Final Research Report
Research Project T9903, Task 96
Salmon Thru Culvert

JUVENILE AND RESIDENT SALMONID MOVEMENT AND PASSAGE THROUGH CULVERTS

by

Thomas H. Kahler Research Assistant	Thomas P. Quinn Associate Professor

Fisheries Research Institute
School of Fisheries, 357980
University of Washington
Seattle, Washington 98195-7980

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
University District Building
1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

Washington State Department of Transportation
Technical Monitor
Paul Wagner
Biology Mitigation and Wildlife Program Manager
Environmental Affairs

Prepared for

Washington State Transportation Commission
Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

July 1998

1. REPORT NO.
WA-RD 457.1

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
Juvenile and Resident Salmonid Movement and Passage Through Culverts

5. REPORT DATE
July 1998

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Thomas H. Kahler and Thomas P. Quinn

8. PERFORMING ORGANIZATION REPORT NO.

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Washington State Transportation Center (TRAC)
University of Washington, Bx 354802
University District Building; 1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.
Agreement T9903, Task 96

12. SPONSORING AGENCY NAME AND ADDRESS
Washington State Department of Transportation
Transportation Building, MS 7370
Olympia, Washington 98504-7370

13. TYPE OF REPORT AND PERIOD COVERED
Research Report

14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

An outcome of the Washington State Department of Transportation's Juvenile Fish Passage Workshop on September 24, 1997, was agreement that a literature review was necessary to determine the state of knowledge about juvenile salmonid movement and passage through culverts at road crossings. This report summarizes the findings of the literature review. The conclusion of this literature review is that stream dwelling salmonids are often highly mobile. Upstream movement was observed in nearly all studies that were designed to detect it, and in all species, age classes, and seasons. There are variations in the movement patterns of fish populations both between and within river systems. The role of turbulence in affecting the ability of fish to pass through culverts is poorly understood and deserves further investigation. Countersunk culverts have proved to be better for fish passage than culverts with or without other modifications for fish passage.

17. KEY WORDS
Juvenile salmonid, resident salmonid, fish movement, spawning migration, swimming ability, fishway, fish passage, countersunk culvert, culvert hydraulics, baffled culvert.

18. DISTRIBUTION STATEMENT
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report)
None

20. SECURITY CLASSIF. (of this page)
None

21. NO. OF PAGES

22. PRICE

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington State Transportation Commission, Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

INTRODUCTION

An outcome of the Washington State Department of Transportation's Juvenile Fish Passage Workshop on September 24, 1997, was agreement that a literature review was necessary to determine the state of knowledge about juvenile salmonid movement and passage through culverts at road crossings. We proposed to conduct a literature review on the ecology of juvenile salmonid movement that would apply to culvert design and hydraulic modeling. The proposed review would focus on the motivation and capacity of juvenile salmonids to move upstream at different times of the year, as well as their ability to pass through culverts of different designs. Additionally, the review would include literature on the hydraulics of culverts, including the effects of various parameters such as slope and roughness on the conditions that affect fish passage.

The literature review was completed in April 1998. A workshop was convened on April 29, 1998, to report the results of the literature search to the research advisory committee. This report summarizes the findings of the literature review. Specific topics covered by this summary include the movements of juvenile and resident adult salmonids, culvert hydraulics, the ability of fish to pass through culverts, and salmonid swimming performance.

THE MOVEMENTS OF JUVENILE AND RESIDENT ADULT SALMONIDS

The literature review focused on studies of the movements of anadromous and resident juveniles, as well as resident adult salmonids. Studies of both regional fish populations and other populations from North America and Europe were included in the review. Upstream fish movement was found in nearly all of the studies that were designed to detect upstream movement. In many cases, more upstream movement was observed than downstream movement. Upstream movement was observed in all species, age classes, and seasons. Fish movement patterns vary among systems, making it difficult to categorize fish behavior by species or region. Despite this variation, some general statements can be made about fish movement on the basis of species, life-history stage, and region.

SPAWNING MIGRATIONS

Salmonids can be categorized by the timing of spawning, in fall or spring. In general, rainbow trout and cutthroat trout are spring spawners, and brook trout, brown trout, Dolly Varden, bull trout, Atlantic, and Pacific salmon are fall spawners. The timing of the spawning migrations of resident adult salmonids varies among river systems. In general, fall spawners migrate from July through December, and spring spawners from December through June, although exceptions to these generalizations are common (e.g., Dodge and MacCrimmon 1971; Brown 1994). The presence of both spring- and fall-spawning species within the same system may indicate the occurrence of year-round spawning migrations. Furthermore, the absence of spawning adults does not indicate that the stream is not utilized by another life-history stage (c.f., Skeesick 1970; Scrivener et al. 1994).

MOVEMENT OF FRY FOLLOWING EMERGENCE

In general, newly emerged salmonid fry disperse from the vicinity of the redd. Distances moved range from a few meters to several kilometers. In some cases, upstream fry movement is more prevalent than downstream movement (e.g., Hunt 1965; Pearsons et al. 1996). Fry have been observed using non-natal tributaries and tributaries where spawning has not occurred (e.g., Scrivener et al. 1994). Because the dispersal of fry is primarily a spring event, many studies noted a peak in movement during the spring to early summer (e.g., Hartman et al. 1982; Elliott 1986).

Summer Movement

Summer movements of salmonids are commonly reported for both coastal and interior populations. Distances moved range from a few meters to tens of kilometers, with movements of several hundred meters most commonly reported. This movement is a continuation of the dispersal of fry, especially for late emerging species, as well as movements of older fish. In some studies upstream movement was predominant (e.g., Riley et al. 1992). Many studies reported minimal movement in late August (e.g., Hartman and Brown 1987), and some showed movement peaks in July as flows decreased (e.g., Gowan and Fausch 1996). Fish may move to avoid the dewatering of intermittent sections (e.g., Hubble 1992), to seek refuge from high water temperatures (e.g., Nielsen and Lisle 1994), and to avoid high turbidity (e.g., Scrivener et al. 1994).

Autumn Redistribution

In the fall the population redistributes from summer habitats to winter habitats (Northcote 1992). Distances moved range from a few meters to over 50 kilometers (Bendock 1989). This redistribution is independent of spawning migrations. For interior (east of the Cascade crest, continental climate regime) populations, fish often seek warmer temperatures (e.g., Bjornn and Mallet 1964) or substrate of a suitable size for concealment (Bjornn 1971; Hillman et al. 1987). Movement may be upstream or downstream (Clapp et al. 1990; Meyers et al. 1992). For coastal (west of the Cascade crest, maritime climate regime) populations, fish primarily seek refuge from the high velocities common during winter freshets (e.g., Cederholm and Scarlett 1982). Movement is mostly up lower-order tributaries and into off-channel habitats (e.g., Murphy et al. 1984), although these upstream movements may be preceded by a downstream movement (e.g., Peterson 1982). Most studies report the largest peak in upstream movement during fall to early winter (e.g., Peterson and Reid 1984). In some coastal populations, upstream movement into off-channel habitats in response to freshets continues throughout the winter (e.g., Lowry 1965).

MOTIVATION FOR MOVEMENT

It is difficult to determine what combinations of environmental stimuli and internal motivations result in movement. In some cases, relationships between the behavior of an animal and an environmental factor may seem straightforward, but often the relationships are less clear. The following is a discussion of the environmental stimuli for movement proposed by the authors of the studies reviewed for this report.

The most obvious motivation for the movement of stream fishes is spawning. The variation in the timing of spawning migrations, even within the same watershed (Pearsons et al. 1996), suggests that the residents of each stream have adapted to the local conditions. These local adaptations may result from some selective feature of that stream, such as obstacles that can be negotiated only at certain discharges.

Fish may move in response to changing water temperatures. Movements to warmer water in fall and winter and cooler water in spring and summer have been observed in several studies (Clapp et al. 1990; Meyers et al. 1992). Concealment in interstitial spaces within the substrate is a common behavior of juvenile salmonids as stream temperatures drop below some threshold (Rimmer et al. 1983). If substrate of a size suitable for concealment is not available, migration may occur (Bjornn 1971; Young 1998).

Another factor that influences fish movement is stream discharge. Current velocity, turbidity, and habitat availability are all functions of stream discharge. The massive fall redistribution observed in coastal populations is primarily a migration to low velocity habitats in response to increasing discharges (e.g., Peterson 1982). Much of the upstream migration of fry in the spring is also a movement to low velocity habitats (e.g., Cederholm and Scarlett 1982). As discharge decreases in the summer, the availability of habitat also decreases. This reduction in habitat is considered to be a primary motivator of summer movement, especially in streams with intermittent sections (Hubble 1992). Finally, movement to avoid the high turbidity that often occurs during high discharge has been observed in several studies (e.g., Murray and Rosenau 1989).

The factors that influence fish mobility are interrelated in some cases. Habitat availability is a function of population density as well as discharge. Flick and Webster (1975) found a decrease in fish movement that corresponded with a decrease in population density. Decreases in population density may increase the relative amount of food available to the remaining fish, and food availability affects fish movement (Wilzbach 1985). This interrelatedness produces uncertainty in attempts to explain observed behavior patterns in a fish population.

See appendices A and B for details on the movement patterns of individual species.

CONCLUSIONS

For the construction and design of road crossings that are passable to juvenile and resident adult salmonids, it is important to first determine whether passage by those fish is necessary. The conclusions of this literature review are that resident and anadromous juveniles, as well as resident adult salmonids, are often highly mobile. Upstream movement was observed in nearly all studies that were designed to detect it. There are variations in the movement patterns of fish populations both between and within river systems. Consequently, a prudent assumption is that if salmonids are present within the system of interest, they will likely move upstream, but the timing and extent of that movement may vary on a stream-by-stream basis.

To determine the species and age-class composition of a stream, a single survey is inadequate. This review found that it is common for fish to use different parts of a stream or watershed at different times of the year. The presence of juveniles in tributaries that support no spawners, as well as non-natal tibutaries, shows that spawning surveys may not indicate juvenile usage. Additionally, the timing of spawning runs may vary within the same watershed. Multiple surveys are necessary to determine the species and age-class composition in a stream, as well as the timing of spawning migrations. All tributaries upstream of the proposed construction project should be considered in the population assessment.

This review concentrated only on studies of salmonid populations. Several of the reviewed studies contained information on the movement of non-salmonid species (e.g., Linfield 1985). Pearsons et al. (1996) found that in both biomass and numbers, non-salmonids represented the majority of the fish moving during the study period in a tributary of the Yakima River. The implication is that these species may be at least as mobile as, if not more mobile than, the salmonid population and should also be considered in the design of road stream-crossings.

RESEARCH NEEDS

Information is lacking on the movement of salmonids in high-gradient streams. For this review, most of the studies were of streams with gradients of less than 3 percent. No studies of fish movement in streams of greater than 10 percent were found, and many studies failed to report stream gradient. In the studies reviewed, upstream movement occurred even in the steepest streams (9.6 percent, Osborn 1981).

The mobility of resident salmonid populations in high-gradient (greater than 10 percent) step-pool channels remains in question. Providing for upstream fish passage in those channels may be unnecessary. However, Rinne (1982) reported finding adult trout moving upstream over log weirs 0.85 meters high. In a stream with a 5.9 percent gradient, Diana and Lane (1978) found upstream movement to be more common than downstream movement, and a 1-meter high waterfall did not block upstream movement. Determining the conditions, such as channel type and stream gradient, under which fish movement ceases remains an important research need.

CULVERTS AS FISHWAYS

For a fish on an upstream migration to successfully negotiate a culvert road crossing, it must be able to enter the culvert barrel, traverse the length of the barrel, exit the barrel at the upstream end, and proceed upstream to the first resting area. Fish entrance to the culvert may be restricted by obstructions at the entrance, excessive outlet velocity, or perch height. Passage through the culvert barrel may be restricted by excessive barrel velocity or inadequate water depth. Successful exit of the culvert may be restricted by excessive inlet velocity. Excessive velocity is a common factor in each instance.

Water velocity within a culvert is a function of the cross-sectional area, slope, and roughness of the culvert, as well as stream discharge. Culvert roughness is the most readily manipulated factor that influences velocity. A variety of methods for increasing culvert roughness have been investigated, including baffles, corrugations, and the placement of bedload material. Each of these methods has the common objective of producing a region of lower velocity within the culvert that fish would be able to utilize while the velocity in the remainder of the culvert exceeded the fishes' swimming ability.

CULVERT HYDRAULICS

Besides the primary focus of this literature review--the movement patterns of salmonids--literature on culvert hydraulics was also searched. A review of the literature on culvert design specifications for juvenile fish passage showed a general similarity of specifications for slope, minimum depth, and maximum velocity for fish passage design flows. Given this agreement within the literature, the attention of the review was directed toward finding studies that presented information that was substantially different from the majority of the studies or offered new insights into culvert hydraulics.

The observation that fish apparently utilize the boundary layer when passing through culverts has resulted in efforts to model the velocity distribution within roughened pipes. Barber and Downs (1996) tested the abilities of two different equations to predict the widths of relative velocity contours within any size circular pipe with annular corrugations (relative velocity = the velocity at any position within the cross-section divided by the maximum velocity within the culvert). One of the equations satisfactorily predicted the contour widths, and a computer program called Juvenile Fish Passage Program (JUFIPP) was developed using this equation to predict the size of the "migration area," the area of the culvert that fish were observed in during passage.

White (1996) developed a regression equation for determining the extent of low velocity zones suitable for juvenile fish passage in countersunk culverts. The equation generally underestimated the amount of low velocity area present. Consequently, the equation would be useful for culvert design because it provides a conservative estimate of the amount of low velocity area available for fish utilization. Additionally, White (1996) found the countersunk culverts that he investigated to be resistant to erosion and capable of conveying high discharges. Several high-gradient (2 to 7.6 percent) culverts were investigated, and all retained their bedload during 5-year to 10-year flood events. Unfortunately for the analysis of bedload stability, the steepest culverts were not subjected to flows greater than 5-year floods.

Browning (1990) also investigated the performance of countersunk culverts. The study determined that pipes and pipe arches with natural stream beds provided better fish passage conditions than pipes with or without features designed to aid fish passage. Browning (1990) also found that the barrel velocity to channel velocity ratio is negatively proportional to fish passage ability. Browning (1990) recommended that as a design criteria, a headwater-to-rise ratio that does not exceed 1.0 during a 50-year flood event should be used to determine the culvert dimensions.

A series of studies of the hydraulics of various baffle systems in culverts was completed by Canadian researchers (Rajaratnam et al. 1988, 1989, 1990, 1991; Rajaratnam and Katopodis 1990). They developed equations to describe the relationship between relative water depth and the dimensionless discharge value, as well as equations to predict the barrier velocities at the baffles for spoiler baffles, offset baffles, Alberta fish weirs and baffles, weir baffles, and slotted weir baffles. They reported similar hydraulic performance for all baffle designs with the exception of the Alberta fish baffles, which performed poorly.

Finally, Behlke (1987) reported that under certain fishway conditions, fish must contend with buoyant forces and weight in addition to the forces typically encountered in a fishway. These forces become important in culverts with slopes equal to or exceeding 10 percent, or where pressure gradients exist such as in culvert inlets and perched outlets. Including the buoyant force and weight of the fish in the analysis of forces that the fish must overcome to successfully negotiate the fishway will ensure more accurate predictions of passability.

FISH PASSAGE THROUGH CULVERTS

There are few studies of juvenile salmonid passage through culverts. The studies discussed in this report made unique observations or involved unusual study designs. These studies include a report on the use of the "stream simulation" design; a comparison of several roughness elements designed to provide low velocity areas for fish passage; a report on the effects of turbulence on fish passage through a steep, baffled culvert; and a report on the use of corrugations as "resting" areas.

McKinnon and Hnytka (1985) studied the effects of culverts constructed with the "stream simulation" technique on the passage of local fish species. Stream simulation is meant to "maintain natural stream properties within the culvert(s) (i.e., average cross-section, width, slope, substrate) for flows up to fish migration discharge, concentrate low flows, and provide within the culvert(s) a rock substrate, stable at the 1:50 year flood" (McKinnon and Hnytka 1985). Four long culverts (140 to 190 ft) with slopes of from 0.0 to 1.0 percent were studied. No passage delays or failures were reported for Arctic grayling, northern pike, or longnose suckers during the spring high water migratory period. The stream simulation technique was concluded to be a "valid concept," and velocities within the culverts were similar to those in the natural stream.

Belford (1986) and Belford and Gould (1989) investigated the ability of resident trout to pass through culverts designed with three different modifications for fish passage. One culvert contained a “ladder” structure designed to hold bed material, another had plate weir baffles with notches, and one culvert was countersunk. Resident trout were able to pass through culverts from 42 to 93 m long with slopes of from 0.2 to 4.4 percent. The authors developed a non-linear regression curve to delineate the boundary between the water velocity and culvert length conditions through which fish were or were not able to pass. This curve can be used to predict the average velocity at which a resident trout can negotiate a culvert of a specified length.

Bryant (1981) tested the ability of juvenile coho salmon, cutthroat trout, and Dolly Varden to pass through a 90-cm-diameter, 9-m-long culvert with offset baffles and a 10 percent gradient. Fish from 50 to 150 mm long successfully passed through the culvert. Passage by coho salmon was improved with the addition of a baffle at the outlet. Discharges of from 0.4 cfs to 0.6 cfs did not affect fish passage. At discharges of greater than 0.65 cfs no fish passed through.

Powers et al. (1997) tested the ability of coho salmon fry and fingerlings to pass through culverts of different diameters and corrugations, including smooth pipe, at different slopes and velocities. For the smooth pipe, the velocities that the fish were able to pass through were equivalent to the velocities reported in studies on fish swimming ability. In corrugated pipes turbulence apparently interfered with fish passage ability at maximum velocities of above 2 fps.

Douglas Kane and Charles Behlke are currently studying the ability of juvenile salmonids to pass through culverts in Alaska. They confirm the passage of juvenile coho salmon 50 mm long through a 116 feet long culvert with a maximum slope of 5.3 percent (D. L. Kane, PO Box 755860, Fairbanks, AK 99775-5860, personal communication). Velocities within the culvert ranged from 3.2 fps to 7.6 fps along the centerline. Fish were observed resting between the corrugations near the water surface as they moved along the culvert wall. Velocity and turbulence conditions near the culvert inlet made it impossible for the fish to maintain resting positions between corrugations. The coho were observed using burst speed to pass the culvert inlet, at which point they would dive toward the lower velocity region at the stream bottom.

FISH SWIMMING ABILITY

The literature on fish swimming abilities generally agrees on the swimming speeds and times to fatigue of various species of salmonids. Differences among the studies can mostly be attributed to differences in study design and testing apparatus. The approach for the review of this literature was to locate studies that contained information that was different from the others. Of special interest were studies indicating fish swimming capabilities that exceeded those predicted by theory.

Carpenter (1987) tested the swimming abilities of several salmonid species as swim-up fry. Her data, when compared with predicted velocities extrapolated from adult swimming ability data, showed that swim-up fry of all species tested were capable of swimming at greater velocities than those predicted by extrapolation. Belford (1986) and Belford and Gould (1989) developed regression curves of adult resident trout swimming ability from their data on trout culvert passage. They found that the trout in their study were able to successfully pass through culverts at higher average velocities than the velocities predicted in laboratory studies or extrapolated from anadromous salmonid data.

The results of Carpenter (1987), Belford (1986), Belford and Gould (1989), and qualitative data such as those from Kane and Behlke (D. L. Kane, PO Box 755860, Fairbanks, AK 99775-5860, personal communication) all indicate that under certain conditions, fish are capable of swimming through higher velocities than those indicated by current culvert design guidelines. The ability of fish to exploit zones of lower velocity within a culvert is the most likely explanation for the differences between predicted and actual swimming performance. More in situ studies that examine the culvert passage ability of salmonids should be performed to determine their potential capabilities

Katopodis (1992) consolidated most swimming ability data and produced a database from over 500 references on fish swimming ability. From this database, Katopodis has produced fish endurance and swimming distance vs. water velocity curves for nine species of salmonids.

CONCLUSIONS AND RECOMMENDATIONS

The role of turbulence in affecting the ability of fish to pass through culverts is poorly understood and deserves further investigation. In road crossings that use natural bed materials to mimic local stream conditions, turbulence should not represent a hindrance to fish passage. In corrugated pipes and pipes with artificial structures to increase roughness, turbulence may interfere with fish passage. The ability of fish in the field to exceed both theoretical limitations and laboratory performances indicates the importance of incorporating a field component into investigations of culvert hydraulics.

Countersunk culverts have proved to be better for fish passage than culverts with or without other modifications for fish passage. Countersunk culverts have also been capable of conveying high discharges without erosion of the bed material. However, none of the countersunk culverts in this review were subject to flows of greater than 10-year flood events. Further investigation into the ability of steep countersunk culverts to retain their bedload during flood events of greater magnitude would be useful.

ACKNOWLEDGMENTS

We would like to thank Jim Schafer and Paul Wagner of the Washington State Department of Transportation; Tom Burns, Larry Cowan and Pat Powers of the Washington Department of Fish and Wildlife; and George Robison of the Oregon Department of Forestry for their time and comments during the literature review.

REFERENCES

Barber, M. E., and R. C. Downs. 1996. Investigation of culvert hydraulics related to juvenile fish passage. Washington State Transportation Center (TRAC), Department of Civil and Environmental Engineering, Washington State University. Final Research Report. No. WA-RD 388.1.

Behlke, C. E. 1987. Hydraulic relationships between swimming fish and water flowing in culverts. *In* Proceedings of the 2nd International conference on Cold Region Environmental Engineering, CSCE-ASCE, University of Alberta, Edmonton, Alberta. pp. 112-132.

Belford, D. A. 1986. Abilities of trout to swim through highway culverts. Master of Science thesis. Montana State University, Bozeman, MT.

Belford, D. A., and W. R. Gould. 1989. An evaluation of trout passage through six highway culverts in Montana. N. Am. J. Fish. Manage. **9:** 437-445.

Bendock, T. 1989. Lakeward movements of juvenile chinook salmon and recommendations for habitat management in the Kenai River, Alaska, 1986-1988. Alaska Department of Fish and Game, Division of Sport Fish. Fishery Manuscript Series No. 7.

Bjornn, T. C. 1971. Trout and salmon movements in two Idaho streams as related to temperature, food, stream flow, cover, and population density. Trans. Am. Fish. Soc. **100:** 423-438.

Bjornn, T. C., and J. Mallet. 1964. Movements of planted and wild trout in an Idaho river system. Trans. Am. Fish. Soc. **93:** 70-76.

Brown, L. 1992. On the zoogeography and life history of WA native charr; Dolly Varden *Salvelinus malma* (Walbaum) and bull trout *Salvelinus confluentus* (Suckley). Washington Department of Wildlife, Fisheries Management Division. No. 94-04.

Browning, M. C. 1990. Oregon culvert fish passage survey. Western Federal Lands Highway Division, Federal Highway Administration. Vancouver, WA.

Bryant, M. D. 1981. Evaluation of a small diameter baffled culvert for passing juvenile salmonids. U. S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. Research Note. No. PNW-384.

Carpenter, L. T. 1987. A comparative study of short-term swimming performance in fry of five salmonid species at different temperatures. Master of Science thesis. University of Washington, Seattle, WA.

Cederholm, C. J., and W. J. Scarlett. 1982. Seasonal immigrations of juvenile salmonids into four small tributaries of the Clearwater River, Washington, 1977-1981. *In* Salmon and Trout Migratory Behavior Symposium, 3-5 June 1981. *Edited by* E. L. Brannon and E. O. Salo. School of Fisheries, University of Washington, Seattle, WA.

Clapp, D. F., R. D. J. Clark, and J. S. Diana. 1990. Range, activity, and habitat of large, free-ranging brown trout in a Michigan stream. Trans. Am. Fish. Soc. **119:** 1022-1034.

Diana, J. S., and E. D. Lane. 1978. The movement and distribution of Paiute cutthroat trout, *Salmo clarki seleniris*, in Cottonwood Creek, California. Trans. Am. Fish. Soc. **107:** 444-448.

Dodge, D. P., and H. R. MacCrimmon. 1971. Environmental influences on extended spawning of rainbow trout (*Salmo gairdneri*). Trans. Am. Fish. Soc. **100:** 312-318.

Elliott, J. M. 1986. Spatial distribution and behavioral movements of migratory trout *Salmo trutta* in a lake district stream. Journal of Animal Ecology. **55:** 907-922.

Flick, W. A., and D. A. Webster. 1975. Movement, growth, and survival in a stream population of wild brook trout (*Salvelinus fontinalis*) during a period of removal of non-trout species. J. Fish. Res. Board Can. **32:** 1359-1367.

Gowan, C., and K. D. Fausch. 1996. Mobile brook trout in two high-elevation Colorado streams: re-evaluating the concept of restricted movement. Can. J. Fish. Aquat. Sci. **53:** 1370-1381.

Hartman, G. F., B. C. Anderson, and J. C. Scrivener. 1982. Seaward movement of coho salmon *(Oncorhynchus kisutch)* fry in Carnation Creek, an unstable coastal stream in British Columbia. Can. J. Fish. Aquat. Sci. **39:** 588-597.

Hartman, G. F., and T. G. Brown. 1987. Use of small, temporary, floodplain tributaries by juvenile salmonids in a west coast rain-forest drainage basin, Carnation Creek, British Columbia. Can. J. Fish. Aquat. Sci. **44:** 262-270.

Hillman, T. W., J. S. Griffith, and W. S. Platts. 1987. Summer and winter habitat selection by juvenile chinook salmon in a highly sedimented stream. Trans. Am. Fish. Soc. **116:** 185-195.

Hubble, J. D. 1992. A study of the summer steelhead, *Oncorhynchus mykiss* in several intermittent tributaries of the Satus Creek basin, Washington. Master of Science thesis. Central Washington University, Ellensburg, WA.

Hunt, R. L. 1965. Dispersal of wild brook trout during their first summer of life. Trans. Am. Fish. Soc. **94**(2)**:** 186-188.

Katopodis, C. 1992. Introduction to fishway design. Freshwater Institute, Central and Arctic Region, Department of Fisheries and Ocean. Working Document.

Linfield. 1985. An alternative concept to home range theory with respect to populations of cyprinids in major river systems. J. Fish. Biol. **27**(Supplement A): 187-196.

Lowry, G. R. 1965. Movement of cutthroat trout, *Salmo clarki clarki* (Richardson) in three Oregon coastal streams. Trans. Am. Fish. Soc. **94:** 334-338.

McKinnon, G. A., and F. N. Hnytka. 1985. Fish passage assessment of culverts constructed to simulate stream conditions on Liard River tributaries. Department of Fisheries and Oceans, Western Region. Can. Tech. Rep. Fish. Aquat. Sci. No. 1255.

Meyers, L. S., T. F. Thuemler, and G. W. Kornely. 1992. Seasonal movements of brown trout in northeast Wisconsin. N. Am. J. Fish. Manage. **12:** 433-441.

Murphy, M. L., J. F. Thedinga, K. V. Koski, and G. B. Grette. 1984. A stream ecosystem in an old-growth forest in Southeast Alaska: Part V: Seasonal changes in habitat utilization by juvenile salmonids. *In* Fish and Wildlife Relationships in Old-Growth Forests: Proceedings of a symposium held in Juneau, Alaska, 12-15 April 1982. *Edited by* W. R. Meehan, T. R. Merrell, Jr. and T. A. Hanley. Amer. Inst. Fish. Res. Biol. 425 p.

Murray, C. B., and M. L. Rosenau. 1989. Rearing of juvenile chinook salmon in nonnatal tributaries of the lower Fraser River, British Columbia. Trans. Am. Fish. Soc. **118:** 284-289.

Nielsen, J. L., and T. E. Lisle. 1994. Thermally stratified pools and their use by steelhead in northern California streams. Trans. Am. Fish. Soc. **123:** 613-626.

Northcote, T. G. 1992. Migration and residency in stream salmonids--some ecological considerations and evolutionary consequences. Nord. J. Freshwater Res. **67:** 5-17.

Osborn, J. G. 1981. The effects of logging on cutthroat trout (*Salmo clarki*) in small headwater streams. Master of Science thesis. University of Washington, Seattle, WA.

Pearsons, T. N., G. A. McMichael, S. W. Martin, E. L. Bartrand, J. A. Long, and S. A. Leider. 1996. Yakima species interactions studies, annual report 1994. U.S. Department of Energy Bonneville Power Administration. Report. No. DOE/BP--99852-3.

Peterson, N. P. 1982. Immigration of juvenile coho salmon (*Oncorhynchus kisutch*) into riverine ponds. Can. J. Fish. Aquat. Sci. **39:** 1308-1310.

Peterson, N. P., and L. M. Reid. 1984. Wall-base channels: their evolution, distribution, and use by juvenile coho salmon in the Clearwater River, Washington. *In* Proceedings of the Olympic Wild Fish Conference, Port Angeles, WA, 23-25 March 1983. *Edited by* J. M. Walton and D. B. Houston.

Powers, P. D., K. Bates, T. Burns, B. Gowen, and R. Whitney. 1997. Culvert hydraulics related to upstream juvenile salmon passage. Washington Department of Fish and Wildlife. Olympia, WA.

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

Rajaratnam, N., C. Katopodis, and M. A. Fairbairn. 1990. Hydraulics of culvert fishways V: Alberta fish weirs and baffles. Canadian Journal of Civil Engineering. **17:** 1015-1021.

Rajaratnam, N., C. Katopodis, and S. Lodewyk. 1988. Hydraulics of offset baffle culvert fishways. Canadian Journal of Civil Engineering. **15:** 1043-1051.

Rajaratnam, N., C. Katopodis, and S. Lodewyk. 1991. Hydraulics of culvert fishways IV: spoiler baffle culvert fishways. Canadian Journal of Civil Engineering. **18:** 76-82.

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

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.

Rimmer, D. M., U. Paim, and R. L. Saunders. 1983. Autumnal habitat shift of juvenile Atlantic salmon (*Salmo salar*) in a small river. Can. J. Fish. Aquat. Sci. **40:** 671-680.

Rinne, J. N. 1982. Movement, home range, and growth of a rare southwestern trout in improved and unimproved habitats. N. Am. J. Fish. Manage. **2:** 150-157.

Scrivener, J. C., T. G. Brown, and B. C. Anderson. 1994. Juvenile chinook salmon *(Oncorhynchus tshawytscha)* utilization of Hawks Creek, a small and nonnatal tributary of the upper Fraser River. Can. J. Fish. Aquat. Sci. **51:** 1139-1146.

Skeesick, D. G. 1970. The fall immigration of juvenile coho salmon into a small tributary. Fish Commission of Oregon, Research Division. Research Report of the Fish Commission of Oregon.

White, D. 1996. Hydraulic performance of countersunk culverts in Oregon. Master of Science thesis. Oregon State University, Corvallis, OR.

Wilzbach, M. A. 1985. Relative roles of food abundance and cover in determining the habitat distribution of stream-dwelling cutthroat trout (*Salmo clarki*). Can. J. Fish. Aquat. Sci. **42:** 1668-1672.

Young, M. K. 1998. Absence of autumnal changes in habitat use and location of adult Colorado River cutthroat trout in a small stream. Trans. Am. Fish. Soc. **127:** 147-151.

APPENDIX A.

A SUMMARY OF INFORMATION ON THE MOVEMENTS OF STREAM-DWELLING SALMONIDS

This appendix is designed to provide the reader with greater detail on the movement patterns of resident and juvenile anadromous salmonids than was provided in the report. Nearly 100 papers about salmonid movements from a variety of sources were reviewed for this report. The following is a summary of the details from those papers that may be important to the individuals responsible for the design and assessment of stream road-crossing structures. It is not intended to be a comprehensive review. This summary is based upon an interpretation of the documents reviewed for this report. It would be prudent for those interested in greater detail on the movement patterns of resident and juvenile anadromous salmonids, or on the details of a specific study, to read the original studies after examining this report.

This summary has been arranged by fish species. Because of the large number of sources reviewed for this report and the obscurity of some of them (i.e., unpublished agency reports), using the standard "name-and-year" citation system would have been cumbersome. Instead, summary statements that are supported by the majority of the sources reviewed do not include literature citations. However, summary statements that present exceptional information do include citations. Following the summary is a bibliography that is also arranged by fish species. Some of the studies reviewed for this report include information about multiple species. Therefore, there is some repetition in the bibliography.

BROOK TROUT

Spawning is generally from October through December, but all age classes have been observed moving upstream year-round. Age 0+ fish moved up to 5 km upstream during the summer (Hunt 1965). Several studies reported that upstream movement peaked in the spring as flow declined and in the fall during the spawning migration. Non-spawning fish moved upstream in the fall with the spawners.

BROWN TROUT

Brown trout spawn in the fall. Following spawning, adults move to warmer water to overwinter. Adults move to cooler water in the spring and summer. The magnitude of these seasonal movements has been determined, using radio telemetry, to be thousands of meters (e.g., 10-20 km, Meyers et al. 1992).

Movement patterns of age 1+ and older fish appear to be related to habitat productivity. Population mobility increases with decreasing productivity. Fish in high elevation, low productivity streams were generally mobile, moving thousands of meters (mostly upstream) between captures (Gowan and Fausch 1996). Fish in low elevation, highly productive streams were sedentary (Bachman 1984). Age 0+ fish may move upstream during the spring and summer.

Adults become piscivorous when they reach about 300 mm in length. Piscivorous adults forage widely at night during the summer and rest in deep pools during the day. Studies that do not include methods for determining nocturnal foraging may underestimate the incidence of movement within the study population.

BULL TROUT AND DOLLY VARDEN

The taxonomic separation of bull trout and Dolly Varden into distinct species is not unanimously accepted by fisheries scientists. For the purpose of this review, bull trout and Dolly Varden are not distinguished, rather they are both referred to as native charr.

Native charr have four different life history patterns: resident, fluvial, adfluvial, and anadromous. Ratliff (1996) found fish switching between adfluvial and fluvial strategies. Most populations spawn in September and October, but some spawn as early as August or as late as December. The timing of spawning migrations varies among populations. Migration may begin as early as April or as late as December. Immature and non-spawning mature fish may move upstream with spawning fish. Interior populations may migrate downstream following spawning to overwinter in large rivers with warmer temperatures.

Juveniles move both up and downstream. Coastal juveniles move upstream to low-order tributaries to overwinter. Interior juveniles move upstream to colder water in the summer and will utilize tributaries that did not support spawners. Ratliff (1996) used radio telemetry to track one sub-adult fish down one tributary and up another, a total of 19 km.

COHO SALMON

Coho salmon fry begin emerging in March (though this varies regionally). Upstream movement may occur shortly after emergence. Upstream movement can occur throughout the summer--often more fish move upstream than downstream (Thomas H. Kahler, unpublished data). One study showed an upstream response to decreasing flow (Shirvell 1994). Much of the spring/summer upstream movement is into off-channel rearing areas such as wall-base channels and ponds. Generally, upstream movement peaks in April and May, but June peaks are reported in some studies. August had the least amount movement in many studies.

Redistribution upstream to winter rearing areas often begins in September, usually triggered by the first major freshet. Most studies showed a peak in movement in October-November. Upstream movement was often into smaller tributaries from larger rivers or into off-channel habitats. The distances moved ranged from hundreds of meters to tens of kilometers. Many studies found fish moving upstream into off-channel areas throughout the winter.

CHINOOK SALMON

Age 0+ fish moved up to 6 km upstream into non-natal tributaries of the Fraser River when the turbidity was high in the main stem during summer runoff (Murray and Rosenau 1989). Both upstream and downstream movements have been observed in interior populations of age 0+ spring chinook. Over 90 percent of the age 0+ fish in an interior stream moved upstream during the summer (Pearsons et al. 1996).

Juvenile chinook may hide in the substrate during winter, preferring cobble substrate under overhanging banks. The lack of substrate of appropriate size may influence emigration. Experiments show that fish may move upstream as temperatures fall if large substrate is not available (Bjornn 1971). Bendock (1989) found that age 0+ fish moved upstream over 50 km to overwinter in a lake in response to declining discharges and temperatures.

CUTTHROAT TROUT

Coastal Populations

Some coastal streams have both resident and anadromous forms of cutthroat trout. Anadromous fish spawn earlier than residents. Anadromous fish may start upstream migration in July and spawn from September to May. The timing of spawning may differ within and among river systems and is often earlier in large rivers. Anadromous fish commonly spawn in small headwater streams.

Fry may emerge from late March through early July and may move upstream to off-channel areas soon after emergence. Age 0+ fish moved throughout the summer between stream channels and off-channel areas, often more upstream than downstream. Age 1+ fish behave in a similar manner.

Fall and winter upstream movement into low-order tributaries and off-channel habitats is found in all age classes. Upstream movement may be triggered by freshets. Anadromous fish may overwinter in a nonnatal stream, return to salt water in the spring, and then migrate to their natal stream to spawn.

An experiment on adult residents found that emigration was strongly related to food abundance but only weakly related to cover (Wilzbach 1985). When food availability was low the population was more mobile. The experiment was performed at summer temperatures, and the movement induced was 70 percent downstream and 30 percent upstream.

Interior Populations

In large river systems adults may move downstream in the fall to larger, warmer rivers, then upstream in the spring to spawn in the tributaries. Non-spawners move upstream with the spawners. However, in one high elevation headwater stream the adults showed no fall/winter redistribution (Young 1998). The stream had abundant cobble and boulders, and summer water temperatures were below the threshold temperatures for seasonal habitat shifts described in other studies (Young 1998).

Young's (1996) summer radio-telemetry study of small, high elevation streams, reported that fish movements of hundreds of meters were common and that some fish moved over 1000 m, more often upstream than downstream.. Diana and Lane (1978) observed that fish 56 to 207 mm long in a high elevation, high gradient stream moved thousands of meters upstream, some over a 1 meter cascade.

RAINBOW TROUT

The timing of spawning migrations of adults varies, even within river systems. Spawners are reported to move upstream from October to May. Following spawning, fish may establish a new home range or return to their original location (Hockersmith et al. 1995).

Summer movement is common for all age classes. For immature fish, more upstream movement is reported than downstream. The peak of upstream movement for age 0+ fish in one study was the first of August (Pearsons et al. 1996). Age 1+ and older fish temporarily occupied a tributary of the Fraser River while the turbidity was high in the main stem during the spring and summer (Scrivener et al. 1994).

Studies of rainbow trout movement in high elevation streams report conflicting results. Pearsons et al. (1996) found less movement with increasing elevation, but Gowan and Fausch (1996) observed more movement at higher elevations. Gradient may be a factor in salmonid movement but was not reported in either study.

STEELHEAD TROUT

Steelhead fry emerge from April through June. Following emergence steelhead may move upstream into small tributaries or off-channel habitats. Upstream movement may occur throughout the summer and may be more prevalent than downstream movement. Nielsen et al. (1994) found a diel migration between foraging sites and thermal refuges in stratified pools during the summer.

Fall and winter freshets trigger movement upstream from larger rivers to smaller tributaries or off-channel habitats. In one study juvenile steelhead moved from a large river upstream into ponds during freshets until the flow subsided, then they returned to the main stem (Cederholm and Scarlett 1982). Murphy et al. (1984) found that juvenile steelhead in one southeast Alaska system moved downstream through an estuary then up another stream to a lake.

Two studies reported upstream movement of smolts. Hubble (1992) found age 1+ fish and older fish that appeared to be smolts moving upstream above an intermittent stream reach. In another study smolts released in a tributary migrated down to the main stem then upstream over 12 km (Pearsons et al. 1996).

REFERENCES

Bachman, R. A. 1984. Foraging behavior of free-ranging wild and hatchery brown trout in a stream. Trans. Am. Fish. Soc. **113**(1)**:** 1-32.

Bendock, T. 1989. Lakeward movements of juvenile chinook salmon and recommendations for habitat management in the Kenai River, Alaska, 1986-1988. Alaska Department of Fish and Game, Division of Sport Fish. Fishery Manuscript Serial No. 7.

Bjornn, T. C. 1971. Trout and salmon movements in two Idaho streams as related to temperature, food, stream flow, cover, and population density. Trans. Am. Fish. Soc. **100:** 423-438.

Cederholm, C. J., and W. J. Scarlett. 1982. Seasonal immigrations of juvenile salmonids into four small tributaries of the Clearwater River, Washington, 1977-1981. *In* Salmon and Trout Migratory Behavior Symposium, June 3-5, 1981. *Edited by* E. L. Brannon and E. O. Salo. School of Fisheries, University of Washington, Seattle, WA.

Diana, J. S., and E. D. Lane. 1978. The movement and distribution of Paiute cutthroat trout, *Salmo clarki seleniris*, in Cottonwood Creek, California. Trans. Am. Fish. Soc. **107:** 444-448.

Gowan, C., and K. D. Fausch. 1996. Long-term demographic responses of trout populations to habitat manipulation in six Colorado streams. Ecological Applications. **6**(3)**:** 931-946.

Hockersmith, E., J. Vella, and L. Stuehrenberg. 1995. Yakima River radio-telemetry study, rainbow trout, annual report 1993. U.S. Department of Energy, Bonneville Power Administration. Annual Report. No. DOE/BP-00276-3.

Hubble, J. D. 1992. A study of the summer steelhead, *Oncorhynchus mykiss* in several intermittent tributaries of the Satus Creek basin, Washington. Master of Science thesis. Central Washington University, Ellensburg, WA.

Hunt, R. L. 1965. Dispersal of wild brook trout during their first summer of life. Trans. Am. Fish. Soc. **94**(2)**:** 186-188.

Meyers, L. S., T. F. Thuemler, and G. W. Kornely. 1992. Seasonal movements of brown trout in northeast Wisconsin. N. Am. J. Fish. Manage. **12:** 433-441.

Murphy, M. L., J. F. Thedinga, K. V. Koski, and G. B. Grette. 1984. A stream ecosystem in an old-growth forest in Southeast Alaska: Part V: Seasonal changes in habitat utilization by juvenile salmonids. *In* Fish and Wildlife Relationships in Old-Growth Forests: Proceedings of a symposium held in Juneau, Alaska, 12-15 April 1982. *Edited by* W. R. Meehan, T. R. Merrell, Jr. and T. A. Hanley. Amer. Inst. Fish. Res. Biol. 425 p.

Murray, C. B., and M. L. Rosenau. 1989. Rearing of juvenile chinook salmon in nonnatal tributaries of the lower Fraser River, British Columbia. Trans. Am. Fish. Soc. **118:** 284-289.

Nielsen, J. L., and T. E. Lisle. 1994. Thermally stratified pools and their use by steelhead in northern California streams. Trans. Am. Fish. Soc. **123:** 613-626.

Pearsons, T. N., G. A. McMichael, S. W. Martin, E. L. Bartrand, J. A. Long, and S. A. Leider. 1996. Yakima species interactions studies annual report 1994. U.S. Department of Energy Bonneville Power Administration. Annual Report 1994. No. DOE/BP--99852-3.

Ratliff, D. E., S. L. Thiesfeld, W. G. Weber, A. M. Stuart, M. D. Riehle, and D. V. Buchanan. 1996. Distribution, life history, abundance, harvest, habitat, and limiting factors of bull trout in Metolius River and Lake Billy Chinook, Oregon, 1983-94. Oregon Department of Fish and Wildlife. Information Report. No. 96-7.

Scrivener, J. C., T. G. Brown, and B. C. Anderson. 1994. Juvenile chinook salmon *(Oncorhynchus tshawytscha)* utilization of Hawks Creek, a small and nonnatal tributary of the upper Fraser River. Can. J. Fish. Aquat. Sci. **51:** 1139-1146.

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

Wilzbach, M. A. 1985. Relative roles of food abundance and cover in determining the habitat distribution of stream-dwelling cutthroat trout (*Salmo clarki*). Can. J. Fish. Aquat. Sci. **42:** 1668-1672.

Young, M. K. 1996. Summer movements and habitat use by Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*) in small, montane streams. Can. J. Fish. Aquat. Sci. **53:** 1403-1408.

Young, M. K. 1998. Absence of autumnal changes in habitat use and location of adult Colorado River cutthroat trout in a small stream. Trans. Am. Fish. Soc. **127:** 147-151.

APPENDIX B.

A BIBLIOGRAPHY OF FISH MOVEMENT LITERATURE

This bibliography was prepared as a guide to the fish movement literature that was reviewed both for the report, Juvenile and Resident Adult Salmonid Movement and Passage through Culverts, and for Appendix A. It is not a complete bibliography of all the available literature on fish movement. The literature reviewed was selected for its pertinence to the designers of stream road-crossings in Washington State, specifically studies that investigated the upstream movement of stream-dwelling salmonids.

The references are arranged alphabetically by fish species. Because some of the studies investigated the behavior of more than one species, there is some repetition of references.

ATLANTIC SALMON

Hutchings, J. A. 1986. Lakeward migrations by juvenile Atlantic salmon, *Salmo salar.* Can. J. Fish. Aquat. Sci. **43:** 732-741.

Rimmer, D. M., U. Paim, and R. L. Saunders. 1983. Autumnal habitat shift of juvenile Atlantic salmon (*Salmo salar*) in a small river. Can. J. Fish. Aquat. Sci. **40:** 671-680.

BROOK TROUT

Bjornn, T. C. 1971. Trout and salmon movements in two Idaho streams as related to temperature, food, stream flow, cover, and population density. Trans. Am. Fish. Soc. **100:** 423-438.

Burgess, S. A. 1980. Effects of stream habitat improvements on invertebrates, trout populations, and mink activity. J. Wildl. Manage. **44**(4)**:** 871-880.

Flick, W. A., and D. A. Webster. 1975. Movement, growth, and survival in a stream population of wild brook trout (*Salvelinus fontinalis*) during a period of removal of non-trout species. J. Fish. Res. Board Can. **32:** 1359-1367.

Gowan, C., and K. D. Fausch. 1996. Long-term demographic responses of trout populations to habitat manipulation in six Colorado streams. Ecological Applications. **6**(3)**:** 931-946.

Gowan, C., and K. D. Fausch. 1996. Mobile brook trout in two high-elevation Colorado streams: re-evaluating the concept of restricted movement. Can. J. Fish. Aquat. Sci. **53:** 1370-1381.

Hunt, R. L. 1965. Dispersal of wild brook trout during their first summer of life. Trans. Am. Fish. Soc. **94**(2)**:** 186-188.

McFadden, J. T. 1961. A population study of the brook trout, *Salvelinus fontinalis*. Wildl. Monogr. **7:** 73.

Naslund, I., G. Milbrink, L. O. Eriksson, and S. Holmgren. 1993. Importance of habitat productivity differences, competition and predation for the migratory behavior of Arctic charr. Oikos. **66:** 538-546.

Needham, P. R., and F. K. Cramer. 1943. Movement of trout in Convict Creek, California. J. Wildl. Manage. **7:** 142-148.

Riley, S. C., and K. D. Fausch. 1995. Trout population response to habitat enhancement in six northern Colorado streams. Can. J. Fish. Aquat. Sci. **52:** 34-53.

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.

Stefanich, F. A. 1952. The population and movement of fish in Prickley Pear Creek, Montana. Trans. Am. Fish. Soc. **81:** 260-274.

BROWN TROUT

Bachman, R. A. 1984. Foraging behavior of free-ranging wild and hatchery brown trout in a stream. Trans. Am. Fish. Soc. **113**(1)**:** 1-32.

Bridcut, E. E., and P. S. Giller. 1993. Movement and site fidelity in young brown trout *Salmo trutta* populations in a southern Irish stream. J. Fish. Biol. **43:** 889-899.

Clapp, D. F., R. D. J. Clark, and J. S. Diana. 1990. Range, activity, and habitat of large, free-ranging brown trout in a Michigan stream. Trans. Am. Fish. Soc. **119:** 1022-1034.

Elliott, J. M. 1986. Spatial distribution and behavioral movements of migratory trout *Salmo trutta* in a lake district stream. Journal of Animal Ecology. **55:** 907-922.

Fies, T., and G. P. Robart. 1988. Metolius River wild trout investigations 1982-1985. Oregon Department of Fish and Wildlife. Information Report. No. 88-4.

Gowan, C., and K. D. Fausch. 1996. Long-term demographic responses of trout populations to habitat manipulation in six Colorado streams. Ecological Applications. **6**(3)**:** 931-946.

Hayes, J. W. 1995. Spatial and temporal variation in the relative density and size of juvenile brown trout in the Kakanui River, North Otago, New Zealand. New Zealand Journal of Marine and Freshwater Research. **29:** 393-407.

Heggenes, J. 1988. Effect of experimentally increased intraspecific competition on sedentary brown trout *(Salmon trutta)* movement and stream habitat choice. Can. J. Fish. Aquat. Sci. **45:** 1163-1172.

Jonsson, N., B. Jonsson, J. Skurdal, and L. P. Hansen. 1994. Differential response to water current in offspring of inlet- and outlet-spawning brown trout *Salmo trutta*. J. Fish. Biol. **45:** 356-359.

Jorgensen, J., and S. Berg. 1991. Stocking experiments with 0+ and 1+ trout parr, *Salmo trutta* L., of wild and hatchery origin: 2. post-stocking movements. J. Fish. Biol. **39:** 171-180.

Meyers, L. S., T. F. Thuemler, and G. W. Kornely. 1992. Seasonal movements of brown trout in northeast Wisconsin. N. Am. J. Fish. Manage. **12:** 433-441.

Needham, P. R., and F. K. Cramer. 1943. Movement of trout in Convict Creek, California. J. Wildl. Manage. **7:** 142-148.

Riley, S. C., and K. D. Fausch. 1995. Trout population response to habitat enhancement in six northern Colorado streams. Can. J. Fish. Aquat. Sci. **52:** 34-53.

Shuler, S. W., B. R. Nehring, and K. D. Fausch. 1994. Diel habitat selection by brown trout in the Rio Grande River, Colorado, after placement of boulder structures. N. Am. J. Fish. Manage. **14:** 99-111.

Solomon, D. J. 1981. Migration and dispersion of juvenile brown and sea trout. *In* Salmon and Trout Migratory Behavior Symposium, June 3-5, 1981. *Edited by* E. L. Brannon and E. O. Salo. School of Fisheries, University of Washington, Seattle, WA.

Stefanich, F. A. 1952. The population and movement of fish in Prickley Pear Creek, Montana. Trans. Am. Fish. Soc. **81:** 260-274.

Young, M. K. 1994. Mobility of brown trout in south-central Wyoming streams. Can. J. Zool. **72:** 2078-2083.

BULL TROUT AND DOLLY VARDEN

Bjornn, T. C. 1971. Trout and salmon movements in two Idaho streams as related to temperature, food, stream flow, cover, and population density. Trans. Am. Fish. Soc. **100:** 423-438.

Bjornn, T. C., and J. Mallet. 1964. Movements of planted and wild trout in an Idaho river system. Trans. Am. Fish. Soc. **93:** 70-76.

Bramblett, R., B. E. Wright, M. D. Bryant, and R. White. 1997. Seasonal movements and distribution of juvenile steelhead and coho salmon in a southeastern Alaska drainage basin. *In* From the Mountains to the Sea: Linked Ecosystems. American Fisheries Society, Alaska Chapter, 24th Annual Meeting., Juneau, Alaska. Unpublished abstract.

Brown, L. 1992. On the zoogeography and life history of WA native charr; Dolly Varden *Salvelinus malma* (Walbaum) and bull trout *Salvelinus confluentus* (Suckley). Washington Department of Wildlife, Fisheries Management Division. No. 94-04.

Fies, T., and G. P. Robart. 1988. Metolius River wild trout investigations 1982-1985. Oregon Department of Fish and Wildlife. Information Report. No. 88-4.

Murphy, M. L., J. F. Thedinga, K. V. Koski, and G. B. Grette. 1984. A stream ecosystem in an old-growth forest in Southeast Alaska: Part V: Seasonal changes in habitat utilization by juvenile salmonids. *In* Fish and Wildlife Relationships in Old-Growth Forests: Proceedings of a symposium held in Juneau, Alaska, 12-15 April 1982. *Edited by* W. R. Meehan, T. R. Merrell, Jr. and T. A. Hanley. Amer. Inst. Fish. Res. Biol. 425 p.

Ratliff, D. E., S. L. Thiesfeld, W. G. Weber, A. M. Stuart, M. D. Riehle, and D. V. Buchanan. 1996. Distribution, life history, abundance, harvest, habitat, and limiting factors of bull trout in Metolius River and Lake Billy Chinook, Oregon, 1983-94. Oregon Department of Fish and Wildlife. Information Report. No. 96-7.

CHINOOK SALMON

Bendock, T. 1989. Lakeward movements of juvenile chinook salmon and recommendations for habitat management in the Kenai River, Alaska, 1986-1988. Alaska Department of Fish and Game, Division of Sport Fish. Fishery Manuscript serial No. 7.

Bjornn, T. C. 1971. Trout and salmon movements in two Idaho streams as related to temperature, food, stream flow, cover, and population density. Trans. Am. Fish. Soc. **100:** 423-438.

Bradford, M. J., and G. C. Taylor. 1997. Individual variation in dispersal behavior of newly emerged chinook salmon (*Oncorhynchus tshawytscha*) from the upper Fraser River, British Columbia. Can. J. Fish. Aquat. Sci. **54:** 1585-1592.

Hillman, T. W., J. S. Griffith, and W. S. Platts. 1987. Summer and winter habitat selection by juvenile chinook salmon in a highly sedimented stream. Trans. Am. Fish. Soc. **116:** 185-195.

Murray, C. B., and M. L. Rosenau. 1989. Rearing of juvenile chinook salmon in nonnatal tributaries of the lower Fraser River, British Columbia. Trans. Am. Fish. Soc. **118:** 284-289.

Pearsons, T. N., G. A. McMichael, S. W. Martin, E. L. Bartrand, J. A. Long, and S. A. Leider. 1996. Yakima species interactions studies annual report 1994. U.S. Department of Energy Bonneville Power Administration. Annual Report 1994. No. DOE/BP--99852-3.

Richards, C., and P. J. Cernera. 1989. Dispersal and abundance of hatchery-reared and naturally spawned juvenile chinook salmon in an Idaho stream. N. Am. J. Fish. Manage. **9:** 345-351.

Scrivener, J. C., T. G. Brown, and B. C. Anderson. 1994. Juvenile chinook salmon *(Oncorhynchus tshawytscha)* utilization of Hawks Creek, a small and nonnatal tributary of the upper Fraser River. Can. J. Fish. Aquat. Sci. **51:** 1139-1146.

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

COHO SALMON

Bilby, R. E., and P. A. Bisson. 1987. Emigration and production of hatchery coho salmon (*Oncorhynchus kisutch*) stocked in streams draining an old-growth and a clear-cut watershed. Can. J. Fish. Aquat. Sci. **44:** 1397-1407.

Bramblett, R., B. E. Wright, M. D. Bryant, and R. White. 1997. Seasonal movements and distribution of juvenile steelhead and coho salmon in a southeastern Alaska drainage basin. *In* From the Mountains to the Sea: Linked Ecosystems. American Fisheries Society, Alaska Chapter, 24th Annual Meeting. Juneau, Alaska. Unpublished abstract.

Carman, R., and J. Cederholm. 1981. Copper mine bottom pond, survival and production rates for 1980 hatchery plant and native coho. Washington Department of Natural Resources. Unpublished report.

Cederholm, C. J., and W. J. Scarlett. 1982. Seasonal immigrations of juvenile salmonids into four small tributaries of the Clearwater River, Washington, 1977-1981. *In* Salmon and Trout Migratory Behavior Symposium, June 3-5, 1981. *Edited by* E. L. Brannon and E. O. Salo. School of Fisheries, University of Washington, Seattle, WA.

Chapman, D. W. 1962. Aggressive behavior in juvenile coho salmon as a cause of emigration. Journal of Fisheries Research Board of Canada. **19:** 1047-1080.

Chapman, D. W. 1965. Net production of juvenile coho salmon in three Oregon streams. Trans. Am. Fish. Soc. **94**(1)**:** 40-52.

Fraser, J. 1985. Evaluation of seasonal migration of juvenile salmonids into and out of a pond in the Cowlitz River flood plain. Washington Department of Fisheries. Unpublished Washington Department of Fisheries report for Chapter 232 of the Northwest Steelheaders, Salkum, WA.

Hartman, G. F., B. C. Anderson, and J. C. Scrivener. 1982. Seaward movement of coho salmon *(Oncorhynchus kisutch)* fry in Carnation Creek, an unstable coastal stream in British Columbia. Can. J. Fish. Aquat. Sci. **39:** 588-597.

Hartman, G. F., and T. G. Brown. 1987. Use of small, temporary, floodplain tributaries by juvenile salmonids in a west coast rain-forest drainage basin, Carnation Creek, British Columbia. Can. J. Fish. Aquat. Sci. **44:** 262-270.

Jonasson, B. 1983. Upstream movement and distribution of private hatchery produced coho salmon smolts into Yaquina River tributaries. Oregon Department of Fish and Wildlife, Research and Development Section. Information Reports. No. 83-13.

Murphy, M. L., J. F. Thedinga, K. V. Koski, and G. B. Grette. 1984. A stream ecosystem in an old-growth forest in Southeast Alaska: Part V: Seasonal changes in habitat utilization by juvenile salmonids. *In* Fish and Wildlife Relationships in Old-Growth Forests: Proceedings of a symposium held in Juneau, Alaska, 12-15 April 1982. *Edited by* W. R. Meehan, T. R. Merrell, Jr. and T. A. Hanley. Amer. Inst. Fish. Res. Biol. 425 p.

Peterson, N. P. 1982. Immigration of juvenile coho salmon (*Oncorhynchus kisutch*) into riverine ponds. Can. J. Fish. Aquat. Sci. **39:** 1308-1310.

Peterson, N. P., and L. M. Reid. 1984. Wall-base channels: their evolution, distribution, and use by juvenile coho salmon in the Clearwater River, Washington. *In* Proceedings of the Olympic Wild Fish Conference, Port Angeles, WA, 23-25 March 1983. *Edited by* J. M. Walton and D. B. Houston.

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

Skeesick, D. G. 1970. The fall immigration of juvenile coho salmon into a small tributary. Fish Commission of Oregon, Research Division. Research Report of the Fish Commission of Oregon.

CUTTHROAT TROUT

Coastal Populations

Cederholm, C. J., and W. J. Scarlett. 1982. Seasonal immigrations of juvenile salmonids into four small tributaries of the Clearwater River, Washington, 1977-1981. *In* Salmon and Trout Migratory Behavior Symposium, June 3-5, 1981. *Edited by* E. L. Brannon and E. O. Salo. School of Fisheries, University of Washington, Seattle, WA.

Fraser, J. 1985. Evaluation of seasonal migration of juvenile salmonids into and out of a pond in the Cowlitz River flood plain. Washington Department of Fisheries. Unpublished Washington Department of Fisheries report for Chapter 232 of the Northwest Steelheaders, Salkum, WA.

Fuss, H. J. 1982. Age, growth and instream movement of Olympic Peninsula coastal cutthroat trout (*Salmo clarki clarki*). Master of Science thesis. University of Washington, Seattle, WA.

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

Johnston, J. M. 1981. Life histories of anadromous cutthroat trout with emphasis on migratory behavior. *In* Salmon and Trout Migratory Behavior Symposium, June 3-5, 1981. *Edited by* E. L. Brannon and E. O. Salo. School of Fisheries, University of Washington, Seattle, WA.

June, J. A. 1981. Life history and habitat utilization of cutthroat trout (*Salmo clarki*) in a headwater stream on the Olympic Peninsula, Washington. Master of Science thesis. University of Washington, Seattle, WA.

Lestelle, L. 1978. The effects of forest debris removal on a population of resident cutthroat trout in a small headwater stream. Master of Science thesis. University of Washington, Seattle, WA.

Lowry, G. R. 1965. Movement of cutthroat trout, *Salmo clarki clarki* (Richardson) in three Oregon coastal streams. Trans. Am. Fish. Soc. **94:** 334-338.

Murphy, M. L., J. F. Thedinga, K. V. Koski, and G. B. Grette. 1984. A stream ecosystem in an old-growth forest in Southeast Alaska: Part V: Seasonal changes in habitat utilization by juvenile salmonids. *In* Fish and Wildlife Relationships in Old-Growth Forests: Proceedings of a symposium held in Juneau, Alaska, 12-15 April 1982. *Edited by* W. R. Meehan, T. R. Merrell, Jr. and T. A. Hanley. Amer. Inst. Fish. Res. Biol. 425 p.

Osborn, J. G. 1981. The effects of logging on cutthroat trout (*Salmo clarki*) in small headwater streams. Master of Science thesis. University of Washington, Seattle, WA.

Trotter, P. C. 1989. Coastal cutthroat trout: a life history compendium. Trans. Am. Fish. Soc. **118:** 463-473.

Wilzbach, M. A. 1985. Relative roles of food abundance and cover in determining the habitat distribution of stream-dwelling cutthroat trout (*Salmo clarki*). Can. J. Fish. Aquat. Sci. **42:** 1668-1672.

Interior Populations

Bjornn, T. C., and J. Mallet. 1964. Movements of planted and wild trout in an Idaho river system. Trans. Am. Fish. Soc. **93:** 70-76.

Bowler, B. 1975. Factors influencing genetic control in lakeward migrations of cutthroat trout fry. Trans. Am. Fish. Soc. **104:** 474-482.

Diana, J. S., and E. D. Lane. 1978. The movement and distribution of Paiute cutthroat trout, *Salmo clarki seleniris*, in Cottonwood Creek, California. Trans. Am. Fish. Soc. **107:** 444-448.

Labar, G. W. 1971. Movement and homing of cutthroat trout (*Salmo clarki*) in Clear and Bridge Creeks, Yellowstone National Park. Trans. Am. Fish. Soc. **100:** 41-49.

Miller, R. B. 1957. Permanence and size of home territory in stream-dwelling cutthroat trout. J. Fish. Res. Board Can. **14:** 687-691.

Raleigh, R. F. 1971. Innate control of migrations of salmon and trout fry from natal gravels to rearing areas. Ecology. **52:** 291-297.

Raleigh, R. F., and D. W. Chapman. 1971. Genetic control in lakeward migrations of cutthroat trout fry. Trans. Am. Fish. Soc. **100:** 33-40.

Rinne, J. N. 1982. Movement, home range, and growth of a rare southwestern trout in improved and unimproved habitats. N. Am. J. Fish. Manage. **2:** 150-157.

Young, M. K. 1996. Summer movements and habitat use by Colorado River cutthroat trout (*Oncorhynchus clarki pleuriticus*) in small, montane streams. Can. J. Fish. Aquat. Sci. **53:** 1403-1408.

Young, M. K. 1998. Absence of autumnal changes in habitat use and location of adult Colorado River cutthroat trout in a small stream. Trans. Am. Fish. Soc. **127:** 147-151.

RAINBOW TROUT

Alexander, D. R., and H. R. MacCrimmon. 1974. Production and movement of juvenile rainbow trout (*Salmo gairdneri*) in a headwater of Bothwell's Creek, Georgian Bay, Canada. J. Fish. Res. Board Can. **31:** 117-121.

Bjornn, T. C. 1971. Trout and salmon movements in two Idaho streams as related to temperature, food, stream flow, cover, and population density. Trans. Am. Fish. Soc. **100:** 423-438.

Bjornn, T. C., and J. Mallet. 1964. Movements of planted and wild trout in an Idaho river system. Trans. Am. Fish. Soc. **93:** 70-76.

Dodge, D. P., and H. R. MacCrimmon. 1971. Environmental influences on extended spawning of rainbow trout (*Salmo gairdneri*). Trans. Am. Fish. Soc. **100:** 312-318.

Fies, T., and G. P. Robart. 1988. Metolius River wild trout investigations 1982-1985. Oregon Department of Fish and Wildlife. Information Report. No. 88-4.

Gowan, C., and K. D. Fausch. 1996. Long-term demographic responses of trout populations to habitat manipulation in six Colorado streams. Ecological Applications. **6**(3)**:** 931-946.

Hockersmith, E., J. Vella, and L. Stuehrenberg. 1995. Yakima River radio-telemetry study, rainbow trout, annual report 1993. U.S. Department of Energy, Bonneville Power Administration. Annual Report. No. DOE/BP-00276-3.

Kelso, B. W., T. G. Northcote, and C. F. Wehrhahn. 1981. Genetic and environmental aspects of the response to water current by rainbow trout *(Salmo gairdneri)* originating from inlet and outlet streams of two lakes. Can. J. Zool. **59**(11)**:** 2177-2185.

Matthews, K. R. 1996. Diel movement and habitat use of California golden trout in the Golden Trout Wilderness, California. Trans. Am. Fish. Soc. **125:** 78-86.

Needham, P. R., and F. K. Cramer. 1943. Movement of trout in Convict Creek, California. J. Wildl. Manage. **7:** 142-148.

Northcote, T. G. 1962. Migratory behavior of juvenile rainbow trout, *Salmo gairdneri*, in outlet and inlet streams of Loon Lake, British Columbia. J. Fish. Res. Board Can. **19:** 201-270.

Northcote, T. G. 1981. Juvenile current response, growth and maturity of above and below waterfall stocks of rainbow trout, *Salmo gairdneri.* J. Fish. Biol. **18:** 741-751.

Northcote, T. G., and B. W. Kelso. 1981. Differential response to water current by two homozygous LDH phenotypes of young rainbow trout *(Salmo gairdneri).* Can. J. Fish. Aquat. Sci. **38**(3)**:** 348-352.

Pearsons, T. N., G. A. McMichael, S. W. Martin, E. L. Bartrand, J. A. Long, and S. A. Leider. 1996. Yakima species interactions studies annual report 1994. U.S. Department of Energy Bonneville Power Administration. Annual Report 1994. No. DOE/BP--99852-3.

Riley, S. C., and K. D. Fausch. 1995. Trout population response to habitat enhancement in six northern Colorado streams. Can. J. Fish. Aquat. Sci. **52:** 34-53.

Scrivener, J. C., T. G. Brown, and B. C. Anderson. 1994. Juvenile chinook salmon *(Oncorhynchus tshawytscha)* utilization of Hawks Creek, a small and nonnatal tributary of the upper Fraser River. Can. J. Fish. Aquat. Sci. **51:** 1139-1146.

Stefanich, F. A. 1952. The population and movement of fish in Prickley Pear Creek, Montana. Trans. Am. Fish. Soc. **81:** 260-274.

STEELHEAD TROUT

Bramblett, R., B. E. Wright, M. D. Bryant, and R. White. 1997. Seasonal movements and distribution of juvenile steelhead and coho salmon in a southeastern Alaska drainage basin. *In* From the Mountains to the Sea: Linked Ecosystems. American Fisheries Society, Alaska Chapter, 24th Annual Meeting., Juneau, Alaska. Unpublished abstract.

Cederholm, C. J., and W. J. Scarlett. 1982. Seasonal immigrations of juvenile salmonids into four small tributaries of the Clearwater River, Washington, 1977-1981. *In* Salmon and Trout Migratory Behavior Symposium, June 3-5, 1981. *Edited by* E. L. Brannon and E. O. Salo. School of Fisheries, University of Washington, Seattle, WA.

Fraser, J. 1985. Evaluation of seasonal migration of juvenile salmonids into and out of a pond in the Cowlitz River flood plain. Washington Department of Fisheries. Unpublished Washington Department of Fisheries report for Chapter 232 of the Northwest Steelheaders, Salkum, WA.

Hartman, G. F., and T. G. Brown. 1987. Use of small, temporary, floodplain tributaries by juvenile salmonids in a west coast rain-forest drainage basin, Carnation Creek, British Columbia. Can. J. Fish. Aquat. Sci. **44:** 262-270.

Hubble, J. D. 1992. A study of the summer steelhead, *Oncorhynchus mykiss* in several intermittent tributaries of the Satus Creek basin, Washington. Master of Science thesis. Central Washington University, Ellensburg, WA.

Leider, S. A., M. W. Chilcote, and J. J. Loch. 1986. Movement and survival of presmolt steelhead in a tributary and the main stem of a Washington river. N. Am. J. Fish. Manage. **6:** 526-531.

Murphy, M. L., J. F. Thedinga, K. V. Koski, and G. B. Grette. 1984. A stream ecosystem in an old-growth forest in Southeast Alaska: Part V: Seasonal changes in habitat utilization by juvenile salmonids. *In* Fish and Wildlife Relationships in Old-Growth Forests: Proceedings of a symposium held in Juneau, Alaska, 12-15 April 1982. *Edited by* W. R. Meehan, T. R. Merrell, Jr. and T. A. Hanley. Amer. Inst. Fish. Res. Biol. 425 p.

Nielsen, J. L., and T. E. Lisle. 1994. Thermally stratified pools and their use by steelhead in northern California streams. Trans. Am. Fish. Soc. **123:** 613-626.

NON-SPECIFIC MOVEMENT LITERATURE

Behnke, R. 1997. About trout. Movement, migration and habitat. Trout. **Winter 1997**: 45, 46, 53.

Fausch, K. D., and M. K. Young. 1995. Evolutionarily Significant Units and Movement of Resident Stream Fishes: a Cautionary Tale. American Fisheries Society Symposium. **17**: 360-370.

Godin, J.-G. J. 1981. Migrations of salmonid fishes during early life history phases: daily and annual timing. *In* Salmon and Trout Migratory Behavior Symposium, June 3-5, 1981. *Edited by* E. L. Brannon and E. O. Salo, School of Fisheries, University of Washington, Seattle, WA.

Gowan, C., M. K. Young, K. D. Fausch, and S. C. Riley. 1994. Restricted movement in resident stream salmonids: a paradigm lost? Can. J. Fish. Aquat. Sci. **51:** 2626-2637.

Hall, C. A. S. 1972. Migration and metabolism in a temperate stream ecosystem. Ecology. **53:** 585-604.

Linfield. 1985. An alternative concept to home range theory with respect to populations of cyprinids in major river systems. J. Fish. Biol. **27(Supplement A):** 187-196.

Meehan, W. R. 1991. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society Special Publication 19. American Fisheries Society, Bethesda, MA.

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

Young, M. K. 1995. Resident trout movement: consequences of a new paradigm. USDA Forest Service. Fish Habitat Relationships Technical Bulletin. Number 18**:** 1-5.

APPENDIX C.

A BIBLIOGRAPHY OF LITERATURE ON CULVERTS AS FISHWAYS

This bibliography is a list of the literature on culverts as fishways and on fish passage capabilities that was reviewed for the report Juvenile and Resident Adult Salmonid Movement and Passage through Culverts. The list includes all documents reviewed for the report with the exception of documents specifically about fish movement. It does not include the many unpublished memoranda from state agencies or the personal communications that were reviewed. It is not a complete bibliography of all the available literature on culverts as fishways.

Many of the documents contain information about a variety of topics related to culverts as fishways, e.g., hydraulics, fish swimming ability, installation guidelines, and others, making it a challenge to arbitrarily assign a document to a general topic heading. To avoid confusion, a single alphabetical list of literature is provided. The document titles provide sufficient descriptions of their contents.

Abt, S. R., J. F. Ruff, and C. Mendoza. 1984. Scour at culvert outlets in multibed materials. Transportation Research Record. **948:** 55-62.

Anderson, J. W. 1974. Vincent Creek fishpass. U.S. Department of the Interior-Bureau of Land Management. Technical Note. No. T/N 253.

Anderson, L., and M. Bryant. 1980. Fish passage at road crossings: an annotated bibliography. USDA Forest Service, Pacific Northwest Forest and Range Experiment Station. General Technical Report. No. PNW-117.

Ashton, W. S., and R. F. Carlson. 1983. Predicting fish passage design discharges for Alaska. *In* Permafrost: Fourth International Conference. National Academy Press, Fairbanks, AK, USA.

Barber, M. E., and R. C. Downs. 1996. Investigation of culvert hydraulics related to juvenile fish passage. Washington State Transportation Center (TRAC), Department of Civil and Environmental Engineering, Washington State University. Final Technical Report. No. WA-RD 388.2.

Barber, M. E., and R. C. Downs. 1996. Investigation of culvert hydraulics related to juvenile fish passage. Washington State Transportation Center (TRAC), Department of Civil and Environmental Engineering, Washington State University. Final Research Report. No. WA-RD 388.1.

Bates, K. M. 1992. Fishway design guidelines for Pacific salmon. Washington Department of Fish and Wildlife. Working Paper. No. 1.6.

Behlke, C. E. 1987. Hydraulic relationships between swimming fish and water flowing in culverts. *In* Proceedings of the 2nd International Conference on Cold Regions Environmental Engineering. CSCE-ASCE, University of Alberta, Edmonton, Alberta. pp. 112-132.

Behlke, C. E., D. L. Kane, R. F. McLean, J. B. Reynolds, and M. D. Travis. 1988. Spawning migration of Arctic grayling through Poplar Grove Creek culvert, Glennallen, Alaska 1986. State of Alaska Department of Transportation and Public Facilities, Research Section. Final Report. No. FHWA-AK-RD-88-09.

Behlke, C. E., D. L. Kane, R. F. McLean, and M. D. Travis. 1991. Fundamental of culvert design for passage of weak-swimming fish. Alaska Department of Transportation & Public Facilities Statewide Research. Final Report. No. FHWA-AK-RD-90-10.

Belford, D. A. 1986. Abilities of trout to swim through highway culverts. Master of Science thesis. Montana State University, Bozeman, MT.

Belford, D. A., and W. R. Gould. 1989. An evaluation of trout passage through six highway culverts in Montana. N. Am. J. Fish. Manage. **9:** 437-445. Brett, J. R. 1965. The swimming energetics of salmon. Scientific American. **213:** 80-85.

Brett, J. R., M. Hollands, and D. F. Alderice. 1958. The effect of temperature on the cruising speed of young sockeye and coho salmon. J. Fish. Res. Board Can. **15**(4)**:** 587-605.

Browning, M. C. 1990. Oregon culvert fish passage survey. Western Federal Lands Highway Division, Federal Highway Administration. Vancouver, WA.

Bryant, M. D. 1981. Evaluation of a small diameter baffled culvert for passing juvenile salmonids. U. S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. Research Note. No. PNW-384.

Carpenter, L. T. 1987. A comparative study of short-term swimming performance in fry of five salmonid species at different temperatures. Master of Science thesis. University of Washington, Seattle, WA.

Clancy, C. G., and D. R. Reichmuth. 1990. A Detachable Fishway for Steep Culverts. N. Am. J. Fish. Manage. **10:** 244-246.

Clay, C. H. 1995. Design of fishways and other facilities. Second edition. Lewis Publishers, Boca Raton.

Evans, W. A., and B. Johnston. 1980. Fish migration and fish passage: a practical guide to solving fish passage problems. USDA Forest Service. Region 5. No. EM-7100-12. 43 p.

Flanagan, S. A., and M. J. Furniss. 1997. Field Indicators of Inlet Controlled Road Stream Crossing Capacity. USDA Forest Service, Technology and Development Program. No. 9777 1807-SDTDC.

Flanagan, S. A., M. J. Furniss, T. S. Ledwith, M. A. Love, K. Moore, and J. Ory. 1998. Review Draft. Handbook for Inventory and Environmental Risk Assessment of Road Drainage Structures. USDA Forest Service. Technology and Development Program, Water/Road Interaction Technology Series. In review.

Furniss, M. J., M. Love, and S. A. Flanagan. 1997. Diversion potential at road-stream crossing. USDA Forest Service, Technology and Development Program. No. 9777 1814-SDTDC.

Glova, G. J., and J. F. McInerey. 1977. Critical swimming speeds of coho salmon (*Oncorhynchus kisutch*) fry to smolt stages in relation to salinity and temperature. J. Fish. Res. Board Can. **34:** 151-154.

Griffiths, J. S., and D. F. Alderice. 1972. Effects of acclimation and acute temperature experience on the swimming speed of juvenile coho salmon. J. Fish. Res. Board Can. **29:** 251-264.

Hynson, J., P. Adamus, S. Tibbetts, and R. Darnell. 1982. Handbook for Protection of Fish and Wildlife From Construction of Farm and Forest Roads, Best Management Practices for Building Activities Associated with the Discharge of Dredged or Fill Material. Eastern Energy and Land Use Team, Office of Biological Services, USDI Fish and Wildlife Service. Handbook. No. FWS/OBS-82/18.

Kane, D. L., C. E. Behlke, D. L. Basketfield, R. E. Gieck, R. F. McLean, and M. D. Travis. 1989. Hydrology, hydraulics and fish passage performance of Arctic grayling (*Thymallus arcticus*) at Fish Creek, Denali Highway near Cantwell, Alaska. State of Alaska Department of Transportation and Public Facilities, Research Section. Final Report. No. FHWA-AK-RD-89-03.

Kane, D. L., and P. M. Wellen. 1985. Appendix to a hydraulic evaluation of fish passage through roadway culverts in Alaska. State of Alaska Department of Transportation and Public Facilities, Research Section. Final Report. No. FHWA-AK-RD-85-24A.

Kane, D. L., and P. M. Wellen. 1985. Fish passage design criteria for culverts. Institute of Water Resources/Engineering Experiment Station, University of Alaska Fairbanks. No. IWR-108.

Kane, D. L., and P. M. Wellen. 1985. A hydraulic evaluation of fish passage through roadway culverts in Alaska. State of Alaska Department of Transportation and Public Facilities, Research Section. Final Report. No. FHWA-AK-RD-85-24.

Katopodis, C. 1990. Advancing the art of engineering fishways for upstream migrants. *In* Proceedings of the International Symposium on Fishways '90 in Gifu. *Edited by* Publications Committee of the International Symposium on Fishways '90 in Gifu Japan, Gifu, Japan. pp. 19-28.

Katopodis, C. 1992. Introduction to fishway design. Freshwater Institute, Central and Arctic Region, Department of Fisheries and Ocean. Working Document.

Katopodis, C. 1993. Fish passage at culvert highway crossings. Presentation notes. Highways and the Environment, Charlottetown, 17-19 May 1993.

Katopodis, C., P. R. Robinson, and B. G. Sutherland. 1978. A study of model and prototype culvert baffling for fish passage. Western Region, Fisheries and Marine Service, Department of Fisheries and the Environment. Fisheries & Marine Service Technical Report. No. 828.

Lauman, J. E. 1976. Salmonid passage at stream-road crossing, a report with department standards for passage of salmonids. Oregon Department of Fish and Wildlife. Portland, OR.

McKinnon, G. A., and F. N. Hnytka. 1985. Fish passage assessment of culverts constructed to simulate stream conditions on Liard River tributaries. Department of Fisheries and Oceans, Western Region. Canadian Technical Report of Fisheries and Aquatic Sciences. No. 1255.

Powers, P. D., K. Bates, T. Burns, B. Gowen, and R. Whitney. 1997. Culvert hydraulics related to upstream juvenile salmon passage. Washington Department of Fish and Wildlife. Olympia, WA.

Powers, P. D., and J. F. Orsborn. 1985. Analysis of barriers to upstream fish migration. Department of Civil and Environmental Engineering, Washington State University. Final Project Report, Part 4 of 4. No. DOE/BP-297.

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

Rajaratnam, N., C. Katopodis, and M. A. Fairbairn. 1990. Hydraulics of culvert fishways V: Alberta fish weirs and baffles. Canadian Journal of Civil Engineering. **17:** 1015-1021.

Rajaratnam, N., C. Katopodis, and S. Lodewyk. 1988. Hydraulics of offset baffle culvert fishways. Canadian Journal of Civil Engineering. **15:** 1043-1051.

Rajaratnam, N., C. Katopodis, and S. Lodewyk. 1991. Hydraulics of culvert fishways IV: spoiler baffle culvert fishways. Canadian Journal of Civil Engineering. **18:** 76-82.

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

Saltzman, W., and R. O. Koski. 1971. Fish passage through culverts. Oregon State Game Commission. Special Report.

Schneider, M. J., and T. J. Connors. 1982. Effects of elevated water temperature on the critical swim speeds of yearling rainbow trout, *Salmo gairdneri*. Thermal Biology. **7:** 227-229.

Slatick, E. 1971. Passage of adult salmon and trout through an inclined pipe. Trans. Am. Fish. Soc. **:** 448-455.

Taylor, E. B., and M. J. D. 1985. Burst swimming and size-related predation of newly emerged coho salmon *Oncorhynchus kisutch*. Trans. Am. Fish. Soc. **114:** 546-551.

Taylor, E. B., and J. D. McPhail. 1985. Variation in burst and prolonged swimming performance among British Columbia populations of coho salmon, *Oncorhynchus kisutch*. Can. J. Fish. Aquat. Sci. **42:** 2029-2033.

Thomas, A. E., and M. J. Donahoo. 1977. Differences in swimming performance among strains of rainbow trout (*Salmo gairdneri*). J. Fish. Res. Board Can. **34:** 304-306.

Videler, J. J. 1993. Fish swimming. Chapman and Hall, London

White, D. 1996. Hydraulic performance of countersunk culverts in Oregon. Master of Science thesis. Oregon State University, Corvallis, OR.

Yee, C. S., and T. D. Roelofs. 1980. Influence of forest and rangeland management on anadromous fish habitat in western North America. 4. Planning forest roads to protect salmonid habitat. U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. General Technical Report. No. PNW-109.