Fish Passage Through Culverts

An Annotated Bibliography

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This bibliography includes 96 annotated citations on culvert design for fish passage, risk analysis, and fish swimming ability. This collection is a subset of a larger bibliography on culverts and sizing, repair, maintenance, installation, failure, hydraulics, and hydrology.

Author's abstracts were included if available, if not, each paper was read and abstracted.

This work was funded, in part, by the San Dimas Technology and Development Center of the USDA-Forest Service. See also: Copstead, Moore, Ledwith and Furniss. 1998. Water/road interaction: An annotated bibliography. Water/road interactions technology series. USDA Forest Service, Technology and Development Program. (http://www.stream.fs.fed.us/water-road)

Fish Passage Bibliography

Adams, M.A. and Whyte, I.W. **Obstruction Removal, Culverts, Fishways, and Fish Screens**. In: *Fish Habitat Enhancement, a Manual for Freshwater, Estuarine, and Marine Habitats*, edited by Envirowest,Vancouver:Department of Fisheries and Oceans, Government of Canada, 1990,p. 122-169.

> Abstract : Project design criteria for fisheries enhancement are given for removal of fish passage obstructions, culverts, fishways, and fish screens. For each topic, background information relating to fisheries needs is given as well as maintenance and factors influencing costs. Advantages and disadvantages are listed. Examples of use for locations in British Columbia and references complete each section.

Adams, P.W., Campbell, A.J., Sidle, R.C., Beschta, R.L., and Froehlich, H.A. **Estimating streamflows on small forested watersheds for culvert and bridge design in Oregon**. Corvallis, Oregon:Forest Research Laboratory, Oregon State University. 55:1-8, 1986. Research Bulletin.

> Abstract: Streamflow records were combined with basic watershed data from 80 small forested basins to develop equations for predicting peak flows in Oregon. Area of drainage basin was most strongly and consistently related to streamflows, while mean basin elevation and mean annual precipitation were also related to flows in areas of western Oregon. The equations can be used with these and other site-specific data and risk assumptions to help design adequate culverts and bridges.

American Fisheries Society, **A Workshop on Hydrology and Hydraulics for Biologists**. Eureka, CA:American Fisheries Society, California-Nevada Chapter. 1986. Eureka, CA.1986 October 27-31. Notes : Presented by John F. Orsborn, at the California Department of Transportation, Eureka, CA.

> Abstract: Theory, applications, examples, and problem sets on the basic principles of hydrology and hydraulics are presented in the form of a manual for fisheries biologists. Culvert information focuses on culvert sizing techniques, designing culverts for fish passage, and culvert hydraulics. Fisheries biology including life history, swimming capabilities, and habitat needs is provided in the context of hydrology and hydraulics. Other sections are on fish passage barrier analysis and stream flow estimation techniques.

Anderson, J.W. **Vincent Creek Fish Pass**. Denver, Colorado:U.S. Department of the Interior, Bureau of Land Management. 253:1-13, 1974. .Technical Note.

> Abstract: A fish passage designed to mitigate effects of road fill and a perched culvert at a tributary entrance to Vincent Creek, Oregon is presented. Anadromous fish were unable to access Explorer 155 Creek from Vincent Creek. The cost to remove fill and replace the existing culvert with a bridge was high, with the possibility that the resulting gradient would still be a barrier to fish passage. The gradient of the existing culvert was determined not to be a barrier to fish. The fish passage design is a 30 foot Modified Alaskan Steeppass designed to withstand high winter flows. Salmon and steelhead were observed moving upstream from the culvert. Problems with the installation occurred from bedload movement out of the culvert into the fish passage resulting in clogging of the baffle fins of

the fishpass. Design criteria, site plans, recommendations are included along with before and after photographs.

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. -10 p. 1980. Gen. Tech. Report PNW-117.

Abstract: A report of special interest to fishery biologists, resource managers, hydrologists, and road engineers, this bibliography lists publications pertinent to road crossings of salmon and trout streams. Topics include bridge and culvert installation, design criteria, mechanics, hydraulics, and economics, as well as their biological effects.

Anonymous ***Forest Road Engineering Guidebook (Forest Practices Code of British Columbia)***, Province of British Columbia:British Columbia, Ministry of Forests and BC Environment, 1995.pp. 1-153.

Abstract : The Guidebook provides current information and recommended procedures for designing, building, and maintaining forest roads. It is aimed at users who are already capable of carrying out the technical operations related to road engineering, but who require guidance on how to meet the requirements of the *Forest Practices Code of British Columbia Act* and regulations. Culvert related topics include site data requirements for minor stream culverts and site surveys for bridges and major culverts. Culvert design for corrugated steel and corrugated polyethylene pipes include assessment of appropriate materials for a specific site, sizing, and installation. Advantages and disadvantages of each material, types of couplers, choices for headwalls, backfilling and compaction procedures are discussed. In addition, log culvert design criteria and installation practices are given in detail.

Culverts addressed here have a design discharge of less than 6 m^3 per second and a diameter of less than 2000 mm. Culverts larger than this need a professional design. For forest road construction it is recommended that unless soil and runoff conditions require increased sizes, minimum pipe culvert diameter sizes should be 400 mm east of the Cascade Mountains and 600 mm west of the Cascade Mountains, and a minimum opening size for log culverts should be 0.5 m in depth and 1.5 m in width. Options for determining flow quantities for stream culverts at a recurrence interval of 100 years to provide a benchmark of relative risk to be attached to stream culverts for the passage of stream flow include procedures for determining Q_{100} from site information.

Additional road design and construction topics covered in the Guidebook include road alignment, clearing widths, design specifications, site preparation, ditch construction, ford design and construction, inspection, maintenance, and shutdown indicators. Procedures for field identification of soils cover types of soils, size, consistency, density, and compressibility.

Ashton, W.S. and Carlson, R.F. **Determination of Seasonal, Frequency and Durational Aspects of Streamflow with Regard to Fish Passage Through Roadway Drainage Structures**. Fairbanks, Alaska:Institute of Water Resources, University of Alaska, Fairbanks, 99701. AK-RD-85-06:1-51, 1984.

Abstract: Optimal design of culverts for fish passage for each stream crossing requires the magnitude, duration, frequency and seasonal relationship of the flow and the timing of fish movement. Although previous studies have measured fish swimming abilities and culvert water velocity profiles, there are limited studies in northern regions of the hydrologic relationship among magnitude, duration, frequency and season of discharge for the design of culverts for fish passage. We analyzed streamflow records from 33 gaging stations in south-central, western, interior, and arctic Alaska (from watershed with a drainage area less than 100 $mi.^2$ each) to determine the highest consecutive mean discharge with one-, three-, seven-, and fifteen-day durations, and the lowest consecutive mean discharge with three-, seven-, fourteen-, and thirty day-durations. Streamflow during three seasons were analyzed: spring, April 1 to June 30; summer, July 1 to August 31; and fall, September 1 to November 30. The log normal distribution, using the Blom plotting position formula, was used to estimate flows at recurrence intervals of 1.25, 2, 5, 10, and 20 years. Multiple linear regression equations were developed to predict flows from ungaged watersheds. Significant basin and climatic characteristics for high flows were drainage area, mean annual precipitation and percent of the drainage basin with forest cover. Significant characteristics at low flows were drainage area, mean minimum January temperature, mean annual precipitation and percent of drainage basin covered by forests. This report provides the culvert designer with equations to predict flows, other than the instantaneous peak flow, for use in designing culverts for fish passage. Two example problems are given to show the application of these equations. (Author's abstract).

Baker, C.O. and Votapka, F.E. **Fish Passage Through Culverts**. San Dimas, CA:USDA, Forest Service Technology and Development Center. FHWA-FL-90-006:1-67, 1990.

Abstract: As the number and range of many fish species have declined and the recreation demand for fish has increased, the importance of protecting the remaining populations has also multiplied. At new culvert installations, fish passage considerations and needs have increased in complexity. a high percentage of existing drainage structures are approaching or have passed their life expectancy. The task of replacing, modifying, and/or retrofitting the surviving structures will dwarf past programs for providing fish passage through culverts.

This report is intended to review, summarize, and update current information on fish passage through culverts. The scope of the report is limited to highway drainage structures, not including bridges. This distinction was made in an effort to concentrate on those road drainage structures that are most commonly used in fish passage situations. The publication is primarily issued for the fish biologists, engineers, and hydrologists who will be designing the projects and making current decisions on fish passage at drainage structures. (Author's abstract).

The most common problems with culverts are typically associated with excessive water velocities or vertical barriers to fish passage. Other problems include the velocity of water over a given length of structure in relation to fish capabilities, depth of water, icing and debris flows, design flows in relation to fish migration upstream or downstream, and size and species of fish passing through the structure. Guidelines for culvert design to meet these considerations are addressed, including considerations for the timing of fish migration, culvert type choice, control of water velocities by baffle installation, and methods to correct hydraulic problems. Included in the report is a glossary and annotated bibliography.

Ballinger, C.A. and Drake, P.G. **Culvert Repair Practices Manual.** Research and Development, Turner-Fairbank Highway Research Center, McLean, Virginia:U.S. Department of Transportation, Federal Highway Administration. FHWA-RD-94-096:1-265, 1995.

> Abstract: All culverts with openings of more than 20 feet, measured parallel to the roadway, must be inspected on a two-year cycle in accordance with the National Bridge Inspection Standards. (NBIS). Many highway agencies also inspect smaller culverts on the same cycle. The NBIS, and prudent engineering, requires that culverts that are structurally weak or hydraulically inadequate be inspected on a more frequent cycle.
> This manual has been developed to provide guidance to highway agencies on procedures that may be used to repair a wide variety of types of problems that beset metal and concrete culverts of all types. Many of the procedures are also applicable to the repair of timber and stone masonry culverts. Procedures are also presented on ways to improve the inlet and outlet ends of culverts as well as the streambed channels leading to and from them.
> Information presented in this manual has been compiled from numerous contacts with representatives of the culvert industry as well as many highway agencies through the United States and Canada. (Author's abstract).
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> This is a two volume report. Volume I contains information on culvert materials, shapes, construction, problem identification including hydraulic capacity, maintenance, retrofitting, repair, and replacement. Fish passage and beaver control problems are briefly addressed. Volume II consists of appendices on standards, repair and retrofit procedures, specifications, and an annotated bibliography. The report number for Volume II is FHWA-RD-95-089.

Bao, Y., Tung, Y., and Hasfurther, V. **Evaluation of uncertainty in flood magnitude estimator on annual expected damage costs of hydraulic structures**. *Water Resources Research* 23, No. 11(November):2023-2029, 1987.

> Abstract : In the risk-based design for hydraulic structures, the major task is the evaluation of the annual expected damage costs caused by floods. Due to the use of a limited amount of data in flood frequency analysis, the computed flood magnitude of a specified return period is subject to uncertainty. A methodology to integrate such uncertainty in the evaluation of annual expected flood damage is developed and illustrated through an example in culvert design. The effect of uncertainty in estimating flood magnitude using different hydrologic probability models with different sample sizes on the annual expected damage costs is examined. Results of the study show that the effect of the uncertainty in a flood magnitude estimate on annual expected damage is quite significant and is sensitive to the sample sizes and the probability distribution models used. (Author's abstract)

Barber, M.E. and Downs, R.C. **Investigation of Culvert Hydraulics Related to Juvenile Fish Passage**. Pullman, Washington:Washington State Transportation Center (TRAC), Washington State University. WA-RD-388.1:1-54, 1996.

> Abstract: Culverts often create barriers to the upstream migration of juvenile fish. Fish will not travel upstream under high water velocity conditions. It is hypothesized that low velocity regions exist near culvert boundaries. Therefore, the objective of this study was to determine hydraulic characteristics of culverts with different flow conditions. Methods of predicting flow profiles were developed by both Chiu and Mountjoy. Two equations were compared to experimental results. The Mountjoy equation proved to yield better results for

velocity profile predictions. An area of flow corresponding to a predetermined allowable velocity can be calculated using the Mountjoy equation. This can then be used in the design of culverts as fish passage guidelines. The following report contains a summary of background information, experimental methodology, the results of experimental tests, and an analysis of both the Chiu and Mountjoy equations. (Author's abstract).

Barber, M.E. and Downs, R.C. **Investigation of Culvert Hydraulics Related to Juvenile Fish Passage.** Pullman, Washington:Washingtion State Transportation Center (TRAC), Washingtion State University. WA-RD-388.2:1-172, 1996. Final Technical Report.

Abstract: Culverts often create barriers to the upstream migration of juvenile fish. Fish will not travel upstream under high water velocity conditions. It is hypothesized that low velocity regions exist near culvert boundaries. Therefore, the objective of this study was to determine hydraulic characteristics of culverts with different flow conditions. Methods of predicting flow profiles were developed by both Chiu and Mountjoy. Two equations were compared to experimental results. The Mountjoy equation proved to yield better results for velocity profile predictions. An area of flow corresponding to a predetermined allowable velocity can be calculated using the Mountjoy equation. This can then be used in the design of culverts as fish passage guidelines. The following technical report contains a detailed description of background information, experimental methodology, the results of experimental tests, and an analysis of both the Chiu and Mountjoy equations. (Author's abstract).

Bartos, L.R. **Peak flow hydrology in relation to bridge and culvert design problems in southeast Alaska**. National Applied Wildland Hydrology Workshop. 1-8, 1978. Atlanta, Georgia.1978 May 1-5.

Abstract: An overview of geomorphologic, soils, vegetation, and precipitation in southeastern Alaska which set the stage for large streamflow amplitudes. Strong relationships of drainage geometry and peak flow events enabled development of sound hydrologic design techniques for bridges and culverts on forest roads for southeastern Alaska conditions. Passage of extreme peak flow events, structural safety, and maintenance of optimum passage for anadromous fish at low flows were adequately achieved through hydrologic design. (Author's abstract).

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

Abstract: A handbook containing practical guidelines for the design of fish passage facilities for upstream migrating anadromous fish is presented including specifics for the passage of fish through new or existing culverts. The scale of systems to which these guidelines apply includes mainstem passage in rivers such as the Columbia to small culverts under county roads. A fishway is any structure or modification to a natural or artificial structure for the purpose of fish passage. The fishway is a system that may include attraction features, barrier dam, entrances, auxiliary water system, collection and transportation channels, the fish ladder itself, trash rack, an exit, and operating and maintenance standards. It can be a formal concrete structure, pools blasted in the rock of a waterfall, or log controls in the bed of a channel. A variety of physical, hydrologic, and biologic considerations will determine whether a given obstruction is passable and are necessary predesign data requirements. Water and fish are of course central to the fishway system. Design considerations for culverts must consider the hydraulic effects of

culvert size, slope, material and elevation to create depths, velocities, and a hydraulic profile suitable for fish passage. Those criteria are presented along with information regarding baffle design and retrofitting culverts for fish passage. The addition of baffles is not recommended unless under extreme situations as they require maintenance to keep clean and replacement when they fail. Culvert installation standards from the Washington Department of Fisheries and the Alaskan Department of Fish and Game are included as is a glossary of fish passage terms.

Bates, K; Barnard, R.; Heiner, B; Klavas, P.; Powers, P. 1999. **Fish Passage Design at Road Culverts: A design manual for fish passage at road crossings.** Washington Department of Fish and Wildlife, Habitat and Lands Program, Environmental Engineering Division. Olympia, WA. http://www.wa.gov/wdfw/hab/engineer/cm/culvertm.htm#int

Abstract: This manual is for the design of permanent new, retrofit, or replacement road crossing culverts that will not block the migration of salmonids. The manual is intended for use by designers of culverts including private landowners and engineers. The level of expertise necessary to use this manual varies depending on site conditions and the design option selected. For all but the no-slope design option (described below), it is assumed that the designer has a basic background of hydraulic engineering, hydrology, and soils/structural engineering to accomplish an appropriate design.

Formal fishways may be required at some culvert sites to provide passage. The design of fishways is beyond the scope of this manual though there is a brief description of some basic design concepts included here. A fish passage engineer should be consulted for additional assistance for the design of fishways.

Behlke, C. **Power and Energy Implications of Passage Structures for Fish**. *American Fisheries Society Symposium* 10:289-298, 1991.

Abstract: Fluid mechanic equations are used to show effects of virtual mass force, non-Archimedean buoyant force, and profile drag force on fish in several fish passage structures. Example problems are worked to show computational procedures for calculating net propulsive force, net power, and net energy necessary for fish to swim in a lake, up a steep chute, and through the outlet, barrel, and inlet of a culvert. (Author abstract)

Behlke, C., Kane, D., McLean, R.F., and Travis, M.D. **Fundamentals of Culvert Design for Passage of weak-Swimming Fish**. 2301 Peger Road, Fairbanks, AK 99709:Alaska DOT & PF. Research Station. FHWA-AK-RD-90-10:1-203, 1991.

Abstract: Properly designed culverts do not produce water velocities that exceed fish swimming abilities. Fish have two different musculature systems for swimming; a white muscle system generates power for short, vigorous swimming, and a red muscle system furnishes power for long, sustained swimming. The culvert design must account for both swimming modes. Therefore, the engineer must know the hydraulic conditions where the fish swims. These conditions change throughout the culvert. The engineer determines acceptable hydraulic conditions for fish by matching known fish swimming power and energy capabilities.
Subcritical flow is necessary to pass weak-swimming fish. This requirement precludes the use of inlet control. The engineer may use artificial roughness to create areas of slower water velocities within culverts. Examples of these are depressed inverts, weir baffles, and deep culvert corrugations.

The manual presents design procedures to pass upstream-migrating, weak fish. The manual also displays criteria for retrofitting existing culverts. This paper does not present cost-effective design criteria for strong-swimming fish. (Author's abstract).

Behlke, C., Kane, D., McLean, R.F., and Travis, M.D. **Economic Culvert Design Using Fish Swimming Energy and Power Capabilities**. Fish Passage Policy and Technology. Bates, K. American Fisheries Society. 95-100, 1993. September 1993.
Notes : Proceedings of a Symposium entitled Fish Passage Policy and Technology, sponsored by the Bioengineering Section, American Fisheries Society. September 1993, Portland, Oregon.

Abstract: Utilizing fish swimming power and energy capabilities and the hydraulic properties of culverts in those locations within culverts where fish actually swim, the writers have prepared a detailed manual of culvert design procedures for culverts which must provide safe passage of upstream moving, weak swimming fish (Behlke, Kane, McLean, and Travis, 1991). The design procedures utilize hydraulic formulae for profile drag, non-Archimedean buoyant forces, and virtual mass force to quantify the hydraulic conditions within a culvert that the design fish can sustain without exhaustion for various time durations. Final culvert design may then be selected on economic or other bases from the full range of trail designs that are hydraulically suitable for fish passage. This paper provides an overview of the analytical and biological methods used in the preparation of the design procedures and its associated software. (Author's abstract)

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

Abstract: Combinations of water velocity and passage length in highway culverts were evaluated to determine conditions that enabled or prevented the passage on nonanadromous rainbow trout *Oncorhynchus mykiss*, brown trout *Salmo Trutta*, cutthroat trout *O. clarki*, and brook trout *Salvelinus fontinalis*. Fish passage through six culverts 45-93 m long was determined by trapping and electrofishing. Water velocities were measured 5 cm above the bottom (bottom velocity) and at 0.6 of the water depth at intervals between rest sites throughout the lengths of the culverts. Nonlinear regression lines specific to species and state of sexual maturity were fit to the combinations of mean bottom velocity and passage length representing the most strenuous conditions that allows the upstream passage of trout. Because of the similarity of the strenuous passage relations among species, the spawning rainbow trout relation could be used as the general criterion for passage of the trout studied. This relation indicated that fish could swim distances of 10, 30, 50, 70, and 90 m with mean bottom velocities up to 0.96, 0.80, 0.74, 0.70, and 0.67 m/sec respectively. (Author's abstract).

Bell, M. ***Fisheries Handbook of Engineering Requirements and Biological Criteria***, Portland, Oregon:US Army Corps of Engineers, North Pacific Division, 1990.pp. 1~1-35~7.

Abstract : The Handbook sets forth design criteria that may be used for fish habitat needs including size of facilities, water requirements, general costs and operating procedures. Fisheries biology topics include life history of western sport, commercial, predaceous, forage, and nuisance species. Water quality parameters covered are oxygen, turbidity, temperature, heavy metals, and toxicants. Engineering aspects include culverts, channel sizing, fishways, fish passage designs, hatcheries, pumps, and mechanical hauling of fish.

Culvert design requirements as outlined in the Handbook are related to fish swimming velocity needs of targeted fish.

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

Abstract: The design of structures for fish passage in rivers and streams provides an opportunity to apply expert system concepts to a design problem. Fishways contribute to the sustainable development of water resources projects by providing a path that allows fish migrations to be maintained. A prototype expert system (FDES) has been developed to recommend the most suitable fishway type for given design conditions. A recommendation is provided on the basis of fishway hydraulics, fish passage performance, and cost requirements. Fishway design demands expertise in various scientific disciplines such as hydrology, hydraulics, and fish biology. Expert system technology may be used to reduce design time requirements and to serve as a teaching aid to inexperienced engineers by organizing and assessing the cumulative knowledge of the most experienced designers. The rule-based expert system development tool, VP-Expert, supplies the backward chaining control structure for accessing the knowledge within the prototype. (Author's abstract).

Beschta, R.L. **Road Drainage Structures: Culvert Sizing at Stream Crossings**. Corvallis, Oregon:College of Forestry, Oregon State University. 1-28, 1984.

Abstract: Drainage structures are an important aspect in the design and maintenance of forest road systems. Culvert sizing at stream crossings involves several important variables, including: 1) peak flow estimation and associated recurrence interval as peak flows are of greater importance in culvert sizing than is the total volume or duration of flow, 2) design life of structure, and 3) risk of failure during design life.

Three general types of methods for instantaneous peak flow associated with a given recurrence interval are: 1) local evidence, 2) empirical formulas, and 3) flood frequency analysis. An example of the empirical method is the use of Talbot's formula to directly relate drainage area to culvert size. The type and size of the culvert is usually determined by the characteristics of the inlet. Other design considerations include gradient recommendations, alignment to streams, organic debris, installation guidelines, fish passage, and flow capacity requirements.

Risk of failure over the design life of the culvert needs to be specified so as to be incorporated into the design of the culvert. This can be accomplished by first determining the design life of the culvert and the recurrence interval of a design flow that a culvert can sustain without failure. Data in tabular format illustrating the associated probability of failure for a culvert installation once the above decisions are made is included in an appendix. Local site characteristics often require an increase in designed capacity to minimize the potential for failure.

Notes : Presented at "Forest Roads Conference" in May of 1984. College of Forestry, Oregon State University, Corvallis.

Bryant, M.D. **Evaluation of a Small Diameter Baffled Culvert for Passing Juvenile Salmonids**. Pacific Northwest Forest and Range Experiment Station:USDS Forest Service. PNW-384:1-7, 1981. Research Note.

> Abstract: A 90-cm-diameter culvert with off-set baffles was set at a 10 percent gradient in an artificial stream channel on Admiralty Island, Alaska. Coho salmon, Dolly Varden char, and cutthroat trout, all less than 120-mm fork length, were able to move up the 9-m culvert. Additional work is needed to determine an upper discharge limit and to evaluate field installations. (Author's abstract).

Butler, M. **PEAK/RISK/CULVERT: A Program to Compute Peak Flows, Hydrologic Risk, and Circular Culvert Sizes at Forest Road Crossings**. Roseburg, OR:U.S. BLM, Roseburg District Office. BLM/YA/PT-86/0104341:1-37, 1986. BLM Technical Note 374.

> Abstract: Describes the use of a BASIC computer program to aid the hydrologist (and other specialists involved in water projects) in the calculation of design peak flows, evaluation of hydraulic risk, and selection of circular culverts. The program is written for the sizing of circular culverts at forest road crossings, but may be extended to other applications such as bridges, watershed management projects, and other areas where the calculation of design events and hydrologic risk is needed. A discussion of each subject is included in the text, with instructions on how to use the program. Example problems are used to illustrate the program.
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> The peak flow portion may be adapted to other locations were regional flood frequency equations have been developed. The computational methods are described briefly. For a more detailed discussion, consult the references cited. (Author's abstract)
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> Peak flow estimators which utilize regression equations for estimating peak flows at ungaged stations are the U.S. Geological Survey Method and Water Resources Research Institute (WRRI). Hydrologic risk is defined as the probability that one or more events will exceed a given flood magnitude within a specified period of years. The BASIC program calculates culvert diameter by the equation $D = (Q/C_q)^{2/5}$ where D is the pipe diameter in feet, Q is discharge in cfs and C_q is a discharge coefficient, given in the paper.

Clancy, C.G. and Reichmuth, D.R. **A detachable fishway for steep culverts.** *North American Journal of Fisheries Management* 10(2):244-246, 1990.

> Abstract: A fishway constructed of angle iron and reinforcing bar was installed in a high-gradient culvert to allow the passage of Yellowstone cutthroat trout *Onchoryhynchus clarki bouvieri* to upstream spawning areas in Cedar Creek, a tributary of the Yellowstone River in southwestern Montana. The structure was detachable from the culvert, inexpensive, and portable. The fishway was still effective 8 years after installation. (Author's abstract).

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, Pacific Region. 811:1-57, 1978.

> Abstract: This report examines the hydraulic criteria that should be satisfied at a culvert installation to ensure that fish can migrate through the facility with a minimum of stress.

The report also outlines guidelines that, if incorporated into the culvert design, should produce a facility that will permit the free passage of fish in most situations. The design of auxiliary fish passage structures such as culvert baffles and tailwater control facilities are discussed and exampled by drawings. Consideration is also given to the installation of culverts to avoid conflicts with fish use in the stream both during and after the construction period. Guidance is also given concerning the procedures to follow for necessary approval of a proposed culvert installation by the Fisheries and Marine Service. (Author's abstract).

Dane, B.G. A Review and Resolution of Fish Passage Problems at Culvert Sites in British Columbia. Vancouver, B.C., Canada:Department of Fisheries and Environment. 810:1-126, 1978. Fisheries and Marine Service Technical Report.

Abstract: Culverts can have a major impact upon anadromous fish populations by impeding or preventing upstream migration. Often, a culvert may determine the extent of fish utilization in a stream and, in an extreme situation, the presence of a culvert could exclude all anadromous fish from a particular watershed. The success or failure of a fish in migrating through a culvert depends upon the swimming ability of the fish and the hydraulic conditions present at the site. In general, culverts represent a streamlined, hydraulically efficient flow channel in which velocities are maximized and usually constant throughout most of the culvert length. This feature is in stark contrast to a natural stream channel which provides an endless variety of landscapes throughout its length ad width, thus offering the fish a choice of routes that are suited to its swimming ability.

Through experimentation and observation, the swimming ability of salmon and steelhead trout has been documented and from this it is possible to determine the hydraulic criteria that must be satisfied at the site to ensure that free fish passage is maintained. However, as a delay of as little as one day can have serious consequences for spawning fish, it is important that the appropriate hydraulic criteria be maintained at the site throughout the spawning migration period. This would normally require that detailed streamflow records in the form of a hydrograph be studied and compared with the fish migration period to determine the maximum and minimum discharges upon which to base fish passage design, However, do to the lack of detailed streamflow records for small streams in British Columbia, it is therefore, impractical to apply concise standards to fish passage design in most situations and a more general system must be used.

The "Recommendations for Culvert Design" contained in this report are, therefore as et of guidelines that, if incorporated into the culvert design, should result in a facility that will permit the free passage of fish under most circumstances. In addition, the design of auxiliary fish passage structures such as culvert baffles and tailwater control facilities are discussed in some detail and exampled by drawings. Recommendations are also made for the installation of culverts to avoid conflict with fish use in the stream during the construction period. An outline of the procedure to follow for approval of the project prior to commencement of the work is also included in the report.

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. 80-4:1-103, 1980.

Abstract: Fish movements and flows at the Goose Creek road crossing near Churchill, Manitoba, were monitored from April 29 to May 20, 1997. The crossing consists of five arch-rib multiplate culverts which are 27.4 m long with an opening of 2.7 x 3.9 m. There

are three culverts in the east channel and two in the west. The mean daily discharge recorded in the east channel of Goose Creek during the monitoring period was 16.4 m^3/second. An average daily discharge of 8.4 m^3/second was recorded in the west channel. Average water velocities at the downstream ends of the culverts exceeded 0.91 m/second in all five culverts throughout the 22-day monitoring period.

A total of 1044 fish were captured in hoop nets set immediately downstream of the crossing. Longnose suckers constituted 69.4 per cent of the catch. Other species caught included burbot, lake whitefish, round whitefish and Arctic grayling. Most (69%) of the fish were caught from the west channel. None of the 13 Arctic grayling tagged and released below the Goose Creek crossing was recaptured, although 30 unmarked grayling were netted upstream of the culverts. Twenty-six of the 198 pike were recovered; 17 recoveries were made during the monitoring period. Only four of the 17 recoveries were from upstream of the crossing. These four fish may have moved through the west channel culverts.

From the observed data and comparisons with the swimming performances of similar fish species as described in the literature, it was concluded that water velocities experienced in the Goose Creek culverts in 1977 presented a near-total barrier to the upstream migration of spring spawning fishes (Arctic grayling, northern pike and longnose suckers) in Goose Creek. (Author's abstract)

DeVries, J.J.E. **Proceedings of a Workshop on County Hydrology Manuals**. DeVries, J.J. Mission Viejo, CA 92692:Lighthouse Publications. 1-124, 1991. Water Resources Center, University of California, Davis.1990 August 16-17.

Abstract: Information on 'county level' hydrologic techniques in California based on county hydrology manuals is presented. County hydrology manuals address public works aspects of surface water runoff management for flood control purposes and water conservation. Emphasis of papers is: 1) to give an overview of county hydrology manuals and general hydrologic analysis procedures used for county-level hydrology, and 2) a review of specific hydrologic and stormwater drainage procedures. Papers include: an application of a county adopted hydrology manual for the town of Apple Valley, California, discussions of frequently used hydrologic techniques for small watershed analysis including precipitation, loss rate estimation, and runoff computations, guidelines for detention basin design procedures, and a general review of the rainfall-runoff models.

Dimeo, A. **Correcting Vertical Fish Barriers; Investigation of Steeppass and Fish Ladders**. Missoula, Montana:US Forest Service, Equipment Development Center. 2613:1-28, 1977.

Abstract: Improperly installed culverts have created vertical barriers for fish moving upsteam. Reinstallation costs can be prohibitive. The Equipment Development Center at Missoula (MEDC) determined methods successful in correcting fish passage barriers without removing or altering the flow characteristics of the original culvert. In addition MEDC determined equipment needs for correcting fish passage barriers. Results of the MEDC investigations are reported. Some general hydrologic and ichthyologic design parameters are summarized to provide basic information for those unfamiliar with the subject. A selected bibliography, to serve resource managers designing more intensive study, is included. (Author's abstract)

Dryden, R.L. and Jessop, C.S. **Impact Analysis of the Dempster Highway Culvert on the Physical Environment and Fish Resources of Frog Creek.** Resource Management Branch, Central Region:Environment Canada, Fisheries and Marine Service. CEN/T-74-5:1-59, 1974. Technical Report Series.

Abstract: The impacts of improper culvert design and effects on the hydrology and fish biology of Frog Creek, N.W.T. are discussed. Fish migration discharge design, as required by Fisheries and Marine Service, Environment Canada for northern highway culverts is defined. At this or lower discharges, flow conditions within the culvert must allow for the upstream passage of fish. Fish migration discharge for Frog Creek, N.W.T. is calculated as 22.4 m^3/s (800 cfs). If the culvert at Frog Creek had been designed to allow fish passage at this discharge, the delay to fish migrations would have been only 3 to 4 days. Water velocities in the Frog Creek culvert during 1973 exceeded the maximum allowable velocity of 1.5 m/s (5 fps) for 40 days from May 26 to July 5.
Bank erosion downstream from the culvert caused retreat of the river bank at a rate of 15 cm (6 inches) per day. Siltation of the stream resulting from construction was evident, but appeared to be insignificant. During the peak discharge period, extensive ponding occurred upstream of the culvert. Ice buildup inside the culvert occurred primarily during early spring as a result of over-ice flow.
High water velocities within the culvert blocked the spawning migration of approximately 600 northern pike *Esox lucius* (Linnaeus) and appeared to block movements of some broad whitefish *Coregonus nasus* (Pallas). Fish passage did not become generally possible until July 5, when water velocities of less than 1.5 m/s (5 fps) were attained. After passage became possible, both pike and broad whitefish dispersed equally in upstream and downstream directions.
It was estimated that only a small proportion of the total pike population of the Frog Creek drainage was blocked by the culvert. No physiological effects of culvert delay on ripe pike were evident. Feeding habits of northern pike and broad whitefish are described in relation to available food organisms, as indicated by drift and artificial substrate samples. Age and growth and length frequency distributions for pike and broad whitefish are described. Maximum ages recorded in Frog Creek were 8 years for pike and 6 years for broad whitefish. (Author's abstract).

Dryden, R.L. and Stein, J.N. **Guidelines for the Protection of the Fish Resources of the Northwest Territories During Highway Construction and Operation**. Resource Management Branch, Central Region:Environment Canada, Fisheries and Marine Service. CEN/T-75-1:1-32, 1975. Technical Report Series.

Abstract: Based on the results of fisheries investigations conducted between 1971 and 1974 guidelines have been designed to protect the fish resources of the Districts of Keewatin and Mackenzie, as well as Baffin and Southampton Islands, from major disruptions resulting from the construction and operation of highway and road systems. These guidelines are not intended to serve as regulations but merely as an aid in meeting Fisheries and Marine Service requirements, as defined by the Fisheries Act of Canada. Culvert average cross-sectional velocities must not exceed 0.9 m/s (3 fps) when fish passage is a requirement, unless it can be satisfactorily demonstrated that the culvert design includes a selected region wherein velocities are low enough to permit fish passage. This selected region must be continuous throughout the culvert length and of sufficient size to permit the fish to locate it and to swim through it. Alternatives such as baffles should be considered when these velocity criteria can not be met through regular design procedures. The minimum desirable water level within culverts during periods of fish movement should be 20.3 cm (8 inches).

In general, no instream construction activity should be attempted from May 1 to June 30 and from September 1 to November 15, as these periods are considered critical to fish migrations and spawning. However, these dates vary slightly with geographical spread and variations in the timing of freeze-up and break-up. The spring or fall restrictions may be lifted if it can be satisfactorily demonstrated that fish spawning activities do not occur during either or both of these periods in the stream under consideration.

Three days is considered the maximum time period during which blockage to annual spawning migrations can be tolerated without causing serious disruption to the spawning cycle. During this three day period, the above mentioned velocity criteria need not be adhered to. Variables such as the timing of fish migration and the timing and duration of peak flows will determine when this three day limitation should be in effect.

The removal of stream gravel may seriously damage spawning habitat and therefore should not be attempted without first consultation with Fisheries and Marine service. Highway routing should avoid close proximity or paralleling of streams or water bodies, and should cross river systems as far upstream from the river mouth or as far downstream from a lake outlet as possible.

Specific restrictions, other than those discussed within these guidelines, may have to be imposed where unique fish species or life history aspects are involved. Conversely, the guidelines may be tempered upon consideration of species composition or the individual characteristics of a stream system. Fisheries and Marine Service is available to provide advice and guidance with respect to the fisheries resource for any highway design for construction proposal in the Northwest Territories. (Author's abstract).

Engle, P. **Fish Passage Facilities for Culverts of the MacKenzie Highway**. Burlington, Ontario:Department of the Environment, Hydraulics Division, Canada Centre for Inland Waters. :1-33, 1974.

Abstract: Most stream crossings on the Mackenzie Highway will be made using large culverts. In many of these culverts, the velocities will be too high for fish migration. A model of a culvert of circular cross-section was constructed to design and test devices which will provide regions of low currents so that the fish can travel upstream during the spawning run. Care was taken to keep the losses as low as possible. Three different design of fish passage facilities were developed, called Spoilers, Offset Baffles, and Side Baffles. Each design has been recommended for a specific range of flow depth and culvert slope. The effectiveness of all three design is inversely proportional to culvert slope. The maximum recommended slope is 5%. Suggestions for application of the fish passage facilities to elliptical and arch culverts are also made. Minor problems are expected with debris and sediment. Ice problems could be serious in the Side Baffles and some further consideration of this problem may be necessary. (Author's abstract).

Evans, W.A. and Johnson, F.B. **Fish Migration and Fish Passage: A Pracitical Guide to Solving Fish Passage Problems**. USDA Forest Service, Region 5. 1-41, 1972.

Abstract: This guide discusses the swimming ability of fish species in upstream and downstream migrations, and discusses natural and man-made barriers fish encounter in their migrations. Barriers include natural bed rock, debris jams, thermal barriers, short and long-term dams, culverts, fords, and bridges. included is a procedure for designing new installations of stream crossing structures which includes checking into migration

periods, stream flow, and site data. Inspection of and correcting existing culverts is discussed with an inventory used in Forest Service Region 5 to identify fish passage problems. A case history from Forest Service Region 6 of a fish passage problem with a successful solution is presented in detail. Graphs for water velocity and depth in circular, box, and arch culverts are in the Appendix. These graphs are for approximation only but are accurate enough for fish migration problems. The graphs are not intended for determining size and slope of culverts. Hydraulic data for bottomless arches and bridges is not in this guide. (from Baker and Votapka, 1990).

Federal Highway Administration and USDA, F.S. **Fish Passage Through Culverts**. 1996. Video.

Abstract: The fourteen minute long video explains how a hydrologist, a fish biologist, and an engineer all play a crucial role in the designing of a roadway over a stream. It describes the types of culverts and some factors to look for in deciding the type to use. The video gives the advantages and disadvantages to both fish and engineers if the culvert is not maintained. The video is appropriate for all engineering and maintenance staff and is available via the Northwest Technology Transfer Center, March 1996 catalog.

Fitch, G.M. **Nonanadromous Fish Passage in Highway Culverts**. 530 Edgemont Road, Charlottesville, VA 229903-0817:Virginia Departent of Transportation. VTRC 96-R6:1-18, 1995. Final Report.

Abstract: Highway culverts may hinder the normal migrations of various trout species in wild trout streams, due to increased flow velocity, shallow water depths, increased turbulence, and perching. This can impede migrational movements, affecting the genetic diversity and long-term survival of some species. Often, the proper installation of culverts can reduce the adverse effects on fish while maintaining hydraulic efficiency. This study characterized the problems with existing culverts to develop guidelines for the future use of culverts in areas with high gradient streams. Installation criteria will ideally limit the use of bridges where culverts are appropriate, and eliminate the use of culverts where they would create fish passage problems. This will reduce installation, maintenance, and retrofitting costs. The study concluded that culverts can be considered the primary option for crossing trout streams if the following criteria are met:

* the culvert can be placed on the same slope as that of the streambed,
* the slope of the stream is less than three percent,
* the flow velocity does not exceed 1.2 meters/second under normal flow conditions,
* the barrel of the culvert can be properly countersunk at the outlet to prevent perching.

Bridges should be used at those crossings if any of the above criteria cannot be met. Also, baffles should not be used to control stream velocities in new culverts, and concrete aprons should not be used at culvert outlets. If culvert bottoms could be cast to have a roughness coefficient equal to that of the streambed, this would allow greater use of culverts at stream crossings without impeding the passage of trout. (Author's abstract).

Francfort, J.E., Cada, G.F., Dauble, D.D., Hunt, R.T., Jones, D.W., Rinehart, B.N., Sommers, G.L., and Costello, R.J. **Environmental Mitigation at Hydroelectric Projects**, Volume II. Benefits and Costs of Fish Passage Protection.Anonymous Idaho Falls, Idaho:Idaho National Engineering Laboratory, EG&G Idaho, Inc. DE-AC07-76ID01570:1~1-27~6, 1994.

Abstract: The study examines environmental mitigation practices that provide upstream and downstream fish passage and protection at hydroelectric projects. The study includes a survey of fish passage and protection mitigation practices at 1,825 hydroelectric plants

regulated by the Federal Energy Regulatory Commission (FERC) to determine frequencies of occurrence, temporal trends and regional practices based on FERC regions. The study also describes, in general terms, the fish passage/protection mitigation costs at 50 non-Federal hydroelectric projects. Sixteen case studies are used to examine in detail the benefits and costs of fish passage and protection. The 16 case studies include 15 FERC licensed or exempted hydroelectric projects and one Federally-owned and -operated hydroelectric project. The 16 hydroelectric projects are located in 12 states and range in capacity from 400 kilowatts to 840 megawatts. The fish passage and protection mitigation methods at the case studies include fish ladders and lifts, an Eicher screen, spill flows, airburst-cleaned inclined and cylindrical wedgewire screens, vertical barrier screens, and submerged traveling screens. The costs, benefits, monitoring methods, and operating characteristics of these and other mitigation methods used at the 16 case studies are examined. (Author's abstract).

Notes : Prepared for the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, Under DOE Idaho Operations Office Pages at WA center, McKinleyville, include: abstract, executive summary, table of contents, list of figures and tables, chapters 1, 2, 3, 4, 5 (Arbuckle Mountain, California Case Study), 9 (Jim Boyd, Oregon, Case Study), 11 (Leaburg, Oregon, Case Study), 15 (Potter Valley, California, Case Study),21, 22, 23, 24, 25, 26, 27, and appendix.

Gebhards, S. and Fisher, J. **Fish Passage and Culvert Installations**. Idaho:Idaho Fish and Game Department. 1-12, 1972.

Abstract: Idaho has a number of fish species requiring free access to streams. Access may be required at varying stream flow conditions depending upon the species and life stage of the fish. A number of potential situations are possible at a culvert installation which could block fish during critical passage period. Those conditions may include a barrier to fish at the outfall of the culvert, a barrier within the culvert, a barrier at the culvert inlet, and/or barriers during the construction phase of the project. Design criteria for culvert installation on Idaho streams are given to alleviate the above fish passage barriers, and include gradient choice, water velocity and depth, length of culvert, baffles, multiple installations, downstream controls, and fishways. Specifics for the above criteria are provided in the form of charts, plans, and descriptions.

Genskow, J.R. **Fish passage in urban streams**. In: Domencia, Michael F., ed. Proceedings of the 22nd annual conference on integrated water resources planning for the 21st century. American Society of Civil Engineers. 241-244, 1995. May 7-11.

Abstract: This paper discusses fish passage criteria for culverts and how these criteria were applied to planning a culvert rehabilitation project along an urban creek. It also discusses how fisheries issues impact urban 'in-stream' drainage system maintenance and facility rehabilitation projects. (Author abstract).

Hansen, W.F. **Some applications of flood frequency and risk information in forest management**. In: *Application of Frequency and Risk in Water Resources*, edited by Singh, V.P.D. Reidel Publishing Company, 1987,p. 219-226.

Abstract : Floods have been responsible for the damage or destruction of numerous forest road, channel, and water diversion structures. Some of the losses are to be expected

because it is too costly to design for all circumstances. Other losses occur because of little or no flood design, debris accumulations, slope instability, and poor awareness and understanding of the problem. Presented are some applications of flood frequency and risk information in forest land management. Some of the problems of application are discussed. A simple approach to refine water resource records to meet local needs is included as a tool to check other flood analyses or provide design assistance. (Author's abstract)

Example based on culvert or bridge design choice for a stream crossing compares initial costs, life spans, abilities to pass floods, and fish passage capabilities. Second example uses flood frequency information to determine culvert spacing needs for a road.

Hetherington, E.D. **The 25-year Storm and Culvert Size: A Critical Appraisal**. Victoria, British Columbia:Pacific Forest Research Centre, Canadian Forestry Service. BC-X-102:1-28, 1974.

Abstract: The British Columbia Forest Service Coastal Logging Guidelines, recognizing that adequately sized culverts at stream crossings are essential for stream protection and maintenance of good road conditions, specify that culverts be designed to handle the 25-year storm. Because of insufficient precipitation and small-stream flow data, realistic evaluation of 25-year storm flows is severely restricted in most parts of the province. Hence, adherence to this guideline is problematical at the present time. The main purpose of this report is to outline the problems and severe limitations associated with evaluating 25-year frequency peak flows by indirect methods. The concepts of return period and risk are reviewed to clarify what is meant by the phrase "25-year peak flow." Regional differences in peak flow generation processes are then outlined to indicate the need for different types of data and analytical procedures. A number of techniques for evaluating peak flows are described in detail to illustrate the extent and significance of data limitations, to provide some insight into the techniques themselves, and to point out relevant reference material. A second objective is to place the role computed 25-year peak flow values in perspective. Once a design peak flow has been determined, an appropriate culvert size must be selected. Risk of culvert plugging and changes in runoff following logging are additional factors to be considered. Suggestions for selecting safety factors are offered and recommendations are made concerning collection and analysis of required precipitation and streamflow data. (Author's summary)

Notes : Revised summary of presentation at short course of Practical Forest Watershed Management held at Parksville, British Columbia, November 19-20, 1973, and sponsored by the University of British Columbia and the Association of British Columbia Professional Foresters.

Hunter, Larry A. and Lesley Mayor, 1986. **Analysis of Fish Swimming Performance Data, Volume I.**

Abstract:An analysis of fish swimming performance data collected during a comprehensive literature search was performed. The data was analyzed at the species level and for three distinct swimming categories (sustained cruising, prolonged, and burst) when sufficient data was available. Regression equations were calculated for velocity/length and velocity/time relationships and, with adequate data, a multiple regression equation was determined using velocity, length, and time. Additional calculations of maximum swimming distance versus water velocity and specimen length were performed on those species where multiple regressions were available.
These maximum swimming distance equations are directly applicable to fishway design.

Hydrology Subcommittee of the Interagency Advisory Committee on Water Data Feasibility of **Assigning a Probability to the Probable Maximum Flood**. Office of Water Data Coordination. 1-79, 1986.

Abstract: The difficulty in assigning a probability to the probable maximum flood (PMF) and in defining the distribution between the 100-year flood and the PMF impairs the ability to use risk-cost analysis. Given this focus, the purpose of the paper is to address the following questions: 1) is the calculation of the PMF within definable confidence or error bands within the state of the art, and 2) how far out on the probability scale can flood probability be determined within definable confidence and error bounds? In practice, computed PMF's are dangerously small or wastefully large.

The methodology utilized to answer the above questions involved multiple searches of bibliographic sources covering published material resulting in five categories of methods: 1) extrapolation of frequency methods, 2) joint probability techniques, 3) regional analysis techniques, 4) determination of paleohydrologic extremes, and 5) Bayesian techniques, for determining flood frequency probabilities. Reviewers were looking for a description of the methodology, variations among papers reviewed, and determining whether the methodology captures the PMF.

Few of the papers reviewed dealt with extremely rare events. It is the conclusion of the work group that no procedure proposed to date is capable of assigning an exceedence probability to the PMF or to the near-PMF flood in a reliable, consistent, and credible manner. Reviewed methods have not been systematically tested, therefore, selection of a method or assigning a probability to the PMF would be arbitrary.

Johnson, A. and Orsborn, J.F. **Welcome to Culvert College**. P.O. Box, Duvall, Washington, 98019:Washington Trout. 1996.

Abstract: Welcome to Culvert College is a compilation of papers relating to fish passage through culverts. The manual is designed for use in a classroom situation and includes a working draft of a protocol for assessing fish passage and culverts. The goal of the protocol is to assist in quickly but methodically identify which culverts warrant extensive analysis for fish passage concerns. Also included is the laws and regulations pertaining to fish passage in the State of Washington, the State of Washington water classification system, and fish swimming capabilities.

Jordan, M.C. and Carlson, R.F. **Design of Depressed Invert Culverts**. Fairbanks, Alaska:Water Research Center, Instituite of Northern Engineering, University of Alaska-Fairbanks. FHWA-AK-RD-87-23:1-64, 1987. Final Report.

Abstract: The hydraulic characteristics of a depressed invert culvert were studied. Also, a design procedure for depressed invert culverts is outlined. The hydraulic characteristics were studied by reviewing pertinent literature and by the use of a hydraulic model. The design procedure is similar to that already used by state hydrologists. Formulas for determining the geometric properties of a depressed invert culvert are presented. The hydraulic model was used to determine the discharge coefficients for a depressed invert culvert flowing under inlet control and set flush to a vertical headwall. A literature review was performed which examined velocity profiles, flow over permeable beds, and flow resistance in culverts and over rough beds. The design procedure is applicable to depressed invert culverts flowing under nonsubmerged conditions and set flush to a vertical

headwall. The design procedure can be used as an outline for the development of a comprehensive design manual for depressed invert culverts. (Author's abstract).

Kane, D. and Wellen, P.M. **A Hydraulic Evaluation of Fish Passage Through Roadway Culverts in Alaska**. Fairbanks, Alaska:Water Center/Intitiute of Water Engineering, University of Alaska-Fairbanks. FHWA-AK-RD-85-24:1-54, 1985. Final Report.

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

Kane, D. and Wellen, P.M. **Appendix to: A Hydraulic Evaluation of Fish Passage Through Roadway Culverts in Alaska**. Fairbanks, Alaska:Water Center/Institute of Northern Engineering. FHWA-AK-RD-85-24/24A:1-240, 1985. Final.

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

The appendix includes field methods with data sheet example for determining prevailing conditions at culvert sites regarding fish passage. Specific data for each site is given in the form of plan view design, water velocity profile, photographs, narrative, and site location. Approximately 100 sites are covered.

Katopodis, C. **Introduction to Fishway Design**. 501 University Crescent, Winnipeg, Manitoba, Canada, R3T 2N6:Freshwater Institue, Central and Arctic Region. 1-66, 1991. Working Document.

Abstract: Fish passage over dams and weirs or through culverts is an important consideration in fish bearing streams. Biological requirements such as fish behavior, motivation, preferences, migration timing, and swimming ability drive design and construction criteria for fish passage. Fishway types consist of a sloping channel partitioned by weirs, baffles, or vanes with openings for fish to swim through. A culvert fishway consists of a sloping pipe flowing partly full with regularly spaced baffles or weirs on the bottom. Components to fishway design include the biological requirements of the species of concern, hydraulics of the fishway, and careful choice of design flow. This manual describes the theory, design considerations, ichthyomechanics for thirty-five fish species, gives design examples for fishway design and cost analysis of completed projects.

Katopodis, C., Robinson, P.R., and Sutherland, B.G. **A Study of Model and Prototype Culvert Baffling for Fish Passage**. Winnipeg, Manitoba:Western Region, Fisheries and Marine Service, Department of Fisheries and the Environment. 828:1-78, 1978. Fisheries and Marine Service Technical Report.

Abstract: Most streams, crossed by roads or highways are culverted. Many such crossings are impassable to migrating fish because of the culvert length and the high water velocities in them. A hydraulic model study tested and developed devices to aid fish passage through culverts. Based on the model study recommendations, Offset baffles and Spoiler baffles were designed and installed at the Mackenzie Highway crossing of the Redknife River.

Field testing showed good agreement between model and prototype results. The effectiveness of both baffle types is inversely proportional to culvert slope. Maximum recommended slope is 5%. A method of judging baffle adequacy is provided. The Offset and Spoiler baffles are recommended, primarily for correcting existing culvert installations and for proposed stream crossings where alternative designs are neither practical nor economical. Minor problems were presented by ice, debris and sediment.

Unsuccessful attempts by Arctic grayling and longnose sucker to enter the Redknife River were observed. Their failures were attributed to overwhelming water velocities associated with culvert outlets. (Author's abstract).

Kay, A.R. and Lewis, R.B. **Passsage of Anadromous Fish Thru Highway Drainage Structures**. State of California, Department of Public Works, Division of Highways, District 01, Hydraulics Section. 629110:1-30, 1970. Research Report.

Abstract: Highway drainage structures can be an impassable barrier to the migration of anadromous fish and thereby damage the fisheries resource of an area. Investigation of 40 existing drainage structures indicates that these structures can be designed so as not to be a block to migrating fish. A design procedure is presented which enables the engineer to determine if a given structure requires special consideration for fish passage. (Author's abstract).

The report contains flow duration curves for estimating flow at stream crossings in north coastal California if the average annual precipitation is known. The proposed design procedure includes considerations as follows: establish that the stream in question does sustain runs of anadromous fish, estimate flow that is equaled or exceeded 10% of the time

October through April, determine the resulting velocity, determine if the resulting velocity is limiting for the culvert length under consideration, and if it is limiting for fish passage.

King County, **Culvert and bridge design criteria**. In: *King County Surface Water Design Manual*, Seattle:King County, Washington State, 1990, p. 4.3.5~1-4.3.5~16.

Abstract : Procedures are presented to provide for the analysis of both inlet and outlet control conditions to determine which of those two conditions are governing flow capacity. Design criteria for headwater elevation, inlet and outlet control of culvert flow are presented in the form of lists. Tables of constants for control equations and nomographs for headwater elevation for inlet or outlet control for use in flow analysis are included. Methods of analysis required to provide for fish passage/migration are given in the form of criteria. Estimating procedures for flow in ungaged streams and design criteria and analysis methods for bridges are also included.

Knapp, S.M. **Evaluation of Juvenile Fish Bypass and Adult Fish Passage Facilities at Water Diversions in the Umatilla River**. Oregon Department of Fish and Wildlife. Project 89-024-01:1-130, 1994. Annual Report 1993.

Abstract: Three reports on efforts to rehabilitate anadromous fish stocks in the Umatilla River Basin, including restoration of coho salmon (*Oncorhynchus kistuch*) and chinook salmon (*Oncorhynchus tshawytscha),* as well as enhancement of summer steelhead (*Oncorhynchus mykiss)* are combined in this document. Report A, by the Oregon Department of Fish and Wildlife (ODFW), evaluates fish injury, fry impingement, and water velocities in the Westland Canal fish bypass facility on the Umatilla River. Report B, by the Confederated Tribes of the Umatilla Indian Reservation (CTUIR), examines the passage of adult salmonids past diversions in the lower Umatilla River using radio telemetry. Report C, by ODFW, examines delayed mortality of juvenile salmonids as responses to stressors during trapping and transportation.

Notes : Prepared for the US Department of Energy, Bonneville Power Administration, Division of Fish and Wildlife, P.O. Box 3621 Portland, Oregon 97208-3621.

Laird, A. **Analysis of Road Induced Fish Migration Barriers in the Trinity River Basin: A Stream Crossing Inventory.** Trinity Fisheries Consulting. :1-146, 1988.

Abstract: This report contains an analysis of fish migration barriers in the Trinity River Basin caused by roads crossing streams. A comprehensive literature review was involved in the development of this report. A synthesis of barrier analysis and fishway design information currently available has been accomplished, but no new research has been initiated by the authors in the course of performing the basin-wide inventory and barrier analysis. The inventory aspect of the report identifies for the first time a data base of one hundred and twelve (112) anadromous tributaries in the Mainstem and South Fork of the Trinity River. A Trinity River Basin Anadromous tributary map has been compiled and included in this report. A total of two hundred and twenty (220) road crossings were identified and field checked on eighty three (83) of the tributaries that had stream crossing in the anadromous reaches of their basins.

Eight (8) of the stream crossings are complete barriers to anadromous fish migration of adult salmonids; thirteen (13) are partial barriers, twenty (20) are low flow barriers, and

twenty (20) stream crossings had received barrier modifications from a number of different agencies. Seven (7) of the previous barrier modifications require additional modification to upgrade the structures to permit swim-in access for all age classes of anadromous fish utilizing these basins. The design and cost for these modifications is included in this report. Twenty (20) of the stream crossings have excessive velocities at the time of adult migration and require modifications to increase the roughness element of the culverts to permit access to the upstream habitat.

The location, design and cost for twenty-five (25) stream crossings that are barriers to migration of adult salmonids are included in this report. These stream crossings prevent access to forty-two (42) miles of anadromous spawning and/or nursery and overwintering habitat, primarily for Steelhead Trout. All anadromous tributaries that have stream crossings which are barriers within their anadromous reaches have a basin map locating all of the stream crossings. Descriptive designs, costs for modification of the barriers, and field data collected follow each map. (Author's abstract).

Notes : Prepared for the California Department of Fish and Game, Inland Fisheries Division, Standard Agreement No. C-1927.

Leedy, D.L. **Highway-Wildlife Relationships: Volume I; A State-of-the-Art Report, Volume II; An Annotated Bibliography**. Ellicott City, Maryland:Urban Wildlife Research Center, Inc. FHWA-RD-76-4:1-193, 1975.

Abstract: This study assesses, primarily through an extensive literature review, what is known about highway-wildlife relationships and suggests research and management approaches to protect and enhance fish, wildlife, and environmental quality. A cooperative effort to this end among natural resource and highway agency personnel is needed on a continuing basis from the initial planning stages for new highway construction through operation and maintenance. The 20 million or more acres in highway rights-of-way have been largely neglected as wildlife habitat. Opportunities exist for creating valuable fish and wildlife impoundments has generally not been made. The Nation's four million miles of streets and highways often create "edges" conductive to wildlife. Many millions of wild vertebrates are killed annually, but apparently most wildlife populations are not seriously affected by such losses. Highway construction through limited ranges of endangered species can be a serious problem, as can erosion, wetland drainage, stream alteration, structures which block the passage of anadromous fish, and pollutants resulting from highway maintenance and use. Better measures for mitigating habitat losses, predicting effects of highways on fish and wildlife, reducing animal-vehicle accidents, and enhancing highway environment for fish, wildlife, and people are sorely needed. (Author's abstract).

Lewis, G.L. **Jury verdict: Frequency versus risk-based culvert design.** *Journal of Water Resources Planning and Management* 118, No. 2(March/April):166-184, 1992.

Abstract : A federal district court jury in Cheyenne, Wyoming, ruled that an Act-of-God defense could not be used when a railroad culvert backed water onto residential properties during a catastrophic "10,000-year" rainstorm. The culvert capacity not only met but exceeded industry design standards, yet the jury concluded that the railroad was negligent for not installing a structure large enough to accommodate the "monster" storm. The 5-foot diameter culvert, installed to replace a larger, deteriorating trestle, is sized by frequency-based methods to discharge the 50-year peak flow rate, with a nominal surcharge anticipated during the 100- year event. It is agreed by both sides that the selected

structure could have safely passed more than a 500-year event, but is not able to discharge all the flows from the freak storm. Backwater ponded 9 feet over the top of the culvert, flooding more than 20 basements in one subdivision. The defendant is held liable for the damages and cited as negligent for not anticipating the storm and for failing to consider the risks to homeowners. Under court order, a large structure is installed, This paper is a review of several matters debated during the trial and in subsequent analyses, presented as a case study from the writer's perspective. The writer participated as an expert witness who performed the analysis for the defense, but was called to the stand as a witness for the plaintiff. The jury verdict was in favor of the plaintiff. Implications for improvement in drainage design and expert testimony are discussed. (Author's abstract).

Lowman, B. **Investigation of Fish Passage Problems Through Culverts**. Missoula, Montana:USDA Forest Service, Equipment Development Center. 2427:1-17, 1974.

Abstract: Missoula, Montana Equipment Development Center investigated fish passage problems encountered at culverts to determine if an engineering effort was warranted to alter basic culvert designs to solve or at least reduce these problems. In this investigation, no testing or fieldwork was done. The report is based on previous publications and opinions expressed by experts contacted during the investigation. Fish passage problems at culverts result from increased velocity through the culvert, lack of resting areas above, below, or within the culvert, insufficient water depth in the culvert, or perching of the culvert above the stream gradient. From this study it was concluded that fish barriers occur from poor planning prior to installation. Sufficient engineering expertise exists to provide for fish passage with further design work not necessary. The biggest problem is to correct existing culverts with fish passage problems without expensive removal and reinstallation. Methods to change the flow characteristics such as the placement of gabions or baffles should be considered. Results of a survey on fish passage needs recommend formation of an interagency work group to review solutions to highway stream crossing fish passage problems.

MacPhee, C. and Watts, F.J. **Swimming Perfomance of Arctic Grayling in Highway Culverts**. Moscow, Idaho:University of Idaho, Forest, Wildlife and Range Experiment Station. 13:1-41, 1976. Bulletin.

Abstract: Both 18.3- and 30.5-meter tiltable highway culverts (0.6 m in diameter) were used for evaluating the swimming performance of Arctic grayling (*Thymallus arcticus*) and longnose sucker (*Catastomus catastomus*) at velocities ranging from 0.6 to 1.9 m/s. Fish migrating upstream during their annual 2-week spawning run were utilized for the culvert tests. In 1-day tests at water temperatures of 5-8 ^{o}C, 25, 50 and 75 percent of the grayling succeeded in ascending a 30.5 m culvert at flows of 4.0, 3.8 and 3.5 times the fork length, respectively, and an 1.3 m culvert at flows of 6.2, 5.6 and 5.0 times the fork length of the fish, respectively. At 9-12 ^{o}C, 25, 50 and 75 percent of the grayling succeeded in stemming a 30.5 m culvert at flows of 4.7, 4.2 and 3.8 times the fork length of the fish, respectively, For 2-day tests, a second day permitted only 0 to 7 percent more of the first day failures to stem a 30.5 m culvert, with the exception of the initial tests of the series when stream temperatures were lowest. Suckers swam at about two-thirds the speed of grayling. The state of maturation of females affected the upstream drive of grayling. Volunteer swimming speeds for grayling for 10-min. and 1-hour intervals were determined for various temperature regimes in a circular flume with controlled flows. The swimming capability of grayling (141-172 mm) increased about 80 percent with an increase in temperature from 0 to 14 ^{o}C. At 8 ^{o}C grayling cruised (1 hour) at 94 percent of the

sustained speed. Grayling migrating downstream were less motivated to swim vigorously than those migrating upstream. (Author's abstract).

McClellan, T. **Fish Passage Through Highway Culverts**. Portland, Oregon:U.S. Department of Transportation, Federal Highway Administration. 800332:1-223, 1971.

Abstract: A field review of highway culverts installed with special consideration for the passage of fish was made during the summer of 1970 by Thomas J. McClellan, Professor of Civil Engineering at Oregon State University. The study was undertaken to determine the effectiveness of various provisions incorporated over a period of years to preserve fish habitat in areas upstream from highway crossings of Oregon streams.

Culverts installed throughout the State from 1916 to 1970 were evaluated by Professor McClellan in company with Game Commission fish biologists. Sixty-two culvert sites were visited including several designed without special facilities, but representative of field conditions conductive or otherwise to the passage of fish. Notes made of the condition of the installations and adjacent streambed are included with photographs.
Biologists' and engineers' evaluations of the installations visited are presented as well as recommendations for consideration by engineers and fisheries personnel concerned with the design of similar facilities. Prepared in cooperation with the Oregon State Game Commission. (Author's abstract).

McKinley, W.R. and Webb, R.D. **A proposed correction of migratory fish problems at box culverts**. *Fish.Res.Papers* 1(4):33-45, 1956.

Abstract: Upstream passage of migratory fish through culverts long has been a critical fisheries problem in Washington State. A culvert is normally expected to pass a maximum runoff from its drainage area at the highest possible rate. This flow is generally counterproductive for fish passage which requires a relatively easy and direct path with lower velocities. A model box culvert, based on six criteria for fish passage with the least delay and expenditure of energy, was constructed to scale at the University of Washington hydraulics laboratory. Paired, alternate, and offset baffles were tested under three different discharges and three different slopes. The first discharge flowed on to the top of the baffles; the second discharge submerged the baffles slightly; and the third discharge overtopped the baffles by several inches. The intervals of slope were 1.5, 3.5, and 5 percent. To judge the merits of each baffle arrangement, a grading system based on the six criteria for successful fish passage was used. No mathematical formulae were used to predict flow pattern, energy dissipation, and other hydraulic peculiarities. As a result of the tests, an offset self-cleaning design worked efficiently over the entire range of slopes and discharges.

McKinnon, G.A. and Hnytka, F.N. **Fish Passage Assessment of Culverts Constructed to Simulate Stream Conditions on Liard River Tributaries**. Winnipeg, Manitoba, Canada:Western Region, Department of Fisheries and Oceans. 1255:1-121, 1985. Canadian Technical Report of Fisheries and Aquatic Sciences.

Abstract: From 1978 to 1981 four small streams crossed by the Liard Highway were studied to assess the effects of culverts on fish. The culverts were constructed in 1979 and rock riprap was placed on the culvert floor to provide areas of low water velocity for

migrating fish. Stream grade and cross-sectional dimensions were used to set culvert slope and size. This approach, named "stream simulation", attempts to simulate natural rapids that present no difficulty to migrating fish. Flow levels in all four streams varied widely but did not exceed the mean annual flood estimated by hydrologic analysis, in any of the four years of study.

Culvert placement together with internal riprap and slope stabilization at the inlet and outlet areas were completed in stages over approximately a one year period. As a result severe erosion produced ditch gullies and added large amounts of sediment to the stream bed. This also had the effect of burying culvert riprap and in many cases rendering it ineffective in reducing culvert velocity. Culvert riprap, when not buried by sediment, was effective in reducing culvert velocities. An added benefit was that culvert icing became suspended by culvert riprap allowing flow and subsequently, fish migration under the ice between boulders.

The highway crossing of the streams varied from 3.7 to 5.1 km upstream of the Liard River confluence. Spawning migrations of Arctic grayling (*Thymallus arcticus*) and longnose sucker (*Catastomus catastomus*) at the highway crossing occurred in three of the four streams studied; one stream also had significant numbers of northern pike (*Esox lucius*). The streams in the vicinity f the highway crossing provide a mainly feeding and rearing habitat with only a small amount of spawning habitat located this distance upstream from the Liard River mainstream. The culverts did not present a barrier to fish migration in any year of study. (Author's abstract)

Metsker, H.E. **Fish Versus Culverts: Some Considerations for Resource Managers**. Washington, D.C.Technical Information Center, Division of Engineering, USDA Forest Service. ETR-7700-5:1-19, 1970. Technical Report.

Abstract: A culvert designed to hydrologically and hydraulically pass the stream flow through a fill may not be acceptable for fish passage. The most common culvert installation practice is to reduce the channel cross sectional area, effectively decreasing the channel width resulting in an increase in velocity through the channel. Fishery restriction problems may come from the wall effect, water turbulence, inadequate stimulus to the fish or outfall barriers. Manipulation of the channel for passing fish can be accomplished by methods which raise the stream gradient necessary for fish passage. Those methods may include the addition of downstream weirs, cribs or low head dams. Stacked culverts in elevated stages may be used in streams that experience a wide flow range. Place baffles in existing culverts to reduce velocities in the culvert and provide resting areas for fish. The effects of light intensity changes that may cause a deterrent to movements of fish populations may be reduced by planting riparian vegetation. In areas with unstable stream beds it may become necessary to provide desilters, gradient control structures, or a bedload catcher upstream from the culvert location. In addition, physical requirements of fish habitat such as water temperature, dissolved oxygen and swimming ability of the fish species of concern must be considered. Many of the recommendations to facilitate fish passage may increase the total cost on new construction to the point that the arch or bridge will be competitive.

Moll, J. **Ecosytem Roads Management Project**. San Dimas Technology Center:USDA Forest Service. 25:7-32, 1993. Engineering Field Notes.

Abstract: The intention of the Ecosystem Roads Management (ERM) project was to gather information and provide it to the filed as an aid in conducting environmentally sound and ecosystem enhancing transpiration system activities. Projects discussed in this article are grouped by project intent; fish passage, wetlands and watershed restoration, soil retention, low water crossings including fords, historical and visual restoration, road maintenance and sediment reduction, road closure techniques, and use of recycled materials.

Culvert retrofitting techniques to repair damage inverts on corrugated metal pipe (CMP) incorporated the placement of rock baffles to provide resting pools for fish. Additional fish passage projects included the use of concrete curbs, oversize culvert installation at lowered invert elevation to provide for sedimentation, and multiple culvert use. Where the goal is wetland restoration, culvert inverts can be raised to the natural meadow elevation thus increasing runoff ponding, encouraging sedimentation, and slowing headwall retreat. Culverts constructed by the Civilian Conservation Corps (CCC) during the 1930's are being reconstructed to retain historical values. The original design using rock inverts and stone box culverts are being replicated on new construction.

Moll, J. **Paving of Corrugated Metal Pipe Inverts for Repair and Fish Passage**. USDA Forest Service, Technology and Development Program. 1-4, 1993. Engineering Tech Tips.

Abstract: Benefits from corrugated metal pipe (CMP) invert paving include ease of rehabilitation and environmental benefits of fish passage and streambed stability. By manually trowelling a cement grout mix into a deteriorated CMP invert rather than removal and replacement of the culvert, costs were decreased, disruption of normal stream flow was minimized, and sediment and erosion effects were also eliminated. With the addition of embedded rock baffles forming a fish passage modification, orangebelly darters successfully passed through the pipe. Design specifications and baffle placement patterns are included.

Murphy, G. and Pyles, M.R. **Cost-effective selection of culverts for small forest streams**. *Journal of Forestry* 87(10):45-50, 1989.

Abstract: Selecting a culvert size for a stream crossing should be based on an economic evaluation of the alternatives. Minimizing the total discounted cost of the culvert (TDC) is a simple method of comparing culverts for a cost effective design. TDC includes hydrologic probability functions and cost components obtained by summing the original installation cost, the discounted annual maintenance costs and the discounted expected costs of culvert failures that could be caused by peak flows.

This paper uses two hydrologic probability functions, the probability of occurrence of possible annual peak flows in a given year and the probability of failure associated with those flows. The product of these two functions gives the probability of failure in a given year. The expected annual failure cost of a culvert is obtained by multiplying the cost of a single failure by the sum of the product of the probability of occurrence of annual peak flow and probability of failure for that peak flow for the series of peak flow classes.

An example of the analysis procedure is given for pipe diameters ranging from 36 to 84 inches. Results indicate that the qualitative factors that are often present but not easily quantified for an economic analysis can be used as justification for selecting larger pipes to obtain a lower probability of failure without a significant cost increase.

Powers, P.D. **Culvert Hydraulics Related to Upstream Juvenile Salmon Passage**. Washington State Department of Fish and Wildlife, Habitat Program. :1-15, 1996.

Abstract: A study was performed by the Washington Department of Fish and Wildlife (WDFW) in cooperation with the Washington State Department of Transportation (WSDOT) to determine the culvert characteristics that allow upstream passage of juvenile coho salmon. The purpose of the study was to investigate the premise that small fish (60 to 90 mm fork length) would use the low velocity boundary layer near the wall of a roughened pipe to pass upstream.

The study objectives were to 1) determine if fish would use the low velocity boundary layer of a roughened pipe to pass upstream and compare this to passage through a smooth pipe, and 2) explore relationships between velocities and turbulence in the boundary layer to passage success. Once the hydraulic conditions which provide optimal passage are determined, a hydrologic analysis for determining passage design flows for juvenile fish will be initiated by WDFW.

The tests consisted of placing fish in culverts with varying roughness and slope. Fish were counted as they passed, held or failed. To meet the first objective, upstream passage success was compared to the maximum velocity (V_{max}) in the culvert. For the second objective, two variables were compared to passage success; 1) the velocity in the zone the fish occupied while attempting to pass (V_{occ}), and 2) the effective width in the boundary layer of the migration area (W_c). A simple linear regression model relating V_{max} to percent passage showed that velocities for the 80 percent passage level were 1.3 and 2.0 feet per second (fps) for the coho fry and fingerlings respectively. A major finding of the study was that turbulence in the boundary layer actually created a blockage to fish. For the tests with higher velocities, passage success was higher for the smooth pipe. (Author's introduction).

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**. Washington State University, Pullman, Washingtion, 99164-3001:Albrook Hydraulics Laboratory. 82-14:1-119, 1985. Final Project.

Abstract: This paper presents a detailed analysis of waterfalls and culverts as physical barriers to upstream migration by salmon and trout. Analysis techniques are based on combining barrier geometry and stream hydrology to define the existing hydraulic conditions within the barrier. These conditions then can be compared to known fish capabilities to determine fish passage success. A systematic classification system id developed which defines the geometric and hydraulic parameters for a given stream discharge. This classification system is organized in a format that can be used to catalog barriers in fisheries enhancement programs. The analysis compares hydraulic conditions and fish capabilities in detail, as the fish enters the barrier, attempts passage and exits the barrier. From this comparison the parameters which prohibit passage cam be determined. Hydraulic conditions are a function of the barrier geometry and stream hydrology, and the stream flow is constant at the time each step in analysis is performed. Therefore, the barrier geometry must be modified to alter the hydraulics to meet fish capabilities. Modifications can be accomplished by: installing instream "control" structures which deflect the flow or raise pool levels; blasting to alter or remove rock; and installing a fishway to bypass the barrier. Modifications should not be attempted until the analysis defines the excessive parameters which should be modified. (Author's abstract).

Notes : Submitted to Bonneville Power Administration. Part of a BPA Fisheries Project on the Development of New Concepts in Fishladder Design, Part 4 of 4, Contract DE-A179-82BP36523.

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

> Abstract: This paper presents the results of a laboratory study of culvert fishways with weir-type baffles. Baffles with heights equal to 0.15 and 0.1 times the diameter (D) of the culvert were studied with longitudinal spacings of 0.6D and 1.2 D. Equations have been developed to describe the relation between the discharge, slope, diameter, and the depth of flow. It has been possible to predict the barrier velocity that would exist at the baffles. The performance of the weir baffles had been found to be as good as that of slotted -weir baffles. (Author's abstract).

Rajaratnam, N. and Katopodis, C. **Hydraulics of steepass fishways**. *Canadian Journal of Civil Engineering* 18(6):1024-1032, 1991.

> Abstract: This paper presents the results of an experimental study on the hydraulics of steeppass fishways. Using theoretical considerations and experimental observations, an expression has been developed that relates the flow rate, slope of the fishway, and depth of flow. It was also found that the characteristic (similarity) velocity profile found earlier, for smaller values of depth to width ratio, y_0/b, with the maximum velocity near the bottom, changes to a rather symmetrical profile with the maximum velocity occurring somewhere near the mid-depth for larger values of y_0/b. A correlation has also been found for the maximum velocity. This paper also includes some observations on the M-type backwater curves that would appear in the fishway when the tailwater depths exceed uniform flow depths. (Author's abstract).

Rajaratnam, N., Katopodis, C., and Fairbairn, M.A. **Hydraulics of culvert fishways V: Alberta fish weirs and baffles**. *Canadian Journal of Civil Engineering* 17(6):1015-1021, 1990.

> Abstract: This paper presents the results of a laboratory study of the hydraulic performance of fish weirs and fish baffles used by Alberta Transportation for improving the fish-passing capacity of culverts. It was found that if the longitudinal spacing of the weirs is limited to 0.6 and 1.2 times the diameter of the culvert, their performance is comparable to that of the corresponding weir and baffle-weir systems, with regard to the depth of pool between the baffles as well as the barrier velocity. On the other hand, the fish baffles did not perform as well as the fish weirs under the conditions tested. (Author's abstract).

Rajaratnam, N., Katopodis, C., and Lodewyk, S. **Hydraulics of offset baffle culvert fishways.** *Canadian Journal of Civil Engineering* 15(6):1043-1051, 1988.

> Abstract: This paper presents the results of an experimental study on the hydraulics of culverts with offset baffles to pass fish. Using analytical consideration and experimental observations a flow equation has been developed between the discharge, diameter, depth, and slope for a culvert fishway with the standard offset baffle system. The velocity field at the slot has also been evaluated. Some further experiments were performed to assess the

effect of baffle spacing and height on the hydraulics of the culvert fishway. (Author's abstract).

Rajaratnam, N., Katopodis, C., and Lodewyk, S. **Hydraulics of culvert fishways IV: spoiler baffle culvert fishways**. *Canadian Journal of Civil Engineering* 18(1):76-82, 1991.

Abstract: This paper presents the results of an experimental study on the hydraulics of culvert fishways with spoiler baffles. Four designs were studied with the heights of the baffles equal to 0.09D and 0.15D and longitudinal spacings of 0.53D and 1.06D, where D is the diameter of the culvert. Design equations have been developed relating the flow depth to the flow rate, the diameter and the slope of the culvert for each baffle design. Expressions have also been found for the barrier velocity. (Author's abstract).

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

Abstract: This paper presents the results of an experimental study on the hydraulics of culvert fishways with a slotted-weir baffle system. Six designs with two baffle heights and three spacings were tested. A flow equation has been developed to predict the flow depth for any given discharge, diameter, and slope. The barrier velocity that would exist at the slot in the baffles has also been predicted in a general manner. This relatively simple slotted-weir baffle system has been found to match the performance of the more complicated but frequently used offset baffle system of similar dimensions. (Author's abstract).

Reeder, R. **Riparian Road Guide: Managing Roads to Enhance Riparian Areas**. Washington, D.C.Terrene Institute, in cooperation with the US Environmental Protection Agency and USDA Forest Service, Southwestern Region. 1994.

Abstract: The booklet contains a number of cost effective road construction practices for maintaining clean water while simultaneously enhancing and restoring the health and value of riparian areas. The guide is divided into three sections; history of road-riparian interfaces, common road and riparian conflicts, and solutions to correct existing problems and ways to avoid them in the future. Common culvert problems and cost-effective and environmentally beneficial solutions are identified. Problems include increased water velocities through the culvert, channel erosion, water quality, diversion potential, and barriers to fish passage.

This guide was written primarily for local government personnel, elected officials, and road designers and contractors in the arid and semiarid southwestern United States. The general principles, however, are applicable in other regions of the country if techniques are modified accordingly. It is applicable to suburban and rural road systems, less applicable to roads in heavily urbanized areas.

Remnant, R.A. and Bernhardt, W.J. **An Assessment of Fish Utilization of Goose Creek, near Churchill, Manitoba, 1993**. 202-1475 Chevrier Blvd. Winnipeg, Manitoba, Canada:North/South Consultants Inc. 1-248, 1994. Prepared for Manitoba Hydro.

Abstract: North/South Consultants Inc. was contracted by Manitoba Hydro to assess fish passage through culverts in the west channel of Goose Creek, a tributary of the lower Churchill River, Manitoba, during 1993. Objectives of the study were as follows: to assess fish passage through culverts in the west channel and under a bridge in the east channel of Goose Creek during spring; to assess fish movements in Goose Creek during spring and fall, and to determine whether fish were capable of overwintering in Warkworth Lake.

The Goose Creek spring monitoring program was conducted from 13 May to 30 June 1993 while fall monitoring was carried out between 26 August and 01 October, 1993. Water velocities and stream discharge were measured using a current meter. Larval drift traps were set to determine whether fish were successfully spawning in the Goose Creek system. Hoopnets and a conduit weir were used to assess fish passage and fish movements in Goose Creek and Warkworth Creek. Gillnets were used to assess fish abundance in Warkworth and Fletcher lakes and in the Churchill River. A local knowledge survey also was conducted.

Goose Creek spring breakup took place on 07 May 1993, with a peak discharge of 57.8 m^3/second occurring on 10 May. Peak discharge was relatively low, with an 82% chance of being equaled or exceeded in a given year (a 1.22 return period). Mean velocities at the inlet and outlet of the culverts in the west channel exceeded maximum prolonged swimming speeds of migrant fish species present in Goose Creek for more than 18 days following peak discharge, more than 15 days longer than suggested in the recommended fish protection procedures for stream crossings in Manitoba. However, the use of mean velocities as criteria for fish passage guidelines is questionable. Studies have shown that the distribution of water velocities within a culvert may be more important to fish than mean velocities. Fish passing through the culverts in the west channel are also subject to irregular velocities and inlet drop.

Absolute comparison of results from this study with a study conducted in 1977 was not credible due to differences in gear types, and temperature and flow regimes. However, some comparison was possible. Comparison of the two studies over a similar 17-day period during early spring indicate that numbers of Arctic grayling and northern pike were similar between years. Longnose sucker abundance may have decreased since 1977.

It is recommended that fish passage through the culverts in the west channel of Goose Creek be reassessed to substantiate data collected in 1993. Fish passage through the culvert in the westernmost side channels of Goose Creek should also be assessed at the time. Consideration should be given to improving the hydraulics at the inlets of culverts 4 and 5 by reducing the amount of inlet drop at the damaged sections. The effect of the Churchill River Diversion on the hydraulic regime of Goose Creek should be modeled to attempt to understand if, and to what degree, water velocities and storage in the Goose Creek system has been altered. To address concerns of residents of the community of Churchill, it is recommended that a sample of Arctic grayling and lake whitefish be radio-tagged in order to better understand fish movements in Goose Creek, including the definition of spawning and overwintering areas for these species. (from Author's executive summary).

Saltzman, W. and Koski, R.O. **Fish Passage Through Culverts**. Oregon State Game Comission. 1-8, 1971. Special Report.

Abstract: A series of culvert velocity curves has been developed by the U.S. Army Corps of Engineers and the Engineering Section of the Oregon Game Commission. The curves predict water velocities encountered at different water levels in round corrugated steel

culverts from two to seven feet in diameter and on gradients from 0.25 to 5.0 percent. Maximum allowable velocities for fish passage are combined with the rating curves to give design criteria for fish passage. Fish passage design criteria for other methods of stream crossing techniques including pipe-arch culverts and box- type concrete culverts are mentioned.

Schmidt, L. **The Use of Risk in Specifying Job Quality**. Soutwestern Region:U.S.D.A. Forest Service. 8:1-8, 1978. Hydrology Notes.

Abstract: Management activities involving natural resources have an element of risk involved. Hydrologists have traditionally calculated risks usually related as the return interval for a given climatic event. The concept is often confusing to other land managers who at times fail to understand that the costs associated with reduced risks are exponential.
Through the use of the "Risk Objective Statement" it is possible to better define a reasonable return period for a climatic event for a given project life and risk. The return period may be calculated from an equation, graphs, or a table. Examples are based on erosion control, sediment control and culvert design. (Author's abstract).

Shoemaker, R.H. **Hydraulics of Box Culverts with Fish-Ladder Baffles**. *Highway Research Board Proceedings* 35:196-209, 1956.

Abstract: he placement of transverse baffles in box culverts for the purpose of providing for traverse of fish has become increasingly necessary in recent years. Consequently, model studies were made to determine design factors for baffled culverts as related to baffle height and spacing and to develop hydraulically efficient baffle shapes for use in the culverts. The results of the studies, based on the treatment of the baffles as roughness in a rectangular conduit, were obtained in the form of velocity head coefficients; on dependent upon and the other independent of friction effects. The first of these is given in the form of a Darcy-Weisbach friction factor, and the second, which accounts for energy components at entrance and outlet, in the form on an "energy coefficient." The studies were conducted under the auspices of the Engineering Experiment Station of Oregon State College, and were jointly sponsored by the Oregon State Highway Commission and the US Bureau of Public Roads. (Author's abstract)

Notes : Published by the National Research Council. Alternative Reference: Shoemaker R. H. 1956.Hydraulics of box culverts for fish passage design. Engineering Experiment Station, Oregon State College. Report No. 53.

Skaugset, A.E. and Pyles, M.R. **Peak flow estimation and streamflow simulation for small forested watersheds**. Design and Maintenance of Forest Road Drainage. 1-18, 1991. Oregon State University.1991 November 18-20.

Abstract: The single piece of hydrologic information that is needed most often for adequate design and maintenance of forest roads is design peak flow estimates for stream crossings. Current forest road layout, especially in steep forest terrain, results in a large number of stream crossings of small, ungaged, forest streams. In the past, methods for estimating design peak flows for these streams included Talbot's formula, the Rational Method, or the SCS method. Because of the lack of applicability to forested streams the

preceding methods are not recommended. A method for estimating peak flows in Oregon, Campbell's equations, which correlate peak flows for a given design return period with watershed characteristics, is recommended. For the above four methods; theory, formulas, rationale for use and drawbacks are presented. To estimate magnitude of intermediate flows for fish passage, the Antecedent Precipitation Index (ADI) which requires a record of precipitation intensity and watershed area, is recommended. The development and theory of flow frequency analysis using principles of statistical estimation to make inferences about the total population of streamflows from finite streamflow records is included along with examples.

Slatick, E. **Passage of Adult Salmon and Trout Through Pipes**. Special Scientific Report--Fisheries. Hacker, R.L. Washington, D.C.US Fish and Wildlife Service. 592:1-18, 1970. Special Scientific Report-Fisheries.

Abstract: Pipes which are relatively inexpensive and easily installed, are an economical and efficient solution to certain problems of fish passage at dams and at other obstacles blocking migratory routes. The purposes of the study (1963-64) were to determine: (1) if adult salmon and trout at Bonneville Dam on the Columbia River would use a pipe as a passageway and (2) how the conditions at the entrance and within the pipe, diameter, and length, illumination, and flow would influence passage. The pipes were 0.3, 0.6, and 0.9 m. in diameter and were 27.4 to 82.3 m. long.

Chinook salmon (Oncoryhynchus tshawytscha), sockeye salmon (O. nerka), coho salmon (O. kisutch), and steelhead trout (Salmo gairdneri) passed through unilluminated pipes up to 82.3 meters long. Of the four species tested, only steelhead trout appeared to benefit appreciably from illumination. For distances up to 82.3 m., a 0.6-m. diameter pipe was large enough to pass all salmon and trout. The fish passed through a 0.6-m diameter pipe when it was flooded or partially filled with water, but did not readily enter a 0.3-m. pipe until special conditions of water velocity and transition from pool to pipe were provided. (Author's abstract)

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

Abstract : During the summer of 1982, the fisheries unit of the Willamette National Forest inventoried culverts placed in streams with fish. The intent of the survey was to locate barriers to fish passage and diagram possible solutions. One hundred and seventy culverts were inspected, with sixty-three projects located. The inventory provides the Forest with an easily used list of needed projects which can improve fish habitat. The report includes individual culvert survey results, photographs, and recommendations to improve habitat.

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

Abstract: Gabions are used frequently to improve aquatic habitat and rehabilitate damaged fish habitat in low-gradient streams. However, gabions should not be installed perpendicular to the stream flow if water velocities are expected to exceed 5 ft/s. This recommendation would preclude the use of gabions to improve fish passage at waterfalls. Also, gabions installed below culverts should be placed well downstream of the culvert. Weirs constructed of reinforced concrete and/or large boulders could be used as alternatives to gabions to provide for fish passage. (Author's abstract).

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

Abstract: An experimental procedure was developed to analyze the ability of a highway culvert to pass fish. By using a visual technique, the swimming performance of Arctic grayling (*Thymallus arcticus*) was monitored in Poplar Grove Creek, Alaska. The highway culvert is 110 feet long and 5 feet in diameter, and is inadequate for fish passage if the Alaska Department of Fish and Game criteria are applied. The drainage area experienced a 20-year flood (Q_{20}) during spring 1995. Excessive pipe velocities prevented the fish from passing the culvert for 8 days. A large portion of the fish in the downstream scour pool were removed by sport fisherman during the period of high flow. Approximately 78 percent of the fish attempting to swim through the culvert were successful when the outlet velocity dropped to 7.3 feet per second (fps) and about 95 percent swam through when the outlet velocity receded to 6.9 fps. A request for information on fish passage was sent to US and Canadian highway departments and fishery agencies. Forty-four state an all Canadian provinces responded. Twenty states reported that they generally do not have problems with fish passage through highway culverts. Eighteen highway departments reported having a good working relationship with resource agencies when addressing fish passage problems These 18 states commonly suggested that (a) early coordination would occur between highway and resources agencies during the design phase, (b) culvert inverts should be depressed approximately 1 to 2 feet below the natural stream be, (c) culverts having slopes greater than 1 percent should have a baffling system and (d) the remaining culvert volume should be able to handle approximately a Q_{50} discharge. (Author's abstract).

USDA, F.S. **Making Culverts Good Fish Passage**. US Forest Service Equipment Development Center. :1-4, 1975. Equip Tips.

Abstract: Briefly reviews fish passage factors at culverts including water velocity, culvert length and gradient, fish species, streambed conditions, and culvert design. References that describe fish passage problems and solutions in detail are listed.

USDA, F.S. **Roadway Drainage; Guide for Installing Culverts to Accomodate Fish**. Juneau, Alaska:Engineering and Aviation Management Division, Forest Service. 42:1-126, 1976. Equip Tips.

Abstract: The guide is designed as an aid to engineers, biologists, and hydrologists to help solve the problem of providing fish passages through drainage structures. Decreasing culvert gradients to meet fish passage requirements (velocities less than 1.5 feet per second) also significantly reduces culvert capacity, requiring larger culverts, if designing for both fish passage and design flows. Minimum flows for fish passage are based on the 5-year recurrence. Data requirements for drainage types define information needs. Aids to the design procedure include survey forms, a method for risk assessement, procedures for caluculating design flows for southeast Alaska, hydraulic charts and culvert design methods.Administrative Document.

USDA, F.S. **Fish/Culvert Roadway Drainage Guide**. USDA, Forest Service. R-10-42:1-125, 1978. Draft.

Abstract: The guide is designed as an aid to engineers, biologists, and hydrologist to help solve the problem of providing fish passages through drainage structures. Decreasing culvert gradients to meet fish passage requirements (velocities less than 1.5 feet per second) also significantly reduces culvert capacity, requiring larger culverts, if designing for both fish passage and design flows. Minimum flows for fish passage are based on the 5-year recurrence interval. Data requirements for drainage types define information needs. Aids to the design procedure include survey forms, a method for risk assessment, procedures for calculating design flows for southeast Alaska, hydraulic charts, and culvert design methods.

Notes : This is a later version of USDA, Forest Service, Alaska Region Administrativie Document 42, Roadway Drainage, Guide for Installing Culverts to Accomomdate Fish.

Valentine, W.H. **Obsolescence, overloads, and failures**. *Engineering Technical Information System, Field Notes* 6(8):1-10, 1974.

Abstract: A common objective of culvert design is to achieve some specified result or capacity with design. By incorporating a risk of obsolescence and a study of consequences with risk of failure due to overload in a culvert analysis, the designer will come closer to the most economic selection. If failure would cause heavy damage, it may be economical to oversize the culvert, even if it has a very short life. The costs of failure should be included in the analysis. The approach to this problem is to find the flood risk associated with the capacity of several alternative selections, then make an analysis of the comparative economics and consequences of failure of the several alternatives. A mathematical model is provided to solve the above problem based on economic selection between alternatives with different first costs and different life spans. Two examples for culvert selection based on alternatives are presented.

Notes : Published by USDA Forest Service.

VanHaveren, B.P. **Hydrologic Risk and Return Period Selection for Water Related Projects**. U. S. Department of the Interior, Bureau of Land Management. 337:1-14, 1979. Technical Note.

Abstract: Hydrologists are frequently asked to provide design flows or stages for spillways, bridge openings, culverts, diversion dams, waterways, fish improvement structures, and land treatment measures. Too often a return period or recurrence interval is arbitrarily chosen or a standard return period is used by the hydrologist.

The design event chosen by the hydrologist should be based on the risk of failure rather than on an arbitrary or predetermined return period, incorporating the fact that risk increases with increasing project life.

The purpose of this Technical Note is to assist the hydrologist in understanding hydrologic risk and in communicating this understanding to the land manager. By combining statistical relationships with tables and graphs, a reference is developed for the hydrologist and other specialists involved with water-related projects where the frequency of hydrologic events is a concern. (Author's abstract).

Washington State Design Policy. In: *Hydraulics Manual (M23-03)*,Anonymous Washington State Department of Transportation, 1989,p. 1-1-1-7.

Abstract : Design policy guidelines for responsibility of initiation and permits, hydraulic reports, storm frequency policy, and risk analysis for drainage facilities are presented. Requirements for information required on hydraulic reports including culvert installation is given in tabular format. Factors considered in determination of design frequency include potential damage to roadway, hazards and inconvenience to motorists, classification of highway, the ADT of the highway and the cost of the hydraulic structure. Design frequency in years for culvert installation is 100 years or largest flood of record. Risk analysis may be appropriate when all design considerations can be equated to dollars. A risk analysis considers the initial cost of the hydraulic structure and compares this to the probably cost of operating and maintaining the structure over its entire useful life.

Watts, F.J. **Design of Fishways**. Moscow, Idaho:Water Resources Research Institute, University of Idaho, Moscow, ID. :1-62, 1974.

Abstract: Types of fish migration and typical fish blockage problems associated with culverts are reviewed. Swimming capability of fish as a function of specie, fish length and water temperature are discussed. The hydrologic characteristics of streams and the importance of considering the timing of fish runs and peak discharge is reviewed. A procedure for analyzing corrugated metal pipe and pipe arches for recommended swimming velocities is presented. Slot orifice fishways for box culverts (slot orifice placed perpendicular to the flow and skewed wing-wall slot orifice) are discussed. Design aids developed for hydraulic analysis are presented. Instream construction in or near prime fish habitat is discussed. (Author's abstract).

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, Idaho:Water Resources Research Institute, University of Idaho. A-027-IDA:1-7, 1973.

Abstract: A method for the design of slot orifice fishways for box culverts was developed. Characteristics for a satisfactory fishway are identified. Appropriate graphs for sizing slot orifice fishways for a given performance capability of a fish are presented. The hydraulics of slot orifices constructed in the face of skewed wingwalls is explained. A table listing the swimming capability of various species of fish was compiled from existing literature. A hodograph for the wake boundary behind a flat plate placed normal to free surface flow was developed. A comparison of the size of wakes produced by a flat plate, a 90-degree wedge and a circular cylinder were made. The shape of wakes produced by an embedded sphere with different degrees of submergence was also studied. (Author's abstract)

Weaver, W.E. and Hagans, D.K. **Handbook for Forest and Ranch Roads: A Guide for Planning, Designing, Constructing, Reconstructing, Maintaining and Closing Wildland Roads**, Arcata, CA:Pacific Watershed Associates, 1994.pp. 1-161.

Abstract : The handbook is a practical guide and field manual designed to cover the fundamentals of road planning, design, construction, reconstruction, maintenance and closure. The book is organized by these topics in the general order encountered in the road building process. It is assumed that the users of the handbook have a basic understanding of road terms and roading practices. A glossary of defined terms and references are included as appendices.

Culvert design information is covered in the chapter on road drainage and includes legal requirements in California, stream crossing design choices, fish passage criteria, debris control, culvert installation techniques, maintenance, and culvert removal in road closure. Planned useful life of a road is given in the form of risk analysis for failure of culverts designed for the 50 year flood flow event. A procedure for determining the correct length of culvert needed for stream crossings of ditch relief drains is outlined in an appendix.

Webb, Paul W., 1975. **Hydrodynamics and Energetics of Fish Propulsion**, Bulletin of the Fisheries Research Board of Canada, 190: 159 p.

Abstract: The object of this monograph is to span the gap between biological and physical science approaches to fish propulsion problems. An attempt is made to summarize and collate the two principal disciplinary approaches as a basis for dialogue and ongoing research.
Principles of hydrodynamics are discussed, oriented to biologists. Following a discussion of kinematics and swimming performance, the hydrodynamic principles are applied in discussing the fundamental problem of drag and thrust. Movements made by most fish during swimming are likely to severely distort flow. As a result, the flow around a swimming fish is not likely to be mechanically equivalent to that assumed by the rigid-body analogy. Alternative methods of calculating thrust power from hydrodynamic models based on the movements of swimming fish are discussed. Development of both basic models and a semiempirical model is contingent upon further comparative research on propulsion kinematics.
A variety of mechanisms to reduce the drag of swimming fish has been proposed in the literature. Only a few are likely to operate.
Principles of biological energy metabolism are discussed oriented to nonbiologists. Biological energetics and mechanics are integrated in a discussion of propulsion efficiency. Discussion is largely restricted to caudal fin and body propulsion at relatively low activity levels. Few data are available for other propulsion modes. A preliminary model is constructed to describe mechanical energy expenditure during acceleration. This suggests that highest final swimming speeds are reached in the shortest time with the lowest energy expenditure at highest acceleration rates.

White, D. **Hydraulic Performance of Countersunk Culverts in Oregon**.Oregon State University. :1-95, 1996. Master of Science.

Abstract: Countersunk culverts have long been recommended as crossing structures where fish passage is desired. This project provides design and performance information on existing countersunk culverts in Oregon. Twenty-eight countersunk culverts were surveyed for three issues: assessment of the ability of countersunk culverts to provided for passage of target species and age groups; evaluation of the stabily of the countersunk configuration; and derivation and critical analysis of a method of predicting the extent of low velocity zones within the flow cross-section. A qualitative assessment of each site conducted in 1995 was followed up by a reassessment of culvert condtions after a large 20 year storm event in 1996. All twenty-eight culverts resisted erosion and effectivly carried high discharges as determined from survey data. Detailed documentation of water velocity distributions in several culverts under fall and winter discharges showed the presence of zones of velocity of a mangitude currently acceptable in the literature as passable by juvenile salmonids. Results of the velocity data analysis suggest that the extent of low velocity zones, or perhaps the lower limit of their extent, in the channel cross-sections of countersun cluvert with small scale rougness may be predicatble using

common paramenters such as cross-sectional area and hydraulic depth. Recommendations based on the study are: the use of multiple, parallel culverts in place of a larger single culvert is discouraged except in special cases; countersink a culvert to allow for natural downstream transport of sediment; the culvert barrel shoud be placed as coincident with the direction of the incident streamflow as possible; and unless mitering is necessary to enhance the conveyance capacity of the culvert, the inlet should not be mitered.

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. :1-53, 1976.

Abstract: In order to establish standards for culvert design and installation to ensure fish passage, a review of existing literature on fish swimming performance in culverts and in conditions resembling those in culverts was undertaken.

Measured swimming abilities of game (mainly salmonids) and non-game fish species were taken from many sources. Swimming capabilities at different life-history stages, under various physical and chemical conditions were documented. Under proper stimulus (undefined) adult salmon and steelhead (length 25-30 inches or 63.5-76.2 cm) have traveled distances up to 100 feet (30.5 m) against water velocities near 27 fps (820 cm/sec). Normally adult salmon and large trout are capable of negotiating velocities of 12 fps (370 cm/sec) over shorter distances (20 ft or 6.1 m). To ensure fish passage through a culvert water velocities should be much less than the sustained swimming speed of upstreaming fish for a reasonable length of time. For salmonid under-yearlings this would definitely be less than 1 fps (30 cm/sec) and nearer 0.5 fps (15 cm/sec). Some other important factors affecting swimming performance include water temperature, dissolved oxygen content and degree of previous exertion.

Poor design and /or installation of culverts can bring about problems of fish passage. One poorly placed culvert could detrimentally affect fish populations of an entire drainage. Accepted parameters governing successful fish passage are water velocity and depth through the culvert, length and slope of the culvert, entrance and exit conditions (e.g. jumping pool), and size species and sexual maturation of fish using the stream. Some methods frequently employed to alleviate passage problems at culverts include baffles, downstream controls and multiple installations. (based on Author's abstract)

Ziemer, G.L. **Fish Transport in Waterways**. Alaska Department of Fish and Game. :1-12, 1961.

Abstract: The mechanics of fish passage at and in pipe culvert waterways under highways are presented in the form of notes from a presentation. Physiology of salmon swimming abilities as an analogue to a non-refuelable engine is combined with theory on the mechanics of force and energy. Use of outlet control design procedures are recommended for culverts based on energy requirements of migrating fish.

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. 29:1-34, 1995. Water Resources Research.

Abstract: Culverts may be obstacles to migrating fish species. Baffled culvert fishways are considered for high slope design or for remedial work on existing culvert stream crossings.

Much of the design practice for installing baffles to aid fish migration is based on experience or standard historical designs. Field evaluations and hydraulic modeling studies are limited but growing. There is a need for more structured use of hydraulic fish passage study results. Although biological uncertainties make it difficult to identify hydraulically and biologically efficient designs, study results may help to understand elements of risk and design robustness for fish passage. A form of sensitivity analysis of interdependent variables is developed and used to evaluate a field-tested design for freshwater migrants. The presented design approach moves fish passage evaluation from post-design adaptations to pre-design understanding of alternatives. Results of hydraulic modeling studies are used to provide the basis for analysis of uncertainties in discharge, slope, migratory fish length, and water velocity criteria. (Author's abstract)