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Final Report:

Fish Passage Through Retrofitted Culverts

Fish Passage Research Project

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INTRODUCTION

Culverts and road crossings potentially create barriers that restrict or prevent movement and migration of all life stages of resident and anadromous fish. Increased flow velocities, shallow water depths, increased turbulence, and perched outlets are all problems that may restrict fish movement through culverts (Fitch 1995). These barriers impact both resident and anadromous fish populations by preventing movement at critical life stages and blocking access to critical habitats, potentially affecting genetic diversity and long-term survival of some species.

Fish movement and migration in streams vary greatly by species and depend on the life stage of the fish (Groot and Margolis 1991). Movement of anadromous juvenile salmonids and resident adult cutthroat in coastal streams is poorly documented. In a study on Carnation Creek, researchers trapped juvenile coho salmon and steelhead trout at the mouth of a tributary. Upstream movements occurred predominantly in November and December and downstream movements occurred from February through May. Most of the movements were associated with high flows and water temperatures above 6°C (Bustard and Narver 1975). The extent of juvenile salmonids movements was not measured in this study, and in general is poorly understood. A study of a small coastal stream by Heggenes et al. (1991) found that the majority of the cutthroat trout population was static and resided within a home range of less than 22 m. They also found that a small fraction (17.9%) of the population was more mobile and moved more than 50 m, with some individuals moving more than 300 m upstream and downstream. This movement was stable during winter, spring, and summer. These studies indicate that juvenile and resident adult trout are active throughout the year moving up and downstream in response to a number of environmental factors.

If the benefits of moving to one or more new habitats outweigh the energetic costs of movement and the risk of predation, life history types that move should be favored (Gross et al. 1988). Resident stream fishes may increase their fitness by moving to find habitat needed to complete certain life history stages or to search for optimum habitat as present locations become unsuitable (Fausch 1995). In small headwater streams where populations are often "sinks", movement is required to drive metapopulation dynamics and even modest migration may promote persistence (Fausch 1995). Some possible reasons for juvenile salmonid movement upstream are to find suitable over-winter areas in smaller tributaries with milder conditions, disperse from areas of high population density, or escape predators that are more prevalent in larger streams or rivers.

To navigate through their environment, fish use two muscle systems: red (aerobic) for longer-term, low intensity activities and white (anaerobic) for short, high-intensity activities (Allen 1999). Prolonged use of the white muscle system leaves a fish exhausted and requires a long period of rest (Webb and Weihs 1983). Fish use these muscles to achieve three different swimming speeds: cruising, sustained, and darting or burst. Cruising speeds can be maintained for extended periods of time, whereas sustained and darting/burst speeds can be performed for only minutes or seconds at a time, respectively (Bell 1986). Adult cutthroat trout have cruising, sustained, and darting speeds of about 0.9 m/s, 1.82 m/s, and 4.24 m/s. Adult steelhead trout (*Oncorhynchus* *mykiss*) are strong swimmers with cruising, sustained, and darting speeds of about 1.52 m/s, 4.24 m/s, and 7.88 m/s (Bell 1986). Information about the swimming ability of juvenile cutthroat and steelhead trout is not abundant, but the swimming abilities of juvenile coho salmon should be relatively similar. Juvenile wild and hatchery coho ranging in size from 40 to 70 mm had burst speeds that averaged 0.64 to 0.73 m/s with a maximum of 1.04 m/s (Powers 1997). Sustained swimming speed stamina was tested in tanks with a velocity of 0.37 m/s; fatigue times ranged from 17 to 28 min (Powers 1997). For most salmonid species, swimming ability is a function of body length (Jones et al. 1974, Bell 1986). White muscles are required to move past the culvert entrance (sustained or darting speed) to enter a culvert with a velocity or jump barrier, and red muscle groups would be used to swim through the remainder of the culvert length. If white muscles are required to swim the length of the culvert after entry, the fish may exhaust itself before successfully passing through longer culverts.

Culverts can create multiple problems that restrict the movement of salmonids upstream. In natural streams, boulders, logs, pools and riffles, meanders, and other sources of friction provide zones of low water velocities where fish can rest. Therefore, fish traverse only short distances through high velocities. In culverts, velocities are nearly uniform throughout their length and usually greater than in natural channels (Katopodis 1978). Fish must traverse long distances against high water velocities with no resting areas. Retrofitted culverts designed to create "hydraulic shadows" or low velocity areas where fish can rest before moving through the next high velocity zone.

Shallow water depths can also obstruct fish passage. This occurs when the culvert floor is wide and flat with no obstructions. Water disperses across the entire floor creating very shallow water depths, particular at low discharges. Retrofitted culverts increase the depth of flow through the culvert allowing easier passage for fish of all life stages.

The design of culverts in the past focused primarily on the diameter required to pass a high flow event of a given exceedance interval. In contrast, culverts designed for fish passage are based on water depth and velocity ranges that are passable by fish at high-flow and low-flow conditions (Klingeman 2000). These are determined from daily and seasonal flows for critical periods of fish passage, rather than from flood-peak frequencies. Most culverts have been designed for maximum hydraulic capacity rather than fish passage. Due to the significant capital investment in road networks and existing culverts, it is unlikely that every culvert that impairs fish passage will be removed and replaced with an adequate design. Thus, lower cost alternatives for making culverts passable for fish are attractive to resource managers (Wright 2000).

The term "culvert retrofit" is used to describe modifications placed in the existing culvert and/or the stream channel in an attempt to remedy fish passage barriers and improve fish passage. Culvert retrofits are typically much more economical than full culvert replacements (Wright 2000). Retrofits commonly used include baffles and weirs inside the culvert barrel. Baffles and weirs are normally transverse steel, concrete, or plastic linear elements installed in culverts to create hydraulic conditions suitable for fish passage over a range of flow levels (Wright 2000). Hydraulic performance characteristics have been related to laboratory determinations of swimming speeds and endurance capabilities of the fish species of concern for design purposes (McKinley and

Webb 1956, Shoemaker 1956, Katopodis and Rajaratnam 1991). There is little information on whether fish can move through these culverts outside of a laboratory and which baffle design is the most efficient at passing fish.

There have been few studies of juvenile and resident fish passage through culverts outside of the laboratory setting. Fitch (1995) looked at nonanadromous trout passage in culverts in Virginia. Due to small numbers of tagged fish, none of the fish were recaptured. Juvenile salmon swimming upstream in culverts use the low velocity zones located close to the culvert wall (Barber and Downs 1996). Apparently, roughness of the corrugated culvert wall provides a low velocity boundary zone where passage for these small fish is possible. Kane (2000) used minnow traps baited with salmon eggs to assess juvenile salmonid movement through four different culverts in Alaska. Only one culvert had baffles. They found that all age classes of juvenile coho salmon successfully passed upstream through a 90-m culvert with 13 baffles and velocities of up to 1.52 m/s. Kane concluded that food (salmon eggs) was sufficient incentive for upstream juvenile movement in Alaskan streams. This study also tracked the path of juvenile movement through the baffled culvert with underwater video cameras. They concluded that juvenile fish did not leap over the baffles but swam through a slot between the culvert wall and the end of the baffle. They concluded that slots may be an acceptable technique for improving juvenile fish passage in culverts with baffles. In each case, Kane (2000) concluded that juvenile fish look for the paths that minimize energy expenditure.

Total replacement of inadequate road crossings with a bridge or stream-simulated culvert is the most desirable solution, but not always financially or logistically possible. Retrofitting culverts with baffles and flow deflectors to make internal hydraulics more conducive to fish movement is a less expensive and less labor-intensive alternative. Although these retrofits are not long-term solutions, they potentially allow fish passage until it is financially and logistically possible to replace the existing culvert. While many of these problem culverts have already been retrofitted, the effectiveness of these interim retrofit approaches for improving fish passage has not been tested in the field.

This study was funded by the Oregon Department of Transportation (ODOT) and designed to assess the ability of fish to move through these retrofitted culverts in the field and to determine on the relative effectiveness of different retrofit designs. The tested designs included 90° baffle weirs and 30° and 45° angled baffles. These designs were the most common retrofit designs and covered a wide range of flow characteristics. The working hypothesis was that retrofitted culverts would not restrict the movement of juvenile trout through the culvert in either direction and there would be no difference between retrofit designs in their ability to pass juvenile trout.

METHODS

Two different studies were developed to determine juvenile cutthroat and steelhead trout movements through retrofitted culverts. A mark-recapture study documented long-term movement, and a controlled short-term movement study determined efficiency of different retrofit techniques. Seven culvert sites representing current retrofit techniques were selected for the fish tagging study. The small number of retrofitted culverts in the state prevented a replicated study of different designs in the field. A single culvert without retrofits was used as the basis for the short-term movement study. Culverts with factors such as a perched outlet, close proximity to a mainstem river, potential barriers to fish passage up or downstream and excessive length were not included.

Mark-Recapture Study of Long-term Movement

Culvert sites were selected based on experimental requirements. Culverts with confounding characteristics such as a perched outlet, close proximity to the mainstem river, potential barriers to fish passage up or downstream of the culvert, excessive length of culvert, etc. were eliminated as potential study sites. Perched outlets of greater than 12 inches would block most juvenile fish from entering the culvert and prevent assessment of the culvert retrofit. Culverts that were in close proximity (<100 yards) to the mainstem river could potentially lose large numbers of tagged fish. This would result in the recovery of a small number of tagged fish. Potential barriers to passage above or below the culvert, such as large falls, beaver dams, or unmodified culverts, may not provide and accurate representation of juvenile fish movement. Regardless of retrofits, long culverts (>100 ft) may impede fish movement due to the absence of light, while also imposing logistical research difficulties not found in small culverts.

Seven culverts that had been retrofitted previously by ODOT met the requirements of our study (i.e., presence of salmonids, appropriate habitat above and below the culvert, retrofitted culvert to improve fish passage). As a result, the seven study sites represented several retrofitting techniques, including steel baffles, racks, and weirs.

- Hough Creek, Lincoln County, Siletz River Basin, T9S, R10W, Sec 10
- Stemple Creek, Lincoln County, Siletz River Basin, T8S, R10W, Sec 36
- Little Lobster Creek, Benton County, Alsea River Basin, T15S, R8W, Sec 3
- Hayden Creek, Benton County, Alsea River Basin, T13S, R7W, Sec 38
- Alder Brook Creek, Lincoln County, Salmon River Basin, T6S, R10W, Sec 25
- Canyon Creek, Douglas County, Umpqua River Basin, T31S, R5W, Sec 2

The seven culverts selected for the long-term movement study represented a variety culvert designs and retrofit techniques. Baffles and weirs were the primary retrofit designs studied. Weirs are flow deflection structures that are perpendicular to the culvert sidewalls and span the entire width of the culvert. Baffles are similar to weirs except that they are set at a 30° or 45° angle to the culvert sidewalls and do not completely span the width of the culvert, leaving a gap along one sidewall. Descriptive characteristics of each culvert are reported in Table 1 followed by photographs and map locations of each culvert (Photo 1-7; Map 1-3).

Table 1: Characteristics of culverts used in field studies. Culvert types include reinforced concrete box culvert (RCBC), corrugated metal pipe culvert (CMP), and half corrugated metal pipe with a concrete floor (CMP-CF). Active channel width of the natural stream upstream and downstream of the culvert is represented by the acronym ACW.

	Little Lobster	Canyon #2	Canyon #3	Hough	Stemple	Hayden	Alder Brook
Basin	Alsea	Umpqua	Umpqua	Siletz	Siletz	Alsea	Salmon
Culvert type	RCBC	RCBC	CMP-CF	CMP	RCBC	RCBC	RCBC
Retrofit design	11 baffles	31 baffles	19 weirs	7 weirs	7 baffles	8 baffles	Rack
Length (m)	24.5	83	84	26.8	16.5	14.5	11.7
Width (m)	2.5	2.4	4.7	2.1	1.9	1.9	1.8
Height (m)	2.5	2.4	4.3		2.5	1.2	1.9
Culvert slope (%)	4.4	1.15	0.95	3.1	0.75	2.3	2.7
Upstream slope (%)	9.6	1.7	1.5	2.3	0.4	1.8	3.7
Downstream slope (%)	3.1	1.6	1.2	3	1.7	1.5	3.1
Upstream ACW (m)	4.4	4.7	8.3	4.3	3.1	3.6	4.4
Downstream ACW (m)	4.7	5.3	8.7	3.6	4.1	3.4	4.3
Mean Summer Flow (m^3/s)	0.05	0.19	0.38	0.08	0.15	0.02	0.20
Max Summer Velocity (m/s)	0.43	1.11	0.76	2.57	1.60	0.33	1.39
Maximum Depth in Culvert (cm)	20	20	22	35	25	23	28
Summer Jump Height (cm)	28	40	10	0	11	20	0
Pool Depth Below Jump (cm)	19	110	100	24	30	40	45

Photo 1. Little Lobster Creek

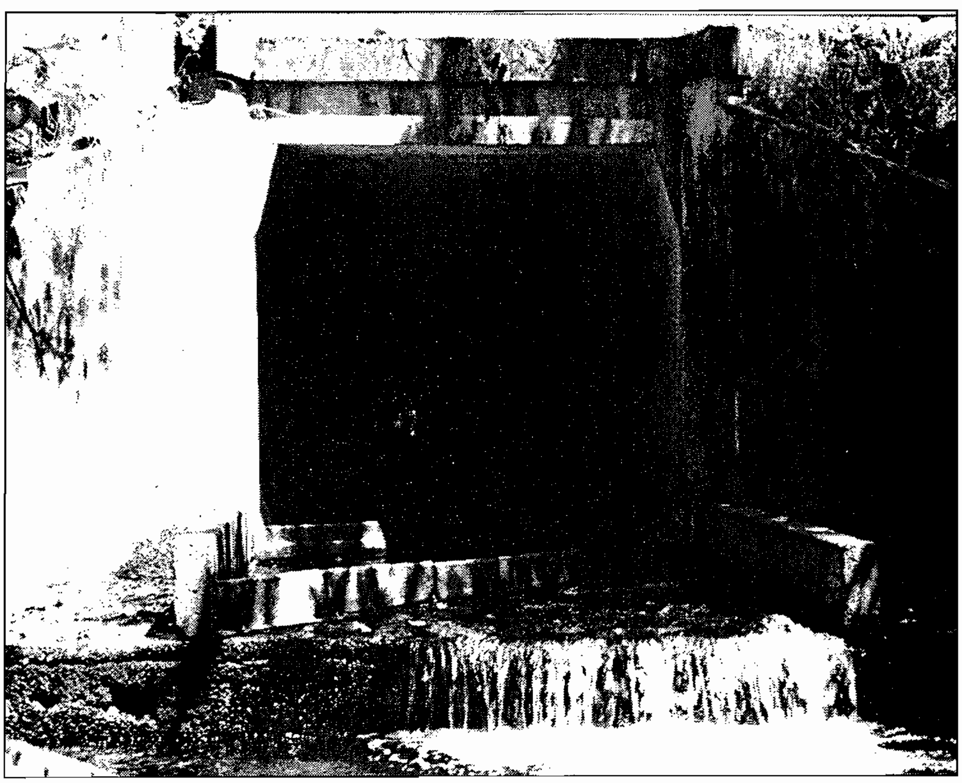


Photo 2. Canyon Creek #2

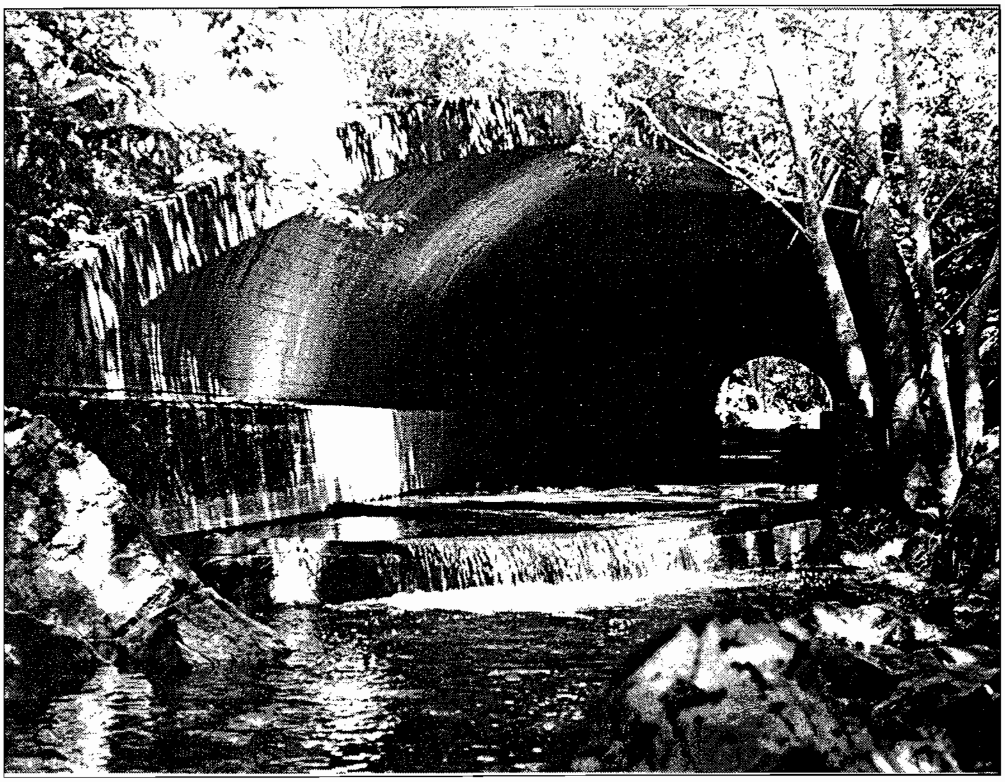


Photo 3. Canyon Creek #3

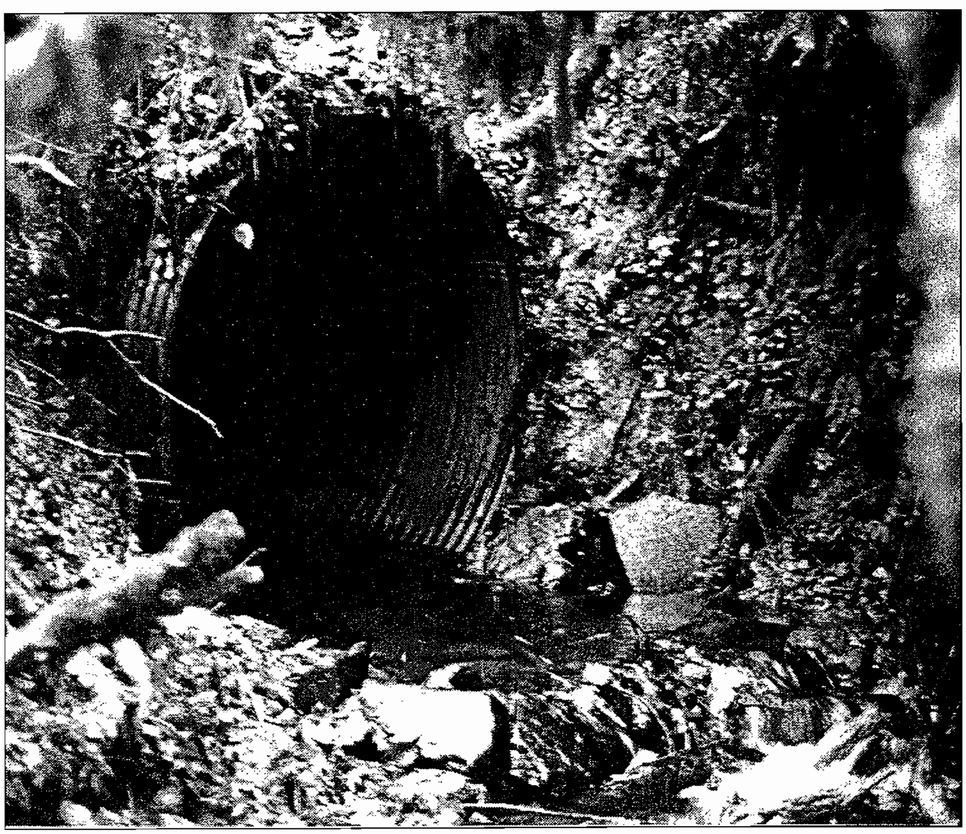


Photo 4. Hough Creek

Photo 5. Stemple Creek

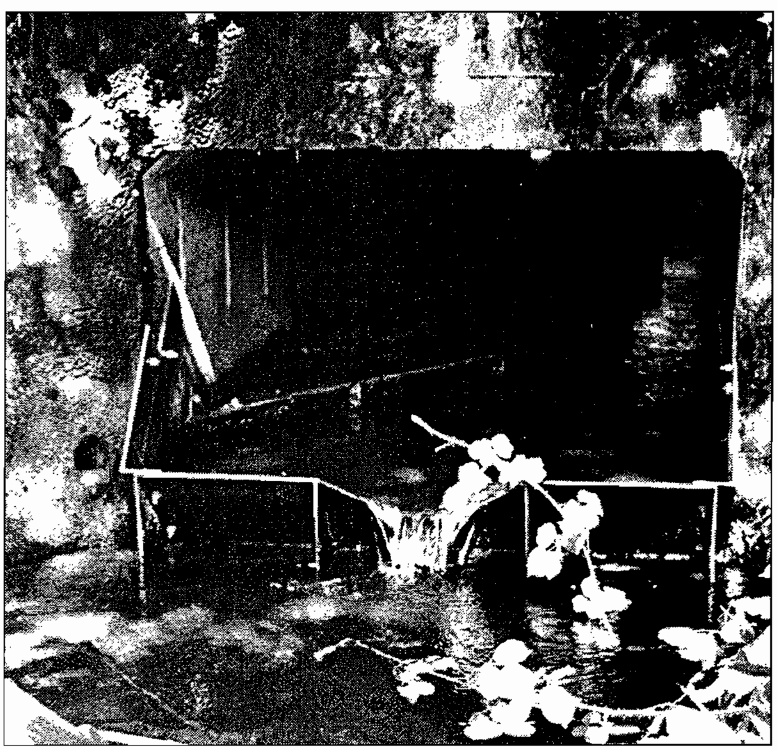


Photo 6. Hayden Creek

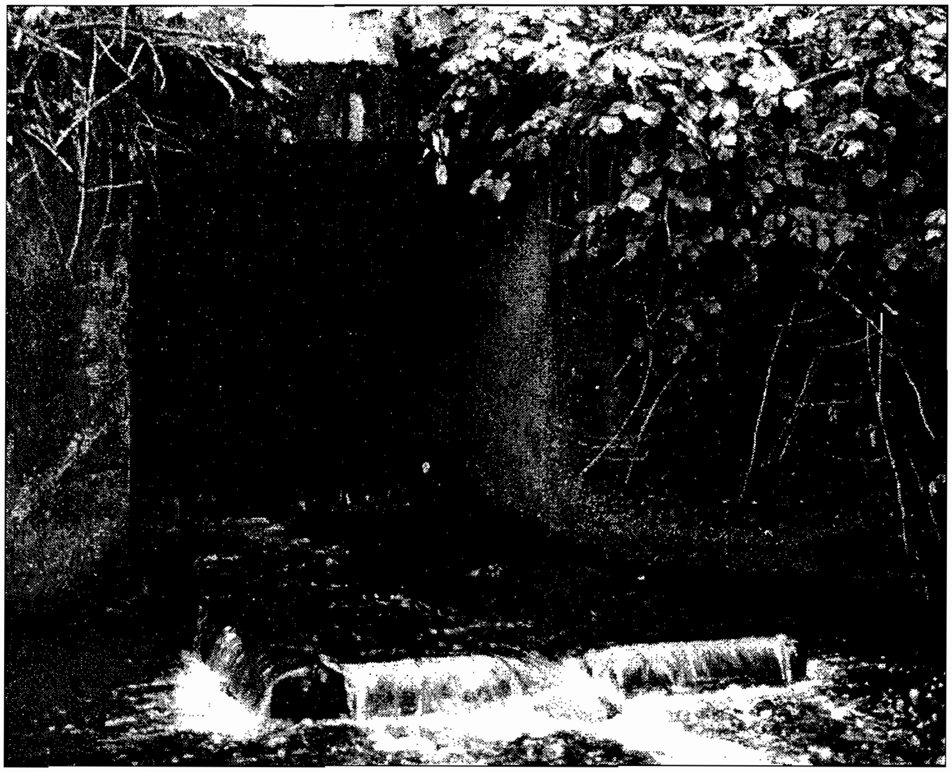
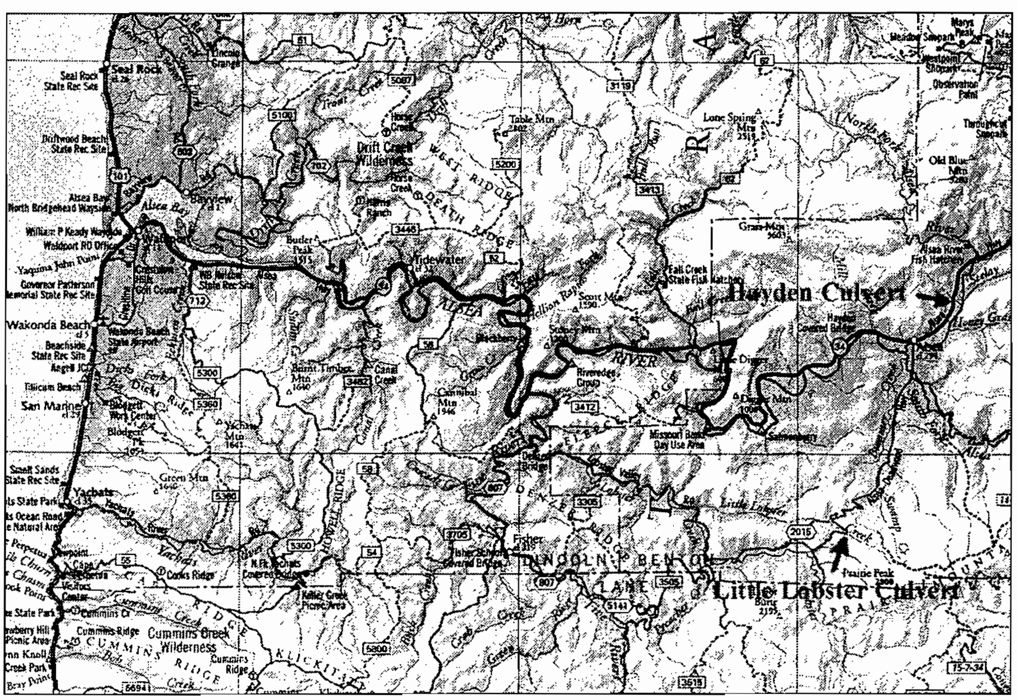
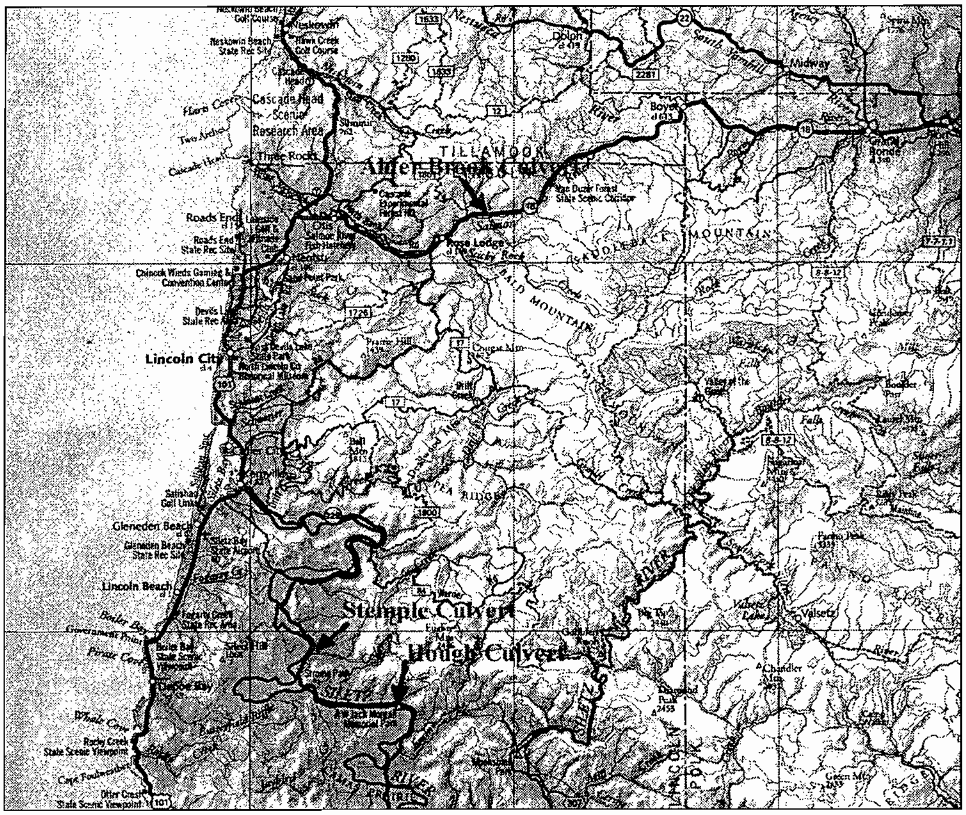


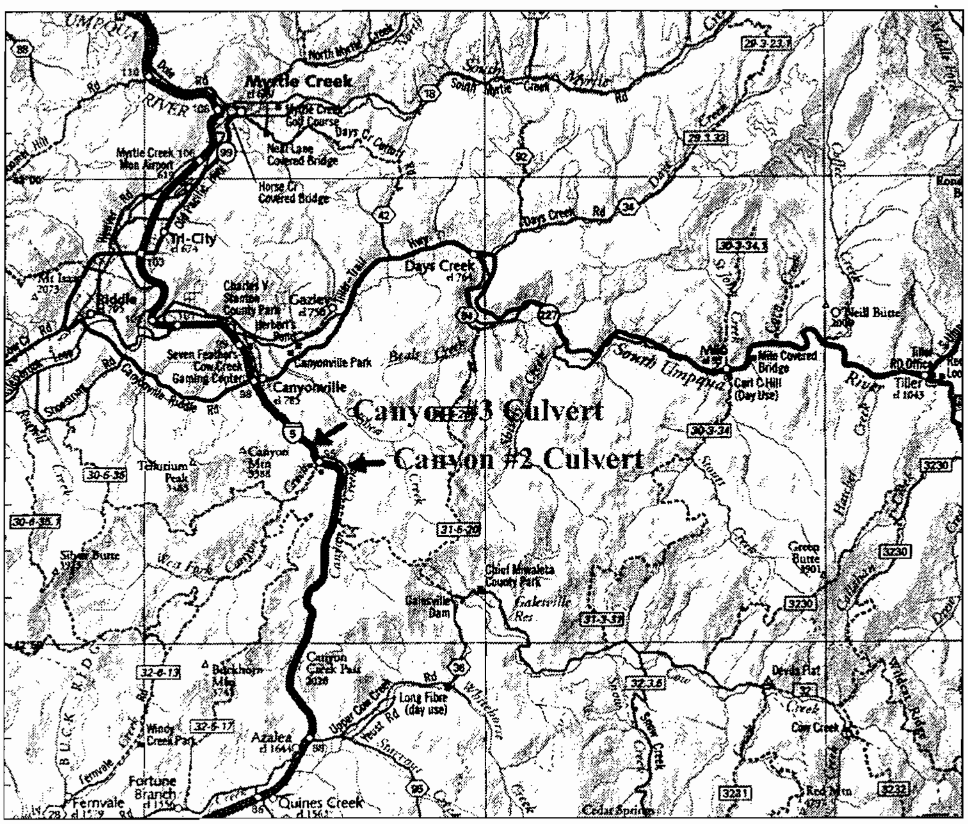
Photo 7. Alder Brook



Map 1. Locations of culverts on Hayden Creek and Little Lobster Creek.



Map 2. Locations of culverts on Alder Brook, Stemple Creek, and Hough Creek.



Map 3. Locations of Canyon Creek culverts.

Study reaches for each site were set at a distance of 200 m upstream and downstream of the culvert with a total reach length of 400 m, which was divided into four 100 m sections, two above and two below the culvert. When the mainstem river was closer than 200 m downstream, length of the reaches above and below the culvert was set to the distance to the river. Each of these reaches was then divided to create four study sections of equal length. A longer study reach was established on Little Lobster Creek because it had long sections of natural stream channel above and below the culvert. A reach of 400 m downstream and 400 m upstream was established, further breaking that down into four 200 m study sections.

Block nets were placed at the upstream and downstream ends of each study section and left in the stream for one hour after electrofishing to prevent any unnatural movement. A Smith-Root electrofisher was used to capture juvenile and adult cutthroat and juvenile steelhead trout to be tagged. Each captured fish was anesthetized with Tricane methanesulfonate (MS-222) and tagged with a small blue dot using a Panjet gun with Alcian blue dye. The dye tag persists for 15 to 18 months and should only be placed on fish 80 mm or larger. A mark was placed at the base of each paired fin depending on the study section the fish was first captured in. Fish in the farthest downstream section were marked on the left pelvic fin. Fish in the study section immediately below the culvert were marked on the right pelvic fin. A left pectoral fin mark was used on fish captured immediately above the culvert. The right pectoral fin was marked in the farthest upstream section. Data recorded for each fish tagged included the previous tag location, new tag location, stream section, fork length, and species.

Study sites were sampled four times. The initial tagging was concluded on October 19, 2000 with subsequent mark-recaptures in March and August 2001, and June 2002. During each recapture, fish were examined for a previous tag. If a previous tag was found, the fish was retagged in the same location. If the fish did not have a previous tag, they were marked with the appropriate tag for that study section. All fish were released in the same section in which they were captured, regardless of tag location.

Short-term Movement Controlled Release Study

The second element of this study involved installing various baffle designs in a culvert with no previous retrofits. The study site was located on Big Noise Creek in Clatsop County, OR, USA, originating in the Clatsop State Forest at an elevation of approximately 1,200 feet above sea level. It flows North under Route 30 at Oregon Highway mile marker 78.9 and joins Gnat Creek which eventually enters the Columbia River. Big Noise Creek is a second-order stream with a drainage area of 0.47 hectares. The annual hydrologic pattern is low flows during the summer months and high flows during the winter months. December, January and February typically have the highest flows. The culvert that crosses under Highway 30 is a reinforced concrete box culvert that is 30 m long, 2.4 m wide, and 2.4 m tall. The outlet is slightly backwatered by a logjam so there is no jump into the culvert. The culvert's slope is 1.5 percent.

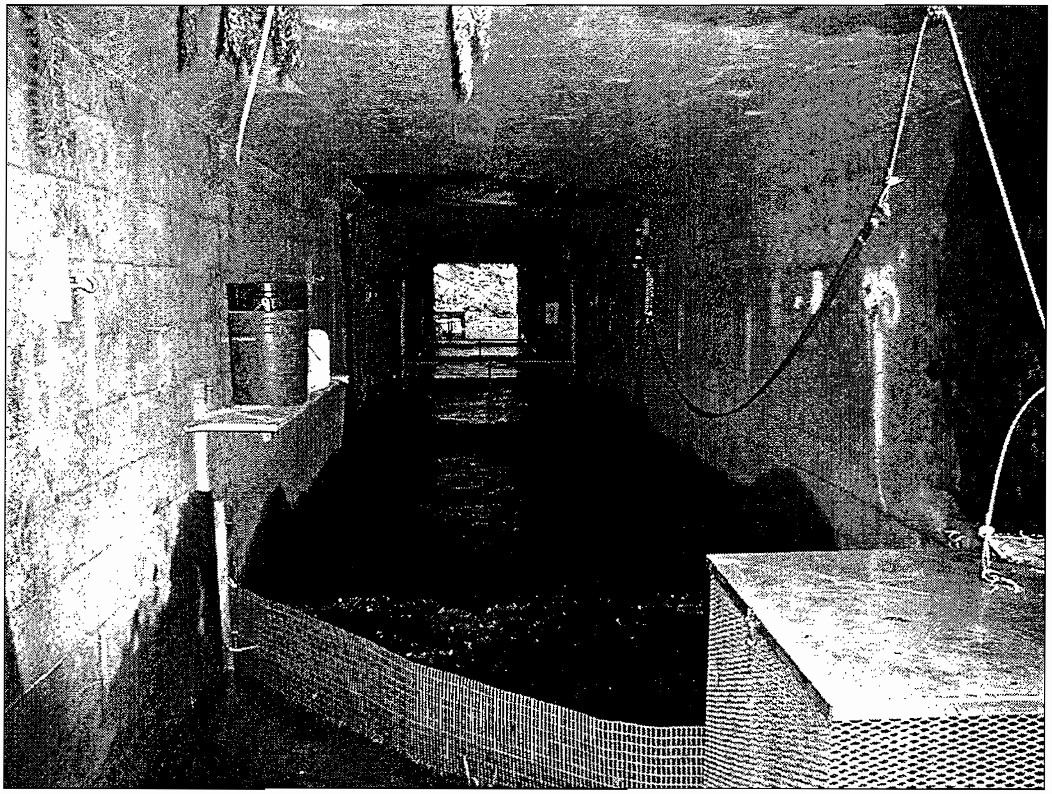


Photo 8. Downstream end of culvert on Big Noise Creek, illustrating the lower fish trap.

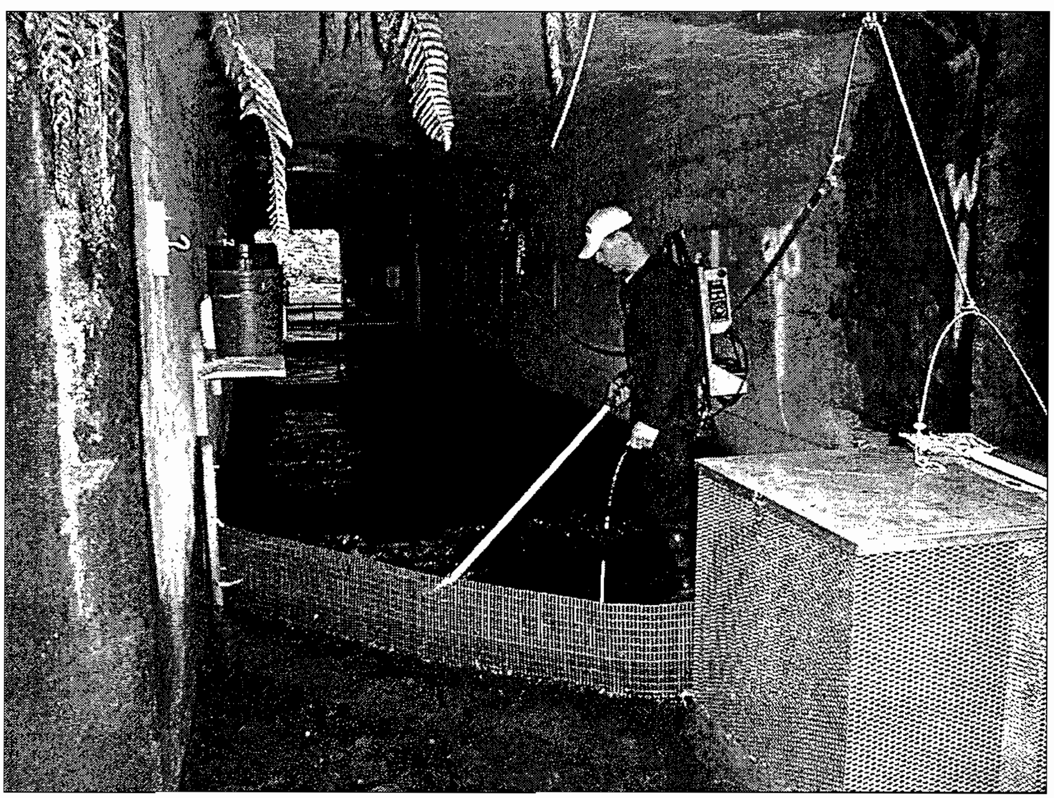


Photo 9. Downstream end of culvert on Big Noise Creek, illustrating backpack electroshocking for steelhead trout in lower section above the fish trap.

Juvenile steelhead (*Oncorhynchus mykiss*) trout from the Big Creek Fish Hatchery (Oregon Dept. of Fish & Wildlife) were used for each release during summer and winter base flows. The juvenile trout were randomly selected from the hatchery raceways for each release. A new set of fish was used for each release to remove the possibility of learned behavior. The trout were transported via buckets approximately 10 km from the hatchery to the culvert, where they were allowed to acclimate in stream water for at least 30 min. Buckets were placed in the shade with aerators to ensure that the fish were stressed as little as possible before being placed in the culvert.

Fish traps (0.9 x 0.9 x 0.9m) were placed against one sidewall at each end of the culvert with a screen to divert fish into the trap attached to the other sidewall. Drop screens that spanned the width of the culvert were placed 3.5 m on each side of the culvert center point. The drop screens could be lowered or raised from outside the culvert by a series of ropes and pulleys. A release cage was placed in the middle of the culvert between the two drop screens. The release cage had doors on the sides and front that could be opened by pulling ropes outside of the culvert (Fig. 1). Twenty acclimated juvenile steelhead trout were placed in the release cage and allowed to sit for three minutes. After this time, the doors on the cage were opened from outside the culvert, and the fish were allowed to move freely in the culvert for a period of three hours. The release time was chosen to allow two releases per day in the winter, and three releases per day in the summer.

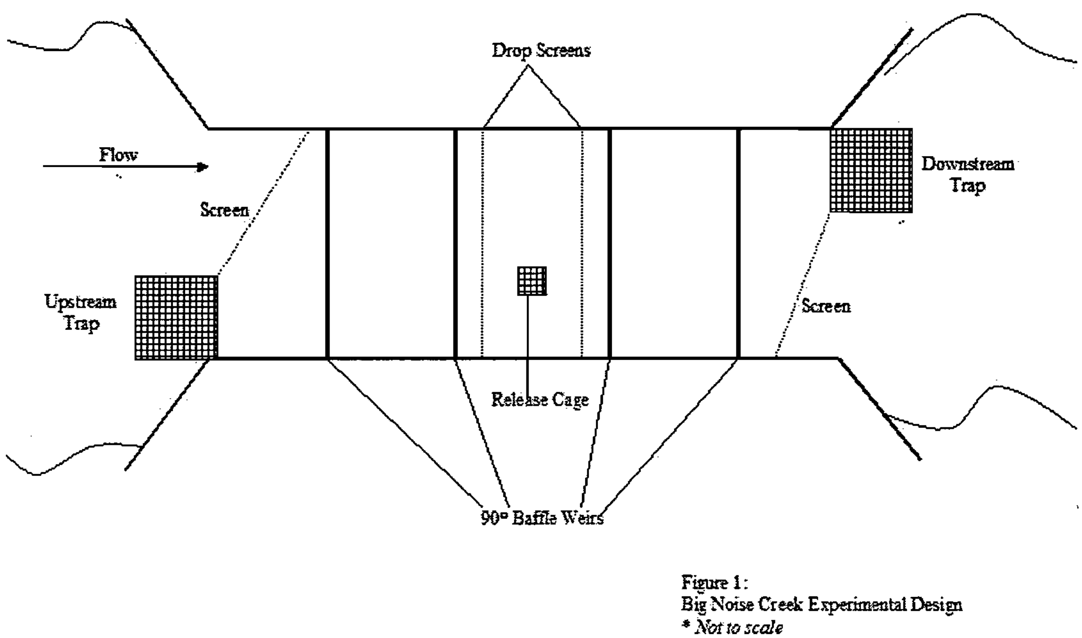


Figure 1. Experimental layout of fish traps and release cage in culvert on Big Noise Creek.

After the three hour period was over, the drop screens were released dividing the culvert into five sections; upstream through the culvert (upstream trap), upstream in the culvert, no movement (between drop screens), downstream in the culvert, and downstream through the culvert (downstream trap). Both traps were checked first, and the entrances to the traps were blocked after the fish were removed to prevent movement into the traps during collection of the other sections. A Smith-Root backpack electrofisher was used to capture fish that were not in the traps. Shocking started at the downstream end of the culvert and worked upstream, with fish from each section being placed into separate buckets. Each section had two to four passes with the electrofisher, until at least 80% of the fish were recaptured. After all the fish had been collected, they were anesthetized with MS-222 to measure length (fork length). After recovery, fish were released below a barrier falls downstream of the culvert.

Plastic baffles with a vertical back and a 45° upstream face were bolted to the floor of the culvert for each baffle configuration. Releases were divided into four groups for the winter study: control (no baffles), 30° and 45° baffles angled downstream, and 90° weirs. A field review of the project found that the research team misunderstood the designs used by ODOT for diagonal baffles. ODOT typically angles the 30° and 45° baffles in an upstream direction to create more depth between baffles. This is particularly important during low flow because the upstream baffles backwaters the flow, providing more volume of water between baffles for fish. The summer study was expanded to include the four treatments (control (no baffles), 30° and 45° baffles angled downstream, and 90° weirs) plus additional treatments of 30° and 45° baffles angled upstream.

In all cases the 90° weir design used 30-cm tall plastic baffles, while all the 30° and 45° designs used 20-cm tall baffles. The 90° weirs design consisted of 5 weirs with a spacing of 5.4 m, the 45° baffle design had 12 baffles with a spacing of 2.1 m, and the 30° baffle design contained 7 baffles with a spacing of 3.5 m. The angled baffles had a 0.9-m gap between the end of the baffle and the culvert wall. Locations of the baffles for each design were marked on the culvert wall so that summer and winter releases would have the same exact baffle configurations. All of the baffle systems were designed by an ODOT engineer to be similar to the most common designs used in ODOT culverts.

Eight experimental releases were performed for each baffle design. The first four releases were conducted without incentives for replication, and the second four releases consisted of various incentives to attempt to increase trout movement upstream through the culvert. The four different incentives included lights, bait, overcrowding, and scare tactics. Artificial lights in the culvert were left on for the entire three-hr release in an attempt to move fish out of the normally shaded culvert. A screened bottle containing crushed hatchery pellets, salmon eggs, sand shrimp, and scented oils was placed just above of the upstream trap to provide a positive "bait" incentive for movement up through the culvert. The overcrowding incentive involved leaving the lower drop screen down during the release so that the fish could only move upstream. The fright incentive consisted of moving from the downstream trap up with the electroshocker on a low setting and creating noise by hitting a steel bar with a hammer under water. Drop screens were lowered when they were passed to prevent "scared" fish from moving back downstream.

Due to the ineffectiveness of the incentives and time constraints, the summer experimental releases for the control, 30°, and 45° upstream baffle configurations did not have incentives.

RESULTS

LONG-TERM MARK-RECAPTURE

The long-term movement mark-recapture was an observational study with weak statistical power. The study culverts could not be randomly selected and were chosen based on attributes that would facilitate a mark-recapture study of this type. The data set for the statistical analysis was small due to the relatively few fish that moved between study sections. Observations from this study cannot be applied to a larger set of culverts but provide supplemental data for the short-term movement study.

Culvert Hydraulics

The seven study culverts were selected to be relatively similar, but they differed in several design characteristics and physical properties. Culvert types included five reinforced concrete box culverts (RCBC), one corrugated metal pipe culvert (CMP), and one half corrugated metal pipe with a concrete floor (CMP-CF). Culvert slopes ranged from 0.75% to 4.4% (Table 1). Stream channels ranged from 3.1 m to 8.7 m in width and stream slopes ranged from 1.2% to 3.1% downstream of the culverts. Maximum summer velocities ranged from 0.33 m/s to 2.57 m/s (Table 1).

Velocities in the culverts and the streams around them were compared in November 2000. In general, velocities were greater within the culverts than in the streams outside the culverts (Table 2). Both maximum velocity and average velocity inside the culvert was more than four times greater than velocities in the upstream and downstream reaches in Stemple Creek. Velocities inside the culvert were relatively similar to velocities in the surrounding stream reaches in Little Lobster Creek, both Canyon Creek sites, Hough Creek, and Alder Brook. Velocities in Hayden Creek were difficult to measure but appeared to be less than the velocities in the surrounding stream reaches.

Table 2. Velocities in retrofitted culverts at the seven study sites in November 2000. Data are presented as English units and metric units in 2a and 2b, respectively.

2a.

Stream	Maximum Culvert Velocity (ft/s)	Average Culvert Velocity (ft/s)	Maximum Stream Velocity (ft/s)	Average Stream Velocity (ft/s)
Little Lobster Creek	1.42	0.21	1.22	0.17
Canyon Cr. # 2	3.63	1.48	1.99	0.43
Canyon Cr. # 3	2.49	0.36	3.22	0.38
Hough Creek	2.26	0.72	2.52	0.71
Stemple Creek	5.25	1.10	1.24	0.27
Hayden Creek	0.10	0.01	1.28	0.35
Alder Brook	4.55	1.37	3.67	0.81

2b.

Stream	Maximum Culvert Velocity (m/s)	Average Culvert Velocity (m/s)	Maximum Stream Velocity (m/s)	Average Stream Velocity (m/s)
Little Lobster Creek	0.433	0.064	0.372	0.052
Canyon Cr. # 2	1.106	0.451	0.607	0.131
Canyon Cr. # 3	0.759	0.110	0.981	0.116
Hough Creek	0.689	0.219	0.768	0.216
Stemple Creek	1.600	0.335	0.378	0.082
Hayden Creek	0.030	0.003	0.390	0.107
Alder Brook	1.387	0.418	1.119	0.247

Fish Movement in Field Surveys

Study sites were surveyed by snorkeling in order of their priority. Number, length, and species of fish in pools were recorded. Snorkeling began with the pool immediately up from the mainstem river or 500 meters downstream of the culvert whichever came first. The same distance that was snorkeled downstream of the culvert was snorkeled upstream of the culvert.

The snorkel survey data were analyzed from above and below each culvert. The graphs below depict longitudinal distributions of salmonids below each culvert and above each culvert. The lines for upstream and downstream reaches represent the cumulative number of salmonids observed as the reach was observed in an upstream direction. In a natural stream, you would expect each line to have relatively the same slope. Hough and Hayden Creek did not have enough snorkeling data to justify a longitudinal graph, but graphs are presented of each of the other culverts (Fig. 2-6). Most of the distributions have smaller slopes on the upstream end of the culvert. We did not observe fish for more than 50 m upstream of the culvert in Little Lobster Creek and Canyon Creek #2. Total numbers of fish observed upstream of the culverts were always less than the numbers of fish observed downstream of the culverts. These differences indicate that fish potentially move through the culverts but the culverts possibly decrease upstream passage because of unfavorable flow conditions inside the culvert, unsuitable habitat upstream of the culvert, or lack of spawning habitat upstream of the culvert.

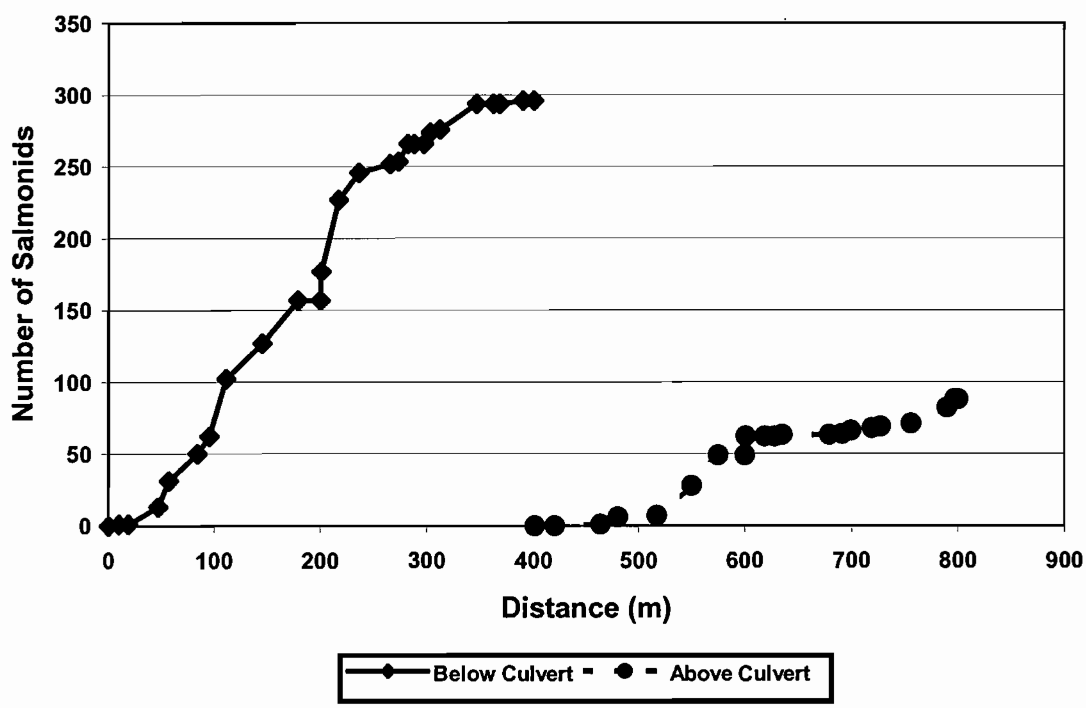


Fig. 2: Longitudinal distribution of salmonids below and above the culvert at Little Lobster Creek.

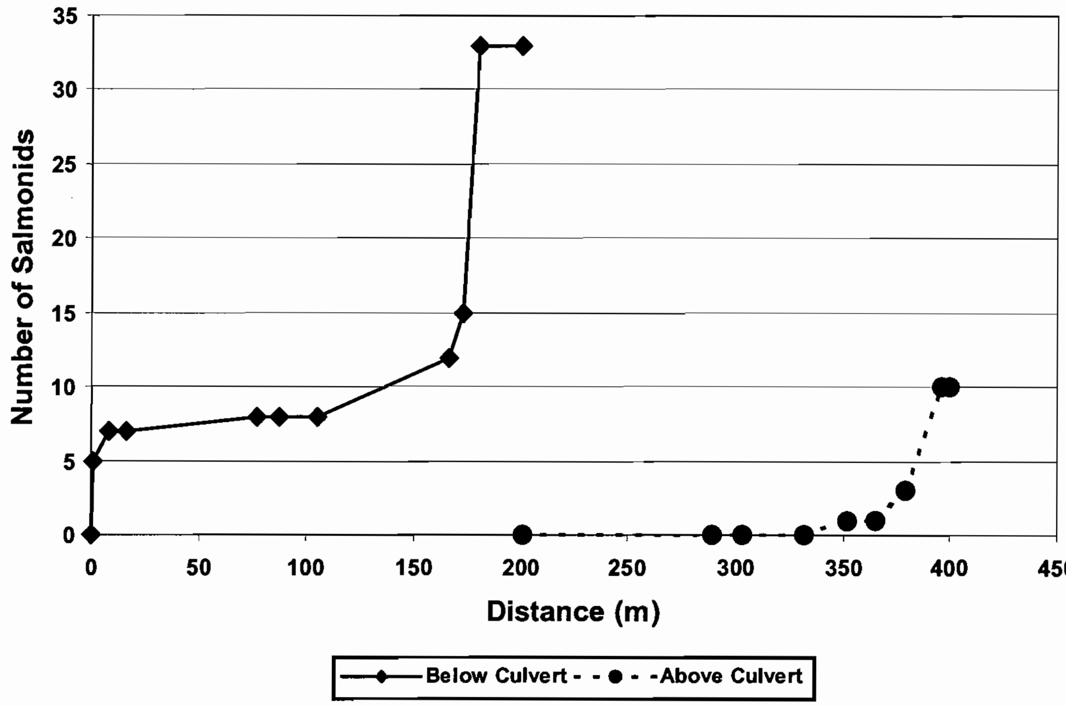


Fig. 3: Longitudinal distribution of salmonids below and above the culvert at Canyon Creek Site #2.

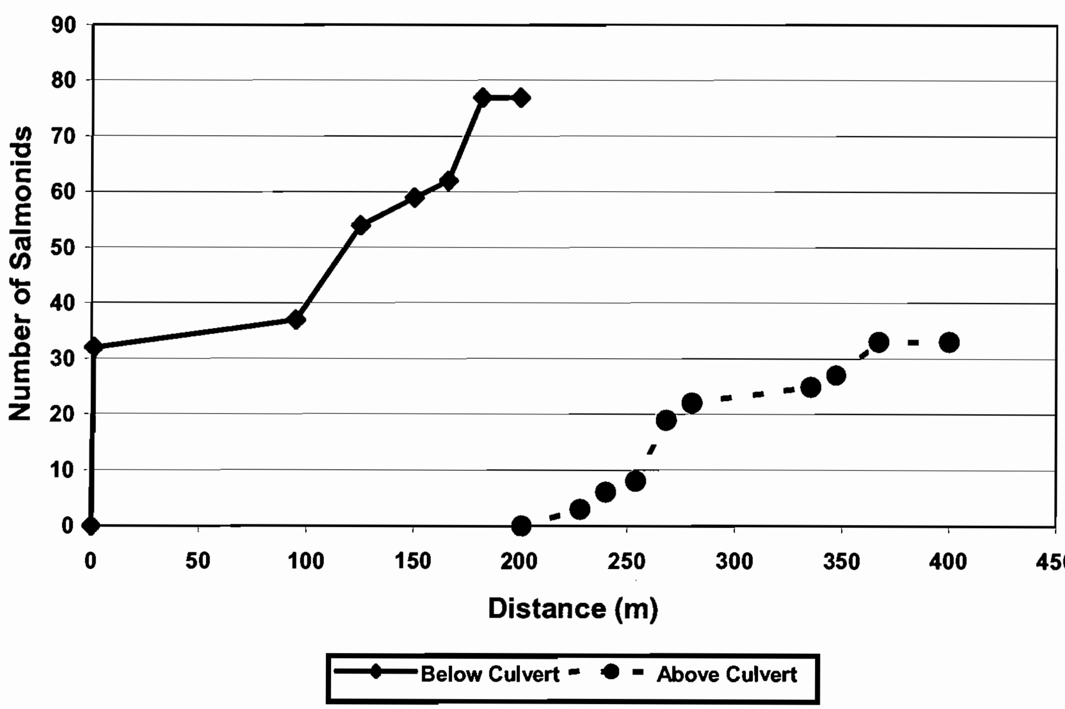


Fig. 4: Longitudinal distribution of salmonids below and above the culvert at Canyon Creek Site #3.

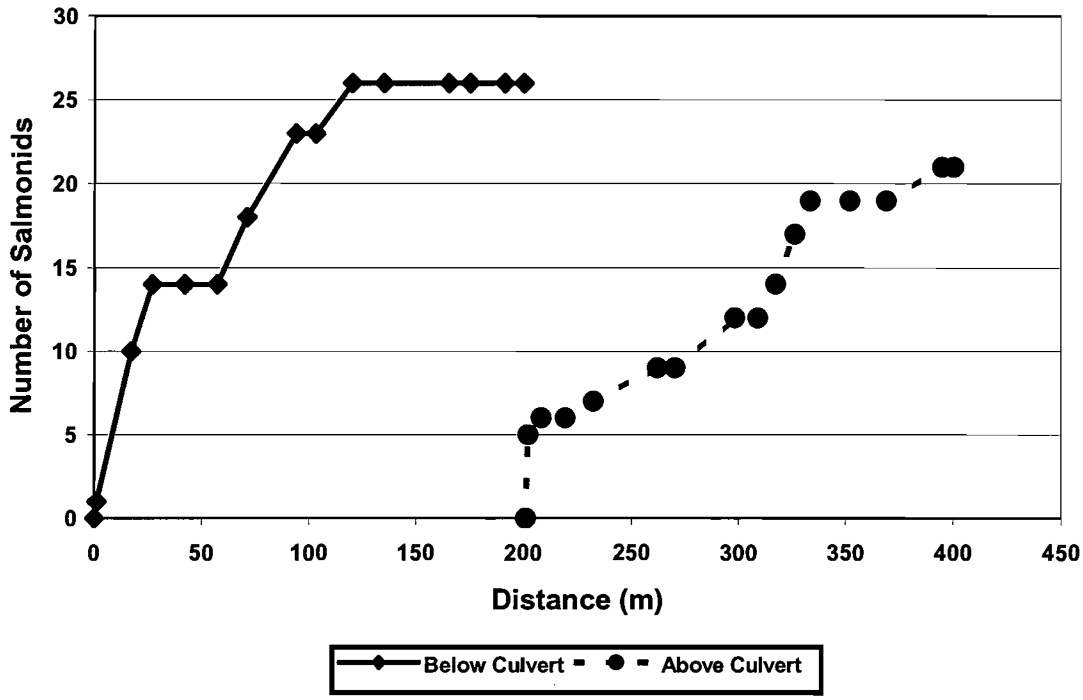


Fig. 5: Longitudinal distribution of salmonids below and above the culvert at Stemple Creek.

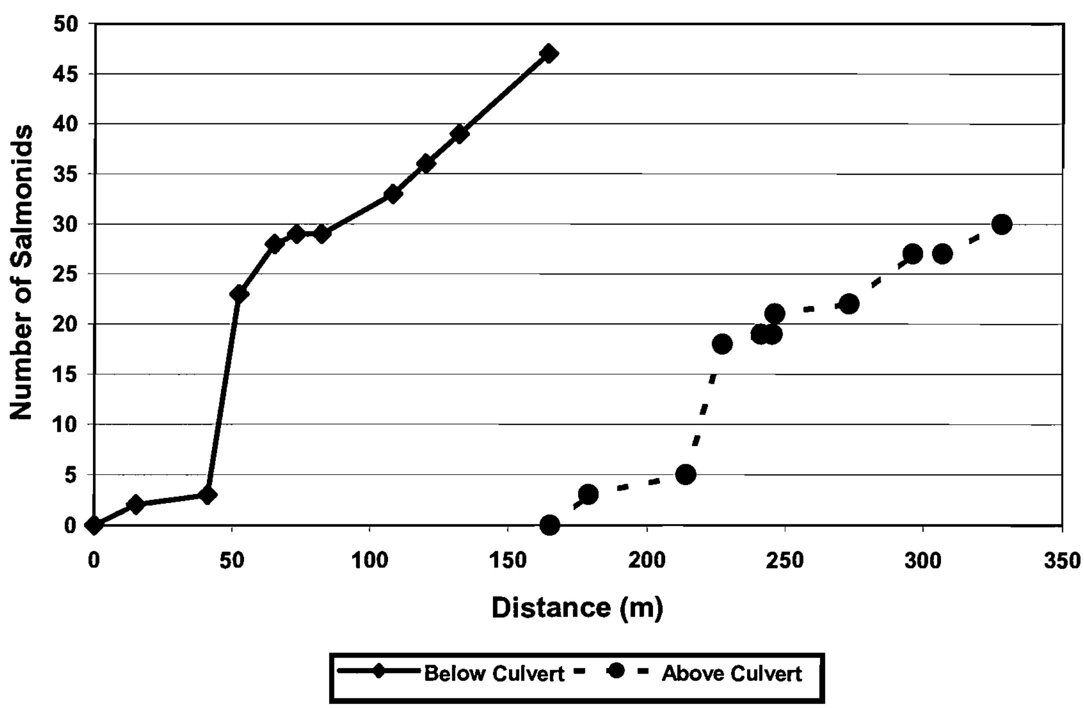


Fig. 6: Longitudinal distribution of salmonids below and above the culvert at Alder Brook.

Fish movement within the study reaches can be compared in terms of the percent of recaptured fish that moved between study sections. The four classes of movement include downstream within, downstream through, upstream within, and upstream through. Percentages of fish that moved downstream or upstream within the study reach indicate that the fish moved within the study reach but not through the culvert. Percentages of fish that moved through the culvert either downstream or upstream indicate successful passage through the culvert.

In all, 1627 cutthroat and steelhead trout were tagged in the seven study reaches during the study (Table 3). Of those 1627 fish, 223 were recaptured for a total recapture rate of 13.7%. The total percent of fish that moved between sections was 17.9% or 40 fish out of the 223 recaptured. 20% of the fish that moved within the study reach were steelhead trout, while the remaining 80% were cutthroat trout. The average size of the fish for each movement category was 121 mm for upstream through culvert, 138 mm for downstream through culvert, 129 mm for upstream within the study reach, and 128 mm for downstream within the study reach.

Table 3: Percent of recaptured fish that moved for each study reach

	Downstream		Upstream	
	Within	Through	Within	Through
Little Lobster Cr.	8.7	4.8	7.5	0
Canyon Cr. # 2	7.7	0	3.8	3.8
Canyon Cr. # 3	0	3.8	3.8	7.7
Hough Cr.	0	0	10	0
Stemple Cr.	11.8	0	0	0
Hayden Cr.	0	0	14.3	28.6
Alder Brook	0	6.1	6.1	0

A two-sample t-test was used to determine if there was a significant difference between the percent movements of trout within each stream. Three comparisons were made for each stream; downstream within versus downstream through, upstream within versus upstream through, and upstream through versus downstream through. Only Little Lobster Creek exhibited movement patterns that were statistically significant. The percent of fish that move downstream through the culvert in Little Lobster Creek was significantly different than the percent of fish that moved upstream through the culvert (p-value = .01). All other comparisons were not statistically significant (p-value = >0.25). General data on the total number of fish tagged, percent of tagged fish that were cutthroat and steelhead, percent of the tagged fish recaptured, and average size of a moving fish are reported in Table 4.

Table 4: Mark-recapture data for each study reach. Percent recapture refers to all marked salmonids in the stream. Mean size refers to the size of fish (mm fork length) that moved between sections.

	Total Fish Tagged	Percent Cutthroat	Percent Steelhead	Percent Recapture	Mean Size (mm)
Little Lobster	568	93	7	18	126
Canyon #2	216	29	71	12	140
Canyon #3	287	18	82	9	126
Hough	109	81	19	9	106
Stemple	134	100	0	13	103
Hayden	80	100	0	9	120
Alder Brook	232	53	47	14	176

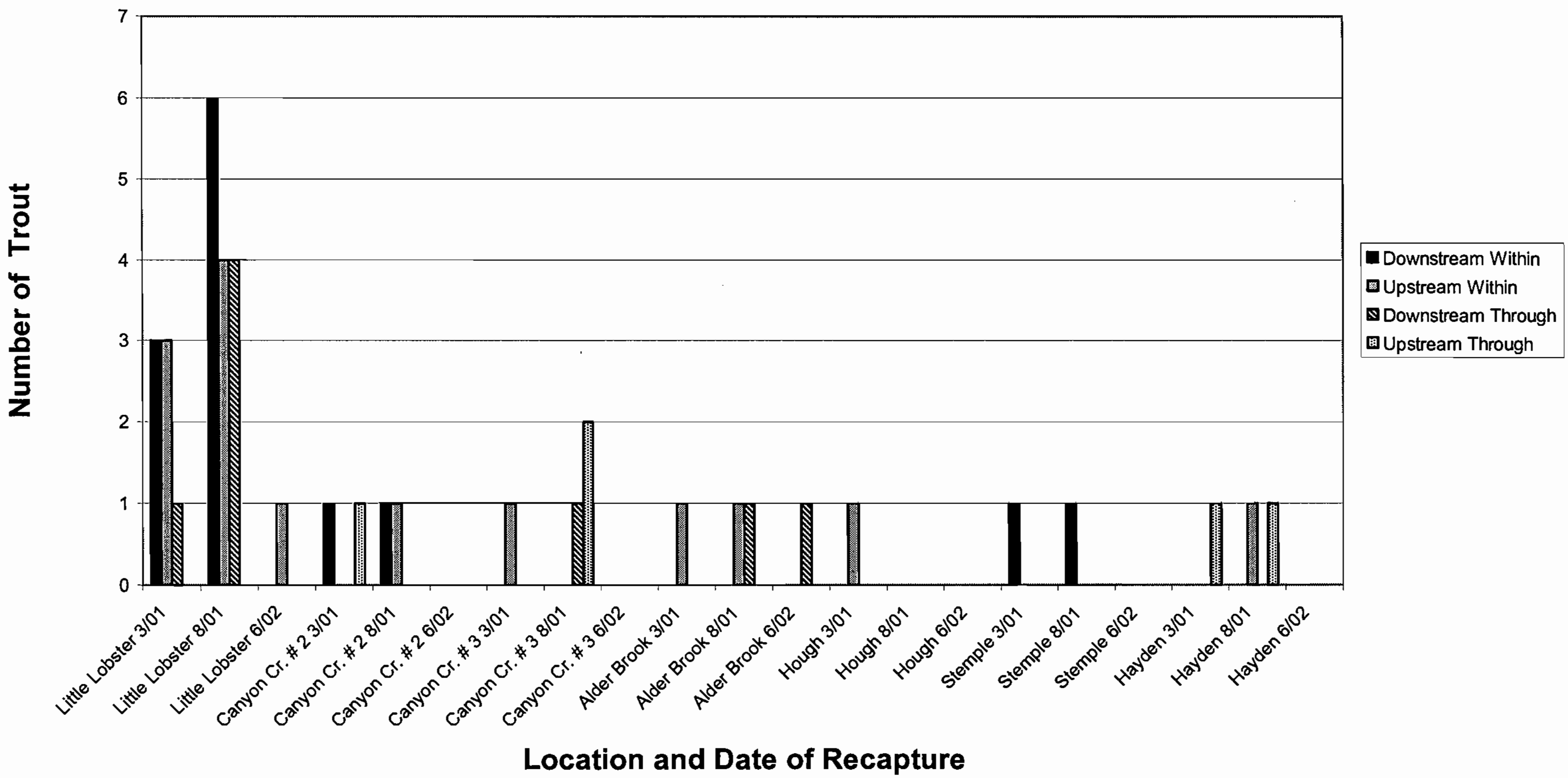


Figure 7. Number of trout that moved between sections for all study sites. Date of capture is indicated in figure axis. Movement between upper and lower sections of a reach above or below a culvert is indicated as movement "within" a reach. Movement through as culvert between downstream and upstream sections is indicated as movement "through" adjacent reaches.

Little Lobster Creek Culvert

The Little Lobster Creek culvert had the largest number of tagged fish move between the study sections, but did not have any fish move upstream through the culvert. The total number of tagged fish in Little Lobster Creek was 568 (528 cutthroat trout, 40 steelhead trout). All ten of the tagged steelhead juveniles that were recaptured remained within the study section in which they were tagged. All fish that moved were cutthroat trout, with an average size of 126 mm. Of the 22 recaptured cutthroat trout that moved; nine moved downstream between sections but not through the culvert, four moved downstream through the culvert, eight moved upstream between sections but not through the culvert, and zero fish moved upstream through the culvert.

Canyon Creek Culvert #2

Canyon Creek contained both steelhead and cutthroat juveniles. The total number of tagged fish in this study reach was 216 fish (63 cutthroat trout, 153 steelhead trout). One cutthroat and three steelhead trout moved between study sections. The average size of these moving trout was 140mm. Two trout moved downstream within the study section but not through the culvert, zero moved downstream through the culvert, one moved upstream within the study sections but not through the culvert, and one trout moved upstream through the culvert. The cutthroat trout that moved upstream through the culvert between October 2000 and March 2001 had a fork length of 155 mm at the time of recapture and moved from the study section just downstream of the culvert to the section just upstream of the culvert, a distance of at least 83 m.

Canyon Creek Culvert #3

The total number of tagged fish in this study reach was 287 (51 cutthroat trout, 236 steelhead trout). One cutthroat and three steelhead trout moved between study sections. The average size of these moving trout was 126 mm. One trout moved downstream through the culvert, one moved upstream within the study sections but not through the culvert, and two trout moved upstream through the culvert. Two steelhead trout moved upstream through the culvert between March and August 2001. These two trout were the smallest fish that moved upstream through any of the culverts with fork lengths of 107 and 108 mm. Both trout moved from the farthest downstream study section. The steelhead that was 108 mm moved up to the study section just upstream of the culvert, a distance of at least 184 m. The 107-mm trout moved up to the farthest upstream study section, a distance of at least 284 m.

Hough Creek Culvert

Out of the 109 trout tagged in this study reach, 88 were cutthroat trout and 21 were steelhead trout. One cutthroat trout moved upstream between study sections but not through the culvert. It had a fork length of 106 mm.

Stemple Creek Culvert

134 cutthroat trout were tagged in this study reach. Two of these trout moved downstream between study sections but not through the culvert. The average size of these fish was 103 mm.

Hayden Creek Culvert

A total of 80 cutthroat trout were tagged in the study reach at around the Hayden Creek culvert. Trout at this site only moved upstream and had an average size of 120 mm. One cutthroat moved upstream between study sections but not through the culvert and two trout moved upstream through the culvert. A cutthroat trout with a fork length of 125 mm moved between October 2000 and March 2001, and a trout with a fork length of 111 mm moved between March and August 2001. Each trout moved at least 15 m.

Alder Brook Culvert

The total number of tagged fish in this study reach was 232 fish (122 cutthroat trout, 110 steelhead trout). Two cutthroat and two steelhead trout moved between study sections. The average size of these moving trout was 176 mm. Two trout moved downstream through the culvert and two trout moved upstream between study sections but not through the culvert.

SHORT-TERM CONTROLLED RELEASE

Winter tests were conducted between February 9 and March 15, 2002. Flows in the culvert during this time ranged from 1.5 to 5.1 m^3/s (Fig. 4). Discharge through the culvert at Big Noise Creek for each trial is reported in Fig. 3. All trout released could not always be recaptured because some of them moved inside the plastic baffles and were difficult to detect and remove. Even though some trout escaped, recapture rates for the winter and summer releases averaged greater than 95%. Average size hatchery juvenile steelhead in the winter trials was 179 mm, with a range of 116 to 246 mm.

Experimental releases during summer flows were conducted between September 9 and October 4, 2002. Discharge during this season remained constant at 0.14 m^3/s. The average size juvenile steelhead used in the summer trials was 127 mm, with a range of 80 to 156 mm. The size difference between the summer and winter trials was unavoidable due to juvenile growth rates in a hatchery setting. Two additional baffle configurations were tested during the summer trials because the flow patterns in the downstream angled baffles were similar to the control flow patterns. Angling the 30° and 45° baffles upstream increased the depth of water in the culvert and appreciably altered the flow patterns.

Culvert Hydraulics

The experimental retrofit designs produced complex flow patterns within the culverts. All baffle designs resulted in lower maximum, minimum, and average velocities within the culvert as compared to the culvert without retrofitted baffles (Table 5). In general, the baffles reduced the velocity profiles to about half of the velocities in the non-retrofitted culvert.

Table 5. Maximum, minimum, and average velocities within the culvert on Big Noise Creek for different baffles designs in winter 2002. Table 2a and 2b report velocities in English units and metric units, respectively.

5a.

Retrofit Design	Date	Maximum Velocity (ft/s)	Minimum Velocity (ft/s)	Average Velocity (ft/s)
None	March 19, 2002	5.69	2.04	4.06
30° Baffle	March 9, 2002	2.77	1.05	1.71
45° Baffle	February 24, 2002	3.41	1.81	2.71
90° Weir (between weirs)	February 8, 2002	2.26	0.56	1.44
90° Weir (top of weirs)	February 8, 2002	3.24	2.49	2.82

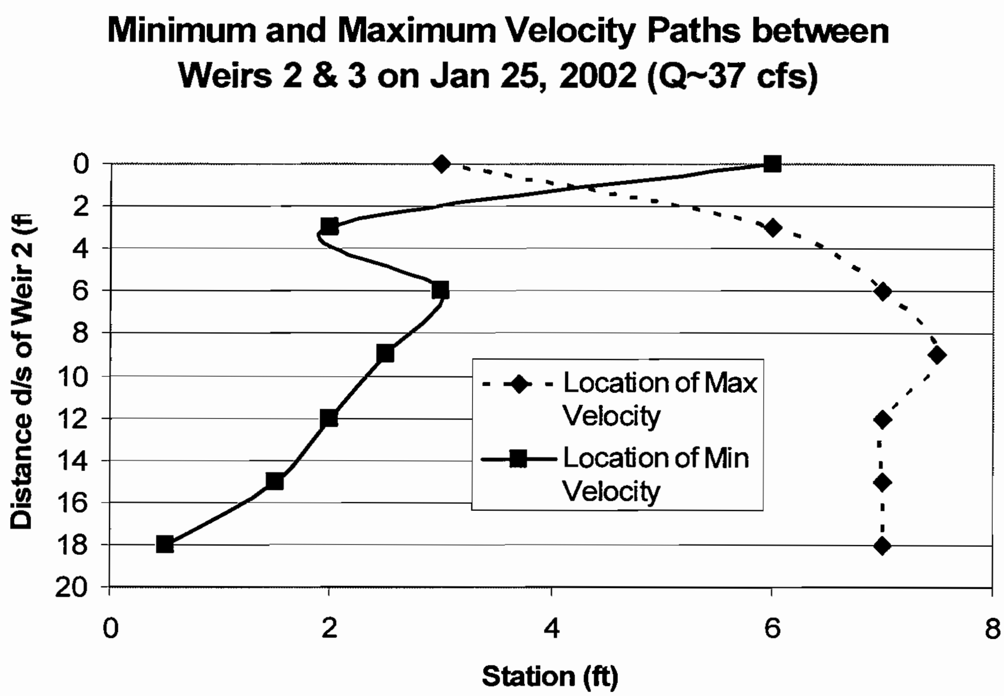
5b.

Retrofit Design	Date	Maximum Velocity (m/s)	Minimum Velocity (m/s)	Average Velocity (m/s)
None	19-Mar-02	1.73	0.62	1.24
30° Baffle	9-Mar-02	0.84	0.32	0.52
45° Baffle	24-Feb-02	1.04	0.55	0.83
90° Weir (between weirs)	8-Feb-02	0.69	0.17	0.44
90° Weir (top of weirs)	8-Feb-02	0.99	0.76	0.86

Weirs reduced velocities and created areas of low velocity and high velocity between weirs (Fig. 8). Velocities across the tops of the weirs were much higher than velocities within weirs (Fig. 9 and 10). In general, the velocities were twice as great at the crest of the weir than velocities in the sections between weirs and were similar to average velocities found in the culvert without retrofitting (Table 5). These reductions in velocity reduce velocities in the culvert in winter to ranges that fall within the swimming capacity of most salmonids (see Introduction).

Discharges during the experimental trials ranged from 5 ft3/s to 17 ft/s and were generally constant for a baffle design. Discharge during experimental releases for 90° weirs spanned the full range of observed discharges.

8a.



8b.

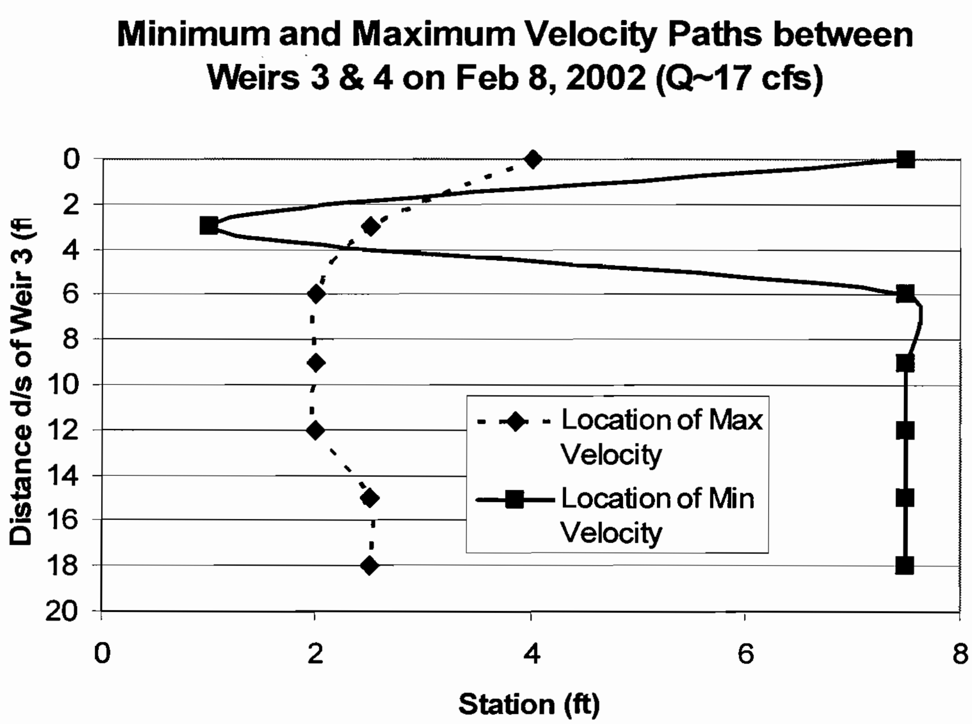
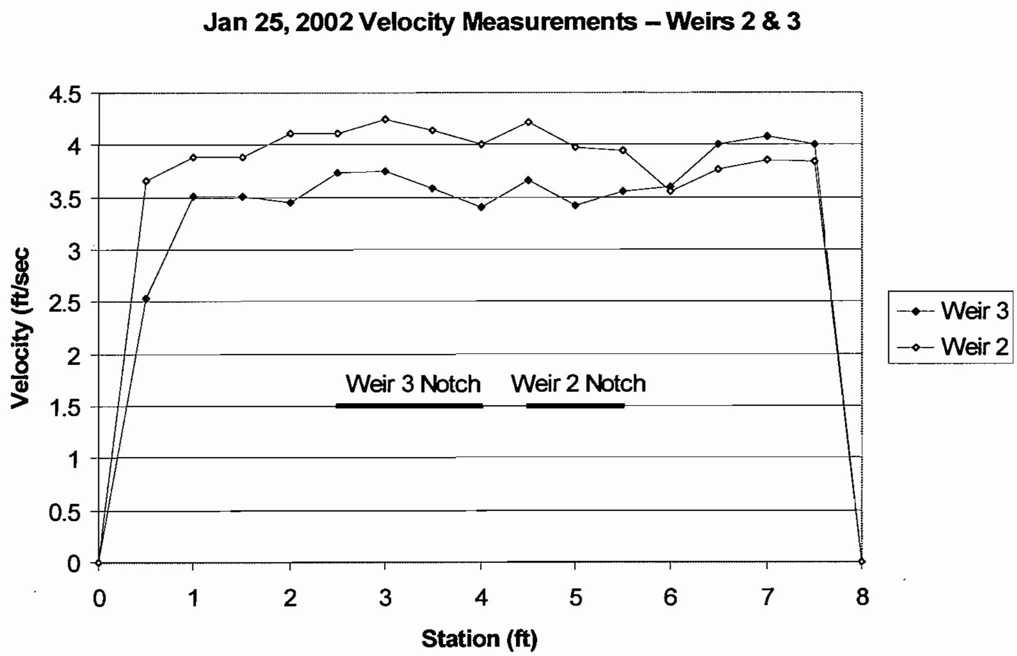


Figure 8. Paths of maximum and minimum velocities between weirs in the 90° weir design in winter 2002. 8a. illustrates the paths between weirs 2 and 3 and 8b. illustrates the paths between the next lower set of weirs.

9a.



9b.

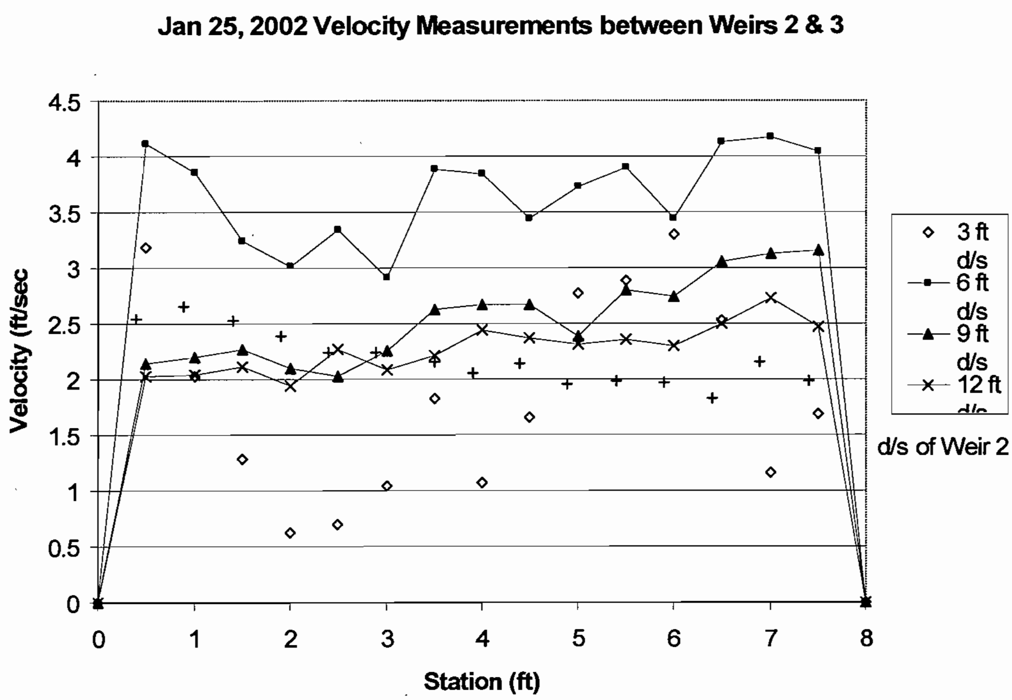
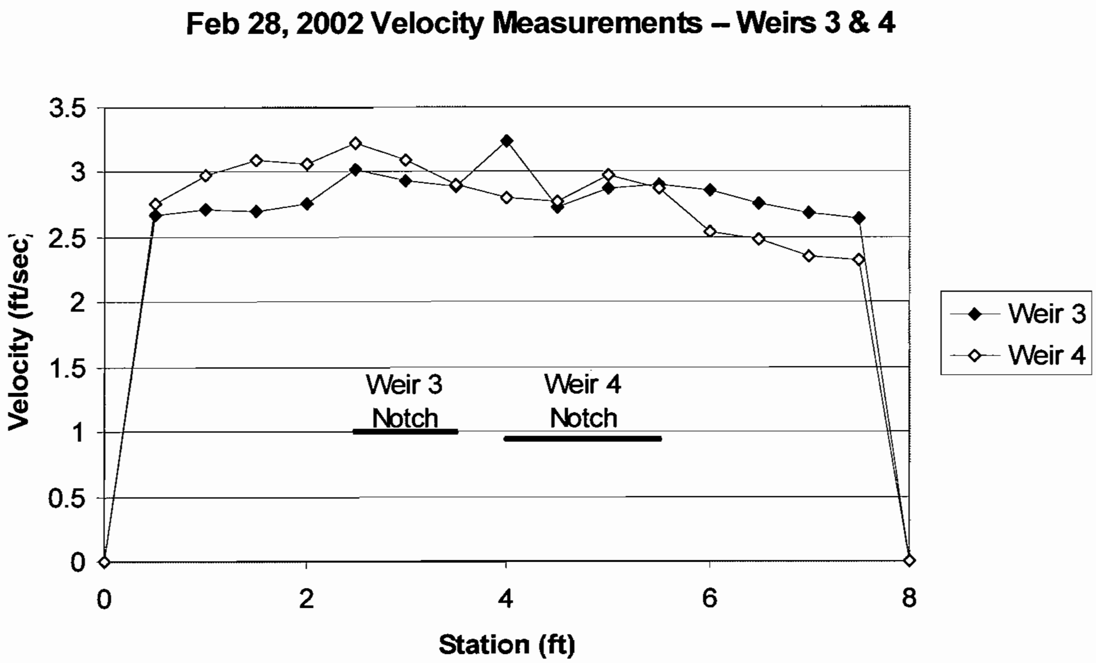


Figure 9. Velocities across the channel at the crest of weirs 2 and 3 (9a) and across the channel at cross-sections between weirs 2 and 3 (9b) in the 90° weir design in winter 2002.



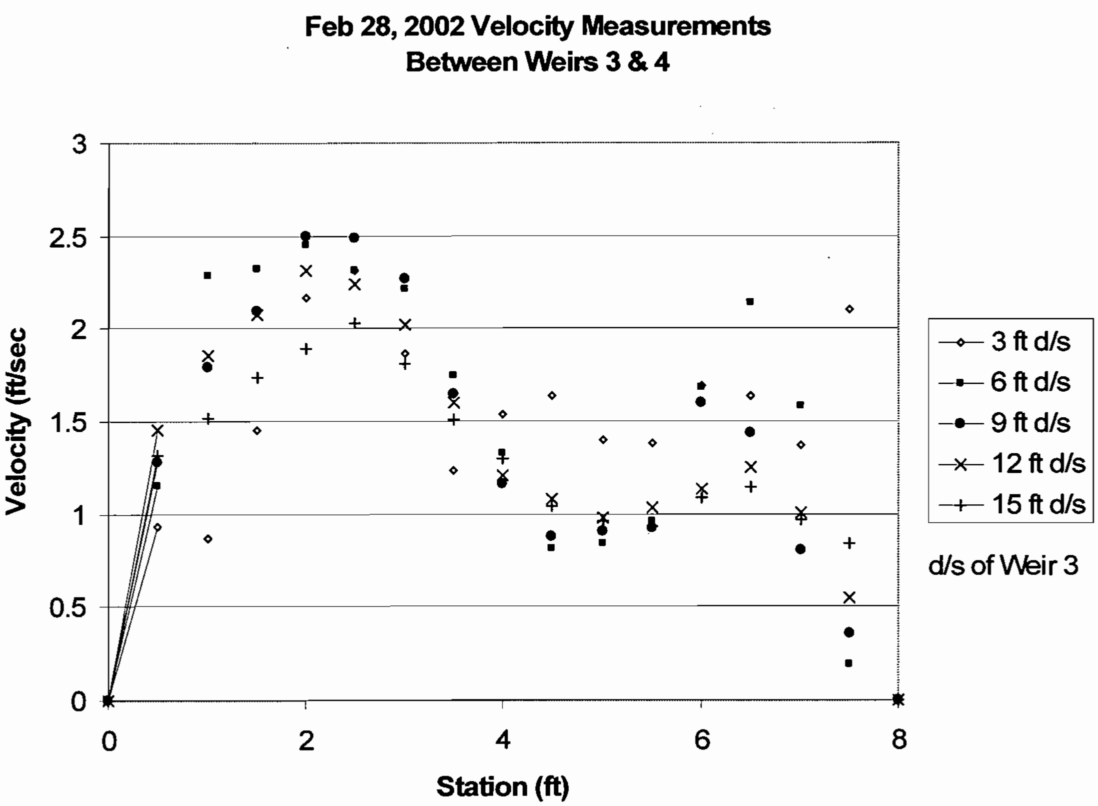


Figure 10. Velocities across the channel at the crest of weirs 3 and 4 (10a) and across the channel at cross-sections between weirs 3 and 4 (10b) in the 90° weir design in winter 2002.

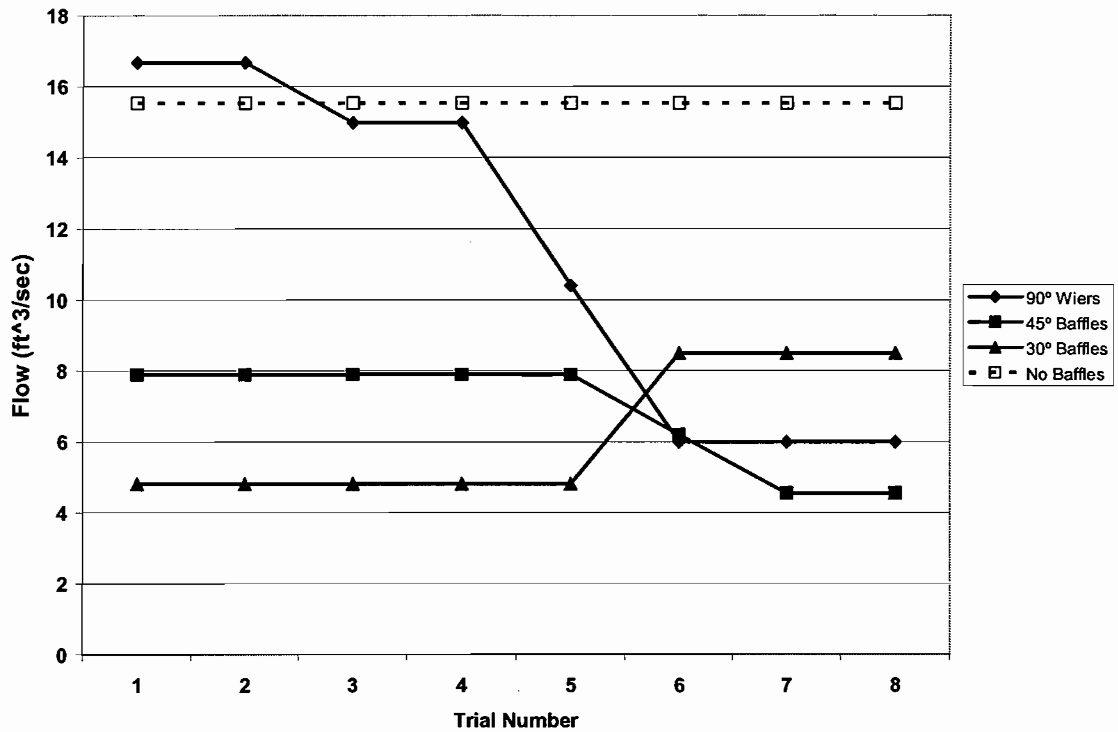


Figure 11. Total discharge (ft^3/s) for the different experimental trials.

Fish Movement

Juvenile steelhead trout successfully navigated upstream through the culvert for all of the baffle designs tested during winter and summer flows except for the 30° baffles in winter flows. The smallest trout to make it into the upstream trap completely through the culvert was 103 mm and the largest was 194 mm (Fig. 12). The total number of fish that made it upstream through the culvert for any of the baffle designs is reported in Appendix I.

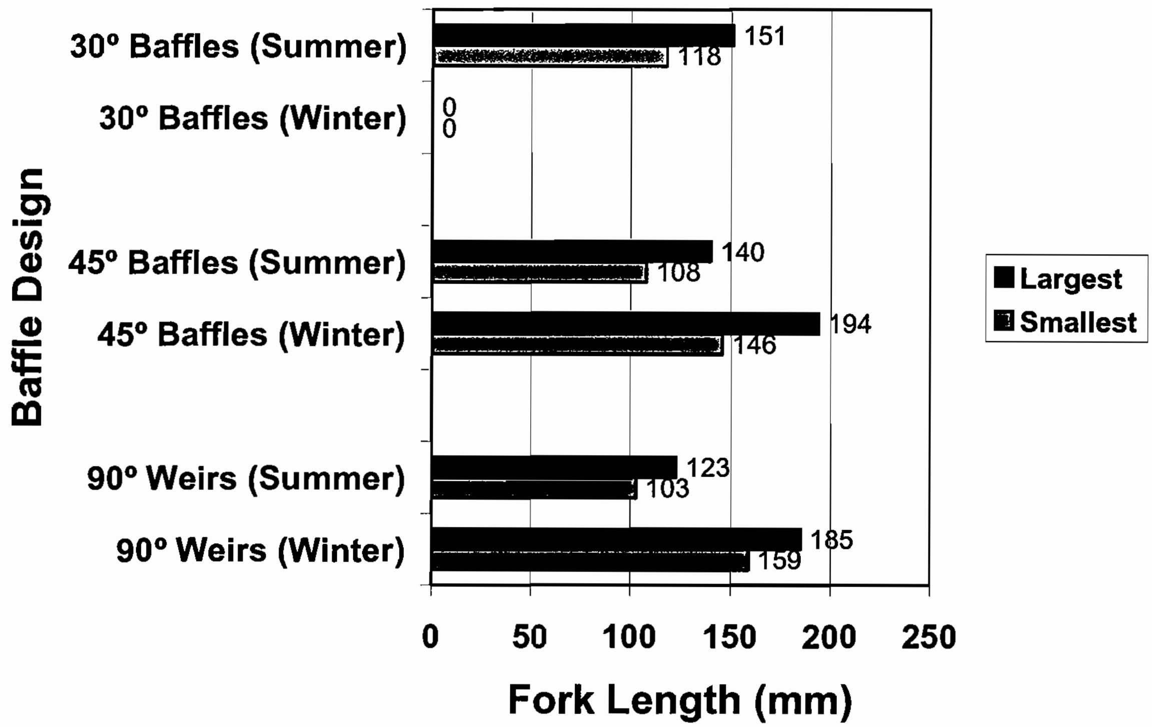


Figure 12. Sizes of steelhead trout that moved upstream during experimental releases under different baffles designs.

The percent of fish that maintained position or moved upstream was used as an indicator of the efficiency of each retrofit design. Adding baffles to the culvert increased the ability of steelhead trout to maintain their position within the culvert and allowed a small proportion to move upstream (Fig. 5). None of the trout moved upstream in the culvert prior to adding baffles. Only 2% of the released fish remained in the middle section of the culvert and 98% moved downstream during control releases. When baffles were added, 29% of the trout maintained position or moved upstream with the 30° baffle deflectors, 39% with the 45° baffle deflectors, and 38% with the 90° baffle weirs. Fish successfully passed through the culvert to the upstream trap with only the 45° baffle deflectors and 90° baffle weirs. Raw data from the individual releases are reported in Appendix I.

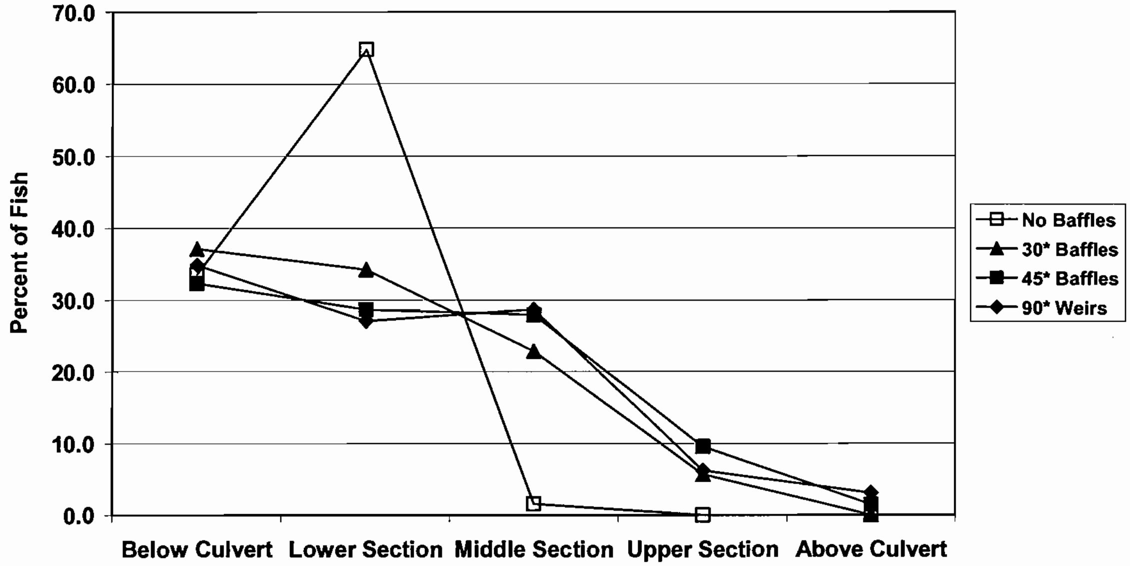


Figure 12. Fish movement through the culvert on Big Noise Creek during winter base flows.

During summer base flows, the addition of baffles also increased the ability of steelhead trout to maintain their position within the culvert and allowed a small proportion of trout to move upstream with certain retrofit designs (Fig. 13). None of the trout maintained position or moved upstream in the culvert prior to adding baffles. In the control releases 100% of fish moved downstream in the culvert. Downstream angled baffles were also ineffective at allowing fish to maintain their position with in the culvert. Over 95% of the released trout moved downstream with 30° and 45° baffles angled downstream. When the baffles were angled upstream, 27% of the trout maintained position or moved upstream with the 45° baffle deflectors, and 43% with the 30° baffle deflectors. The 90° baffles allowed 71.9% of juvenile trout to maintain position or move upstream. Fish successfully passed through the culvert to the upstream section with both the upstream angled baffles and 90° baffle weirs. The 45° baffles angled upstream had the most fish move up through the culvert (10%). Raw data from the individual releases are reported in Appendix I.

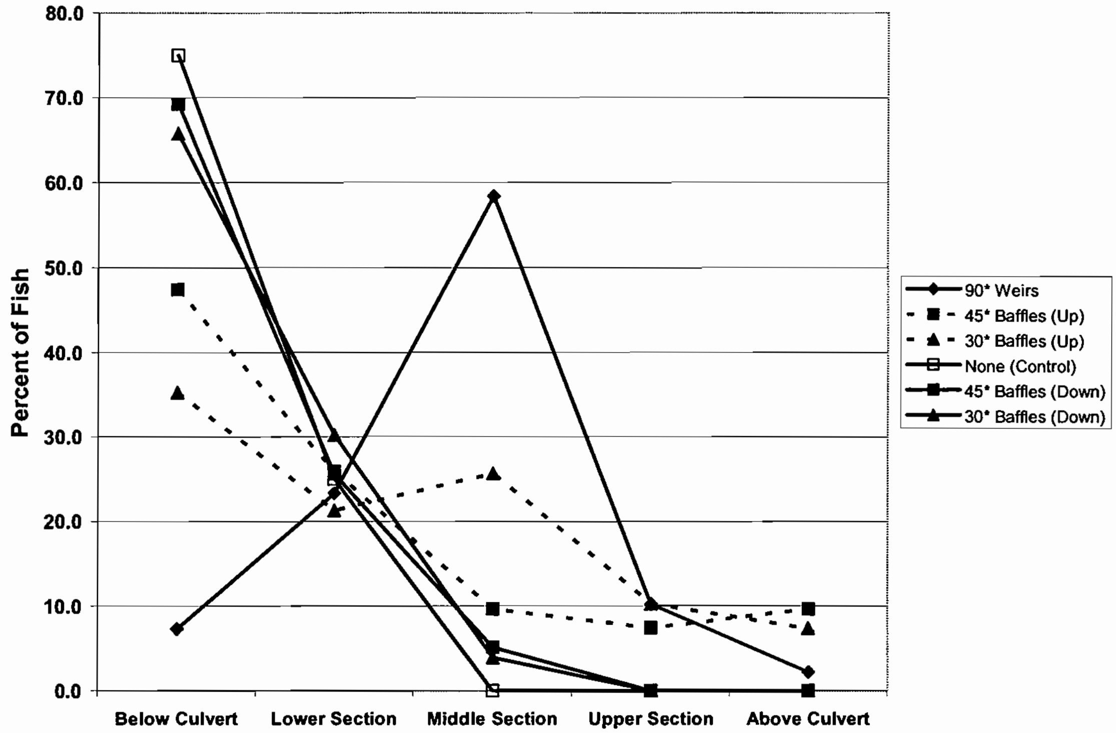


Figure 13. Fish movement through the culvert on Big Noise Creek during winter base flows.

Logistic regression was used to statistically analyze the results of the release studies at the Big Noise Creek culvert. Logistic regression is similar to linear regression except that the data does not have to be normally distributed. The data from Big Noise Creek was not distributed normally because the responses are discrete instead of continuous. The results are discrete because responses are whole fish and cannot be a fraction of a fish. The five zones the trout could move to within the culvert were divided into two groups for analyses; trout that maintained position or moved upstream and trout that moved downstream. The resulting distribution is a binomial distribution. Since the data were not normally distributed, a link function was used to create a normal distribution. This link is similar to a transformation typical in linear regression methods. The link is the logit function which is log (proportion/(1-proportion)). Once the regression coefficients have been calculated they must be back transformed into odds due to the logit link.

To analyze the data, we started with a full mixed generalized linear model with both continuous data (flow rates) and categorical data (baffle configuration). Flow data presented two problems. The flow rates were the same for all releases during the summer ,so there is co-linearity between the two variables when comparing seasons. In other words, we can determine whether the season effects (temp, food availability, etc.) or the difference in flow are causing the observed effects. The co-linearity does not allow us to discern if flow is affecting movement, so flow during the summer study could not be included in the model. During the winter studies, flow rates varied and were included in the model because they could be an explanatory variable for fish movement. When the winter flow rates were included in the model, flow was not a significant explanatory variable explaining fish movement (p-value=0.48), so it was removed from the model. Within the flow rates measured during the winter study (0.47 to 0.14 m^3/s), flow was not significantly related to movement of fish, but flow could be significant outside the range of rates that were measured.

When the regression coefficients are back transformed, resulting values are odds. Odds are represented by the omega symbol (?). For example if the odds of a baffle configuration were 6 to 1, then six fish moved downstream for every fish that maintained position or moved upstream. The lower the odds, the better a baffle configuration functioned at allowing trout to maintain position or move upstream within the culvert.

To compare baffle configurations to the control or to each other, the odds ratio must be calculated. If two configurations have odds of ? 1 and ? 2, then the odds ratio is calculated as f = ? 2/? 1. If the resulting ratio was 3, then the odds of ? 2 are 3 times greater than the odds of ? 1. If the odds ratio equals one, then the odds of the two separate events are equal. If the odds ratio does not equal one, then the odds may be significantly different. To test for significance, we must determine if the regression coefficients for each baffle configuration are equal to zero. A Wald test was used to determine if the coefficient was significantly different from zero (S-plus 6.1 statistical program,. The coefficients were calculated using maximum likelihood estimation and thus are asymptotically standard normal, which is why the Wald test was appropriate. The p-values were calculated using the least significant difference method.

Winter Baffle Comparisons

During winter base flows, movement through all of the retrofit designs were significantly different from the control. Trout generally maintained position or moved upstream. Under control conditions, the odds of a trout moving upstream were 75 to 1. In other words, 75 fish moved downstream for every fish that maintained position or moved upstream. The odds of the control were 48 times the odds of the 90° baffle weirs, 36 times the odds of the 45° baffles, and 20 times the odds of the 30° baffles. The odds ratios for all three retrofits compared to the control were significantly different from one (p-values <0.01). If the odds were equal to one, then there would be no difference between the control and the retrofit design. The 90° baffle weirs had the best odds at 1.56 to 1, next was the 45° baffle deflectors at 1.59 to 1, and finally the 30° baffles at 3.71 to 1 (Table 4).

Table 4: Statistical summary comparing each winter retrofit to the control

Configuration	Odds	Odds Ratio	p-value	SE	95% CI
Control	75.00 to 1	--	--	1	73.04 to 76.96
90°	1.56 to 1	48.2	< 0.001	1.03	-0.46 to 3.58
45°	1.59 to 1	36.1	< 0.001	1.03	-0.43 to 3.61
30°	3.71 to 1	20.2	0.002	1.04	1.67 to 5.75

The 90° weirs appear to be slightly better than other baffle configurations in allowing trout to maintain position or move upstream. The odds of the 45° baffle design are 1.36 times those of the 90° weirs, and this odds ratio was not significantly different from one indicating that the two designs were similar in their ability to allow trout to move upstream (p-value = 0.2). The odds ratio between the 90° and the 30° baffles indicates that the odds of the 30° baffles were 2.38 times larger. This ratio was significantly different from one indicating that there is a difference in trout response between the two designs (p-value = 0.01). Finally, the odds ratio between the 45° and the 30° baffles indicates that the 30° baffles odds are 1.78 times the 45° baffles, this ratio was not significantly different from one (p-value = 0.06). The 90° and the 45° baffles were similar in allowing trout to maintain position or move upstream within the culvert, while the 30° baffles were significantly different from the 90° baffles, but not significantly different from the 45° baffles. Table 6 is a statistical summary of the winter baffle comparisons.

Table 6. Statistical summary comparing the winter baffle configurations to each other

Configuration	Odds Ratio	p-value	SE	95% CI
90° vs. 45°	1.34	0.2	0.35	0.67 to 2.01
90° vs 30°	2.38	0.01	0.37	1.65 to 3.11
45° vs. 30°	1.78	0.06	0.37	1.05 to 2.51

Summer Baffle Comparisons

In summer, trout movement did not differ among the different baffle designs as compared to the control culvert conditions (odds ratios were not statistically significantly different). In the summer control releases, every trout moved downstream, so a large standard error resulted when comparing the control with the other configurations. Under control conditions the odds of a trout maintaining position or moving upstream were 121,016 to one, in other words 121,016 trout will move downstream for each trout that maintains position or moves upstream. As with the winter trials, the 90° baffle weirs had the best odds at 0.53 to 1. This was the only set of trials to have more fish maintain position or move upstream than moved downstream. For every trout that moved downstream 1.9 trout maintained position or moved upstream within the culvert. The 45° and 30° baffles that were angled downstream as in the winter trials had the largest odds at 24.3 to 1 and 18.5 to 1 respectively. When the 45° and 30° baffles were angled upstream, they increased the depth of flow and altered the hydraulics within the culvert to allow better trout passage. This increase in fish passage is represented by the dramatically decreased odds for each retrofit. The 45° upstream angled baffles had odds of 2.4 to 1, and the 30° baffles had odds of 1.2 to one. In other words when the 45° baffles were angled downstream 24.3 trout moved downstream for every trout that maintained position or moved upstream; when the baffles were angled upstream the number of trout that moved downstream for every trout that moved upstream decreased ten-fold to 2.4. This information is summarized in Table 7.

Table 7. Statistical summary comparing each retrofit to the control (summer)

Configuration	Odds	Odds Ratio	p-value	SE
Control	121,016.0 to 1	--	--	23.59
90°	0.53 to 1	229,066	0.3	23.59
45° upstream	2.39 to 1	50,607	0.32	23.59
30° upstream	1.20 to 1	101,069	0.31	23.59
45° downstream	24.33 to 1	5006	0.36	23.59
30° downstream	18.50 to 1	6541	0.36	23.59

In the experimental releases in summer, the 90° baffle weirs exhibited better fish passage than any other configuration (Table 8). The odds ratio when the 90° baffles were compared to the 30° upstream baffles was 2.27. Again, this ratio indicates that the odds of the 30° upstream baffles were 2.27 times the odds of the 90° baffle weirs. This ratio is significantly different from one signifying that there is a difference in the number of trout the maintained position or moved upstream between the two designs (p-value = <0.001). The odds ratio between the 90° baffle weirs and the 45° upstream angled baffles was 4.53, which was significantly different from one (p-value = <0.001). The downstream angled baffles had much higher odds ratios than was observed for the 90° weirs. The 30° baffles had an odds ratio of 35.02, while the 45° baffles had an odds ratio of 46.06. Theses ratios are about one order of magnitude larger than when the baffles were angled upstream. They are significantly different from one, indicating a difference in trout response between the weirs and the downstream angled baffles (p-value = <0.001). The 90° baffle weirs allowed the most fish to maintain their position or move upstream within the culvert during the summer trials.

After comparing the 90° baffle weirs to all the other designs, the 45° upstream baffles were then compared to the rest of the designs. The odds ratio between the 45° and the 30° upstream angled baffles was 0.5. The trout response was similar between these two designs because the odds ratio is not significantly different from one (p-value = 0.02). As with the 90° weirs, the downstream angled baffles had much higher odds ratios when compared with the 45° upstream baffles. The odds ratios for the 45° and 30° downstream angled baffles were 10.18 and 7.74 when compared to the 45° upstream baffles. These ratios were significantly different from one (p-value = <0.001). The 30° upstream angled baffles also had significantly different odds ratios when compared with the 45° and 30° downstream angled baffles (p-value = <0.001).

Table 8. Statistical summary comparing the summer baffle configurations

Configuration	Odds Ratio	p-value	SE	95% CI
90° vs. 45° up	4.53	< 0.001	0.34	3.86 to 5.2
90° vs. 30° up	2.27	< 0.001	0.33	1.62 to 2.92
90° vs. 45° down	46.06	< 0.001	0.63	44.83 to 47.29
90° vs. 30° down	35.02	< 0.001	0.56	33.92 to 36.12
45° up vs. 30° up	0.5	0.02	0.34	-0.17 to 1.17
45° up vs. 45° down	10.18	< 0.001	0.64	8.93 to 11.43
45° up vs. 30° down	7.74	< 0.001	0.57	6.62 to 8.86
30° up vs. 45° down	20.28	< 0.001	0.63	19.05 to 21.51
30° up vs. 30° down	15.42	< 0.001	0.56	14.32 to 16.52
45° down vs. 30° down	1.32	0.36	0.78	-0.21 to 2.85

There was essentially no difference in trout response between the two downstream angled baffles. When the 45° baffles were compared with the 30° baffles an odds ratio of 1.32 was derived, this was not significantly different from one indicating that the trout response was similar between the two designs (p-value = 0.36). The downstream angled baffles had a shallower depth of flow than the upstream angled baffles. This may have accounted for the differences in their ability to allow trout to maintain their position or move upstream inside the culvert compared to the upstream angled baffles.

Winter vs. Summer Baffle Comparisons

During the winter (variable flow) studies, all of the baffle designs were significantly better than the control (no baffles) at allowing trout to maintain position or move upstream within the culvert. The 90° weirs and the 45° baffles were similar in their ability to allow trout movement upstream. The 30° baffle design was significantly different from the 90° weirs, but not significantly different from the 45° baffles. The designs were in the following order from best odds to worst; 90° baffle weirs, 45° baffles, 30° baffles, and the control.

During the summer (constant low flow) trials, none of the baffle designs were significantly different from the control due to a large standard error. This error was a result of every fish moving downstream during the control releases. The odds of the control are four to six orders of magnitude larger than the various baffle designs, but could not be shown to be significantly different because not a single trout was able to maintain its position during the control releases. This was most likely due to extremely shallow water depths and high velocities within the culvert under control conditions. When the designs were compared to one another, the 90° weirs had the best odds of allowing fish to maintain their position or move upstream. The weirs were significantly different from all of the other designs. The 45° and 30° baffles that were angled downstream during winter flows were also angled upstream during summer flows to change flow characteristics. These designs were not significantly different from one another when angled the same direction, but the upstream angled baffles were significantly different from the same baffle designs angled downstream. The designs were in the following order from best odds to worst; 90° weirs, 30° upstream baffles, 45° upstream baffles, 30° downstream baffles, 45° upstream baffles, and the control.

Table 9. Comparison of baffle designs between winter and summer flows

Configuration	Odds Ratio	p-value	SE	95% CI
30° Down Winter	--	--	--	--
30° Down Summer	1.91	0.002	0.65	1.49 to 2.33
45° Down Winter	--	--	--	--
45° Down Summer	6.68	< 0.001	0.52	6.66 to 7.7
90° Weirs Winter	--	--	--	--
90° Weirs Summer	0.34	< 0.001	0.34	-0.33 to 1.01

The only baffle designs that were comparable between winter and summer flows were the 30° and 45° downstream angled baffles and the 90° baffle weirs (Table 9). The odds of a fish maintaining position or moving upstream within the culvert were 1.91 times greater during summer flows for the 30° downstream angled baffles. This value was significantly greater than one signifying a difference in fish response (p-value = 0.002). The odds for the 45° downstream angled baffles were 6.68 times greater during summer flows and were also significantly different (p-value = <0.001). The 90° weirs were more effective during the constant summer flows than during the variable winter flows. The odds during the winter were 2.94 times greater than during the summer. The two odds were significantly different from each other (p-value = <0.001). Each pair of identical baffle designs had significantly different abilities to allow trout to maintain position or move upstream between summer (constant, low) flows and winter (variable, higher) flows. Figure 14 compares the odds for each baffle design between summer and winter trials. The lower the odds the better the retrofit was at allowing fish to maintain their position or move upstream.

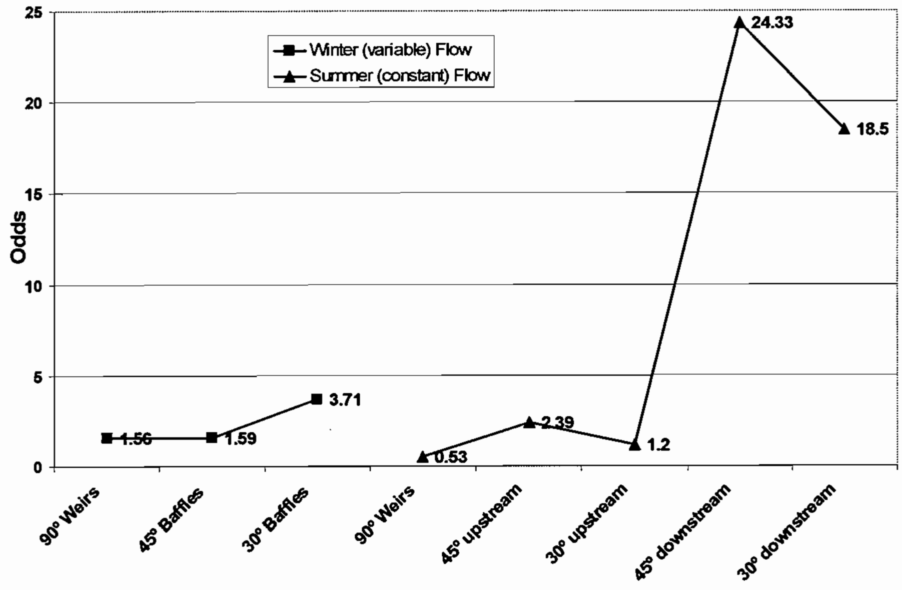


Figure 14. Comparison of odds ratios for movement with different baffle designs during summer and winter of 2002.

DISCUSSION

Long-term Experimental Study of Fish Movement

Although there were few findings of statistical significance in the tagging study, several important responses were observed. Cutthroat and steelhead trout moved upstream through three culverts in the study (Hayden, Canyon Cr. #2, and Canyon Cr. #3). The Hayden Creek culvert was 14.5 m long, had a 2.3% slope, a summer jump height into the culvert of 20 cm, and was retrofitted with 30° steel baffles. The Canyon Creek #2 culvert had a length of 83 m, a slope of 1.2%, a summer jump height of 40 cm, and was retrofitted with 30° plastic baffles. The Canyon Creek #3 culvert was similar with a length of 84 m, a slope of 1.0%, a summer jump height of 10 cm, and was retrofitted with 90° steel baffles. One movement up through the Canyon Creek #3 culvert is noteworthy. Between March and August 2001, a juvenile steelhead that was 107 mm in length moved upstream through the Canyon Creek #3 culvert. This culvert is retrofitted with 90° steel weirs and is 84 m long with a 10 cm jump into the culvert during summer flows. The minimum distance moved by this juvenile was 284 m within the 400 m study reach.

The only statistically significant difference in movements was at Little Lobster Creek. The percent of fish that moved downstream through the culvert (4.8%) was significantly different from the percent of fish that moved upstream through the culvert (0%). This culvert could be a barrier to upstream movement because no trout were found to pass up through the culvert. During the course of the study winter flows destroyed two large beaver dams upstream of the culvert. Many of the trout that were tagged in the upstream sections were found in the ponds behind these beaver dams. Some or most of these trout probably moved downstream after the collapse of the dams and the subsequent draining of the beaver ponds.

The relatively low recapture rates observed in the tagging study could be attributed to the size of the study reach. This is not unusual in studies of short reaches, and recent studies of fish in intermittent winter streams of the Willamette Valley observed less than 1% recapture (Randy Colvin, personal communication). If the tagged trout had larger home ranges than the study reach in which they were tagged, they could have easily moved outside the reach in between recapture dates. Another possible factor in the low recapture rates is that the stress of capturing and processing the juveniles cold have caused delayed mortalities in some of the tagged fish. Finally, the electrofishing procedure is not 100% effective in capturing all fish in a given reach. The streams selected for this study often had substantial amounts of large wood and other structures that made the capture of trout difficult. Future movement studies may look at alternatives to electrofishing such as telemetry or PIT-tag detector arrays.

With the exception of fish in Hayden Creek, less than 10% of the recaptured fish moved within the study reaches. Heggenes (1991) theorized that only a small fraction of a fish population may be mobile while a larger fraction is sedentary. The exploratory behavior exhibited by this mobile fraction ensures a certain amount of spatial flexibility in the population. When fish mortality or habitat disturbances create vacant niches, this mobile fraction will occupy those vacancies (Heggenes 1991). Our findings support Heggenes theory of a small mobile fraction of the population. Although this mobile fraction is relatively small compared to the whole population, it is important to allow connectivity within the stream environment for these mobile individuals. These individuals drive metapopulation dynamics and allow sink populations to persist through migrations from source populations. By establishing connectivity throughout the stream system, the carrying capacity for the stream is increased by allowing the mobile fraction of the population to quickly fill open niches within the system.

Short-term Experimental Study of Fish Movement

The short-term movement study at the Big Noise Creek culvert allowed us to test three baffle designs and a control within the same stream and culvert. Although variables such as temperature and flow could not be controlled, this design did allow almost all of the fish that were released to be recaptured. This part of the study provided greater statistical power than the tagging study while still maintaining an in-the-field setting.

Initially, we tried to provide various incentives to facilitate trout movement up through the culvert. The four incentives did not change trout movements in the culvert, and thus were not included in the statistical analysis. It should be noted that Dane (2000) found that food was an incentive for upstream movement of juvenile salmonids in Alaska. This was not the case in our study an Oregon coastal stream; baiting the upstream trap did not change movements within the culvert. Scaring the trout resulted in random movements away from the stimulus and not a general upstream movement. Overcrowding resulted in most of the fish staying where they were released, and only a few fish moving upstream, but no more than without the incentive. Leaving the lights on in the culvert did not appear to change movements within the culvert. If there is an incentive for upstream movement we could not find it. The incentive for upstream movement could be genetic or some combination of environmental stimulus that could not be included in this study.

Winter and summer releases included three retrofit design types (30° angled downstream, 45° baffles angled downstream, and 90° weirs) and a control (no baffles). A field review of the project found that the research team misunderstood the designs used by ODOT for diagonal baffles. ODOT typically angles the 30° and 45° baffles in an upstream direction to create more depth between baffles. This is particularly important during low flow because the upstream baffles backwaters the flow, providing more volume of water between baffles for fish. The summer study was expanded to include the four treatments (control (no baffles), 30° and 45° baffles angled downstream, and 90° weirs) plus additional treatments of 30° angled upstream and 45° baffles angled upstream.

During the larger, more variable winter flows the 90° and the 45° baffles had the best odds at allowing trout to maintain their position or move upstream within the culvert. The 30° baffles were significantly different than the two other designs, but were still much better than the control at allowing trout to maintain or move up. All of the baffle designs during the winter were significantly different than the control. These results indicate that movement up through a culvert similar to the Big Noise Creek culvert is only possible when that culvert has some structure within it. Without baffles, the streamflow within the culvert was shallower with a uniform velocity, and areas of hydraulic shadow (resting areas) were non-existent. When baffles were installed the streamflow within the culvert became deeper with more variable velocities, and areas of hydraulic shadow were frequent. Under these conditions juvenile steelhead were more likely to maintain their position or move upstream rather than immediately heading downstream.

During the lower volume constant summer flows the hydraulic conditions under control conditions were even worse. The depth of flow was less than the height of a juvenile steelhead, and again there were no areas of hydraulic shadow. Although not statistically significant from any of the baffle designs, the odds of a trout maintaining position or moving upstream under control conditions was 4 to 6 orders of magnitude larger than any of the baffle designs. As in the winter studies, the 90° weirs had the best odds of allowing steelhead trout to maintain their position or move upstream. The odds for the 90° weirs were significantly different from the other designs. Although the 45° and 30° downstream angled baffles allowed passage during winter flows, the summer flows were too low and the depth of the water in the culvert was in many cases less than the height of the juvenile steelhead trout. The odds greatly increased during summer trials from 1.59 to 24.33(45°) and 3.71 to 18.5(30°). We decided to test the baffles when they were angled upstream to see if any changes in movement were identifiable. When the baffles were angled upstream the depth of flow increased, but other hydraulic characteristics were similar. The odds of a steelhead trout maintaining position or moving upstream dropped an order of magnitude to 2.39 (45°) and 1.2 (30°) when the baffles were angled upstream. Unfortunately the winter trials were already concluded, so the upstream angled baffles could not be tested under variable winter flow conditions.

Many of the juvenile trout were captured or observed in the small gaps between the plastic baffles and the culvert wall, even within the baffle (the ends of the baffle were not closed to flow). Dane (2000) observed juveniles moving through gaps between weirs within a culvert and the culvert wall rather than leaping over the baffles. Leaving small gaps between the baffles and the culvert wall and leaving the ends of baffles open to flow may facilitate juvenile fish passage through the culvert. Juvenile steelhead seem to prefer to follow the culvert wall and move through gaps, rather than leap over obstructions. Not once during this project were juvenile trout observed leaping within the culvert.

Future studies should incorporate a larger study area than the one used in this study to capture mobile fish with large home ranges. The use of PIT tags would also be useful to identify individual fish and determine if the trout that are moving are the same or different fish in the population. Large PIT antennas that are left in the stream would allow more continuous observations of fish movements through a culvert. Large PIT antennas would also allow researchers to determine the timing of juvenile fish movements both daily and seasonal. Once mobile fish are identified via PIT tags, it would then be possible to use radio tags to follow these fish's movements throughout the year. The use of large PIT antennas and radio telemetry tags would expand on the observations made during the tagging portion of this study. Future studies similar to the controlled release portion of this study should incorporate other species of fish than steelhead trout and try different culvert retrofit options such as different baffle designs and stream simulation culverts. PIT tags would also be helpful with a similar controlled release study to test the same fish multiple times to see if they move upstream or downstream consistently.

Future Research

This research project focused on existing retrofitted culverts. We attempted to overcome the lack of statistical design caused by the small number of available culverts and the high variation in retrofit designs used in these culverts. The short-term releases in Big Noise Creek were designed to provide a common setting for comparing different baffle and weir designs with replication. Future studies could expand on this approach in several aspects:

- Research could include different species of salmon and trout.
- Before and after studies could be incorporated into new projects for retrofitting culverts to improve fish passage.
- Additional research with adult salmon in both field trials and experimental culverts would increase our understanding of the effectiveness of retrofitted culverts.
- Experiments could be designed to monitor movement through natural stream reaches. Natural unimpeded movement could be compared with 1) movement through natural impediments to movement (e.g., wood, boulder obstacles, falls or steps of different heights) and 2) obstacles or barriers created by culverts and retrofitted culverts.

Recommendations and Conclusions

- We conclude that culvert retrofitting using baffles or weirs increases the probability of salmonids moving upstream through a culvert during low flow and high flow.
    - Salmonids were observed to move through retrofitted culverts in field studies.
    - Weirs or baffles increased the likelihood of fish moving upstream in experimental trials in a culvert in Big Noise Creek.

- We conclude that 90° weirs and 45° upstream baffles are more effective in increasing upstream fish movement than other baffles designs or non-retrofitted culverts.

- Additional research with adult salmon in both field trials and experimental culverts would increase our understanding of the effectiveness of retrofitted culverts for passage of resident and anadromous salmonids.

Literature Cited

Allen, M. and Pyles, M. 1999. Designing Forest Road Stream Crossings for Fish Passage. International Mountain Logging and 10th Pacific Northwest Skyline Symposium; Corvallis, OR. Oregon State University.

Barber, M. E. and Downs, R. C. 1996. Investigation of culvert hydraulics related to juvenile fish passage. Pullman, Washington: Washington State Transportation Center. Washington State University, Dept. of Civil and Environmental Eng.

Bates, K.; Barnard, R.; Heiner, B.; Klavas, P., and Powers, P. 1999. Fish Passage Design at Road Culverts: A design manual for fish passage at road crossings. Olympia, WA: Washington Department of Fish and Wildlife, Habitat and Lands Program, Environmental Engineering Division.

Behlke, C.; Kane, D.; McClean, R. F., and Travis, M. D. 1991. Fundamentals of Culvert Design for Passage of Weak-Swimming Fish. Fairbanks, AK: Alaska DOT & PF, Research Station; FHWA-AK-RD-90-10. 2301 Peger Road, Fairbanks, AK 99709.

Bell, M. C. 1986. Fisheries handbook of engineering requirements and biological criteria. Portland, Oregon: Fish passage development and evaluation program, Corps of Engineers, North Pacific Division.

Bernard, D. R. and Israelson, E. K. 1982. Inter- and intrastream migration of cutthroat trout (Salmo clarki) in Spawn Creek, a tribuitary of the Logan River, Utah. Northwest Science. 56:148-158.

Bustard, D. R. and D. W. Narver. 1975. Aspects of the winter ecology of juvenile coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Salmo gairdneri*). Journal of the Fisheries Research Board of Canada 32:667-680.

Cotterell, E. 1998. Fisheries guidelines for design of stream crossings. Queensland Department of Primary Industrues; FHG 001.

Dane, B. G. 1978. Culvert Guidelines: Recommendations for the Design and Installation of Culverts in British Columbia to Avoid Conflict with Anadromous Fish. Vancouver, British Columbia: Fisheries and Marine Service, Department of Fisheries and Environment; 811.

Fausch, K. D. and Young, M. K. 1995. Evolutionary Significan Units and Movement of Resident Stream Fishes: A Cautionary Tale. American Fisheries Society Symposium.

Fitch, G. M. 1995. Nonanadromous Fish Passage in Highway Culverts. Charlottesville, VA: Virginia Department of Transportation; VTRC 96-R6. 530 Edgemont Road, Charlottesville, VA 229903-0817.

Groot, C., and L. Margolis, editors. 1991. Pacific salmon life histories. University of British Columbia Press, Vancouver.

Gross, M. R.; Coleman, R. M., and McDowall, R. M. 1988. Aquatic productivity and the evolution of diadromous fish migration. Science. 239:1291-1293.

Heggenes, J., T.G. Northcote, and A. Peter. 1991. Spatial stability of cutthroat trout (*Oncorhynchus clarki*) in a small, coastal stream. Can. J. Fish. Aquat. Sci. 48: 757-762.

Jones, D. R.; Kiceniuk, J. W., and Bamford, O. S. 1974. Evaluation of the swimming performance of several fish species from the Mackenzie River. J. Fish.

Kane, D. L.; Belke, C. E.; Gieck, R. E., and McLean, R. F. 2000. Juvenile Fish Passage Through Culverts in Alaska. Fairbanks, AK: Water and Environmental Research Center, University of Alaska-Fairbanks; INE/WERC 00.05.

Katopodis, C. 1991. Introduction to Fishway Design. Winnipeg, Manitoba: Freshwater Institute, Central and Arctic Region; R3T2N6. 510 University Crescent, Winnipeg, Manitobe, Canada.

Katopodis, C.; Robinson, P. R., and Sutherland, B. G. 1978. A Study of Model and Prototype Culvert Baffling for Fish Passage. Winnepeg, Manitoba: Fisheries and Marine Service, Department of Fisheries and the Environment; 828.

Klingeman, P. C. 2000. Streams and stream simulation for culvert fish passage. Culverts 2000: Oregon State University, Civil Engineering Department.

McKinley, W. R. and Webb, R. D. 1956. A proposed correction of migratory fish problems at box culverts. Fish. Res. Papers. 1:33-45.

Northcote, T.G. 1992. Migration and residency in stream salmonids: some ecological considerations and evolutionary consequences. Nordic Journal of Freshwater Resources 67:5- 17.

Powers, P. D. 1996. Culvert Hydraulics Related to Upstream Juvenile Salmon Passage. Washington Department of Fish and Wildlife, Habitat Program.

Saltzman, W. and Koski, R. O. 1971. Fish Passage Through Culverts. Oregon State Game Comission.

Shirvell, C. S. 1994. Effects of changes in streamflow on the micorhabitat use and movements of sympatric juvenile coho (Oncorhynchus kisutch) and chinook salmon (O.tshawytscha) in a natural stream. Can. J. Fish. Aquat. Sci. 51:1644-1652.

Shoemaker, R. H. 1956. Hydraulics of Box Culverts with Fish-Ladder Baffles. Highway Research Board Proceedings. 35.

Watts, F. J. 1974. Design of Fishways. Moscow, ID: Water Resources Institute, University of Idaho.

Webb, P. W. and Weihs, D. 1983. Fish biometrics. New York, New York: Praeger Publishers.

Additional Culvert Literature

--. A Review and Resolution of Fish Passage Problems at Culvert Sites in British Columbia. Vancouver, British Columbia: Department of Fisheries and Environment; 1978; 810.

---. Hydraulics of culvert fishways IV: spoiler baffle culvert fishways. Canadian Journal of Civil Engineering. 1991; 18(1):76-82.

---. Hydraulics of culvert fishways V: Alberta fish weirs and baffles. Canadian Journal of Civil Engineering. 1990; 17(6):1015-1021.

---. Hydraulics of offset baffle culvert fishways. Canadian Journal of Civil Engineering. 1988; 15(6):1043-1051.

---. Hydraulics of steepass fishways. Canadian Journal of Civil Engineering. 1991; 18(6):1024-1032.

Allen, M. and Pyles, M. Designing Forest Road Stream Crossings for Fish Passage. International Mountain Logging and 10th Pacific Northwest Skyline Symposium; Corvallis, OR. Oregon State University; 1999.

Amundsen, P. A.; Damsgård, B.; Arnesen, A. M.; Jøbling; M.; Jorgensen, E. H. 1995. Experimental evidence of cannibalism and prey specialization in Arctic charr, Salvelinus alpinus . Environmental Biology of Fishes 43: 285-293.

Anderson, L. and Bryant, M. D. Fish passage at road crossings: an annotated bibliography. Portland, OR: USDA, Forest Service, Pacific Northwest Forest and Range Experimental Station; 1980; General Technical Report PNW-117.

Avery, E. L. 1985. Sexual maturity and fecundity of brown trout in central and northern Wisconsin streams. Technical Bulletin No. 154. Madison, WI: Wisconsin Department of Natural Resources.

Bachman, R.A. 1984. Foraging behavior of free-ranging wild and hatchery brown trout in a stream. Transactions of the American Fisheries Society 113:1-32

Baker, C. O. and Votapka, F. E. Fish Passage Through Culverts. San Dimas, CA: USDA, Forest Service Technology and Development Center; 1990; FHWA-FL-90-006.

Baltz, D. M.; Moyle, P. B. 1984. Segregation by species and size classes of rainbow trout, Salmo gairdneri, and Sacramento sucker, Catostomus occidentalis, in three California streams. Environmental Biology of Fishes 10: 101-110.

Baltz, D. M.; Vondracek, B.; Brown, L. R.; Moyle, P. B. 1987. Influence of temperature on microhabitat choice by fishes in a California stream. Transactions of the American Fisheries Society 116: 12-20.

Barrett, J. C.; Grossman, G. D.; Rosenfeld, J. 1992. Turbidity-induced changes in reactive distance of rainbow trout. Transactions of the American Fisheries Society 121: 437-443.

Bates, K. Fishway Design Guidelines for Pacific Salmon. Olympia, WA: Washington Department of Fish and Wildlife; 1994; 1.5:1~1~13~4.

Bates, K.; Barnard, R.; Heiner, B.; Klavas, P., and Powers, P. Fish Passage Design at Road Culverts: A design manual for fish passage at road crossings. Olympia, WA: Washington Department of Fish and Wildlife, Habitat and Lands Program, Environmental Engineering Division; 1999.

Behlke, C.; Kane, D.; McClean, R. F., and Travis, M. D. Fundamentals of Culvert Design for Passage of Weak-Swimming Fish. Fairbanks, AK: Alaska DOT & PF, Research Station; 1991; FHWA-AK-RD-90-10. 2301 Peger Road, Fairbanks, AK 99709.

Behnke, R. J. 1992. Native trout of western North America. Bethesda MD: American Fisheries Society; 275 p.

Belford, D. A. and Gould, W. R. An evaluation of trout passage through six highway culverts in Montana. North American Journal of Fisheries Management. 1996; 9:437-445.

Bell, M. Fisheries Handbook of Engineering Requirements and Biological Criteria. Portland, OR: US Army Corps of Engineers, North Pacific Division; 1990.

Bender, M. J.; Katopodis, C., and Simonovic, S. P. A prototype expert system for fishway design. Environmental Monitoring and Assessment. 1992; 23:115-127.

Beschta, R. L. Road Drainage Structures: Culvert Sizing at Stream Crossings. Corvallis, OR: College of Forestry, Oregon State University; 1984.

Binns, N.A. 1977. Present status of indigenous populations of cutthroat trout, Salmo clarki in southwest Wyoming. Wyoming Game and Fish Department, Cheyenne. Fisheries Technical Bulletin 2.

Bjornn, T.C., and J. Mallet. 1964. Movements of planted and wild trout in an Idaho river system. Transactions of the American Fisheries Society 93: 70-76.

Bovee, K. D. 1982. A guide to stream habitat analysis using the Instream Flow Incremental Methodology. Instream Flow Information Paper 12, FWS/OBS-82/26. Washington, DC: U. S. Fish and Wildlife Service, Office of Biological Services; 248 p.

Bowen, M. D. 1996. Habitat selection and movement of a stream-resident salmonid in a regulated river and tests of four bioenergetic optimization models. Logan: Utah State University; 154 p. Ph.D. dissertation.

Bozek, M.A. 1990. Generality of habitat models for Colorado River cutthroat trout fry and the influence of adults on habitat choice and behavior. Doctoral dissertation, University of Wyoming, Laramie.

Brown, H. W. 1974. Handbook of the effects of temperature on some North American fishes. Canton, Ohio: American Electric Power Service Corporation.

Brown, L. C.; Barnwell, T. O. J. 1987. The enhanced stream water quality models QUAL2E and QUAL2E-UNCAS: documentation and user manual. EPA/600/3-87/07. Athens, GA: Environmental Research Laboratory, U.S. Environmental Protection Agency; 189 p.

Brown, L. R.; Moyle, P. B. 1991. Changes in habitat and microhabitat partitioning within an assemblage of stream fishes in response to predation by Sacramento squawfish (Ptychocheilus grandis). Canadian Journal of Fisheries and Aquatic Sciences 48: 849-856.

Bryant, M. D. Evaluation of a Small Diameter Baffled Culvert for Passing Juvenile Salmonids. Pacific Northwest Forest and Range Experiment Station: USDA, Forest Service; 1981; PNW-384.

Bull, C. D.; Metcalfe, N. B.; Mangel, M. 1996. Seasonal matching of foraging to anticipated energy requirements in anorexic juvenile salmon. Proceedings of the Royal Society of London B 263: 13-18.

Bustard, D. R. and Narver, D. W. Preferences of Juvenile Coho Salmon and Cutthroat Trout Relative to Simulated Alteration of Winter Habitat. J. Fish. Res. Board Can. 1975; 32(5):681-687.

Campbell, A. J. and Sidle, R. C. Prediction of Peak Flows on Small Watersheds in Oregon for Use in Culvert Design. Water Resources Bulletin. 1984; 20(1):9-14.

Carlander, K. D. 1969. Handbook of freshwater fishery biology, Vol. 1. Ames, IA: The Iowa State University Press.

Clapp, D.F., R.D. Clark, Jr., and J.S. Diana. 1990. Range, activity, and habitat of large free-ranging brown trout in a Michigan stream. Transactions of the American Fisheries Society 119:1022-1034.

Clay.C.H. Design of fishways and other facilities. Boca Raton: Lewis Publishers; 1995.

Conder, A.L., and T.C. Annear. 1987. Test of weighted usable area estimates derived from a PHABSIM model for instream flow studies on trout streams. North American Journal of Fisheries Management 7:339-350

Cotterell, E. Fisheries guidelines for design of stream crossings. Queensland Department of Primary Industrues; 1998; FHG 001.

Cunjak, R. A.; Prowse, T. D.; Parrish, D. L. 1998. Atlantic salmon (Salmo salar) in winter: "The season of parr discontent"? Canadian Journal of Fisheries and Aquatic Sciences 55(Suppl. 1): 161-180.

Cutts, C. J.; Brembs, B.; Metcalfe, N. B.; Taylor, A. C. 1999. Prior residence, territory quality and life-history strategies in juvenile Atlantic salmon (Salmo salar L.). Journal of Fish Biology 55: 784-794.

Dane, B. G. Culvert Guidelines: Recommendations for the Design and Installation of Culverts in British Columbia to Avoid Conflict with Anadromous Fish. Vancouver, British Columbia: Fisheries and Marine Service, Department of Fisheries and Environment; 1978; 811.

Decker, L.M., and D.C. Erman. 1992. Short-term seasonal changes in composition and abundance of fish in Sagehen Creek, California. Transactions of the American Fisheries Society 121:297-306

Derksen, A. J. Evaluation of Fish Passage Through Culverts at the Goose Creek Road Crossing near Churchill, Manitoba, in April and May, 1977. Province of Manitoba: Manitoba Department of Natural Resources; 1980; 80-4.

DeVries, P. 1997. Riverine salmonid egg burial depths: review of published data and implications for scour studies. Canadian Journal of Fisheries and Aquatic Sciences 54: 1685-1698.

Dickerson, B. R.; Vinyard; G. L. 1999. Effects of high chronic temperatures and diel temperature cycles on the survival and growth of Lahontan cutthroat trout. Transactions of the American Fisheries Society 128: 516-521.

Dimeo, A. Correcting Vertical Fish Barriers; Investigation of Steeppass and Fish Ladders. Missoula, MT: USDA, Forest Service, Equipment Development Center; 1977; 2613.

Dingman, S. L. 1989. Probability distribution of velocity in natural channel cross sections. Water Resources Research 25: 509-518.

Eiserman, F. 1958. A fisheries survey of the Little Snake River drainage. Wyoming Game and Fish Commission, Cheyenne. Fisheries Technical Report 6.

Elliott, J. M. 1994. Quantitative ecology and the brown trout. New York: Oxford University Press; 286 p.

Engle, P. Fish Passage Facilities for Culverts of the MacKenzie Highway. Burlington, Ontario: Department of the Environment, Hydraulics Division, Canada Center for Inland Waters; 1974.

Essington, T. E.; Sorensen, P. W.; Paron, D. G. 1998. High rate of redd superimposition by brook trout (Salvelinus fontinalis) and brown trout (Salmo trutta) in a Minnesota stream cannot be explained by habitat availability alone. Canadian Journal of Fisheries and Aquatic Sciences 55: 2310-2316.

Evans, W. A. and Johnson, F. B. Fish Migration and Fish Passage: A Practical Guide to Solving Fish Passage Problems. USDA, Forest Service, Region 5; 1972.

Fausch, K. D. 1984. Profitable stream positions for salmonids: relating specific growth rate to net energy gain. Canadian Journal of Zoology 62: 441-451.

Fausch, K.D., and M.K. Young. In press. Movement of resident stream fishes and managing ESU'S: a cautionary tale. In Proceedings of the conference on evolution and the aquatic ecosystem: defining unique units in population conservation. American Fisheries Society, Bethesda, Maryland.

Fausch, K.D., C.L. Hawkes, and M.G. Parsons. 1988. Models that predict standing crop of stream fish from habitat variables: 1950-85. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon. General Technical Report PNW-GTR-213.

Fitch, G. M. Nonanadromous Fish Passage in Highway Culverts. Charlottesville, VA: Virginia Department of Transportation; 1995; VTRC 96-R6. 530 Edgemont Road, Charlottesville, VA 229903-0817.

Gebhards, J. R. and Fisher, J. Fish Passage and Culvert Installations. Idaho: Idaho Fish and Game Department; 1972.

Gerking, S.D. 1959. The restricted movement of fish populations. Biological Review 34:221-242.

Giannico, G. R. and Healey, M. C. Effects of Flow and Food on Winter Movements of Juvenile Coho Salmon. Transactions of the American Fisheries Society. 1998; 127:645-651.

Gilpin, M.E. 1987. Spatial structure and population vulnerability. Pages 125-140 in M.E. Soule', editor. Viable populations for conservation. Cambridge University Press, Cambridge.

Gowan, C. 1995. Trout responses to habitat manipulation in streams at individual and population scales. Fort Collins: Colorado State University; 232 p. Ph.D. dissertation.

Gowan, C., M.K. Young, K.D. Fausch, and S.C. Riley. In press. The restricted movement of stream-resident salmonids: a paradigm lost? Canadian Journal of Fisheries and Aquatic Sciences.

Gowan, C.; Fausch, K. D. 1996. Mobile brook trout in two high-elevation Colorado streams: re-evaluating the concept of restricted movement. Canadian Journal of Fisheries and Aquatic Sciences 53: 1370-1381.

Grant, J. W. A.; Kramer, D. L. 1990. Territory size as a predictor of the upper limit to population density of juvenile salmonids in streams. Canadian Journal of Fisheries and Aquatic Sciences 47: 1724-1737.

Gregory, R. S.; Levings, C. D. 1999. The effects of turbidity and vegetation on the risk of juvenile salmonids, Oncorhynchus spp., to predation by adult cutthroat trout, O. clarki . Transactions of the American Fisheries Society 127: 275-285.

Griffiths, J. S.; Alderdice, D. F. 1972. Effects of acclimation and acute temperature experience on the swimming speed of juvenile coho salmon. Journal of the Fisheries Research Board of Canada 29: 251-264.

Grimm, V.; Wyszomirski, T.; Aikman, D.; Uchmanski, J. 1999. Individual-based modelling and ecological theory: synthesis of a workshop. Ecological Modelling 115: 275-282.

Hanski, I., and M. Gilpin. 1991. Metapopulation dynamics: brief history and conceptual domain. Biological Journal of the Linnean Society 42:3-16.

Hanson, P.; Johnson, T.; Kitchell, J.; Schindler, D. E. 1997. Fish bioenergetics 3.0. Madison, WI: University of Wisconsin Sea Grant Institute.

Harper, S. J.; Westervelt, J. D.; Trame, A. M. 2000. Management application of an agent-based model: control of cowbirds at the landscape scale. In: Gimblett, R., ed. Integrating geographic information system and agent based modeling techniques for simulating social and ecological processes. Oxford: Oxford University Press.

Harvey, B. C. 1998. The influence of large woody debris on retention, immigration and growth of coastal cutthroat trout (Oncorhynchus clarki clarki) in stream pools. Canadian Journal of Fisheries and Aquatic Sciences 55: 1902-1908.

Harvey, B. C.; Nakamoto, R. J.; White, J. L. 1999. The influence of large woody debris and a bankfull flood on movement of resident coastal cutthroat trout during fall and winter. Canadian Journal of Fisheries and Aquatic Sciences 56: 2161-2166.

Harvey, B. C.; Stewart, A. J. 1991. Fish size and habitat depth relationships in headwater streams. Oecologia 87: 336-342.

Haschenburger, J. K. 1999. A probability model of scour and fill depths in gravel-bed channels. Water Resources Research 35: 2857-2869.

Heggenes, J., T.G. Northcote, and A. Peter. 1991. Spatial stability of cutthroat trout (Oncorhynchus clarki) in a small, coastal stream. Canadian Journal of Fisheries and Aquatic Sciences 48:757-762.

Heggenes, J.; Bagliniere, J. L.; Cunjak, R. A. 1999. Spatial niche variability for young Atlantic salmon (Salmo salar) and brown trout, (S. trutta) in heterogeneous streams. Ecology of Freshwater Fish 8: 1-21.

Herger, L.G., W.A. Hubert, and M.K. Young. In review. Evaluation of a basin-wide inventory of cutthroat trout habitat in small mountain streams. North American Journal of Fisheries Management.

Hill, J.; Grossman, G. D. 1993. An energetic model of microhabitat use for rainbow trout and rosyside dace. Ecology 74: 685-698.

Hokanson, K. E. F.; Kleiner, C. F.; Thorslund, T. W. 1977. Effects of constant temperatures and diel temperature fluctuations on specific growth and mortality rates and yield of juvenile rainbow trout (Salmo gairdneri). Journal of the Fisheries Research Board of Canada 34: 639-648.

Hoover, E.E., and M.S. Johnson. 1937. Migration and depletion of stocked brook trout. Transactions of the American Fisheries Society 67:224-227.

Hughes, N. F. 1992a. Ranking of feeding positions by drift-feeding arctic grayling (Thymallus arcticus) in dominance hierarchies. Canadian Journal of Fisheries and Aquatic Sciences 49: 1994-1998.

Hughes, N. F. 1992b. Selection of positions by drift-feeding salmonids in dominance hierarchies: Model and test for arctic grayling (Thymallus arcticus) in subarctic mountain streams, interior Alaska. Canadian Journal of Fisheries and Aquatic Sciences 49: 1999-2008.

Hughes, N. F. 1998. A model of habitat selection by drift-feeding stream salmonids at different scales. Ecology 79: 281-294.

Hughes, N. F.; Dill, L. M. 1990. Position choice by drift-feeding salmonids: model and test for arctic grayling (Thymallus arcticus) in subarctic mountain streams, interior Alaska. Canadian Journal of Fisheries and Aquatic Sciences 47: 2039-2048.

Hunter, L. A. and Mayor, L. Analysis of Fish Swimming Performance Data, Volume 1. 1986.

Johnsson, J.I.; Nöbbelin, F.; Bohlin, T. 1999. Territorial competition among wild brown trout fry: effects of ownership and body size. Journal of Fish Biology 54: 469-472.

Jonsson, B. 198.5. Life history patterns of freshwater resident and sea-run migrant brown trout in Norway. Transactions of the American Fisheries Society 114:82-194.

Jordan, M. C. and Carlson, R. F. Design of Depressed Invert Culverts. Fairbanks, AK: Water Research Center, Institute of Northern Engineering, University of

Alaska-Fairbanks; 1987; FHWA-AK-RD-87-23.

June, J. A. 1981. Life history and habitat utilization of cutthroat trout (Salmo clarki) in a headwater stream on the Olympic Peninsula, Washington. Seattle: University of Washington; 115 p. M.S. thesis.

Jungwirth, M.; Schmutz, S., and Weiss, S. Fish Migration and Fish Bypasses. Oxford: Fishing News Books; 1998.

Kane, D. and Wallen, P. M. A Hydraulic Evaluation of Fish Passage Through Roadway Culverts in Alaska. Fairbanks, AK: Water Center/Institute of Water Engineering, University of Alaska-Fairbanks; 1985; FHWA-AK-RD-85-24.

Kane, D. L.; Belke, C. E.; Gieck, R. E., and McLean, R. F. Juvenile Fish Passage Through Culverts in Alaska. Fairbanks, AK: Water and Environmental Research Center, University of Alaska-Fairbanks; 2000; INE/WERC 00.05.

Katopodis, C. Introduction to Fishway Design. Winnipeg, Manitoba: Freshwater Institute, Central and Arctic Region; 1991; R3T2N6. 510 University Crescent, Winnipeg, Manitobe, Canada.

Katopodis, C.; Robinson, P. R., and Sutherland, B. G. A Study of Model and Prototype Culvert Baffling for Fish Passage. Winnepeg, Manitoba: Fisheries and Marine Service, Department of Fisheries and the Environment; 1978; 828.

Kay, A. R. and Lewis, R. B. Passage of Anadromous Fish Thru Highway Drainage Structures. California: Department of Public Works, Division of Highways, District 01, Hydraulics Section; 1970; 629110.

Knapp, S. M. Evaluation of Juvenile Fish Bypass and Adult Fish Passage Facilities at Water Diversions. Oregon Department of Fish and Wildlife; 1994; 89-024-01.

Kondolf, G. M. 2000. Assessing salmonid spawning gravel quality. Transactions of the American Fisheries Society 129: 262-281.

Lowman, B. Investigation of Fish Passage Problems Through Culverts. Missoula, MT: USDA, Forest Service, Equipment Development Center; 1974; 2427.

MacPhee, C. and Watts, F. J. Swimming Performance of Arctic Grayling in Highway Culverts. Moscow, ID: University of Idaho, Forest, Wildlife, and Range Experiment Station; 1976; 13.

Mangel, M. 1996. Life history invariants, age at maturity and the ferox trout. Evolutionary Ecology 10: 249-263.

Mangel, M.; Clark, C. W. 1986. Toward a unified foraging theory. Ecology 67: 1127-1138.

McClellan, T. Fish Passage Through Highway Culverts. Portland, OR: US Department of Transportation, Federal Highway Admnistration; 1971; 800332.

McKinley, W. R. and Webb, R. D. A proposed correction of migratory fish problems at box culverts. Fish. Res. Papers. 1956; 1:33-45.

Metsker, H. E. Fish Versus Culverts: Some Considerations for Resource Managers. Washington, D.C.: Techincal Information Center, Division of Engineering, USDA Forest Service; 1970; ETR-7700-5.

Meyers, L.S., T.F. Thuemler, and G.W. Kornely. 1992. Seasonal movements of brown trout in northeast Wisconsin. North American Journal of Fisheries Management 12:433- 441.

Miller, R.B. 1957. Permanence and size of home territory in stream-dwelling cutthroat trout. Journal of the Fisheries Research Board of Canada 14:687-691.

Milner, A.M., and R.G. Bailey. 1989. Salmonid colonization of new streams in Glacier Bay National Park, Alaska. Aquaculture and Fisheries Management 20: 179-192.

Mirati, A. H. Assessment of road culverts for fish passage problems on state and county-owned roads: statewide summary report. Portland, OR: Oregon Department of Fish and Wildlife; 1999.

Moll, J. Paving of Corrugated Metal Pipe Inverts for Repari and Fish Passage. USDA Forest Service, Technology and Development Program; 1993.

Morin, A.; Dumont, P. 1994. A simple model to estimate growth rate of lotic insect larvae and its value for estimating population and community production. Journal of the North American Benthological Society 13: 357-367.

Moyle, P. B.; Baltz, D. M. 1985. Microhabitat use by an assemblage of California stream fishes: Developing criteria for instream flow determinations. Transactions of the American Fisheries Society 114: 695-704.

Myrick, C. A. 1998. Temperature, genetic, and ration effects on juvenile rainbow trout (Oncorhynchus mykiss) bioenergetics. Davis: University of California; 65 p. Ph.D. dissertation.

Myrick, C. A.; Cech, J. J., Jr. 1996. The effects of elevated rearing temperatures and genetics on trout bioenergetics. In: Swanson, C.; Young, P.; MacKinlay, D., editors. Proceedings of the applied environmental physiology of fishes symposium; Bethesda, Maryland: American Fisheries Society; 41-47.

Nielsen, J. L. 1992. Microhabitat-specific foraging behavior, diet, and growth of juvenile coho salmon. Transactions of the American Fisheries Society 121: 617-634.

Nislow, K.; Folt, C.; Seandel, M. 1998. Food and foraging behavior in relation to microhabitat use and survival of age-0 Atlantic salmon. Canadian Journal of Fisheries and Aquatic Sciences 55: 116-127.

Northcote, T.G. 1992. Migration and residency in stream salmonids: some ecological considerations and evolutionary consequences. Nordic Journal of Freshwater Resources 67:5- 17.

ODOT. Salmon Restoration Plan (A Component of the Oregon Plan). Portland, OR: Oregon Department of Transportation; 1997.

Pacific Gas and Electric Company (PG&E). 1994. Evaluation of factors causing variability in habitat suitability criteria for Sierra Nevada trout. Report 009.4-94.5. San Ramon, CA: Pacific Gas and Electric Company, Department of Research and Development.

Pacific Gas and Electric Company (PG&E). 1997. Guidance for using a bioenergetics model to assess effects of stream temperature. Report 001.8-97.8. San Ramon, CA: Pacific Gas and Electric Company, Department of Technical and Ecological Services.

Peake, S.; McKinley, R. S., and Scruton, D. A. Swimming performance of various freshwater Newfoundland salmonids relative to habitat selection and fishway design. Journal of Fish Biology. 1997; 51:710-723.

Platts, W.S., and R.L. Nelson. 1988. Fluctuations in trout populations and their implications for land-use evaluations. North American Journal of Fisheries Management 8:333-345.

Poff, N. L.; Huryn, A. D. 1998. Multi-scale determinants of secondary production in Atlantic salmon (Salmo salar) streams. Canadian Journal of Fisheries and Aquatic Sciences 55: 201-217.

Post, J. R.; Parkinson, E. A.; Johnston, E. A. 1998. Spatial and temporal variation in risk to piscivory of age-0 rainbow trout: patterns and population level consequences. Transactions of the American Fisheries Society 127: 932-942.

Power, M. E. 1987. Predator avoidance by grazing fishes in temperate and tropical streams: importance of stream depth and prey size. In: Kerfoot, W. C.; Sih, A., eds. Predation, direct and indirect impacts on aquatic communities. Hanover: University Press of New England; 333-352.

Powers, P. D. Culvert Hydraulics Related to Upstream Juvenile Salmon Passage. Washington Department of Fish and Wildlife, Habitat Program; 1996.

Powers, P. D. and Orsborn, J. F. Analysis of Barriers to Upstream Fish Migration--An Investigation of the Physical and Biological Conditions Affecting Fish Passage Success at Culverts and Waterfalls. Pullman, WA: Washington State University, Albrook Hydraulics Laboratory; 1985; 82-14.

Preall, R. J.; Ringler, N. H. 1989. Comparison of actual and potential growth rates of brown trout (Salmo trutta) in natural streams based on bioenergetic models. Canadian Journal of Fisheries and Aquatic Sciences 46: 1067-1076.

Pyles, M. R. and Skaugset, A. E. Peak flow estimation and streamflow simulation for small forested watersheds. Oregon State University; 1991.

Railsback, S. F. [In press.] Getting "results": the pattern-oriented approach to analyzing natural systems with individual-based models. Natural Resource Modeling.

Railsback, S. F. 1999. Reducing uncertainties in instream flow studies. Fisheries 24(3): 24-26.

Railsback, S. F.; Harvey, B. C. 2001. Analysis of salmonid habitat selection rules using an individual-based model. Unpublished draft supplied by authors.

Railsback, S. F.; Lamberson, R. H.; Harvey, B. C.; Duffy, W. G. 1999c. Movement rules for spatially explicit individual-based models of stream fish. Ecological Modelling 123: 73-89.

Railsback, S. F.; Rose, K. E. 1999. Bioenergetics modeling of stream trout growth: temperature and food consumption effects. Transactions of the American Fisheries Society 128: 241-256.

Railsback, S.; Harvey, B.; Jackson, S.; Lamberson, R.; Duffy, W. G. 1999a. California individual-based fish simulation system trout instream flow model formulation, version 1, Tule River rainbow and brown trout model. Arcata, CA: Lang, Railsback & Associates; 93 p.

Railsback, S.; Jackson, S.; Ropella, G.; Langton, C. 1999b. California individual-based fish simulation system, trout instream flow model user guide and software documentation. Arcata, CA: Lang, Railsback & Associates; 90 p.

Rajaratnam, N. and Katopodis, C. Hydraulics of culvert fishways III: weir baffle culvert fishways. Canadian Journal of Civil Engineering. 1990; 17(4):558-568.

Rajaratnam, N.; Katopodis, C., and McQuitty, N. Hydraulics of culvert fishways II: slotted weir culvert fishways. Canadian Journal of Civil Engineering. 1989; 16(3):375-383.

Rand, P. S.; Stewart, D. J.; Seelbach, P. W.; Jones, M. L.; Wedge, L. R. 1993. Modeling steelhead population energetics in lakes Michigan and Ontario. Transactions of the American Fisheries Society 122: 977-1001.

Reeder, R. Riparian Road Guide: Managing Roads to Enhance Riparian Areas. Washington, D.C.: USDA Forest Service, Southwestern Region; 1994.

Reiser, D. W.; White, R. G. 1983. Effects of complete redd dewatering on salmonid egg-hatching success and development of juveniles. Transactions of the

American Fisheries Society 112: 532-540.

Remnant, R. A. and Bernhardt, W. J. An Assessment of Fish Utilization of Goose Creek, near Churchill, Manitoba. Winnepeg, Manitoba: North/South Consultants Inc.; 1994202-1475 Chevrier Blvd. Winnepeg, Manitoba, Canada.

Riley, S.C., and K.D. Fausch. In press. Trout population response to habitat enhancement in six northern Colorado streams. Canadian Journal of Fisheries and Aquatic Sciences.

Riley, S.C., K.D. Fausch, and C. Gowan. 1992. Movement of brook trout (Salvelinus fontinalis) in four small subalpine streams in northern Colorado. Ecology of Freshwater Fish 1:112-122.

Ross, S.T., W.J. Matthews, and A.A. Echelle. 1985. Persistence of stream fish assemblages: effects of environmental change. American Naturalist 126:24-40.

Saltzman, W. and Koski, R. O. Fish Passage Through Culverts. Oregon State Game Comission; 1971.

Shetter, D.S., and A.S. Hazzard. 1938. Species composition by age groups and stability of fish populations in sections of three Michigan trout streams during the summer of 1937. Transactions of the American Fisheries Society 68:281-302.

Shoemaker, R. H. Hydraulics of Box Culverts with Fish-Ladder Baffles. Highway Research Board Proceedings. 1956; 35.

Slatick, E. Passage of Adult Salmon and Trout Through Pipes. Washington, D.C.: US Fish and Wildlife Service; 1970; 592.

Slawski, T. M. and Ehlinger, T. J. Fish Habitat Improvement in Box Culverts: Management in the Dark&quest. North American Journal of Fisheries Management. 1998; 18:676-685.

Stearley, R. F. 1992. Historical ecology of Salmoninae, with special reference to Oncorhynchus. In: Mayden, R. L., ed. Systematics, historical ecology, and North American freshwater fishes. Stanford, CA: Stanford University Press; 622-658.

Stefanich, F.A. 1952. The population and movement of fish in Prickly Pear Creek, Montana. Transactions of the American Fisheries Society 81:260-274.

Stewart, D. J. 1980. Salmonid predators and their forage base in Lake Michigan: a bioenergetics-modeling synthesis. Madison: University of Wisconsin. Ph.D. dissertation.

Stewart, K. Culverts and Fish Passage on the Willamette National Forest. 1982.

Studley, T. K.; Baldrige, J. E; Wise, L. M.; Spina, A. P.; Railsback, S. F.; McElravy, E.; Travanti, L.; Yuen, T. D. F; Lindahl, R. B.; Chase, S. D.; Smith, R.W. 1995. Response of fish populations to altered flows project, volume I: predicting trout populations from streamflow and habitat variables. Report 009.4-94.3. San Ramon, CA: Pacific Gas and Electric Company, Department of Research and Development.

Tappel, P. D. Limitations on the use of gabions to improve fish passage. North American Journal of Fisheries Management. 1986; 6:131-132.

Thomas R. Payne & Associates (TRPA). 1998. User's manual, RHABSIM 2.0. TRPA. Arcata, CA: TRPA. USDA Forest Service Gen. Tech. Rep. PSW-GTR-182. 2001. 79

Thompson, P. D. and Rahel, F. J. Evaluation of Artificial Barriers in Small Rocky Mountain Streams for Preventing the Upstream Movement of Brook Trout. North American Journal of Fisheries Management. 1998; 18:206-210.

Thorpe, J. E.; Mangel, M.; Metcalfe, N. B.; Huntingford, F. A.; 1998. Modelling the proximate basis of salmonid life-history variation, with application to Atlantic salmon, Salmo salar L. Evolutionary Ecology 12: 581-599.

Thut, R. N. 1970. Feeding habits of the dipper in southwestern Washington. Condor 72: 234-235.

Travis, M. D. and Tilsworth, T. Fish passage through Poplar Grove Creek culvert, Alaska. Transportation Research Record. 1986; 1075:21-26.

USDA, F. S. Roadway Drainage; Guide for Installing Culverts to Accomodate Fish. Juneau, AK: Engineering and Aviation Management Divisiong, Forest Service; 1976; 42.

Van Winkle, W.; Jager, H. I.; Holcomb, B. D. 1996. An individual-based instream flow model for coexisting populations of brown and rainbow trout. EPRI TR-106258. Palo Alto, CA: Electric Power Research Institute.

Van Winkle, W.; Jager, H. I.; Railsback, S. F.; Holcomb, B. D.; Studley, T. K.; Baldrige, J. E. 1998. Individual-based model of sympatric populations of brown and rainbow trout for instream flow assessment: model description and calibration. Ecological Modelling 110: 175-207.

Van Winkle, W.; Rose, K. A.; Chambers, R. C. 1993. Individual-based approach to fish population dynamics: an overview. Transactions of the American Fisheries Society 122: 397-403.

Vogel, J. L.; Beauchamp, D. A. 1999. Effects of light, prey size, and turbidity on reaction distances of lake trout (Salvelinus namaycush) to salmonid prey. Canadian Journal of Fisheries and Aquatic Sciences 56: 1293-1297.

Vondracek, B.; Longanecker, D. R. 1993. Habitat selection by rainbow trout Oncorhynchus mykiss in a California stream: implications for the instream flow incremental methodology. Ecology of Freshwater Fish 2: 173-186.

Warren, M. L. and Pardew, M. G. Road Crossings as Barriers to Small-Stream Fish Movement. Transactions of the American Fisheries Society. 1998; 127:637-644.

Watts, F. J. Design of Fishways. Moscow, ID: Water Resources Institute, University of Idaho; 1974.

Watts, F. J.; Dass, P.; Liou, C. P., and Harrison, M. Investigation of Culverts and Hydraulic Structures Used for Fishways and the Enhancement of Fish Habitat. Moscow, ID: Water Resources Research Institute, University of Idaho; 1973; A-027-IDA.

Webb, P. W. Hydrodynamics and Energetics of Fish Propulsion. Bulletin of the Fisheries Research Board of Canada; 1975.

White, D. Hydraulic Performance of Countersunk Culverts in Oregon. Oregon State University; 1996.

Wightman, J. C. and Taylor, G. D. Salmonid Swimming Performance in Relation to Passage Through Culverts. Victoria, British Columbia: Fish Habitat Improvement Section, Fish and Wildlife Branch, Ministry of Recreation and Conservation; 1976.

Wilcock, P. R.; Barta, A. F.; Shea, C. C.; Kondolf, G. M.; Matthews, W. V. G.; Pitlick, J. 1996. Observations of flow and sediment entrainment on a large gravel-bed river. Water Resources Research 32: 2897-2909.

WSDOT. Hydraulics Manual. Environmental and Engineering Service Center, Hydraulics Branch; 1997.

Young, M. K.; Rader, R. B.; Belish, T. A. 1997. Influence of macroinvertebrate drift and light on the activity and movement of Colorado River cutthroat trout. Transactions of the American Fisheries Society 126: 428-437.

Young, M.K. In press. Brown trout mobility in south-central Wyoming streams. Canadian Journal of Zoology.

Young, M.K. In review. Telemetry-determined movement and habitat use of Colorado River cutthroat trout (Oncorhynchus clarki pleuriticus). Canadian Journal of Fisheries and Aquatic Sciences.

Young, M.K., technical editor. 1995. Conservation assessment for inland cutthroat trout. USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. General Technical Report RM-GTR-256.

Zrinji, Z. and Bender, M. Experimental Risk Evaluation for Baffled Culvert Fishway Design. Winnipeg, Canada: Department of Civil and Geological Engineering, The University of Manitoba.; 1995.

Appendix A

Table A1. Steelhead trout recaptured by zone during winter flows.

		Number of Fish Recaptured in Zone							
Baffle Config	Trial #	Below Culvert	Lower Culvert	Middle Culvert	Upper Culvert	Above Culvert	Total Recap.	Date	Flow (m³/sec)
90* Weirs	1	5	11	2	0	0	18	2/9/02	5.1
	2	4	0	5	2	4	15	2/9/02	5.1
	3	6	6	5	0	0	17	2/10/02	4.6
	4	5	5	7	2	0	19	2/10/02	4.6
45* Baffles	1	7	5	4	4	0	20	2/22/02	2.4
	2	9	6	2	2	1	20	2/23/02	2.4
	3	7	3	5	3	0	18	2/23/02	2.4
	4	8	7	2	2	0	19	2/24/02	2.4
30* Baffles	1	4	7	8	1	0	20	3/3/02	1.5
	2	13	4	2	1	0	20	3/4/02	1.5
	3	11	4	2	3	0	20	3/8/02	1.5
	4	10	10	0	0	0	20	3/9/02	1.5
None (Control)	1	10	9	0	0	0	19	3/14/02	4.7
	2	6	13	1	0	0	20	3/14/02	4.7
	3	0	19	0	0	0	19	3/15/02	4.7
	4	14	4	0	0	0	18	3/15/02	4.7

Table A2. Steelhead trout recaptured by zone during summer flows.

		Number of Fish Recaptured in Zone							
Baffle Config	Trial #	Below Culvert	Lower Culvert	Middle Culvert	Upper Culvert	Above Culvert	Total Recap.	Date	Flow (m³/sec)
90* Weirs	1	0	6	14	0	0	20	9/9/02	0.14
	2	2	5	10	2	0	19	9/9/02	0.14
	3	4	2	12	4	0	20	9/10/02	0.14
	4	0	9	10	1	0	20	9/10/02	0.14
45* Baffles	1	13	5	0	0	0	18	9/23/02	0.14
(Upstream)	2	8	4	2	5	1	20	9/23/02	0.14
	3	9	5	2	1	3	20	9/24/02	0.14
	4	6	5	0	2	7	20	9/24/02	0.14
30* Baffles	1	4	5	7	2	0	18	10/2/02	0.14
(Upstream)	2	10	5	0	4	1	20	10/2/02	0.14
	3	7	3	6	2	1	19	10/2/02	0.14
	4	6	2	7	2	3	20	10/4/02	0.14
None (Control)	1	15	5	0	0	0	20	10/6/02	0.14
	2	18	2	0	0	0	20	10/6/02	0.14
	3	11	9	0	0	0	20	10/6/02	0.14
	4	16	4	0	0	0	20	10/7/02	0.14
30* Baffles	1	12	6	1	0	0	19	10/11/02	0.14
(Downstream)	2	14	4	0	0	0	18	10/12/02	0.14
	3	9	11	0	0	0	20	10/12/02	0.14
	4	15	2	2	0	0	19	10/12/02	0.14
45* Baffles	1	16	3	0	0	0	19	10/18/02	0.14
(Downstream)	2	13	5	1	0	0	19	10/18/02	0.14
	3	17	3	0	0	0	20	10/19/02	0.14
	4	8	9	3	0	0	20	10/19/02	0.14

ppendix B

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Table ___: Steelhead trout recaptured by zone during summer flows

		Number of Fish Recaptured in Zone							
Baffle Config	Trial #	Below Culvert	Lower Culvert	Middle Culvert	Upper Culvert	Above Culvert	Total Recap.	Date	Flow (ft³/sec)
90* Weirs	1	0	6	14	0	0	20	9/9/02	0.14
	2	2	5	10	2	0	19	9/9/02	0.14
	3	4	2	12	4	0	20	9/10/02	0.14
	4	0	9	10	1	0	20	9/10/02	0.14
45* Baffles (Upstream)	1	13	5	0	0	0	18	9/23/02	0.14
	2	8	4	2	5	1	20	9/23/02	0.14
	3	9	5	2	1	3	20	9/24/02	0.14
	4	6	5	0	2	7	20	9/24/02	0.14
30* Baffles (Upstream)	1	4	5	7	2	0	18	10/2/02	0.14
	2	10	5	0	4	1	20	10/2/02	0.14
	3	7	3	6	2	1	19	10/2/02	0.14
	4	6	2	7	2	3	20	10/4/02	0.14
None (Control)	1	15	5	0	0	0	20	10/6/02	0.14
	2	18	2	0	0	0	20	10/6/02	0.14
	3	11	9	0	0	0	20	10/6/02	0.14
	4	16	4	0	0	0	20	10/7/02	0.14
30* Baffles (Downstream)	1	12	6	1	0	0	19	10/11/02	0.14
	2	14	4	0	0	0	18	10/12/02	0.14
	3	9	11	0	0	0	20	10/12/02	0.14
	4	15	2	2	0	0	19	10/12/02	0.14
45* Baffles (Downstream)	1	16	3	0	0	0	19	10/18/02	0.14
	2	13	5	1	0	0	19	10/18/02	0.14
	3	17	3	0	0	0	20	10/19/02	0.14
	4	8	9	3	0	0	20	10/19/02	0.14

Table ___: Steelhead trout recaptured by zone during winter flows

Baffle Config	Trial #	Number of Fish Recaptured in Zone: Below Culvert	Lower Culvert	Middle Culvert	Upper Culvert	Above Culvert	Total Recap.	Date	Flow (m^3/sec)	Culvert Max Vel. (m/s)
90* Weirs	1	5	11	2	0	0	18	2/9/02	5.1	1.33
	2	4	0	5	2	4	15	2/9/02	5.1	1.33
	3	6	6	5	0	0	17	2/10/02	4.6	1.33
	4	5	5	7	2	0	19	2/10/02	4.6	1.33
45* Baffles	1	7	5	4	4	0	20	2/22/02	2.4	1.71
	2	9	6	2	2	1	20	2/23/02	2.4	1.71
	3	7	3	5	3	0	18	2/23/02	2.4	1.71
	4	8	7	2	2	0	19	2/24/02	2.4	1.71
30* Baffles	1	4	7	8	1	0	20	3/3/02	1.5	1.29
	2	13	4	2	1	0	20	3/4/02	1.5	1.29
	3	11	4	2	3	0	20	3/8/02	1.5	1.29
	4	10	10	0	0	0	20	3/9/02	1.5	1.29
None (Control)	1	10	9	0	0	0	19	3/14/02	4.7	2.05
	2	6	13	1	0	0	20	3/14/02	4.7	2.05
	3	0	19	0	0	0	19	3/15/02	4.7	2.05
	4	14	4	0	0	0	18	3/15/02	4.7	2.05