we recommend that the State's existing culvert water velocity design criteria be accepted and used as a reasonable approximation (although possibly slightly conservative) of fish sustained swimming speed capabilities, and be applied to the mean weighted culvert barrel velocity, *rather than the mean cross-sectional culvert outlet velocity.*

2. We further recommend that design criteria include an additional specification that culvert outlet and inlet water velocities not exceed the burst swimming (related to the total power limitation) capabilities of the design fish. In general, the burst speed capabilities of fish are approximately 100% greater (2x) than the sustained swimming speed capabilities. Until more refined power and energy equations are developed, incorporation of these separate culvert barrel and culvert outlet and inlet water velocity design specifications will afford increased protection to fish populations and will simultaneously increase design flexibility with resultant cost savings.

3. On a site-specific basis, consideration should be given to utilizing the predictive V-occupied culvert water velocities as the design

velocities rather than the mean weighted culvert barrel velocity. Particularly in the case of larger culverts (typically multi-plates with deeper corrugations), water velocities within the V-occupied zone appear to be appreciably less than the more frequently specified mean weighted or cross-sectional design velocities. To the extent that more reliable predictive equations for the V-occupied velocities can be developed, utilization of the V-occupied velocity (which is what the fish actually swim through) would significantly increase design flexibility and reduce costs, while maintaining equivalent levels of protection for fish populations.

4. Pending completion of the Alaska Cooperative Fishery Research Unit's spawning migration delay study (commissioned by the Inter-Agency Fish Passage Task Force), the 48 hour duration (Q 2.33) flood discharge event for the specific watershed should be utilized for the design discharge.

ADDITIONAL RECOMMENDATIONS

1. Fisheries biologists and hydraulic engineers should expressly recognize and consider that fish must negotiate three separate hydraulic situations (culvert inlet, outlet and barrel) in order to pass successfully through a culvert. Far too frequently, culvert design recommendations appear to have been limited to only partial consideration of these interrelated, yet separate, hydraulic situations.

2. Optimally, the culvert design process should yield culverts that fully consider and address fish power and energy requirements in the culvert inlet, outlet and barrel, and permissible delays of spawning migration. In addition, culverts should be designed so the cumulative energy requirements for a fish to overcome successfully both profile drag (water velocity) and adverse virtual mass, and so pressure gradient forces at a culvert's inlet and outlet do not exceed the design fish's power potential. Finally, culverts must be designed so the energy requirements within the culvert barrel, coupled with the energy requirements at the culvert outlet and inlet, do not exceed the total energy reserves of the design fish.

3. Considerable care should be taken when designing drainage structures for fish passage to ensure that only directly comparable culvert velocity parameters are utilized. It appears that many, if not most, differences in professional opinion and field research relative to the

swimming performance of fish (and hence the appropriate design velocity) have stemmed not from actual differences in observed fish performance, but from the inappropriate comparison of different velocity parameters (i.e., average outlet velocity; 0.6 depth centerline outlet velocity; mean weighted culvert barrel velocity; skin or V-occupied velocity; etc.).

4. Culverts are frequently designed for the 50-year flood but must also accommodate fish for the mean annual flood (Q-2.33). To design successfully for fish passage, the relationship must be determined between the 50-year flood and the mean annual flood (or other design "fish passage" flood) relative to culvert water velocities and potential fish passage delays. This is not addressed in our report. Some light should be shed on this topic by studies of grayling spawning delays presently being pursued on Fish Creek. However, the ratio of Q_{50} to the fish passage design flood must be known before a proposed culvert can be analyzed for velocity conditions, and inlet and outlet conditions which would occur under partially full, fish passage conditions.

5. Observations of our study, although not unique to it, indicate that, for mildly sloping culverts, outlet problems for fish can be obviated if the water surface level in the receiving pool matches the hydraulic normal depth at the outlet lip of the culvert (i.e., tailwater control practices should be incorporated that match the receiving water's surface elevation to that of the hydraulic normal depth in the culvert at its outlet lip. Thus, scour-pool water surface levels that match the culvert outlet water level at design fish passage flows would eliminate outlet problems where they occur. How this would be achieved in individual situations leaves much to the imagination because of the various possible culvert outlet situations.

6. If the culvert is designed with negligible adverse pressure gradient and virtual mass forces at the culvert outlet (by raising the elevation of the outlet pool water to match the water surface profile at the outlet lip of the culvert), the additive power requirements of the outlet pressure gradient and virtual mass forces are eliminated. Under

such conditions, the profile drag power requirements presented in Table 16 appear safe for 220 mm or larger (fork length) fish.

7. For existing culverts that do not meet fish passage requirements, it may be possible to retrofit the culvert with an appropriate structure to facilitate fish passage. If the problem exists at the culvert outlet or because of a lack of backwater into the culvert barrel or inlet, appropriate tailwater devices that reduce the degree of perching of the culvert or increase the depth of flow in the culvert might be installed. Addition of appropriate baffling in the inverts of existing culverts could be added to reduce water velocities where fish appear to prefer to swim in the culvert (close to the invert in the Poplar Grove Creek culvert).

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GLOSSARY OF TERMS

Term	Definition	Units SI	Units US
A	Culvert cross-sectional flow area	m^2	ft^2
a	Acceleration	m/sec^2	ft/sec^2
b	Water surface width across culvert	m	ft
ADT	Alaska Daylight Time		
AST	Alaska Standard Time		
C	Degrees centigrade		
C_d	Profile drag coefficient	dimensionless	
CFS	Cubic feet per second		ft^3/sec
CMP	Corrugated metal pipe		
E	Energy expended by a fish	N-m (joules)	ft-lb
g	Acceleration of gravity	9.81 m/sec^2	ft/sec^2
HGL	Hydraulic grade line. Locus of the local piezometric head, except in zones of rapid acceleration as defined by the local water surface.		
L	Fish fork length	mm	in
L_c	Culvert length	m	ft
N_R	Reynolds Number = $V_{fw}L/\nu$	dimensionless	
NTU	Nephelometric Turbidity Units		
n	Manning's roughness factor	$m^{-1/3}$-sec	$ft^{-1/3}$-sec
p	Water pressure	N/m^2	$\#/ft^2$
Pwr	Net power delivered by fish	N-m/sec (Watts)	ft-#/sec
Q	Water discharge	m^3/sec	ft^3/sec
Q_{50}	Flood water discharge with a 50-year return period	m^3/sec	ft^3/sec
V	Velocity m/sec ft/sec		
V_{ave}	Average culvert cross-sectional velocity	m^3/sec	ft3/sec
V_f	Velocity of fish with respect to a fixed reference	m/sec	ft/sec
V_{fw}	Velocity of fish with respect to the moving water	m/sec	ft/sec

(continued)

V_o	V-occupied. Average velocity of water in the area where fish swim (usually close to the culvert boundary)	m/sec	ft/sec
V_w	Water velocity	m/sec	ft/sec
$V_{weighted}$	Distance weighted mean cross-sectional water velocity within the culvert barrel	m/sec	ft/sec
z	Elevation of a point or water surfaced above a stated reference elevation	m	ft
γ	Specific weight of water	N/m^3	$\#/ft^3$
θ	Angle with the horizontal at which the hydraulic grade line (HGL) slopes.	radians	
ρ	Mass density of water	kg/m^3	$\#\text{-}sec^2/ft^4$
ϕ	Angle at which the fish swims with respect to the horizontal	radians	
ν	Kinematic viscosity of water for stream water temperatures	m^2/sec	ft^2/sec

APPENDIX

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/18		242		1044
86/05/18		257		1045
86/05/18		265		1046
86/05/18		255		1047
86/05/18	M	286		1048
86/05/18	M	268		1049
86/05/18		251		1050
86/05/18		262		1051
86/05/18	M	265		1052
86/05/18	M	235		1053
86/05/18	M	302		1054
86/05/18	M	226		1055
86/05/18		245		1056
86/05/18	M	236		1057
86/05/18	M	268		1058
86/05/18		248		1059
86/05/18	M	232		1060
86/05/18	F	247		1061
86/05/18		255	828	1062
86/05/18	F	301		1063
86/05/18		249		1064
86/05/18	M	244		1065
86/05/18	M	252		1066
86/05/18	F	248		1067
86/05/18	M	231		1068
86/05/18	F	263		1069
86/05/18	M	234		1070
86/05/18	F	301	039	1071
86/05/18	M	270		1072
86/05/18	F	275		1073
86/05/18	M	253		1074
86/05/18	M	246		1075
86/05/18	F	260		1076
86/05/18	F	292		1077
86/05/18	F	266		1078
86/05/18	F	272		1079
86/05/18	M	266		1080
86/05/18	M	250		1081
86/05/18	F	292		1082
86/05/18	F	257		1083
86/05/18	M	235		1084
86/05/18		280		1085
86/05/18	M	220		1086

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/18	M	259	808	1001
86/05/18		281	269	1002
86/05/18		238		1003
86/05/18		258		1004
86/05/18		231		1005
86/05/18		265		1006
86/05/18		240		1007
86/05/18		230		1008
86/05/18		266		1009
86/05/18		240		1010
86/05/18		240		1011
86/05/18		259		1012
86/05/18		232		1013
86/05/18		223		1014
86/05/18		224		1015
86/05/18		265		1016
86/05/18		239		1017
86/05/18		261		1018
86/05/18		296		1019
86/05/18		270		1020
86/05/18		242		1021
86/05/18	M	242		1022
86/05/18		243		1023
86/05/18		235		1024
86/05/18		257		1025
86/05/18		262		1026
86/05/18		235		1027
86/05/18		245		1028
86/05/18		288	078	1029
86/05/18		268	222	1030
86/05/18		260	844	1031
86/05/18		285		1032
86/05/18		223		1033
86/05/18		317		1034
86/05/18		244		1035
86/05/18		265	142	1036
86/05/18		274		1037
86/05/18		236		1038
86/05/18		245		1039
86/05/18		236		1040
86/05/18		246		1041
86/05/18		255		1042
86/05/18		255		1043

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/18	M	225		1087
86/05/18	F	223		1088
86/05/18	F	270		1089
86/05/18	M	232		1090
86/05/18	M	260		1091
86/05/18		211	082	1092
86/05/18	F	253		1093
86/05/18	F	226		1094
86/05/18	M	274		1095
86/05/18	M	245		1096
86/05/18	F	279		1097
86/05/18	M	260		1098
86/05/18	M	238		1099
86/05/18	M	265		1100
86/05/18	F	313	048	1101
86/05/18	M	225		1102
86/05/18	M	270		1103
86/05/18	M	298		1104
86/05/18	M	245		1105
86/05/18	M	249		1106
86/05/18	M	261		1107
86/05/18	M	257	158	1108
86/05/18	M	261	199	1109
86/05/18	F	244		1110
86/05/18	M	260		1111
86/05/18	M	212		1112
86/05/18	M	252		1113
86/05/18	F	264		1114
86/05/18	M	252		1115
86/05/18	F	243		1116
86/05/18	M	255		1117
86/05/18	M	263		1118
86/05/18	M	234		1119
86/05/18	M	252		1120
86/05/18	F	252		1121
86/05/18	F	241		1122
86/05/18	M	294		1123
86/05/18	M	274	185	1124
86/05/18	M	271		1125
86/05/18	M	260		1126
86/05/18	M	217		1127
86/05/18	F	242		1128
86/05/18	M	252		1129

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/18	M	212		1130
86/05/18	M	252		1131
86/05/18	M	228	023	1132
86/05/18	M	265		1133
86/05/18	F	255		1134
86/05/18	F	250		1135
86/05/18	M	222		1136
86/05/18	F	254		1137
86/05/18	M	226		1138
86/05/18	M	217		1139
86/05/18	F	281		1140
86/05/18	F	242		1141
86/05/18	F	286		1142
86/05/18	M	278		1143
86/05/18	F	287		1144
86/05/18	M	247	156	1145
86/05/18	M	255		1146
86/05/18	F	256		1147
86/05/18	M	241		1148
86/05/18	F	308		1149
86/05/18	M	227		1150
86/05/18	M	257		1151
86/05/18	F	237		1152
86/05/18	F	255		1153
86/05/18	M	223		1154
86/05/18	M	233		1155
86/05/18	F	243		1156
86/05/18	M	240		1157
86/05/18	M	220		1158
86/05/18	F	244		1159
86/05/18	M	227		1160
86/05/18	M	236		1161
86/05/18	M	229		1162
86/05/18	F	238		1163
86/05/18	M	227		1164
86/05/18	M	237		1165
86/05/18	M	236	157	1166
86/05/18	M	250		1167
86/05/18	M	220		1168
86/05/18	F	266		1169
86/05/18	M	252		1170
86/05/18	M	212		1171
86/05/18	M	222		1172

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/18	F	260		1173
86/05/18	M	234		1175
86/05/18	M	235	561	1176
86/05/18	M	232		1180
86/05/18	M	248		1181
86/05/18	F	258		1182
86/05/18	M	220		1183
86/05/18	M	242		1184
86/05/18	M	247		1185
86/05/18	F	232		1186
86/05/18	F	274		1187
86/05/18	F	234	016	1188
86/05/18	M	240		1189
86/05/18	M	255		1190
86/05/18	M	218		1191
86/05/18	F	224		1192
86/05/18	M	252		1193
86/05/18	M	230		1194
86/05/18	F	260		1195
86/05/18	M	224		1196
86/05/18	F	251		1197
86/05/18	M	231		1198
86/05/18	F	242		1199
86/05/18	F	285	820	1200
86/05/18	F	317		1201
86/05/18	F	221		1202
86/05/18	M	206		1203
86/05/18	M	210		1204
86/05/18	M	232		1205
86/05/18	M	252		1206
86/05/18	F	250		1207
86/05/18	M	247		1208
86/05/18		235		1209
86/05/18	F	282		1210
86/05/18	F	237	345	1211
86/05/18	F	250		1212
86/05/18	F	272		1213
86/05/18	F	262		1214
86/05/18	M	242		1215
86/05/18	F	228		1216
86/05/18	F	248		1217
86/05/18	F	262		1218
86/05/18	M	282		1219

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/18	F	254		1220
86/05/18	F	248		1221
86/05/18	M	225		1222
86/05/18	F	258		1223
86/05/18	M	275	167	1224
86/05/18	M	267		1225
86/05/18	M	268		1226
86/05/18	M	226		1227
86/05/18	F	230		1228
86/05/18	F	242		1229
86/05/18	F	231		1230
86/05/18	M	242		1231
86/05/18	F	300		1232
86/05/18	M	260		1233
86/05/18	F	306	183	1234
86/05/18	F	274		1235
86/05/18	F	248		1236
86/05/18	M	216		1237
86/05/18	M	260		1238
86/05/18	F	302		1239
86/05/18	F	268		1240
86/05/19	M	223		1241
86/05/19	M	233		1242
86/05/19	M	282		1243
86/05/19	M	220		1244
86/05/19	M	240		1245
86/05/19	F	237		1246
86/05/19	M	232		1247
86/05/19	F	250		1248
86/05/19	M	222		1249
86/05/19	F	250		1250
86/05/19	M	214		1251
86/05/19	F	227		1252
86/05/19	F	250		1253
86/05/19	F	240		1254
86/05/19	F	226		1255
86/05/19	F	260		1256
86/05/19	M	225		1257
86/05/19	M	280		1258
86/05/19	M	251		1259
86/05/19	M	210		1260
86/05/19	F	228		1261
86/05/19	F	236		1262

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	212		1263
86/05/19	M	226		1264
86/05/19	F	257		1265
86/05/19	M	214		1266
86/05/19	F	246		1267
86/05/19	F	255		1268
86/05/19	M	248		1269
86/05/19	F	228		1270
86/05/19	F	268		1271
86/05/19	F	244		1272
86/05/19	M	240		1273
86/05/19	F	238		1274
86/05/19	F	240		1275
86/05/19	F	240		1276
86/05/19	M	264	301	1277
86/05/19	F	252		1278
86/05/19	F	238		1279
86/05/19	M	230		1280
86/05/19	M	232		1281
86/05/19	M	211		1282
86/05/19	F	283		1283
86/05/19	M	237		1284
86/05/19	M	221		1285
86/05/19	M	227		1286
86/05/19	M	238		1287
86/05/19	F	247	163	1288
86/05/19	F	250		1289
86/05/19	M	237		1290
86/05/19	M	232		1291
86/05/19	M	275		1292
86/05/19	M	240		1293
86/05/19	M	250		1294
86/05/19	M	220		1295
86/05/19	F	282		1296
86/05/19	M	254		1297
86/05/19	F	255		1298
86/05/19	M	226		1299
86/05/19	F	239		1300
86/05/19	M	222		1301
86/05/19	M	228		1302
86/05/19	F	227		1303
86/05/19	F	248		1304
86/05/19	M	252		1305

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	242		1306
86/05/19	M	240		1307
86/05/19	F	251		1308
86/05/19	M	220		1309
86/05/19	M	222		1310
86/05/19	F	214		1311
86/05/19	F	269		1312
86/05/19	F	227		1313
86/05/19	F	216		1314
86/05/19	F	310	724	1315
86/05/19	F	252		1316
86/05/19	M	240		1317
86/05/19	M	220		1318
86/05/19	F	244		1319
86/05/19	F	232		1320
86/05/19	F	295	626	1321
86/05/19	F	240	607	1322
86/05/19	F	268		1323
86/05/19	M	262		1324
86/05/19	M	220		1325
86/05/19	M	214		1326
86/05/19	F	244		1327
86/05/19	M	275		1328
86/05/19	M	206		1329
86/05/19	M	280		1330
86/05/19	M	237		1331
86/05/19	M	242		1332
86/05/19	F	264		1333
86/05/19	F	238		1334
86/05/19	M	242		1335
86/05/19	F	222		1336
86/05/19	M	235		1337
86/05/19	M	224		1338
86/05/19	M	217		1339
86/05/19	F	211		1340
86/05/19	F	244		1341
86/05/19	F	270		1342
86/05/19	M	230		1343
86/05/19	M	260		1344
86/05/19	M	242		1345
86/05/19	M	265		1346
86/05/19	F	262		1347
86/05/19	M	231		1348

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	223		1349
86/05/19	M	263		1350
86/05/19	M	227		1351
86/05/19	F	241		1352
86/05/19	F	237		1353
86/05/19	M	250		1354
86/05/19	M	234		1355
86/05/19	F	242		1356
86/05/19	M	217		1357
86/05/19	M	212		1358
86/05/19	M	237		1359
86/05/19	M	263	603	1360
86/05/19	M	248	361	1361
86/05/19	M	240		1362
86/05/19	F	272		1363
86/05/19	F	327		1364
86/05/19	F	220		1365
86/05/19	M	225		1366
86/05/19	M	232	077	1367
86/05/19	F	230		1368
86/05/19	M	218		1369
86/05/19	M	235		1370
86/05/19	M	212		1371
86/05/19	F	250		1372
86/05/19	M	225		1373
86/05/19	M	234		1374
86/05/19	M	217		1375
86/05/19	F	230		1376
86/05/19	M	225		1377
86/05/19	M	238		1378
86/05/19	M	252		1379
86/05/19	F	227		1380
86/05/19	F	252		1381
86/05/19	F	240		1382
86/05/19	M	255		1383
86/05/19	F	245	550	1384
86/05/19	M	255		1385
86/05/19	M	258		1386
86/05/19	M	232		1387
86/05/19	F	217		1388
86/05/19	F	225		1389
86/05/19	F	258		1390
86/05/19	M	231		1391

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	270		1392
86/05/19	F	224		1393
86/05/19	F	267		1394
86/05/19	M	244		1395
86/05/19	F	250		1396
86/05/19	M	230		1397
86/05/19	F	227		1398
86/05/19	M	218		1399
86/05/19	M	238		1400
86/05/19	M	214		1401
86/05/19	M	231		1402
86/05/19	M	218		1403
86/05/19	F	224		1404
86/05/19	M	249	418	1405
86/05/19	F	242		1406
86/05/19	F	252		1407
86/05/19	M	220		1408
86/05/19	M	229		1409
86/05/19	F	258		1410
86/05/19	M	212		1411
86/05/19	M	254	393	1412
86/05/19	F	217		1413
86/05/19	F	224		1414
86/05/19	M	235		1415
86/05/19	M	196		1416
86/05/19	M	252		1417
86/05/19	F	226		1418
86/05/19	F	254		1419
86/05/19	M	249	814	1420
86/05/19	F	212		1421
86/05/19	M	274		1422
86/05/19	F	282		1423
86/05/19	M	206		1424
86/05/19	M	214		1425
86/05/19	M	224		1426
86/05/19	M	228		1427
86/05/19	M	260		1428
86/05/19	M	200		1429
86/05/19	M	220		1430
86/05/19	M	225		1431
86/05/19	M	224		1432
86/05/19	F	206		1433
86/05/19	M	216		1434

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	230		1435
86/05/19	F	224		1436
86/05/19	F	252		1437
86/05/19	M	230		1438
86/05/19	F	275	468	1439
86/05/19	F	272		1440
86/05/19	M	195		1441
86/05/19	F	247		1442
86/05/19	M	228		1443
86/05/19	F	252		1444
86/05/19	F	294		1445
86/05/19	M	228		1446
86/05/19	F	225		1447
86/05/19	M	234		1448
86/05/19	M	258		1449
86/05/19	F	247		1450
86/05/19	F	227		1451
86/05/19	M	245		1452
86/05/19	M	234		1453
86/05/19	M	251		1454
86/05/19	F	222		1455
86/05/19	F	230		1456
86/05/19	M	235	638	1457
86/05/19	F	230		1458
86/05/19	M	234		1459
86/05/19	M	222		1460
86/05/19	F	257		1461
86/05/19	M	268		1462
86/05/19	F	232		1463
86/05/19	F	247		1464
86/05/19	M	214		1465
86/05/19	F	222		1466
86/05/19	F	220		1467
86/05/19	F	256	661	1468
86/05/19	M	262		1469
86/05/19	M	210		1470
86/05/19	F	214		1471
86/05/19	F	245		1472
86/05/19	M	230		1473
86/05/19	F	242		1474
86/05/19	M	224		1475
86/05/19	M	220		1476
86/05/19	F	225		1477

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	240		1478
86/05/19	M	217		1479
86/05/19	M	256		1480
86/05/19	F	281		1481
86/05/19	F	245		1482
86/05/19	F	208		1483
86/05/19	M	215		1484
86/05/19	F	212		1485
86/05/19	F	265		1486
86/05/19	M	202		1487
86/05/19	M	212		1488
86/05/19	F	242		1489
86/05/19	M	227		1490
86/05/19	M	215		1491
86/05/19	F	212		1492
86/05/19	F	230		1493
86/05/19	M	224		1494
86/05/19	F	255		1495
86/05/19	M	232		1496
86/05/19	F	225		1497
86/05/19	F	291		1498
86/05/19	M	215		1499
86/05/19	M	225		1500
86/05/19	F	212		1501
86/05/19	M	214		1502
86/05/19	M	212		1503
86/05/19	M	232		1504
86/05/19	M	217		1505
86/05/19	M	230		1506
86/05/19	M	214		1507
86/05/19	F	238		1508
86/05/19	F	225		1509
86/05/19	M	232		1510
86/05/19	F	238		1511
86/05/19	F	242		1512
86/05/19	M	218		1513
86/05/19	M	214		1514
86/05/19	F	232		1515
86/05/19	F	230		1516
86/05/19	M	240		1517
86/05/19	F	220		1518
86/05/19	F	212		1519
86/05/19	F	246		1520

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	223		1521
86/05/19	M	228		1522
86/05/19	F	220		1523
86/05/19	F	192		1524
86/05/19	F	266		1525
86/05/19	F	227		1526
86/05/19	M	240	738	1527
86/05/19	F	242		1528
86/05/19	M	206		1529
86/05/19	F	245		1530
86/05/19	F	232		1531
86/05/19	F	238		1532
86/05/19	M	235		1533
86/05/19	F	217		1534
86/05/19	F	267		1535
86/05/19	F	219		1536
86/05/19	M	252		1537
86/05/19	M	227		1538
86/05/19	F	182		1539
86/05/19	F	237		1540
86/05/19	F	276		1541
86/05/19	M	234		1542
86/05/19	F	230		1543
86/05/19	F	212		1544
86/05/19	F	235		1545
86/05/19	M	227		1546
86/05/19	F	243		1547
86/05/19	F	268		1548
86/05/19	M	254		1549
86/05/19	F	270		1550
86/05/19	F	247		1551
86/05/19	M	225		1552
86/05/19	F	208		1553
86/05/19	M	188		1554
86/05/19	F	235		1555
86/05/19	M	222		1556
86/05/19	M	212		1557
86/05/19	M	232		1558
86/05/19	F	242		1559
86/05/19	F	250		1560
86/05/19	M	238		1561
86/05/19	M	264		1562
86/05/19	F	248		1563

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	215		1564
86/05/19	M	200		1565
86/05/19	M	242		1566
86/05/19	F	216		1567
86/05/19	M	232		1568
86/05/19	M	224		1569
86/05/19	M	207		1570
86/05/19	F	248		1571
86/05/19	M	217		1572
86/05/19	F	222		1573
86/05/19	M	214		1574
86/05/19	F	236		1575
86/05/19	M	246		1576
86/05/19	F	237		1577
86/05/19	M	217		1578
86/05/19	F	272		1579
86/05/19	F	204		1580
86/05/19	M	240	436	1581
86/05/19	F	220		1582
86/05/19	F	222		1583
86/05/19	F	241		1584
86/05/19	M	302		1585
86/05/19	M	200		1586
86/05/19	F	250		1587
86/05/19	M	236		1588
86/05/19	F	252		1589
86/05/19	M	196		1590
86/05/19	M	206		1591
86/05/19	F	228		1592
86/05/19	F	194		1593
86/05/19	F	214		1594
86/05/19	F	230		1595
86/05/19	M	206		1596
86/05/19	M	216		1597
86/05/19	M	210		1598
86/05/19	M	220		1599
86/05/19	F	282		1600
86/05/19	M	229		1601
86/05/19	M	216		1602
86/05/19	M	258		1603
86/05/19	M	230		1604
86/05/19	M	235		1605
86/05/19	M	224		1606

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	220		1607
86/05/19	F	240		1608
86/05/19	M	247	062	1609
86/05/19	M	241		1610
86/05/19	F	228		1611
86/05/19	F	261	558	1612
86/05/19	M	251		1613
86/05/19	F	217		1614
86/05/19	M	252		1615
86/05/19	F	219		1616
86/05/19	F	226		1617
86/05/19	M	226		1618
86/05/19	M	235		1619
86/05/19	M	216		1620
86/05/19	M	211		1621
86/05/19	M	220		1622
86/05/19	F	244		1623
86/05/19	M	227		1624
86/05/19	M	226		1625
86/05/19	M	231		1626
86/05/19	M	214		1627
86/05/19	M	227		1628
86/05/19	M	256		1629
86/05/19	F	237		1630
86/05/19	M	228		1631
86/05/19	F	234		1632
86/05/19	M	227		1633
86/05/19	M	209		1634
86/05/19	F	255		1635
86/05/19	M	260		1636
86/05/19	M	215		1637
86/05/19	M	214		1638
86/05/19	M	236		1639
86/05/19	F	223		1640
86/05/19	M	238		1641
86/05/19	M	245		1642
86/05/19	M	217		1643
86/05/19	M	240		1644
86/05/19		210		1645
86/05/19	M	211		1646
86/05/19	F	219		1647
86/05/19	M	225		1648
86/05/19	F	224		1649

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	238		1650
86/05/19	M	234		1651
86/05/19	M	222		1652
86/05/19	M	221		1653
86/05/19	F	228		1654
86/05/19	F	259		1655
86/05/19	M	258		1656
86/05/19	F	255		1657
86/05/19		196		1658
86/05/19	M	227		1659
86/05/19	M	224		1660
86/05/19	F	241		1661
86/05/19	F	226		1662
86/05/19	F	220		1663
86/05/19	F	270		1664
86/05/19	M	256		1665
86/05/19	F	255		1666
86/05/19	M	224		1667
86/05/19		195		1668
86/05/19	M	230		1669
86/05/19	F	244		1670
86/05/19	M	212		1671
86/05/19	M	246		1672
86/05/19	F	239		1673
86/05/19	M	237		1674
86/05/19	M	218		1675
86/05/19	F	219		1676
86/05/19	F	223		1677
86/05/19	F	249	247	1678
86/05/19	M	209		1679
86/05/19	F	260		1680
86/05/19	F	246		1681
86/05/19	M	275		1682
86/05/19		215		1683
86/05/19	F	267	248	1684
86/05/19	M	220		1685
86/05/19	M	198		1686
86/05/19	F	248		1687
86/05/19	F	252		1688
86/05/19	F	238		1689
86/05/19	F	217		1690
86/05/19	F	248		1691
86/05/19	M	230		1692

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	251		1693
86/05/19	F	243	760	1694
86/05/19	M	220		1695
86/05/19	F	216		1696
86/05/19	F	258		1697
86/05/19	M	224		1698
86/05/19	F	241		1699
86/05/19	M	218		1700
86/05/19	M	224		1701
86/05/19	M	236	536	1702
86/05/19	F	284	177	1703
86/05/19	M	247	473	1704
86/05/19	F	248	383	1705
86/05/19	F	215		1706
86/05/19	M	253	422	1707
86/05/19	F	221		1708
86/05/19	F	221		1709
86/05/19	F	230		1710
86/05/19	F	235		1711
86/05/19	F	236		1712
86/05/19	F	222		1713
86/05/19	M	235		1714
86/05/19	M	229		1715
86/05/19		210		1716
86/05/19	F	240		1717
86/05/19		204		1718
86/05/19	M	219		1719
86/05/19	M	230		1720
86/05/19	M	259		1721
86/05/19	F	252		1722
86/05/19	F	241		1723
86/05/19	F	258		1724
86/05/19	M	235		1725
86/05/19	F	271		1726
86/05/19	M	227		1727
86/05/19	M	230		1728
86/05/19	M	224		1729
86/05/19	F	220		1730
86/05/19	M	202		1731
86/05/19		206		1732
86/05/19		214		1733
86/05/19	M	220		1734
86/05/19	M	233		1735

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	223		1736
86/05/19	F	249		1737
86/05/19	M	211		1738
86/05/19	M	229		1739
86/05/19	M	218		1740
86/05/19	M	232		1741
86/05/19	F	277	575	1742
86/05/19	F	270		1743
86/05/19	M	260		1744
86/05/19	M	267	022	1745
86/05/19	F	243	455	1746
86/05/19	M	233		1747
86/05/19	M	238		1748
86/05/19	F	275		1749
86/05/19	M	246		1750
86/05/19	M	258		1751
86/05/19	F	222		1752
86/05/19	F	220		1753
86/05/19	M	258		1754
86/05/19	F	265		1755
86/05/19	F	260		1756
86/05/19	F	227		1757
86/05/19	M	262		1758
86/05/19	F	270		1759
86/05/19	F	265	485	1760
86/05/19	M	201		1761
86/05/19	F	217		1762
86/05/19	F	208		1763
86/05/19	M	210		1764
86/05/19	M	227		1765
86/05/19	M	238		1766
86/05/19	M	232		1767
86/05/19	M	243	722	1768
86/05/19	M	215		1769
86/05/19	F	194		1770
86/05/19	F	237		1771
86/05/19	F	239	747	1772
86/05/19	M	230		1773
86/05/19	F	247		1774
86/05/19	M	192		1775
86/05/19	F	226		1776
86/05/19	M	263		1777
86/05/19	M	215		1778

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	212		1779
86/05/19	F	240		1780
86/05/19	F	215		1781
86/05/19	F	252		1782
86/05/19	F	272		1783
86/05/19	F	230		1784
86/05/19	F	225		1785
86/05/19	F	225		1786
86/05/19	M	220		1787
86/05/19	M	190		1788
86/05/19	M	217		1789
86/05/19	M	237		1790
86/05/19	F	215		1791
86/05/19	M	222		1792
86/05/19	M	196		1793
86/05/19	M	200		1794
86/05/19	M	240	573	1795
86/05/19	F	216		1796
86/05/19	F	222		1797
86/05/19	M	208		1798
86/05/19	M	215		1799
86/05/19	M	212		1800
86/05/19	F	230		1801
86/05/19	M	217		1802
86/05/19	F	242		1803
86/05/19	F	226		1804
86/05/19	F	227		1805
86/05/19	F	218		1806
86/05/19	F	236		1807
86/05/19	M	215		1808
86/05/19	F	260		1809
86/05/19	M	248		1810
86/05/19	F	216		1811
86/05/19	F	232		1812
86/05/19	M	216		1813
86/05/19	M	201		1814
86/05/19	F	212		1815
86/05/19	F	259	648	1816
86/05/19	F	234		1817
86/05/19	M	315		1818
86/05/19	F	242		1819
86/05/19	M	220		1820
86/05/19	M	216		1821

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	267		1822
86/05/19	F	252		1823
86/05/19	F	230		1824
86/05/19	F	278		1825
86/05/19	F	228		1826
86/05/19	M	231		1827
86/05/19	F	245		1828
86/05/19	F	222		1829
86/05/19	M	216		1830
86/05/19	M	208		1831
86/05/19	F	232		1832
86/05/19	F	265		1833
86/05/19	F	215		1834
86/05/19	M	226		1835
86/05/19	M	271	744	1836
86/05/19	F	237		1837
86/05/19	M	236		1838
86/05/19	M	192		1839
86/05/19	F	204		1840
86/05/19	F	222		1841
86/05/19	F	221		1842
86/05/19	F	237		1843
86/05/19	F	220		1844
86/05/19	F	240		1845
86/05/19	M	216		1846
86/05/19	M	260	596	1847
86/05/19	M	250		1848
86/05/19	M	202		1849
86/05/19	F	237		1850
86/05/19	F	217		1851
86/05/19	F	242		1852
86/05/19	M	227		1853
86/05/19	F	194		1854
86/05/19	F	238		1855
86/05/19	F	227		1856
86/05/19	M	202		1857
86/05/19	M	210		1858
86/05/19	F	227		1859
86/05/19	F	230		1860
86/05/19	F	224		1861
86/05/19	F	231		1862
86/05/19	F	262		1863
86/05/19	M	196		1864

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	212		1865
86/05/19	M	200		1866
86/05/19	F	223		1867
86/05/19	M	225		1868
86/05/19	F	252		1869
86/05/19	F	221		1870
86/05/19	M	227		1871
86/05/19	F	215		1872
86/05/19	M	252		1873
86/05/19	M	251		1874
86/05/19	M	276		1875
86/05/19	F	210		1876
86/05/19	M	196		1877
86/05/19	F	216		1878
86/05/19	M	256		1879
86/05/19	F	222		1880
86/05/19	F	252		1881
86/05/19	F	218	279	1882
86/05/19	F	274		1883
86/05/19	F	246		1884
86/05/19	F	238		1885
86/05/19	M	244		1886
86/05/19	F	220		1887
86/05/19	M	247		1888
86/05/19	F	273	357	1889
86/05/19	F	232		1890
86/05/19	F	252		1891
86/05/19	F	225		1892
86/05/19	M	226		1893
86/05/19	F	250		1894
86/05/19	F	215		1895
86/05/19	F	241		1896
86/05/19	M	231		1897
86/05/19	F	215		1898
86/05/19	M	201		1899
86/05/19	F	206		1900
86/05/19	F	250	672	1901
86/05/19	M	248		1902
86/05/19	M	235		1903
86/05/19	F	235		1904
86/05/19	F	309		1905
86/05/19		227		1906
86/05/19	F	247		1907

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	229		1908
86/05/19	F	218		1909
86/05/19		201		1910
86/05/19	M	213		1911
86/05/19	M	234		1912
86/05/19	F	240		1913
86/05/19	M	232		1914
86/05/19	M	233		1915
86/05/19	F	282		1916
86/05/19	M	294		1917
86/05/19	F	230		1918
86/05/19	F	239		1919
86/05/19	F	222		1920
86/05/19	M	225		1921
86/05/19	F	216		1922
86/05/19	M	267	493	1923
86/05/19	F	227		1924
86/05/19	M	240		1925
86/05/19	M	225		1926
86/05/19	F	247		1927
86/05/19	M	234		1928
86/05/19	F	267	544	1929
86/05/19	M	215		1930
86/05/19	F	219		1931
86/05/19		220		1932
86/05/19	M	238		1933
86/05/19	M	255	651	1934
86/05/19	F	244		1935
86/05/19	F	204		1936
86/05/19	F	252		1937
86/05/19	F	250		1938
86/05/19	F	214		1939
86/05/19	M	225		1940
86/05/19	M	219		1941
86/05/19	M	230		1942
86/05/19	F	205		1943
86/05/19	M	210		1944
86/05/19	M	233		1945
86/05/19	F	237		1946
86/05/19	M	228		1947
86/05/19	F	234		1948
86/05/19	M	247		1949
86/05/19		200		1950

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	216		1951
86/05/19	F	271	524	1952
86/05/19	F	290		1953
86/05/19	M	252		1954
86/05/19	F	239		1955
86/05/19	F	238		1956
86/05/19		219		1957
86/05/19	F	305		1958
86/05/19	F	210		1959
86/05/19	M	265	639	1960
86/05/19	F	220		1961
86/05/19		220		1962
86/05/19	F	245		1963
86/05/19	F	254		1964
86/05/19	F	239		1965
86/05/19	M	211		1966
86/05/19	F	242		1967
86/05/19	F	241		1968
86/05/19	M	240		1969
86/05/19	F	217		1970
86/05/19	F	218		1971
86/05/19	F	230		1972
86/05/19	F	231		1973
86/05/19	F	270		1974
86/05/19	F	252		1975
86/05/19		210		1976
86/05/19	F	229		1977
86/05/19	M	285		1978
86/05/19	F	232		1979
86/05/19	M	224		1980
86/05/19	M	253		1981
86/05/19	M	243		1982
86/05/19	F	244		1983
86/05/19	F	290	643	1984
86/05/19	F	223		1985
86/05/19	M	218		1986
86/05/19	F	260	420	1987
86/05/19	F	279		1988
86/05/19	F	243		1989
86/05/19	F	234		1990
86/05/19	F	242	262	1991
86/05/19	M	223		1992
86/05/19	F	235		1993

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove **Creek** culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	290		1994
86/05/19	F	254	341	1995
86/05/19	F	230		1996
86/05/19	M	219		1997
86/05/19		221		1998
86/05/19	F	232		1999
86/05/19	F	226		2000
86/05/19	M	255		2001
86/05/19	M	226		2002
86/05/19		214		2003
86/05/19	F	218		2004
86/05/19	F	294	374	2005
86/05/19	M	269	846	2006
86/05/19	M	220		2007
86/05/19	F	247		2008
86/05/19	F	205		2009
86/05/19		210		2010
86/05/19	M	228		2011
86/05/19	M	250	065	2012
86/05/19		200		2013
86/05/19	M	225		2014
86/05/19	F	230		2015
86/05/19	F	248	475	2016
86/05/19		201		2017
86/05/19	M	244		2018
86/05/19	M	235	796	2019
86/05/19	M	209		2020
86/05/19	M	265		2021
86/05/19	F	269		2022
86/05/19	M	270		2023
86/05/19	M	223		2024
86/05/19	M	236		2025
86/05/19	M	292	403	2026
86/05/19	M	238		2027
86/05/19	M	220		2028
86/05/19	M	212		2029
86/05/19		225		2030
86/05/19	F	249		2031
86/05/19	M	262	237	2032
86/05/19	F	256		2033
86/05/19	F	220		2034
86/05/19	F	231		2035
86/05/19	F	220		2036

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	245		2037
86/05/19		209		2038
86/05/19	F	217		2039
86/05/19	M	228		2040
86/05/19	F	227		2041
86/05/19	F	218		2042
86/05/19	F	239		2043
86/05/19	M	255		2044
86/05/19	F	217		2045
86/05/19	M	222		2046
86/05/19	F	242		2047
86/05/19	F	234		2048
86/05/19	M	238		2049
86/05/19	F	210		2050
86/05/19	F	242		2051
86/05/19	F	236		2052
86/05/19	M	206		2053
86/05/19	F	257		2054
86/05/19	F	225		2055
86/05/19	M	208		2056
86/05/19	F	237		2057
86/05/19	F	224		2058
86/05/19	F	234		2059
86/05/19	M	201		2060
86/05/19	F	217		2061
86/05/19	M	225		2062
86/05/19	F	214		2063
86/05/19	F	230		2064
86/05/19	F	219		2065
86/05/19	M	216		2066
86/05/19	F	240		2067
86/05/19	F	237		2068
86/05/19	F	220		2069
86/05/19	F	288		2070
86/05/19	F	252		2071
86/05/19	M	236		2073
86/05/19	F	235		2074
86/05/19	M	242		2075
86/05/19	M	250		2076
86/05/19	M	202		2077
86/05/19	F	244		2078
86/05/19	F	243		2079
86/05/19	M	214		2080

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	224		2081
86/05/19	F	240		2082
86/05/19	M	240		2083
86/05/19	M	224		2084
86/05/19	F	228		2085
86/05/19	M	242		2086
86/05/19	M	220		2087
86/05/19	M	212		2088
86/05/19	F	210		2089
86/05/19	M	274		2090
86/05/19	F	220		2091
86/05/19	F	225		2092
86/05/19	F	262		2093
86/05/19	F	220		2094
86/05/19	F	232		2095
86/05/19	M	218		2096
86/05/19	M	246		2097
86/05/19	M	230		2098
86/05/19	M	240		2099
86/05/19	F	247		2100
86/05/19	M	206		2101
86/05/19	M	226	497	2102
86/05/19	F	218		2103
86/05/19	F	262		2104
86/05/19	F	235		2105
86/05/19	F	234		2106
86/05/19	M	206		2107
86/05/19	F	347		2108
86/05/19	M	227		2109
86/05/19	F	216		2110
86/05/19	M	211		2111
86/05/19	M	216		2112
86/05/19	F	257		2113
86/05/19	F	242		2114
86/05/19	F	276		2115
86/05/19	F	224		2116
86/05/19	F	257		2117
86/05/19	F	277		2118
86/05/19	F	206		2119
86/05/19	M	216		2120
86/05/19	F	246		2121
86/05/19	M	221		2122
86/05/19	F	257		2123

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	222		2124
86/05/19	F	215		2125
86/05/19	F	275		2126
86/05/19	F	237		2127
86/05/19	M	210		2128
86/05/19	F	222		2129
86/05/19	F	227		2130
86/05/19	M	228		2131
86/05/19	F	198		2132
86/05/19	F	206		2133
86/05/19	F	215	014	2134
86/05/19	F	257	116	2135
86/05/19	M	275		2136
86/05/19	M	225		2137
86/05/19	M	215		2138
86/05/19	F	242		2139
86/05/19	F	226		2140
86/05/19	F	220		2141
86/05/19	M	204		2142
86/05/19	M	225		2143
86/05/19	M	250		2144
86/05/19	M	220		2145
86/05/19	M	236		2146
86/05/19	M	225		2147
86/05/19	M	222		2148
86/05/19	F	268	667	2149
86/05/19	F	251	637	2150
86/05/19	M	240		2151
86/05/19	M	228		2152
86/05/19	M	211		2153
86/05/19	M	215		2154
86/05/19	F	224		2155
86/05/19	M	196		2156
86/05/19	M	196		2157
86/05/19	M	203		2158
86/05/19	F	242		2159
86/05/19	M	220		2160
86/05/19	M	215		2161
86/05/19	M	240		2162
86/05/19	M	230		2163
86/05/19	F	252		2164
86/05/19	F	250		2165
86/05/19	M	208		2166

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	236		2167
86/05/19	F	235		2168
86/05/19	M	224		2169
86/05/19	F	264		2170
86/05/19	M	198		2171
86/05/19	M	224		2172
86/05/19	M	220		2173
86/05/19	F	246		2174
86/05/19	M	218		2175
86/05/19	M	208		2176
86/05/19	F	220		2177
86/05/19	F	252		2178
86/05/19	M	206		2179
86/05/19	M	202		2180
86/05/19	F	260		2181
86/05/19	F	238		2182
86/05/19	F	206		2183
86/05/19	F	252		2184
86/05/19	F	234		2185
86/05/19	M	220		2186
86/05/19	F	232		2187
86/05/19	M	268		2188
86/05/19	F	235		2189
86/05/19	F	218		2190
86/05/19	F	262		2191
86/05/19	M	230		2192
86/05/19	M	198		2193
86/05/19	F	234		2194
86/05/19	F	236		2195
86/05/19	F	243		2196
86/05/19	F	225		2197
86/05/19	M	222		2198
86/05/19	F	218		2199
86/05/19	M	186		2200
86/05/19	M	210		2201
86/05/19	F	228		2202
86/05/19	M	242		2203
86/05/19	M	220		2204
86/05/19	M	210		2205
86/05/19	F	245		2206
86/05/19	M	206		2207
86/05/19	M	242		2208
86/05/19	F	250		2209

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	248		2210
86/05/19	M	230		2211
86/05/19	M	218		2212
86/05/19	M	250		2213
86/05/19	M	212		2214
86/05/19	F	227		2215
86/05/19	M	200		2216
86/05/19	M	217		2217
86/05/19	F	224		2218
86/05/19	M	216		2219
86/05/19	M	217		2220
86/05/19	F	232		2221
86/05/19	F	220		2222
86/05/19	M	206		2223
86/05/19	F	242		2224
86/05/19	F	235		2225
86/05/19	M	241		2226
86/05/19	F	245		2227
86/05/19	M	232		2228
86/05/19	M	238		2229
86/05/19	M	220		2230
86/05/19	M	208		2231
86/05/19	M	215		2232
86/05/19	M	200		2233
86/05/19	F	220		2234
86/05/19	M	246		2235
86/05/19	F	220		2236
86/05/19	F	218		2237
86/05/19	F	255		2238
86/05/19	M	215		2239
86/05/19	M	220		2240
86/05/19	F	255		2241
86/05/19	F	218		2242
86/05/19	M	217		2243
86/05/19	F	220		2244
86/05/19	F	243	583	2245
86/05/19	F	222		2246
86/05/19	F	236		2247
86/05/19	F	220		2248
86/05/19	M	210		2249
86/05/19	F	240		2250
86/05/19	M	235		2251
86/05/19	M	253	477	2252

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	218		2253
86/05/19	F	245		2254
86/05/19	F	235		2255
86/05/19	F	250		2256
86/05/19	M	215		2257
86/05/19	M	224		2258
86/05/19	F	238		2259
86/05/19	M	230		2260
86/05/19	F	202		2261
86/05/19	M	196		2262
86/05/19	M	225		2263
86/05/19	M	223		2264
86/05/19	F	216		2265
86/05/19	M	192		2266
86/05/19	F	263		2267
86/05/19	F	274		2268
86/05/19	M	216		2269
86/05/19	M	240		2270
86/05/19	F	235		2271
86/05/19	M	210		2272
86/05/19	F	232		2273
86/05/19	M	228		2274
86/05/19	F	254		2275
86/05/19	M	230		2276
86/05/19	M	212		2277
86/05/19	M	228		2278
86/05/19	F	220		2279
86/05/19	M	220		2280
86/05/19	M	234		2281
86/05/19	F	225		2282
86/05/19	F	224		2283
86/05/19	F	222		2284
86/05/19	M	228		2285
86/05/19	M	210		2286
86/05/19	M	218		2287
86/05/19	F	246		2288
86/05/19	F	232		2289
86/05/19	M	288		2290
86/05/19	F	222		2291
86/05/19	M	218		2292
86/05/19	M	224		2293
86/05/19	M	258		2294
86/05/19	M	196		2295

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	252		2296
86/05/19	M	240		2297
86/05/19	M	220		2298
86/05/19	F	216		2299
86/05/19	M	228		2300
86/05/19	F	286		2301
86/05/19	M	251		2302
86/05/19	M	253		2303
86/05/19	M	208		2304
86/05/19		209		2305
86/05/19	M	226		2306
86/05/19	M	230	659	2307
86/05/19	M	265	613	2308
86/05/19	M	260		2309
86/05/19	F	242	072	2310
86/05/19	F	218		2311
86/05/19	M	230	317	2312
86/05/19	F	219		2313
86/05/19	F	229		2314
86/05/19	M	226		2315
86/05/19	F	201		2316
86/05/19	M	234		2317
86/05/19	F	250		2318
86/05/19	F	237		2319
86/05/19	F	272		2320
86/05/19	F	233		2321
86/05/19	M	263	207	2322
86/05/19	M	258		2323
86/05/19	M	212		2324
86/05/19	M	225		2325
86/05/19	M	207		2326
86/05/19	F	206		2327
86/05/19	F	232		2328
86/05/19	M	212		2329
86/05/19	M	228		2330
86/05/19	F	207		2331
86/05/19	F	236		2332
86/05/19	M	216		2333
86/05/19	M	235		2334
86/05/19		187		2335
86/05/19	M	227		2336
86/05/19	M	238		2337
86/05/19	F	296		2338

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	238		2339
86/05/19	F	229		2340
86/05/19		211		2341
86/05/19		195		2342
86/05/19		212		2343
86/05/19	M	216		2344
86/05/19	F	243		2345
86/05/19	F	229		2346
86/05/19	F	246	519	2347
86/05/19	M	224	414	2348
86/05/19	F	232	214	2349
86/05/19	F	276		2350
86/05/19	F	245		2351
86/05/19	F	231		2352
86/05/19	M	224		2353
86/05/19	M	219		2354
86/05/19	F	225		2355
86/05/19		206		2356
86/05/19	M	211		2357
86/05/19	F	287		2358
86/05/19	M	223		2359
86/05/19	M	275		2360
86/05/19		206		2361
86/05/19	F	249		2362
86/05/19	F	240		2363
86/05/19	M	215		2364
86/05/19	F	251		2365
86/05/19	M	234		2366
86/05/19	F	230		2367
86/05/19	M	252		2368
86/05/19	F	214		2369
86/05/19		201		2370
86/05/19	M	232		2371
86/05/19	M	224		2372
86/05/19	F	220		2373
86/05/19	M	232		2374
86/05/19	F	226		2375
86/05/19	F	217		2376
86/05/19	M	222		2377
86/05/19	F	235		2378
86/05/19	F	212		2379
86/05/19	F	225		2380
86/05/19	F	270		2381

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	246		2382
86/05/19	M	238		2383
86/05/19	F	250		2384
86/05/19	M	208		2385
86/05/19	F	250		2386
86/05/19	M	213		2387
86/05/19	M	220		2388
86/05/19	M	231		2389
86/05/19	F	233		2390
86/05/19	F	237		2391
86/05/19	F	272	502	2392
86/05/19	F	229	298	2393
86/05/19	M	230		2394
86/05/19	M	226		2395
86/05/19	F	238		2396
86/05/19	F	231		2397
86/05/19	M	230		2398
86/05/19	F	220		2399
86/05/19	F	232		2400
86/05/19	M	240		2401
86/05/19	F	235		2402
86/05/19	F	209		2403
86/05/19	M	200		2404
86/05/19	F	247		2405
86/05/19	F	251		2406
86/05/19	M	218		2407
86/05/19	F	229		2408
86/05/19		215		2409
86/05/19		201		2410
86/05/19	M	256		2411
86/05/19	M	196		2412
86/05/19	M	242		2413
86/05/19	M	208		2414
86/05/19	M	252		2415
86/05/19	F	230		2416
86/05/19	M	217		2417
86/05/19	F	216		2418
86/05/19	M	226		2419
86/05/19	M	232		2420
86/05/19	F	232		2421
86/05/19	M	186		2422
86/05/19	F	262		2423
86/05/19	F	217		2424

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	242		2425
86/05/19	M	234		2426
86/05/19	M	267		2427
86/05/19	F	260		2428
86/05/19	F	264		2429
86/05/19	M	206		2430
86/05/19	F	237		2431
86/05/19	M	264		2432
86/05/19	F	215		2433
86/05/19	M	215		2434
86/05/19	F	252		2435
86/05/19	M	234		2436
86/05/19	F	285		2437
86/05/19	M	212		2438
86/05/19	M	214		2439
86/05/19	F	204		2440
86/05/19	F	233		2441
86/05/19	M	200		2442
86/05/19	M	196		2443
86/05/19	M	250		2444
86/05/19	M	215		2445
86/05/19	M	238		2446
86/05/19	M	235		2447
86/05/19	F	250		2448
86/05/19	M	240		2449
86/05/19	M	200		2450
86/05/19	M	205		2451
86/05/19	F	230		2452
86/05/19	F	220		2453
86/05/19	M	192		2454
86/05/19	M	190		2455
86/05/19	M	218		2456
86/05/19	M	230		2457
86/05/19	M	225		2458
86/05/19	F	282		2459
86/05/19	M	245		2460
86/05/19	M	210		2461
86/05/19	M	238		2462
86/05/19	M	213		2463
86/05/19	M	207		2464
86/05/19	M	240		2465
86/05/19	M	204		2466
86/05/19	M	206		2467

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	250		2468
86/05/19	M	204		2469
86/05/19	M	218		2470
86/05/19	M	214		2471
86/05/19	M	204		2472
86/05/19	M	235	719	2473
86/05/19	F	210		2474
86/05/19	F	228		2475
86/05/19	F	268		2476
86/05/19	M	242		2477
86/05/19	M	230		2478
86/05/19	F	238		2479
86/05/19	F	258		2480
86/05/19	F	228		2481
86/05/19	M	240		2482
86/05/19	M	223		2483
86/05/19	M	215		2484
86/05/19	F	290		2485
86/05/19	M	216		2486
86/05/19	F	240		2487
86/05/19	F	237		2488
86/05/19	F	227		2489
86/05/19	F	225		2490
86/05/19	M	218		2491
86/05/19	F	220		2492
86/05/19	M	198		2493
86/05/19	F	216		2494
86/05/19	M	206		2495
86/05/19	M	248		2496
86/05/19	M	212		2497
86/05/19	F	252		2498
86/05/19	F	232		2499
86/05/19	F	236		2500
86/05/19	M	258		2501
86/05/19	M	235		2502
86/05/19	F	225		2503
86/05/19	M	247		2504
86/05/19	F	208		2505
86/05/19	M	245		2506
86/05/19	M	235		2507
86/05/19	M	281		2508
86/05/19	M	252		2509
86/05/19		228		2510

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove **Creek** culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	M	241		2511
86/05/19	M	232		2512
86/05/19	F	263		2513
86/05/19	M	234		2514
86/05/19	M	244		2515
86/05/19	M	248		2516
86/05/19	M	265		2517
86/05/19	M	243		2518
86/05/19	M	211		2519
86/05/19	M	239		2520
86/05/19	M	232		2521
86/05/19		216		2522
86/05/19	F	221		2523
86/05/19	M	238		2524
86/05/19	F	273		2525
86/05/19	M	242		2526
86/05/19	F	251		2527
86/05/19	F	215		2528
86/05/19	F	234		2529
86/05/19	M	229		2530
86/05/19		209		2531
86/05/19	F	244		2532
86/05/19		207		2533
86/05/19		198		2534
86/05/19	M	217		2535
86/05/19	F	218		2536
86/05/19	F	237		2537
86/05/19	F	231	450	2538
86/05/19	F	216		2539
86/05/19	M	218		2540
86/05/19		195		2541
86/05/19		209		2542
86/05/19	M	218		2543
86/05/19	F	235		2544
86/05/19	M	226		2545
86/05/19	F	238		2546
86/05/19	F	251		2547
86/05/19	M	226		2548
86/05/19	F	222		2549
86/05/19	F	239		2550
86/05/19		206		2551
86/05/19	F	265		2552
86/05/19	F	221		2553

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	232		2554
86/05/19	F	216		2555
86/05/19		208		2556
86/05/19	F	231	413	2557
86/05/19	M	252		2558
86/05/19	M	295		2559
86/05/19	M	218		2560
86/05/19	M	228		2561
86/05/19	F	268	343	2562
86/05/19	M	272		2563
86/05/19	M	269		2564
86/05/19		214		2565
86/05/19	M	214		2566
86/05/19	M	243		2567
86/05/19	F	231		2568
86/05/19		211		2569
86/05/19	F	247		2570
86/05/19	F	208		2571
86/05/19	F	261		2572
86/05/19	M	254		2573
86/05/19	F	240		2574
86/05/19	F	216		2575
86/05/19	F	254		2576
86/05/19	M	237		2577
86/05/19	M	216		2578
86/05/19	F	265		2579
86/05/19	F	255		2580
86/05/19	F	216		2581
86/05/19	M	235		2582
86/05/19	F	281	520	2583
86/05/19	F	215		2584
86/05/19	F	224		2585
86/05/19		204		2586
86/05/19	F	228		2587
86/05/19	M	221		2588
86/05/19	M	238		2589
86/05/19	M	228		2590
86/05/19	M	226		2591
86/05/19	F	221		2592
86/05/19	F	257		2593
86/05/19	M	247		2594
86/05/19	M	256		2595
86/05/19	M	238		2596

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/19	F	215		2597
86/05/19	F	254		2598
86/05/19	F	252		2600
86/05/19	M	229		2601
86/05/19	M	273		2602
86/05/19	M	212		2603
86/05/19	F	237		2604
86/05/19	F	229		2605
86/05/19	F	214		2606
86/05/19	F	219		2607
86/05/19	M	209		2608
86/05/19	F	220		2609
86/05/19	M	218		2610
86/05/19	F	232		2611
86/05/19	F	217		2612
86/05/19	F	235		2613
86/05/19	F	215		2614
86/05/19	F	208		2615
86/05/19	F	280		2616
86/05/19	M	262		2617
86/05/19	F	257		2618
86/05/19	F	335		2619
86/05/19	M	249		2620
86/05/19	F	261		2699
86/05/19	F	238		3072
86/05/20	M	229		2621
86/05/20	M	238		2622
86/05/20	M	237		2623
86/05/20	F	250		2624
86/05/20	F	218		2625
86/05/20	F	222		2626
86/05/20	F	221		2627
86/05/20	M	245		2628
86/05/20	F	234		2629
86/05/20	F	220		2630
86/05/20	M	220		2631
86/05/20	F	225	193	2632
86/05/20	F	298		2633
86/05/20	F	244		2634
86/05/20	M	245		2635
86/05/20	F	259		2636
86/05/20	F	254		2637
86/05/20	F	238		2638

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	F	243		2639
86/05/20	M	233		2640
86/05/20	F	207		2641
86/05/20	M	217		2642
86/05/20	M	212		2643
86/05/20	F	248		2644
86/05/20	M	206		2645
86/05/20	M	245		2646
86/05/20	M	236		2647
86/05/20	F	228		2648
86/05/20	F	226		2649
86/05/20	M	241		2650
86/05/20	F	221		2651
86/05/20	F	246		2652
86/05/20	M	233		2653
86/05/20	M	214		2654
86/05/20	F	232		2655
86/05/20	F	249		2656
86/05/20	F	222		2657
86/05/20	F	221		2658
86/05/20	F	204		2659
86/05/20	M	225		2660
86/05/20	M	211		2661
86/05/20	M	208		2662
86/05/20	M	189		2663
86/05/20	M	222		2664
86/05/20	M	208		2665
86/05/20	M	234	555	2666
86/05/20	M	265	227	2667
86/05/20	M	246		2668
86/05/20	F	220		2669
86/05/20	F	263		2670
86/05/20	F	257		2671
86/05/20	M	325	699	2672
86/05/20	F	249		2673
86/05/20	F	275	501	2674
86/05/20	F	282		2675
86/05/20	M	218		2676
86/05/20	F	210		2677
86/05/20	F	234		2678
86/05/20	F	217		2679
86/05/20	M	230		2680
86/05/20	F	217		2681

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20		199		2682
86/05/20	F	227		2683
86/05/20	F	232		2684
86/05/20	M	257		2685
86/05/20	F	206		2686
86/05/20	F	217		2687
86/05/20	F	222		2688
86/05/20	M	224		2689
86/05/20	F	209		2690
86/05/20	F	252		2691
86/05/20	M	223		2692
86/05/20	F	227		2693
86/05/20	M	212		2694
86/05/20	F	264		2695
86/05/20	F	232		2696
86/05/20	M	262	586	2697
86/05/20	M	230		2698
86/05/20	M	212		2699
86/05/20	F	203		2700
86/05/20	F	213		2701
86/05/20	M	269		2702
86/05/20	F	236	448	2703
86/05/20	M	249		2704
86/05/20	F	213		2705
86/05/20	M	223		2706
86/05/20	F	215		2707
86/05/20	M	246		2708
86/05/20		176		2709
86/05/20	M	263		2710
86/05/20	M	220	340	2711
86/05/20	F	215	456	2712
86/05/20	F	223		2713
86/05/20	M	258		2714
86/05/20	F	225		2715
86/05/20	M	265		2716
86/05/20	M	230		2717
86/05/20	M	233		2718
86/05/20	M	233		2719
86/05/20	M	216	762	2720
86/05/20	M	209		2721
86/05/20	F	232		2722
86/05/20	F	209		2723
86/05/20	F	204		2724

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	F	217		2725
86/05/20	F	231		2726
86/05/20	F	259		2727
86/05/20	M	212		2728
86/05/20	F	233		2729
86/05/20	F	242		2730
86/05/20	F	225		2731
86/05/20	M	218		2732
86/05/20	M	225		2733
86/05/20	F	211		2734
86/05/20	M	253		2736
86/05/20	M	224		2737
86/05/20	M	229		2738
86/05/20	M	217		2739
86/05/20	M	215		2740
86/05/20	M	239		2741
86/05/20	F	207		2742
86/05/20	F	200		2743
86/05/20	M	258		2744
86/05/20	F	209		2745
86/05/20	M	210		2746
86/05/20	M	218		2747
86/05/20	M	223		2748
86/05/20	F	228		2749
86/05/20	M	240		2750
86/05/20	M	214		2751
86/05/20	M	266	415	2752
86/05/20	F	247		2753
86/05/20	F	208		2754
86/05/20	M	224		2755
86/05/20	F	208		2756
86/05/20	F	233		2757
86/05/20	F	217		2758
86/05/20	F	245		2759
86/05/20	F	220		2760
86/05/20	M	238		2761
86/05/20	F	245		2762
86/05/20	M	248		2763
86/05/20	M	210		2764
86/05/20	M	224		2765
86/05/20	F	201		2766
86/05/20	M	261		2767
86/05/20	F	215		2768

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	M	232		2769
86/05/20	M	250		2770
86/05/20	M	234		2771
86/05/20	M	241		2772
86/05/20	M	222		2773
86/05/20	M	255	303	2774
86/05/20	F	235		2775
86/05/20	M	253		2776
86/05/20	F	215		2777
86/05/20	F	261		2778
86/05/20	F	203		2779
86/05/20	M	239	379	2780
86/05/20	F	200		2781
86/05/20	F	222		2782
86/05/20	F	233		2783
86/05/20	F	218		2784
86/05/20	M	229		2785
86/05/20	M	238		2786
86/05/20	F	238		2787
86/05/20	F	228		2788
86/05/20	M	214		2789
86/05/20	M	257		2790
86/05/20	F	206		2791
86/05/20	F	232		2792
86/05/20	M	247		2793
86/05/20	M	217		2794
86/05/20	F	247		2795
86/05/20	M	208		2796
86/05/20	F	244		2797
86/05/20	F	207		2798
86/05/20	M	239		2799
86/05/20	F	228		2800
86/05/20	M	272		2801
86/05/20	M	216		2802
86/05/20	F	211		2803
86/05/20	F	279		2804
86/05/20	F	218		2805
86/05/20	M	247		2806
86/05/20	M	225		2807
86/05/20	M	215	584	2808
86/05/20	M	224	066	2809
86/05/20	F	248		2810
86/05/20	F	223		2811

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	F	239	408	2812
86/05/20	F	203		2813
86/05/20	F	205		2814
86/05/20	M	228		2815
86/05/20	F	206		2816
86/05/20	M	220		2817
86/05/20	M	219		2818
86/05/20	M	238		2819
86/05/20	F	217		2820
86/05/20	M	256		2821
86/05/20	M	253		2822
86/05/20	F	215		2823
86/05/20	M	228		2824
86/05/20	M	225		2825
86/05/20	F	200		2826
86/05/20	M	201		2827
86/05/20	M	228		2828
86/05/20	M	241		2829
86/05/20	M	262		2830
86/05/20	M	237		2831
86/05/20	F	206		2832
86/05/20	M	215		2833
86/05/20	M	214		2834
86/05/20	M	213		2835
86/05/20	F	233		2836
86/05/20	M	255		2837
86/05/20	M	223		2838
86/05/20	M	264		2839
86/05/20	M	250		2840
86/05/20	F	234		2841
86/05/20	F	207		2842
86/05/20	F	218		2843
86/05/20	M	229		2844
86/05/20	M	223		2845
86/05/20	M	251		2846
86/05/20	F	215		2847
86/05/20	M	224		2848
86/05/20	F	205		2849
86/05/20	M	218		2850
86/05/20	F	230		2851
86/05/20	F	213		2852
86/05/20	M	271	213	2853
86/05/20	M	240		2854

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	M	223		2855
86/05/20	F	207		2856
86/05/20	M	222		2857
86/05/20	M	224		2858
86/05/20	M	213		2859
86/05/20	M	225		2860
86/05/20	F	208		2861
86/05/20	F	204		2862
86/05/20		221		2863
86/05/20	M	218		2864
86/05/20	M	238		2865
86/05/20	M	233		2866
86/05/20	M	234		2867
86/05/20	M	218		2868
86/05/20	M	218		2869
86/05/20	F	227		2870
86/05/20	F	215		2871
86/05/20	M	289		2872
86/05/20	F	206		2873
86/05/20	M	240		2874
86/05/20	M	223		2875
86/05/20	M	245		2876
86/05/20	F	210		2877
86/05/20	M	263		2878
86/05/20	F	213		2879
86/05/20	M	262		2880
86/05/20	M	218		2881
86/05/20	F	230		2882
86/05/20	F	200		2883
86/05/20	M	310		2884
86/05/20	F	240		2885
86/05/20	F	233		2886
86/05/20	F	216		2887
86/05/20	M	249		2888
86/05/20	M	261		2889
86/05/20	F	221		2890
86/05/20	M	214	640	2891
86/05/20	M	227		2892
86/05/20	M	220		2893
86/05/20	M	216		2894
86/05/20	M	312		2895
86/05/20	M	230		2896
86/05/20	M	225	027	2897

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	M	245		2898
86/05/20		210		2899
86/05/20	M	242		2900
86/05/20	M	237		2901
86/05/20	F	248		2902
86/05/20	F	240		2903
86/05/20	M	243		2904
86/05/20	F	286		2905
86/05/20	M	244		2906
86/05/20	M	229		2907
86/05/20	M	249	390	2908
86/05/20	M	208		2909
86/05/20	M	245		2910
86/05/20	F	217		2911
86/05/20	F	215		2912
86/05/20	F	220		2913
86/05/20	M	217		2914
86/05/20	F	278		2915
86/05/20	M	215		2916
86/05/20	M	232		2917
86/05/20	F	230		2918
86/05/20	F	245		2919
86/05/20	M	222		2920
86/05/20	M	218		2921
86/05/20	F	220		2922
86/05/20	F	242		2923
86/05/20	M	198		2924
86/05/20	M	210		2925
86/05/20	F	213		2926
86/05/20	F	229		2927
86/05/20	M	233		2928
86/05/20	F	194		2929
86/05/20	M	245		2930
86/05/20	M	200		2931
86/05/20	M	219		2932
86/05/20	M	241		2933
86/05/20	M	191		2934
86/05/20	F	260		2935
86/05/20	F	249		2936
86/05/20	M	186		2937
86/05/20	F	290		2938
86/05/20	F	201		2939
86/05/20	M	208		2940

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	F	230		2941
86/05/20	M	180		2942
86/05/20	F	238		2944
86/05/20	F	280		2945
86/05/20	M	212		2946
86/05/20	M	194		2947
86/05/20	M	226	404	2948
86/05/20	M	241		2949
86/05/20	M	260		2950
86/05/20	F	251		2951
86/05/20	M	228		2952
86/05/20	F	244		2953
86/05/20	M	265	095	2954
86/05/20	F	218		2955
86/05/20	M	297		2956
86/05/20	F	238		2957
86/05/20	M	242		2958
86/05/20	M	249	040	2960
86/05/20	F	268		2961
86/05/20	F	259		2962
86/05/20	M	218		2963
86/05/20	F	227		2964
86/05/20	F	228		2965
86/05/20	F	226		2966
86/05/20	M	187		2967
86/05/20	F	224		2968
86/05/20	F	214		2970
86/05/20	F	246		2971
86/05/20	M	215		2972
86/05/20	M	212		2973
86/05/20	F	249		2974
86/05/20	M	204		2975
86/05/20	M	204		2976
86/05/20	F	231	400	2977
86/05/20	F	278		2978
86/05/20	F	274	535	2979
86/05/20	M	294		2980
86/05/20	M	228		2981
86/05/20	M	247		2982
86/05/20	M	211		2983
86/05/20	F	254	431	2984
86/05/20	F	208		2985
86/05/20	M	252		2986

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	M	233		2987
86/05/20	M	200		2988
86/05/20	M	234		2989
86/05/20	M	238		2990
86/05/20	M	205		2991
86/05/20	F	222		2992
86/05/20	F	232		2993
86/05/20	M	214		2994
86/05/20	M	234		2995
86/05/20	M	209		2996
86/05/20	F	221		2997
86/05/20	M	265		2998
86/05/20	M	208		2999
86/05/20	F	220		3000
86/05/20	F	251		3969
86/05/20	F	224		4001
86/05/20	F	183		4002
86/05/20	F	216		4003
86/05/20	M	221		4004
86/05/20	M	216		4005
86/05/20	M	220		4006
86/05/20	F	221		4007
86/05/20	F	250		4008
86/05/20	M	206		4009
86/05/20	M	233		4010
86/05/20	F	246		4011
86/05/20	M	234		4012
86/05/20	F	240		4013
86/05/20	M	217		4014
86/05/20	F	231		4015
86/05/20	F	249		4016
86/05/20	F	218		4017
86/05/20	F	253		4018
86/05/20	M	241		4019
86/05/20	F	240		4020
86/05/20	F	204		4021
86/05/20	F	253		4022
86/05/20	F	210		4023
86/05/20	F	217		4024
86/05/20	F	224		4025
86/05/20	F	227		4026
86/05/20	F	266		4027
86/05/20	F	231		4028

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	M	236		4029
86/05/20	F	262		4030
86/05/20	M	239		4031
86/05/20	M	227		4032
86/05/20	M	279		4033
86/05/20	F	245		4034
86/05/20	M	245	419	4035
86/05/20	M	224		4036
86/05/20	F	196		4037
86/05/20	F	214	743	4038
86/05/20	F	211		4039
86/05/20	F	245		4040
86/05/20	M	231		4041
86/05/20	F	204		4042
86/05/20	F	196		4043
86/05/20	F	210		4044
86/05/20	F	246		4045
86/05/20	M	223		4046
86/05/20	F	224		4047
86/05/20	F	237		4048
86/05/20	M	240	545	4049
86/05/20	M	240		4050
86/05/20	M	220		4051
86/05/20	M	217		4052
86/05/20	F	216		4053
86/05/20	F	230		4054
86/05/20	F	229		4055
86/05/20	F	231		4056
86/05/20	M	247		4057
86/05/20	F	192		4058
86/05/20	F	210		4059
86/05/20	F	263		4060
86/05/20	M	226		4061
86/05/20	F	232		4062
86/05/20	F	244		4063
86/05/20	F	208		4064
86/05/20	F	203		4065
86/05/20	M	236		4066
86/05/20	F	203		4067
86/05/20	F	222		4068
86/05/20	F	218		4069
86/05/20	F	217		4070
86/05/20	F	251		4071

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	M	205		4072
86/05/20	M	218		4073
86/05/20	F	215		4074
86/05/20	F	235		4075
86/05/20	M	248		4076
86/05/20	F	231		4077
86/05/20	F	234		4078
86/05/20	M	230		4079
86/05/20	M	240		4080
86/05/20	F	243		4081
86/05/20	M	218		4082
86/05/20	F	231		4083
86/05/20	F	214		4084
86/05/20	M	230		4085
86/05/20	F	213		4086
86/05/20	F	235		4087
86/05/20	F	232		4088
86/05/20	M	215	363	4089
86/05/20	F	208		4090
86/05/20	F	233		4091
86/05/20	M	217		4092
86/05/20	M	253		4093
86/05/20	M	218		4094
86/05/20	F	209		4095
86/05/20	M	289		4096
86/05/20	M	254		4097
86/05/20	F	222		4098
86/05/20	M	249		4099
86/05/20	F	215		4100
86/05/20	M	298	837	4101
86/05/20	M	230		4102
86/05/20	M	261		4103
86/05/20	M	230		4104
86/05/20	M	202		4105
86/05/20	M	218		4106
86/05/20	F	217		4107
86/05/20	M	225		4108
86/05/20	M	212		4109
86/05/20	F	267		4110
86/05/20	M	254		4111
86/05/20	M	227		4112
86/05/20	M	232		4113
86/05/20	M	231		4114

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	M	219		4115
86/05/20	M	209		4116
86/05/20	F	213		4117
86/05/20	F	231		4118
86/05/20	M	247		4119
86/05/20	M	206		4120
86/05/20	F	232		4121
86/05/20	M	235		4122
86/05/20	M	246		4123
86/05/20	F	230		4124
86/05/20	F	257		4125
86/05/20	M	206		4126
86/05/20	M	259		4127
86/05/20	M	235		4128
86/05/20	F	201		4129
86/05/20	F	205		4130
86/05/20	M	251		4132
86/05/20	M	204		4133
86/05/20	M	242		4134
86/05/20	M	233		4135
86/05/20	F	231		4136
86/05/20	F	228		4137
86/05/20	M	234		4138
86/05/20	F	207		4139
86/05/20	M	231		4140
86/05/20	M	225		4141
86/05/20	M	208		4142
86/05/20	M	227		4143
86/05/20	F	211		4144
86/05/20	M	248		4145
86/05/20	M	233		4146
86/05/20	M	221		4147
86/05/20	M	248		4148
86/05/20	M	210		4149
86/05/20	F	251		4150
86/05/20	M	244		4151
86/05/20	M	218		4152
86/05/20	M	221		4153
86/05/20	M	218		4154
86/05/20	M	213		4155
86/05/20	F	241		4156
86/05/20	F	201		4157
86/05/20	M	243		4158

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	M	213		4159
86/05/20	F	219		4160
86/05/20	M	251		4161
86/05/20	M	223		4162
86/05/20	M	211		4163
86/05/20	F	213		4164
86/05/20	M	221		4165
86/05/20	F	202		4166
86/05/20	M	223		4167
86/05/20	F	252		4168
86/05/20	F	216		4169
86/05/20	F	223		4170
86/05/20	M	208		4171
86/05/20	M	232		4172
86/05/20	M	222		4173
86/05/20	M	240		4174
86/05/20	M	212		4175
86/05/20	F	214		4176
86/05/20	M	200		4177
86/05/20	F	202		4178
86/05/20	F	233		4179
86/05/20	M	202		4180
86/05/20	M	212		4181
86/05/20	F	222		4182
86/05/20	F	228		4183
86/05/20	F	239		4184
86/05/20	F	241		4185
86/05/20	F	218		4186
86/05/20	F	221		4187
86/05/20	F	213		4188
86/05/20	F	240	578	4189
86/05/20	M	238		4190
86/05/20	M	219		4191
86/05/20	F	222		4192
86/05/20	M	270		4193
86/05/20	M	228		4194
86/05/20	M	224		4195
86/05/20	M	224		4196
86/05/20	M	229		4197
86/05/20	M	252		4198
86/05/20	M	221		4199
86/05/20	F	242		4200
86/05/20	M	264		4201

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	F	232		4202
86/05/20	M	210		4203
86/05/20	M	218		4204
86/05/20	F	215		4205
86/05/20	M	218		4206
86/05/20	M	245		4207
86/05/20	M	247		4208
86/05/20	M	222		4209
86/05/20	M	224	320	4210
86/05/20	F	209		4211
86/05/20	F	215		4212
86/05/20	M	208		4213
86/05/20	F	233		4214
86/05/20	M	225		4215
86/05/20	M	218		4216
86/05/20	M	217	281	4217
86/05/20	F	227		4218
86/05/20	F	237		4219
86/05/20	M	218		4220
86/05/20	F	212		4221
86/05/20	F	212		4222
86/05/20	F	211		4223
86/05/20	F	204		4224
86/05/20	F	206		4225
86/05/20	M	223	038	4226
86/05/20	M	238		4227
86/05/20	M	269		4228
86/05/20	M	245		4229
86/05/20	M	226		4230
86/05/20	M	286		4231
86/05/20	M	231		4232
86/05/20	M	225		4233
86/05/20	M	234	581	4234
86/05/20	F	258		4235
86/05/20	M	223		4236
86/05/20	F	251		4237
86/05/20	M	236		4238
86/05/20	F	230		4239
86/05/20	M	222		4240
86/05/20	M	244		4241
86/05/20	M	232		4242
86/05/20	M	225		4243
86/05/20	M	220		4244

APPENDIX TABLE 1. Length frequencies of Arctic grayling that successfully ascended Poplar Grove Creek culvert, May 1986.

DATE	SEX	LENGTH (mm)	OLD TAG#	NEW TAG#
86/05/20	F	223		4245
86/05/20	F	220		4246
86/05/20	M	215		4247
86/05/20	M	217		4248
86/05/20	M	225		4249
86/05/20	M	210		4250

APPENDIX TABLE 2

POPLAR GROVE CREEK - 1986
ARCTIC GRAYLING MIGRATION TIMING
Mouth to McPhee and Watts (Lower Weir)

TAG #	Length(mm)	Sex	TLOC	RLOC	ELAPSE (hrs.)
56	248	X	M	M&W	25.6
60	267	X	M	M&W	25.2
24	301	X	M	M&W	24.3
61	218	X	M	M&W	25.0
2	252	M	M	M&W	49.6
29	226	M	M	M&W	25.9
43	284	M	M	M&W	25.3
15	283	M	M	M&W	25.8
65	250	M	M	M&W	23.9
95	265	M	M	M&W	46.5

AVG. Length - All Sexes Combined = 259.4 mm
Std. Deviation (Length) = 24.66 mm
AVG. Elapsed Time - All Sexes Combined = 29.71 hrs.
Std. Deviation (Time) = 9.215 hrs.
N = 10

AVG. Length - Male = 260.0 mm
Std. Deviation (Length) = 20.2 mm
AVG. Elapsed Time (Male) = 32.83 hrs.
Std. Deviation (Time) = 10.81 hrs.
N = 6

AVG. Length - Unknown Sex = 258.5 mm
Std. Deviation (Length) = 30.12 mm
AVG. Elapsed Time (Unknown) = 25.02 hrs.
Std. Deviation (Time) = 0.47 hrs.
N = 4

LEGEND KEY

TLOC = Tagging Location
RLOC = Tag Recovery Location
M = Mouth (70 yrds. upstream of Gulkana River junctio
M&W = MacPhee and Watts (Lower Weir)
X = Unknown Sex

APPENDIX TABLE 3

POPLAR GROVE CREEK - 1986
ARCTIC GRAYLING MIGRATION TIMING
Mouth to Upper Weir

TAG #	Length(mm)	Sex	TLOC	RLOC	ELAPSE (hrs.)
82	211	X	M	UW	95.8
78	288	X	M	UW	94.8
17	271	X	M	UW	98.3
25	225	X	M	UW	120.7
38	223	M	M	UW	120.0
66	224	M	M	UW	144.0
23	228	M	M	UW	97.2
22	267	M	M	UW	120.0
40	249	M	M	UW	144.0
27	225	M	M	UW	144.0
62	247	M	M	UW	120.0
77	232	M	M	UW	120.0
48	313	F	M	UW	96.9
14	215	F	M	UW	120.0
72	242	F	M	UW	120.0
39	301	F	M	UW	96.3
16	234	F	M	UW	96.0

AVG. Length - All Sexes Combined = 246.76 mm
Std. Deviation (Length) = 29.80 mm
AVG. Elapsed Time (Combined Sexes) = 114.58 hrs.
Std. Deviation (Time) = 17.34 hrs.
N = 17

AVG. Length - Female = 261.0 mm
Std. Deviation (Length) = 38.75 mm
AVG. Elapsed Time (Female) = 105.8 hrs.
Std. Deviation (Time) = 11.56 hrs.
N = 5

AVG. Length - Male = 236.8 mm
Std. Deviation (Length) = 14.82 mm
AVG. Elapsed Time (Male) = 126.1 hrs.
Std. Deviation (Time) = 15.59 hrs.
N = 8

AVG. Length - Unknown Sex = 248.7 mm
Std. Deviation (Length) = 31.72 mm
AVG. Elapsed Time (Unknown) = 102.4 hrs.
Std. Deviation (Time) = 10.64 hrs.
N = 4

LEGEND KEY

TLOC = Tagging Location
RLOC = Tag Recovery Location
UW = Upper Weir
M = Mouth (70 yrds. above Gulkana River junction)
X = Unknown Sex

APPENDIX TABLE 4

POPLAR GROVE CREEK - 1986
ARCTIC GRAYLING MIGRATION TIMING
McPhee and Watts (Lower Weir) to Upper Weir

TAG #	Length(mm)	Sex	TLOC	RLOC	ELAPSE (hrs.)
369	244	X	M&W	UW	74.1
269	281	X	M&W	UW	70.6
338	274	X	M&W	UW	74.4
195	220	X	M&W	UW	90.3
745	213	X	M&W	UW	95.7
440	205	X	M&W	UW	119.0
777	255	X	M&W	UW	71.3
668	222	X	M&W	UW	96.5
509	254	X	M&W	UW	76.7
490	275	X	M&W	UW	73.0
222	268	X	M&W	UW	71.6
579	219	X	M&W	UW	73.3
142	265	X	M&W	UW	72.4
570	257	X	M&W	UW	51.9
518	268	X	M&W	UW	74.2
361	248	M	M&W	UW	96.0
497	226	M	M&W	UW	96.0
167	275	M	M&W	UW	75.4
744	271	M	M&W	UW	72.0
404	226	M	M&W	UW	120.0
237	262	M	M&W	UW	96.0
185	274	M	M&W	UW	73.7
738	240	M	M&W	UW	72.0
473	247	M	M&W	UW	96.0
213	271	M	M&W	UW	120.0
581	234	M	M&W	UW	96.0
301	264	M	M&W	UW	96.0
415	266	M	M&W	UW	120.0
158	257	M	M&W	UW	73.9
659	230	M	M&W	UW	72.0
317	230	M	M&W	UW	96.0
419	245	M	M&W	UW	120.0
199	261	M	M&W	UW	73.5
584	215	M	M&W	UW	96.0
719	235	M	M&W	UW	72.0
422	253	M	M&W	UW	96.0
303	255	M	M&W	UW	120.0
586	262	M	M&W	UW	96.0
613	265	M	M&W	UW	72.0
436	240	M	M&W	UW	96.0
363	215	M	M&W	UW	120.0
596	260	M	M&W	UW	72.0
379	239	M	M&W	UW	120.0

414	224	M	M&W	UW	96.0
390	249	M	M&W	UW	120.0
156	247	M	M&W	UW	74.2
403	292	M	M&W	UW	96.0
651	255	M	M&W	UW	72.0
227	265	M	M&W	UW	120.0
393	254	M	M&W	UW	96.0
536	236	M	M&W	UW	72.0
418	249	M	M&W	UW	96.0
724	310	M	M&W	UW	72.0
640	214	M	M&W	UW	96.0
722	243	M	M&W	UW	72.0
340	220	M	M&W	UW	120.0
699	225	M	M&W	UW	96.0
127	289	M	M&W	UW	76.6
281	217	M	M&W	UW	120.0
639	265	M	M&W	UW	72.0
207	263	M	M&W	UW	96.0
157	236	M	M&W	UW	75.0
477	253	M	M&W	UW	96.0
638	235	M	M&W	UW	72.0
545	240	M	M&W	UW	96.0
796	235	M	M&W	UW	72.0
561	235	M	M&W	UW	51.0
625	231	M	M&W	UW	73.0
320	224	M	M&W	UW	120.0
607	240	M	M&W	UW	72.0
555	234	M	M&W	UW	96.0
762	216	M	M&W	UW	96.0
573	240	M	M&W	UW	72.0
493	267	M	M&W	UW	96.0
456	215	F	M&W	UW	120.0
575	277	F	M&W	UW	72.0
214	232	F	M&W	UW	96.0
672	250	F	M&W	UW	72.0
247	249	F	M&W	UW	96.0
262	242	F	M&W	UW	96.0
603	263	F	M&W	UW	72.0
558	261	F	M&W	UW	72.0
163	247	F	M&W	UW	96.0
345	237	F	M&W	UW	73.7
448	236	F	M&W	UW	120.0
341	254	F	M&W	UW	96.0
468	275	F	M&W	UW	96.0
343	268	F	M&W	UW	96.0
357	273	F	M&W	UW	96.0
550	245	F	M&W	UW	72.0
374	294	F	M&W	UW	96.0
383	248	F	M&W	UW	96.0

420	260	F	M&W	UW	96.0
544	267	F	M&W	UW	72.0
408	239	F	M&W	UW	120.0
116	257	F	M&W	UW	96.0
455	243	F	M&W	UW	96.0
298	229	F	M&W	UW	96.0
413	231	F	M&W	UW	96.0
535	274	F	M&W	UW	96.0
578	240	F	M&W	UW	96.0
279	218	F	M&W	UW	96.0
183	306	F	M&W	UW	72.0
524	271	F	M&W	UW	72.0
637	251	F	M&W	UW	72.0
743	214	F	M&W	UW	96.0
475	248	F	M&W	UW	96.0
520	281	F	M&W	UW	72.0
643	290	F	M&W	UW	72.0
248	267	F	M&W	UW	96.0
450	231	F	M&W	UW	96.0
519	246	F	M&W	UW	72.0
661	256	F	M&W	UW	72.0
502	272	F	M&W	UW	72.0
400	231	F	M&W	UW	120.0
192	235	F	M&W	UW	75.6
485	265	F	M&W	UW	96.0
747	239	F	M&W	UW	72.0
648	259	F	M&W	UW	72.0
501	275	F	M&W	UW	96.0
667	268	F	M&W	UW	72.0
193	225	F	M&W	UW	96.0
431	254	F	M&W	UW	120.0
626	295	F	M&W	UW	72.0
583	243	F	M&W	UW	72.0
177	284	F	M&W	UW	96.0
760	243	F	M&W	UW	72.0

AVG. Length - All Sexes Combined = 250.0 mm
Std. Deviation (Length) = 21.4 mm
AVG. Elapsed Time (Combined Sexes) = 88.54 hrs.
Std. Deviation (Time) = 17.14 hrs.
N = 127

AVG. Length - Female = 254.2 mm
Std. Deviation (Length) = 20.89 mm
AVG. Elapsed Time (Female) = 88.4 hrs.
Std. Deviation (Time) = 15.2 hrs.
N = 53

AVG. Length - Male = 246.9 mm
Std. Deviation (Length) = 20.31 mm
AVG. Elapsed Time (Male) = 91.08 hrs.
Std. Deviation (Time) = 18.36 hrs.
N = 59

AVG. Length - Unknown Sex = 248.0 mm
Std. Deviation (Length) = 24.68 mm
AVG. Elapsed Time (Unknown) = 79.0 hrs.
Std. Deviation (Time) = 15.09 hrs.
N = 15

LEGEND KEY

TLOC = Tagging Location
RLOC = Tag Recovery Location
UW = Upper Weir
M&W = MacPhee and Watts (Lower Weir)
X = Unknown Sex

APPENDIX TABLE 5

POPLAR GROVE CREEK - 1986
ARCTIC GRAYLING MIGRATION TIMING
McPhee and Watts (Lower Weir) to Culvert Scour Pool

TAG #	Length(mm)	Sex	TLOC	RLOC	ELAPSE (hrs.)
444	260	X	M&W	SP	67.0
111	324	X	M&W	SP	48.9
277	299	X	M&W	SP	46.0

AVG. Length - All Sexes Combined = 294.3 mm
Std. Deviation (Length) = 26.33 mm
AVG. Elapsed Time - All Sexes Combined = 53.96 hrs.
Std. Deviation (Time) = 9.29 hrs.
N = 3

LEGEND KEY

TLOC = Tagging Location
RLOC = Tag Recovery Location
SP = Culvert Scour Pool
M&W = MacPhee and Watts (Lower Weir)
X = Unknown Sex

APPENDIX TABLE 6

POPLAR GROVE CREEK - 1986
ARCTIC GRAYLING MIGRATION TIMING
Culvert Scour Pool to Upper Weir

TAG #	Length(mm)	Sex	TLOC	RLOC	ELAPSE (hrs.)
820	285	F	SP	UW	27.3
837	298	M	SP	UW	72.0
814	249	M	SP	UW	48.0
808	259	M	SP	UW	23.8
846	269	M	SP	UW	48.0
844	260	X	SP	UW	22.0
828	255	X	SP	UW	24.3

AVG. Length - All Sexes Combined = 267.8 mm
Std. Deviation (Length) = 16.32 mm
AVG. Elapsed Time - All Sexes Combined = 37.91 hrs.
Std. Deviation (Time) = 17.38 hrs.
N = 7

AVG. Length - Female = 285.0 mm (single measurement)
Std. Deviation (Length) = N/A
AVG. Elapsed Time (Female) = 27.3 hrs. (single measurement)
Std. Deviation (Time) = N/A
N = 1

AVG. Length - Male = 268.7 mm
Std. Deviation (Length) = 18.3 mm
AVG. Elapsed Time (Male) = 47.95 hrs.
Std. Deviation (Time) = 17.04 hrs.
N = 4

AVG. Length - Unknown Sex = 257.5 mm
Std. Deviation (Length) = 2.5 mm
AVG. Elapsed Time (Unknown) = 23.15 hrs.
Std. Deviation (Time) = 1.15 hrs.
N = 2

LEGEND KEY

TLOC = Tagging Location
RLOC = Tag Recovery Location
SP = Culvert Scour Pool
UW = Upper Weir
X = Unknown Sex