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C. Fisheries

AQUATIC HABITAT GUIDELINES IN WASHINGTON

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Abstract

Originating as the Stream Corridor Management Workgroup early in 1997, the first major milepost in seeking a statewide-integrated approach to working in and near streams, lakes, and wetlands was a Stream Corridor Management Symposium, held in Ellensburg in June 1998. Major partners in this effort were the Washington Departments of Transportation, Ecology, and Fish and Wildlife.

The three-day symposium was structured with three areas of emphasis:

- The first section presented the fundamentals of watershed assessment, stream channel classification, hydrology, geomorphology, aquatic and terrestrial riparian ecology, function and fate of woody debris in streams.
- The second emphasis section was a presentation of alternative approaches to stream restoration, streambank stabilization, and the regulatory environment.
- The third emphasis section was an intensive, all-day peer review workshop for the draft *Integrated Streambank Protection Guidelines (ISPG),* developed by a team led by Ken Bates and Michelle Kramer, at WDFW.

Continuing efforts by WDOT toward regulatory streamlining, the rapidly expanding list of anadromous salmonids designated Threatened or Endangered under the federal ESA, the creation of Washington's salmon recovery plan and Salmon Recovery Funding Board, combined with a widespread recognition that many private and government stream habitat restoration efforts were well-meant but poorly designed and executed. Many regulatory agency staff have general skills in resource and environmental management, and project proponents are often lay persons. Neither regulated community or regulators typically have skills in stream sciences. Anadromous salmonid recovery efforts must incorporate important marine and estuarine habitats, as well as freshwater components.

The Stream Corridor Management Symposium peer review workshop, subsequent technical editing and rewriting of the ISPG led to an understanding among WDOT, WDFW and Ecology that a systematic, structured approach was needed to address the technical and scientific dimensions of most routine activities and initiatives for watershed restoration efforts throughout Washington. Thus, the original workgroup became the steering committee for what is now known as the Aquatic Habitat Guidelines project.

The project addressed this huge task by developing a systematic survey of the issues and current state of the knowledge on categories including gravel mining and dredging in freshwater environments, marine dredging, freshwater overwater structures, marine overwater structures, process based channel design, treated wood in marine and freshwater environments, floodplain-riparian ecological issues, shoreline modifications, et cetera. These "white papers" were drafted by the best experts obtainable from resource and environmental management agencies, academia, and the private sector, and were subjected to peer review and iterative revision as in accepted scientific practice. From these peer reviewed white papers, a number of Guidance Documents will be produced, similar in scope and utility to the ISPG and guidance prepared by WDFW for culvert design and installation, and fishways and fish passage.

An $850K grant from the Washington Salmon Recovery Funding Board underwrote eight advanced White Paper drafts, which will be available by the end of April, 2001, for review and downloading electronically, with links from the participating agencies. The first guidance document will be the much-needed Channel Design Guidelines, which will be ready in 2002.

The US Army Corps of Engineers is joining the AHG Steering Committee, with their need for ESA programmatics for Section 404 CWA permitting and Section 10 Rivers and Harbors Act responsibilities. NMFS and USFWS were invited, and attended the peer review workshop in Tacoma in November 2000.

Funding for continued development of guidelines documents for freshwater and marine overwater structures, treated wood, shoreline modifications, dredging and gravel mining, and AHG training and implementation are not yet committed by participating agencies.

The AHG program will be integrated into statewide implementation of transportation facility design, construction and maintenance, streamlined local, state, and federal regulatory review of activities in or near aquatic, riparian, and floodplain environments, stream restoration design, and we anticipate federal review of projects, programmatics, and Habitat Conservation Plans (HCPs) under Sections 4D, 7 and 10 of the federal ESA, using AHGs. Aquatic Habitat Guidelines are to be integrated into the Washington Salmon Recovery Plan, granta review under Centennial Clean Water Fund and Section 319, federal Clean Water Act grants, and other grant sources.

CULVERT DESIGNS FOR FISH PASSAGE IN PENNSYLVANIA

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Abstract: Pennsylvania contains approximately 83,000 miles (133,547 km) of streams and 119,000 miles (191,471 km) of public roadways. Fish movement can be impeded by highway culvert designs that create sheet flow or increased current velocity within the culvert barrel, and/or perched outlet conditions. The Pennsylvania Fish and Boat Commission and the Pennsylvania Department of Transportation reviewed performance measures of existing culvert designs and conducted a literature review to develop culvert designs that enhance fish passage. Design guidelines were established for pipe culverts and statewide design standards have been adopted for single cell and twin cell box culverts. Pipe culverts can be depressed at varying depths below streambed elevation depending upon the upstream drainage area and the diameter of the pipe. Single and twin cell box culverts are depressed twelve inches (305 mm) below streambed elevation. Box culverts installed in waterways with a stream slope less than four percent are constructed with a different baffle design than those installed with stream slopes greater than four percent. Stream flows are directed to the primary cell of the twin cell box culvert structure while the secondary cell is designed only to accept storm flows. All culvert structures are installed parallel to stream gradient and riprap used to protect the inlet and outlet is placed to match the invert elevation of the structure.

Background

Prior to the 1970s, there were few environmental regulations in place to prevent adverse impacts to aquatic resources from highway construction activities. The Pennsylvania Department of Transportation (PennDOT) and the Pennsylvania Fish and Boat Commission (PFBC) developed a memorandum of understanding in 1968, which allowed for environmental reviews to occur during the proposed highway development process. In 1969, the National Environmental Policy Act was legislated and allowed for all Act 120 agencies to review and comment on proposed highway projects.

Fish passage designs were first included within the PennDOT's Design Manual for box culvert construction during the early 1970s. The early designs included several baffle configurations or a notch placed within the culvert floor. These designs were rarely installed, and there was minimal documentation as to their success. Throughout the 1990s, the PFBC recommended that the invert of the box culvert bottoms be installed six to twelve inches (152-305mm) below streambed elevation to allow for fish passage in perennial streams that contained fish populations. These "depressed" culverts were frequently installed across Pennsylvania and often included baffles.

In 1999, several personnel from PennDOT and the PFBC formed a task force to develop fish passage designs for both pipe and box culvert installations. Measurements and physical observation were conducted on hundreds of depressed box culverts that were installed during the 1990s. These data and an extensive literature review were used to develop the culvert designs for fish passage.

Accomplishments

Pipe Culverts

In Pennsylvania, pipe culverts are normally used in highway drainage for ephemeral, intermittent and small perennial stream channels. The guidelines that were developed for pipe culvert installation are dependent upon the diameter of the pipe and upstream drainage area (Table 2).

Table 2.
Standards for Installation of Pipe Culverts

PHYSICAL CRITERIA	INVERT DEPRESSION
Pipe Diameter < 8.0 feet (2.4 m) Drainage Area ≤ 100 acres (0.405 sq km) 100 to 640 acres (2.59 sq km) ≥ 640 acres	 None Required 0.5 feet (152 mm) 1.0 feet (305 mm)
Pipe Diameter ≥ 8.0 feet	1/5 Pipe Diameter

Additional guidance for the installation of pipe culverts includes the following:

- Pipes shall be installed parallel to stream slope so that both the inlet and outlet is depressed at specified depths.
- The hydraulic capacity of depressed pipes shall be computed assuming no flow in the depressed area of the pipe.
- The value of Manning's n for the pipe shall be a weighted average of the wetted perimeter of flow. Assume the pipe fills with natural stream material to the level of the natural streambed. Refer to Appendix B of *Hydraulic Design of Highway Culverts, Hydraulic Design Series No. 5. Report No. FHWA-IP-85-15*, Federal Highway Administration, Washington, D.C.
- Riprap used to protect inlets and outlets of drainage pipes shall be placed so that the height of the riprap matches the inverts of the pipe culvert. Excess natural streambed material could be used to choke the riprap and to finish backfilling the streambed to the natural grade line.
- There may be unusual circumstances (i.e., bedrock) in which the standard design guidance for pipe culvert depression may not be practicable. In these cases, the PFBC should be contacted for specific guidance at the earliest opportunity.

Box Culverts

Single and twin cell box culverts are normally installed on perennial stream channels in Pennsylvania for highway drainage. Perennial streams contain benthic macroinvertebrate communities and in most cases support fish populations. The task force decided to depress the invert of the floor of all reinforced concrete box culverts types twelve inches below streambed elevation to enhance fish passage. The intent of this design feature is for the natural stream bottom substrates to "fill in" the newly created channel depression and eventually form a natural channel through the culvert barrel.

Baffles were incorporated into the box culvert designs to enhance fish passage immediately following construction and to promote the collection of natural stream substrates within the culvert barrel. Observations of existing depressed culverts indicated a need to develop different baffle designs for stream gradients less than or greater than four percent. For stream gradients less than four percent, alternating eight-inch (203mm) high baffles are constructed within single cell box culverts at lengths and spacing dependent upon the existing stream channel width (see figure 1, end of paper). Subsequent to project completion, these eight-inch high baffles should eventually be covered by natural stream substrates.

A different type of baffle design was developed for the construction of a single cell box culvert on streams with gradients greater than four percent. The baffle height drops from twelve inches to six inches at a location dependent upon existing stream width (see figure 2, end of paper). This full-length baffle design is recommended for steeper gradient streams to promote stream substrates to collect within the culvert barrel, and to maintain channel stability both upstream and downstream of the culvert placement location.

Twin cell box culverts are designed to be installed offset to the configuration of the stream channel (see figures 3 and 4, end of paper). The primary cell is aligned to accept normal stream flows while the secondary cell has an eighteen-inch (457mm) high weir on the upstream end, and is designed only to transport excess flows during storm events. Baffles within the primary cell of the twin cell structures should follow the design criteria as previously described for single cell culverts on stream gradients less than or greater than four percent.

Summary

The PFBC and PennDOT formed a partnership to develop culvert designs for fish passage. Box culvert designs (see figures 1-4) were adopted for statewide implementation by PennDOT, and are referenced as their Design Standard BD-632M. Additional details to the box culvert design standards can be located on PennDOT's Web site at http://www.dot.state.pa.us/newproducts/index.htm. Fish passage guidelines were also established for pipe culvert installation, however those guidelines have not been adopted for statewide standards to date. Other public road stakeholders such as the local municipalities, Pennsylvania Turnpike Commission, National Forest Service, and the Pennsylvania Department of Conservation and Natural Resources will also be encouraged to follow these fish passage designs for culvert construction on their respective roadways. We plan to conduct assessments of these new types of culvert structures as they are installed across the Commonwealth and will recommend design changes if necessary.

Biographical Sketch: David E. Spotts has been employed by the Pennsylvania Fish and Boat Commission for the past 22 years, and is currently serving as the Chief of the Watershed Analysis Section within the Division of Environmental Services. His primary responsibilities include the review and comment on statewide transportation projects, solid waste applications, and acid deposition issues. He has been an American Fisheries Society member since 1980, and has held many Pennsylvania Chapter offices including Chapter President in 1993. Dave graduated from Mansfield State University with a B.A. degree in biology and a minor in chemistry. He has received notable awards such as the Outstanding Service Award form the Pennsylvania Chapter AFS in 1992 and Vice President Al Gore's Hammer Award in 1996.

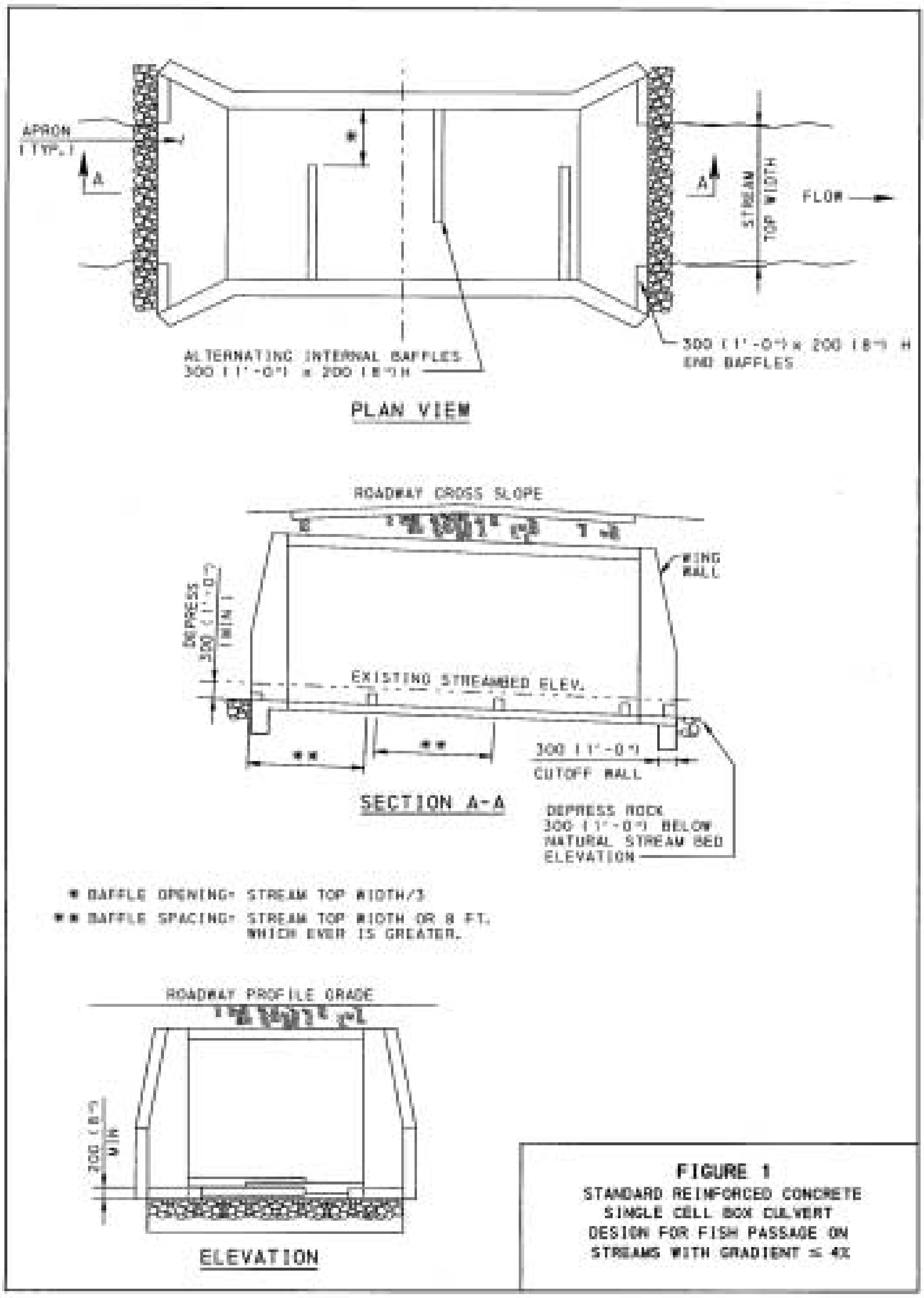

FIGURE 1
STANDARD REINFORCED CONCRETE SINGLE CELL BOX CULVERT DESIGN FOR FISH PASSAGE ON STREAMS WITH GRADIENT ≤ 4%

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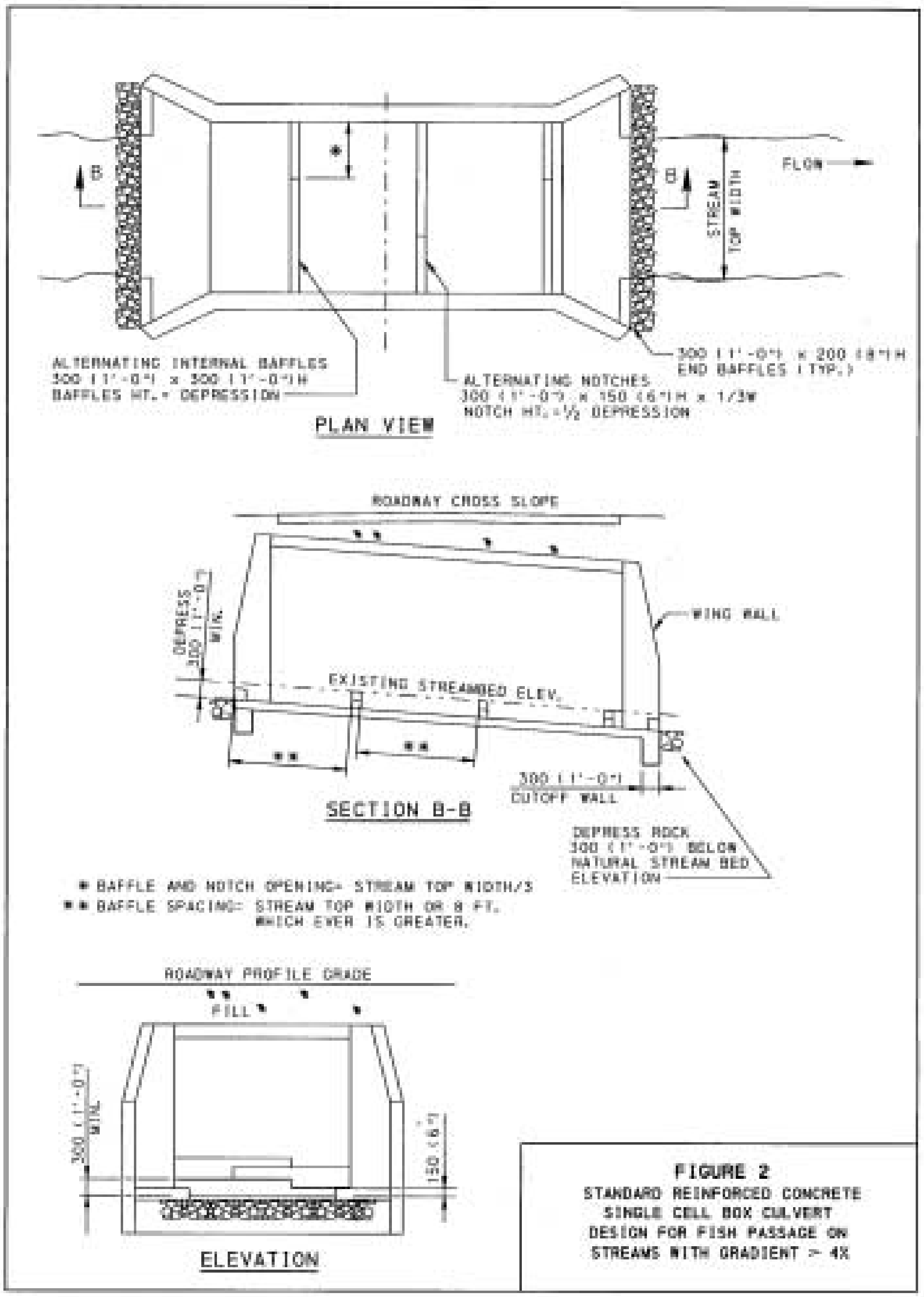

FIGURE 2
STANDARD REINFORCED CONCRETE
SINGLE CELL BOX CULVERT
DESIGN FOR FISH PASSAGE ON
STREAMS WITH GRADIENT > 4%

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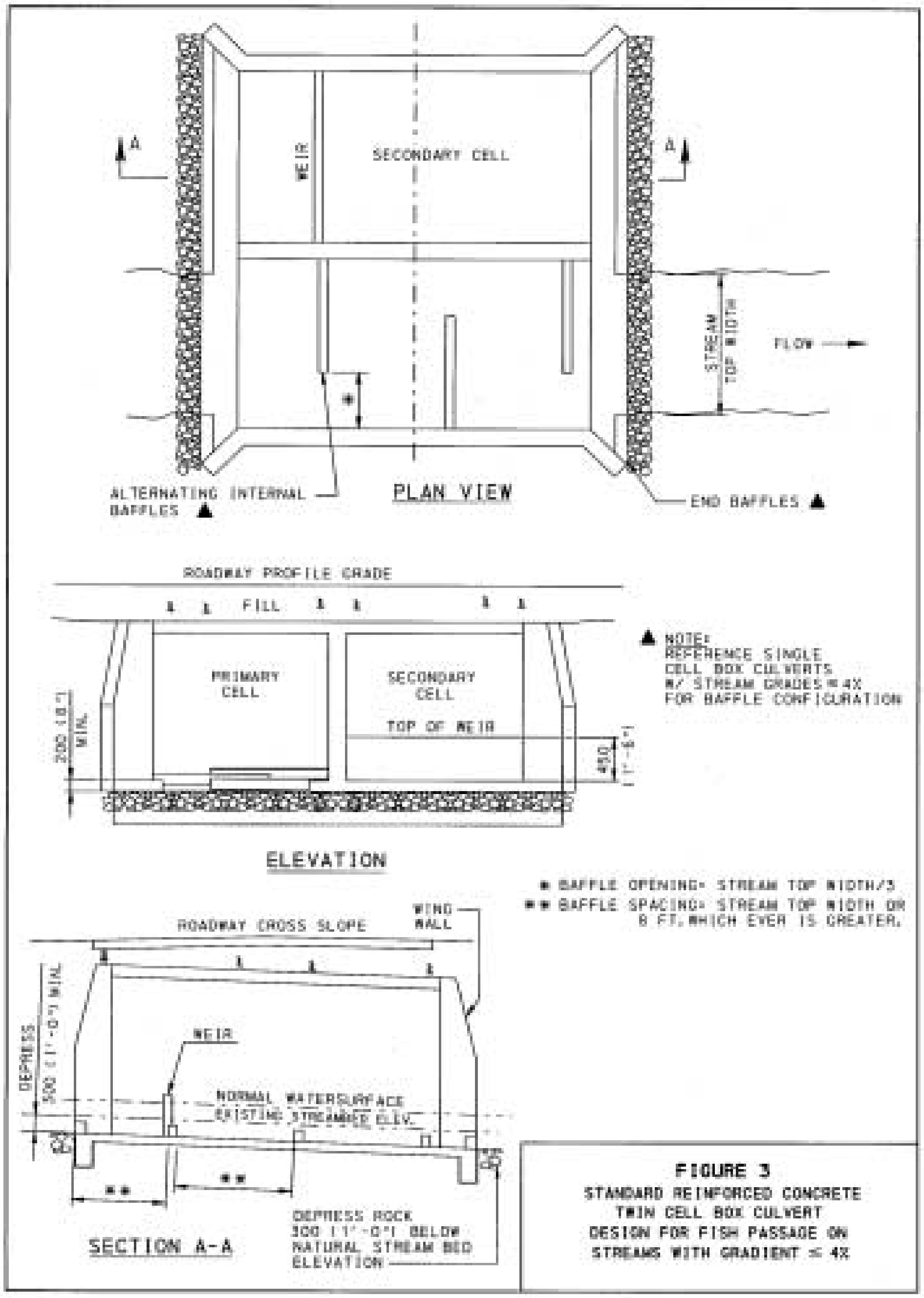

FIGURE 3
STANDARD REINFORCED CONCRETE TWIN CELL BOX CULVERT DESIGN FOR FISH PASSAGE ON STREAMS WITH GRADIENT ≤ 4%

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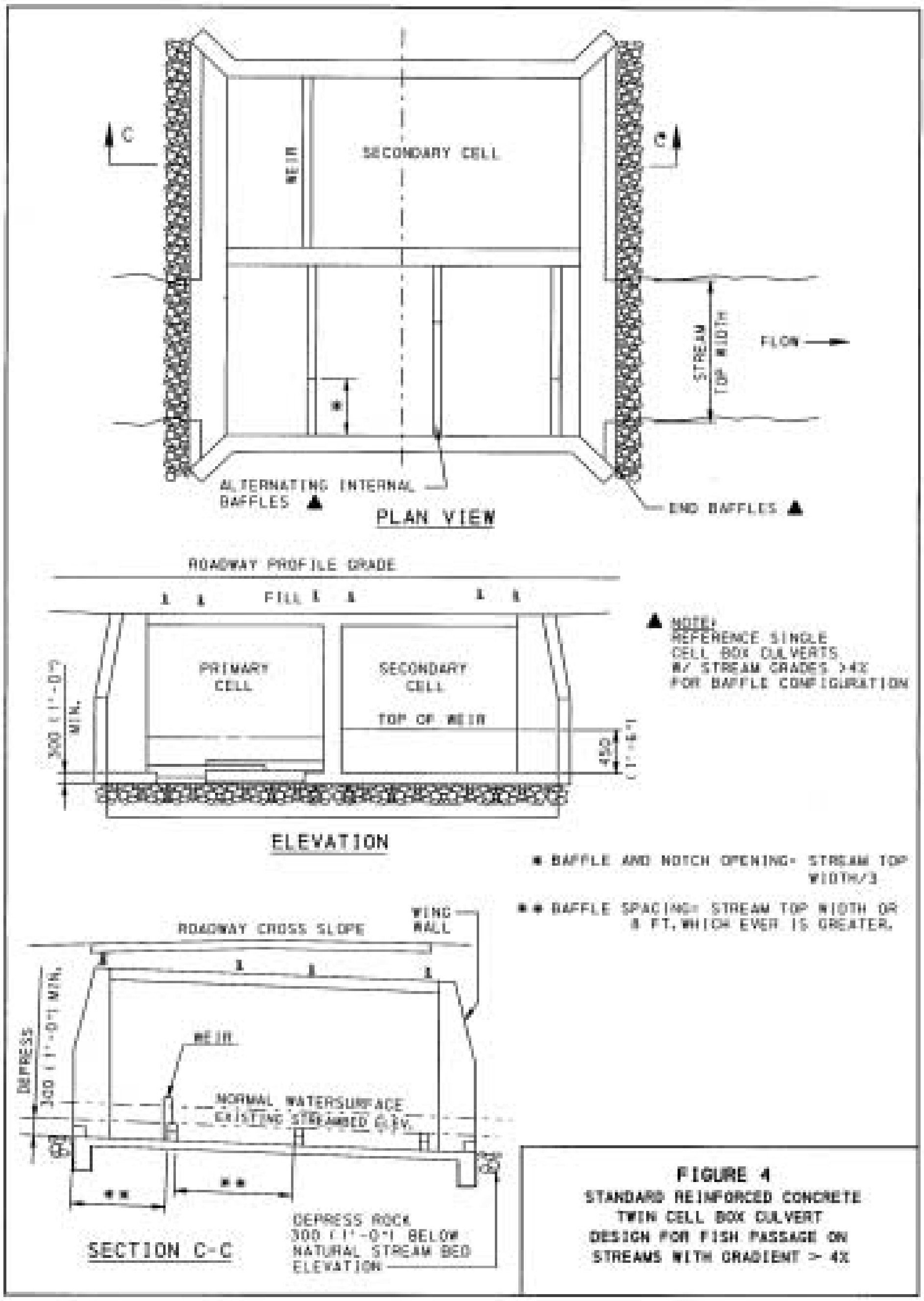

FIGURE 4
STANDARD REINFORCED CONCRETE TWIN CELL BOX CULVERT DESIGN FOR FISH PASSAGE ON STREAMS WITH GRADIENT > 4%

CULVERT TESTING PROGRAM FOR JUVENILE SALMONID PASSAGE

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Abstract: The Washington State Department of Transportation (WSDOT) has identified the need to evaluate all aspects of Department programs that may affect Pacific salmon and their habitats under the Endangered Species Act, and to correct situations where adverse effects exist. The great deal of research and engineering conducted to date has resulted in enhanced passage of returning adult salmon. However, the movement of juvenile salmonid both up and downstream throughout the year is now recognized as substantial, and the need for them to pass this life stage has made the problem even larger in scope. Tens of thousands of culverts exist in the state of Washington alone, and many are judged as blocking juvenile salmonids from thousands of miles of habitat. Determining appropriate hydraulic and fish passage designs for new and retrofitted culverts before installation has both substantial cost and environmental implications. The optimal conditions for culvert passage by juvenile salmonids are not well understood, and thus are a key area upon which WSDOT has decided to focus its research efforts.

In partnership with WSDOT, the Pacific Northwest National Laboratory has undertaken a phased program to address the hydraulic and behavioral issues associated with juvenile salmonid fish passage through culvert systems. This program addresses the testing and assessment of culvert designs, along with associated measurements of hydraulic conditions and fish behavior occurring in full-scale physical models of culvert systems deployed in an experimental test bed. Experiments in the testing apparatus will measure the hydraulic conditions (velocity, turbulence, and water depth) associated with various culvert designs under various slopes and flow regimes and then relate these measures to repeatable, quantitative measures of fish passage success. The long-term intent is to develop the test bed into a regional and national-level capability that can be used by other agencies that need to develop appropriate culvert designs to enhance the passage juvenile fish.

Introduction

The Washington State Department of Transportation (WSDOT) has identified the need to evaluate all aspects of Department programs that may affect Pacific salmon and their habitats under the Endangered Species Act (ESA) and to correct situations where adverse effects exist. The great deal of research and engineering conducted to date has resulted in enhanced passage of returning adult salmon (Copstead et al. 1998; WDFW 1998). However, juvenile salmonid movement both up and downstream throughout the year is now recognized as substantial (Kahler and Quinn 1998), and the need for them to pass this life stage has made the problem even larger in scope. Barriers to movement across city, county, and state roads in the state of Washington block an estimated 3,000 miles of habitat; the U.S. Forest Service (USFS) in Washington and Oregon estimate there are between 6,000 and 9,000 culverts on their lands and 80% of those act as barriers to movement. WSDOT alone has over 500 barriers out of 1,585 culverts that should pass fish. Tens of thousands of culverts exist in the State of Washington, and many will be found to be barriers to habitat. Moreover, with the recent Endangered Species Act listing of Atlantic salmon, the issues associated with culvert passage could become more widespread.

Determining appropriate hydraulic and fish passage designs for new and retrofitted culverts before installation now has both substantial cost and environmental implications at state, regional, and national levels. The optimal conditions for culvert passage by juvenile salmonids are not well understood and thus are a key area upon which WSDOT has decided to focus its research efforts. In partnership with WSDOT, the Pacific Northwest National Laboratory (PNNL) has undertaken a phased program to address the hydraulic and behavioral issues associated with juvenile salmonid fish passage through culvert systems. After providing a preliminary conceptual model of juvenile fish passage, this paper outlines the approach taken in the program and briefly describes the status and future directions of the program.

Conceptual Model of Juvenile Fish Passage

An initial step in the design of the program was the development of a conceptual model for the passage of juvenile salmonids through culverts. This preliminary conceptual model of fish passage emerged primarily from analysis of Powers et al. (1997), Kahler and Quinn (1998), WDFW (1998), Reeve (1999) and Kane et al. (2000). Also, the conceptual model benefited from work by Byrant (1981), Taylor and McPhail (1985), and Kane et al. (1989) on juvenile salmonid swimming abilities. Most recently, Powers et al. (1997) in a temporary test culvert and Kane et al. (2000) in the field found that juvenile fish use the low-velocity boundary layer to pass upstream in culverts. Powers et al. (1997) found that juvenile salmon switched to a boundary layer near the water surface and next to the culvert wall when water velocity increased above 0.4 feet per second (fps). The maximum velocity in the boundary layer that permitted successful juvenile fish passage was at or below 2 fps. Increased turbulence lowered the maximum velocity at which juvenile fish can pass the culvert. Also, fish size influenced behavioral response to turbulence and to culvert structures. Powers et al. (1997) urged more research on turbulence and other culvert characteristics that determine successful fish passage.

It is clear that fish pass culverts at higher mean velocities than their swimming performance indicates because they utilize low-velocity pathways and adaptive behaviors to accomplish the passage. Two major factors determine the occurrence of upstream passage:

- Motivation. Environmental factors and cues provide the ultimate and proximate determinants of upstream movement.
- Capability and Behavior. Once motivated to move upstream, the capabilities and adaptive behaviors of the fish interact with the culvert physical structure and hydraulic conditions to determine the success of passage.

A variety of environmental factors have been hypothesized for motivating and influencing upstream movement, and there are several possible cues providing triggers and orientation in upstream movement (Table 1).

Table 1
Possible Environmental Factors and Cues Motivating and Influencing Upstream Movement of Juvenile Salmonids

Possible behaviors influenced by environmental factors:

- Avoiding extreme water temperatures
- Avoiding poor substrate
- Moving to low velocity habitats after hatching in the spring
- Moving from degrading habitat in the summer (e.g., low dissolved oxygen, high temperature)
- Moving to over-wintering habitat in the fall
- Avoiding high turbidity
- Avoiding predation
- Moving from high-density areas (from competition or occupied territories)
- Moving to feeding areas

Possible cues providing triggers and orientation:

- Abrupt changes in flow characteristics
- Changes in water temperature
- Changes in turbidity
- Chemosensory cues for prey (food sources), conspecifics, or “habitat”
- Light and dark patterns

The model suggests that once juvenile fish are motivated to move upstream, successful passage of the culvert is determined by interactions between the swimming abilities, adaptive behaviors, and stamina (i.e., endurance, time to fatigue) of the fish and the nature of the low-velocity and low-turbulence pathway(s) within the culvert system. The physical structure and the patterns of velocities, turbulence, and resting areas within the culvert system determine the nature of the passage corridor. Adaptive behaviors in culvert passage include the following:

- Using burst speed (darting speed) to enter the downstream end of the culvert (outlet)
- Using low-velocity/low-turbulence pathways (e.g., boundary layer) to move up the barrel of the culvert
- Using prolonged swimming ability (cruising speed) to move up the culvert
- Using holding or resting areas (e.g., corrugations or other low-velocity areas)
- Using prolonged or burst speed to move through high-velocity areas from resting area to resting area
- Using burst speed (darting speed) to exit the upstream end of the culvert (inlet)
- Jumping.

Thus, passage of the culvert is determined by interactions between the swimming abilities and energy reserves of the fish and the pattern of velocities and resting areas in the culvert system.

Although the conceptual model provides insight into the mechanism of upstream passage, it is not complete enough to fully assess all the behavioral, environmental, and hydraulic issues influencing fish-passage success. Important factors such as fatigue and the ability to feed or avoid predators once through the culverts need to be included in a more detailed and realistic approach to understanding the influence of culverts on juvenile fish passage. Switches among behavioral strategies related to fish size that allow for successful passage through these culverts also need to be understood. The triggering factors and their quantitative thresholds need to be determined.

The conceptual model is at a basic stage. To guide culvert design, attempts have been made to develop mathematical models that incorporate fish swimming abilities and endurance plus hydraulic properties of culverts (Powers and Orsborn 1985, as cited in Reeve 1999; Behlke et al., 1991 and 1993, as cited in Moore et al. 1999; USFS 2000). Unfortunately, to convert the conceptual model to a mathematical model requires a better understanding of the relationships among the determinants plus empirical data to provide values for the model parameters. The experimental work necessary to obtain this understanding and data remains to be done for juvenile fish. Such research needs to be in a full-scale physical model in which both the fish behavior and the hydraulics can be well characterized in controlled experiments.

Approach: A Test Bed for Evaluation of Culvert Designs

To address the issues in culvert designs for juvenile fish passage, a multi-organizational partnership was developed to design and implement a passage research program. WSDOT lead the partnership that now includes Washington Department of Fish and Wildlife (WDFW), Alaska Department of Transportation, Alaska Department of Fish and Game, and the Pacific Northwest National Laboratory of the U.S. Department of Energy. The program will employ a specially fabricated test bed to identify the culvert designs and associated hydraulic conditions that allow successful upstream movement of juvenile salmonids at different life stages. The program addresses three main questions:

- What new culvert and retrofit designs pass juvenile salmonids?
- For such designs, how do hydraulic conditions and culvert characteristics influence the extent or degree of passage success?
- How does passage success vary with fish species and fish size?

The program addresses the testing and assessment of culvert designs, along with associated measurements of hydraulic conditions and fish behavior, occurring in full-scale physical models of culvert systems deployed in an experimental test bed. Experiments in the testing apparatus will measure the hydraulic conditions (velocity, turbulence, and water depth) associated with various culvert designs under various slopes and flow regimes and then will relate these measures to repeatable, quantitative measures of fish passage success.

Simulating actual full-scale culvert hydraulics is a complex undertaking. First, hydraulic effects cannot be scaled down and still generate natural responses from fish. The study by Powers et al. (1997) demonstrates why one must work at full scale to obtain appropriate results when behavior related to fish size interacts with the size patterns of culvert structures. Second, the quantity of water required to simulate the 2- to 3-fps velocities believed to be limiting to fish passage in culverts ranges up to 5 to 10 cubic feet per second (cfs) of water flow with culverts ranging in diameter from 2 to 3 feet. This is a considerable volume of water flow to maintain for the 30 to 60 minutes that the fish require to move through culvert lengths of 30 to 40 feet (times estimated from Powers et al. 1997). The scale and water supply issues had to be addressed in the design of the testing program and test bed.

Similarly, the testing program needs to address how to conduct controlled experiments on upstream juvenile salmonid passage under a variety of different culvert system designs and under a range of flow conditions. The design features to be addressed included various types of baffling, bed configurations, and culvert types. The slopes to be tested were to be as high as 10% and the flows as high as 20 to 24cfs. As the combination of factors to be tested increases, the amount of testing to be done increases multiplicatively. Therefore, the program will need to assess the full range of factors and questions to be addressed and identify an appropriate order in which to address them.

Program Status

The program was structured to have the following phases:

- Develop a conceptual design of the testing program and test bed
- Develop draft protocols for behavioral testing and hydraulic measurements
- Select an appropriate site for the test bed
- Design, fabricate, and install the test bed and associated instrumentation
- Conduct behavioral and hydraulic testing using the test bed
- Prepare final program technical reports.

As of August 2001, the conceptual and detailed engineering designs of the test bed have been completed. An appropriate site has been selected and approved. The draft protocols have been prepared. A draft testing sequence has been submitted for discussion among the partners. Bids on fabrication and installation work have been received. Some preliminary preparations at the site have been accomplished.

The Test Bed Location

The test bed is to be installed at the WDFW's Skookumchuck Fish Hatchery near Tenino, Washington. The advantages of this location include the following:

- Availability (nearly year-round) of coho salmon
- Availability of different sizes of juvenile coho
- Capability of using trout as a test species
- Potential to use other species in testingreservoir, providing an abundant supply of high-quality water that supports the rearing of coho salmon

Test-Bed Design

The test bed (Figure 1) has been designed to test different culvert types and bed configurations. The test bed can accept culverts of about 40 feet in length. Insert supports have been designed for round culverts in widths of 2, 3, and 6 feet, as well as for 81-inch pipe arch and 60-inch box culverts, and can be designed for mounting other culverts. Once a given culvert is chosen for mounting in the test bed, then different configurations of baffles can be placed within the mounted culvert. Corrugations of different patterns and sizes can be tested as well as baffle systems of different sizes, shapes, and spacing. Gravel bed configurations up to 12 inches deep can be tested.

The test bed also allows testing at culvert slopes from level to 10% in increments of 0.66% slope. Valves and meters enable water flow to be measured and controlled from about 0.5cfs to 20cfs. Acoustic doppler velocimeters mounted in specially fabricated frameworks permit fine-scale, three-dimensional measurements of hydraulic conditions, including turbulence in the boundary layer and around corrugations and baffles. Overall, the test bed enables experimental trials to relate success of fish passage to hydraulic measurements for specific culvert and bed configurations.

Using the test bed offers several distinct benefits. Controlled trials can be conducted within an appropriate statistical design. Moreover, the program enables the trials to be conducted in a much shorter timeframe than is possible for field installations and evaluations. Coupling the behavioral and hydraulic data will enable the

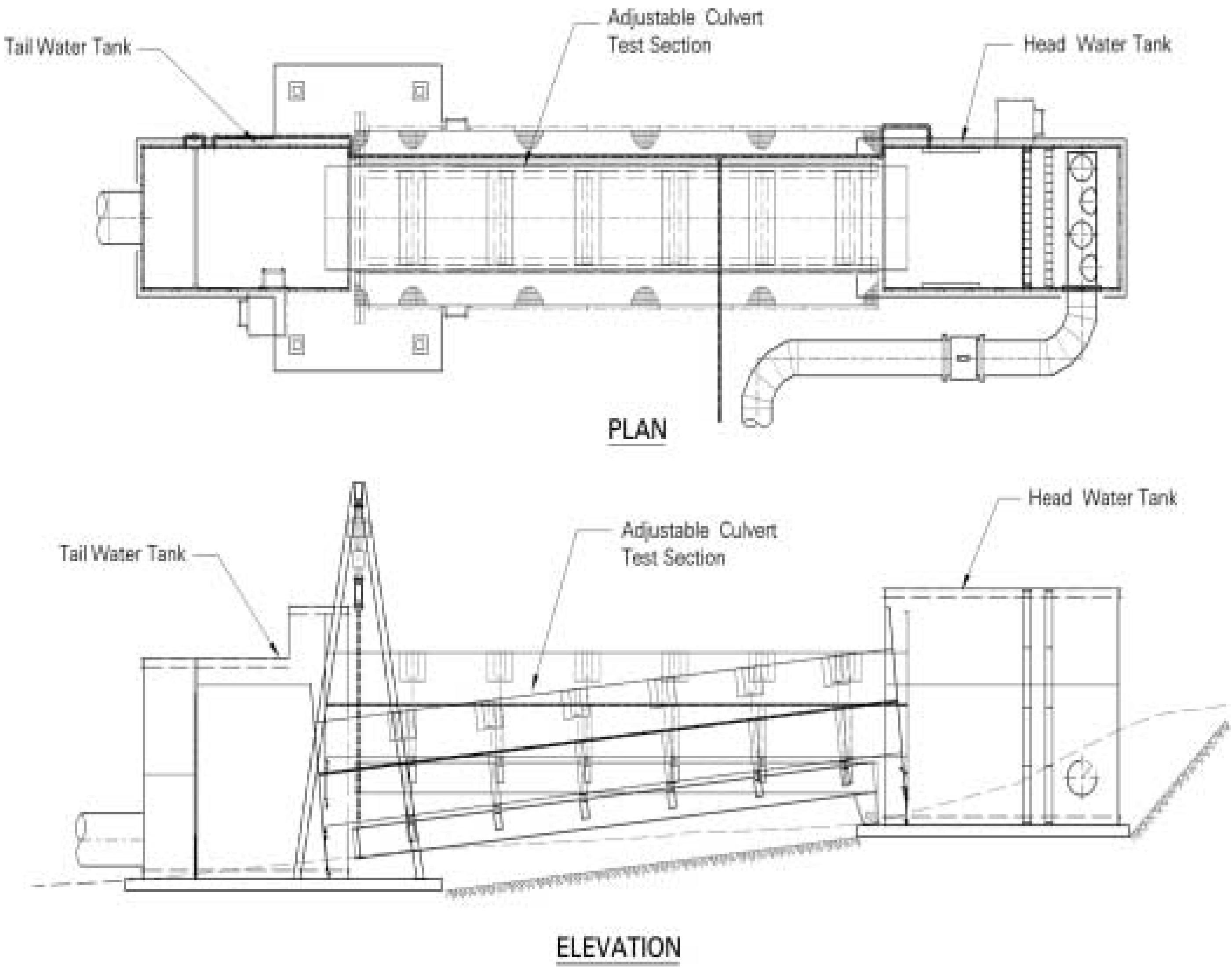

Fig. 1. Test Bed for Evaluation of Passage of Juvenile Salmon through Culverts designed by the Pacific Northwest National Laboratory and Montgomery Watson Harza for the Washington State Department of Transportation.

program to develop and test predictive numerical models for culvert hydraulics and fish passage. Analysis of the results for several designs and over a range of conditions will allow us to
discern optimum engineering principles for future culvert and retrofit designs. Such information is extremely valuable to support engineering of cost-effective solutions to juvenile fish passage through culverts.

Future Directions

The next steps in the program are to fabricate and install the test bed and then begin hydraulic and behavioral evaluations of specific culvert designs and configurations. Our long-term goal is to develop the test bed into a regional- and national-level capability that can be used by other agencies that need to develop appropriate culvert designs to enhance the passage juvenile fish. In pursuit of that goal, the partnership is actively seeking to expand its membership to other interested parties.

Acknowledgements: The development of the conceptual and engineering design was supported by the Washington Department of Transportation. We gratefully acknowledge the insightful technical input by Mr. Ken Bates of the Washington Department of Fish and Wildlife and the input on technical requirements by the other partners, the Alaska Department of Transportation and the Alaska Department of Fish and Game. We thank Dr. D. Kane of the University of Alaska for insightful comments during design. The dedication and engineering skills of Mr. Harry Dunham and his colleagues at Montgomery Watson Harza, who accomplished the detailed engineering design, are especially appreciated.

Biographical Sketch: Dr. Walter H. Pearson's primary area of expertise is the study of the effects of pollution and human activities on marine and estuarine environments, and especially on the fisheries they support. His recent experience has been in leading large multidisciplinary, multiorganizational studies to assess natural resource damages to fisheries and marine environments. Dr. Pearson returns to Battelle after 3 years in the United Arab Emirates, where he served as Head of the Marine Environmental Research Center and as Acting Head of the Terrestrial Environmental Research Center as part of the Environmental Research and Wildlife Development Agency. In this capacity, Dr. Pearson developed programs for sea turtles, dugong, fisheries, seagrasses, the inventory of biodiversity of protected areas, the rehabilitation of select species, water quality, oil spill contingency planning, and natural resource damage assessment in the Gulf region, among other issues.

Dr. Pearson is currently leading a phased program sponsored by the Washington State Department of Transportation to apply a specially fabricated test bed to identify culvert designs and hydraulic conditions that allow upstream passage of juvenile salmonids at different life stages. In other programs, he is presently reviewing background documents to address biological assessments of the Channel Improvement EIS in the Lower Columbia River and estuary. Drs. Ron Thom and Walt Pearson developed a conceptual model that provides a blueprint of physical and biological interactions, including structural and functional features relevant to the use and support of salmonids in the Lower Columbia River ecosystem.

References

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

Copstead, R.L., K. Moore, T. Ledwith, and M. 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).

Kahler, Thomas M., and Thomas P. Quinn. 1998. *Juvenile and Resident Salmonid Movement and Passage through Culverts*. Final Report WA-RD 457.1 to the Washington State Department of Transportation, Olympia, Washington from The University of Washington. Seattle, Washington.

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

Kane, D.L., C.E. Belke, R.E. Gieck, and R.F. McLean. 2000. *Juvenile Fish Passage Through Culverts in Alaska: A Field Study*. Report Number INE/WERC 00.05. Water and Environmental Research Center, University of Alaska, Fairbanks, Alaska.

Moore, K., M. Furniss, S. Firor, and M. Love. 1999. *Fish Passage Through Culverts: An Annotated Bibliography*. Six Rivers National Forest Watershed Interactions Team, Eureka, CA (http://www.stream.fs.fed.us/fishxing).

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

Reeve, R. 1999. *Biological Elements of Fish Passage at Roadway Stream Crossings*. Culvert Fish Passage Improvement Training for the State of Oregon Department of Transportation. January-April, 1999.

Taylor, E.B. and J.D. McPhail. 1985. Variation in Burst and Prolonged Swimming Performance among British Columbia Populations of Coho Salmon, Oncorhynchus kisutch. *Can. J. Fish. Aquat. Sci*. 42: 2029-2033.

U.S. Forest Service. 2000. *FishXing* Web site: http://www.strea.fs.fed.us/fishxing/index.html.

WDFW (Washington Department of Fish and Wildlife). 1998. *Fish Passage Barrier Assessment and Prioritization Manual.* Washington Department of Fish and Wildlife, Habitat and Lands Service.

NATURAL FISH PASSAGE STRUCTURES IN URBAN STREAMS
(PART 1: HYDROLOGIC AND RESOURCE ISSUES)

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Abstract: Fish passage is now an integral part of compensatory mitigation under the new Nationwide Permit regulations. Engineered structures and stream restoration designs are common solutions to fish passage; however, in urban systems such solutions may not be feasible. Natural structures such as riffle grade controls and flow constrictor/step pools can provide low-maintenance stable solutions to fish passage in urban systems. Steps to designing such structures include an evaluation of the target fish species characteristics, site-specific baseflow hydrology, and hydraulics of the structure. Analyzing baseflow is essential because urban flood flows exhibit relatively high velocities and short durations precluding upstream migration. Fish characteristics, hydrology, and hydraulics are all used to generate fish passage design criteria.

Introduction

Restoring fish passage has received significant attention by regulatory agencies and elected officials, and is a growing issue on many public works and land development projects. Fish passage is accomplished using either engineered structures (i.e., pool-weirs or fish ladders) or natural channel designs (partial or total stream restoration). Engineered structures are used to provide passage over or through an obstruction such as dams and culverts. Natural designs generally focus on restoring channel geomorphology by providing stable dominant-discharge geometry to properly transport sediments and pass flood flows (100-year events). However, in both natural and urban stream design the low-flow or aquatic habitat channel are forgotten. Engineered structures and natural channel design methods experience significant problems in urban stream systems due to debris and sediment loads, flashy storm flows, low baseflows, and the inability to properly locate the dominant-discharge stage.

Although fish ladders commonly pass sediment loads, they often clog with debris and thus require maintenance. Since daily maintenance is generally required during the migration season, a clogged ladder could prevent significant amounts of fish from reaching spawning areas. Pool-weir structures frequently accumulate sediment in urban streams rendering them ineffective for fish passage. Without the pool volume, fish would need to swim directly upstream negotiating velocities that would likely be overwhelming.

Natural design approaches are adequate in rural or wilderness watersheds because the natural baseflow can be relatively close to dominant discharges. In urban settings, baseflows decrease and flood flows become flashy, scouring channels to unnatural widths resulting in shallow homogeneous channel that are unable to struggle to support fish populations (Sovern 1997). Designing for dominant discharge in urban streams does not necessarily translate to fish passage because of the relatively large disparity between baseflow and dominant discharge. Consequently, the common use of stone cross vanes and other “natural” grade control structures in urban streams can create additional fish passage blockages in our wide urban streams (Figure 1). When these “natural” structures are added to the endless list of exposed utilities, dams, culverts and over-widened channels, fish passage is nearly impossible in these urban areas.

Fig. 1. Example of Natural Structure Becoming a Blockage

This paper is the first of a two-part document designed to present natural approaches for solving urban fish passage problems, by exploring the nested channel and grade control approaches, riffle grade control (RGC) structures, and specially designed flow constrictor/step pool (FC/SP) systems. This part focuses on regulatory issues and the methods to develop design criteria by examining the hydraulic conditions that promote fish passage and the use of baseflow data for estimating design flows. Examples used, herein, are based on designs within the Chesapeake Bay watershed; however, the concepts are applicable to any watershed.

Purpose and Need

Urban fish passage is necessary to reopen and/or create habitat for anadromous fish migration and, to a lesser extent, resident fish movement. Increasing the quantity and quality of spawning habitat would likely increase the size of fisheries for commercial/sport fishing, food, and attracting other wildlife.

Seven species of anadromous fish occur in the Chesapeake Bay watershed: American shad (*Alosa sapidissima*), hickory shad (*Alosa mediocris*), alewife (*Alosa pseudoharenqus*), blueback herring (*Alosa aestivalis*), white perch (*Morone americana*), yellow perch (*Perca flavescens*), and striped bass (*Morone saxatilis*). Anadromous fish are those that live in brackish or ocean water and migrate to freshwater to spawn. Between 1976 and 1985, commercial harvest of these fishes declined by 82 percent due to the pressures of over-fishing and habitat loss. Virginia and Maryland placed moratoria on these fish, which have allowed some fish to recover (i.e., striped bass); however, populations of alewife and blueback herring remain low (Chesapeake Bay Program 2000). Moratoria, in the absence of improved fish passage, will likely preclude some of these anadromous fish species from experiencing a rebound.

Similar to other environs, the quantity and quality of fish spawning habitat has diminished with increased urbanization. Effects of urbanization on streams are well documented and could include increased sediment load, decreased baseflow, higher flood flows, and channel instability. Urbanization may also result in anthropogenic stream blockages such as dams, utility lines, and weirs and culverts that further degrade the channel and habitat, precluding fish migration. Resident fish may be more adaptable to stream alterations caused by blockages; however, these blockages completely eliminate anadromous fish spawning habitat, contributing to fish species decline.

To address fish passage problems, the Anadromous Fish Conservation Act of 1965 was enacted requiring fish passage for large dams. Recently, fish passage has become an integral part of compensatory mitigation for construction projects under the Nationwide Permit (NWP) program. According to the Federal Register dated

March 9, 2000, the U.S. Army Corps of Engineers (USACE) views fish passage as stream enhancement. The Federal Register states, "Stream restoration and enhancement, including the restoration or preservation of riparian zones, can also provide compensatory mitigation for losses resulting from activities authorized by NWPs." NWP 27 authorizes such mitigation under the new NWP program. In addition, General Condition No. 4 of the new NWP program prohibits the disruption of indigenous or migratory aquatic species movement and requires that culverts be installed in a manner that maintains low flow conditions. In some regions of the United States, fish passage and stream restoration are commonplace because of the number of impacted streams located in urbanized watersheds. Recognizing the disproportional impacts to our fisheries and river systems, elected officials in Washington are considering a bill to help restore these resources in our urban environments. The Fishable Waters Act of 2001 (H.R. 325/5678) could provide significant funding over the next six years to improve the valuable resources.

Review of Existing Projects

Completed Structures

Numerous types of natural rock structures are available for stream restoration and habitat enhancement projects, some of which are described below. In California, the USACE --, Sacramento District constructed a Gradient Facility on the Sacramento River as a diversion device for an irrigation canal (Figure 2). As part of the design criteria, three feet of head was required on the RGC to provide fish passage and recreational boating (Hogan 2000).

The U.S. Bureau of Reclamation (BOR) constructed a Gradient Control Structure (GCS) downstream of Marble Bluff Dam in California, which was designed to provide sufficient head for the existing fish lock system to function properly. According to BOR, fish successfully migrated up the GCS and into the lock. BOR indicated that 500,000 fish migrated up the GCS in 1999, and that a second fish lock system is necessary to accommodate the quantity of fish migrating up the GCS (Valentine 2000).

Riffle designs in Canada are presented in a manual by Newbury Hydraulics, Ltd., in which a steep upstream glide surface meets the longer downstream riffle surface (Newbury 1993). Boulders are placed on the riffle surface to provide flow diversity and reduce velocities. Like the two preceding examples, design examples provided in Newbury's manual occur in relatively rural streams. However, each of these structures was designed to pass fish.

Fig. 2. GF in Sacramento River

Fig. 3. RGC in White Marsh Run

In Baltimore County, Maryland, six RGCs were constructed to stabilize White Marsh Run, a high bedload stream that has previously rendered traditional stabilization structures ineffective due to high sediment deposition (KCI 1995). Although these structures were not designed specifically for fish passage, spring flow depth and velocity measurements on these RGCs indicate that they would promote fish passage (MDNR 2000). The White Marsh Run RGCs are unique in that they are installed in series, whereas most constructed riffles were installed as point location structures (Figure 3).

More recently, the U.S. Environmental Protection Agency (USEPA) conducted a large study of stream restoration practices, including 290 grade control structures in the Baltimore/Washington D.C. area and northeastern Illinois to determine if restoration goals were being achieved (Center for Watershed Protection 2000). Grade control structures evaluated in this study were rock vortex weirs, rock cross vanes, step pools, and log drop/v-log drops. All structures were installed for stream restoration, except some of the step pool structures that were installed for habitat enhancement. According to the USEPA, step pool structures were resilient to flood flows and met the habitat enhancement/fish passage objectives. However, the study did not confirm through measurements or sampling that fish are actually passing through the structures. In general, the report stated that less than 60 percent of the inspected structures did not meet habitat enhancement goals.

Based on our review of these and other existing projects, one fact became apparent: restoration projects in urban streams will not likely pass fish if fish passage is an afterthought. However, stream restoration can be successful if it is the result of natural fish passage design. In the Baltimore County project, the fact that the RGCs provide hydraulic conditions conducive to fish passage was a coincidence.

Woodrow Wilson Bridge Project

Natural fish passage design became a substantial part of the compensatory mitigation for the $1,970,000,000 Woodrow Wilson Bridge Project occurring over the Potomac River through the southern tip of Washington D.C. To mitigate impacts of the new bridge construction and ancillary infrastructure construction, the Maryland State Highway Administration (SHA) was required to remove or traverse 21 blockages in 5 different streams, which in turn would re-open 17 miles of urban stream habitat to anadromous fish. These 21 blockages included dams, utility lines, gabion basket weirs, bridge culverts, and concrete fords.

To meet the fish passage goals, SHA first investigated engineered structures. A few factors weighed heavily against the use of engineered structures. Permitting agencies desired a more natural, self-sustaining approach *in-lieu* of engineered structures. Some of the blockages were in a historic park; therefore, visual impacts were a serious consideration. Furthermore, SHA's experience with engineered structures in urban streams indicated that a significant level of maintenance was required to keep them operational (ESA 2000). Significant organic debris loads typically block ladders, and high sediment loads filled concrete pool/weir structures.

SHA decided to use natural fish passage structures such as RGCs and FC/SPs to provide the required fish passage over blockages in Rock Creek, Northwest Branch (of the Anacostia River), Sligo Creek, Little Paint Branch, and Indian Creek. RGCs were designed for blockages in Northwest Branch, Little Paint Branch, and Indian Creek since the blockages where these streams flow (primarily through the Atlantic Coastal Plain Physiographic Province) exhibit high bed-loads, and the blockages are low profile (i.e., culverts, utility lines). FC/SPs were selected for Sligo Creek because the blockages were higher profile (sheet-pile dams) and the hydraulic gradients were too steep to provide the hydraulic environment for migration. For Rock Creek, FC/SPs were a necessity because the blockages are in Rock Creek Park, which is a national park and a historic district, and the fish passage structures could not visually impact the historic scene.

General Concepts

Natural fish passage structures such as FC/SPs and RGCs are used to restore passage over relatively low-profile blockages such as weirs, utility lines, culverts, and low-head dams. These rock structures are designed to produce a hydraulic regime that promotes fish passage, as well as providing additional habitat. Other uses include inducing backwater effects for water supply diversion and providing head for traditional fish structures. For higher head dams (hydraulic drops less than 8 feet) natural structures would not likely be used because construction costs would be excessive, in most cases. Therefore, engineered structures would be the primary means of providing fish passage through higher head dams.

Natural fish passage designs should be pursued sequentially by developing the hydraulic criteria, assessing the hydrology, and designing the structure. Essential components of the hydraulic criteria are documenting the species of concern and evaluating swimming and migrating behaviors. Hydrology evaluations should result in a complete understanding of present and past watershed conditions, future development plans, flood flow trends and frequencies, and base flow trends and frequencies.

Hydraulic Design Criteria

Hydraulic criteria must first address the species of concern and the manner in which they migrate. Migration behavior includes such characteristics as:

- Cruising and burst swimming speeds: Used to set the stream velocity limits through the natural structure. More than one species will likely be addressed by a fish passage structure; therefore, the velocities should be set to accommodate the weakest species.
- Duration of cruising or burst speeds: Measure of the distance a fish can swim before resting. This criterion is used to judge whether a structure is too long for a fish to successfully traverse. If this were the case, resting places such as pools or boulder clusters would be required.
- Leaping ability: Leaping ability could affect the slope of some structures or the size of steps.
- Size of fish. Fish size will help determine the slope of the structure and the minimum depth of flow required for fish passage.
- Months of migration: The period of migration is necessary to define the scope of the hydrologic study and design flow calculations.
- Water Movement: Considers turbulence and velocity. Velocity barriers occur in areas of abrupt change from slow or moderate flowing water to fast flow, and can greatly affect fish that do not leap. Excessive turbulence will also create a barrier because fish do not get useful information regarding current direction. Turbulence in step pool design is quantified by a parameter known as the Energy Dissipation Factor (EDF) (Washington Department of Fish and Wildlife 1999).

Figures 4 and 5 provide useful information regarding the swimming speeds and swimming durations for some anadromous fish. The U.S. Fish and Wildlife Service or state natural resource agencies can likely provide most or all of the above information. The Freshwater Institute, Manitoba, Canada, produced a fishway design document that contains useful information regarding swimming characteristics of anadromous fish (Katopodis 1992).

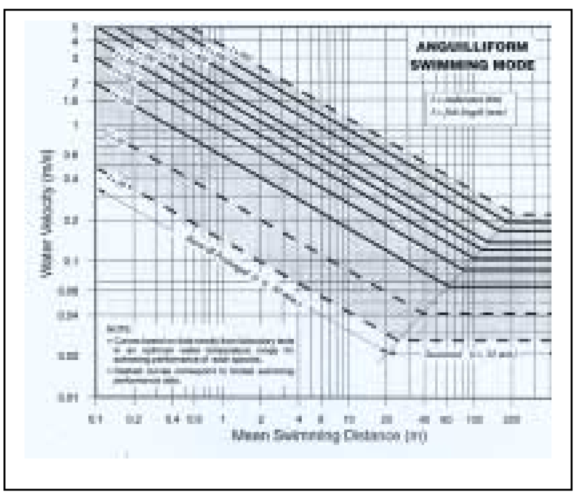

Fig. 4. Anquilliform Swimming Chart

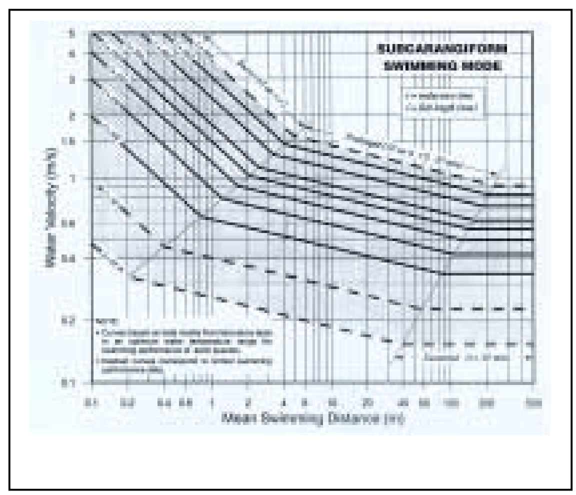

Fig. 5. Subcarangiform Swimming Chart

Hydrology

Project Area Watershed Characteristics

As with any hydrologic study, knowledge of the watershed is particularly important to understanding and modeling the characteristics of the study area. Primary watershed characteristics include: percentage of impervious surface, soil hydraulic parameters, topography, drainage density, future development, and watershed shape. Although not every parameter is used in actual design computations, this background information will guide the design in more subtle ways. For example, if the subject watershed will undergo future development, baseflows and flood frequency will likely be impacted. The designer must estimate the future baseflow impacts and design the natural rock structures to provide fish passage under reduced flow conditions. Future development would also increase flood flow frequency; therefore, rock must be sized appropriately to remain stationary under those conditions.

Urban Watersheds Storm Responses

Over the last two centuries, urbanization has caused significant changes to the landscape surrounding the urban centers and affecting natural hydrologic processes. Increasing percentages of impervious surfaces reduces rainfall infiltration and groundwater storage causing increased surface runoff and flashy stormflows. A common geomorphic response to such hydrologic changes is streambed erosion and/or channel widening. Reduced infiltration will also reduce baseflows, which compounded by an over widened channel, causes significant impacts to fish and macroinvertebrate habitats. Constantly changing environmental conditions and streambed instability are one of the primary limiting factors in urban systems affecting the sustainability of aquatic populations (Sovern 1997). If natural fish passage structures are to be successful, the proper flow depths and velocities must be attained at baseflow conditions.

Effects of Urbanization on Baseflow – Example

To highlight the impacts of urbanization on baseflow, the authors examined stream gage data from the Northwest Branch gage near Colesville, Maryland (USGS Gage No. 01650500), located in southeastern Montgomery County approximately 16 miles northeast of Washington, D.C. This particular gage was selected because it contained a lengthy data set covering watershed conditions from rural to developed (water years 1923 to 1982). Baseflow data were derived from the gage record using the fixed-interval method (USGS 1996).

After collecting the data, a hydrograph was constructed and a linear regression was performed to evaluate any obvious trends (Figure 6). A review of Figure 6 indicates that the regression line exhibits a slight downward trend indicating that baseflow decreased over the length of the record. Two sharp breaks were observed in the hydrograph; one in 1930 due to a significant drought and the second in 1955. The 1955 break corresponds to the beginning of a more permanent trend of lower baseflow due to development. Figure 7 presents development trends in the gaged watershed. According to land development data, significant development started in the 1950s and increased in the 1960s (Maryland Office of Planning 1998).

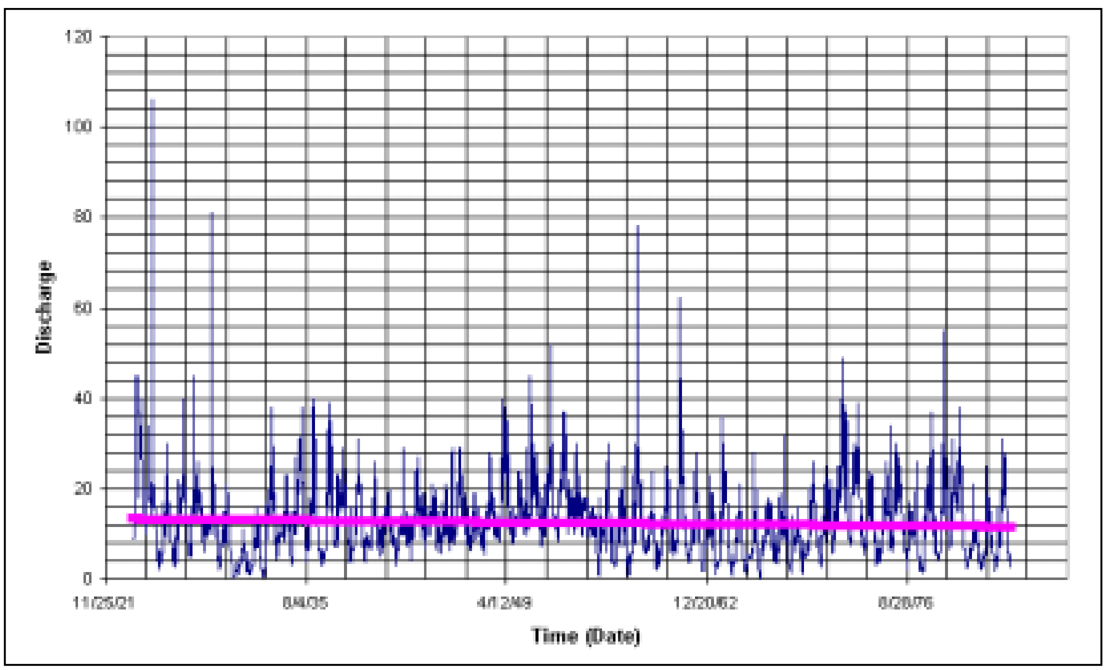

Fig. 6. Baseflow Hydrology, Northwest Branch near Colesville, MD

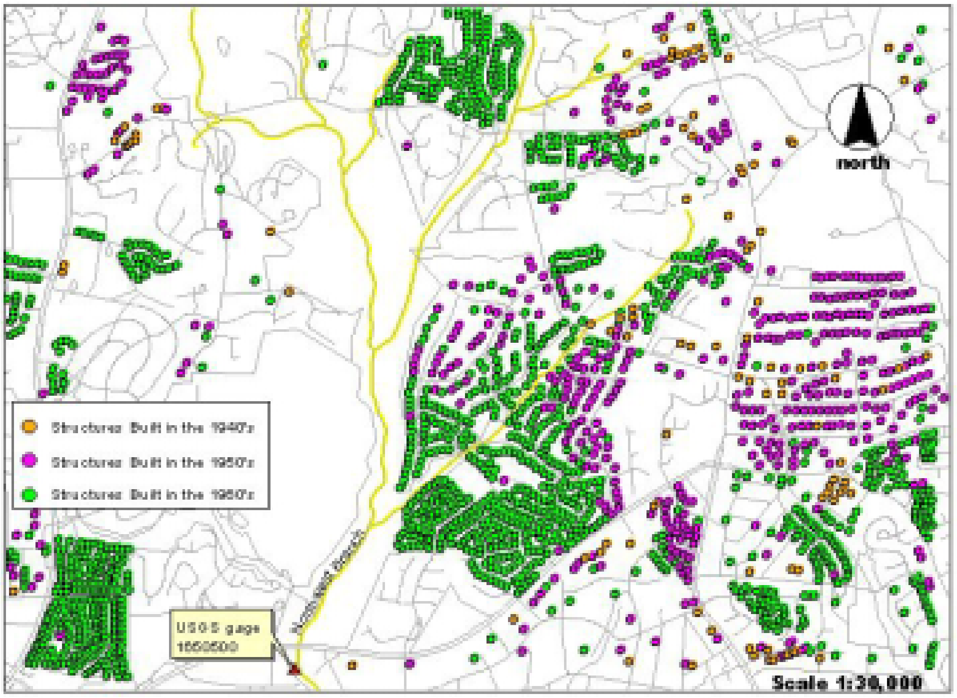

Fig. 7. Development Trends, Colesville, MD

Although the regression indicates a trend, the mechanism of the trend is not apparent; therefore, six 10-year histograms were constructed to review the flow frequencies through time (Table 1).

Table 1
Histogram results from baseflow separation of Northwest Branch Gage near Colesville, Maryland.

Histogram	**0-0.14 m3/s**	**0.14-0.28 m3/s**	**0.28-0.43 m3/s**	**0.43-0.57 m3/s**	**0.57-0.71 m3/s**	**0.71 – 0.85 m3/s**	**0.85-1.00 m3/s**	**1.00-1.13 m3/s**	**1.1-1.3 m3/s**	**>1.3 m3/s**
1923 – 1932	175	196	168	112	34	15	10	10	6	2
1933 – 1942	52	269	219	118	54	18	7	5	0	0
1943 – 1952	0	157	309	145	72	34	7	8	1	1
1953 – 1962	113	273	181	112	33	15	1	1	0	3
1963 – 1972	151	263	140	88	55	25	5	5	0	1
1973 – 1982	148	238	143	119	54	21	3	3	1	1

Table 1 shows that the frequency of low baseflows dramatically increases as development increased. Low baseflow is only one mechanism impairing fish passage.

Depth of flow is another critical mechanism for fish passage designs and may also be impacted by urbanization. As previously discussed, urbanization tends to cause increases in storm flows that over widen and incise stream channels over time. Over widening will spread flow over a greater surface area, reducing flow depths and ultimately precluding fish passage. While some urban channels have the ability to restore themselves through the creation of a new low flow/aquatic habitat channel with characteristics similar to the predevelopment channel. This process, however, is more the exception than the rule and without assistance will provide little to no aquatic habitat value especially for fish populations.

Baseflow Estimation for Natural Fish Passage

The previous discussion establishes the need for designing natural fish passage structures using baseflows. This section will discuss some available methods for calculating baseflows in gaged and ungaged streams.

Baseflow Estimation in Gaged Streams

In gaged streams, deriving baseflows first requires hydrograph separation from a gage record. Any hydrograph analysis requires that the designer select the applicable portion of the gage record and the applicable timeframe generally corresponding to a migration season. Since baseflows in urban watersheds likely experienced a reduction over time, statistical analyses are required to identify the applicable length of record that is most representative of current conditions. This may be accomplished by a double mass curve analysis, regression analysis, or t-tests. Limiting the analysis to a particular migration season (i.e., March 1 through June 30 of each year) ensures that the final design flows will be artificially biased toward the hydrology that fish use for upstream migration.

After isolating the gage records of concern, hydrograph separation is performed. At least seven different methods are available, including the following:

McCuen 1998
Constant-Discharge Baseflow Separation
Constant-Slope Baseflow Separation
Concave Baseflow Separation
Master-Depletion-Curve Method

Sloto 1996
Fixed-Interval Method
Sliding-Interval Method
Local-Minimum Method

For the Woodrow Wilson Bridge Project, hydrograph separation was performed using the fixed-interval method for the last 30 years of data (only the period between February and May for each year of data used, since this represents the fish migration period). Although some fish can migrate upstream in June, flows are so low in the project streams that large-scale migration is highly unlikely.

After compiling the baseflow data, average baseflows were calculated for each month for each year and the entire data set was regrouped by month. A frequency analysis was performed for each month using the Log-Pearson III distribution for specific exceedance probabilities. However, resulting flows were reported as annual non-exceedance probabilities, which were the 9-, 50-, and 90-percentile flows. These probabilities were selected based on recommendations from fisheries experts. Designers can select any probability deemed applicable; however, the usual non-exceedance probabilities would be 0.10, 0.50, and 0.90. Gages included in this analysis and the resulting flows are included in Table 2.

Table 2
Gages and Associated Baseflow Data

Gage	Watershed Area (mi^2)	9-Percentile Flow (cfs)	50-Percentile Flow (cfs)	90-Percentile Flow (cfs)
Northwest Branch at Hyattsville, MD	49.3	28.08	40.85	63.70
Rock Creek at Sherrill Drive	62.4	30.50	55.25	95.00

For Rock Creek and Northwest Branch, the drainage area ratio method was used to calculate flows at the sites that are distant from the Sherrill Drive and Northwest Branch gages. The drainage area ration method adjusts flows calculated from a gage based on the watershed area for different locations along the gaged stream (Maidment). Tables 3 and 4 present the discharges for the Rock Creek and Northwest Branch sites, respectively.

Table 3
Design flows in Rock Creek.

Site	Watershed Area (mi^2)*	9-Percentile Flow (cfs)	50-Percentile Flow (cfs)	90-Percentile Flow (cfs)
RC-1	74.4	36.37	65.88	113.27
RC-2	73.9	36.12	65.43	112.51
RC-3	69.0	33.73	61.09	105.05
RC-4	65.8	32.16	58.26	100.18
RC-5	65.8	32.16	58.26	100.18
RC-6	64.0	31.28	56.67	94.44
RC-7 (gage site)	62.4	30.50	55.25	95.00
RC-8	62.3	30.50	55.16	94.84

*Watershed areas obtained from GISHydro 2000 (University of Maryland, 2000)

Table 4
Design Flows in Northwest Branch

Site	Watershed Area (mi^2)	9-Percentile Flow (cfs)	50-Percentile Flow (cfs)	90-Percentile Flow (cfs)
NW-1	48.8	27.80	40.44	63.05
NW-2	49.2	28.08	40.85	63.70
NW-3	49.2	28.08	40.85	63.70
NW-4	48.8	27.80	40.44	63.05
NW-5	48.8	27.80	40.44	63.05
NW-6	46.7	26.60	38.70	60.34
NW-7	46.7	26.60	38.70	60.34
NW-8	34.9	19.88	28.92	45.09

*Watershed areas obtained from GISHydro 2000 (University of Maryland, 2000)

Baseflow Estimation in Ungaged Streams

Estimating flows at Little Paint Branch, Indian Creek and Sligo Creek posed a different problem. Although these streams are tributaries of gaged streams, they are far removed from the gage sites; therefore, the Drainage Area Ratio Method was abandoned. Instead, single return-period regression equations were calculated for each return period (non-exceedance probability) of concern using watershed area as a predictor variable. Gages used in this analysis included Northeast Branch, Northwest Branch, Watts Branch, East Branch of Herbert Run, and White Marsh Run. These particular gages were selected due to: 1) proximity to watersheds of interest, 2) watersheds traverse the Fall Line (separates the Piedmont and Atlantic Coastal Plain Physiographic Provinces) and 3) gage records were sufficiently large to use in the analysis. Selection of gages, based on these criteria resulted in only five data points. Although such a small data set weakens our modeled relationships, adding gages in watersheds that occur completely within either the Piedmont or Atlantic Coastal Plain would add another variable and source of error, which is not desirable in this analysis.

During the analysis, the authors discovered that the data did not conform to logarithmic plot, which is typical of stream data. The likely reasons is that the data set was small and the magnitude of the flows represented a small segment of the spectrum of flows that a stream experiences. Therefore, straight-line polynomial regression equations were used to model flows. Watershed area was used as the predictor variable. Although KCI investigated the use of watershed area, percent impervious surface, and a combined term, neither percent impervious surface nor the combined term sufficiently impacted the coefficient of determination, or "goodness-of-fit" (r^2) to warrant its use.

Equations were calculated by a linear regression analysis of flows vs. watershed area, and statistical software was utilized to obtain the b_o and b_1 coefficients. Below are the resulting equations:

- Q9 = 2.61 + 0.42 X1
- Q50 = 2.42 + 0.74 X1
- Q90 = 1.98 + 1.26 X1, where: X1 = watershed area

Table 5 presents the resulting discharges for Sligo Creek, Little Paint Branch, and Indian Creek.

Table 5
Sligo Creek and Little Paint Branch Design Flows

Site	Watershed Area (mi^2)	9-Percentile Flow (cfs)	50-Percentile Flow (cfs)	90-Percentile Flow (cfs)
SC-1 through SC-4	11	7.23	10.56	15.84
LPB-1	9.6	6.64	7.10	14.08
IC-1	26.9	13.91	20.35	34.78

Flows for all sites along Sligo Creek are considered the same because the difference in watershed area between S-1 and S-4 is 0.1 mi^2. Flows for Indian Creek were calculated using both the rational method and the above regression equations because the watershed does not traverse the Fall Line nor is the site near a gage used in the analysis. Results of both methods were relatively identical; however, the flows using the regression equations were reported.

Final Design Criteria

Results from the above investigations are incorporated into the design criteria for natural fish passage structures, which include the following:

- Design Flows
- Maximum velocity at the design flows
- Minimum depth of flow – usually to 12 inches at the 50-percentile baseflow
- Slope of the structure
- Construction materials – based on shear stresses for flows at top of bank, 2-, 10- and 100-year return periods.
- EDF – less than 4 lbs/ft^2s (essential for FC/SP approach)

Conclusions

New federal regulations are focusing on fish passage as part of compensatory mitigation. Fish passage structures such as fish ladders are suitable for dams and potentially culverts in urban streams; however, urban watershed conditions tend to create significant maintenance problems. Urban fish passage designs, accomplished with natural structures such as RGCs and FC/SPs, are more self-sustaining in urban watersheds and can provide habitat enhancement that is not otherwise possible with fish ladders and other engineered structures. Prior to selecting a method, designers must review the characteristics of the target fish species and perform the necessary hydrologic calculations to obtain the design flows. It is incumbent upon the designer to study the watershed and model the flows to correspond to migration patterns and future watershed conditions. The authors believe that designing for baseflow in urban streams provides a conservative platform for a fish passage design. Using the complete gage record for an urban stream may overestimate the design flows, resulting in an effective fish passage structure.

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References

Center for Watershed Protection. 2000. Urban Stream Restoration Practices: An Initial Assessment, October 2000.

Chesapeake Bay Program. 2000. Chesapeake Bay Program Website, www.chesapeakebay.net.

ESA. 2000. Monitoring of Existing Fish Passage Structures, Environmental Systems Analysis, Inc., August 2000.

Hegberg, C.H., S. Jacobs, P.A. Schlindwein, & S.J. Cohen. 2001. "Fish Passage in Urban Streams Part 2: Natural Channel Design Methods," this proceedings.

Hogan, S.A., M.R. Peterson, T.W. Smith & P. Valentine. 2000. "Sacramento River Gradient Restoration Facility," ASCE 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management.

Katopodis, C. Introduction to Fishway Design, Freshwater Institute, Department of Fisheries and Oceans, Manitoba, Canada, 1992.

KCI. 1996. Conceptual Report, White Marsh Run (Main Stem) Stream Restoration, KCI Technologies, Inc., November 1996.

Maidment, D.R. 1993. Handbook of Hydrology, McGraw-Hill, Inc.

Maryland Department of Natural Resources, Verbal Communication During an Inspection of Riffle Grade Control Structures, White Marsh Main Stem, White Marsh, Maryland, March 2000.

Maryland Office of Planning. 1998. Maryland Property View - Montgomery County, Baltimore MD.

McCuen, R.H. 1998. Hydrologic Analysis and Design, Prentice Hall, Saddle River, N.J.

Newbury, R.W. & M.N. Gadoury. 1993. Stream Analysis and Fish Habitat Design, Newbury Hydraulics, Ltd., Gibsons, British Columbia.

Sloto, R. & A. Crouse. 1996. "M.Y., HYSEP: A Computer Program for Streamflow Hydrograph Separation & Analysis," US Geological Survey, Water Resources Investigations Report 96-4040.

SES.1999. Stormwater Management Plan Update, Baltimore/Washington International Airport, Straughan Environmental Services, Inc., May 1999.

Sovern, Douglas T. & Percy M. Washington, PhD, Effects of Urban Growth on Stream Habitats Proceedings, Effects of Watershed Development & Management of Aquatic Ecosystems, ASCE, 1997.

Valentine, P. & C. Rairden. 2000. Personal Correspondence, USACOE, Sacramento, CA.

Washington Department of Fish & Wildlife. 1999. Fish Passage Design at Road Culverts, A Design Manual for Fish Passage at Road Crossings, March 3, 1999.

NATURAL FISH PASSAGE STRUCTURES IN URBAN STREAMS (PART 2: HYDRAULIC DESIGN AND ANALYSIS)

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Abstract: This paper presents a standard list of procedures for designing natural fish passage structures in urban streams. Before any design can commence, designers need to thoroughly investigate the target fish species and the hydrology of the study reach. Designs of riffle grade controls (RGCs) and flow constrictor/step pools (FC/SPs) start with topographic surveys, geomorphic assessments, and tailwater measurements. Results of the geomorphic assessment will determine which structure should be constructed: RGCs for sand/gravel bedded streams and FC/SPs for cobble/boulder bedded streams. Each structure type has a unique hydraulic modeling approach; however, stone sizing and channel bank stabilization procedures are standard. Construction management is of great importance because installing these structures is not routine and it is incumbent on the designer to ensure that the contractor complies with the spirit and the intent of the design.

Introduction

This paper is the second of a two-part document that presents the methods for achieving fish passage in urban streams through the design and construction of natural fish passage structures specifically riffle grade controls (RGCs) and flow constrictor/step pools (FC/SPs). Methods presented herein are the second phase of design and should be undertaken only after gathering fisheries and hydrologic information discussed in the companion paper entitled, "Natural Fish Passage Structures in Urban Streams, Part 1: Hydrologic and Resource Issues," (Hegberg 2001). Although step-wise procedures are presented, readers are cautioned that a thorough understanding of the limitations of these, or any hydraulic modeling exercise, is essential for successful designs. Readers should also understand that these techniques are applicable for natural fish passage designs in rural streams and leaping fish even though the authors are presenting them in the context of urban stream fish passage.

Designing fish passage structures will always require a degree of customization since all sites exhibit unique characteristics that pose design challenges. However, standard activities are necessary for every design and are summarized in Figure 1. As previously stated, identifying target species, collecting fisheries data, and performing hydrologic studies are addressed in companion paper, Hegberg et al. 2001. This paper will continue with conducting an abbreviated geomorphic assessment, selecting an appropriate structure, and explaining the hydraulic modeling procedures.

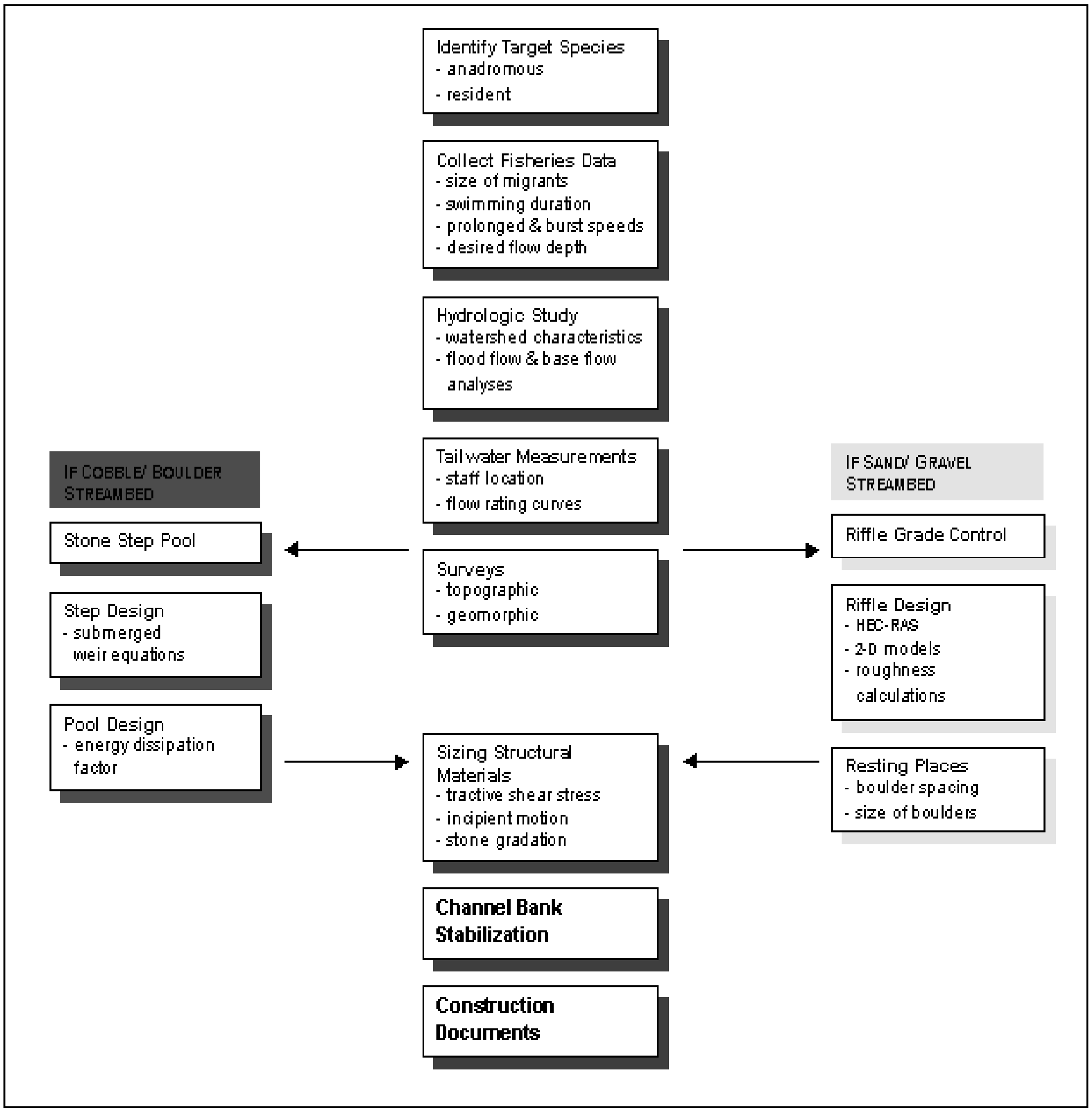


Fig. 1. Natural Fish Passage Design Flow Chart

Initial Design Activities

Topographic Surveys

Detailed topographic surveys involve locating and measuring elevations of floodplains, bank features and streambed features. Study boundaries commonly extend 1000 feet downstream and upstream of each blockage. From this surveying data, a digital terrain model (DTM) is created and can be blended with a DTM obtained locally from general aerial surveying. This combined DTM is used to create cross sections, stream profile and one-foot contour maps of existing conditions. Designers should avoid performing cross sections surveys instead of detailed topographic surveys because a significant amount of detail would be lost. Surveys are also used in floodplain modeling to assess the impacts of the proposed structures.

Geomorphic Surveys

Geomorphic surveys provide valuable information regarding dominant discharge, shear stresses, and the size of the sediment being transported and deposited in the study reach. Careful analysis of the sediment is important because the median particle size (D_{50}) will determine whether the RGC or the FC/SP will be used for fish passage. Geomorphic surveys would consist of pebble counts in the streambed and bar sampling of side, point, and mid-channel bars. Procedures for conducting these surveys may be found in Rosgen (1996). If the median particle size were sand or gravel, an RGC would likely be the structure of choice. FC/SPs would be the preferred structure if the median particle size were cobbles or boulders.

Tailwater Measurements

Tailwater measurements provide the basis for calculating the hydraulic drop, which governs the number of FC/SPs or the length of RGCs. These measurements replace hydraulic modeling for the baseflow condition, as traditional one-dimensional hydraulic models cannot be used to model baseflow. Baseflows are of shallow depths that are significantly effected by channel roughness; one dimensional models may not be sensitive enough to evaluate the required effects. Staff gages or automated transducers/data loggers should be installed downstream of the proposed structure and outside the influence of construction. Stream stages are read for flows ranging from baseflow to low storm flow. A minimum of three flow and stage measurements are required to produce a rating curve of stage versus discharge. If pressure transducers are used frequency analyses can be performed to estimate the dominant tailwater elevation.

Designing Natural Fish Passage Structures

Using the calculated design flows, the preliminary structure is designed using standard hydraulics equations. As part of this process, the following concerns must be thoroughly addressed (Acharya 2000):

- Cross section geometry
- Structures for resting places
- Size and shape of stone
- Profile slope
- Fishway hydraulics including flow division and resistance
- Structural stability

Later stages of design may involve the use of two-dimensional flow models such as FESWMS from the Federal Highway Administration and RMA/TABS from the U.S. Army Corps of Engineers -WES to evaluate key transition surfaces for stability and compliance with the design criteria.

Flow Constrictor/Step Pools

Hydraulic Design

FC/SPs are rock structures designed to concentrate flow to provide necessary water depth and velocity for traversing blockages (Figure 2). In their basic form, FC/SPs are linear structures with multiple rock weirs set at different elevations to provide fish passage for varying flows and stages. Multiple weir openings also provide redundancy to account for debris and the range of design flows. Multiple steps are installed in series with the gaps in these step horizontally offset to force lateral flow through the intermediate pools.

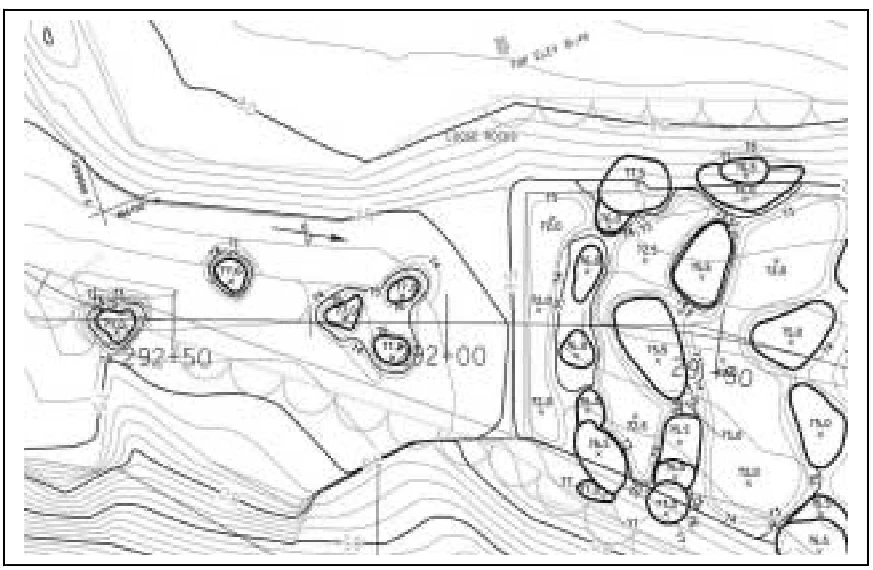


Fig. 2. Flow Constrictor/Step Pool Plan View

For FC/SP design, the hydraulic model for baseflow conditions must be based on rapidly varied flow equations. FC/SP design begins with determining the hydraulic drop between the headwater and tailwater elevations using the low end of the design flow range (i.e., 10-percentile non-exceedance) as the basis for the tailwater elevation. The hydraulic drop is then divided by 6 inches to obtain the number of steps for smooth transitions. A six-inch drop from step to step reduces the flow velocities and submerges the weirs, which provides streaming flow over these steps (Chow 1959). Smooth streaming flow step transitions are required for anadromous species since they are non-leaping, relatively weak swimmers.

This is illustrated in Figure 3. Figure 3 is a photograph of a known fish blockage in a tributary to the Susquehanna River with a hydraulic drop of 8 inches. During the migration season, American shad become trapped at this point and either turn back or die. For salmonids, this location would likely be traversable; however, the plunging flow prevents weaker alosids from moving up the tributary. This example illustrates the importance of understanding the capabilities of the target fish species and designing structures to strict criteria.

Fig. 3. Known Fish Blockage — Susquehanna River Tributary

Modeling FC/SPs is primarily a function of solving rapidly varied flow equations. A spreadsheet model of the entire structure is built to evaluate the widths of each weir opening and the height of each step. Figure 4 is an example of a spreadsheet solution to a single step in a FC/SP design that is based on Equations 1 and 2 (King 1976).

$$\frac{Q}{Q_1} = \left[1 - \left(\frac{H_2}{H_1}\right)^{1.5}\right]^{0.385}$$ Villemonte Submerged Weir (1)

$$Q_1 = CL_W H_1^{1.5}$$ Weir Equation (m^3/s) (2)

Frequency:	9%					
TARGET Q:	30.0	must match		input		
Tail Water elevation:	149	149	149	149	149	
STATION 410+11						
	A	B	C	D	E	54.0
Weir elevation	148.35	148.85	149.35	149.85	150.35	Length Total
Weir length	6.0	6.0	16.0	26.0	0.0	54.00
C coefficient	3.1	2.8	2.2	2.0	2.0	
Tail Water (H2)	0.65	0.15	-0.35	-0.85	-1.35	
Head Water (H1)	1.17	0.67	0.17	-0.33	-0.83	guess
H2 / H1	0.556	0.224	-2.059	2.576	1.627	
Q / Q1	0.814	0.958	1.000	1.000	1.000	
Q1	23.54	9.21	2.47	0.00	0.00	Q Total
Q	19.16	8.82	2.47	0.00	0.00	30.45

Fig. 4. Example Weir Equation Spreadsheet

In the above equations, L_w is the effective length of the weir crest (width of the weir flow opening); H_1 is the upstream head on the weir (measured above the crest elevation); H_2 is the downstream tailwater head (measured above the crest elevation); Q_1 is the unrestricted flow over the weir (with no tailwater); and Q is the adjusted flow over the weir due to tailwater conditions. The value of C should be calibrated based on field measurements of similar structures.

Spreadsheet calculations presented in Figure 4 represent an iterative process for only one design flow. Weir openings are optimized to provide the design fish passage velocity through at least one opening for all of the design flows. In this case, the FC/SP spreadsheet contains five weirs, the two highest weirs representing cumulative crest lengths. The three lowest weir openings are positioned along this crest to provide fish passage at different flow stages. Weir A would operate at the lowest stages. As flow and stage increase, fish would begin to pass through weirs B and C. Weirs D and E are step crest elevations that represent a flow separation at the highest baseflow stages or low storm flows. This flow separation in a national park setting is necessary for the aesthetics of a natural looking fishway. High storm flows would pass over the FC/SP structure and into the floodplain.

Pool design is based on the Energy Dissipation Factor (EDF) (Equation 3) (Washington Department of Fish & Wildlife 1999) and is generally limited by the 90-percentile flow.

$$EDF = \gamma \frac{QD_S}{V_P}$$ Energy Dissipation Factor (Pa/s) (3)

The EDF is a measure of turbulence and the resulting bubble formation. EDF values greater than 4 lb/ft^2s indicate that flow in a pool is turbulent enough to disorient and fatigue individual fish. In the above equation, Q is the flow through individual openings; D_s is the hydraulic drop of the step (H_2-H_1); V_p is the volume of the pool; and γ is the unit weight of water.

Pool volume greatly impacts EDF; however there are limitations on sizing pools. Pool length (for the calculation only) is limited to less than 10 ft; the average width of the pool (for the calculation only) is limited by a 4:1 side expansion from the weir opening; and the depth should be at least 3 D_s and sufficiently deep to submerge any hydraulic jump (Chow 1959).

Measuring Existing Boulder Clusters

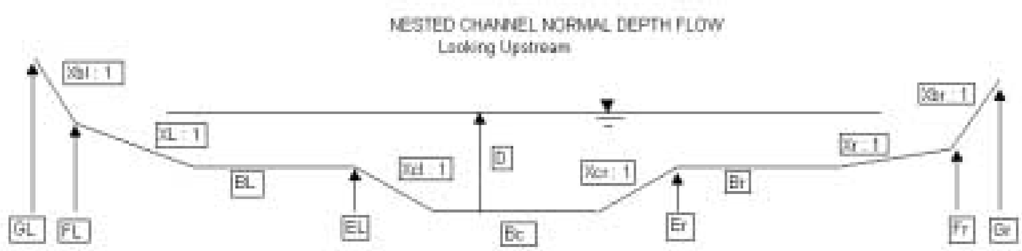
FC/SPs mimic boulder clusters in streams because the type of flow through both structures is similar. Therefore, designers would find it useful to examine boulder clusters in the subject stream or similar streams to attain a deeper understanding of the flow regimes the constructed structures are to mimic. Designers should measure the lengths and flow depths in natural weirs, velocities through the weirs, the lengths and depths of natural pools, and locations of rocks to develop a "map" of the boulder cluster. Information obtained from such a survey can be used to calibrate the designed FC/SPs. Calibration is not intended to strictly measure the adequacy of the design, but is to give the designer qualitative indication of whether the structure will pass fish.

The authors have performed such boulder cluster investigations for the Woodrow Wilson Bridge Project, the results of which are discussed below. Relevant physical data was gathered at reference reaches along Rock Creek known as the 'Boulder Field' to understand naturally occurring velocities, discharges, and EDFs were evaluated. This evaluation process consisted of recording velocity profiles at naturally occurring step pools, a bathymetric survey of pools, identification of channel and bar configurations for high flows events, documenting cross section and longitudinal profiles and photographic documentation. Discharge during field visits ranged from 19 to 25cfs. From this field data energy dissipation factors were calculated for each step pool feature. Velocities in natural weir pools on Rock Creek ranged from 0.05 to 4.7fps, and Energy Dissipation Factors ranged from 1.3 to 11.5lb/ft^2 s.

Riffle Grade Controls

Hydraulic Design

Riffle Grade Controls (RGCs) are rock structures that mimic riffle sections of streams and are designed to stabilize streambeds (Figure 5). RGCs are constructed in four sections: an upstream glide section, a crest transition, a long riffle section, and a downstream run section. Glide sections transition flow from an upstream pool to the crest. The crest is provided to reduce stresses on the upstream end of the riffle. Riffle sections are designed to pass sediment and fish while providing channel stability. Runs are transitions into a downstream pool or an existing run and are designed to prevent scour hole formation.



BL	0
EL	1
FL	2
GL	3
nL	0.06
XL	20
Xbl	2

Bc	6
Dstart	0.5
Xcl	2
Xcr	2
Rock (ft)	1
n	0.06
So	0.016

Br	0
Er	1
Fr	2
Gr	4
nr	0.06
Xr	20
Xbr	2

DESIGN FLOWS

		Left Side		Pilot Channel		Right Side	
Occurance	Q(cfs)	d(ft)	V (fps)	d(ft)	V (fps)	d(ft)	V (fps)
9%	20			1.00	2.62		
50%	40	0.35	0.98	1.35	3.33	0.35	0.98
90%	150	1.15	2.33	2.15	4.74	1.15	2.33

Fig. 5. Example Manning's Equation Spreadsheet

Where baseflows are low, RGCs should be constructed with an armored nested channel to concentrate baseflows for improved depth. This nested channel would pass some light storm flows, while larger storm flows would spread onto a stone or vegetated bench area. Dividing flow in this manner allows coarser sediments to pass down the nested channel, while some fines are deposited on the adjacent bench.

Initial hydraulic baseflow design consists of spreadsheet solutions to Manning's equation for flow (Equation 4) (King 1986). Figure 6 presents an example of a spreadsheet used for the initial design.

$$Q = \frac{R^{2/3} S^{1/2} A}{n} \qquad \text{Manning's Equation (m}^3\text{/s)} \qquad (4)$$

Where R is the hydraulic radius; S is the bed slope (uniform flow assumed); A is the cross section area; and n is assumed from an estimate of bed stone sizes.

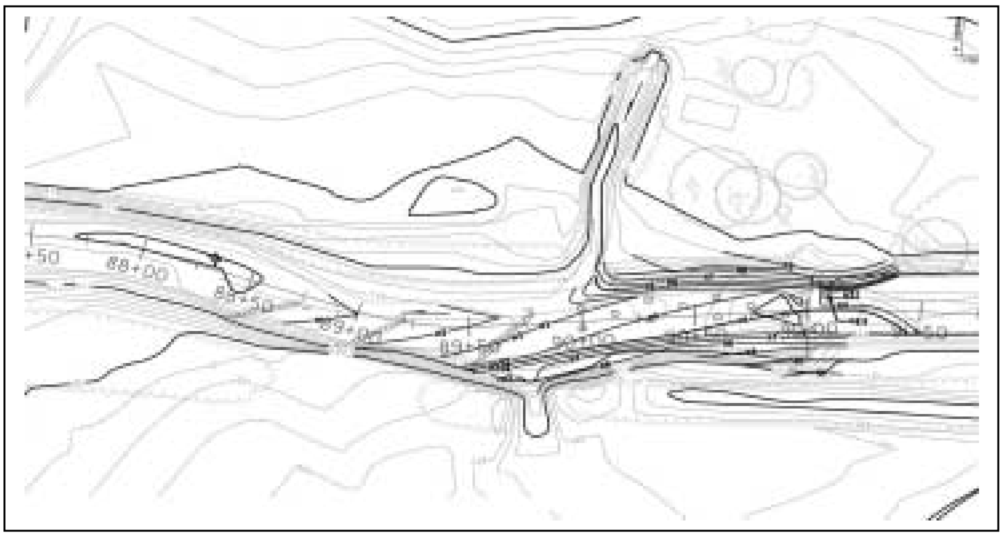


Fig. 6. Preliminary RGC Plan View and Cross Section

This spreadsheet operates by entering the dimensions of the RGC cross section into the spreadsheet. The user must also enter estimates of slope and Manning's n values for the nested channel and the overbank areas. Manning's equation is solved on a back end spreadsheet (not shown) for various flow depths for the nested channel and the overbank areas separately. RGC slope, cross section, and Manning's n values are adjusted until the desired depth and velocity are found.

Gradually Varied Flow Modeling

As the modeling process continues, more detailed hydraulic modeling for baseflow, top of bank and flood conditions should be performed using gradually varied flow equations. One-dimensional (1-D) models, such as HEC-RAS can be used. In general, a HEC-RAS model is created for a long reach to identify flood stages and the water surface for dominant discharge or top-of-bank events. HEC-RAS is limited because these models are based on average cross section conditions, rendering it susceptible to missing local flow variations that may occur at certain locations along the RGC especially at transition points.

To address limitations in 1-D modeling, two-dimensional (2-D) modeling should be performed. These models are useful for identifying areas of excessive shear stress and areas that may not meet the hydraulic design criteria. Finite Element Surface Water Modeling System (FESWMS) is a common 2-D model that is available from the Federal Highway Administration or is a module in commercial surface water modeling programs. This software is useful because the models can be tailored to the site-specific conditions by manipulating elements within computer representations of the proposed structures. Calibration of the model may be desirable and requires modification of the input parameters to a numerical model until the output from the model matches known observed data. Unlike conventional 1-D flow analysis, outputs include flow velocities, flow depths and shear stress on a 2-D plane parallel to the water surface (Figure 7). This type of information allows confident designs ensuring that fish passage requirements are met.

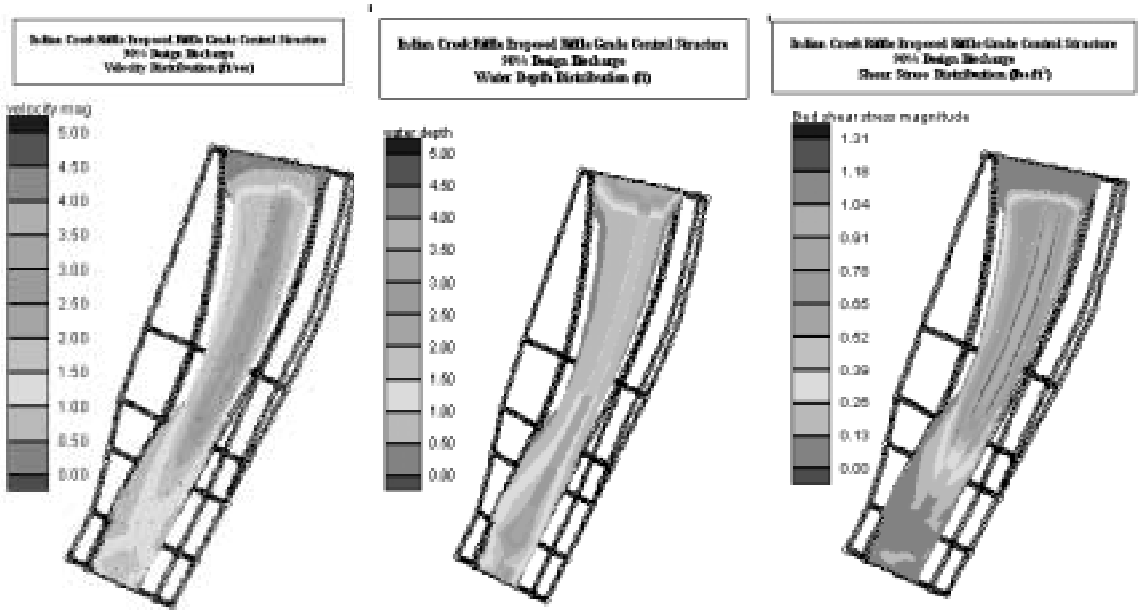


Fig. 7. 2-D Model Output for RGC—Depth Valocity and Shear Stress

A major concern in hydraulic modeling is defining roughness in RGC designs. For top of bank and flood flow conditions, standard methods of determining Manning's n can be used. At these deeper flow depths, roughness is primarily based on the channel geometry and general surface materials. However at baseflow levels, the flow is so shallow that the roughness can be based on flow around and over individual rock. This relative roughness condition requires different methods of predicting and using Manning's n.

As a final step in boulder selection, the initial assumptions concerning roughness are verified. The Manning's n value used in the hydraulic models is estimated using equations developed from relative roughness and natural stream studies. Relative roughness is classified into small-scale, intermediate-scale, and large-scale roughness based on relative submergence as follows: (Bathurst 1978, Shea 2000).

Small-Scale Roughness	Intermediate-Scale Roughness	Large-Scale Roughness
$\frac{d}{D_{50}} > 7.5$	$7.5 > \frac{d}{D_{50}} > 2$	$2 > \frac{d}{D_{50}}$
$\frac{d}{D_{84}} > 4$	$4 > \frac{d}{D_{84}} > 1.2$	$1.2 > \frac{d}{D_{84}}$

Where d is the flow depth; D_{50} is the median particle size; and D_{84} is the 84-percent size of the median axis length.

Since the design flow depths are shallow during migration periods, the large-scale roughness criteria generally applies. A regression-fitted relationship was developed based on measurements of flow in mountain streams composed of boulders and cobbles where the relative submergence in the data ranged between 0.2 and 4 (Mussetter 1989). This relationship is:

$$\sqrt{\frac{8}{f}} = 1.11\left(\frac{d}{D_{84}}\right)^{0.46}\left(\frac{D_{84}}{D_{50}}\right)^{-0.85} S^{-0.39} \quad (5)$$

Where S is the friction slope; and *f* is the Darcy-Weisbach friction factor. The Darcy-Weisbach friction factor can be related to Manning's n by:

$$n = \frac{R^{1/6}}{\sqrt{g}\sqrt{\frac{8}{f}}} \quad (6)$$

Where R is the hydraulic radius and g is the gravitational acceleration.

For small-scale roughness, the Manning's n is estimated using traditional methods. In the hydraulic models, Manning's n can vary with depth. The roughness values for corresponding depths are compared to the original roughness assumptions. If significant differences are found, the hydraulic models are adjusted, rerun, and the shear stresses are reevaluated. Because of site-specific hydraulic issues due to bridges, levees or channel types, each riffle grade control has the potential for needing a unique design. However after evaluating the extremes in site geometry and flow conditions, generalizations and interpolations in between these extremes can be made based on the results of a HEC-RAS model.

Results of 2-D modeling may show that several areas of higher shear stresses localized on the initially proposed channel geometry. For example, a high flow stress zone may be identified at the crest of the RGCs, which has been identified by others (Ayers 1998, Thorncraft 1996, Wildman 2001). To solve this particular problem, a class of stone could be used to compensate for these higher flow stresses. The 2-D model may also indicate that the edges of any nested channel feature will receive high flow stresses. Larger stone and robust vegetative cover could be used to stabilize these areas.

Resting Places

As previously stated, fish exhibit varying degrees of swimming abilities and those of the weakest fish must be accounted for in natural fish passage designs. This is especially true for RGCs since these structures tend to be relatively long, posing potential endurance barrier problems. Therefore, fisheries documents from research (Katopodis 1994) and agencies such as the U.S. Fish and Wildlife Service and state natural resource agencies should be consulted to determine the need for and the appropriate distance between resting places. The spacing of the boulders within a particular boulder garden is based on recent flume studies (Acharya 2000). From their recommendations, spacing of boulders within a garden or cluster is 4D cross channel and 6D longitudinally is chosen, where D is the size of the exposed boulder.

Sizing Structural Materials

The selection of the stone for use in constructing natural fish passage structures is based on a standard channel design method. Stone for RGCs should be well graded to provide for better compaction and a degree of impermeability that will prevent low flows from flowing through the structure instead of over it. Boulders for FC/SPs should be large enough to remain stationary during flood flows and should be well sorted.

The tractive force, or tractive shear stress, method is utilized to determine from calculations or graphs this size particle that corresponds to a particular shear stress that represents the flood stage of highest impact on the structure. Care should be taken when selecting the material sizes because these structures cannot be allowed to mobilize during flood (Johnson 1999). The selection process is iterative and based on assumptions of stone size and roughness, which must be verified and refined with hydraulic modeling.

Proposed RGCs were modeled using HEC-RAS and the 2-D hydraulic software to determine the tractive shear stresses on the fishway. The 2-D model considered 9-, 50- & 90-percent of base flow and the top of bank flow conditions. The actual shear stress values were compared to the upper limit of incipient motion from field and laboratory studies (Leopold 1964). For comparison, a computation of stone size was performed from critical shear stress methods. Conservative values were chosen for a computation of dimensionless critical shear stress from cobble - gravel river studies (Equation 7) (Andrews 1983). Then the incipient stone size was computed from equation 8 (Shields 1936). Additionally, the coefficient of curvature ($C_z = D_{30}^2/(D_{60} * D_{10})$) should range between 1 and 3, suggesting a well-graded material (Craig 1993). Based on this criterion, the stone for the riffle grade control structures were sized.

$$\tau_{ci}^* = 0.0834\left(\frac{d_i}{d_{50}}\right)^{-0.872}$$ Dimensionless Critical Shear Stress (7)

$$\tau_{ci} = \tau_{ci}^*(\rho_s - \rho)gd_i$$ Critical Shear Stress (8)

Where ρ is the density of water; ρ_s is the density of the rock; g is gravity; d_{50} is the median rock size; d_i is the size of the stone for incipient motion.

The sizes of stone used for boulder clusters, boulder gardens, and steps are based on field studies of existing, exposed grade control structures, and include foundation boulders (Rosgen 2001). The advantage of using field studies for boulder sizing is that these studies inherently include the effects of such hazards as debris and ice impact.

Channel Bank Stabilization

Construction of a FC/SP or RGC will likely alter shear stresses on the banks in the vicinity of the structures. In the course of designing these structures, attention should be paid to the changing forces affecting bank stability, and stabilization should be conceived as part of the construction process. Sizing of the stone for bank stabilization can be made using typical bank stability guidelines. If an RGC has a bench, like the natural channel, this bench should be planted using a robust method like brush layering.

Construction Issues

Natural fish passage designs must be followed up with careful construction. Stream flow is very sensitive to changes in slope and cross section; therefore, tight tolerances should be incorporated into every construction contract. The authors have witnessed RGC construction projects where the slope, cross section, and material sizes were incorrectly installed resulting in severe structure scour.

Examples of tolerances are as follows: for RGCs 1) Slope: ± 0.1 percent, 2) Cross Section: ± 2 feet, 3) Elevation: ± 0.2 feet. For FC/SPs, example tolerances are as follows: 1) Elevation: ± 0.2 feet and 2) Weir Width: ± 1 foot.

It is always recommended, as part of the design, that models of proposed structures be manipulated to study the sensitivities of the designs. Since the authors are working with relatively weak fish, slight changes to structure design could have a significant impact. Structures designed to pass salmonids, for example, may be less sensitive to such changes. Tolerances are an extremely important part of these designs and should be thoroughly understood. In addition, field studies of the flow characteristics should be conducted during and after construction of these fishways. The hydraulics of these structures should be verified and computer models calibrated to field conditions during the monitoring phase.

It is also recommended that designers manage the construction of the design to ensure that contractors install them correctly. For example, designers can collect field measurements during construction of FC/SPs to ensure that the flow conditions of the installed structure meet the design criteria. Additionally, elevation data can be collected during the installation of RGCs to ensure the structures are constructed with the proper slopes. Installing these structures is not routine, and a lack of conscientious monitoring could cause problems later.

Conclusion

Design procedures expressed in this paper are based on the present knowledge base. However, procedures will evolve as more of these structures are installed. The authors will be collecting data on RGCs and FC/SPs being installed in the Washington, D.C. metropolitan area in the summer of 2002, all of which were designed for point-blockage fish passage and not total stream restoration.

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References

Acharya, M., J.A. Kells, & C. Katopodis. 2000. “Some Hydraulic Design Aspects of Nature-like Fishways,” Proceedings of the Joint Conference on Water Resources Engineering and Water Resources Planning & Management, ASCE, Reston, VA.

Andrews, E.D. 1983. “Entrainment of Gravel from Natural Sorted Riverbed Material,” Geologic Society of America Bulletin 94, p. 1225-1231.

Ayres Associates. 1998. Two-dimensional Modeling of a Natural Riffle and Gradient Restoration Facility, Riverbed Gradient Restoration Structure Glenn-Colusa Irrigation District (GCID) Intake, prepared for the Army Corps of Engineers, Sacramento District, Contract No. DACW05-90-C-0168.

Bathurst, J.C. 1978. “Flow-resistance of Large-Scale Roughness,” Journal of the Hydraulics Division, ASCE, Vol. 114, No HY12, p. 1587-1603.

Center for Watershed Protection. 2000. *Urban Stream Restoration Practices: An Initial Assessment*, October 2000.

Chesapeake Bay Program. 2000. Chesapeake Bay Program Website, www.chesapeakebay.net.

Chow, V.T. 1959. *Open Channel Hydraulics*, McGraw-Hill, NY, NY.

Craig, R.F. 1993. *Soil Mechanics*, Chapman & Hall, London.

ESA. 2000. *Monitoring of Existing Fish Passage Structures*, Environmental Systems Analysis, Inc., August 2000.

Hegberg, C.H., S. Jacobs, P.A. Schlindwein, & S.J. Cohen. 2001. “Fish Passage in Urban Streams Part 1: Hydrologic and Resource Issues,” this proceeding.

Hogan, S.A., M.R. Peterson, T.W. Smith & P. Valentine. 2000. “Sacramento River Gradient Restoration Facility,” ASCE 2000 Joint Conference on Water Resources Engineering and Water Resources Planning and Management.

Johnson, P. A. 1999. “Comparison of Traditional Engineering Approaches to Natural Channel Design,” Proceedings North Carolina Stream Restoration and Protection Conference, NC State University, Asheville, NC, p. 45-47.

Katopodis, C., *Introduction to Fishway Design*, Freshwater Institute, Department of Fisheries and Oceans, Manitoba, Canada, 1992.

Katopodis, C. 1994. “Analysis of Ichthyomechanical Data for Fish Passage or Exclusion System Design,” Proceedings of an International Fish Physiology Symposium, Vancouver, Canada, Fisheries Society and Fish Physiology Association, p. 318-323.

KCI. 1996. *Conceptual Report*, *White Marsh Run (Main Stem) Stream Restoration*, KCI Technologies, Inc., November 1996.

King, H.C. & E.F. Brater, 1976, *Handbook of Hydraulics*, McGraw-Hill, NY, NY.

Leopold, L.B., M.G. Wolman & J.P. Miller, 1964. *Fluvial Processes in Geomorphology*, Freeman, San Francisco, CA.

Maidment, D.R., 1993. *Handbook of Hydrology*, McGraw-Hill, Inc.

Maryland Department of Natural Resources, Verbal Communication During an Inspection of Riffle Grade Control Structures, White Marsh Main Stem, White Marsh, Maryland, March 2000.

Maryland Office of Planning, 1998. *Maryland Property View - Montgomery County*, Baltimore MD.

McCuen, R.H. 1998. *Hydrologic Analysis and Design*, Prentice Hall, Saddle River, N.J.

Mussetter, R.A.. 1989. *Dynamics of Mountain Streams,* Ph.D. Dissertation, Dept. of Civil Engineering, Colorado State University, Ft. Collins, CO.

Newbury, R.W. & M.N. Gadoury. 1993. *Stream Analysis and Fish Habitat Design*, Newbury Hydraulics, Ltd., Gibsons, British Columbia.

Rosgen, D. 1996. *Applied River Morphology*, Wildland Hydrology, Pagosa Springs, CO.

Rosgen, D. 2001. River Restoration & Natural Channel Design class handouts – excerpts from a draft paper, Wildland Hydrology, Pagosa Springs, CO.

SES. 1999. *Stormwater Management Plan Update*, Baltimore/Washington International Airport, Straughan Environmental Services, Inc., May 1999.

Shea, C. 2000. Project Correspondence, Parsons Brinkerhoff, Baltimore, MD.

Shields, A. 1936. “Application of Similarity Principles and Turbulence Research to Bedload Movement”.

Sloto, R. & A. Crouse. 1996. “M.Y., HYSEP: A Computer Program for Streamflow Hydrograph Separation & Analysis,” US Geological Survey, Water Resources Investigations Report 96-4040.

Translated by W.P. Ott & J.C. Uchelen, California Institute of Technology, Pasadena, CA, Report 167.

Thorncraft, G.A., & J. Harris. 1996. *Assessment of Rock Ramp Fishways*, NWS Fisheries Research Institute and the Cooperative Research Center for Freshwater Ecology.

Valentine, P. & C. Rairden. 2000. Personal Correspondence, USACOE, Sacramento, CA.

Washington Department of Fish and Wildlife. 1999. *Fish Passage Design at Road Culverts, A Design Manual for Fish Passage at Road Crossings*, March 3, 1999.

RECONDITIONING AND STABILIZATION OF UNPAVED ROADS FOR REDUCING ROAD MAINTENANCE AND IMPACTS ON FISHERIES HABITAT

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Abstract: Forest Managers are facing a series of problems that are making it difficult to effectively manage the vast national system of over 644,000km (400,000 miles) of forest roads and protect the environment. Current national funding levels are inadequate to maintain these roads to environmental and safety standards. With years of low maintenance budgets, many of these roads are worn out and not maintainable. Current methods of reconditioning and stabilizing worn-out native and aggregate surface roads have had limited success and can be quite costly. Pit development for aggregate surfacing can also be an expensive and lengthy process. In addition, there may be environmental impacts associated with pit development. Road maintenance is necessary to prevent damage to the road, to maintain safety, and to preclude adverse impacts to resources resulting from lack of road maintenance. When maintenance is not performed, roads can be major sources of sediment deposited into streams. This is especially critical when roads are adjacent to streams with sensitive species and any sediment deposited into the streams could have adverse effects. However, road maintenance activities can also result in direct sediment delivery to streams. Ground disturbance from road blading constitutes the greatest risk to adjacent streams from increased sediment production. Oftentimes, road managers are left with the options of either not maintaining the road at all or with a very short window of operation that may not allow for the best level of maintenance on the road. Obviously, there is a need to develop a tough, stable, long-lasting, maintainable road surface that will weather well, require less maintenance (particularly blading), and cost substantially less than importing or replacing crushed aggregate surfacing. In 1990, the Northern Region of the U.S. Department of Agriculture Forest Service began utilizing and evaluating a machine called the Mobile In Place Processor to recondition native surfaced roads. In 1998, the Forest Service began adding binders to the in place processing to stabilize both aggregate and native surfaced roads. Preliminary studies indicate that roads treated in this manner require less maintenance. The running surface does not washboard, ravel or generate dust, and surface erosion is significantly reduced which equates to less sediment in adjacent drainages. The end product is a much more serviceable road with little to no impact on watersheds and fisheries habitat.

Background

Road System

Nationally, the USDA Forest Service has jurisdiction on over 644,000km (400,000 miles) of roads. The Northern Region of the Forest Service, which includes Montana, portions of North and South Dakota, and Northern Idaho, contains over 88,100km (54,700 miles) of forest roads. Of these roads, approximately 82 percent are native-surfaced, 16 percent are aggregate-surfaced, and only 2 percent are paved.

In general, roads can affect fish habitat and water quality in three different ways. Roads that run parallel to stream channels can reduce shade and increase water temperatures. Secondly, roads create an impermeable surface, which changes an infiltration-dominant surface to a runoff-dominant surface. This leads towards alterations in runoff and affect peak flows. This increased flow can also trigger in-stream channel erosion resulting in degraded fish habitat. The third mechanism is through erosion and sedimentation. As road surfaces are runoff dominant, they allow for transport of sediment from road surfaces, cut-slopes, and ditches to be transported to nearby streams.

Lack of Funding

Proper road maintenance and implementation of best management practices (BMPs) can minimize the amount of sediment being delivered to streams. Often budget shortfalls prohibit any road maintenance or only allow partial maintenance to occur. Many road surfaces are only graded when they should be watered, graded and shaped, and then rolled to re-compact the surface.

Historically, maintenance budgets have been low for many years. Current national funding levels are inadequate to maintain the roads to environmental and safety standards. National annual road maintenance needs have been estimated at $568 million per year, of which $197 million represents an immediate and serious threat to the environment, safety, and Forest Service mission. The 1999 annual maintenance funding was $99 million. That funding is only 20% of the funding necessary to maintain the roads to standards. The backlog of maintenance and capital improvement needs is $8.4 billion and growing.

The Forest Service has spent the last three years trying to determine what the deferred maintenance needs are on a national level and are continuing to update and refine the existing data. Based on the information that is currently in the Forest Service databases from the deferred maintenance surveys, the Northern Region has a $200 million annual maintenance need ($4,000/mile) to maintain these roads to standards identified in the road management objectives. In addition, deferred maintenance surveys identified a backlog need of over $429 million to bring these roads to their identified standard. Capital Improvement needs are estimated at over $228 million. These estimates only partially address the need for all of the roads in the Region. The complete need for roads has yet to be determined.

Un-maintainable Roads

With years of historically low maintenance budgets, many of these native and aggregate surfaced roads are worn-out and not maintainable in their current condition. The existing roadbeds are extremely rough and composed of cobbles, ledge rock, and boulders, with little or no fines. Roads in this condition can be major sources of sediment deposit, in the form of runoff, to nearby streams (See Figure 1).

Fig 1. Typical example of a worn-out, unmaintainable road.

Traditionally, native surfaced roads of this type were maintained by methods which did not always result in a satisfactory end product (either ripping, grading and grid rolling). Surfacing these roads with aggregate surfacing provides a good end product, but is usually cost prohibitive, especially considering the number of road miles on the system.

Resurfacing requires hauling material either from existing pits or developing new pits. Development of new material sources requires the proper permits, royalty fees, environmental assessments or impact statements and can become quite expensive and involve possible delays. In addition, pit sites can have substantial impacts on the environment.

Road Maintenance Activities

Road maintenance activities can also result in direct sediment delivery to streams. Ground disturbance from road blading, particularly where the road is immediately adjacent to streams, constitutes the greatest risk from increased sediment production. Other activities such as culvert and ditch maintenance may also increase sediment delivery to streams. Road maintenance activities may also result in reduction or removal of streamside vegetation through brushing activities, possibly resulting in temperature increases. The risk of temperature increases is highest in very small streams. Brushing may also reduce stabilizing vegetation on cut and fill slopes.

The potential adverse effects of road maintenance must be considered in the context of performing maintenance versus possible consequences of not maintaining roads. Road maintenance is necessary to prevent damage to the road, to maintain safety by reducing dust, washboards and raveling, and to preclude adverse impacts to resources resulting from lack of road maintenance. Proper and timely road maintenance is proven to minimize sediment delivery to streams from open roads. Lack of road maintenance could result in more serious impacts to streams, ranging from washouts to increased risk of vehicle accidents resulting in potential toxic fuels introduced into the stream. Lack of maintenance can result in severe rutting and gullying during wet periods, and consequently, contributes large amounts of sediment into the watershed (see Figure 2).

Fig. 2. Road damage resulting from lack of maintenance.

Obviously maintenance is needed. There is a great need to make unmaintainable, sediment-producing roads into maintainable roads with a tough, stable, long-lasting surface that requires less maintenance (particularly blading), weathers well, and significantly reduces sediment production both from lack of maintenance and from maintenance activities, and costs substantially less than traditional methods of resurfacing.

Mobile In Place Processing
In 1990, the Northern Region began experimenting with an alternate method of reconditioning worn-out, native surfaced roads. The Mobile In Place Processor was first used to recondition 37km (23 miles) of road on the Lolo National Forest. Since then, over 300 kilometers (200 miles) of worn-out native-surfaced roads have been reconditioned in Montana, Idaho, Wyoming and Alaska. The Canadian government and several state and local U.S. governments have also expressed an interest in the machine and the process.

In 1998, the Forest Service expanded the process of road reconditioning by adding binders in order to lengthen the life of the road and reduce required maintenance. The first project used calcium chloride flake to stabilize the top 2.5 inches of an aggregate surfaced road. In year 2000, a native surfaced road was stabilized with the use of calcium chloride flake. Several other projects have since been completed.

Preliminary studies indicate that roads treated in this manner require less maintenance. The running surface does not washboard, rut, pothole, ravel or generate dust, and surface erosion is significantly reduced which results in less sediment into adjacent drainages. The end product is a much more serviceable road with little-to-no impact on watersheds and fisheries habitat.

Initial tests show that using the Mobile In Place Processor and adding a binder such as calcium chloride can be a useful tool to mitigate sediment delivery from road surfaces. Traditional applications of binders sprayed on the road surface form a thin layer of stabilized soil which acts like a crust and quickly breaks down under traffic. However, calcium chloride combined with reprocessing and compaction of the road surface bind a deep layer of the road surface material together, which prevents the finer material from eroding from the road surface. This not only minimizes sedimentation to adjacent streams, but also creates a stable surface that is more durable and does not break down or lose it integrity as fast. Roads treated in this manner require less maintenance including less grading. The end product is a native or aggregate surface road with little to no impact on watersheds and fisheries habitat.

The Northern Region of the Forest Service is continuing to utilize this process to produce a maintainable road, as the process has become a viable, cost effective tool for road maintenance.

Equipment and Operation
The process of recycling and stabilizing existing road surfaces revolves around use of the Mobile In Place Processor, which is usually followed by a motor grader of 135 horsepower or greater, Elliot Grid Roller, traditional vibratory roller, calibrated spreader, and water truck.

The Mobile In Place Processor
The original model for the Mobile In Place Processor was a rock crusher developed by Crude Tool Works of Kenai, Alaska. The 1991 purchase price was $196,500. This machine was designed to break up permafrost and had not been utilized as a road maintenance device.

Triple Tree Inc., of Missoula, Montana, purchased the rock crusher and made over $45,000 in modifications to the machine (patent pending) in order to process road surfaces more effectively.

The machine resembles a giant roto-tiller and consists of a two-component kit: a front rotary drum attachment and a rear power pack. This kit mounts on any suitable carrier such as loaders, graders, or scrapers (see Figure 3). The machine is essentially balanced as the drum and the power pack each weigh approximately 5,450kg (12,000 lbs). The kit components can be mounted or removed from a loader in approximately 12 person-hours.

Fig. 3. Mobile In Place Processor mounted on a "Cat" loader - rotary drum on front lift arms and power pack at rear.

Rotary Drum Attachment

The rotary drum attachment consists of the drum and a 76mm (3in.), removable solid steel rear impact plate. The rotary drum is 0.9m (3ft.) in diameter by 3m (9.5ft.) wide and can turn in forward and reverse motion at 84rpm. It can also be raised for slope work. Three types of drum shave have been constructed: those that produce a level surface, windrow to middle, and windrow to sides.

The drum has 272 carbide tipped teeth in knuckle holders mounted in a spiraled inward pattern. The teeth rotate after every strike to produce even wear. Teeth have an average life of 8 hours and are the only routine replacement item. Teeth are quickly removed with either a forked tool and hammer or an air drill and are easily installed with a tap of the hammer. Teeth cost approximately $3.20 each in 1993. A tooth hits every 3.175mm (0.125in.) of soil. The teeth crush the rock and rip the material as the drum rotates. The loose rock revolves counterclockwise to the impact plate where it is further fractured, crushed and blended (see Figure 4).

Fig. 4. Rotary drum processing a road surface.

Power Pack Attachment

The power pack attachment includes a Caterpillar Model 3406 (D-9) diesel engine, rated at 400hp, a hydraulic pump with reservoir and related hardware, and work lights and taillights. The power pack allows the machine to operate in temperatures ranging from -45 to 26 degrees C (-50 to 80 degrees F).

Machine Modifications

The Mobile In Place Processor has been modified and updated by the road contractor, Triple Tree Inc., in order to increase its efficiency and to produce a better end product that met gradation specifications (Hegman and Kreyns 1991). These modifications resulted in better rock fragmentation and decreased the outcast of larger rocks. They also added additional protection and stability, simplified the machine operation and increased maneuverability.

Machine Capabilities

The machine processes most existing road surface materials to a specified depth of 0 to 150mm (0 to 6in.) and a gradation of minus 100mm (4in.). It cuts a path 3m (10ft.) wide and leaves the road material in a well-mixed state. The materials show a general reduction to approximately the 100mm (4-inch) class with approximately 95% of the material passing through the 50mm (2-inch) size. The underlying fine materials are brought to the surface to bond the newly broken aggregates together. The content of road fines or dirt are not increased significantly, so future erosion potential is low.

Technical Specifications

A Special Project Specification for mobile rock processing was developed for use in the Northern Region and generally controls the work. This specification does not specify the type of equipment to be used, but describes the desired end product. It is modified as needed to meet site-specific conditions.

Measurement for contract payment has usually been by slope distance along the centerline of the road. Payment is either by km (mile), by Station, or by Lump Sum. Some small projects were simply equipment rental by the hour.

Operation

The key to obtaining a maintainable road does not depend solely on the Mobile In Place Processor. It is a combination of several steps.

Generally no preparatory work is required other than blasting or pre-breaking of large oversize rock or outcroppings to save on tooth breakage and machine wear. A hand-held Pionjar Rock Hammer or excavator mounted hydrohammer is used where blasting is not an option.

The optimal procedure has been to operate the machine downhill at idling speed against the grain of the rock. A 3m (10ft.) wide by 100 to 150mm (4 to 6in.) deep pass is made, followed with another pass alongside for most roads over 3m (10ft.) wide. When attempting to grind down to 150mm (6in.) of depth, the machine will usually make two passes to obtain full breakage of the rock material. Small side cast windrows are produced which are reripped to produce a smaller particle size.

A grader smoothes the windrows, a water truck applies compaction water and controls dust (minimal), and a traditional vibratory roller used in conjunction with an Elliot Grid Vibratory Compactor brings up fines and compacts the layer. The surface is then ready for the application of the calcium chloride solid (flakes or pellets).

When a project calls for calcium chloride stabilization, it is applied with a calibrated spreader (see Figure 5). The road is then reprocessed to a depth of 2.5 inches with the Mobile In Place Processor to thoroughly mix the CaCl into the top layer. The surface is smoothed with a blade and roller compacted. After the road surface has been shaped with a motor patrol, a top treatment of chloride is applied to a damp road surface; this helps bond the finished surface together as water will chemically release the calcium chloride.

Fig. 5. Calibrated spreader applying Calcium Chloride to a previously processed road.

The result is a finished road with a hard, smooth, maintainable driving surface. Grinding with the In Place Processor also works well in frozen soil, as the rocks stay in place for crushing. Some dampness in the soil is preferred for decreased machinewear, dust control, and compaction.

Material Quality

The material quality cannot be regulated to a precise gradation that crushed or screened material can. However, tests have shown that there is a substantial improvement to most materials processed by this recycling method and costs are substantially less. The materials show a reduction to approximately the 100mm (4in.) maximum size with good blending of all materials within the processing depth. This, combined with adjustable depth control and good compaction, provides an excellent, long lasting, and maintainable road cushion material. It appears that roads would not need to be recrushed for 6 to 10 years, depending on traffic volumes, and if dust control materials are utilized (see Figures 6 and 7).

Fig. 6. A typical road section before in-place processing.


Fig. 7. A typical road section after in-place processing.

Project Summary
One of the first road reconditioning projects to include the use of calcium chloride was for Copper Creek Road located on the Helena National Forest in Lincoln, Montana (Monllux 2000). A summary of the 1998 project follows:

Project Description
The Copper Creek Road is located next to a critical drainage with sensitive fish species. The road is a 20-foot wide double lane that has good quality, well graded ¾ inch crushed aggregate. The surfacing aggregate had a history of severe wash boarding even though it was maintained by blading, watering and rolling three times a year. Magnesium chloride dust abatement has been applied once every 3 to 4 years. Snow keeps the road closed during winter months. Rain accounts for about 8 of the 19 inches of annual precipitation. Vehicle speeds are greater than 35 miles per hour and grades are 2 percent in the test sections. Traffic volumes are from 20 to 50 light vehicles per day from mid-May through November with intermittent log truck traffic.

Seventeen different test sections were constructed utilizing different maintenance techniques. Calcium chloride flake and Bentonite clay were used on eight of the test sections. In-place processing and mixing was done by the Mobile In Place Processor.

Project Results
The best performing treatment was calcium chloride flake at 4.2 pounds per square yard mixed into a 2.5-inch depth of aggregate. The 4.2#/SY application rate of flake at 77 percent concentration equals about 1.3 percent pure calcium chloride by weight aggregate. This treatment section lasted more than two seasons without blading. Washboards started to appear in the 4.2#/SY section in late June 2000.

The following five benefits were observed:

1. Improved ride comfort and safety
2. Reduced airborne dust
3. Reduced aggregate surfacing loss
4. Reduced blading (no need to surface blade for more than two years)
5. Less erosion from the road surface, and less sediment in nearby streams

These benefits are possible on many other roads that require annual blading maintenance.

Project Cost
Although actual costs per mile are somewhat greater for this treatment, serviceability is significantly improved over other treatments. The serviceability assessment shown on Table 1 is related to the five benefits described above. Detailed cost and performance data is shown in Tables 1 and 2.

Recommendations

Stabilization of aggregate surfacing with Calcium Chloride flake should be considered for roads requiring annual blading maintenance. Due to differences in road aggregate, aspect, and geometrics, specialists suggest including one or more 500 foot long untreated control sections on future projects to verify the effectiveness of the treatment and application rates.

Where realistic, a 20-year cost comparison should be calculated that includes:

1. Calcium chloride flake at 4.2#/SY
2. Magnesium chloride brine at 1.08 gallons/SY
3. Asphalt paving

Magnesium Chloride brine was not used on this project and may require two applications and two mixing passes to keep the liquid product on the road. Review detailed information in Tables 1 and 2.

Table 1
Test Section Blading Requirements, Serviceability and Costs

Treatment Description (Note: All sections were bladed, watered & compacted when treated and when maintained during summer months)	Additional Blade Mtc required in 58 week period 98, 99, 00 Seasons	Serviceability Assessment By # of Weeks *Good*	 *Bad*	Cost of Mtc/ Mile from 6-15-1998 to 6-30-2000 *Actual Costs (a)*	 Costs for Same Serviceability (b)
Traditional Blading, Watering & Compaction	6 (2 in 98, 3 in 99, 1 in 00)	10	48	$3,600 (a)	$19,800
Mixing 2.5 inches deep with In Place Processor	6 (2 in 98, 3 in 99, 1 in 00)	12	46	$4,420 (a)	$19,840
Bentonite Clay mixed 2.5 inches deep with In Place Processor	5 (1 in 98, 3 in 99, 1 in 00)	16	42	$4,940 (a)	$19,240
1.6#/SY CaCl Flake on surface as dust abatement	4 (1 in 98, 2 in 99, 1 in 00)	19	39	$3,900	$17,400
Bentonite Clay mixed 2.5 inches deep with In Place Processor. 1.6#/SY CaCl Flake on surface	4 (1 in 98, 2 in 99, 1 in 00)	20	38	$5,840	$19,040
2.2#/SY CaCl Flake mixed 2.5 inches deep with In Place Processor	3 (0 in 98, 2 in 99, 1 in 00)	40	18	$4,540	$11,740
4.2#/SY CaCl Flake mixed 2.5 inches deep with In Place Processor	0 (0 in 98, 0 in 99, 0 in 00)	58	0	$5,140	$5,140

(a) Cost for these treatment sections should be increased at least $400 per mile for aggregate surfacing replacement since aggregate loss is controlled by calcium chloride flake on other treatment sections.
(b) Costs per mile for the "same serviceability" assume one blading is needed for every two weeks of bad serviceability.

Table 2
Cost Per Mile Calculations for Each Treatment Type
(Based on a 6.2 mile long road segment near Lincoln Montana)

Treatment Description (Note: All sections were bladed, watered & compacted when treated and when maintained during summer months)	Blading Cost per mile (# of blading, watering & rolling) times $600/mile	In Place Processor Mixing Cost/mile	Bentonite Cost/mile @ $100/Ton	Chloride Flake Cost/mile @ $160/Ton	Total of Actual Cost/mile 6-15-98 to 6-30-00	Costs/mile for Same Serviceability (b) (# Bladings) x (Cost/Blading) + Actual costs
Traditional Blading, Watering & Compaction	7 x $600 = $4200	$0	$0	$0	$4200 (a)	24x$600+$4200 = $18,600
Mixing 2.5 inches deep with In Place Processor	7 x $600 = $4200	$640	$0	$0	$4840 (a)	23x$600+$4840 = $18,640
Bentonite Clay mixed 2.5 inches deep with In Place Processor	6 x $600 = $3600	$640	$1300	$0	$5540 (a)	21x$600+$5440 = $17,440
1.6#/SY CaCl Flake on surface as dust abatement	5 x $600 = $3000	$0	$0	$1500	$4500	19.5x$600+$4500 = $16,200
Bentonite Clay mixed 2.5 inches deep with In Place Processor. 1.6#/SY CaCl Flake on surface	5 x $600 = $3000	$640	$1300	$1500	$6440	19x$600+$6440 = $17,840
2.2#/SY CaCl Flake mixed 2.5 inches deep with In Place Processor	4 x $600 = $2400	$640	$0	$2100	$5140	9x$600+$5140 = $10,540
4.2#/SY CaCl Flake mixed 2.5 inches deep with In Place Processor	1 x $500 - $600	$640	$0	$3900	$5140	$5,140

(a) Cost for these treatment sections should be increased at least $400 per mile for aggregate surfacing replacement since aggregate loss is controlled by calcium chloride flake on other treatment sections.
(b) Costs per mile for the "same serviceability" assume one blading is needed for every two weeks of bad serviceability.

Summary

Limitations

There are limitations on materials that can be processed in place. Most large metamorphic or igneous boulders are not easily reduced and may require some pre-processing. Some are just too hard. Generally, if the material can be ripped with a D8 size dozer, then the Mobile In Place Processor can process it. Round rock causes some problems in that they become stuck between the teeth or roll around in the drum until they are side cast, rather than processed.

Performance Benefits for Calcium Chloride Projects

The following five benefits were observed for chloride stabilization projects:

1. Improved ride comfort and safety
2. Reduced airborne dust
3. Reduced aggregate surfacing loss
4. Reduced blading—no need to surface blade for more than two years
5. Less erosion from the road surface, and less sediment in nearby streams

These benefits are possible on many other roads that require annual blading maintenance.

Additional Benefits of In Place Processing

The following additional benefits were observed on native surfaced roads that were in place processed.

Economics

In most cases the cost of in place processing is a fraction of the cost of crushing material or hauling pit run material to the site. Even though in-place processing produces a superior product to conventional methods of ripping, grading and grid rolling, operating costs are quite similar.

This process eliminates the road surface memory, which may contain soft spots, potholes, and washboards. The cushion and sub-surface have been trimmed to a smooth flat plane that will dissipate most moisture laterally and eliminate previous problem areas. The road surfaces produced with this recycling process should require less maintenance and a longer life, resulting in long term cost savings. Critically short maintenance funds could be used on other projects.

Environmental Impacts

The recycling of road surfaces eliminates the need for opening new material sources and any associated new road construction. The actual reconstruction process generates less dust and side casting than traditional methods resulting in fewer impacts on adjacent drainages and any associated fisheries. The process utilizes the existing materials in the road surface to build a stable cushion. When the material is compacted with a vibratory roller, a finished product is developed that will last for years with less environmental damage.

Further Research Needs

Further study needs to be applied on different types of geologies to determine if this process is as effective in reducing maintenance needs and sediment in granitic soils. Further study needs to be done to determine how much sediment is being reduced. Presumably because the road requires less blading, we assume there is less sediment being produced. This is probably a viable assumption, but would be beneficial to compare roads with native surface, gravel surface, and surfaces processed with the calcium chloride treatment in different geologies. The long-term effects of calcium chloride to water quality and fisheries habitat also needs to be determined. Initial research indicates that in the short-term it seems to be fairly benign (Vischer 2001).

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References

Hegman and Kreyns. Field Testing of Roto Trimmer Mobile Rock Processor. USDA Forest Service Engineering Field Notes. Volume 23. September-October 1991.

Monllux. Reducing Maintenance on Aggregate Road Surfacing, Copper Creek Road, Helena National Forest, Final Report. USDA Forest Service, July 2000.

Northrup. Development of Cushion Aggregate on Native Surfaced Roads by Use of the Roto Trimmer. USDA Forest Service, 1994.

Vischer. Preliminary Report of Chloride Concentration Levels and Movement within the Soil for Region 1 Road Projects Treated with Chloride Dust Abatement/stabilization Materials. USDA Forest Service, July 25, 2001.