



WATERWAY and WILDLIFE CROSSING POLICY and DESIGN GUIDE

For Aquatic Organism, Wildlife Habitat, and Hydrologic Connectivity

3rd Edition, July 2008



In Cooperation With:

Maine Atlantic Salmon Commission
Maine Department of Environmental Protection
Maine Department of Inland Fisheries and Wildlife
Maine Department of Marine Resources
Maine Land Use Regulation Commission

National Marine Fisheries Service
Natural Resources Conservation Service
U.S. Army Corps of Engineers
U.S. Fish and Wildlife Service
U.S. Environmental Protection Agency

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CONTENTS

Part I: Policy and Implementation

Section 1: MaineDOT Mission Statement & Passage Policy Statement

A. Mission Statement	2
B. Passage Policy Statement	2
Signature Page	3

Section 2: About this Document

A. MaineDOT's Crossing Goals and Objectives	4
B. The Larger Picture	4
C. Applicability of this Guide	5
D. Implications of Applying this Policy and Design Guide	6
E. Development of this Policy and Design Guide	7

Section 3: Using this Policy and Design Guide

A. Regulatory Review Process	8
B. Regulatory Requirements vs. Recommended Practice	9

Part II: Habitat and Biological Considerations of Providing Passage

Section 1: Physical and Biological Needs for Passage

A. Introduction	13
B. Opportunities and Challenges	14

Section 2: Fish Passage

A. Introduction	14
B. Maine's Fish Species	15
C. Project or Activity-specific Considerations	15
D. Design Criteria for Fish Passage	16
E. Further Considerations for Fish Passage	23
F. Examples of MaineDOT Fish Passage Structures	24
G. Project Review Process	28
H. Recommendations	31

Section 3: Aquatic Organism Passage

A. Background	32
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F. Weir Design _____	81
G. Downstream Weirs _____	88
H. Alternatives to Weirs: Engineered Fishways _____	89
References for Part III _____	91
Appendix A: Culvert Terminology _____	52
Appendix B: Preliminary Site Inventory Form for MaineDOT Passage Policy Compliance _____	53
Appendix C: MaineDOT Culvert Data Form _____	55
Appendix D: Resource Agency Comment Form _____	57
Appendix E: Cost Analyses for Several MaineDOT Crossing Structures _____	59
Appendix F: Regression Equations for Monthly Median Flows in Maine Rivers and Streams _____	92
Appendix G: Calculations for Kindsvater-Carter Sharp-Crested Weir And Correction for Weir Submergence _____	107
Appendix H: Manual Worksheet for Rectangular Weir Notch Sizing _____	112
Appendix I: Weir Notch Sizing and EDF Calculation Example _____	115
Table 1: State and Federal Laws and Regulations Applicable to Waterway and Wildlife Crossings in Maine _____	9
Table 2: Generalized Passage Strategies _____	13
Table 3: Maine Fish Species of Current Management Concern _____	15
Table 4: Migratory Periods and Swimming Speeds for Maine Fish Species _____	18
Table 5: Maine Herptile and Mammal Species Dependent on Riverine Habitat _____	33
Table 6: Equations for Embedded Circular Pipe Geometry _____	71
Table 7: Function Coefficient for Open Area in Embedded Pipe Arch _____	71
Table 8a: Open Area in Embedded Pipe Arch (U.S. Customary) _____	72
Table 8b: Open Area in Embedded Pipe Arch (Metric) _____	73
Figure 1: Fish Migration Velocity Graph _____	20
Figure 2: Velocity Gradients _____	20
Figure 3: Culvert Modeling _____	21
Figure 4: Velocity Gradients (2) _____	21
Figure 5: MaineDOT Steps in Processing Waterway and Wildlife Passage _____	30

Figure 6: Example of Funneling System for Herptile Passage _____	36
Figure 7: Arch Culvert with Funneling Wall for Herptiles and Fencing for Larger Wildlife _____	36
Figure 8: Example of Fencing to Funnel Wildlife through Concrete Box _____	42
Figure 9: Small Span Bridge Crossing for Large Wildlife Passage _____	44
Figure 10: Elliptical Metal Culvert Underpass (4m high x 7m wide) _____	44
Figure 11: Medium-sized Mammal Passage under U.S. Route 89/91 _____	45
Figure 12: Medium-sized Mammal Passage under Territorial Highway _____	46
Figure 13: Small Mammal Shelf Installed in Culvert under Route 93 _____	47
Figure 14: New England Cottontail Trail Demonstrating Use of Drainage Culverts under I-95 _____	47
Figure 15: Embedded Circular Pipe _____	70
Figure 16: End Treatment to Eliminate Drop _____	76
Figure 17: Log Drop Control Structure _____	79
Figure 18: Weir Profile Schematic _____	81
Figure 19: Inter-weir Spacing for Selected Pool Drops (in inches) _____	84
Figure 20: Slotted Weir Detail _____	87
Figure 21: Depth of Water on Broad-crested Weir _____	89
Photo 1: Embedment of Reinforced Concrete Pipe (RCP) _____	25
Photo 2: External Ponding Structure associated with smooth-bore slipline _____	25
Photo 3: Slipline with External Weirs over unnamed stream _____	26
Photo 4: Reinforced Concrete Pipe (RCP) with internal weirs _____	26
Photo 5: Eight-foot diameter RCP with pre-cast internal weirs _____	27
Photo 6: External Fish Ladder with associated weirs installed during invert lining process _____	27
Photo 7: External Pool-and-Chute Fishway, Rt. 178 over Marsh Stream _____	28

PART I:
POLICY AND IMPLEMENTATION

SECTION 1:

MaineDOT MISSION & CROSSING POLICY STATEMENTS

A. Mission Statement

MaineDOT's overarching mission is to responsibly provide a safe, efficient, & reliable transportation system that supports economic opportunity & quality of life. Within MaineDOT, the Environmental Office (ENV) is charged with identifying and managing impacts of the department's actions on the human and natural environments. To this end, ENV coordinates environmental functions and programs statewide; manages a number of environmentally focused transportation programs and projects; and provides services and advice to all DOT bureaus and offices on environmental matters. ENV represents the Department in collaboration with natural resource and permitting agencies when balancing environmental, economic and social interests.

B. Crossing Policy Statement

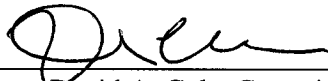
As significant features on the landscape, Maine highways provide both a **challenge** and an **opportunity**.

- **Challenge:** to consider existing or planned highway infrastructure and maintain the benefits of a safe, reliable transportation system while attempting to avoid, minimize or mitigate threats to bioregional sustainability.
- **Opportunity:** to consider both biological and physical systems that exist on the landscape and apply what we learn to shape or preserve landscapes into the future in a thoughtful and cost efficient way.

MaineDOT recognizes that assuring sustainability of habitats, ecosystems, and transportation infrastructure can occur in concert rather than in conflict. Toward that end, MaineDOT endeavors to exercise reasonable and responsible stewardship of both natural resources and transportation infrastructure through its commitment to addressing aquatic organism, wildlife, and hydrologic connectivity in cooperation with natural resource agencies, while weighing all aspects of a proposed project.

When deciding the need to preserve or restore wildlife habitat and/or surface water connectivity, MaineDOT strives for balanced decisions. This "balancing" considers whether such connectivity actions are appropriate, physically feasible, and fiscally responsible given factors such as site conditions, historic and archaeological resources, potentially competing species, habitat quality, confirmation of target species presence, and other potentially action limiting factors.

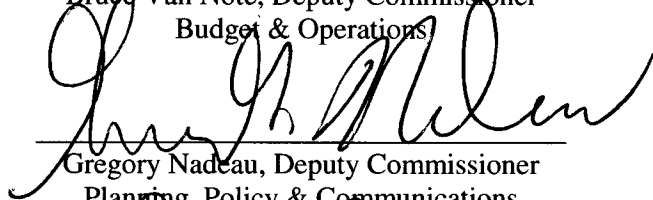
MaineDOT's Core Management fully supports the Policy and Design Guide herein:



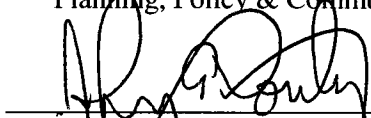
David A. Cole, Commissioner



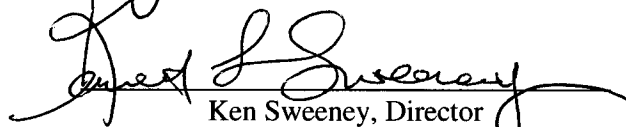
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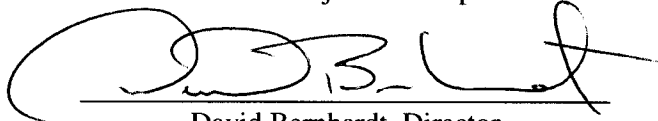
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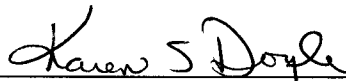
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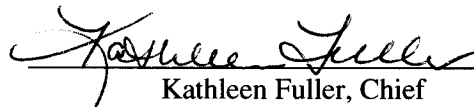
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SECTION 2:

ABOUT THIS DOCUMENT

A. MaineDOT's Crossing Goals and Objectives

Through implementation of this policy and design guide, MaineDOT continues to support its goal of developing effective ways to build, repair and maintain the transportation infrastructure, while protecting important aquatic, wildlife and surface water resources. When examining whether aquatic organism, wildlife habitat, or hydrologic connectivity are compatible with new stream crossing structures, improvements to existing structures or location of new roadways, Maine DOT must balance the interrelated needs of the site, including regulatory, biologic, hydrologic, structural, and economic constraints. Objectives based on these various needs may include, but are not limited to, any of the following:

- ❖ Locate and design projects to avoid and minimize adverse impacts to wetlands, natural stream channels, wildlife habitats, and other natural resources to the extent practicable and “feasible considering cost, existing technology and logistics based on the overall purpose of the project” (Maine Department of Environmental Protection’s Chapter 310, Wetland and Waterbodies Protection Rules, Sections 3(R) and 5(D));
- ❖ Pass peak stream flows in accordance with MaineDOT’s best drainage practices;
- ❖ Meet applicable regulatory standards and comply with state and federal guidance specific to water quality and aquatic and wildlife migration or movement corridors to the extent practicable;
- ❖ Mitigate, to the extent practicable, unreasonable adverse impacts to protected natural resources as determined appropriate by regulatory agencies;
- ❖ Consider potential impacts to private property, utilities and traffic;
- ❖ Meet appropriate engineering standards and safety requirements; and
- ❖ Provide reasonable life cycle costs.

B. The Larger Picture

The blending of ecosystem and transportation network theories has given rise to the field of road ecology, a promising tool that joins a detailed transportation engineering perspective with a broad landscape ecology perspective. The premise of road ecology is that land-use patterns that reflect the type and arrangement of human uses of land strongly influence the pattern of roads in a landscape. In turn, interactions between roads and ecosystems affect flows and movements of people and wildlife across land and fundamentally determine how a landscape works (Forman et al., 2003). Road ecology has an integral part to play in assuring sustainable transportation. While one can speculate that road benefits are balanced by the threats they pose to biological and physical systems, the challenge is to maintain the mandates of safe, reliable transportation while eliminating or mitigating potential adverse impacts from its infrastructure.

On August 10, 2005, President George W. Bush signed the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). SAFETEA-LU authorizes the Federal surface transportation programs for highways, highway safety, and transit for the 5-year period 2005-2009. A provision within SAFETEA-LU requires an increased focus on comprehensive, ecosystem, social and physical planning, through which the principles of road ecology are considered and incorporated into transportation planning processes. Additionally, the National Environmental Policy Act (NEPA) requires all transportation projects involving any federal action to consider environmental factors. There are four entities involved in the administration of the transportation NEPA process: the U.S. Department of Transportation's Federal Highway Administration (FHWA), federal land agencies, and states. Added impetus for cooperation in transportation/landscape planning comes from the FHWA's recent roll-out of its "Eco-Logical" program, which emphasizes streamlining of decision-making and expanding from a project-by-project view to a landscape-level view of projects and resources (FHWA 2006, http://www.environment.fhwa.dot.gov/ecological/eco_index.asp). For a listing of applicable laws, regulations, and governing agencies, see Section 3, Table 1.

The evolution of this Policy and Design Guide continues to track national trends in science, policy, and regulation. Its application to every MaineDOT project provides an important connection between national and state programs, assuring that MaineDOT remains at the forefront of problem-solving through practice. This proactive approach recognizes the economic and environmental benefits of maintaining healthy natural systems in the face of robust growth and increased tourism as well as the benefits of preserving Maine's way of life and traditional landscapes for its residents. Current design practices described in Part III of this guide reflect a shift by FHWA and other transportation agencies from "hard design" practices, such as armoring or piping, toward a preferred approach that favors arches, hydraulic simulation or geomorphic simulation to avoid or replicate natural features where practicable. Measures described in this policy and design guide do not constitute all possible design solutions and it is not intended to serve as a comprehensive guide encompassing the state of the science. Rather it is intended to reflect lessons learned to date and revised recommendations and regulatory requirements that are specific to MaineDOT. It remains important to consider the efficacy of crossings already constructed, advancements in engineering and design, and changes in habitat or species status.

C. Applicability of this Guide

Projects or activities considered by this policy include installation, replacement, repair or maintenance of culverts, pipes, struts, pipe arches bridges or boxes of any type or size that are part of any MaineDOT program. This document was specifically developed for an audience consisting primarily of transportation planners, project managers, and designers working on MaineDOT projects with associated waterway crossings or direct wildlife habitat or travel corridor impacts; however, much of the design guidance could be adapted to similar municipal or private projects. This 3rd edition of the MaineDOT Passage Policy and Design Guide supersedes previous editions released in 2002 and 2004. The format and content of this edition vary significantly from prior editions with the goal of emphasizing practical implications and application of crossing requirements.

Not every design solution is useful, effective, or necessary in every situation. Project purpose and need, variations in site conditions, waterway characteristics, and species present can affect which “best practice” is most appropriate. “Best practice” refers to using the most appropriate design measure for a specific site, species, or project; this may include applying known parameters for erosion and sedimentation control, materials, or installation, or involve piloting a new methodology or material that addresses project-specific issues. In some cases, for example retrofits or replacements of culverts associated with tidal conditions or Endangered or Threatened Species habitat (e.g. Atlantic salmon, short-nosed sturgeon), a site-specific design solution may require input from MaineDOT biologists, hydrologists, engineers and/or resource agency biologists.

Based on experience within MaineDOT, it is indisputable that considering possible design measures during the planning or scoping of transportation projects can reduce costs associated with mitigation, engineering, and regulatory approvals. Broad application of this document to both capital projects and maintenance activities (projects/activities) assures that MaineDOT remains at the forefront of environmental stewardship while pro-actively adhering to regulatory requirements and standards. MaineDOT recognizes that improperly designing, installing or repairing waterway crossings can block spawning runs of migrating fish and seasonal movement of resident fish species as well as the migration and patterns of Maine Heritage fish species (native, wild brook trout and Arctic char), mink, fisher, amphibians and reptiles (collectively referred to as “herptiles”), and invertebrates dependent on stream corridors. New structures should be evaluated, designed and installed so they do not interfere with aquatic organism passage and habitat connectivity, balancing the habitat impacts with increased costs of construction and maintenance. In addition, any selected method of replacement or repair should allow effective aquatic organism passage and maintain, or if necessary improve, habitat and hydrologic connectivity and functionality for site-specific species where appropriate and reasonably possible. Potential impacts on wildlife dispersal corridors, landscape connectivity, and habitat integrity may also be of concern for specific terrestrial (i.e., land-based) vertebrate species.

MaineDOT takes pride that a pro-active approach to project design and implementation has significantly fostered cooperative and collaborative relationships with state and federal agencies whose missions focus on natural resource protection. Also through this document, natural resource agencies recognize certain constraints associated with working on Maine’s transportation network. Providing safe and efficient travel is paramount to MaineDOT’s mandate, as is complying with Federal EO 11988, Protection of Floodplains. Environmental impacts and their mitigation must and will be considered as part of every MaineDOT project, but within the context of the department’s legal mandate to maintain, preserve, improve, expand, and modernize the state’s transportation network must and foremost consider feasibility, accountability, and functionality.

D. Implications of Applying this Policy and Design Guide

The greatest money and time savings can be realized by applying this guide as early in the project planning or proposal process as possible. Costs associated with mitigation, engineering, re-design and regulatory approvals may be minimized or completely avoided if policies and procedures described in this guide are evaluated proactively, early and often. Jurisdiction of regulatory agencies over impacts to natural resources most often hinges on the location and extent of an activity with respect to surface waters, such as streams, ponds, or wetlands. However, not all activities adjacent to these resources

are regulated, and in many cases how or when an activity is performed can affect the level of regulatory oversight.

MaineDOT's Environmental Office (ENV) staff applies their knowledge of regulations and resources to identify potential natural resource impacts associated with projects, assess implications of those impacts, and collaborate with resource agencies before a project or activity design is finalized. As an example illustrating possible benefits of early coordination, species-specific concerns may restrict in-stream work to several months a year, but phasing construction, avoiding disturbance of the substrate, or modifying the type of structure to be installed may negate any restrictions on the activity and/or reduce permitting requirements. MaineDOT activities associated with wetlands, waterbodies or wildlife habitat may also trigger regulatory approvals beyond those related to aquatic organisms or wildlife. For instance, cost, safety, purpose or logistical constraints may require removal of significant substrate to set a crossing structure, which in turn may trigger regulation of the disposal of the dredged material. In addition to short term cost savings, MaineDOT's proactive efforts to avoid and minimize impacts to water quality, aquatic organisms, wildlife, and natural hydrology will maintain its credibility and accountability to environmental interests and regulatory agencies over the longer term.

E. Development of this Policy and Design Guide

Historically, MaineDOT's primary goal regarding waterway crossings has been to meet regulatory requirements for natural resource protection while delivering safe, cost effective, and timely transportation projects in an environmentally responsible manner. Previous editions of this policy and design guide applied only to fish, the resource of concern reflected in most applicable state and federal regulations at that time and the foremost challenge for those charged with oversight of the state's transportation projects. To reach initial agreement on how best to achieve this goal, representatives from state and federal agencies met over several months to develop the document framework for MaineDOT's future stewardship role in addressing fish passage. The original policy and design guide reflected the focus of this effort through its title: Fish Passage Policy and Design Guide. Today however, public and environmental agency concerns and agency regulatory requirements have expanded to include passage for all species of aquatic organisms and land-based wildlife as well as maintaining the natural hydrology of surface water systems.

Processes described in this 3rd edition reflect intra- and inter-agency collaboration toward the goal of efficient and effective screening of and minimizing impacts to aquatic and terrestrial species that may be adversely affected by MaineDOT projects or activities. Changes in this policy and design guide are a result of this shift in public concerns, regulatory focus, "lessons learned" by implementing previous design guidance and agency recommendations, and the current state of knowledge in science and practices of aquatic organism and wildlife passage, and surface water hydrology. As stated previously, but worth emphasizing, the design guide section of this document does not reflect the complete range of options for design and installation of waterway crossings or maintenance of wildlife habitat connectivity. Although developing and revising this policy and design guide was viewed as proactive, the field of road ecology and studies of interactions between wildlife and transportation continue to evolve at a fast pace, constantly adding to the realm of design possibilities.

SECTION 3:

USING THIS POLICY AND DESIGN GUIDE

A. Regulatory Review Process

For waterway and wildlife crossings to successfully meet MaineDOT's objectives, all cooperating parties need sufficient information about the project purpose and need, and about the affected natural resource(s). Even small crossings may have locally important fisheries that need to be considered; conversely, some larger crossings may lack species or habitat of specific concern. Information relative to assumptions and calculations for hydraulic capacities also adds important insight into selected design parameters. To assure that relevant information is available, MaineDOT has continued to refine its process for identifying and considering transportation and habitat issues. Whether the project is undertaken by MaineDOT's Bureau of Maintenance and Operations or its Bureau of Project Development, current practice involves gathering a basic level of resource information and details of the project's design, and coordinating on aquatic and terrestrial species issues with the Maine Department of Inland Fisheries and Wildlife (MDIFW), Maine Department of Marine Resources (DMR), Atlantic Salmon Commission (ASC), U. S. Fish and Wildlife Service (USFWS), and National Marine Fisheries Service (NMFS), as appropriate for each resource. Coordination and communication with these agencies usually occurs within the context of a regulatory review by the Maine Department of Environmental Protection (DEP) and/or the U.S. Army Corps of Engineers, depending on jurisdiction. This early and consistent collaboration allows agencies to resolve potentially conflicting management mandates regarding competing species or objectives. An example of such a conflict is the discussion that occurs around removing barriers or providing passage for anadromous fish species versus restricting the range of those same species to limit predation on freshwater species. In those instances where management conflicts arise, MaineDOT relies on the natural resource agencies to use standing, monthly interagency meetings as a forum for discussion and resolution.

To increase efficiency, proposed state transportation projects and activities are reviewed within MaineDOT's Environmental Office as soon as the project and activities lists are available, preferably following the development of a six-year transportation improvement plan, but at least during development of each two-year work plan. Projects are screened using existing Geographic Information System layers combined with field observations and documentation. Findings are recorded in the relevant database to avoid redundancy and inefficiency wherever possible. As part of this internal review, proposed work is categorized according to whether it falls within a regulatory exemption, an expedited or non-reporting permitting category, or requires full review by relevant regulatory agencies. ENV staff work with design and project management staff whenever possible to reduce impacts and thereby reduce regulatory requirements, which results in time and cost savings. Proposed work requiring expedited or individual permitting is grouped according to potential environmental impact to resources and sent to regulatory agencies for their review as soon as design details are available. Maine's state and federal resource and permitting agencies have committed to timely review of complete information, identifying specific potential adverse impacts that may require design modifications, and providing justification for timing restrictions or construction

provisions. This process has been codified in an ENV standard operating procedure entitled “Aquatic Organism and Wildlife Passage Review Process for In-stream Projects”. In the spirit of collaboration, the timing and nature of coordination should continue to be evaluated and improved. As an additional forum, ENV hosts a monthly Inter-agency Meeting where conceptual, proposed and scheduled projects can be discussed.

B. Regulatory Requirements versus Recommended Practice

Because state and federal regulatory standards are subject to change more frequently than this document, we will not detail specific standards or requirements. However, major governing laws and regulations are summarized in Table 1 with a very brief description of general provisions.

Table 1: State and federal laws and regulations applicable to Waterway and Wildlife Crossings in Maine.

Law or Regulation Title	Regulations Reference	Agency for Coordination & Consultation	Applicability
National Environmental Policy Act	23 CFR 771-772 40 CFR 1500-1508 Executive Order 11514 as amended by Executive Order 11991	▶ U.S. Department of Transportation	All Federal actions (e.g. permitting, funding)
Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)	Section 6001 sec. 135 (f) (2) (D) (i)	▶ Environmental Protection Agency ▶ U.S. Army Corps of Engineers ▶ National Marine Fisheries Service ▶ US Fish and Wildlife Service ▶ Natural Resource Conservation Service ▶ US Fish and Wildlife Service ▶ Maine Department of Inland Fisheries and Wildlife ▶ Maine Department of Conservation ▶ Maine Department of Marine Resources ▶ Maine Department of Environmental Protection ▶ Non-government organizations, counties, towns	Federal actions with impacts on wetlands requires that (t)he long-range transportation plan shall be developed, as appropriate, in consultation with State, tribal, and local agencies responsible for land use management, natural resources, environmental protection, conservation, and historic preservation.”
Clean Water Act	General Permit-39 State of Maine; 33 CFR 209, 320-323, 325, 328, 329 40 CFR 121-125, 129-131, 133, 135-136, 230-231	▶ U.S. Environmental Protection Agency ▶ U.S. Army Corps of Engineers ▶ Maine Department of Environmental Protection (for water quality certification) ▶ National Marine Fisheries Service ▶ U.S. Fish & Wildlife Service	Fills or discharges to waters of the state
Magnuson-Stevens Fisheries	16 U.S.C 1801- et seq	▶ National Marine Fisheries Service	Federal actions that have the potential to impact

Management Act: Essential Fish Habitat			identified fisheries habitat
Rivers and Harbors Act	Section 10	▶ Army Corps of Engineers	Federal actions occurring in navigable waters
Historic Preservation Act	Section 106	▶ Maine Historic Preservation Commission ▶ USDOT ▶ Army Corps of Engineers	Activities affecting stone box culverts, historic bridges
49 USC 303 and 23 USC 138 as amended by Section 6009 of SAFETEA-LU	Section 4f	▶ USDOT	Historic resources, wildlife and waterfowl refuges, public parks
Natural Resources Protection Act (NRPA)	38 M.R.S.A. Sections 480 Chapter 310: Wetlands and Waterbodies Protection Rules Chapter 305, Section 11: Permit by Rule Chapter 335: Significant Wildlife Habitat	▶ Maine Department of Environmental Protection	Activities in, on, over, or adjacent to a river, stream, brook, great pond, coastal wetland, freshwater wetland, and significant wildlife habitats
Maine Land Use Regulation Commission Land Use Districts and Standards	Chapter 10	▶ Land Use Regulation Commission.	Development or jurisdictional land management activities in unorganized territories in Maine.
Statute to ensure anadromous fish passage	12 M.R.S.A., Sections 6121- 6123 7701-A	▶ Maine Department of Marine Resources (to head of tide) ▶ Maine Department of Inland Fisheries and Wildlife (from head of tide to headwaters)	Requires “a fishway to be erected, maintained, repaired or altered by the owners, lessors or other persons in control of any dam or other artificial obstruction within inland and coastal waters frequented by alewives, shad, salmon, sturgeon or other anadromous fish species”
Executive Order 11988-Floodplain Management	23 CFR 650, Subpart A 23 CFR 771	▶ Federal Emergency Management Agency (FEMA) ▶ Maine SPO	Projects located within a mapped floodplain
Endangered Species Act of 1973, as amended	7 CFR 355 50 CFR 17, 23, 81, 222, 225- 227, 402, 424, 450-453	▶ U.S. Fish & Wildlife Service ▶ National Marine Fisheries Service	Projects likely to affect federally listed endangered or threatened species
Maine Endangered Species Act	12 MRSA Sections 12801 et seq	▶ Maine Department of Inland Fisheries & Wildlife	Projects likely to affect state listed endangered or threatened species
Fish and Wildlife Coordination Act	16 U.S.C. 661 et seq	▶ U.S. Fish & Wildlife Service ▶ Maine Department of Inland Fisheries & Wildlife	Any project involving a natural impoundment with a surface area of 10 acres or more or stream modification

Coastal Zone Management Act of 1972	15 CFR 923, 926, 930 23 CFR 771	<ul style="list-style-type: none"> ▶ Maine Department of Environmental Protection; ▶ Maine State Planning Office 	Actions within a coastal zone that affect protected natural resources
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In addition to regulatory mandates, agencies charged with natural resource management often encourage that best management practices be applied to projects not within regulatory jurisdictions, for example projects that qualify as exempt under the NRPA. Examples of such practices include the use of alternative design or construction methods, consideration for non-target species, or partnering on projects thereby altering the schedule of work. These best management practices may be able to be incorporated into projects or activities on a project-specific basis or as standard practice if they do not impose additional financial, logistical, or safety costs to Maine taxpayers.

Although MaineDOT continues to demonstrate its commitment to environmental stewardship, implementing recommendations not directly related to compliance with a regulatory requirement is highly dependent on available funding, feasibility, and potential benefits to transportation infrastructure or priority habitats. Increasingly, requirements aimed at maintaining or restoring connectivity in aquatic organism or wildlife habitat, formerly limited to new alignments and waterway crossing structures, are seen by review agencies as a necessary part of facility replacement, repair, and maintenance. Each agency may need to consider establishing priorities within its mission while MaineDOT's technical, engineering, and construction practices (MaineDOT 2003 a, 2003b) continue to move toward cost efficient yet environmentally responsible solutions. An example of conflicting mandates is the restoration of anadromous fish runs to major rivers sought by the Maine Department of Marine Resources may conflict with MDIF&W's management of competing freshwater species. Additional hindrances to universally applying requirements for aquatic and terrestrial habitat connectivity outside of the regulatory requirements are the lack of resource-specific and/or species-specific information, the lack of consistent requirements applied to local or private entities as well as state agencies, a very limited pool of new construction projects that incorporate provisions for connectivity, and funding for research and implementation.

PART II:
HABITAT AND BIOLOGICAL CONSIDERATIONS OF PROVIDING PASSAGE.

SECTION 1:

PHYSICAL AND BIOLOGICAL NEEDS FOR PASSAGE

A. Introduction

Although fish and wildlife species have differing needs based on a diversity of habitat types, most can be addressed by passage strategies. This section discusses the needs of three groups of species requiring passage through MaineDOT's transportation systems: fish, aquatic organisms other than fish that use stream and riparian habitat for life cycle movements, and animal species that are not necessarily stream dependant, but would benefit from a passage separate from a roadway, including small, medium, and larger mammals.

There are five generalized structural strategies considered when contemplating passage, most of which are built in conjunction with waterways (Table 2). Many constraints (e.g., species status, existence of species management plans, landscape location, geological features, location of the structure within the transportation facility, replacement size constraint, cost, etc.) should be considered during the planning, design and strategy selection process.

Table 2: Generalized Passage Strategies

Type of Structure Habitat requirements	Bridge	Open bottom culvert	Culvert placed at 0% grade; 1.2 bankfull	Engineered strategy (e.g. notch, weirs); 1.2 bankfull	Replaced in-kind or retrofit; Engineered strategy
Aquatic organisms	U	U	U	S	S
Terrestrial wildlife using streams or riparian zones for movement	U	U	M	M	X
Wildlife that is not stream dependant	U	M	M	M	X
U= will use structure; S= Passable for some organisms in this suite; M= may use structures with adequate openness ratio and/or substrate duplicates natural substrate; X= structure will probably not be used.					

B. Opportunities and Challenges

MaineDOT considers potential opportunities for restoration or preservation of natural conditions when planning and designing a waterway or wetland crossing. Through its relationships with state and federal resource management and regulatory agencies, advocacy groups, and the public, MaineDOT actively explores potential partnerships for restoration, research, and implementation. Cooperation with other entities not only furthers the goal of transportation infrastructure improvement, but builds on collective technical expertise, funding, and priorities established through efforts such as MaineDOT's Long Range Plan and MDIF&W's Wildlife Action Plan.

Acknowledging that natural substrates, travel corridors, and hydrology are best preserved through the use of bridges or open-bottom arches that span riparian areas, these structures are not always feasible given site conditions, soils, existing infrastructure, time constraints, installation and life-cycle costs. While MaineDOT strives to exercise responsible environmental stewardship, the reality is that at times the costs of doing so are prohibitive. For example, the costs of accommodating an open span (bridge or bottomless box) can increase the project costs disproportionately over a more conventional culvert with weirs. Costs of maintenance and lifecycle costs may balance initial installation costs, but to date there is little data to substantiate this claim. Constraints to constructing the ideal crossing can result in providing connectivity "to the extent practicable", which is a term of art defined in Maine's Chapter 310, the Wetland and Waterbodies Protection Rules. Determining what is "practicable" in terms of habitat and hydrology hinges not only on cost, but also feasibility and available alternatives. Before presenting a potential design strategy to a regulatory or resource management agency, MaineDOT project management, design, and ENV staff must consider budgetary constraints, such as a comparison of costs for an ideal solution vs. a compromise solution, and the physical characteristics of the site, such as cover over the structure, presence of utilities, the amount of ledge or bedrock present, degree and condition of existing passage downstream, the presence of buildings or other infrastructure constructed above or adjacent to the crossing structure, and the safety of the traveling public.

SECTION 2:

FISH PASSAGE

A. Fish Passage Introduction

By far, fish passage has been the most studied of all passage opportunities. The First Edition of MaineDOT's Fish Passage Policy and Design Guide (2002) drew upon existing procedures developed primarily in the mid to late 1990s and by several states and in the maritime region of Canada. These were based on the hydraulic swimming abilities of the fish species that needed to be accommodated. Strategies for fish passage are still being studied and, while still dependant on hydraulic design, incorporate habitat requirements and natural stream tendencies so that stream area is more natural, and requires less maintenance and less energy expenditure of fish.

B. Maine's Fish Species

Maine's fishery resources are integral to sustaining coastal and inland ecosystems, and providing commercial, recreational, and economic benefits. Species such as alewife, blueback herring, and American shad provide forage for numerous fish and wildlife species and support commercial fisheries. Other species, such as brook trout, are sought by recreational anglers and in 2003 alone brought approximately 300 million dollars into the Maine economy (MDIFW, 2003). Table 3 lists the fish species that should be considered when designing a stream crossing to accommodate fish passage, as confirmed by the participating resource agencies.

Table 3. Maine Aquatic Species of Current Management Concern

<u>Catadromous Species:</u>	<u>Anadromous Species:</u>	<u>Freshwater Species:</u>
American eel	Rainbow smelt	Rainbow smelt
	Blueback herring	Brook trout
	Alewife	Brown trout
	Atlantic salmon*	Rainbow trout
	American shad	Landlocked salmon
	Sea run brook trout	Minnnows, shiners, dace
	Sea run brown trout	White sucker
	Sea Lamprey	Redfin pickerel
	Short-nosed sturgeon*	Swamp darter
	Atlantic tomcod	Tidewater mucket*
	Striped bass	Yellow Lamp mussel*
		Brook floater*
		Creeper
		White and yellow perch [@]
		Banded killifish [@]
		Largemouth bass [@]
		Smallmouth bass [@]
		Two-line salamander [@]
		Red-spotted newt [@]

* Endangered or threatened status

[@] of concern to the extent that this species serves as larval host for target species

C. Project or Activity-specific Considerations

MaineDOT's first responsibility under this policy and design guide is to determine whether the scope of a proposed project or activity involving a stream crossing project falls under the permitting jurisdiction of a state or federal agency. If not, only this Policy and Design Guide applies to the project/activity and ENV staff is the resource for engineers, designers and project managers. In some

cases, regulatory jurisdictions may be avoided through minor modifications in design or construction methods.

If a project/activity falls under state or federal jurisdiction, ENV determines the required level of permitting following procedures described in its standard operating procedure entitled “Regulatory Permitting Procedures”. MaineDOT biologists and environmental staff assess and document the physical condition and biological health of the stream by conducting a resource inventory, considering any information provided by fisheries and wildlife agencies concerning whether species of concern are present and need accommodation. If so, seasonal passage needs are determined using Table 4 as a guide. Even if a resource inventory indicates that fish passage is warranted, additional features of a site need to be considered before decisions are finalized. All site factors **are** balanced to determine the best course of action.

Before a decision is reached, additional questions must be answered, such as:

- ❖ Are there fish passage constraints associated with the existing structure?
- ❖ Which alternative action is least environmentally damaging?
- ❖ Is there a way to accomplish the same transportation objective without working below mean high water of a stream?
- ❖ Is the cost of any alternative prohibitive, considering available funds, condition of a structure, short-term costs and life cycle costs?
- ❖ What is the most reasonable alternative considering property ownership? Utility location? Safety?
- ❖ What design will provide adequate stream flow conditions regarding the resources present (fisheries and others) and flood protection?
- ❖ Is there suitable fish habitat upstream of the crossing?
- ❖ Are there natural or manmade barriers to passage downstream or immediately upstream of the crossing?

In some cases, after it is determined that fish passage may be warranted and appears physically possible, the answers to these questions may alter the final decision on whether passage is practicable and should be provided. For example, MaineDOT considers the lifespan of a replacement crossing structure and coordinates with natural resource agencies to determine the likelihood of downstream or upstream barrier removal within the structure’s lifespan before undertaking complex and/or expensive design modifications to provide passage for a target species.

D. Design Criteria for Fish Passage

When conditions at a site indicate that fish passage can and should be provided, appropriate criteria must be used to design effective passage and assure long term stability at the site. According to MaineDOT best drainage practices, crossings must protect roads against peak flow (50-year or similar low-frequency) events to avoid blocking traffic and minimize wash outs and other damage (MaineDOT 2003a, 2003b). In addition, at sites with fish habitat, stream crossing structures should not block fish passage. A crossing can block passage in several ways. The most obvious is the creation of a physical barrier by its configuration or construction (e.g., a hanging culvert). A more subtle form of barrier can be created hydraulically. Although a crossing may appear to form a clear

and continuous passage for fish, in fact, hydraulics (resulting velocity, depth of flow, and total culvert length) may prevent passage for the target species or life stage.

Ideally, crossings should reproduce, as nearly as possible, the natural hydraulic conditions of the stream. At design peak flows, this is not an issue, as most fish species tend not to move upstream and depth is more than adequate for fish to wait out the limited duration of flood flows. Lower flows are often more critical for fish movement. Natural velocities at lower flows ordinarily permit upstream movement. Undersized crossings can constrict flow and increase velocity above the fish swimming capacity. Oversized crossings can reduce flow depths so they are too shallow for fish to navigate. In either case, the crossing may function as a hydraulic barrier to fish movement.

Ideally, then, to pass fish effectively, crossings must satisfy these criteria:

1. Design Peak Flow: Pass the design peak flow event (typically 50-year for culverts less than 10 feet and 100-year event for larger structures) according to the MaineDOT Highway Design Guide (MaineDOT 2003a, 2003b).
2. Maximum Velocity: Not exceed a specified flow velocity at a specified flow representing conditions during periods of upstream movement as listed in Table 4.
3. Minimum Depth: maintain a minimum depth for fish movement at a specified flow representing low flow conditions when fish may be moving as described in Table 4.
4. Gradient: maintain channel elevation between stream bed and pipe at inlet and outlet through which fish can easily pass (i.e., no excessive drops).

Design for fish passage through new and replacement (“new”) crossings can be different than for passage through rehabilitated crossings. With new crossings, design focuses on reproducing the basic hydraulic geometry of the stream in the pipe with $Q_{1.1}$ flow depth and width as surrogates for critical geometry. There is the implicit assumption that fish passage criteria 2 and 3 are automatically satisfied if $Q_{1.1}$ flow depth and width are preserved. With new and replacement crossings, the opportunity for designing to the 100-year event should be considered as an additional means of protecting the stream at design peak discharges.

Table 4: Migratory Periods and Swimming Requirements for Maine Fish Species.⁽¹⁾

Species/stage	Body Length (inches)	Body Thickness (inches) (% body length)	Direction of Travel (upstream/downstream)	Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec		Sustained Swim Speed (feet per second)	Basis of Swim Speed		
				1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2				
Alewife, adult (anadromous) *****	2.6 - 9.4+	0.8 - 2.8 (30%) +	U							S	S	S	S													3 - 5	Pb		
Alewife, adult (anadromous) *****	2.6 - 9.4+	0.8 - 2.8 (30%) +	D							F	F	F	F	F	F											3 - 5	Pb		
Alewife, juv. (anadromous) *****	1.7-4.5	0.5 - 1.4 (30%) +	D											F	F	F	F	F	F	F	F	F	F			0.6 - 1.0	L		
American eel, adult ***	7.8 - 26***	1 - 2 #	D													S	S	S	S	S	S	S	S			5.2 - 9.1	L		
American eel, juv. (glass/elvers)	2.3 - 5***	1/8 - 1/2	U			F	F	F	F	F	F	F	F													0.8 - 2.6	L		
American shad, adult****	12-17****	2 - 3 (18%) +	U							S	S	S	S	S	S											2.3-15+	Pb		
American shad, adult****	12-17****	2 - 3 (18%) +	D							F	F	F	F	F	F											2.3-15+	Pb		
American shad, juv.****	3****	0.6 (18%) +	D											F	F	F	F	F	F	F	F	F	F			1.0 - 1.8	L/Pb		
Blueback herring, adult*****	9.4 + *****	2.2 (23%)	U							S	S	S	S	S	S											3 - 10+	Pb		
Blueback herring, adult*****	9.4 + *****	2.2 (23%)	D							F	F	F	F	F	F											3 - 10+	Pb		
Blueback herring, juv.*****	1.4 - 2.8*****	0.3 - 0.7 (23%)	D											F	F	F	F	F	F	F	F	F	F			0.4 - 0.8	L		
Salmon, Atlantic adult *	15 - 36*	3 - 7.2 (20%)	Both							S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	5.0 - 15+	L		
Salmon, Atlantic juvenile *	4.5 - 6.8*	1 - 1.4 (20%)	Both					F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	1.6 - 2.6	L		
Salmon, Atlantic smolt *	7.8 - 15*	1.4 - 5 (20%)	D					F	F	F	F	F	F	F	F											2.5 - 4.4	L		
Resident fish movement *	3 - 10#	Varies	Both			F	F	F	F	F	F	S	S	S	S	S	S	F	F	F	F	F	F			1.0 - 1.8	L		
Sea lamprey, adult	28.3-34.6 K		U					S	S	S	S	S	S													1.38 (avg.)	B		
Sea lamprey, transformer	3.9-7.9 K		D															F	F	F	F	F	F	F	F				K
Smelt, adult (anadromous)**	5.5 - 9.7	0.9 - 1.5 (16%) #	U			S	S	S	S	S	S															1.8 - 3.2	L		
Smelt, adult (anadromous)**	5.5 - 9.7	0.9 - 1.5 (16%) #	D			F	F	F	F	F	F															1.8 - 3.2	L		
Smelt, juv. (anadromous)**	0.74 - 5.5	0.1 - 0.9 (16%) #	D			F	F	F	F	F	F															0.2 - 0.4	L		
Smelt, adult (landlocked)	5.5 - 9.7**	0.9 - 1.5 (16%)#	U	S	S	S	S	S	S	S	S															1.8 - 3.2	L		
Sucker, white adult	4 - 14 + #	0.7 - 2.6 (18%)	U					S	S	S	S															1.2 - 2.1	L		
Trout, brown*****	6-16*+	1.6 - 3 (18%)+	Both					F	F	F	F	F	F	F	F					S	S	S	S	S	S	2.3-7.5	Pb		
Trout, sea-run brown	9-16*+	1.6 - 3 (18%)+	U																	S	S	S	S	S	S	2.3-7.1	L		
Trout, brook *****	4 - 6 ¹	1.5 - 4 (25%)	Both					F	F	F	F	F	F	F	F					S	S	S	S	S	S	0.5 - 2.0 ¹	L		
Trout, sea-run brook	6-12#	1.5 - 4 (25%)	U																	S	S	S	S	S	S	2.0 - 3.5	L		
Trout, rainbow	6-18 +	1 - 3 (17%)	Both			S	S	S	S	S	S									S	S	S	S	S	S	2.0 - 3.5	L/P+		
Notes: (1) No feeding or spawning needs noted for January	Body thickness x 1.5= water depth needed for passage																Pb =Published Speeds. b (Bell, 1991); + (Fishbase) Froese and Pauly, 2004												
* USFWS species profiles, refer to reference section* Danie et al , 1984; ** Buckley, 1989; *** USFWS Facey, et al 1987	# Anecdotal or observed ranges																L = Body Length Formula												
USFWS species Profiles (Con't) refer to reference section ***** Mullen et al 1986; **** Stier, et al 1985; ; ***** Raleigh 1986	+ Sizes from: www.fishbase.org																B =Collette and Klein-MacPhee, 2002												
	1 = first half of month																K = Kircheis, 2004												
	2 = second half of month																Swim speeds - based on smallest size measurement												
For culverts just above head-tide; tidal culverts would impact over longer period	F = Feeding, foraging, refugia (any instream movement)																Sustained speed = 4 to 7 body lengths per second												
	S = Spawning or seasonal migration																												

With slip lining and invert lining of existing pipes, which reduce the size and roughness of the pipe, it is generally not possible to maintain or restore natural hydraulic geometry in the structure. In this case, criteria 2 and 3 must be addressed directly. The reduced roughness reduces flow depth and/or increases flow velocity. Often, reduced velocity and increased depth requirements cannot be achieved without additional design measures (e.g., weirs).

The objectives in designing effective fish passage are:

1. Peak Flow Design Event: Design peak flow is the familiar standard for providing flood protection. In theory, it represents the optimal design that minimizes the expected cost associated with flooding. Damages associated with a design smaller than optimal could be reduced by using a larger crossing. A crossing larger than optimal will cost more than the marginal savings in flood damage. In practice, though, the 50-year (or 100-year) event is simply a compromise between under-design and over-design. The relationship between the design flow and optimal design is largely unknown. Design for peak flow is the traditional method of estimating design flow and analyzing hydraulics, as documented in MaineDOT highway and bridge design manuals (MaineDOT, 2003a and b).
2. Water Velocity: Determining approximate maximum water velocities is key to assessing whether the target fish population will be able to swim upstream against the current at critical periods. New and replacement crossings must be sized for consistency with the natural channel bankfull width (bankfull discharge = $Q_{1.3}$) to the extent practicable, with the implicit assumption that such sizing will automatically produce the desired flow velocities and depths.

Various fish species move up or downstream at different times of the year, and have different velocity and depth needs for passage (Table 4). For example, smelt, a weak swimming fish, may be present in the late winter and spring, and require slower velocities than other fish that are present at the same or at different times of year. The same structure may need to sustain a suitable velocity for adult salmonid use in the fall, and to allow low flow passage for juvenile salmon to forage for food during their rearing stage.

Even within species, swimming speeds of fish vary with maturity and size of fish, characteristics of individual fish, and water temperature. There are three categories of swimming speed: cruising, sustained, and burst speed. Cruising speed is the speed a fish can maintain for an extended period of time, sustained speed can be maintained for several minutes and burst speed only for a few seconds. A design to pass fish effectively should be based on sustained speed because it considers swim speed, periods of passage, direction of movement, and size of the target fish species, which is used to determine water depth needed. Figure 1, which compares swimming speeds of several fish species, is useful for guidance in determining if a particular species is capable of passing through a given length of crossing once water velocities are known. It should be noted that MaineDOT relies on fishery agencies to identify specific target species and life stages to be considered if design is to be based on other than generic conditions.

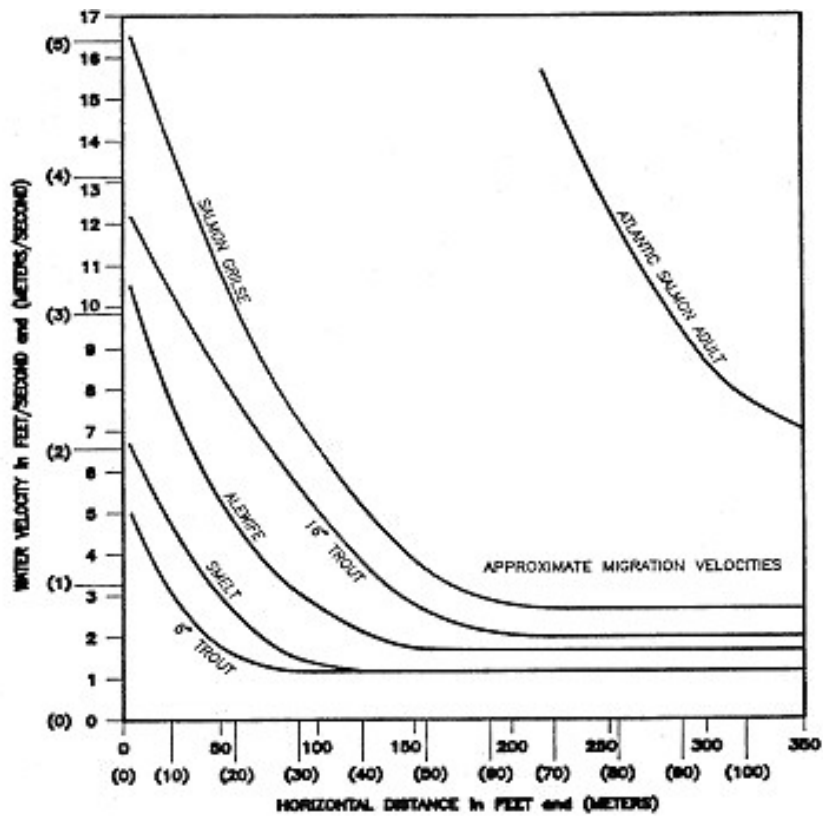


Figure 2. Fish Migration Velocity Graph. Source: Robison, 2000 retrieved from http://www.4sos.org/wssupport/ws_rest/fpsc/CulvertDesignsforFishPassage/sld030.htm

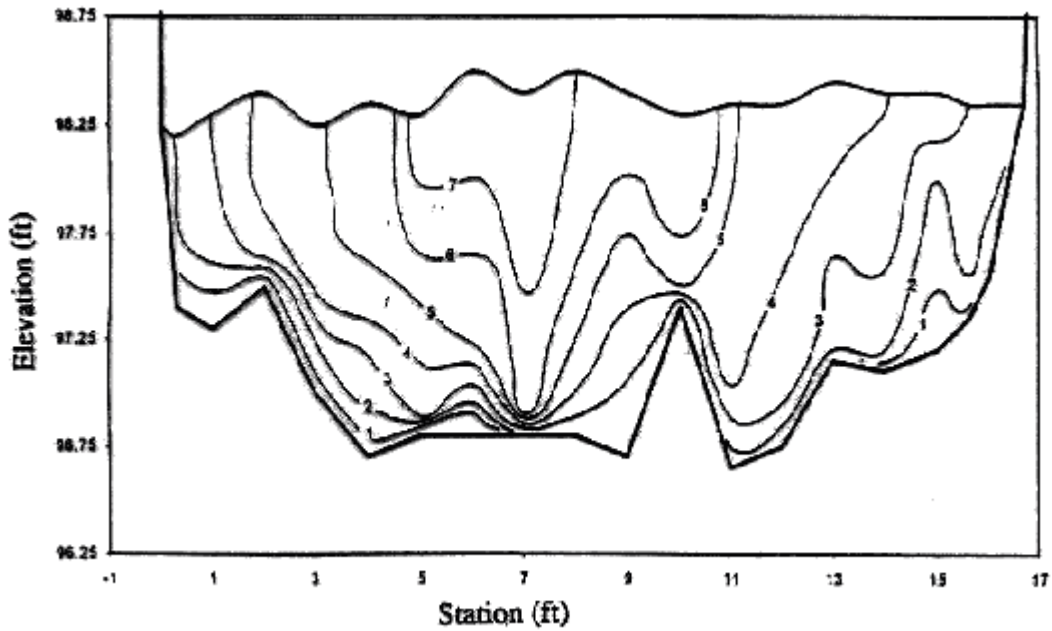


Figure 3: Culvert modeling.

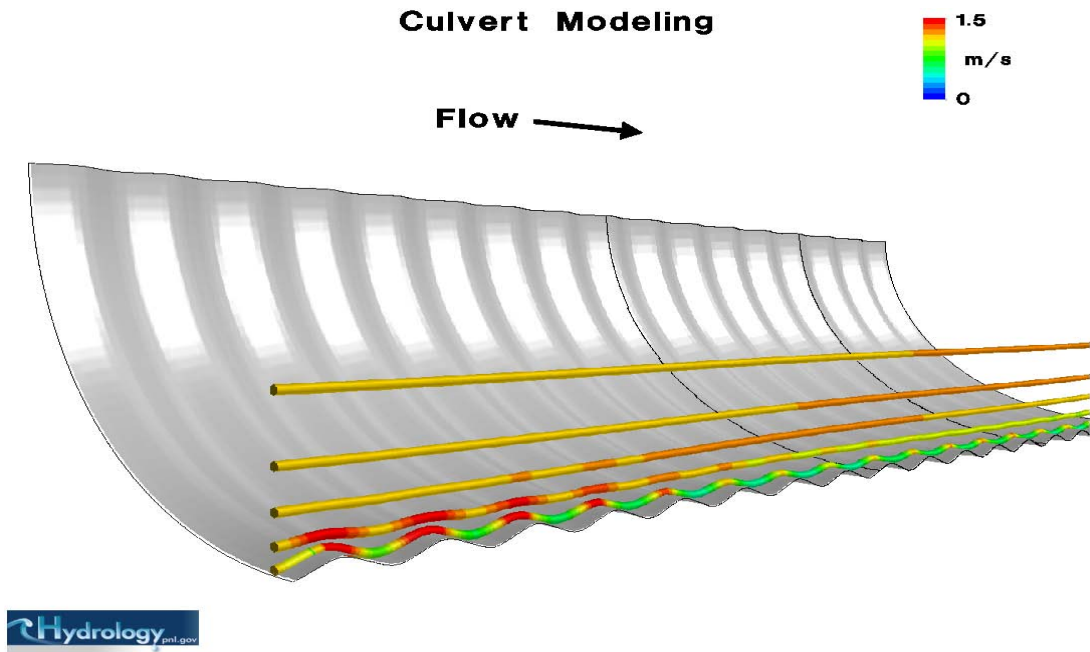
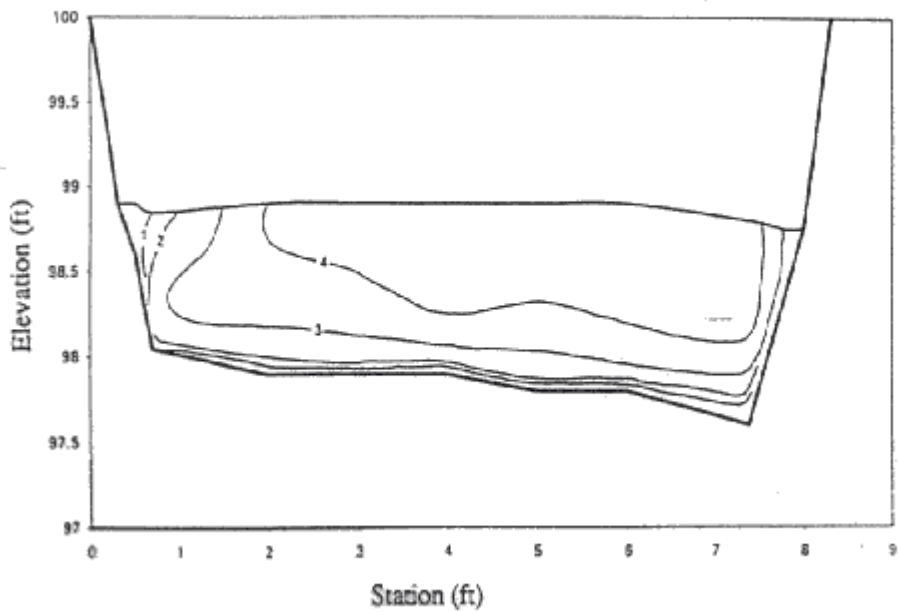


Figure 4: Velocity gradient. Source: Bonneville Power Administration retrieved from <http://www.cbfwa.org/FWProgram/ReviewCycle/fy2002in/projects/34016n.doc>



Flow velocities vary with depth within the barrel of a pipe as a function of pipe cross sectional area and surface roughness. A boundary layer of slower moving water develops near the inner pipe surface. Water in contact with the pipe surface (corrugated or smooth) is slowed by friction by a factor that is related to the roughness of the culvert (measured as Manning's coefficient) and the velocity is less than the flows near the center (or pipe center in case of full pipe flow) and fish will normally seek the lowest water velocity when traversing a crossing (Washington Department of Fish and Wildlife, 1999; Behlke et al, 1991). Culvert rehabilitation may greatly reduce roughness, thus reducing the boundary layer (slow water) thickness to where it may not provide an adequate passage zone. In this case, velocity is nearly uniform across the pipe section and approximately equal to the average velocity as determined by hydraulic equations. When a pipe is sufficiently rough (e.g., deeply corrugated), hydraulic analysis for a specified flow and size may indicate an acceptably thick lower velocity zone adjacent to the pipe surface. If the natural velocity profile in a pipe does not provide an adequate low velocity zone, then alternative designs or actions should be considered (i.e., linings may need to include additional structural measures on site to meet design criteria or it may not be possible to line the pipe).

Designing for a velocity limit requires that target fish species and an appropriate design flow be specified. Table 4 is used to establish maximum allowable velocity, corresponding velocity zone depth requirements, and periods of upstream movement by species. Ideally, the design should be based on a statistical flow criterion. For example, sea-run brook trout move upstream to spawn from September through November. This policy and design guide establishes that the median flow for an appropriate period of interest is an acceptable standard. Statistical measures should be checked against channel geometry measurements and hydraulic calculations, and if possible, actual field velocity measurements.

ENV's Field Services Unit also examined the use of hydrologic software models, such as FishXing from USFS San Dimas Research Center (<http://stream.fs.fed.us/fishxing/>) as design guidance. Although the model is available, the most feasible approach for MaineDOT remains designing site- and species-specific passage using: 1) the hydrologic data available; 2) site-specific design criteria; and 3) in-house expertise.

3. Water Depth: Providing a minimum depth assures adequate water depth during periods of simultaneous low flow and fish movement. As already noted for water velocity considerations, new and replacement pipes will be sized for consistency with the natural channel bankfull width and depth, with the implicit assumption that such sizing will automatically produce the desired flow velocities and depths.

For culvert rehabilitation, the design depth should be based on the target species present and either the corresponding critical depth (1.5 x the body thickness) (Orvis, 2001) for that species during the period of significant movement or the documented prevailing depths during periods of known movement.

Information received from other regions of the U.S. confirms that, because of different geographic and hydrologic conditions at water crossings, sizing and orientation of crossings are regionally specific. For example, Washington State (WSDFW, 1999)

requires that a crossing be 1.2 times the bankfull width (roughly corresponding to $Q_{1.3}$ in Maine) plus 2 feet at the flow line. However, this design is inappropriate for Maine because it would create inadequate depths for resident fish passage in many instances. MaineDOT endorses USFWS (Quinn, October 2000) recommendations to design for varying suitable flow conditions to match existing stream depth at the pipe location during key periods of use.

4. **Gradient**: In addition to a suitable combination of water velocity and depth, fish need a suitable gradient to enter and exit a crossing structure (New York DOT, 2000; Quinn to Lary, USFWS, August 2000; Washington Department of Fish and Wildlife, 1999; Behlke et al, 1991; Votapka, 1991). A drop at a culvert outlet is one of the most common conditions blocking passage, and one of the easiest to remedy. Culverts should be installed at the proper elevation to avoid perched outlets that fish cannot access. This agrees with current MaineDOT practices that pipes should be embedded and allowed to fill in to maintain a continuous, natural gradient. In some instances, notched weirs or a check dam can be placed downstream from an existing culvert to raise the tailwater elevation enough to reduce or eliminate a drop, allow passage, and maintain a required minimum depth, as long as passage at the check dam is maintained.

E. Further Considerations for Fish Passage

Design for fish passage through new and rehabilitated crossings is fundamentally different. Each site where passage is required undergoes biologic and hydraulic analyses by ENV staff, so case by case project review is the optimum way to address passage issues and design. Pipes are designed for appropriate flow depth and velocity, either implicitly (new or replacement) or explicitly (rehabilitation). Design guidance based on these criteria is included as Part C of this document. If a particular site cannot physically meet these criteria or if cost is prohibitive, design criteria for passage may be revised or suspended; this decision should be reached in consultation with resource and regulatory agencies when required.

Considering all the data available and sound current practices, the following actions represent the minimum consideration when fish passage is needed.

1. Considerations for a New or Replacement Crossing

- ❖ Eliminate hanging outlets where practicable based on criteria such as whether a pipe can be embedded without bedrock removal, down-gradient grade control conditions and options, and presence of conflicting species requirements;
- ❖ Install new structures with inverts below streambed elevation. Pipes less than 48 in (1200 mm) in diameter should be embedded 6 in (150 mm); and pipes 48 in (1200 mm) or more in diameter embedded 12 in (300 mm) into the stream bottom. Embedded pipes should be allowed to fill with natural substrate through natural bed load movement whenever possible and practicable. In extreme circumstances, a streambed may have to be constructed within the pipe; however in these cases, the immediate need for a simulated stream bed must be balanced with the cost of constructing a naturalistic bed, the safety of workers in confined spaces, and the potential for increased stability of the simulated bed if

allowed to aggrade naturally. Stream simulation may also require deeper embedments, resulting in a need for an increase in design pipe diameter.

- ❖ Structures should allow existing stream bed characteristics to be naturally maintained to the extent practicable and required to maintain passage for identified species, invertebrate habitat and
- ❖ Do not exceed the existing natural gradient taken over a stream segments up and downstream of the crossings; avoid drops inaccessible to fish.
- ❖ Size and place structures to simulate natural stream hydraulic geometry (including bankfull width). For single pipes, match flow depth to natural stream depth and width at bankfull ($Q_{1.3}$) conditions based on a reference reach outside of the influence of any existing structure.
- ❖ For multiple pipes at the same location, install one pipe to allow fish passage during low flow periods of regular movement; size and place additional pipe to collectively pass the design peak flows. Multi-pipe installations are prone to unintended consequences, such as scouring around inlets and outlets, and should only be designed by experienced hydraulic engineers.
- ❖ Calculate flow depth during species-specific periods of movement for the pipe design at appropriate period-specific passage design flows.
- ❖ Check 100-year event for smaller crossings (less than 10 ft wide)

2. Considerations for a Rehabilitated Crossing

- ❖ Consider strategies, such as downstream grade controls, to provide passage at hydraulic drops at outlets where practicable.
- ❖ Preserve minimum flow depth during critical periods of species-specific movement.
- ❖ Consider strategies that would prevent flows from exceeding maximum flow velocity during periods of species-specific upstream movement.

F. Examples of MaineDOT Fish Passage Structures

The photos included in this sub-section provide a sampling of structures that have been installed or modified by MaineDOT to pass fish. Most of these structures have been determined to pass the target species either indirectly (comparing known swimming speeds versus the water velocity through the structure) or through direct observation of fish using the structure. However, it should be noted that actual passage efficacies of these structures have not been determined.

Photo 1. Embedment of Reinforced Concrete Pipe (RCP) to provide adequate depth and low water velocities. Oakland, Maine. Target Species: brook trout and other resident species.



Photo 2. External Structure Ponding Water into Smooth-bore Slipline to provide adequate depth and low water velocities. Route 27 over unnamed tributary to Carrabassett River, Carrabassett Valley, Maine. Target Species: brook trout.



Photo 3. Slipline with Internal Weirs, Route 1 over Unnamed Stream to provide adequate depth and low water velocities. Belfast, Maine. Target Species: brook trout.



Photo 4. Reinforced Concrete Pipe (RCP) with Internal Weirs to provide adequate depth and low water velocities. Kennebec Road, Newburgh, Maine. Target Species: brook trout



Photo 5. 8-foot Diameter Reinforced Concrete Pipe (RCP) with Precast Internal Weirs to provide adequate depth and low water velocities. Acton, Maine. Target Species: brook trout



Photo 6. External Fish Ladder (with associated weirs installed during invert lining process) to provide adequate depth and low water velocities. Mill Brook, Westbrook, Maine. Target Species: alewives



Photo 7. External Pool-and-Chute Fishway, Rt. 178 over Marsh Stream to provide adequate depth and low water velocities. Eddington, Maine. Target Species: Atlantic salmon, brook trout, and other resident species



G. Project Review Process

1. Project Coordination

Figure 5 outlines the steps in MaineDOT's review process for waterway and wildlife crossings, beginning with publication of the MaineDOT's six-year or two-year work plan and continuing through project construction and post construction monitoring of passage measures. The process depicted in Figure 5 has been revised from that in the original policy adopted in of 2002. The new process was developed in coordination with state and federal fishery agencies and results in earlier and more efficient screening. Note that when site-specific passage needs are determined, all other site considerations are also identified, including potential environmental effects and overall practicability (e.g., costs, property ownership, utilities, safety, etc.). If passage installation appears practicable after all factors have been reviewed, a hydrologic assessment is done to determine whether passage can be effectively designed. The proposed design for a jurisdictional project is submitted to the appropriate regulatory agencies for review. Through the regulatory review, state and federal fisheries agencies have an opportunity to request site visits or design modifications. Design is completed after MaineDOT receives fishery agency comments on the proposed crossing structure. During construction of a weir or other passage measure, a MaineDOT environmental representative is present on the project to assist with placement by offering resource considerations and site-specific adjustments when necessary.

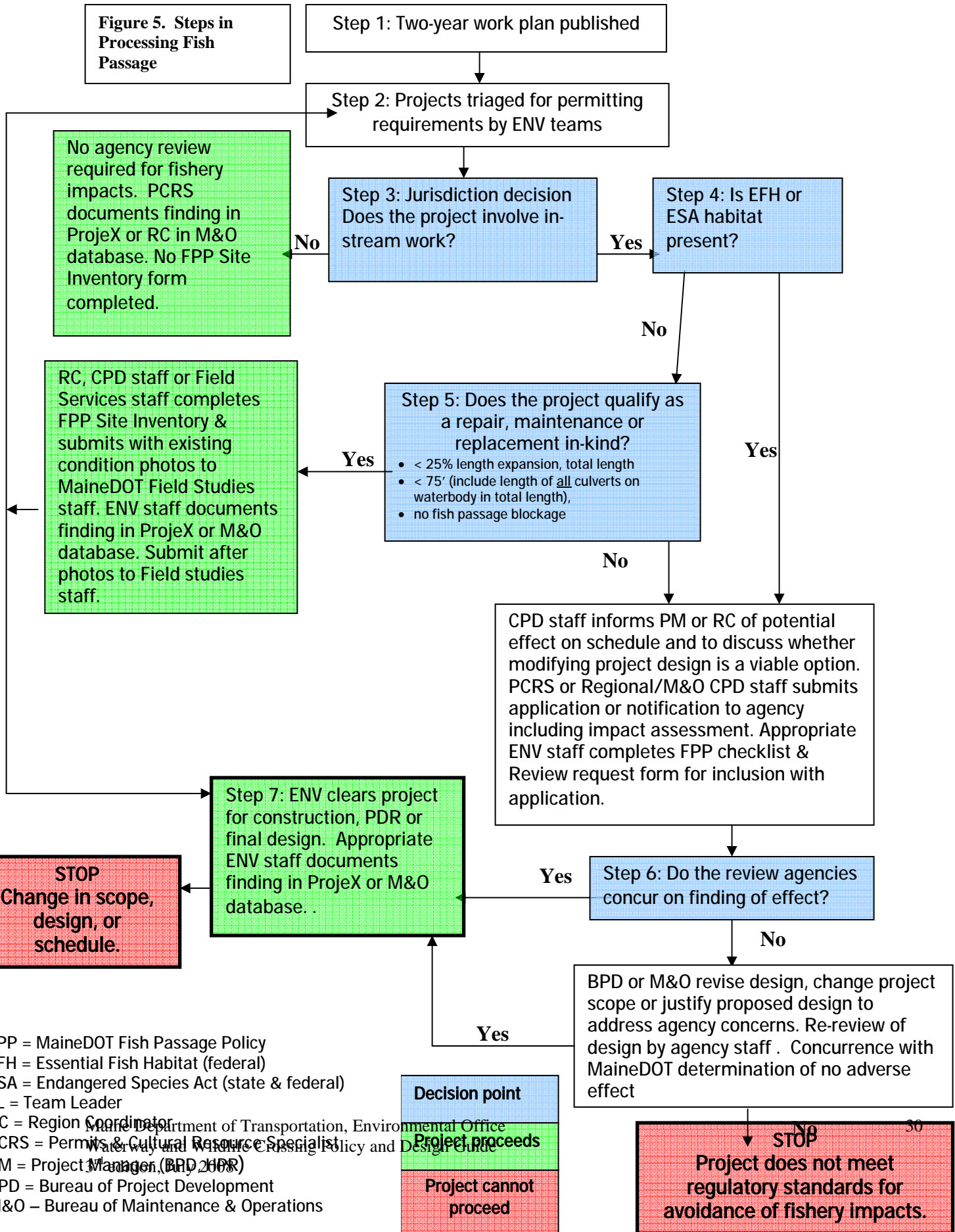
Maintenance projects are currently not included in the department's two-year work plan; however a proposed maintenance work schedule is compiled biennially. When maintenance

projects include the potential to provide, restore, or enhance fish passage, the process used to address fish passage is very similar, but may not require all steps due to exemptions or non-reporting status (see Figure 5). MaineDOT continually explores scoping procedures that are intended to build further efficiencies into the review process.

2. Project Monitoring and Evaluation

Projects completed under the terms of this document are monitored and evaluated for hydraulic performance, site stability and implied or actual use by fish. Monitoring results for any given year are documented in writing and by photographs/videos, presented to the appropriate fishery agency, and kept on file at MaineDOT. Annual reports documenting activities related to fish passage are available at http://www.maine.gov/mdot/environmental-office-homepage/other_environmental.php.

Figure 5. Steps in Processing Fish Passage



FPP = MaineDOT Fish Passage Policy
 EFH = Essential Fish Habitat (federal)
 ESA = Endangered Species Act (state & federal)
 TL = Team Leader
 RC = Region Coordinator
 PCRS = Permits & Cultural Resource Specialist
 PM = Project Manager
 BPD = Bureau of Project Development
 M&O = Bureau of Maintenance & Operations

Decision point

Project proceeds

Project cannot proceed

STOP

Project does not meet regulatory standards for avoidance of fishery impacts.

3. Post Construction

An internal MaineDOT Passage Policy Work Group was established to evaluate engineering practices, biologic and regulatory considerations associated with fish passage. This group assures that examples of successful practices are added to the Design Guide portion of this policy, as appropriate, so they can be used to design future similar projects. Measures that are unsuccessful are examined for the cause of failure and either eliminated as an alternative (with documentation) or modified in a way that makes them effective.

H. Recommendations

To reach MaineDOT's goal of effective, efficient, constructible, and timely projects, the following additional recommendations are provided.

- ❖ Policy and Guidelines. This guide serves as a “living” document for MaineDOT waterway and wildlife crossings, and will be kept current to address future needs and developments concerning resources or crossings. Major proposed changes will be sent to appropriate agencies for review and discussion before being incorporated into the document.
- ❖ Fish Passage Design Guide and BMPs. The design guidance established in this document will also be referenced as appropriate in Department manuals.
- ❖ Data Base. An existing data base is being modified to incorporate information from the Preliminary Site Inventory Form (Appendix B), which will be linked to related, existing MaineDOT data bases. This will help to identify and expedite future repair or replacement of crossings.
- ❖ Site Inventory Form. The site inventory form is also a living document and as such is continually evaluated to assure it reflects the most appropriate data for use in planning, design, construction, and maintenance.
- ❖ Inspection Protocol. MaineDOT will coordinate crossing inspections to identify specific passage considerations can be assessed and crossings replaced or repaired before they fail. This will also allow ample time for agency coordination.
- ❖ In-house Training. Potential users of this Passage Policy and Design guide will be offered training on how to use the information in this guide. These users include MaineDOT staff that coordinate environmental aspects, or design, construct, or maintain crossings.

SECTION 3:

AQUATIC ORGANISM PASSAGE

A. Background

In September 2005, Maine’s federal Programmatic General Permit (PGP) with the U.S. Army Corps of Engineers was modified by that agency to require passage of “aquatic organisms.” The term “aquatic organisms” denotes species that depend on waterways (rivers, streams, and wet drainages) and associated stream bank riparian corridor for part of their life cycle, such as breeding migration, foraging, or population dispersal. In addition to fish, aquatic organisms include groups of animals such as freshwater mussels, crayfish, aquatic insects, and herptiles (amphibians and reptiles collectively), as well as several mammalian species such as mink, river otters, muskrat, and other larger species. For purposes of this policy, this section addresses non-fish aquatic organisms. Table 5 below lists Maine herptile and mammal species that can be considered aquatic organisms for purposes of this policy.

As a result of the 2005 changes to the Maine PGP, all new stream crossings are required to span 1.2 times the bankfull¹ width. This measurement can be based on a reference reach outside the influence of the crossing structure. For example, if a stream is 10-ft. wide at bankfull, a 12-ft. structure is required. This ensures that adequate stream banks are provided in the crossing for species that utilize riparian habitat as travel corridors. In addition, an openness ratio² of 0.60 or higher is recommended for aquatic organism passage. Funneling can be accomplished by incorporating wing walls, fencing, or jersey barriers that are anchored into the slope and backfilled.

Just as transportation infrastructure may interfere with the movements of fish, a constructed crossing may also be an impediment to other aquatic organisms. Current research shows that blocking the dispersal of some of these species results in a lack of proper gene flow (Jackson, 2000). Those species able to traverse the roadway surface are subject to mortality through road kill. While many of the road kill animals appear to be common species, the consequences to the local populations of the loss of the animals may be “masked” by their apparent “commonness”. For example, recent studies in Downeast Maine and New York have shown that the population of snapping and painted turtles adjacent to roadways is predominantly female, largely due to their propensity for nesting in sandy gravel associated with roadsides (Steen et al., 2004; Gibbs et al., 2005). Largely as a result of road mortality, females in these populations are on the decline. It is likely that this trend is similar for other Maine turtle species with similar nesting habitat requirements. Road kill, estimated at a million animals per year nationally, coupled with inadequate gene dispersal, may be driving some aquatic organisms towards localized and even regional extinction (Jackson, 2000).

¹ Bankfull discharge is defined as $Q_{1.3}$.

² The openness aspect or “ratio” of a structure is defined as the width times the height of the structure, which is then divided by the total length of the structure. All units are in meters. Also, the openness aspect refers to what the wildlife species would see *above ground*—it does not include what portion of the structure is embedded below ground.

Table 5. Maine Herptiles and Mammals Dependent on Riverine Habitat⁺

Key: P = Preferred Habitat

U = Uses Habitat

Species	<i>Habitat Type</i>		
	Stream	River	Riparian
<i>Amphibians</i>			
Blue-spotted Salamander	U		U
Spotted Salamander	U		U
Red-spotted (Eastern) Newt	U		U
Northern Dusky Salamander	U		P
Four-toed Salamander	U		U
Northern Spring Salamander	P		U
Northern Two-lined Salamander	P	U	P
Northern Red-backed Salamander			U
American Toad	U		U
Northern Spring Peeper			U
Gray Treefrog			U
Bullfrog	U	U	U
Green Frog	U	U	U
Mink Frog	U	U	U
Wood Frog	U		U
Northern Leopard Frog	U	U	U
Pickerel Frog	P	U	U
<i>Reptiles</i>			
Common Snapping Turtle	U	P	U
Wood Turtle	P	P	P
Eastern Box Turtle*	U		U
Painted Turtle	U	P	U
Blanding's Turtle*	U	U	U
Spotted Turtle*	U		U
Common Musk Turtle	U	P	U
Northern Water Snake	U	U	U
Common Garter Snake	U		U
Eastern Ribbon Snake	U		U
Eastern Racer*			U
Redbelly Snake			U
<i>Mammals</i>			

Virginia Opossum			P
Masked Shrew			U
Water Shrew	P	P	U
Smoky Shrew			U
Pygmy Shrew			U
Northern Short-tailed Shrew			P
Star-nosed Mole	U	U	U
New England Cottontail*			U
Snowshoe Hare			U
Gray Squirrel			U
Beaver	P	P	P
White-footed Mouse			U
Meadow Vole			U
Rock Vole			U
Muskrat	U	U	U
Northern Bog Lemming*			U
Meadow Jumping Mouse			U
Woodland Jumping Mouse			U
Coyote			U
Red Fox			U
Gray Fox			U
Black Bear			U
Raccoon			P
Fisher			U
Ermine			U
Long-tailed Weasel			P
Mink	P	P	P
Striped Skunk			U
River Otter	P	P	P
White-tailed Deer			U
Moose	U	U	U

* Signifies state or federally-listed endangered or threatened species

+ Adapted from DeGraaf and Yamasaki, 2001.

B. Specific recommendations and requirements.

Stream crossings should provide aquatic organism passage with at least 1.2 times bankfull width and an openness aspect or ratio of at least 0.60 meters, when appropriate and practicable given species present, logistics and costs. As with fish species, appropriate and practicable design measures are based on the presence or absence of species of concern, biological health of the water course, upstream or downstream constraints, cost, feasibility, logistics, goals of resource agencies, and other site or project specific considerations.

For purposes of this guide, passage structures for aquatic organisms are divided into general groups and described below.

C. Herptile Passage

The status of herptile populations are at the forefront in Maine, the United States, and globally, as these species are currently experiencing significant declines and in many cases face extinction. Of the 30 species of frogs, turtles, snakes, and salamanders listed in Table 5, four are listed as state threatened or endangered, with four other species listed as Species of Special Concern (Maine Endangered Species Act, 12 MRSA 925 § 12803). Roadways are often cited as one of the contributors to the decline of these animals either directly through habitat destruction or road mortality, or indirectly by blocking access to critical habitat requirements (Forman, 2003).

Herptiles are typically wide-ranging species relative to their body sizes, with frogs and salamanders home ranges requiring at least several acres, while some wide-ranging turtles traverse several square miles or more. To limit adult mortalities as much as possible, stream crossings located adjacent to vernal pools and other wetlands adjacent to streams should consider passage and funneling for species that depend on these isolated, seasonal forest pools, such as state-listed Blanding's and spotted turtles, spotted and blue spotted salamanders, and wood frogs. These animals spend the majority of their life in uplands away from the breeding pools; salamanders can travel over 2,600 feet to get from their forested habitat to the breeding pools. Because salamanders and other herptiles travel primarily over land and not in water environments, several factors should be considered during crossing design.

Passage for organisms that use both terrestrial and aquatic environments can most simply be incorporated by maintaining natural substrate through the use of bottomless arches or boxes that span the waterway plus some or all riparian areas, or by upsizing existing drainage cross-culverts and backfilling them with native, natural bed material, loam and/or leaf-litter whenever possible. Drainage culverts may need to be designed so that the backfilled material is not washed-out during high water events, which may be avoided by providing a dry culvert above bankfull or flooding elevations, backfilling this structure with native substrate possibly from material grubbed from the project, or providing a dry "shelf" in the drainage culvert to provide passage "banks" during draining periods. Although dry shelves appear to be a relatively straightforward method of addressing herptile passage, they pose maintenance and construction challenges. Possible issues include confined space work subject to OSHA regulations, cost of hand-placing materials in confined spaces, longevity of mortared structures, and obstructions created by large woody debris common to most Maine streams.

Research in the Northeastern U.S. has also shown that some source of light may be required in the passage in order for herptiles to use them and it is recommended that in-structure light be provided through surface grating in the median above the structures if possible (Jackson, 2003). To date, logistics, costs, and comprehensive research has limited this application in Maine.

Funneling to the entrances of the structures may encourage use; this can be accomplished by incorporating wing walls, or fencing with jersey barriers or silt fence anchored into the slope and backfilled. An example of funneling system used with crossings is diagramed in Figure 6.

Figure 6. Example of Funneling System for Herptile Passage

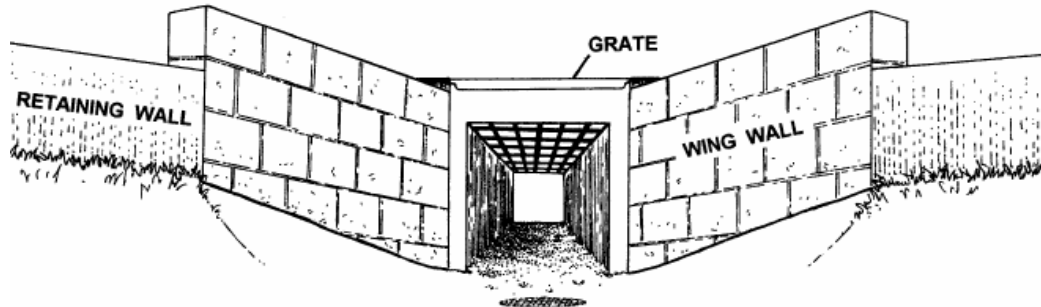


Figure 7. Arch culvert with funneling wall for herptiles and fencing for larger wildlife.

Germany. Source: Federal Highway Administration (http://international.fhwa.dot.gov/wildlife_web.htm)



D. Aquatic Invertebrates, including Mollusks, Crayfish, and Aquatic Insects

Aquatic macro-invertebrates, freshwater mussels, snails, horseshoe crabs, crayfish, and aquatic insects are a few examples of important components of healthy stream ecosystems. In addition to serving as important for food sources and biodiversity, several aquatic invertebrates are state or federally endangered or threatened species. Recognition of this importance and passage for these species is relatively new, in fact it is so new that very little research data (e.g., swimming speeds, seasonal movements) are available to use in the development of specific design concepts. Therefore, while passage for these species may need to be considered, MaineDOT will follow the guidance described below as applicable until adequate scientific research becomes available.

- Because these organisms live on, in, and under the stream bottom, natural bottom substrates should be maintained when possible.
- If natural conditions do not exist in the current structure or are not able to be maintained due to other constraints (e.g. budget considerations) hydraulic simulation (adding rocks and other substrate to the structure) should be considered for fish and aquatic organisms.
- Because freshwater mussels typically disperse in their glochidia larval stage by attaching themselves to fish, fish passage should be maintained or improved whenever possible.
- Just like fish, hanging outlets are barriers to crayfish movements and should be improved whenever possible.
- It is generally recognized that aquatic insects colonize stream reaches upstream of crossing structures by way of dispersal as adults or by drift from habitat further upstream. However, hydraulic simulation (adding rocks and other substrate to the structure) should be considered for aquatic insects.

SECTION 4: WILDLIFE³ CROSSINGS

A. Introduction

The Environmental Office at MaineDOT is developing Standard Operating Procedures (SOPs) for many of its permitting and authorization processes. The SOP for assessing wildlife passage, draft ENV-SOP-407-003, assists staff in determining when wildlife crossing strategies should be considered for MaineDOT projects/activities. This SOP is dynamic and will be updated as strategies are developed and evaluated. MaineDOT is also involved in collaborative studies with MDIF&W, SPO, DOC, USFWS, The Nature Conservancy, and Maine Audubon to map potential areas of functional habitat connectivity. These studies continue to add to MaineDOT's institutional knowledge and increase predictability of passage requirements based on the practicability, efficacy and cost effectiveness of evaluated wildlife passage approaches.

While improvements may be able to be made to water crossings to enhance wildlife passage near rivers and streams, terrestrial wildlife passage involves a different mindset than passages associated with waterways. Unfortunately, wildlife passage in the northeast is currently a fledgling science and data documenting the effectiveness of constructed passages is scarce. This is unfortunate because it severely limits the predictability of what modifications may be required to meet regulatory requirements and prevents ENV from including "rules of thumb" for when terrestrial passage will need to be provided. It is not yet well understood what makes crossing structures attractive to wildlife, although because many wildlife species have an affinity for waterways it is possible that upsizing or retrofitting existing stream crossings will benefit many species. However, there are many more parameters to consider beyond attraction of water flow, including the degree of openness of the structure, through-crossing visibility, vegetative cover and substrate, light inside the crossing, presence and degree of moisture, amount of human disturbance, and the integrity of the adjacent habitat. To provide habitat connectivity for all life stages and life history requirements of wildlife species, wildlife passages of varying types and configurations are necessary to provide permeability of the transportation system for the widest range of species.

Although drainage crossings are commonplace features in road corridors, little is known about their efficacy in maintaining or increasing road permeability and habitat connectivity for terrestrial wildlife. Crossing use by small- and medium-sized mammals was investigated along roads in Banff National Park, Alberta, Canada (Clevenger, et al 2001). An array of crossing types was sampled varying in dimensions, habitat and road features during the winters of 1999 and 2000. Expected passage frequencies were obtained by sampling relative species abundance along transects at the ends of each crossing. In Maine, wildlife use of drainage culverts has been incidentally observed (Figure 14) although the total range of species use and associated efficacies have not been determined.

³ For purposes of this document, "wildlife species" include all species of mammals found in Maine, many of which are listed in Table B2.1 above. Other species not listed in Table B2.1 include but are limited to larger species such as bobcat, Canada lynx, and marten, as well as several species of voles, mice, and other smaller yet ecologically significant species.

While wildlife passage is a relatively new concern in Maine, construction of wildlife passage in other parts of the US and worldwide has been ongoing, usually in response to potential impacts to a specifically identified species of concern. States and provinces such as New Hampshire, Massachusetts, Vermont, New York, Virginia, and Alberta have built and monitored wildlife passage structures, while Montana, Arizona and Ontario have published guidelines for passage design. MaineDOT has constructed several crossing structures designed for wildlife passage, but as of the date of this document they have not been in place long enough to draw general conclusions. These crossings have been constructed in response to specific commitments made during elevated NEPA processes or requirements imposed during state permitting. In these instances, wildlife biologists have confirmed the presence of an endangered or threatened species, a high value cold-water fishery, or a corridor with significant use of larger species, such as moose or deer, that would pose a risk to the traveling public were they to cross over road surfaces.

B. Background

Wildlife can be affected not only through road mortality, but also through fragmentation of habitat and disruption of travel corridors (Jackson and Griffin, 2000). Increased scientific documentation of adverse effects from habitat fragmentation are projected to result in increased regulatory oversight over this type of impact. This section covers regulatory requirements and non-regulatory recommendations for providing effective passage for wildlife species other than aquatic organisms. At the time of these revisions to the Policy and Design Guide, only Maine's Natural Resources Protection Act (NRPA) (38 M.R.S.A. §§ 480 A – BB), administrated by the Maine Department of Environmental Protection, contains specific regulatory standards relating to wildlife and wildlife habitat not otherwise covered under the federal Endangered Species Act or Migratory Waterfowl Act, or the Maine Endangered Species Act. Section 480-D (3) of the NRPA states that a permit will be granted provided that an “activity will not unreasonably harm any significant wildlife habitat, freshwater wetland plant habitat, threatened or endangered plant habitat, aquatic or adjacent upland habitat, travel corridor, freshwater, estuarine or marine fisheries habitat or other aquatic life.” For state-listed endangered or threatened species, proactive consultation with MDIF&W is required to assess potential adverse impacts on any part of the species life cycle or core habitat.

For purposes of projects/activities under the jurisdiction of the NRPA, “significant wildlife habitat” is further specified in Section 480-B (10) of that law. MaineDOT is a partner with MDIFW in the development of the Statewide Wildlife Conservation Plan and the subsequent implementation of the Wildlife Action Plan, which includes consideration of these regulated species. This partnership is consistent with FHWA guidance issued for the implementation of Sections 6001 and 6002 of SAFETEA-LU. Regulatory and resource agencies reviewing proposed projects/activities falling under the federal jurisdiction of the Army Corps of Engineers typically consider wildlife passage for species not considered threatened or endangered in relation to the use of riparian and wetland areas as primary habitat or travel corridors. State and federal threatened or endangered species are considered under the Endangered Species Act of 1973 and/or the Maine Endangered Species Act, under which USFWS and MDIF&W determine what accommodations must be made for species and habitat protection, and when incidental take permits are appropriate.

C. Design Considerations for Wildlife Crossings

As stated, wildlife passage and design criteria is a relatively new concept in Maine and New England. However, work in other states incorporates several basic concepts applicable to Maine's transportation systems. Based on current research, design considerations for wildlife passage⁴ include the following guidelines:

1. Species Present
2. Suitable Habitat
3. Appropriate Size
4. Placement Near or Within Natural Movement Corridors (if known)
5. Minimal Human Activity
6. Funneling/Fencing
7. Wildlife Accessibility
8. Ongoing Maintenance and Monitoring
9. Natural Substrate
10. Lighting

1. Target Species Present: The target species will typically be determined by the wildlife species which inhabit the adjacent habitat. Target species should be determined in conjunction with state and federal wildlife resources, to ensure that species of concern (i.e. rare, threatened, or endangered species) are accounted for, if possible.
2. Suitable Habitat: Suitable habitat relates to the type, amount, and future integrity of adjacent habitat for the target species at either end of the structure. Wildlife structures should only be incorporated where they will benefit wildlife species over the long term, foreseeable future. Some amount of investigation should be conducted into the background of the adjacent properties including the practices of the major landowners, trends in development within the municipality, and future expected growth patterns in the general area of the proposed crossing. While some species can adapt to some habitat loss or will utilize smaller parcels as travel corridors, other species are intolerant of human encroachment or require large or specific habitat types which need to be considered when planning passage systems.
3. Appropriate Size: This relates to the size of the target species to be passed. The size of the passage system will be limited by the physical site constrictions, which in turn may restrict the size of the target species. For example, a wildlife tunnel design to accommodate deer could not be practically installed in a three-foot thick roadbed. Appropriate size also takes into account the openness ratio of the structure. Generally speaking, the greater the openness ratio is of the structure the more likely it will be used by wildlife.

⁴ Adapted from Arizona Department of Game and Fish, Habitat Branch, November 2006
Maine Department of Transportation, Environmental Office
Waterway and Wildlife Crossing Policy and Design Guide
3rd edition, July 2008

Depending on the target species, another consideration of structure design is the height of the ceiling from the substrate. For example, large animals like deer and moose require a higher ceiling due to their size; however, research shows that a structure that has a lower ceiling, but still has the same openness ratio (i.e. wider) may be more conducive to passing species like bobcat and Canadian lynx. These specifications need to be determined for the target wildlife species during planning.

4. Placement Near or Within Natural Movement Corridors (if known): While wildlife species can be found anywhere on the landscape, baseline surveys should be conducted to determine if preferred travel corridors exist. Generally speaking, terrain features such as riverine corridors, wetlands, and gullies or ravines tend to be utilized as travel corridors by a variety of species. Other landscape features such as changes in habitat (e.g. wetland/upland interfaces, nearby agricultural fields, etc) also commonly contain travel corridors.
5. Minimal Human Activity: While some mammals become habituated, and may even thrive in the presence of humans (e.g. raccoons feeding in garbage or deer feeding on ornamental or fruit trees in suburban settings) many animals are secretive and do not adapt well to human disturbance. As stated in Guideline 2 above, the amount of human activity in the landscape should be taken into account when considering the placement of the structure. For example, wolves and bears are more likely to use passage systems where there is no nearby human activity and coyote use of crossings was negatively correlated with traffic volume. Distance from humans is the most important consideration in designing crossing structures for large carnivores (Arizona G&FD 2006). In addition, research from other states has demonstrated that traffic volume, noise levels and road width ranked high as significant factors affecting species' use of the crossings.
6. Funneling/Fencing: When possible, fencing should be incorporated to divert or funnel animals from crossing the roadway and entering the passage system. Research has shown that the lack of funneling dramatically decreases the effectiveness of passage systems. Examples of funneling are shown in Figure 3 (above) and in Figure 5 below.
7. Wildlife Accessibility: Placement of wildlife passages for wildlife accessibility needs to be considered, particularly for target species with limited mobility. For example, locating a passageway for herpetiles along a ledge outcrop, even though it is adjacent to a stream, would greatly limit the structure's efficacy at passing species such as turtles.
8. Ongoing Maintenance and Monitoring: Depending on the location and type of the passage system, maintenance of the structure may be minimal; however, over the long-term repair costs could be substantial if the structure is neglected, particularly if the crossing has been incorporated into a waterway crossing. Likewise, some monitoring of the structure should be conducted not only in the years immediately following construction but also at intervals throughout the life of the structure. To justify expenditure of state and federal funds on and design of a specialized crossing structure, resource agencies must provide information regarding what species use the structure, including specifying the target species. Data collected from the monitoring will guide the decision-making process on passage implementation for future projects.

Figure 8. Example of fencing to funnel wildlife through concrete box. Banff National Park, Canada. Source: Parks Canada website (http://www.pc.gc.ca/pn-np/ab/banff/docs/routes/chap1/sec1/routes1b_E.asp#miti)



9. Natural Substrate : Many wildlife species require a natural substrate at the bottoms of the passage systems as opposed to an artificial bottom, such as exposed metal or concrete. While substrate might be representative of the nearby habitat, it should be of a type suitable to the target species. Generally speaking, earthen material is suitable for the widest range of species, although bare earth without incorporating brush, woody material, or boulders with crawl spaces might not be conducive for smaller, more cover-dependent species.
10. Lighting: In the lack of, or even in addition to, an adequate openness ratio, some form of lighting may need to be incorporated within the passage structure to effectively pass certain species.

For multi-species passage or passage of aquatic dependent (e.g., herptiles, otter, mink, beaver, etc.) and terrestrial species in association with a watercourse, crossings should be wide enough to span the stream to allow for some dry ground or an artificial ledge beneath the bridge/crossing on one or both sides. An additional consideration is that rip rap or stone may be difficult or even impossible for ungulates and amphibians to traverse and should not be placed in front of or on the slopes adjacent to a passageway. If rip rap is required to protect the structure then it should be buried, back-filled with topsoil, and planted with native vegetation

D. Types of Wildlife Passage

In general, passage requirements for large, medium, and small mammals can be differentiated from one another, and as such are discussed in subsequent sub-sections (adapted from Arizona Game and Fish Department, Habitat Branch, 2006).

1. Large Mammals

Large mammals generally stand at least 1.5 ft at the shoulder, and have a length of at least 2 ft (not including tail). This group includes species such as moose, deer, bears, coyotes, and bobcat. As suggested by many studies, large mammals typically prefer large, open crossing structures, such as bridge underpasses and box culverts. To be conducive for use by large mammals, bridges must be at least 6 feet high or larger depending on the target species; have an openness ratio of at least 0.75, but preferably 0.9; be easily accessible to target wildlife; and have an associated chain link or woven wire fence height of approximately 8 feet along the length of project where use is concentrated to prevent large animals from jumping or climbing over lower fencing.

Research data indicates large mammal preferences for structures that are taller in height, shorter in length, with larger cross-sectional areas and openness ratios. These findings support studies indicating that an open field of view must exist in order for large mammals to use a bridge crossing. Basically, a large mammal is more likely to pass under a bridge if suitable habitat is clearly visible on the other side. The need for an open field of view also correlates with the preference for a large openness ratio. Recent research relevant to the Northeastern U.S. out of Ontario and New Brunswick and Massachusetts shows that large mammal passages, designed to accommodate species such as bobcat, deer, and moose, require openness ratios in the range of 0.6 – 1.0 (Ontario MOT 2005; Mike Phillips NBDOT Pers. Comm.). Funneling is usually an associated component and can be accomplished by incorporating wing walls, and fencing incorporated with 8-ft. fencing that can be tied into ROW fencing.

Locating a crossing near natural travel corridors is critical to successful use of these structures by target wildlife species. For many carnivore species, this means placing the structures so that a riparian corridor of sufficient width to provide cover for these species and their prey is maintained. Studies have indicated that all large mammals such as deer and moose are more likely to cross under bridges or viaducts if they have a clear view of the structure's entrance and exit with no overhead ledges as in Figure 8. For a typical low traffic volume, two-lane road approximately 30 ft wide, the cross-sectional area of the structure opening should be 22 sq ft to accommodate a large mammal. For a typical four-lane road, 75 ft or wider including back slopes, the cross-sectional area of the structure opening should be 60 sq ft.

Figure 9. Small bridge span for large wildlife passage. New Brunswick. Photo courtesy of NBDOT



Figure 10. Elliptical, metal culvert underpass (4 m high x 7 m wide) width earthen floor. Banff National Park, Canada. Source: Parks Canada, http://www.pc.gc.ca/pn-np/ab/banff/docs/routes/chap1/sec1/routes1b_E.asp#miti



2. Medium Mammals

Medium mammals include species such as opossum, skunk, raccoon, fox, mink, and hares/rabbit. Medium mammals generally range in height between 6 inches to 1.5 ft at the shoulder, and range from 16 inches to 2 ft in length. Crossings for medium sized mammals should incorporate the following parameters:

- a. Be at least 3 feet high depending on the species
- b. Have an openness ratio of at least 0.4
- c. Be easily accessible to the target species
- d. Have natural vegetation adjacent to the approach and entrances
- e. Have a fence height of approximately 3-6 ft to prevent medium mammals from jumping or climbing over. A fence material such as chain link or woven wire is recommended for species benefiting from funneling toward a crossing, such as herptiles.

Medium mammal preferences are generally for structures that are taller in height, shorter in length, with larger cross-sectional areas. The cross-sectional area of the structure entrance should become larger as the length of the structure increases to maintain a minimum openness ratio of 0.4. For a typical two-lane road (approximately 30 ft wide), the cross-sectional area of the structure opening should be greater than 12 sq ft to accommodate a medium mammal. For a typical four-lane road, 75 ft or wider including back slopes, the cross-sectional area of the structure opening should be 24 sq ft. For a road with six or more lanes, the cross-sectional area of the structure opening should be 30 sq ft.

Figure 11. Medium-sized mammal passage under US Route 89/91. Utah .



Figure 12. Medium-sized mammal passage under Territorial Highway. Loraine, Oregon. Photo by John Levenhagen



3. Small Mammals

This group includes species such as weasels, voles, and mice. Small mammals are generally a few inches high and up to 16 inches long. Crossings for small sized mammals should incorporate the following guidelines:

- a. Provide at least 1 foot of height with structure, depending on the species.
- b. Provide low stature natural vegetation surrounding the approach and entrances.
- c. Provide easy access for target species.

Weasels and deer mice used crossings for passage most frequently, whereas snowshoe hares were the most common small mammals using crossings based on a transects sampled in a study in Banff National Park in Alberta (Clevenger, et al.2001). Structural variables partially explained passage by weasels and martens. Weasel passage was positively correlated with crossing height but negatively correlated with crossing openness. Martens preferred crossings with low clearance and high openness ratios. High through-crossing visibility was important for snowshoe hares but not for weasels. The passage by weasels and snowshoe hares was positively correlated with the amount of vegetative cover adjacent to crossings

In many cases, passage for small mammals can be accomplished by installing or slightly upsizing drainage culverts . In Maine, there is documented use of concrete culverts by state-endangered New England cottontail to cross under I-95 in Kittery (Figure 11). To maximize connectivity across roads for mammals, future road construction schemes should include frequently spaced culverts of mixed size classes and should have abundant vegetative cover present near culvert entrances. Further work is

required to assess the effects of crossings on population demography and gene flow adjacent to large roads.

Figure 13. Small mammal shelf installed in culvert that passes water under US 93. Montana.



Figure 14. New England cottontail trail demonstrating use of drainage culverts under I-95. Kittery, Maine



E. Project Review Process

The Environmental Office at MaineDOT is developing Standard Operating Procedures (SOPs) for many of its processes. The SOP for assessing wildlife passage, draft ENV-SOP-407-003, will define when wildlife strategies will be considered and implemented for highway projects. These SOP's are dynamic and will also be updated as strategies are developed and evaluated. (Final SOP will be incorporated in Next Draft of this document).

MaineDOT is also involved in studies to map potential areas of habitat connectivity. These studies could also affect how wildlife passage is approached.

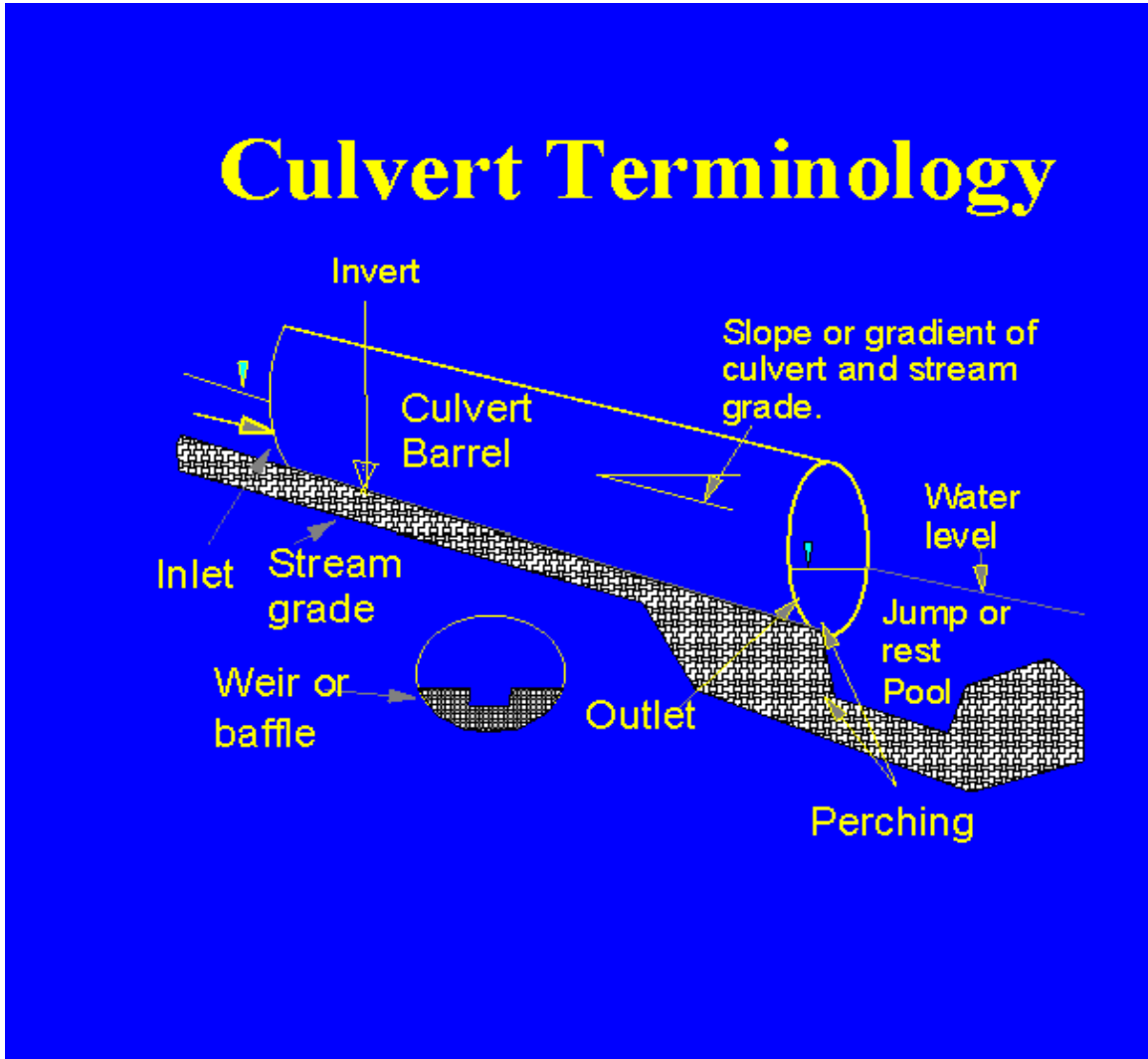
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Appendix A
Culvert Terminology



Appendix B

Preliminary Site Inventory Form for MaineDOT Fish Passage Policy Compliance

Note: Digital photographs (inlet, outlet, upstream and downstream reaches) must be taken and filed in PCRE File

Digital photographs must be taken both before and after Project completion (preferably after Project is stable)

Reviewer is responsible for FPP sign-off

I. General

Date of Review:	Reviewer:	PIN/Br. #:
Town/Township Name:	Route/Road Name:	Region:
Waterbody Name:	DeLorme Map Location:	Station:
Major Watershed:	Lat\Long\UTM:	

Section 7 Consultation Required? Yes No Unsure Species? Other

Essential Fish Habitat? Yes No Unsure Species?

II. Stream\Fisheries Observations

Upstream cover type: forested scrub/shrub grassy/agricultural Describe:

Downstream cover type: forested scrub/shrub grassy/agricultural Describe:

% Gradient upstream: 0-1 1-3 >3 % Gradient downstream: 0-1 1-3 >3

Existing structures or barriers: Upstream Downstream None observed Unknown

Describe (include height/distance away):	Flow Conditions:
--	------------------

Stream velocity through structure: f/s Measurement method: velocity meter estimated

Observed stream conditions/alterations:	
---	--

Culvert width: Matches stream Narrower than stream Wider than stream

Fish present: Yes No Assumed, but none observed None observed

Fish Observed: Upstream Downstream

Other aquatic organisms:

Upstream bed: bedrock boulder cobble gravel sand silt clay rubble/debris Not observed

Downstream bed: bedrock boulder cobble gravel sand silt clay rubble/debris Not observed

Downstream erosion? Yes No If yes, type? Relative severity: Minor Moderate Severe

Other observations:

III. Culvert Observations/Measurements

No. of structures: Structure type(s):

Structure height/diameter:	Width:	Length:	Slope (vert/horiz ft x 100): %
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Embedded invert: Yes No Unsure Approx. depth below substrate at inlet: At outlet:

Water depth in structure: at Inlet: at Outlet: Rust Line:

Inlet: Lifted? Yes No Outlet: Hanging? Yes No If yes, difference from invert to water level:

Outlet drop type: Vertical drop Cascade N/A Apron? Yes No Type:

Depth of water in scour pool:

Is existing structure passable to fish? Yes No Unsure If no, why?

IV. FPP Compliance (check all that apply)

FPP satisfied because:

- Replace in-kind
- Replacement structure will pass fish
- Culvert is in impounded water with sufficient depth to pass fish at all times
- Stream does not contain fish or other aquatic organisms
- Stream is tidal and water depth is sufficient to pass fish >50% of the time
- Other

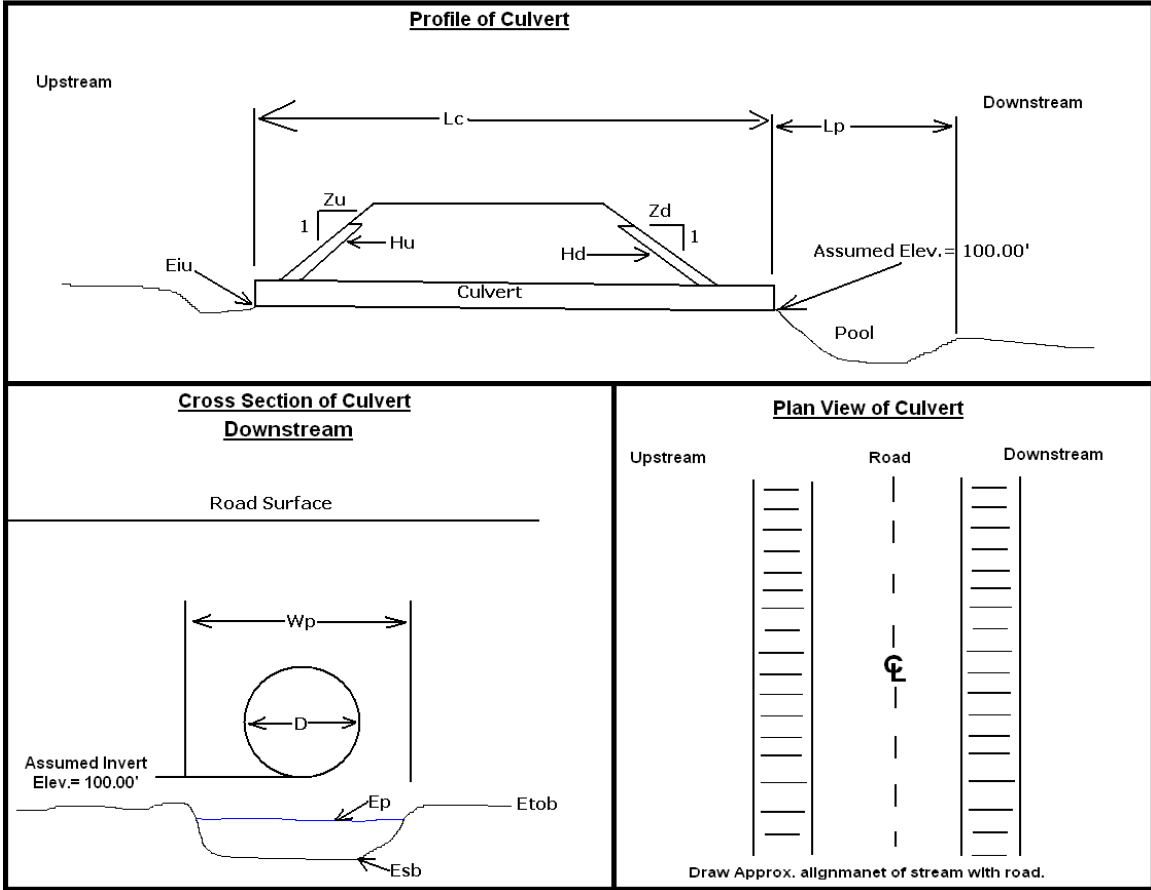
Structure needs further FPP review because:

- Existing structure does not pass fish;
- Replacement structure will not pass fish
- Project is not replacement in-kind
- Structure to be slip lined or invert-lined
- Hydrology of watershed needed
- Gradient of structure exceeds 1%
- Other

Revised 7/7/2006

Appendix C MaineDOT Culvert Data Form

Project Name: _____ Investigator's Name: _____ Date: _____
 Project PIN: _____ Culvert Location: _____
 Additional Notes: _____



All Dimensions in Feet		Existing		Proposed		Existing		Proposed	
L_c	Length of Culvert			E_r	Elev. of Road CL				
L_p	Length of Pool			E_{tob}	Elev. Top of Bank (DS)				
W_p	Width of pool			H_u^*	Headwall Treatment (US)				
E_{iu}	Elev. of Invert (US)			H_d^*	Headwall Treatment (DS)				
E_p	Elevation of Water (DS Pool)			Z_u	Slope Value (US)				
E_{sb}	Elev of Streambed one pipe diameter DS			Z_d	Slope Value (DS)				
E_b	Elev of Outlet Pool Bar								

Elevation of lowest downstream invert is assumed to be 100.00' and all other elevations are relative to it.
 • Types of Headwall Treatments: RR (Rip Rap), CC (Concrete), SB (Stone Block), V (Vegetation)

(EXISTING)

(PROPOSED)

All Dimensions in Feet		Pipe 1	Pipe 2	Pipe 3	Pipe 1	Pipe 2	Pipe 3
D	Diameter of Pipe						
Pt	Type of Pipe*						
Ps	Shape of Pipe**						

* Types of Pipes: RCP (Reinforced Concrete), CMP (Corrugated Metal), HDPE (High density Polyethylene), PA (Pipe arch), OB (open bottom), SB (Stone box) may enter multiple values

** Shapes of Pipes: Round, Oval (enter horiz. dim.), Box (enter horiz. dim.), Arch (enter horiz. dim.)

MaineDOT Contact Information:

Maine Department of Transportation, Environmental Office
State House Station #16 Augusta, ME 04333
207-624-3100

For Review Agency Use Only

Agency completing review: MDIF&W DMR ASC USFWS NMFS EPA

Do you concur with MaineDOT's determination? Yes No

Do you have additional concerns? Yes No

Do you have additional information about this resource that may prove valuable for this or future projects?
No Yes Describe:

Additional information requested:

Plan details ("Peter paper")	<input type="checkbox"/>
Cross sectional plans	<input type="checkbox"/>
Alternative analysis	<input type="checkbox"/>
Construction methods	<input type="checkbox"/>
Site/resource characteristics	<input type="checkbox"/>
Other	<input type="checkbox"/> Describe:

Additional information **your** agency can provide regarding this resource or species of concern:

Special conditions/comments:

Would you like MDOT to coordinate an on-site meeting? Yes No

Representative _____ **Date:** _____

Please forward your comments electronically or in hard copy to the contact for this project. Thank you.

**Appendix E:
Cost Analyses for Several MaineDOT Crossing Structures**

(Note: This table represents a sampling of projects that incorporated hard design features to provide aquatic organism passage. It does not represent a typical project.)

Project location	Resource name	Target species	Design measure	Total cost of design modification
Brownfield, Route 5	Burnt Meadow Pond outlet stream	Brook trout	Concrete fish ladder	\$190,000
Buckfield, Route 117	Bog Brook	Brook trout	Box culvert with weirs	\$370,500 ¹
Biddeford, South Street	Swan Pond Brook	Brook trout	Concrete fishway	\$180,600
Benedicta, Pond Road	Unnamed stream into Plunkett Pond		Embedded culvert with overflow	\$190,600
Gorham, Bypass		Brook trout, herptiles, moose, deer	Bridge spans (2)	\$1,000,000 ² each

¹ Original design proposed by fisheries agency cost \$1,000,000; modifying design saved approximately \$630,000.

² Original design included two 150-foot culverts with structural wing walls and herptile shelves at a cost of over \$1.5 million each.

PART III:
DESIGN GUIDE FOR FISH PASSAGE THROUGH CULVERTS

SECTION 1: WHY DESIGN FOR PASSAGE?

A. Introduction

This manual is intended for the design of new and replacement culverts, as well as culvert rehabilitations, that will not block passage of identified fish species at specified design flows. Engineers will find these design guidelines useful in the implementation of MaineDOT's crossing policy as documented in the companion volume to this work (MaineDOT, 2008a). The manual is intended for use by MaineDOT engineers and designers as well as other engineers designing waterbody crossings in an aquatic environment. Although passage of aquatic organisms is the regulatory and ecological target, little guidance exists at either state or national levels on design for passage of aquatic insects, crustaceans, or herptiles. Therefore, much of the design guidance in this document remains specific to fish species. Reference to "fish" in this guide is not intended to convey that MaineDOT only considers these species in its crossing design. In cases where the target species is another type of organism, site-specific design may vary. Because the design field associated with these crossings is rapidly evolving and highly specialized, at this time crossing design for passage should continue to be performed by or under the direct supervision of an experienced hydraulic engineer working with a fisheries biologist.

This manual is limited to culverts as described in Parts I and II; it does not address dedicated fishway passage structures and stream (geomorphic) simulation. Culverts are often the most desirable road crossing for small and medium sized streams from an engineering standpoint. However, it is recognized that from the larger perspective of aquatic organism passage (AOP) culverts are in fact less desirable than bridges and bottomless arches that preserve or simulate a natural stream bottom. It is recommended that the upcoming U.S. Forest Service design manual be used for stream simulation applications.

B. Culvert Barriers to Fish Passage

Several common conditions at culverts can create barriers to fish movement:

- excess drop in elevation at culvert outlet
- high velocity within culvert barrel
- inadequate water depth within culvert barrel
- turbulence within culvert barrel
- debris accumulation at culvert inlet

Barriers are created by several conditions. Culverts are usually uniform and sized to pass peak design flows, i.e., the 50-year flood (Q_{50}). They do not have the roughness and variability of natural stream channels and therefore do not dissipate kinetic energy effectively. Thus, velocities tend to be higher in a culvert than in the stream. This effect is amplified by the fact that existing culverts are often narrower than the stream,

constricting flow at the inlet. This may have the effect of increasing velocity in the pipe, creating turbulence at the inlet, and creating velocity-induced scour holes at the outlet. Outlet scour may induce a significant drop at the outlet. The last barrier condition, debris accumulation, is due to maintenance at flow constrictions.

New and replacement stream crossings can be designed to avoid the first four, hydraulics related, barrier conditions. The last condition, even in a well-designed culvert, depends on good maintenance attuned to the specific fish passage requirements of a culvert. Fish passage can be difficult to restore in rehabilitated and retrofit culverts. Mitigating design elements in addition to the basic culvert lining are usually needed in order to establish passage under specified conditions.

C. Design Objectives

1. General Objectives: In designing for fish passage through culverts, three objectives are paramount:

- maintain depth equal to or greater than the necessary minimum;
- keep velocity less than or equal to limiting maximum sustainable fish swimming speed (Table 4); and
- avoid excessive elevation drop at the outlet.

The issue of uninterrupted pipe length is related to flow velocity and the ability of a fish to transit a culvert. Culverts with interior grade control structures will generally offer adequate in-pipe resting areas for fish. Culverts longer than 75 ft (23 m) and without interior structures should be referred to MaineDOT's Environmental Office for determination of species-dependent length requirements.

Strictly speaking, these limiting values are determined by the target species and age class of interest, the time of year they are moving, and the direction they are moving in. This information is summarized in Table 4 in Part II of this Policy and Design Guide. These factors, combined with watershed hydrology and channel geomorphology, provide the information necessary for estimating an appropriate passage design flow.

2. Generic Design Standards: While species-specific design is always appropriate, the design process can be simplified by employing generic parameters that produce robust designs suitable for most species of interest in Maine. Therefore, MaineDOT recommends the following generic design standards as a starting point:

- design for passage during September/October low flow period;
- determine design flows using regression equations and also, whenever possible, field-based measurement;
- maintain at least an 8-inch water depth throughout the length of the culvert at design low flows;
- limit flow velocity to no more than 2 ft/s (0.6 m/s) (not including weir notches);
- limit drop in water surface elevation at outlet to 2 in;

- use average of median September and October flows as design flow;
- limit water level drop across grade control structures to 8 in (200 mm); and
- when weirs are employed, weir notches should be at least 8 in (200 mm) wide by 8 in (200 mm) deep. Calculated dimensions should be rounded to the nearest 2 in (50 mm) increment.

The design report shall include

- calculated water surface profiles through the culvert
- calculated Energy Dissipation Factors (EDF)
- passage hydraulic performance results for other months of passage

These generic standards constitute a starting point for design. This design is likely to be overly conservative and therefore may be difficult to realize in particular situations. Consideration should then be given to a species-specific design. The final design should satisfy any particular species requirements, for example as documented in Table 2 of the Fish Passage Policy. Final design may also deviate from these general objectives, depending on site-specific factors. Species-specific factors may allow for some relaxation of these generic standards. For example, many Maine fish species can actually pass over pool drops greater than 8 in (200 mm), and designing for larger drops (e.g., 12 in (300 mm)) permits a wider inter-weir spacing and therefore fewer weirs. Reducing or eliminating the weir notch invert submergence has a similar effect.

3. Atlantic salmon: Atlantic salmon are of special interest. The design low flow for salmon will be based on August median flow. Since salmon are strong swimmers and can jump, water level drops across grade control structures can be as large as 12 in (300 mm) and velocities as large as 8.5 ft/s (2.6 m/s) can be tolerated by adults.

SECTION 2: DESIGN CONSIDERATIONS

A. General Steps in Design for Culvert AOP Passage

The following steps are generally followed when addressing fish passage through culverts.

1. Identify valuable habitat for specific species and need for passage by fisheries biologists in Maine DOT, resource agencies, and regulatory agencies;
2. Determining of calendar periods when passage must be provided;
3. Estimate design flows during passage periods; and
4. Culvert design for a:
 - a. new pipe: size pipe for peak flow (50-yr or similar low-frequency event) capacity and passage performance by hydraulic analysis; check flow surface width for $Q_{1.3}$ in culvert against bankfull channel width; or
 - b. rehabilitated pipe: hydraulic analysis to check performance of proposed rehabilitation; design mitigation measures (e.g., weirs, baffles, outlet notch ramps) if fish passage is inadequate

B. Habitat Considerations In and Adjacent to Culverts

There are several aspects of fish habitat that warrant consideration in passing fish through culverts. Inside the culvert, the issue is the culvert bottom. For traditional enclosed circular culverts and multi-plate pipe arches, a natural bottom can be simulated with varying degrees of success by embedding the pipe and filling it with substrate, generally to a depth of 1 ft – 3 ft (300 mm – 900 mm). Detailed recommendations are given later in this report. Open bottom provide a natural, and therefore superior, bottom habitat and allows for hydraulic variability. However, such structures can cost significantly more than enclosed culverts.

Culvert inlets and outlets are often treated with riprap to protect the structure and prevent erosion and scour. The immediate culvert inlets and outlets usually merit extensive riprap in order to provide structural protection. With regards to stream bank stabilization, it is preferred that riprap be limited to an elevation somewhere in the 2-year to 5-year flow event stages; above this elevation, it is desirable that banks be stabilized by vegetation. Also, it is desirable that vegetation in the vicinity of inlets and outlets provide shading.

C. Section Design Approaches: New & Rehabilitated Culverts

Two basic design approaches are employed by Maine DOT. For new and replacement culverts, the preferred approach is to embed the culvert and match culvert dimensions and gradient to natural bankfull stream channel hydraulic geometry, subject to standard Maine DOT culvert design practices. This approach is in the spirit of simulating the

hydraulic aspects of the stream at fish passage flows, but stops short of creating a natural, variable bottom. The assumption is that by eliminating perched outlets and matching hydraulic geometry in the range of critical fish passage flows, fish passage is assured at those times of year when fish are also present in the adjacent natural channel. The validity of this assumption should be checked in each design. This approach simplifies design and construction and minimizes the hydraulic and hydrologic analysis necessary.

For culvert rehabilitation (e.g., by slip or invert lining), additional hydraulic analysis and design is necessary. In this case, hydraulic analysis is employed to estimate water velocities and depths under design flows. Analysis is also employed to design mitigation measures (e.g., weirs) needed to achieve velocities and depths that will pass fish.

For both new and rehabilitated pipes, grade control structures (i.e. weirs) can be used to provide both acceptable water depths and velocities. In particular, in-pipe weirs will be the preferred means for creating acceptable fish passage hydraulics in rehabilitated pipes. Culverts are typically rehabilitated by concrete invert lining and plastic slip lining. In both cases, the improved pipe is characteristically “smooth bore”, creating potential problems of excessive velocity and shallow depth. Weirs eliminate the roughness/smoothness objection by creating required backwater through the pipe. In-pipe weirs can also be constructed in new pipes; the use of pre-cast concrete pipe weir sections has been demonstrated; pre-fabricated plastic weir sections have also been introduced.

When culverts are not too steep, a single downstream weir may be enough to back water through the entire pipe length, thus resolving flow depth issues as well as resolving perched outlets. External downstream weirs may also be employed to back water to the first in-pipe weir, allowing fish to enter the pipe. In some instances, though, downstream weirs may be precluded by limited right-of-way and other access issues.

D. Hydraulic Considerations in Culvert AOP Passage

New and replacement culverts must be designed to pass the 50-year flow event (or “flood”) in accordance with Maine DOT Drainage Policy. Rehabilitated culverts should be evaluated for their ability to pass the 50-year flood, though the reduction in cross-sectional area and effects of AOP passage mitigation measures may reduce the pipe capacity. Peak flows (50-year or similar low-frequency event) should be estimated according to the methods used by Maine DOT in highway and bridge design.

In addition to the traditional peak flow design standard, culverts in identified fisheries should permit fish passage during a range of low flows. Two potential hydraulic problems are addressed in designing specifically for fish passage. First, water depth in the culvert may be inadequate to permit movement. Also, the velocity in the culvert may be too high for fish to swim against in an upstream direction.

These potential barriers to passage establish three design objectives, as summarized in Parts I and II of this document. Rarely, resource and regulatory agencies specify a

minimum depth and/or maximum velocity to be achieved. The two design objectives relate to depth and velocity:

1. Maintain adequate in-culvert water depth for identified species during low flow conditions to allow passage;
2. During periods of upstream movement, establish a design flow velocity no greater than species swimming “cruising” speed; and
3. Eliminate excessive drop at the outlet.

These design standards are species- and season-dependent. The depth and flow velocity should be determined by hydraulic analysis and checked against species-dependent criteria. In the case of proposed culvert rehabilitation, failure to meet standards will require mitigation measures or possibly a replacement pipe.

E. Energy Dissipation Factor (EDF) and Turbulence

The Energy Dissipation Factor (EDF) quantifies the capacity of a water body to dissipate the energy (potential or kinetic) of an entering flow stream. A high EDF implies high turbulence, potentially a barrier to fish passage. EDF is calculated as the rate of energy flux (i.e. power P) into the pool divided by the pool volume V,

$$EDF = P/V$$

For flow over a weir into a pool, potential energy (PE) is the appropriate measure; the kinetic energy (KE) of the water above the weir is assumed negligible. For discharge to an outlet pool, kinetic energy may be of interest. Alternatively, outlet pool EDF may be calculated as PE from the nearest upstream in-pipe weir. If there are no in-pipe weirs, then EDF can be calculated as PE from pipe inlet.

1. EDF - Potential Energy: Potential energy is calculated relative to the downstream pool elevation. For a pool drop of Δy , water above the weir has a potential energy (per unit volume) $PE = \rho g \Delta y$, where ρ is the density and g is the acceleration due to gravity. The rate at which this PE is conveyed to the pool (i.e., the power P of the water) is given by product of PE and volumetric flow rate: $P = PE \times Q$. Then EDF is calculated as

$$EDF = \rho g(Q\Delta y/V)$$

where ρg = specific weight of water (62.4 lb/ft³ or 9.8x10³ N/m³)
 Q = flow (ft³/s or m³/s)
 Δy = drop in water surface elevation (ft or m)
 V = volume of receiving pool (ft³ or m³)

For passage of salmonids, EDF should be no greater than 5 ft-lb/ft³/s or 250 J/m³/s (Washington State Dept. of Fish and Wildlife, 1999; Bureau of Land Management). An example of EDF calculation is given in Appendix 2D as part of the weir notch

sizing example. EDF can be controlled by decreasing Δy (drop in water surface across weir) and/or by increasing pool volume. Since pool volume depends on the distance between weirs, the culvert bottom slope ultimately imposes a critical constraint on achievable EDF.

2. **EDF – Kinetic Energy:** For discharge directly into an outlet pool, the energy to be dissipated can be taken as entirely kinetic. On a volumetric basis, $KE = \rho v^2/2$ and the energy transport rate is $P = KE \times Q$. Then EDF is calculated as

$$EDF = \rho(v^2Q/2V)$$

where ρ = density of water (1.94 (lb.s²/ft³/ft or 10³ kg/m)

v = flow velocity (ft/s or m/s)

F. Culvert Outlet Hydraulics: Energy Dissipation Pools

Compared to a natural stream reach of the same length, a culvert tends to dissipate less energy and therefore water exits a culvert with more kinetic energy than the stream reach. Unless properly addressed, this elevated energy may tend to dissipate by excavating an outlet scour pool. This pool may develop to such an extent that the culvert becomes perched and blocks fish passage at lower flows. The elevated exit velocities may also exceed the swimming capacity of fish and/or create turbulence that discourages fish from entering the culvert. These undesirable effects can be mitigated by constructing energy dissipation pools at culvert outlets. The pools also provide areas where fish can rest prior to their entry into culverts.

The following guidelines should be followed in pool design:

- Pool outlet should be maintained by a push bar or weir at the appropriate elevation and flow capacity. The design water elevation should enable fish entry into the culvert by backing water through the pipe to adequate depth (no in-pipe weirs) or at least to the first in-pipe weir;
- Pool should be stabilized to prevent scour and erosion. The pool outlet structure elevations should be secure so as to maintain desired hydraulic performance;
- Use of riprap should be minimized and concentrated on protecting the culvert inlet and outlet and pond outlet structure. The banks may also be protected at the discretion of design and environmental staff, typically in the range of the Q_2 to Q_5 stages. Although riprap should generally not be placed in the pool bottom, riprap should be placed from the culvert outlet to the pool bottom;
- Pool width should be at least 2 times the culvert span;
- Pool length should be at least 3 times the culvert span;
- For single barrel installations only, the culvert and pool centerlines should align;
- Pool should be at least 3 ft (0.9 m) deep at the design passage flow;
- Consideration should be given to placing at least three boulders in a triangular pattern in order to create fish resting areas. The boulders should be approximately 3 ft (0.9 m) in diameter (or 2.5 ft (0.75 m) diameter for culvert $D \leq 5$ ft (1.5 m));

- Pool outlet structure (push bar, weir or channel) should be designed for hydraulic consistency with in-culvert weirs and to develop needed backwater at culvert exit;
- Voids in outlet riprap should be filled with smaller rock to prevent underflow and throughflow;
- If a pool does not back water into culvert for the design period, check that pool Energy Dissipation Factor (EDF) is no greater than 5 ft-lb/ft³/s (= 250 J/s/m³); and
- Culvert inlet and outlet should be sealed to prevent underflow.

Scour pools, either natural or constructed, will often be found at existing culverts. MaineDOT general practice will be to retain these pools when such pipes are replaced while taking measures to eliminate or reduce any outlet drops that may have developed. In the case of new culvert locations, the decision to construct outlet pools will be taken on a case-by-case basis, as they may be undesirable in particular circumstances, particularly if predation of resting fish is expected. Also, right-of-way complications may limit the space available for outlet pools.

G. Hydrology and Design Flows for AOP Passage

The passage design flow depends on the time of year for passage, which in turn depends on the species of interest. In general, fish are moving from April through June and September through October; the low-flow months of high summer are periods of lower activity. Final determination of design movement periods should be based on Table 4 in Part II of this document and consultation with ENV staff and the several resource agencies. Design flows will have to be assigned on a case-by-case basis, since they are dependent on both watershed and passage period, which depends on species of interest.

The design flows may be determined by several different methods:

1. Site inspection, channel geometry measurements, and flow measurement during periods of fish movement;
2. Hydraulic calculation from channel geometry measurements and specified or known flow depths for fish passage;
3. Estimation by USGS regression equations for monthly median flows (Dudley, 2004; Appendix 2A); and/or
4. Correlation to similar, gauged watersheds

When using the equations for median monthly flows, the estimates for September and October are significantly lower than for April through June. Therefore, using the average of the September and October medians should produce a conservative design that also maintains needed depths during the late spring, higher flow months. The median flow regression equations are tabulated in Appendix 2A; easy-to-use look-up charts are also given for May, June, September, October, and the September-October average.

Method (1) is the single best method but it may not always be possible to collect data during fish passage periods. Except for winter months, data for method (2) can always be collected and therefore hydraulic estimation should be performed in most cases. Method

(3), regression calculation, should always be carried out because it does not require any field work and only requires data from paper maps or available as GIS coverage from the Maine State GIS Internet web site. Ideally, at least one field-based flow estimate should be prepared along with the regression estimate. Method (4), also statistical in nature, requires a broader understanding of watershed hydrology but allows for a more comprehensive hydrology/hydraulics evaluation.

In support of establishing good measurement-based flow estimates, some sites may warrant installation of a simple staff gage as soon as possible after the need for passage has been established. This will allow for efficient collection of stage data during various flow conditions. Furthermore, final designs for sensitive sites may also include provision for a staff gage so that performance of the new or rehabilitated culvert can be evaluated.

Strictly speaking, the target flow for passage design should be species-dependent. Ultimately, the species type, age, direction of movement, and month(s) of movement should all indicate the flow or multiple flow values that will govern the design for fish passage, as summarized in Table 4 of Part II. As a practical matter, this approach complicates a design process which invariably occurs within a context of sharply limited alternatives. MaineDOT therefore recommends that in the absence of site-specific data, it is sufficient to execute design on the basis of the average of the September and October median monthly flows. This value is close to the lowest baseflow value of the year; if adequate depth is obtained this with flow then higher depths will be obtained for the remainder of the year.

Only a handful of species move upstream to spawn during springtime higher velocities. If one of these species is known to be of interest, then the culvert should be designed for the species-specific period and flow.

Salmon are of particular interest and August has been identified as a period of salmon movement and therefore is the designated low flow design period for salmon. Also, according to the regression equations, August is the lowest average monthly flow.

H. New and Replacement Culverts: Hydraulic Geometry Matching

Designing new and replacement culverts for AOP passage is generally simpler than retrofitting existing pipes. The following guidelines should be followed:

- Employ corrugated elliptical pipe arches with the largest feasible corrugations whenever possible to maximize roughness;
- Embed pipe: for nominal diameter (or rise) $D < 48$ in (1200 mm), embed pipe invert 6 in (150 mm) in stream bed; $D \geq 48$ in (1200 mm), embed pipe invert 12 in (300 mm); allow embedded pipe to fill with natural substrate;
- If outlet pool is present, check that pool push bar creates at least 6 inch (150 mm) water depth through pipe;

- Match pipe and stream flow geometry: flow depth and width in the pipe at bankfull flow Q_{bf} (approximately 1.3-year return period) should approximate depth and width in the stream;
- Place pipe with zero slope, or as nearly flat as possible, not to exceed 3%;
- Size pipe for peak flow: pass the 50-year flood (100-year for $D \geq 10$ ft (3000 mm)); accounting for the capacity lost to embedding; and
- Check fish passage performance: perform hydraulic analysis for depth and velocity during fish passage flows; irregular cross-section flow area (due to embedding and elliptical section) should be accounted for.

The new culvert should not constrict flow at the inlet over the range of design flows, as this will increase flow velocity and attendant kinetic energy complications. If a constriction cannot be avoided, then in-culvert weirs for water level control should be investigated.

Figure 15 shows an embedded circular pipe along with equations in Table 6 for calculating basic geometric quantities. Table 7 gives equations for embedded pipe arches; Table 8 gives corresponding tabulated values. Note that current practice does require that embedded pipes be filled with substrate to the stream channel bottom elevation; it is assumed that the embedded pipe will fill / empty naturally over time.

Figure 15: Embedded Circular Pipe

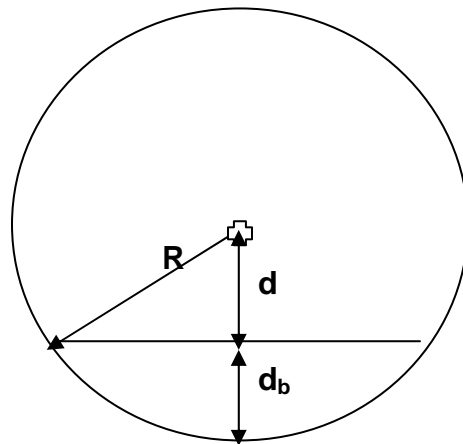


Table 6: Equations for Embedded Circular Pipe Geometry

Radius; diameter; embedded depth	$R; D = 2R; d_b$
Distance from bed to pipe center	$d = R - d_b$
Bottom embedded width	$w_b = 2\{d_b(D-d_b)\}^{1/2}$
Embedded Area	$A_b = R^2 \cos^{-1}[(R-d_b)/R] - dw_b/2$
Open Area	$A_o = \pi R^2 - A_b$
Embedded Perimeter	$P_b = D \cos^{-1}[(R-d_b)/R]$
Open Perimeter	$P_o = \pi D - P_b$

These equations can be used to approximate elliptical pipes, with pipe rise substituted for diameter. More exact results for elliptical pipes can be calculated with the following equation:

$$A = b (\text{pipe rise})^a$$

The coefficients a and b are given in Table 7. Note that two sets of coefficients are given, for corner radii of 18 in (457 mm) and 31 in (787 mm). These coefficients were developed by regression analysis from the exact tabulated areas in Tables 9a and 9b, respectively. The tables can be used in place of the equations.

Table 7: Function Coefficients for Open Area in Embedded Pipe Arch

Corner Radius		Depth of Embedment			
		0 in (0 mm)	6 in (150 mm)	9 in (225 mm)	12 in (300 mm)
18 in	a	2.246	2.316	2.371	2.428
	b	0.743	0.613	0.530	0.453
31 in	a	2.260	2.291	2.320	2.351
	b	0.631	0.571	0.524	0.475
457 mm	a	2.246	2.316	2.371	2.428
	b	0.995	0.893	0.823	0.752
787 mm	a	2.260	2.291	2.320	2.351
	b	0.859	0.807	0.766	0.721
Equation: open area $A = b \times (\text{pipe rise})^a$, in (ft, ft ²) and (m, m ²)					

Table 8a
OPEN AREA IN EMBEDDED PIPE ARCH (U.S. Customary)

	Span (ft)	Rise (ft)	Onen Area (ft ²)			
			Depth of Embedding (in)			
			0 in	6 in	9 in	12 in
Corner Radius = 18 in	6.08	4.58	22.03	19.95	18.64	17.24
	6.33	4.75	24.00	22.17	20.83	19.37
	6.75	4.92	26.17	24.47	23.06	21.54
	7.00	5.08	28.29	26.36	24.88	23.29
	7.25	5.25	30.53	28.38	26.82	25.15
	7.67	5.42	32.94	30.94	29.34	27.60
	7.92	5.58	35.23	33.01	31.32	29.51
	8.17	5.75	37.70	35.20	33.41	31.51
	8.58	5.92	40.27	38.01	36.27	34.27
	8.83	6.08	42.87	40.34	38.44	36.40
	9.33	6.25	45.78	43.48	41.59	39.50
	9.50	6.42	48.44	46.02	43.89	41.72
	9.75	6.58	51.29	48.42	46.29	44.02
	10.25	6.75	54.32	51.82	49.74	47.43
	10.67	6.92	57.48	55.11	52.96	51.00
	10.92	7.08	60.61	58.04	55.90	53.49
	11.42	7.25	64.01	61.61	59.61	57.25
	11.58	7.42	67.08	64.49	62.24	59.83
	11.83	7.58	70.40	67.59	65.24	62.61
	12.33	7.75	74.09	71.47	69.30	66.73
12.50	7.92	77.40	74.58	72.15	69.51	
12.67	8.08	80.93	77.85	75.59	72.39	
12.83	8.33	85.48	82.07	79.33	76.38	
13.42	8.42	88.44	85.39	82.84	79.89	
13.92	8.58	92.52	89.67	87.30	84.50	
14.08	8.75	96.25	93.19	90.55	87.65	
14.25	8.92	100.07	96.76	94.16	90.84	
14.83	9.08	104.57	101.50	98.95	96.21	
15.33	9.25	108.90	106.02	103.61	100.77	
Corner Radius = 31 in	15.50	9.42	112.93	109.86	107.30	104.28
	15.67	9.58	117.09	113.81	111.08	105.54
	15.83	9.83	122.64	119.11	116.17	112.73
	16.42	9.92	126.19	122.91	120.18	116.96
	16.58	10.08	130.55	127.05	124.13	120.68
	13.25	9.33	97.69	95.03	92.68	90.27
	13.50	9.50	101.79	98.94	96.58	93.90
	14.00	9.67	106.29	103.59	101.34	98.70
	14.17	9.83	110.24	107.38	104.96	102.24
	14.42	10.00	114.53	111.46	108.91	106.01
	14.92	10.17	119.28	116.39	113.98	111.14
	15.33	10.33	123.84	121.07	118.76	116.05
	15.58	10.50	128.39	125.47	123.03	120.17
	15.83	10.67	133.08	129.89	127.23	124.10
	16.25	10.83	137.80	134.85	132.39	129.51
	16.50	11.00	142.60	139.49	136.89	133.86
	17.00	11.17	147.81	144.67	142.06	138.99
	17.17	11.33	150.80	147.65	145.03	141.94
	17.42	11.50	157.56	154.24	151.47	148.22
	17.92	11.67	163.02	159.86	157.23	154.12
18.08	11.83	167.92	164.60	161.83	158.56	
18.58	12.00	173.54	170.36	167.71	164.58	
18.75	12.17	178.64	175.30	172.52	169.23	
19.25	12.33	184.47	181.25	178.57	175.42	
19.50	12.50	190.01	186.63	183.83	180.52	
19.67	12.67	195.37	191.82	188.91	185.44	
19.92	12.83	201.11	197.39	194.29	190.63	
20.42	13.00	207.17	203.64	200.69	197.21	
20.58	13.17	212.72	209.00	205.91	202.25	

Table 8b
OPEN AREA IN EMBEDDED PIPE ARCH (metric)

	Span (m)	Rise (m)	Onen Area (m ²)			
			Depth of Embedding (mm)			
			0 mm	150 mm	225 mm	300 mm
Corner Radius = 457 mm	1.855	1.397	2.048	1.854	1.733	1.602
	1.931	1.448	2.231	2.061	1.936	1.800
	2.058	1.499	2.433	2.275	2.143	2.002
	2.134	1.550	2.630	2.450	2.313	2.165
	2.210	1.601	2.838	2.638	2.493	2.338
	2.337	1.651	3.062	2.876	2.727	2.565
	2.414	1.702	3.275	3.068	2.911	2.743
	2.490	1.753	3.504	3.272	3.105	2.929
	2.617	1.804	3.743	3.533	3.371	3.185
	2.693	1.855	3.985	3.750	3.573	3.383
	2.846	1.905	4.255	4.041	3.866	3.672
	2.896	1.956	4.503	4.278	4.080	3.878
	2.973	2.007	4.767	4.501	4.303	4.092
	3.125	2.058	5.049	4.817	4.623	4.409
	3.252	2.109	5.343	5.123	4.923	4.740
	3.328	2.160	5.634	5.395	5.196	4.972
	3.481	2.210	5.950	5.727	5.541	5.321
	3.532	2.261	6.235	5.994	5.785	5.561
	3.608	2.312	6.544	6.283	6.064	5.820
	3.760	2.363	6.887	6.643	6.441	6.203
3.811	2.414	7.194	6.932	6.706	6.461	
3.862	2.464	7.522	7.236	7.026	6.729	
3.913	2.541	7.945	7.628	7.374	7.100	
4.090	2.566	8.221	7.937	7.700	7.426	
4.243	2.617	8.600	8.335	8.115	7.854	
4.294	2.668	8.946	8.662	8.417	8.147	
4.345	2.718	9.302	8.994	7.823	8.444	
4.522	2.769	9.720	9.434	9.197	8.943	
4.675	2.820	10.122	9.855	9.631	9.367	
Corner Radius = 787 mm	4.726	2.871	10.497	10.212	9.974	9.693
	4.776	2.922	10.884	10.579	10.325	9.810
	4.827	2.998	11.399	11.071	10.798	10.478
	5.005	3.023	11.729	11.425	11.171	10.872
	5.056	3.074	12.135	11.809	11.538	11.217
	4.040	2.846	9.080	8.833	8.615	8.391
	4.116	2.896	9.461	9.197	8.977	8.728
	4.268	2.947	9.880	9.629	9.420	9.174
	4.319	2.998	10.247	9.981	9.756	9.503
	4.395	3.049	10.646	10.360	10.123	9.854
	4.548	3.100	11.087	10.819	10.595	10.331
	4.675	3.150	11.511	11.254	11.039	10.787
	4.751	3.201	11.934	11.663	11.436	11.170
	4.827	3.252	12.370	12.073	11.826	11.535
	4.954	3.303	12.809	12.534	12.306	12.038
	5.030	3.354	13.255	12.966	12.724	12.442
	5.183	3.404	13.739	13.447	13.205	12.919
	5.234	3.455	14.017	13.724	13.481	13.193
	5.310	3.506	14.645	14.337	14.079	13.777
	5.462	3.557	15.153	14.859	14.615	14.326
5.513	3.608	15.608	15.300	15.042	14.738	
5.666	3.659	16.131	15.835	15.589	15.298	
5.716	3.709	16.605	16.294	16.036	15.730	
5.869	3.760	17.147	16.847	16.598	16.305	
5.945	3.811	17.662	17.347	17.087	16.779	
5.996	3.862	18.160	17.830	17.559	17.237	
6.072	3.913	18.693	18.348	18.059	17.719	
6.225	3.963	19.257	18.928	18.654	18.331	
6.275	4.014	19.772	19.427	19.139	18.799	

SECTION 3: SITE-SPECIFIC DESIGN MEASURES

A. Steeply Sloped Streams

The approach of matching pipe flow and depth to the natural stream works best with gentle slopes. Steeply sloped streams (slope $S > 3\%$) require extra care and will likely require mitigation through design (e.g., weirs or baffles). Embedding pipes to below natural stream bed elevation may inadvertently allow headcutting to propagate upstream of the culvert inlet. Therefore, pipes should be placed on the natural stream bottom when slope exceeds 3%. Furthermore, the inlet should be armored to discourage headcutting. Hydraulic analysis will likely indicate the need for in-pipe grade control in order to maintain adequate water depths. Downstream control may also be needed.

B. Rehabilitated Culverts - Corrective Measures

Existing culverts can be rehabilitated by slip lining and by invert lining. However, linings may reduce both cross-sectional flow area and surface roughness, with a possible net effect of decreasing flow depth and/or increasing flow velocity. (Corrugated aluminum structures used to line larger (typically > 10 ft diameter) culverts have essentially the same roughness as the original corrugated steel and thus do not markedly increase velocity.) Because of this result, resource agencies usually refer to slip or invert lining as their least preference option. The simplest approach to maintaining passage is to install a new culvert designed for consistency with the prevailing stream hydraulic geometry, though budgetary and other constraints may argue against replacement. If the culvert is on an identified fishery, then design measures should be anticipated in order to insure AOP passage under specified conditions.

When selecting a passage mitigation measure, the first step is to determine if the lined culvert will be a barrier to passage by appropriate hydraulic and hydrologic analysis. Target design flows are chosen according to guidelines presented here and in the Part II. Then the lined pipe is evaluated for acceptable depth and velocity, according to the target species. In general, if downstream control on shallow water depths does not previously exist, then internal as well as external weirs are likely necessary.

When a pipe is lined, the invert is raised by approximately 5 in (125 mm) due to the concrete or plastic lining. This may create a slightly hanging invert or a drop too great for fish to pass over. This effect is separate from the hydraulic aspects of depth and velocity. A sluice channel in the outlet, combined with one or more in-pipe weirs, can be employed to eliminate this drop. Alternatively, downstream external weirs can also be used, though right-of-way complications may eliminate this option.

Culvert hydraulic analysis can be performed with software such as *HY8*, *FishXing* or equivalent proprietary software for the design flows and incorporating tailwater conditions as determined by site inspection. If flow depth is too shallow or velocity too high, the following general measures suggest themselves for increasing depth. Useful

countermeasures include: (1) tailwater control structures (weirs) installed downstream and/or (2) weirs installed in the culvert.

When considering corrective measures, the first choice should be simple downstream weirs. Downstream weirs are particularly useful if a perched outlet is the major problem. Depending on the severity of the perch, more than one weir may be needed. As noted, right-of-way limitations may rule out this option or require an elaborate outlet fishway. Downstream weirs may also be useful for maintaining adequate water depths in culverts that are not too steep. External weirs may offer advantages in construction and maintenance over other available measures, especially for smaller diameter culverts. Plunge pools should follow the guidelines given above.

When the lining-induced drop is not too great, and if downstream weirs are not an option, a simple cutout notched sluice channel in the bottom of the culvert and extending up into the culvert may provide adequate water depth. However, by itself, this cutout channel is usually not adequate. Some potential problems include high velocity within the channel and inadequate depth above the termination of the cutout. In most cases such an outlet will need to be combined with grade control, within the pipe, downstream, or both.

In steeper pipes, in-culvert grade control achieved with simple pool-and-weir sequences should be considered. This approach is limited to larger pipes ($D > 5$ ft (1500 mm) minimum, and preferably $D > 6$ ft (1800 mm)). These measures will now be discussed in more detail.

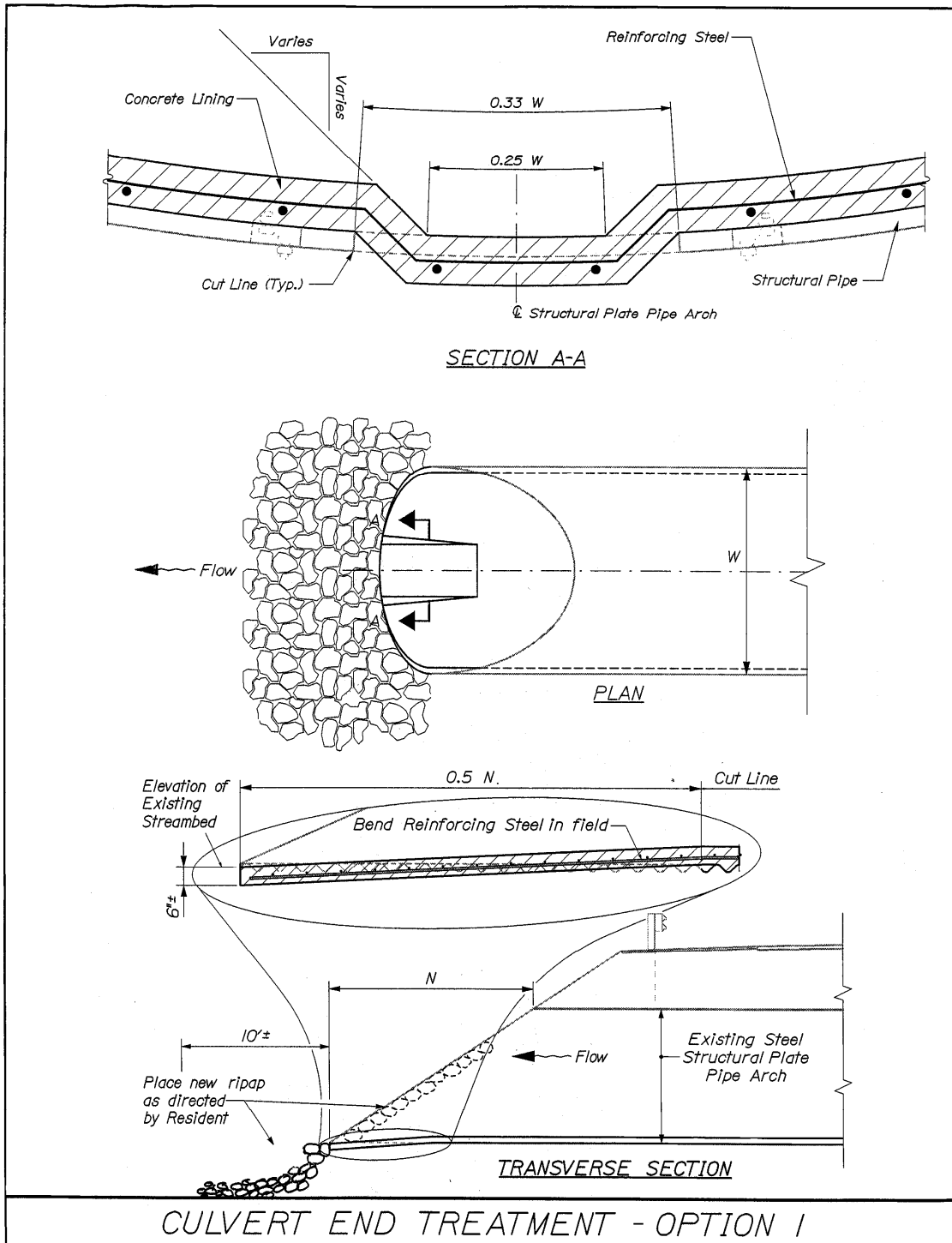
C. Culvert End Treatments for AOP Passage – Cutouts or Notched Outlets

A culvert lining raises the outlet invert. If the induced jump is modest, it can be mitigated by building a ramped notch (cutout or sluice channel) into the culvert bottom. The outlet notch invert is at stream grade, providing a continuous stream/culvert bottom elevation. The channel returns to the prevailing culvert invert elevation some distance into the culvert.

Typical details for end treatment options are shown in Figure 16. This treatment includes a riprap apron to provide a smooth transition from stream bed to the pipe edge. The notched channel should be sized to run full at low flow.

This treatment is used primarily to eliminate hanging inverts. End treatments by themselves will not correct excessive velocities or inadequate depths farther up the culvert. Therefore, they will probably be used with in-culvert grade control. Hydraulic analysis should be performed to check that: (1) adequate flow depth is achieved throughout the pipe; and (2) the velocity standard is not exceeded in either the pipe or notch channel.

Figure 16: End Treatment to Eliminate Drop



D. Downstream Grade Control Structures (Weirs)

Downstream weirs are used to establish grade control, i.e., to back water up into the culvert to the needed depth. It may be possible to maintain adequate depth and velocity solely with external weirs. In a sloping culvert, the minimum depth must be achieved at the culvert inlet. This depth and location helps to fix the design parameters of the downstream weirs; the design flow completes the determination of the weir parameters. Specific weir dimensions and their calculation are discussed in detail for in-culvert weirs.

Drops in water level are created at weirs and this drop may itself constitute a barrier to passage. The drop at any particular weir should ordinarily be limited to 8 in (200 mm) or a species-specific value in order to allow for passage over the weir, and the weir notch should generally be submerged 4 in (100 mm) on the downstream side. Thus, several weirs in series may be needed to create the needed tailwater elevation. The distance between weirs should be about 150% of the stream width in smaller streams, with a target minimum spacing of 16.5 ft (5 m), up to 33 ft (10 m) in larger streams. Actual spacing depends on stream slope. For reasons of cost and downstream impact, the number of structures should be kept to a minimum.

A cost-effective approach to weir construction is to employ standard concrete barrier (e.g., Jersey barrier) sections. Standard Maine DOT weir dimensions are used and notch width is calculated as detailed elsewhere in this report.

When aesthetic considerations are important, weirs can be constructed of natural materials, e.g., logs on a stone foundation in smaller streams; weirs on larger streams may be constructed of rock. The simplest weir extends straight across the stream; an alternative plan form is V-shaped, pointing upstream. The log ends should be anchored to stone or block on the stream bank and keyed into the bank. The banks in the vicinity of the log ends should be riprapped to prevent scour and channel migration at higher flow. The foundation stones should be sized to withstand the 100-year flood and wrapped in geotextile fabric so that they stand as a unit. The wrap also seals the log structure and forces more of the water over the weir or through the spillway, rather than between the logs. The weir face can be stacked vertically or angled downstream; angling creates quiescent water beneath the crest where fish can rest. The weir should be square-notched, according to the idea that fish will be attracted to and pass through the water spilling through the notch. The notch should be sized to flow full at the design passage flow using methods described below. Details for a log weir (grade control) structure (i.e., weir) are shown in Figures 2.3 and 2.4.

The use of downstream grade control will require stream bank protection and anticipation of flow around the ends of the structure. The natural stream banks should be at least 6" – 12" above the top of the weir. It is essential that any grade control structure be keyed into the stream bed and banks so as to prevent flow around and under the structure.

External weirs can create access and right-of-way issues, especially when a series of weirs is needed to obtain the necessary tailwater. With typical inter-weir spacing of 10 ft – 16.5 ft (3 m – 5m), several weirs will probably extend beyond existing right-of-way and thus may not be a practical solution. If additional drainage easement cannot be obtained, in-culvert weirs should be considered for larger pipes ($D \geq 5$ ft (1500 mm)).

Alternatively, a compact fishway can be constructed at the outlet, permitting fish to surmount the overhang and enter the culvert. These outlet structures can be prefabricated (e.g., Steep pass fishway) or custom designed. Another advantage of this approach is that the pipe hang does not have to be eliminated, allowing for the pipe itself to be less steep and avoiding the need for additional excavation and possibly blasting. Even so, in-pipe weirs may still be needed. A simple Jersey barrier structure is much easier to design and build, though it can overcome only the smaller pipe hangs.

Figure 17: Log Drop Control Structure

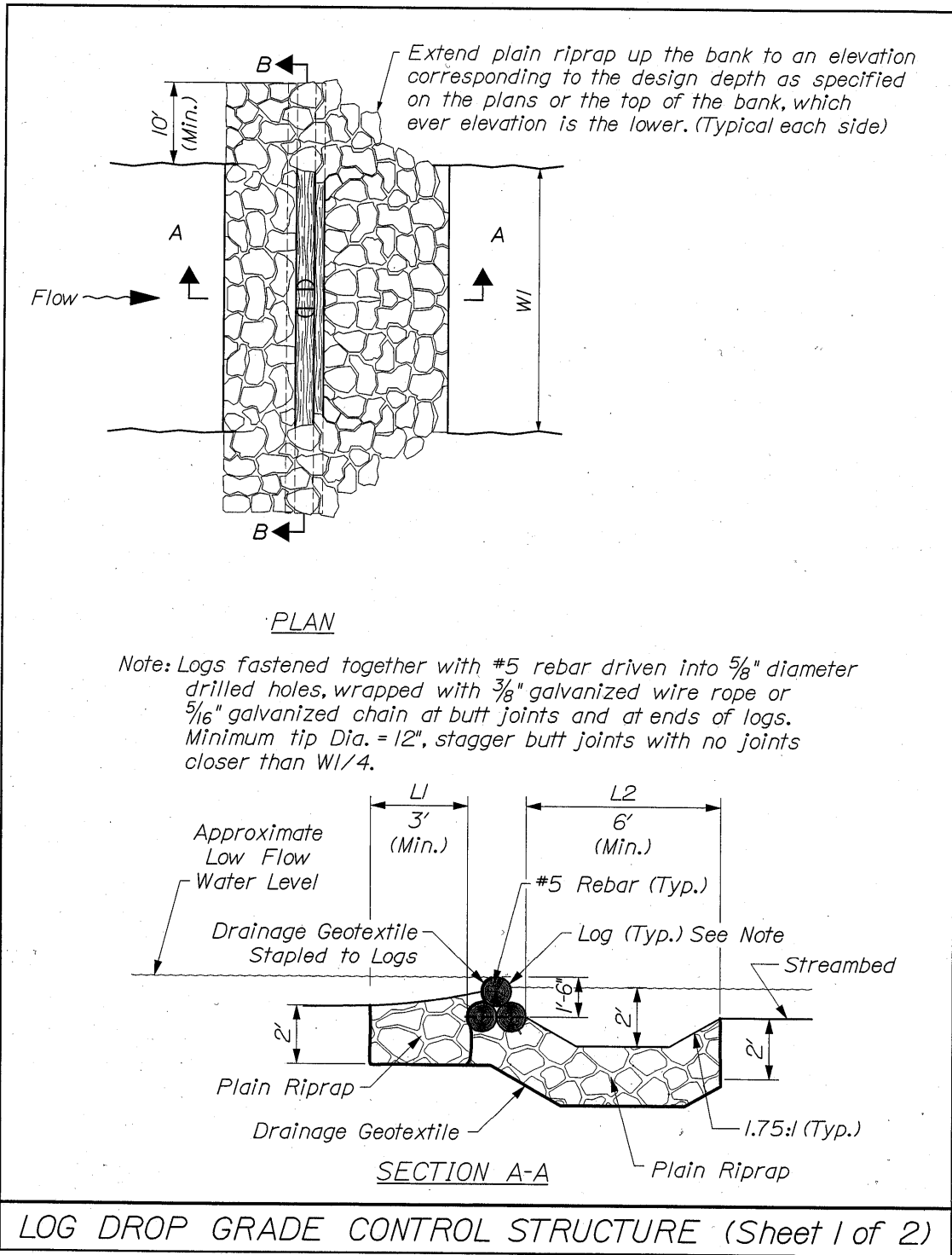
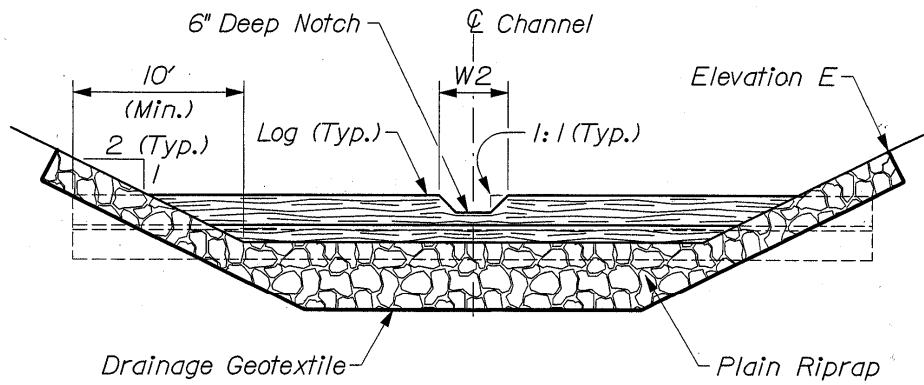


Figure 17(cont.): Log Drop Control Structure



SECTION B-B

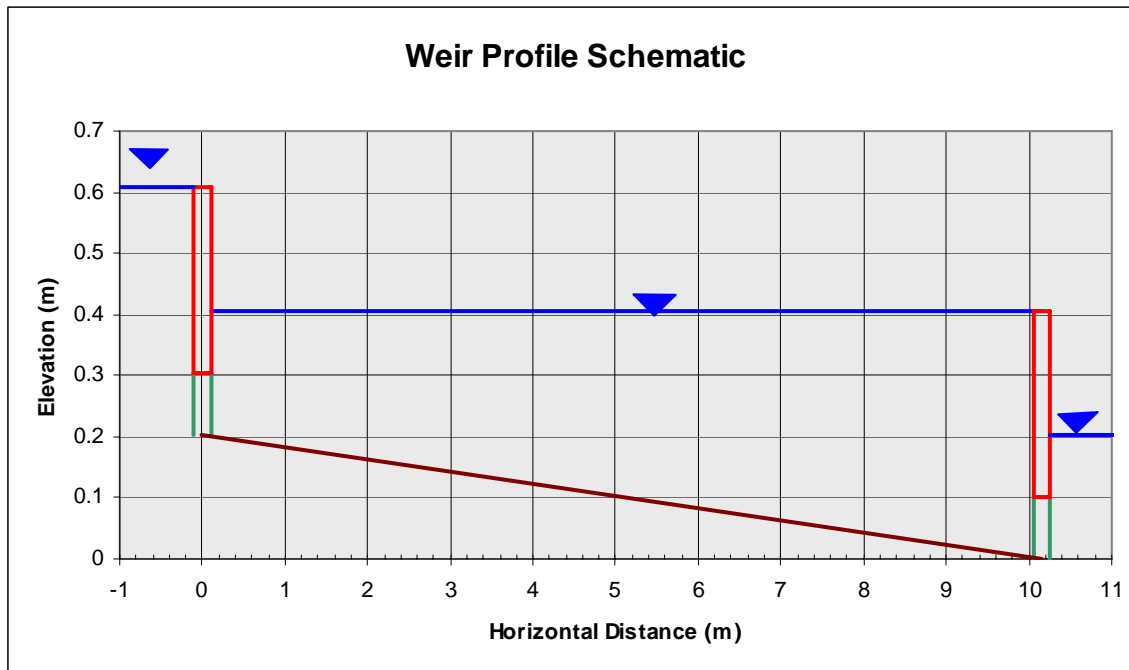
- NOTE:**
- 1.) Channel Width (W1) = as specified on the Plans
 - 2.) Notch Width (W2) = as specified on the Plans
 - 3.) Upstream Length (L1) = as specified on the Plans
 - 4.) Downstream Length (L2) = as specified on the Plans
 - 5.) Top of Riprap Elevation (E) = as specified on the Plans

LOG DROP GRADE CONTROL STRUCTURE (Sheet 2 of 2)

E. In-Culvert Grade Control: Culverts with Weirs

Weirs are added to the interior of a culvert to create adequate water depths at low flows and limit regions of high velocity. They create a series of pools inside the culvert, the effect being increased water depth and reduced velocity to permit fish to move up through the pipe. These pools also have the effect of providing resting areas in long culverts. Such a modified culvert constitutes a type of “weir and pool” fishway. Maine DOT will use rectangular notched weirs in these situations. Due to constructability issues, in-culvert weirs are limited to larger culverts (D generally ≥ 5 ft or 1500 mm).

Figure 18:

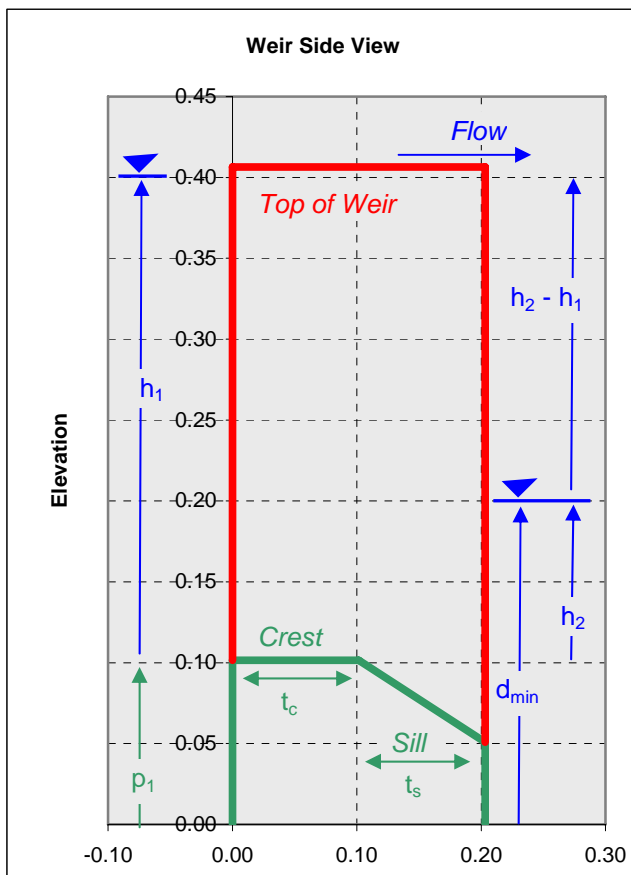


F. Weir Design

The objective in weir design is to pass the specified design flow while maintaining the necessary depth of water behind the weir. The shallowest depth in a weir-pool sequence in a culvert of simple uniform slope is at the downstream base of a weir. Most weir dimensions will be specified as design standards, leaving the inter-weir spacing and weir notch width as the principal parameters to be determined according to specific site topographic and hydrologic conditions and species requirements. The inter-weir spacing will typically be determined by the culvert slope and the specified drop in pool elevation. The notch width is a function of the design flow and the other specified weir dimensions.

1. Weir Specifications: A schematic of a section across the weir is shown below with dimensions indicated; a frontal view is given on the following page. The “invert” is synonymous with the “notch invert” or “notch crest”. Most weir dimensions will be standardized as listed here. The following specifications should be observed, unless the design flow, pipe size, or construction issues indicate otherwise.

- Notch shall be at least 12 in (300 mm) deep (h_1), from top (crest) of weir to notch invert;
- Notch shall be submerged by 4 in (100 mm) in the downstream pool to enable passage by non-jumping fish (h_2);
- Drop between pool elevation across weir shall be 8 in (200 mm) ($h_1 - h_2$);
- Total weir thickness ($t_c + t_s$) shall be at least 12 in (300 mm);
- Notch invert shall be at least 4 in (100 mm) thick (t_c);
- Beveled sill shall be at least 4 in (100 mm) thick (t_s);
- Notch shall be rectangular, beveled in the downstream direction with a sill slope (H:V) = (2:1);
- Distance from notch invert to culvert invert be at least 4 in (100 mm) (p_1);

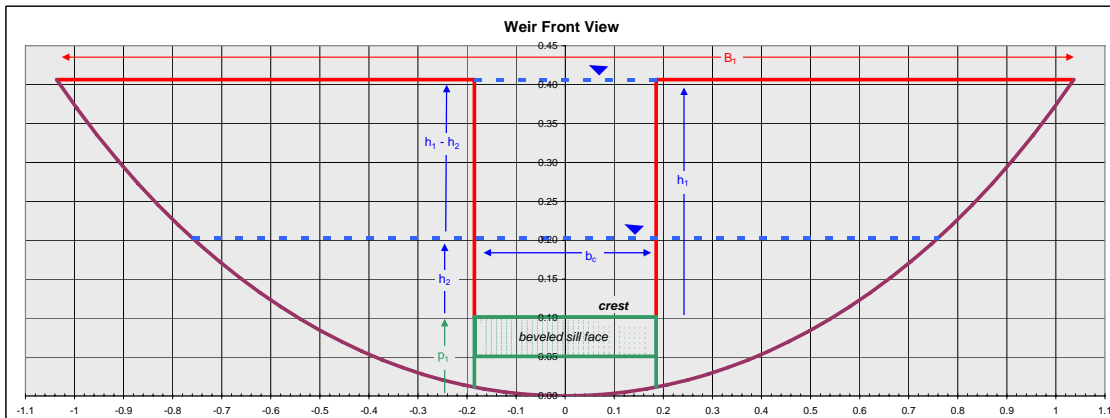


2. Required Depth of Water: Strictly speaking, the required depth of water depends on the species of interest and time of movement. In the interest of simplifying the design process, Maine DOT will generally use a design depth of 8 in (200 mm) at the shallowest point in a pool between weirs. A particular situation may warrant using a different value, based on the fish data in Table 2 of the Fish Passage Policy.

3. Drop Between Pools: The drop ($h_1 - h_2$) in water surface elevation between pools should be set according to the species of interest, depending on the ability of a fish to jump between pools. In the interests of developing a robust design suitable for a variety of species, Maine DOT will design for an 8 in (200 mm) drop between

pool elevations with the notch submerged, unless particular circumstances suggest otherwise (salmon are capable of navigating 12 in drops). Because the weirs are

dimensioned to be partially submerged at the design flow, both jumping and non-jumping species should be able to navigate the weir notch. Table 4 of Part II provides the detailed information useful for alternative individual design standards.



4. **Inter-Weir Spacing:** Spacing between weirs depends on the culvert slope and the specified drop between water pools across weirs. In general, the maximum spacing is calculated according to the simple geometric relationship

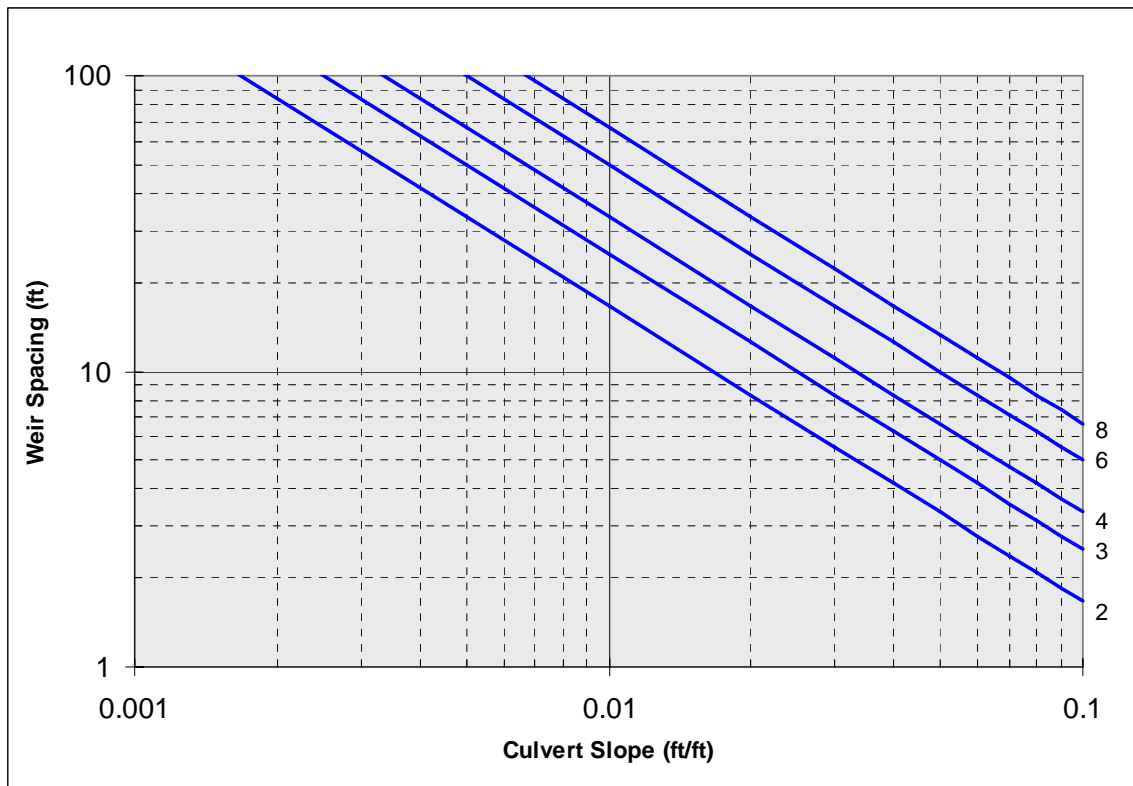
$$L_w = \Delta h / S$$

where L_w = nominal spacing between weirs = pool length
 Δh = drop in water surface elevation between pools
 S = culvert slope

This simple function is presented graphically for several commonly used pool drops Δh . The calculated inter-weir spacing should be interpreted as the maximum allowable spacing. The actual final design spacing may be something less than the nominal calculated value; other design and habitat issues may indicate a smaller value as being more appropriate. When concrete pipe sections with prefabricated weir units are used, select a combination of sections that will give the largest weir spacing that does not exceed the calculated value. The weir and crest elevations should be checked when something other than the initial calculated spacing is elected. The first weir should be placed at the culvert outlet.

For steeper culverts, more weirs are required at closer spacing as illustrated in the figure below. The minimum in-culvert inter-weir spacing acceptable for construction is 6 ft (1.8 m), though spacing this small indicate that alternative approaches may be more appropriate. At close spacing, the weirs function more as baffles and roughness elements as opposed to impoundment structures. The pool volumes are correspondingly smaller and EDF limitations may not be satisfied. Therefore, on steeper culverts that require closely spaced weirs, consideration should be given to using alternative approaches such as true baffle designs (preferably vertical slot weirs) instead of nominal pool-and-weir configurations.

Figure 19: Inter-Weir Spacing for Selected Pool Drops (in inches)



5. Weir Notch Width Calculation: The weir notch depth h_1 is fixed by the specified crest submergence h_2 (usually 4 in or 100 mm) and the pool drop ($h_1 - h_2$; usually 8 in or 200 mm). This leaves the notch width b_c as the weir parameter designed to accommodate the fish passage flow. The notch width is calculated using the Kindsvater-Carter (K-C) sharp-crested weir equation (in dimensionally consistent form):

$$b_c = \{Q/r_s\} / \{C_e(2/3)(2g)^{1/2}h_1^{3/2}\}$$

where

Q = flow passed by freely flowing (i.e., not submerged) weir (ft³/s or m³/s)

b_c = notch width (ft or m)

C_e = effective discharge coefficient
(dimensionless; 0.6 as a first approximation)

g = acceleration due to gravity (32.2 ft/s² or 9.8 m/s²)

h_1 = upstream water surface elevation referenced to crest elevation (ft or m)

This version omits several correction factors but is acceptable given the numerous uncertainties in real applications. A full development of the K-C equation, including corrections, is given in Appendix 2B. Computation worksheets for the complete K-C equation are provided in Appendix 2C.

The fish pass weirs will generally be designed to flow partially submerged at design discharges, in order to pass both jumping and non-jumping species. A submerged weir will pass less water than a freely flowing weir, all other things being equal. Therefore, a weir designed for submerged flow must have a larger notch opening to accommodate the design passage flow. The submergence correction factor r_s is determined following the method of Villemonte:

$$r_s = \{1 - (h_2/h_1)^{3/2}\}^{0.385} = (Q/Q_{\text{free}}) \leq 1$$

where h_1 and h_2 are the respective upstream and downstream pool elevations above the weir crest, Q is the actual flow expected (by hydrology/hydraulics analysis), and Q_{free} is the flow through a freely discharging weir of the same dimensions. Maine DOT in-culvert weirs will usually be designed with 4 inch submergence ($h_2 = 4$ in or 100 mm). The effect of partial submergence is to reduce the flow over the weir. Therefore, the nominal design free flow must be increased over the actual hydrologic flow needed over the weir:

$$Q_{\text{free}} = Q/r_s$$

The weir is sized according to $Q_{\text{free}} (= Q/r_s)$; the actual flow Q is chosen according to watershed hydrology and the flows prevailing during periods of fish movement.

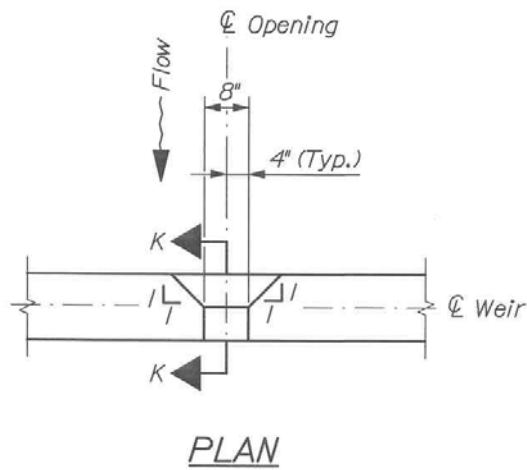
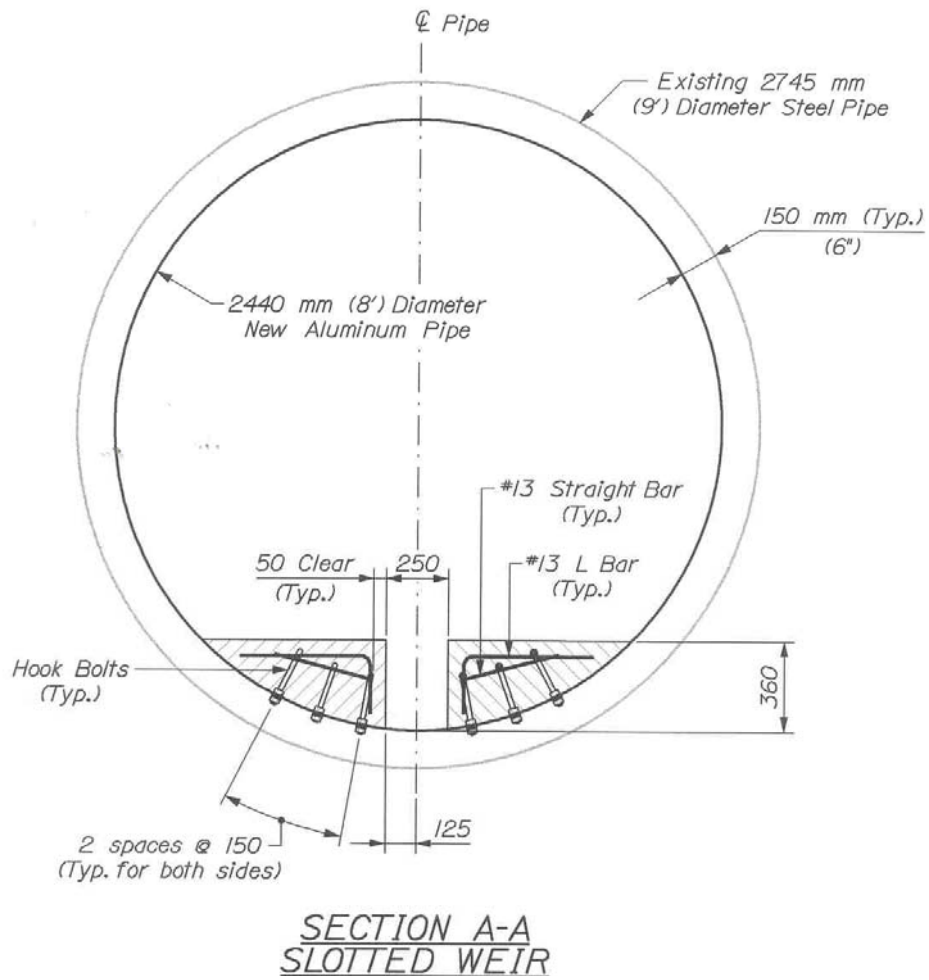
6. Design Procedure: The design procedure for in-culvert weirs is fairly simple and consists of five steps:

1. Estimate a design flow Q according to watershed hydrology and/or channel hydraulics and target species period of movement. If not performing a detailed channel-specific or species-specific analysis, use the average of the September and October median flows (see Appendix 2A);
2. Calculate the nominal distance between weirs based on culvert slope and drop in water surface elevation between weirs. Set final spacing according to constructability requirements so as not to exceed nominal calculated value;
3. Assign weir dimensions and auxiliary hydraulic design parameters. Use the values given under “Weir Specifications” above as starting values; they may have to be revised in the process of developing a final design;
4. Calculate nominal weir notch (crest) width according to K-C sharp-crested weir equation;
5. Set final notch width according to constructability requirements; and
6. Check final design value for compliance with needed minimum pool depth.

An example illustrating the notch design calculations is given in Appendix III-D.

7. Slotted Weirs (Full-Depth Notch): While notched weir-and-pool arrangements are attractive for maintaining water levels and velocities in relatively flat culverts, they can present construction and durability issues, particularly if the notch is not very high. Problems of weir spacing in steep culverts have already been noted. Therefore, slotted weirs (i.e., full-depth notches) may also be considered. Typical details follow in Figure 20; specific dimension values will vary, depending on the site. The design procedure is significantly different than for the notched weir-and-pool approach and is not covered in this edition of the Fish Passage Design Guide. Most significantly, slotted weirs are more properly classified as baffles and tend to be closely spaced. Environmental Office and/or Bridge Program engineering staff should be consulted for further information.

Figure 20: Slotted Weir Detail



G. Downstream Weirs (Grade Control Structures)

When a culvert outlet is excessively perched, downstream grade control may be needed to allow fish entry into the culvert. As a practical matter, right-of-way considerations may limit such options. That said, two types of weirs should be considered: rectangular notch weir as described previously for in-culvert applications; and full channel-width broad-crested weir. Different methods of construction will be used, though. As previously noted, concrete barrier (e.g., Jersey) makes for a simple and cost-effective weir. Rock and boulder weirs have also been used.

1. Rectangular Notch Weir: The rectangular notch weir is sized in the same way as for in-pipe weirs.
2. Broad-Crested Weir: The broad-crested weir is in many cases the pre-existing gravel/cobble push-bar at the exit of the culvert outlet pool. The bar extends fully across the channel. The length (in direction of flow) of the bar is long compared to the depth of water on the bar. The effect is to induce critical flow over the bar. A conservative approach is to adjust the bar elevation and culvert inlet to achieve the nominal desired water depth at the culvert outlet. For example, if 8 inches (200 mm) is needed at the outlet, set the bar elevation (lowest point on the bar) 8 inches above the culvert inlet. However, this will actually produce a water surface elevation somewhat higher than nominal design, since it ignores the depth of flow over the bar. If the bar cannot be set at this relative elevation, then hydraulic design accounting for flow depth on the weir should be developed,

The bar flow depth can be accounted for by using the broad-crested weir equation:

$$Q = C_d(2/3)(2g/3)^{1/2}b_ch_1^{3/2} = \{C_d(2/3)^{3/2}g^{1/2}\}b_ch_1^{3/2}$$

Where C_d = discharge coefficient (0.9 assumed)

b_c = channel width across the bar

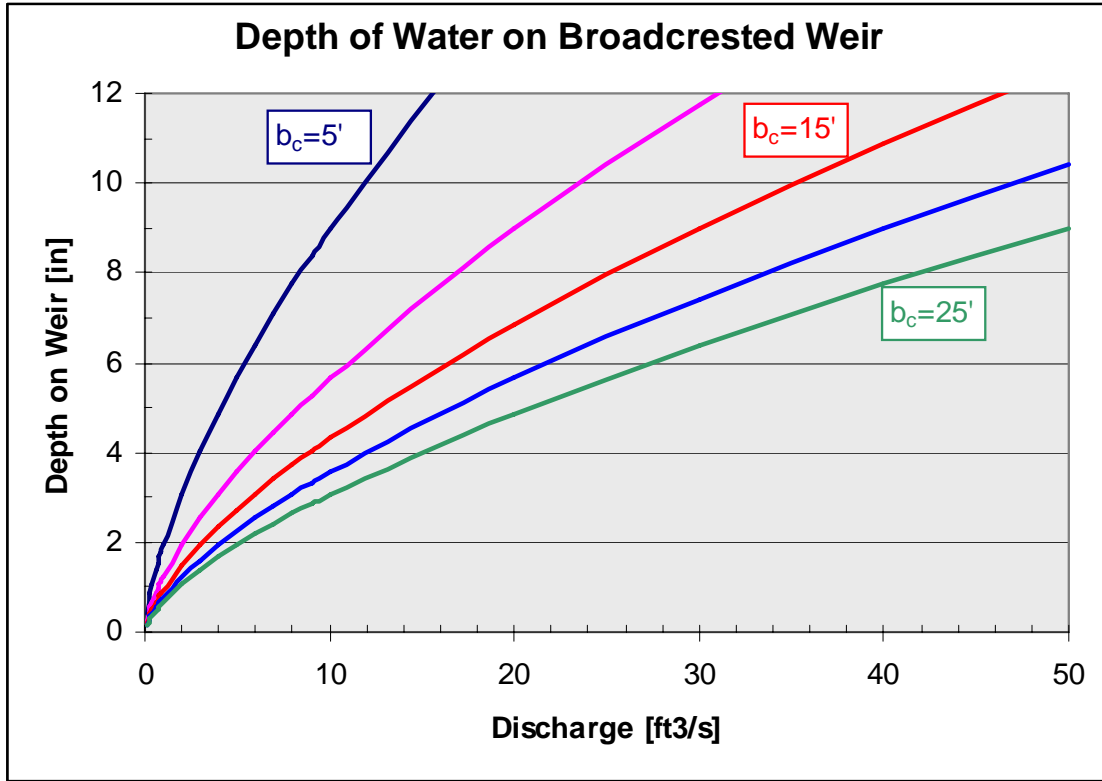
h_1 = water elevation upstream of bar (referenced to bar elevation)

There are a variety of equations and charts available for determining C_d . However, in view of the uncertainty and variability inherent in the weirs contemplated here, it suffices to use a standard value of 0.9. Solving for h_1 gives the necessary depth of the bar below the desired water surface elevation:

$$h_1 = [Q/\{C_d(2/3)(2g/3)^{1/2}b_c\}]^{2/3}$$

This function is illustrated below in Figure 21 for a range of weir widths. Situations where this refinement might be considered include weaker swimming fish that require a minimum water depth on the weir and cannot jump the weir. Wider weirs in lower discharge environments may be prone to such complications.

Figure 21: Depth of Water on Broad-crested Weir



Also, since flow over the weir is critical and therefore swifter than tranquil flow, the critical velocity over the weir should be checked for weaker-swimming fish:

$$v_c = (gh_1)^{1/2}$$

As previously noted, downstream weirs may succeed in creating the needed backwater, but they may present barriers to fish movement. Several weirs may be needed to raise the backwater while permitting fish passage over smaller incremental water level jumps.

H. Alternatives to Weirs: Engineered Fishways

While in-culvert and downstream grade control structures are the preferred approaches to creating the necessary hydraulic conditions for fish passage, there will occasionally be situations where they are not feasible or will not deliver the needed hydraulics. In these cases, Steep pass and Denil fishways should be considered. They are particularly suited to the following situations:

- excessive outlet drop that cannot be mitigated by downstream grade control
- right-of-way unavailable for developing downstream grade control

- steep culvert slope that would require numerous closely spaced internal weir

A drawback of these structures is that they create a long-term maintenance obligation above that of simple weirs.

An alternative to manufactured fishways such Denil or Steep pass is to build a pool-weir sequence at the culvert outlet. This enables fish to negotiate outlet hangs that cannot otherwise be corrected and also maintain minimum water depths in the culvert. A sample is shown below.



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Appendix F

Regression Equations for Monthly Median Flows in Maine Rivers and Streams

Based on

Estimating monthly, annual, and low 7-day, 10-year streamflows for ungaged rivers in
Maine

U.S. Geological Survey Scientific Investigations Report 2004-5026

by

R.W. Dudley
U.S. Geological Survey
Augusta, Maine
2004

Regression equations and their accuracy for estimating monthly median streamflows for ungaged, unregulated streams in rural drainage basins in Maine.

Regression equation	Measures of Accuracy		
	ASEP (in percent)	(PRESS/n) ^{1/2} (in percent)	Average EYR
$Q_{\text{jan median}} = 20.71 (A)^{1.036} (DIST)^{-0.762}$	-16.1 to 19.2	-17.3 to 20.9	8.87
$Q_{\text{feb median}} = 36.54 (A)^{1.017} (DIST)^{-0.890}$	-13.4 to 15.5	-14.9 to 17.5	17.5
$Q_{\text{mar median}} = 183.7 (A)^{0.999} (DIST)^{-1.142}$	-16.9 to 20.4	-19.0 to 23.5	13.3
$Q_{\text{apr median}} = 0.227 (A)^{1.010} 10^{0.028(pptA)}$	-20.8 to 26.2	-22.0 to 28.3	3.75
$Q_{\text{may median}} = 0.262 (A)^{1.070} (DIST)^{0.461}$	-20.4 to 25.6	-21.0 to 26.6	3.92
$Q_{\text{jun median}} = 0.734 (A)^{1.076}$	-22.5 to 29.0	-23.6 to 30.8	4.26
$Q_{\text{jul median}} = 0.210 (A)^{1.149} 10^{1.02(SG)}$	-26.1 to 35.4	-27.3 to 37.5	3.58
$Q_{\text{aug median}} = 0.152 (A)^{1.120} 10^{1.31(SG)}$	-28.6 to 40.2	-29.6 to 42.1	3.86
$Q_{\text{sep median}} = 0.169 (A)^{1.093} 10^{1.25(SG)}$	-26.8 to 36.7	-27.8 to 38.5	5.37
$Q_{\text{oct median}} = 0.307 (A)^{1.074} 10^{1.11(SG)}$	-25.8 to 34.8	-30.0 to 43.0	8.28
$Q_{\text{nov median}} = 1.222 (A)^{1.004}$	-28.9 to 40.6	-30.6 to 44.1	4.39
$Q_{\text{dec median}} = 12.00 (A)^{1.000} (DIST)^{-0.513}$	-13.1 to 15.0	-14.6 to 17.1	21.6

ASEP — average standard error of prediction

PRESS — prediction error sum of squares

EYR — equivalent years of record

Q — streamflow statistic of interest.

A — contributing drainage area, in square miles.

SG — fraction of the drainage basin that has significant sand and gravel aquifer, on a planar area basis, expressed as a decimal. For example, if 15% of a basin's drainage area has significant sand and gravel aquifers, $SG = 0.15$. Based on the significant sand and gravel aquifer maps produced by the Maine Geological Survey and maintained as GIS data sets by the Maine Office of GIS.

$pptA$ — mean annual precipitation, in (in), computed as the spatially averaged precipitation in the contributing basin drainage area. Based on non-proprietary PRISM precipitation data spanning the 30-year period 1961-1990. Data maintained as GIS data sets by the United States Department of Agriculture (1998).

$DIST$ — distance from the coast, in miles, measured as the shortest distance from the contributing drainage basin centroid to a line in the Gulf of Maine. The line in the Gulf of Maine is defined by end points 71.0W, 42.75N and 65.5W, 45.0N, referenced to North American Datum (horizontal) 1983.

Calculation of DIST Parameter

The DIST variable in the monthly flow regression equations is calculated as perpendicular distance from the coast, in miles, from the watershed centroid point P_c to a line in the Gulf of Maine. The line in the Gulf of Maine is defined by lat-long endpoints P_1 (71.0W, 42.75N) and P_2 (65.5W, 45.0N), referenced to North American Datum (horizontal) NAD 1983. The corresponding UTM (zone 19, in meters) endpoint coordinates are P_1 (336321.28E, 4734992.89N) and P_2 (775853.73E, 4988911.83N). The point P_1 is the southwest endpoint and the point P_2 is the northeast endpoint of the reference line. DIST can be calculated using the following worksheet in UTM (metric) coordinates for the endpoints.

P_c	E	N	Watershed centroid (m, UTM)
P_1	336321.28 E	4734992.89 N	SW reference line endpoint
$ P_1P_c $	$\{(P_{cE}-P_{1E})^2+(P_{cN}-P_{1N})^2\}^{1/2}$		Dist bet P_c and P_1 (m)
θ	$\text{Tan}^{-1}\{(P_{cE}-P_{1E})/(P_{cN}-P_{1N})\} - 30.02^\circ$		Angle bet lines P_1P_c & P_1P_2
DIST	$ P_1P_c \sin(\theta) / 1610$		Dist to reference line (miles)

Alternatively, DIST can be estimated using the following figure from Dudley (2004) showing the Gulf of Maine Line with the state map.

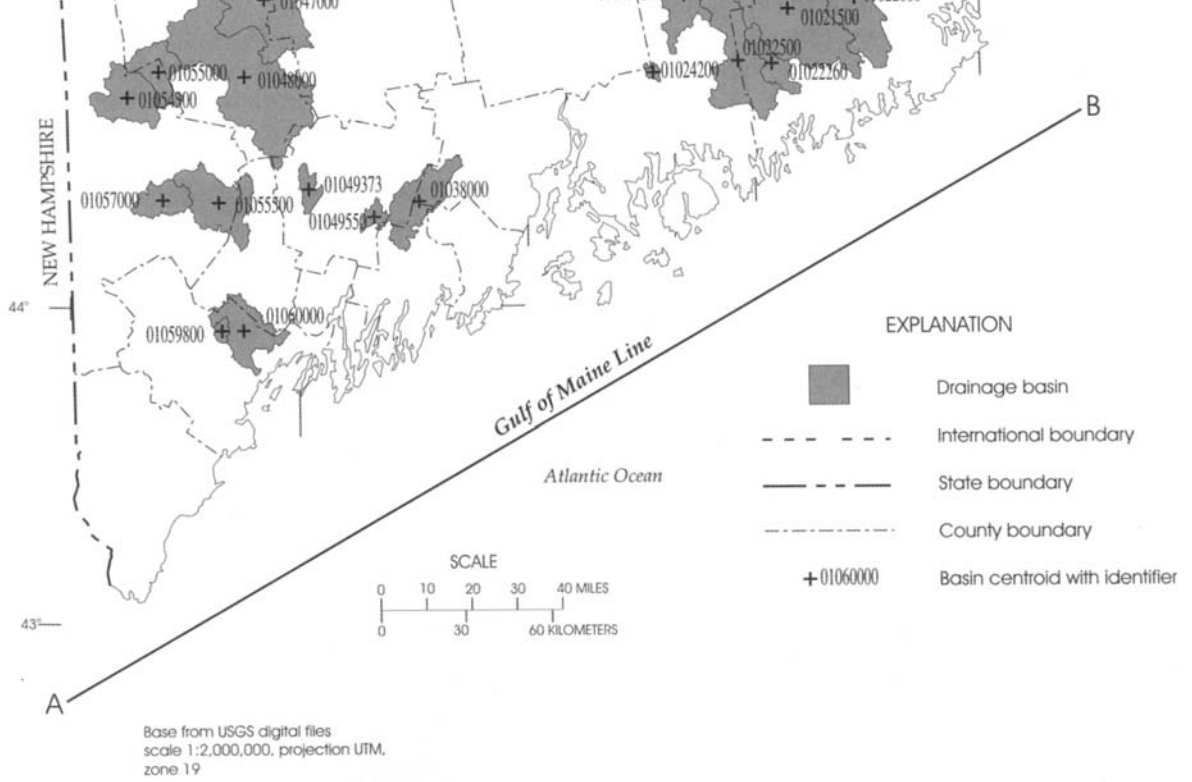


Figure 3. The Gulf of Maine Line (GOM Line) and study basin centroids.

24-Hour Duration Rainfall Depths (inches) for Various Return Periods

Location	Return Period (years)								Annual	Comments
	1	2	5	10	25	50	100	500		
Androscoggin	2.5	3.0	3.9	4.6	5.4	6.0	6.5	7.8	45.3	
Aroostook C	2.1	2.1	3.2	3.6	4.2	4.6	5.0	5.9	36.1	Presque Isle
Aroostook N	2.0	2.3	3.0	3.5	4.0	4.4	4.8	5.7	36.1	Ft Kent
Aroostook S	2.2	2.5	3.3	3.8	4.4	4.9	5.3	6.4	39.0	Houlton
Cumberland NW	2.8	3.3	4.3	5.0	5.8	6.4	6.9	8.3	43.4	NW of Rt 11
Cumberland SE	2.5	3.0	4.0	4.7	5.5	6.1	6.7	8.1	44.4	SE of Rt 11
Franklin	2.4	2.9	3.7	4.2	4.9	5.4	5.9	7.0	45.6	
Hancock	2.4	2.7	3.6	4.2	4.9	5.5	6.0	7.2	45.2	
Kennebec	2.4	3.0	3.8	4.4	5.1	5.6	6.1	7.2	41.7	
Knox-Lincoln	2.5	2.9	3.8	4.4	5.1	5.7	6.2	7.4	46.1	
Oxford E	2.5	3.0	4.0	4.6	5.3	5.9	6.4	7.6	43.0	E of Rt 26
Oxford W	3.0	3.5	4.5	5.2	6.0	6.6	7.1	8.4	43.8	W of Rt 26
Penobscot N	2.2	2.5	3.3	3.8	4.4	4.9	5.4	6.4	41.5	N of Can-Atl RR
Penobscot S	2.4	2.7	3.5	4.1	4.8	5.3	5.8	6.9	39.5	S of Can-Atl RR
Piscataquis N	2.2	2.5	3.3	3.8	4.4	4.9	5.3	6.3	38.5	N of Can-Atl RR
Piscataquis S	2.3	2.6	3.4	4.0	4.6	5.1	5.5	6.6	41.0	S of Can-Atl RR
Sagadahoc	2.5	3.0	3.9	4.6	5.4	5.9	6.5	7.8	45.3	
Somerset N	2.2	2.5	3.3	3.8	4.4	4.9	5.3	6.3	37.3	N of Can-Atl RR
Somerset S	2.4	2.7	3.5	4.1	4.7	5.2	5.7	6.8	39.5	S of Can-Atl RR
Waldo	2.5	2.8	3.7	4.3	4.9	5.5	6.0	7.1	47.2	
Washington	2.4	2.5	3.4	4.0	4.8	5.4	5.9	7.1	44.2	
York	2.5	3.0	4.0	4.6	5.4	6.0	6.6	7.8	46.7	

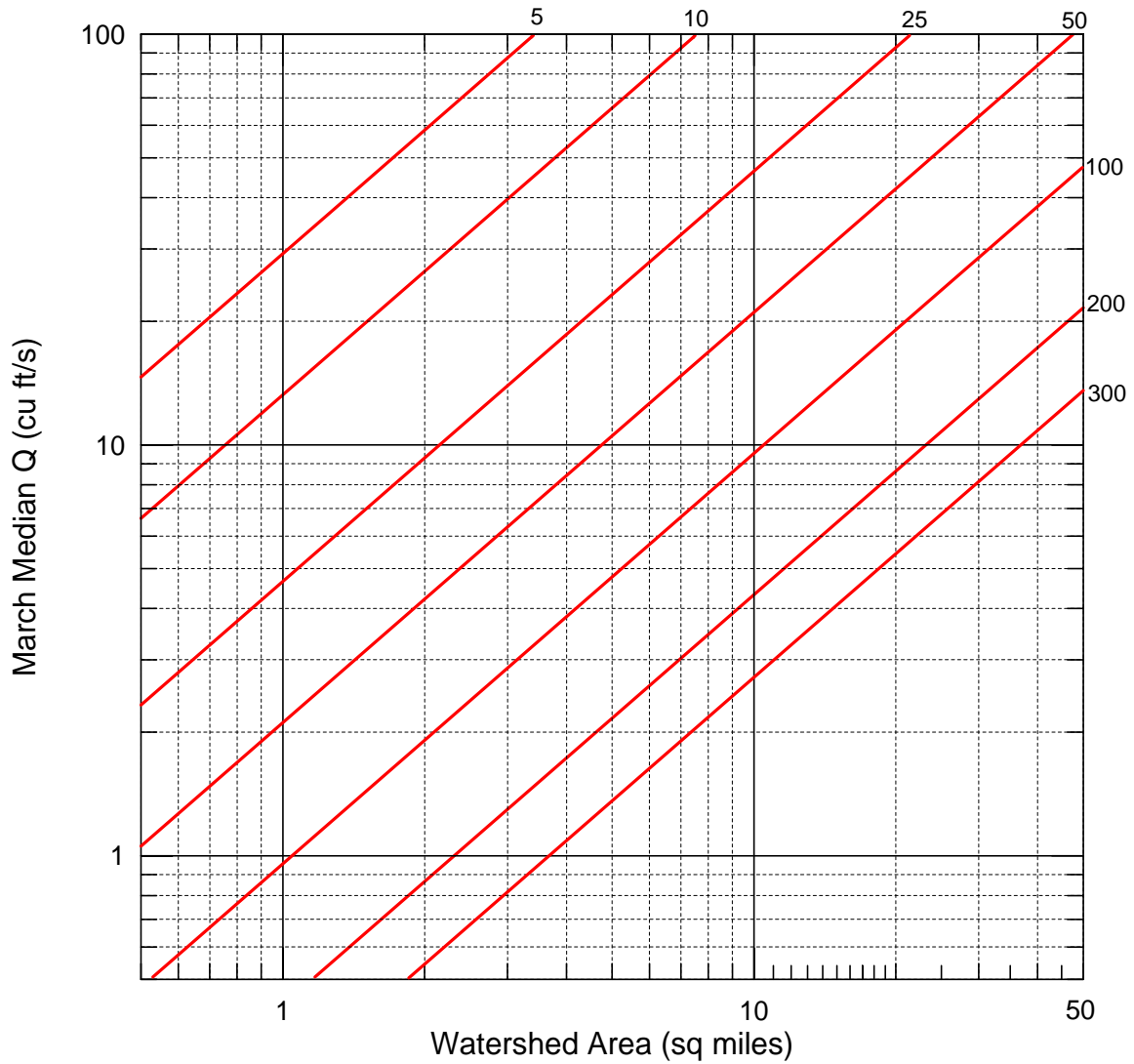
Source: Maine DEP Stormwater BMP Guide, November, 1995.

Note 1: Use Type II Storm for Oxford and Penobscot Counties, excepting towns listed below.

Note 2: Use Type III Storm for all other counties and the following towns in Oxford County (Porter, Brownfield, Hiram, Denmark, Oxford, Hebron, Buckfield, Hartford) and Penobscot County (Dixmont, Newburgh, Hampden, Bangor, Veazie, Orono, Bradley, Clifton, Eddington, Holden, Brewer, Orrington, Plymouth, Etna, Carmel, Hermon, Glenburn, Old Town, Milford, Greenfield).

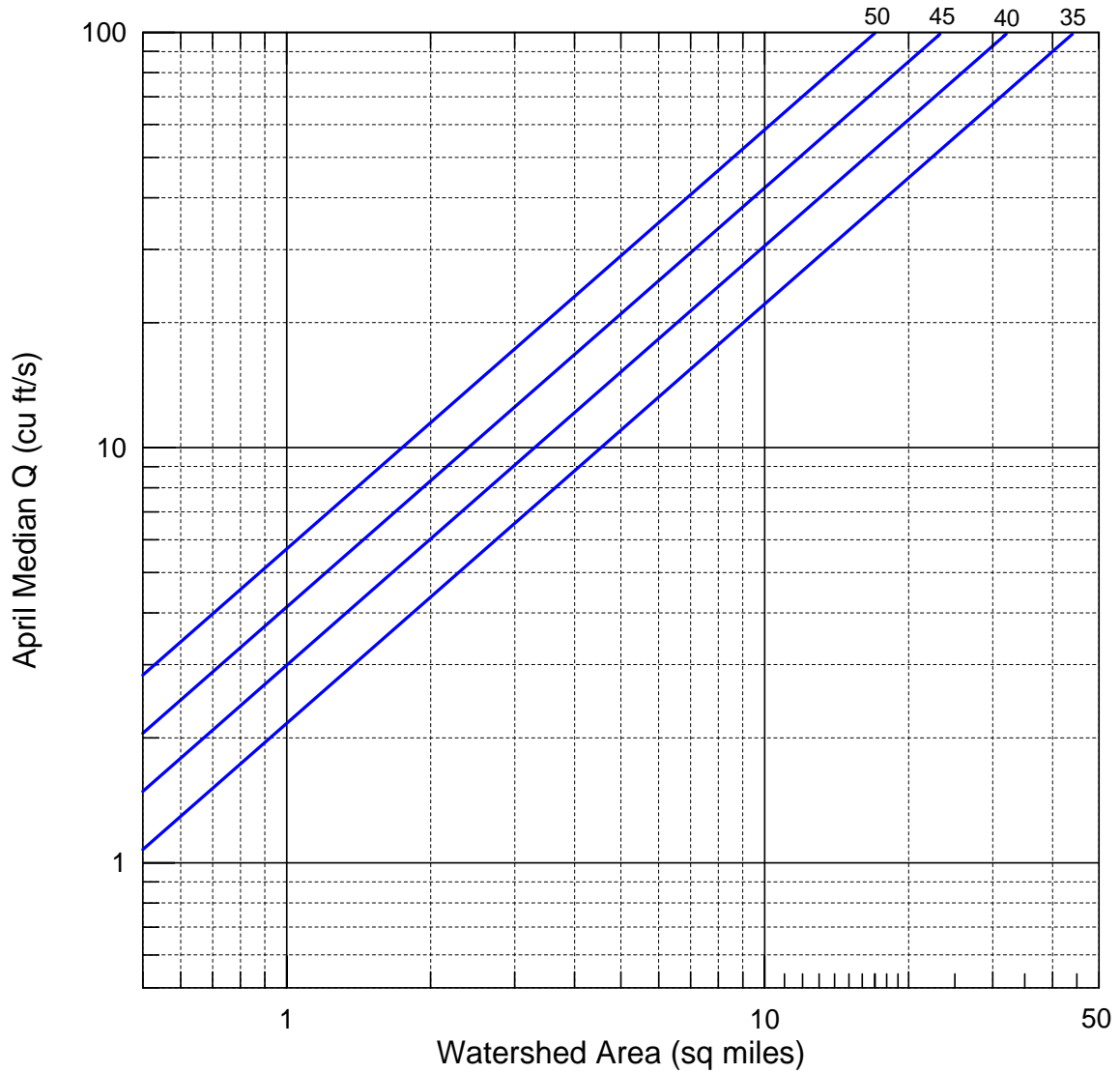
Note 3: 50-yr depths approximated as mid-point between 25- and 100-yr depths based on log-Normal probability plots.

March Median Flows for Selected Distances from Coast



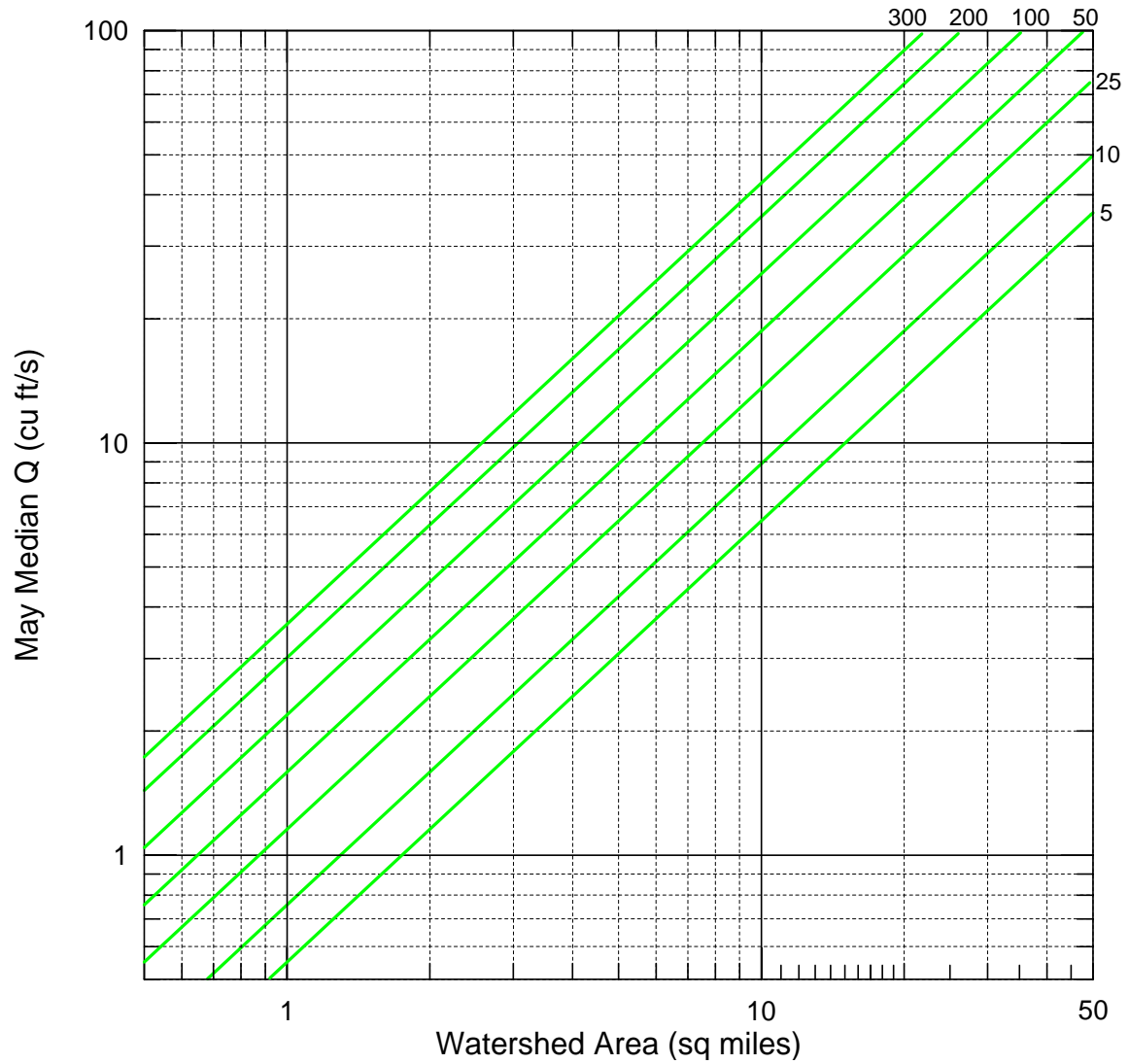
Note: Distance in miles from line in Gulf of Maine.
See flow equation page for explanation of distance determination.

April Median Flows for Selected Average Annual Precipitation



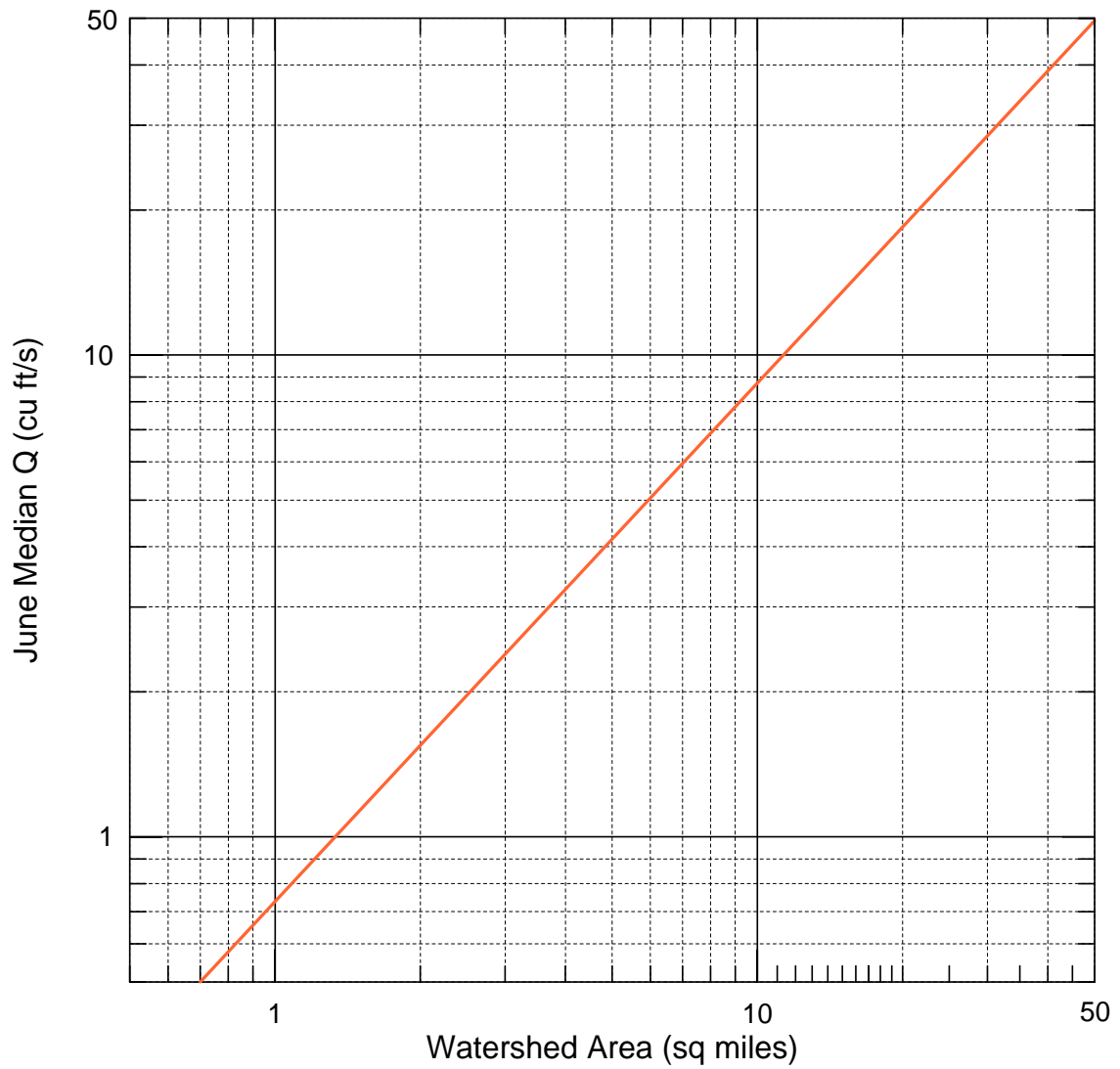
Note: Average annual precipitation in (inches).

May Median Flows for Selected Distances from Coast

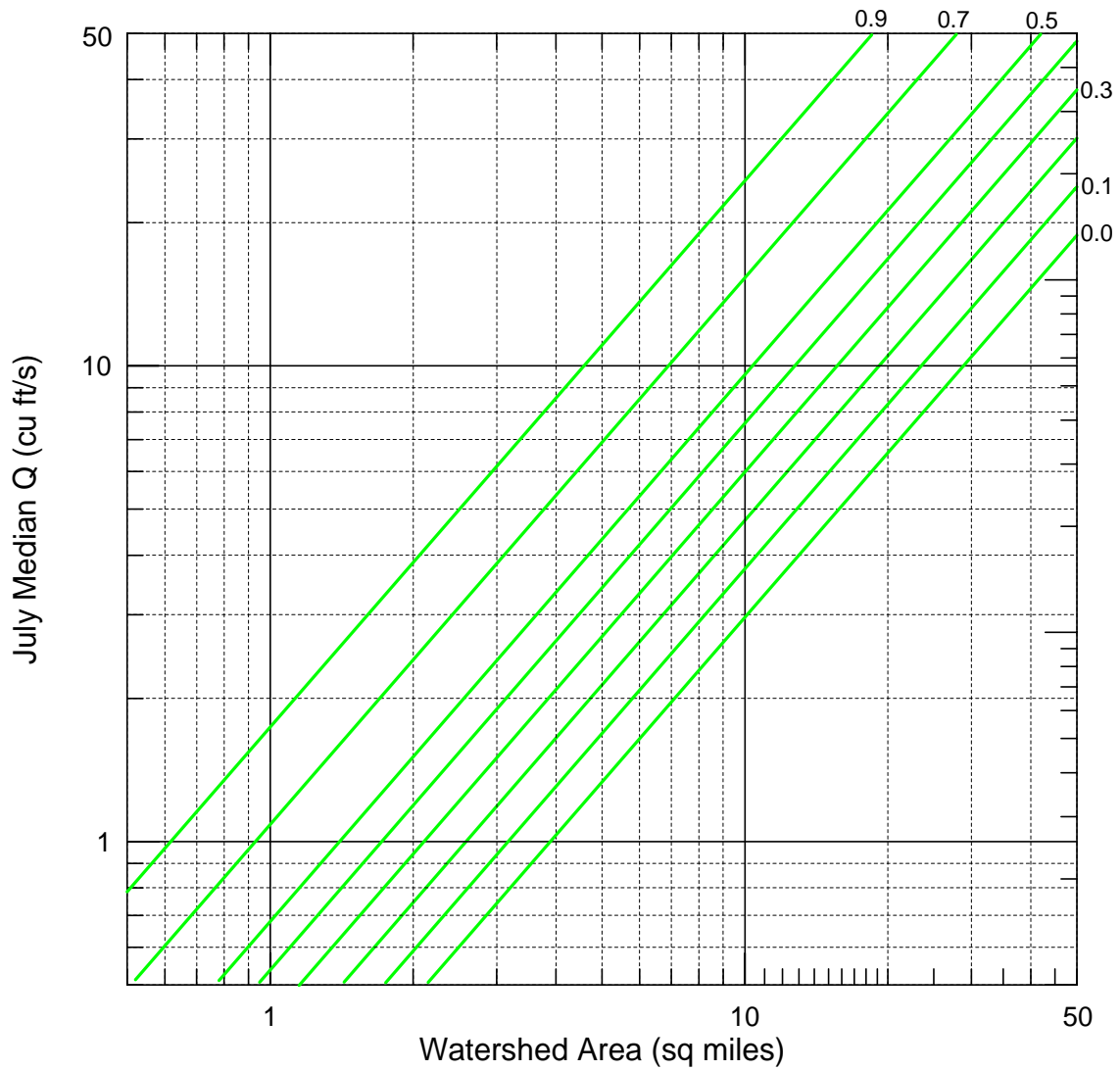


Note: Distance in miles from line in Gulf of Maine.
See flow equation page for explanation of distance determination.

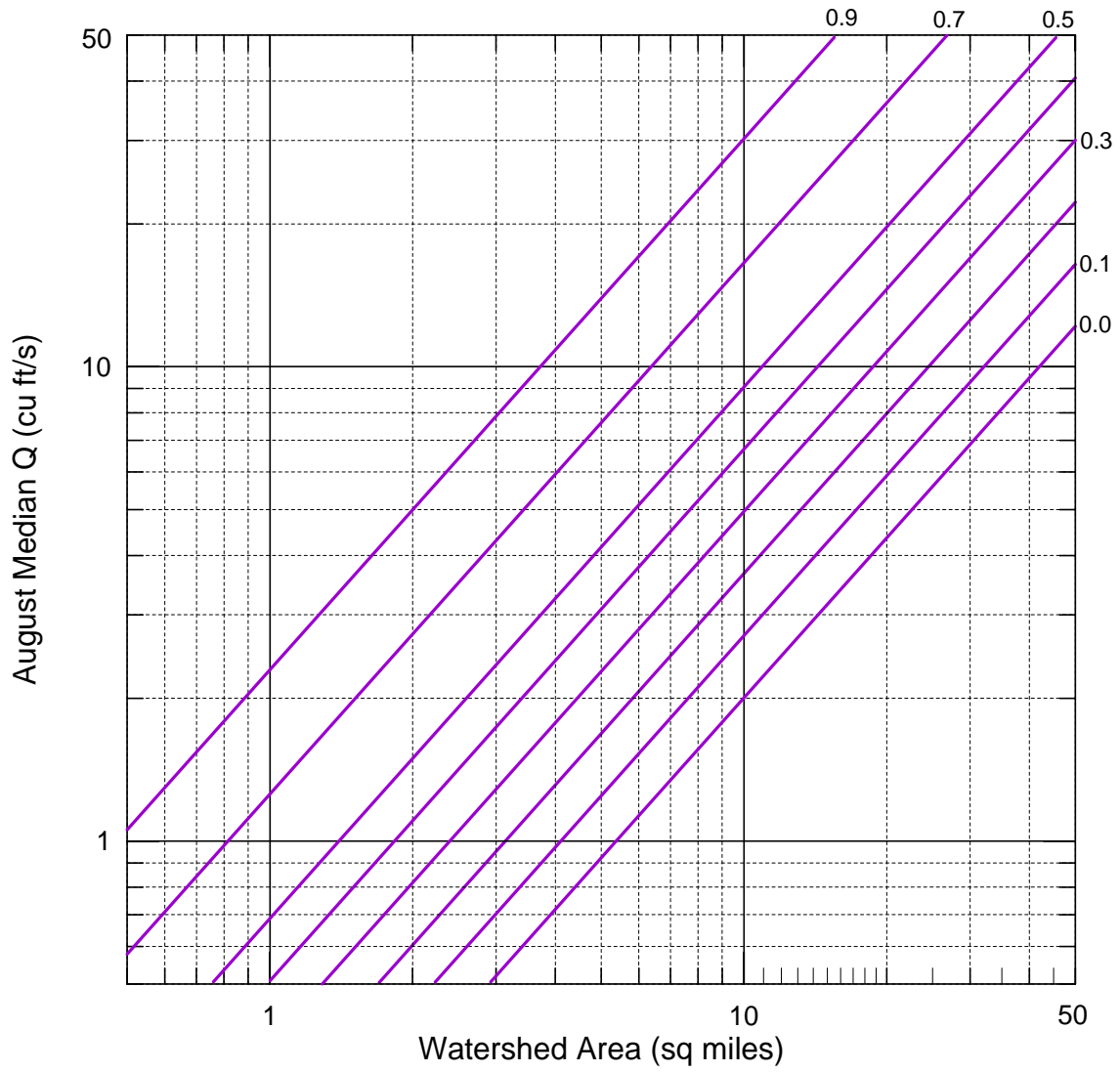
June Median Flows



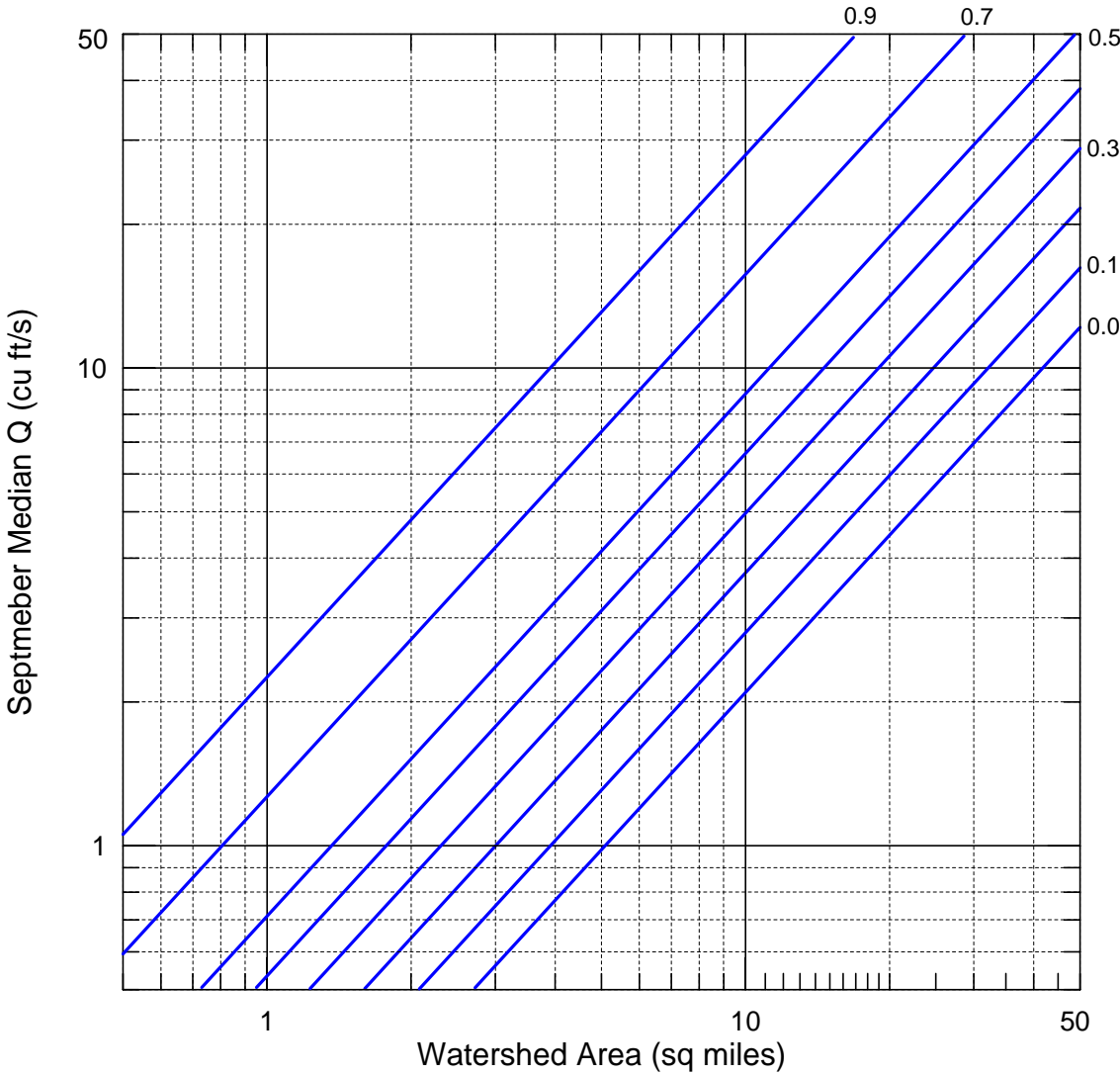
July Median Flows for Selected Sand & Gravel Fractions



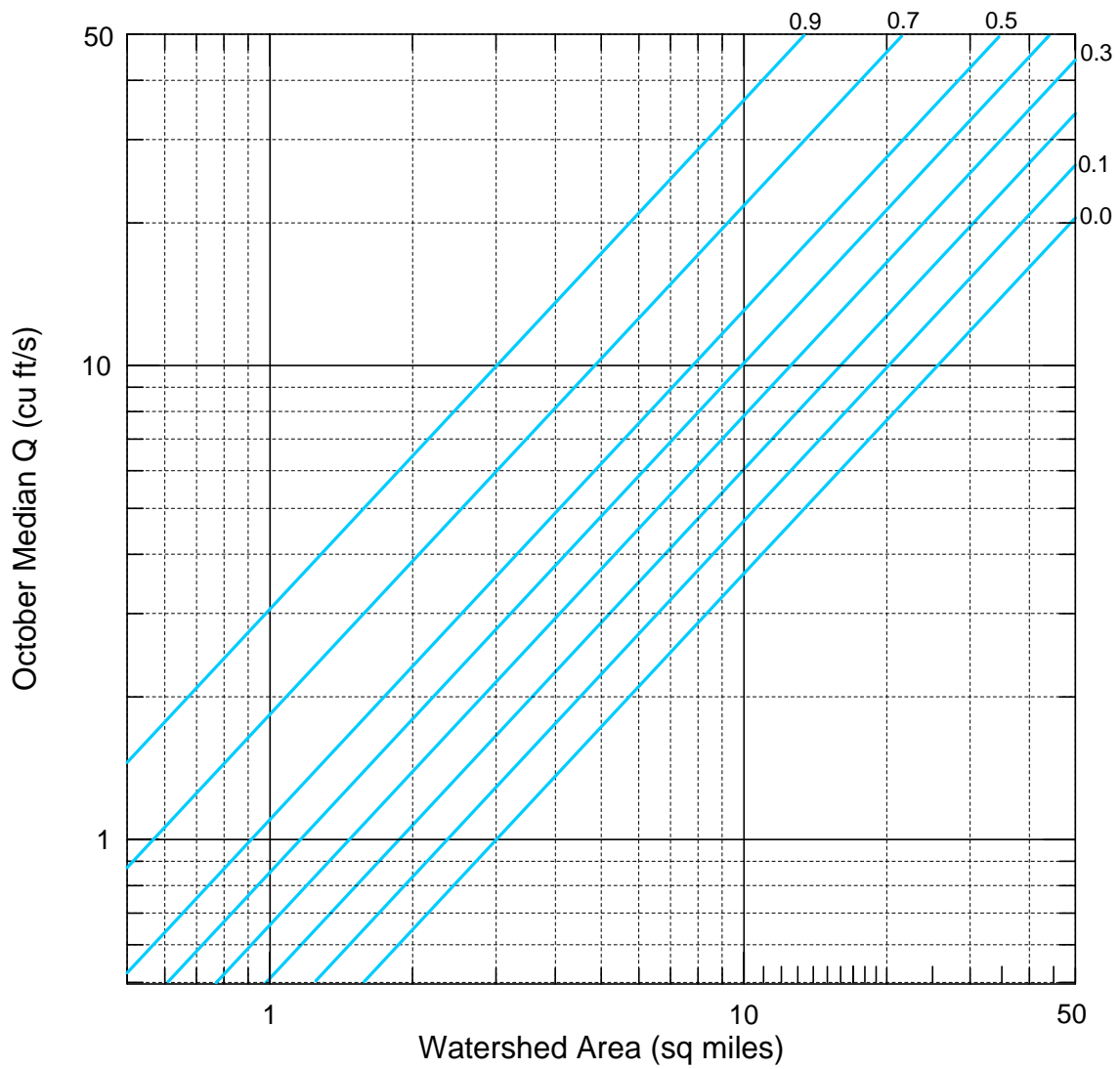
August Median Flows for Selected Sand & Gravel Fractions



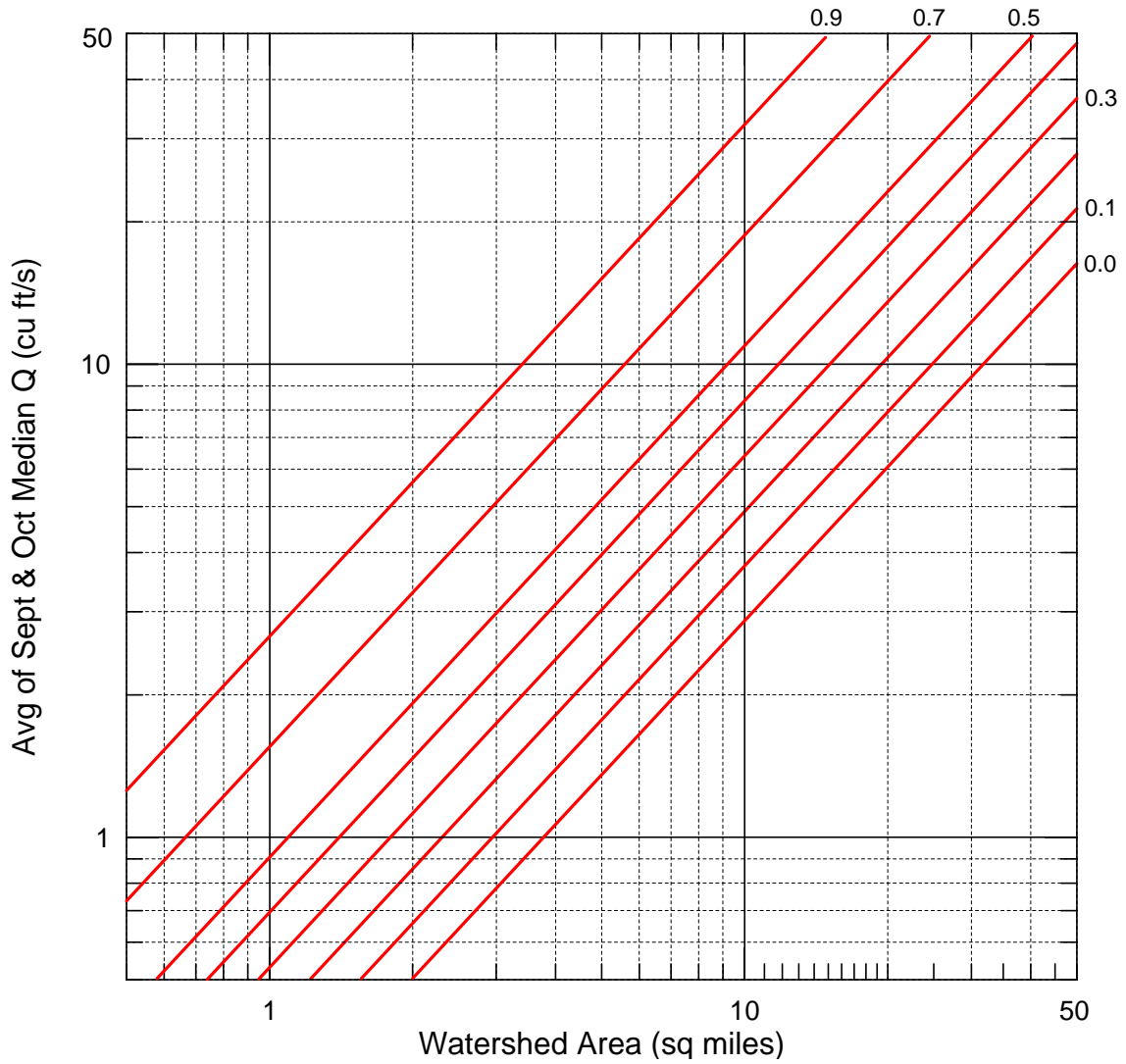
September Median Flows for Selected Sand & Gravel Fractions



October Median Flows for Selected Sand & Gravel Fractions



Average of September & October Median Flows for Selected Sand & Gravel Fractions



Project Name: Example
Stream Name: Any Stream
Bridge Name: Any Bridge
Route No.: Route 999
Analysis by: CSH

PIN: 00000.00
Town: Anytown
Bridge No.: 0000
USGS Quad: Any Quad
Date: 2/3/2004

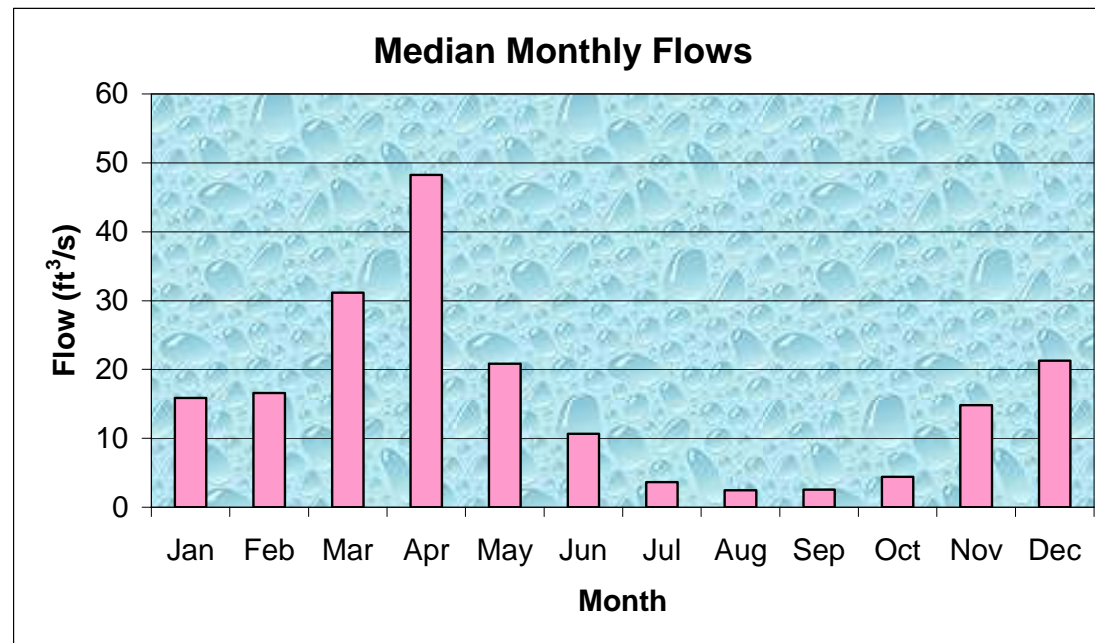
MAINE MONTHLY MEDIAN FLOWS BY USGS REGRESSION EQUATIONS (2004)

Value	Variable	Explanation	31.08
12	A	Area (mi ²)	
625257	P _c	Watershed centroid (E,N; UTM; Zone 19; meters)	
41.57	DIST	Distance from Coastal reference line (mi)	
44.2	pptA	Mean Annual Precipitation (inches)	
0.00	SG	Sand & Gravel Aquifer (decimal fraction of watershed area)	

Worksheet prepared by:

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Month	Q _{median} (ft ³ /s)
Jan	15.88
Feb	16.58
Mar	31.16
Apr	48.26
May	20.86
Jun	10.64
Jul	3.65
Aug	2.46
Sep	2.56
Oct	4.43
Nov	14.81
Dec	21.28



Appendix G

Calculations for Kindsvater-Carter Sharp-Crested Weir And Correction for Weir Submergence

Weir Notch Width Calculation

The weir notch depth h_1 is fixed by the specified crest submergence h_2 (usually 4 in or 100 mm) and the pool drop ($h_1 - h_2$; usually 8 in or 200 mm; 12 in when passing just salmon). This leaves the notch width b_c as the weir parameter designed to accommodate the fish passage flow. The notch width is calculated using the Kindsvater-Carter (K-C) sharp-crested weir equation:

$$Q = C_e b_c (2/3) (2g)^{1/2} h_e^{3/2}$$

where

- Q = flow passed by freely flowing (i.e., not submerged) weir (ft³/s or m³/s)
- b_e = effective notch width = $b_c + K_b$ (ft or m)
- K_b = notch width correction (tabulated function) (ft or m)
- b_c = actual notch width (ft or m)
- C_e = effective discharge coefficient (tabulated function)
- g = acceleration due to gravity (32.2 ft/s² or 9.81 m/s²)
- h_e = effective head = $h_1 + 0.003$ ft (0.001 m)
- h_1 = upstream water surface elevation referenced to notch invert elevation (ft or m)

This equation can be quite accurate when calibrated for carefully constructed sharp-crested weirs used in flow-measurement situations. However, culvert weirs will not be built as “true” sharp-crested weirs and there is also significant uncertainty in the design flow estimates. Therefore, the correction for effective head (0.003 ft) can be ignored and h_1 used in place of h_e . The notch width correction K_b is a tabulated empirical function (see Appendix 2B). Again, it is a very small number (-0.003 ft (-0.04 in) $< K_b < 0.016$ ft (0.19 in)) compared to expected notch widths (b_c typically > 0.5 ft) and so can be ignored. The effective discharge coefficient C_e is a function of the notch width-channel width ratio (b_c/B_1) and above crest–below crest depth ratio (h_1/p_1). This functional dependence on b_c must be accounted for in the solution for b_c . This function is also tabulated in Appendix 2B. Employing the suggested approximations, the weir equation becomes

$$Q = C_e b_c (2/3) (2g)^{1/2} h_1^{3/2}$$

The fish pass weirs will be designed to flow partially submerged at design discharges, in order to pass both jumping and non-jumping species. A submerged weir will pass less water than a freely flowing weir, all other things being equal. Therefore, a weir designed for submerged flow must have a larger notch opening to accommodate the design passage flow. The submergence correction factor r_s is determined following the method of Villemonte:

$$r_s = \{ 1 - (h_2/h_1)^{3/2} \}^{0.385} = (Q/Q_{\text{free}}) \leq 1$$

where h_1 and h_2 are the respective upstream and downstream pool elevations above the weir crest, Q is the actual flow expected (by hydrology/hydraulics analysis), and Q_{free} is the flow through a freely discharging weir of the same dimensions. Maine DOT in-culvert weirs will usually be designed with 4 inch submergence ($h_2 = 4$ in or 100 mm). The effect of partial submergence is to reduce the flow over the weir. Therefore, the nominal design free flow must be increased over the actual hydrologic flow needed over the weir:

$$Q_{\text{free}} = Q/r_s$$

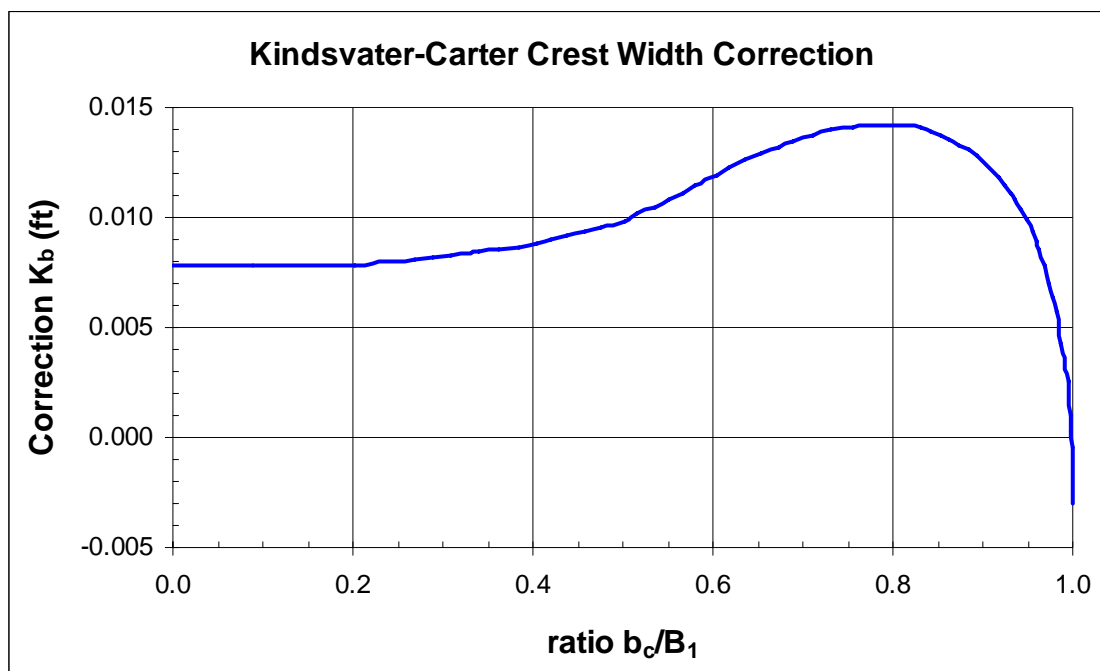
The weir is sized according to Q_{free} ($= Q/r_s$); the actual flow Q is chosen according to watershed hydrology and the flows prevailing during periods of fish movement.

Solving for the design notch width gives

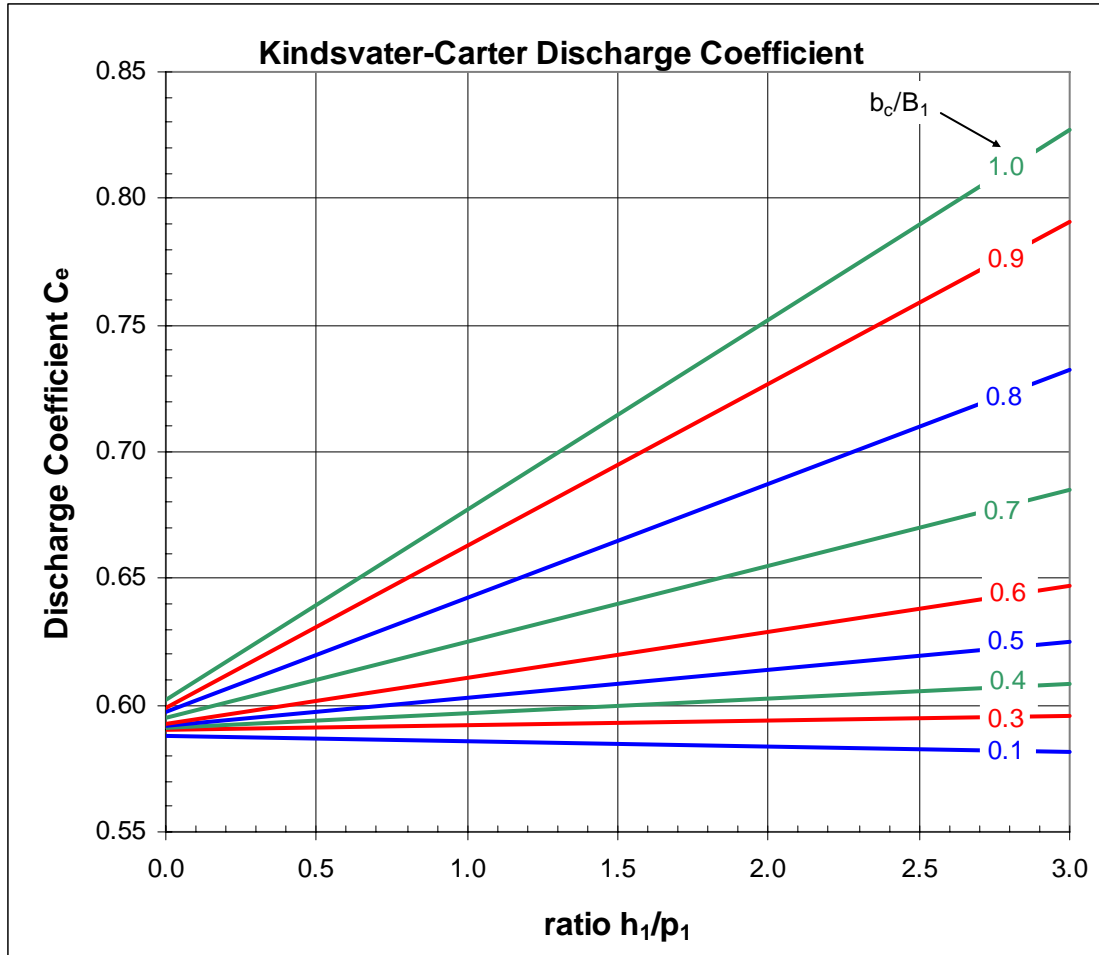
$$b_c = \{Q/r_s\} / \{C_e(2/3)(2g)^{1/2}h_1^{3/2}\}$$

This is actually a non-linear equation in b_c , since the discharge coefficient C_e is a function of b_c . Several iterations will be needed to solve for b_c , using the above equation in conjunction with the K-C charts and tables in Appendix 2B. A manual worksheet for executing the design calculations is provided in Appendix 2C. Alternatively, the calculations can be completed efficiently by computer spreadsheet.

Typical pipe and weir sizes will yield a relative notch width in the range $0.1 < b_c/B_1 < 0.5$; typical notch dimensions and water depths will produce h_1/p_1 approximately = 1. As a good approximation, then, the weir discharge coefficient C_e can be set = 0.6.



Kindsvater-Carter Crest Width Correction					
b_c/B_1	K_b (ft)	K_b (m)	b_c/B_1	K_b (ft)	K_b (m)
0.00	0.0079	0.0024	0.80	0.0141	0.0043
0.20	0.0079	0.0024	0.82	0.0141	0.0043
0.25	0.0082	0.0025	0.84	0.0141	0.0043
0.30	0.0082	0.0025	0.86	0.0135	0.0041
0.35	0.0085	0.0026	0.88	0.0131	0.0040
0.40	0.0089	0.0027	0.90	0.0125	0.0038
0.45	0.0092	0.0028	0.92	0.0118	0.0036
0.50	0.0098	0.0030	0.94	0.0105	0.0032
0.55	0.0108	0.0033	0.96	0.0089	0.0027
0.60	0.0121	0.0037	0.98	0.0056	0.0017
0.65	0.0128	0.0039	1.00	-0.0030	-0.0009
0.70	0.0135	0.0041			
0.75	0.0141	0.0043			



B_1 = weir top width (usually ≥ 2 ft)

p_1 = notch invert elevation above pipe invert (usually 0.25 ft – 0.5 ft)

Kindsvater-Carter Discharge Coefficient Equation Parameters

b_c/B	μ	β	b_c/B	μ	β
0.0	-0.0023	0.587			
0.1	-0.0021	0.588	0.6	0.0180	0.593
0.2	-0.0018	0.589	0.7	0.0300	0.595
0.3	0.0020	0.590	0.8	0.0450	0.597
0.4	0.0058	0.591	0.9	0.0640	0.599
0.5	0.0110	0.592	1.0	0.0750	0.602

Equation: $C_e = \mu(h_1/p_1) + \beta$

Appendix H

Manual Worksheet for Rectangular Weir Notch Sizing

Project Name _____
 Stream Name _____
 Route No. _____
 Designer: _____

PIN _____
 Town _____
 Culvert No. _____
 Date _____

**Maine Department of Transportation
 Culvert Fish Passage Weir-and-Pool Design Worksheet**

Watershed Characteristics and Design Flow

1	Area (A)		sq miles
2	Sand & Gravel Fraction (SG)		Decimal fraction of area
3	Passage Design Flow Q		ft ³ /s

Note: sand & gravel values only needed for Sep and Oct monthly median flow equations; other design flow estimation methods may be used.

Weir, Culvert and Hydraulic Specifications

(perform all calculations in consistent units of feet or meters)

1	$h_1 - h_2$		Water level drop across weir
2	h_2		Submerged depth on weir
3	d_{min}		Min pool depth (downstream base of weir)
4	D		Pipe diameter
5	S		Culvert slope
6	h_1		Upstream depth on weir $h_2 + (h_1 - h_2)$
7	p_1		Height of weir crest above invert $d_{min} - h_2$
8	d_1		Upstream pool depth at weir $h_1 + p_1$
9	r_s		Submergence ratio $\{1 - (h_2/h_1)^{1.5}\}^{0.385}$
10	B_1		Pool top width at weir $2\{d_1(D - d_1)\}^{1/2}$ for circular culverts
11	L_w		Weir spacing $(h_1 - h_2)/S$
12	Q		Design flow adjusted for submergence Q/r_s

Calculations for Weir Rectangular Notch Width

Computation Constants

1	(Q/r_s)		from above
2	$(2/3)(2g)^{1/2}$		5.35 ft ^{1/2} /s; 2.95 m ^{1/2} /s
3	$h_1^{3/2}$		h_1 from above
4	$A = (Q/r_s) / \{(2/3)(2g)^{1/2} h_1^{3/2}\}$		computation constant A
5	B_1		pool width B_1 from above
6	h_1/p_1		above crest-below crest depth ratio

Iteration for Notch Crest Width b_c

Iteration	0	1	2	3	4	5	6	7
b_c/B_1								
K_b								
C_e								
$b_e = A/C_e$								
$b_c = b_e - K_b$								

*Notes: always use consistent units of [feet] or [meters] in hydraulic calculations
 set initial (iteration 0) b_c value = $1/2$ of B_1 ;
 get K_b and C_e by look-up in Appendix B;
 iterate until crest width b_c stops changing*

Appendix I

Weir Notch Sizing and EDF Calculation Example

Design Example

A 10-ft diameter culvert under a deep fill has been identified as needing attention. Whatever approach is taken, passage for trout must be provided. After evaluating several alternatives, concrete invert lining has been identified as the best choice. Design a pool-weir arrangement to pass fish.

Watershed and culvert data are summarized in the following table:

Watershed		Culvert	
Area	12 mi ² (31.1 km ²)	Diameter	10 ft (3000 mm)
NWI area	24.8%	Slope	2%
Sand & gravel aquifer	0 %	Length	60 ft (18.3 m)
Avg annual precip	44.2 in (1123 mm)	Roughness n	0.024 (CMP)
Distance to coast	41.6 mi (67.4 km)		

Fish Requirements

Based on Table 2 in the Fish Passage Policy, trout are moving from April through November, though passage is less critical in the warm-water months of July and August. Flows in the September and October are the lowest flows in the months of interest and therefore provide the basis of a conservative design. The average of the September and October medians will be used, with the understanding that such a design will deliver the needed depths at the other, higher, flows. (Ideally, this regression estimate would be supported by a measurement-based estimate.)

Maine DOT generic design is to provide a minimum of 8 in depth when possible. Trout have a typical maximum body thickness of 4 in (100 mm), indicating a minimum depth for passage of (1.5 x 4 in) = 6 in (150 mm). In a sloping culvert, the minimum depth between weirs occurs at the base of the upper weir. Therefore, initial design will be for a depth $d_{\min} = 8$ in (200 mm) at the downstream side of a weir. Since trout are strong swimmers, this requirement could be relaxed if engineering concerns indicate a preference for more widely spaced structures (as allowed by a bigger drop between pools).

Trout are capable of jumping, so strictly speaking, the weir does not have to be designed for submergence. However, Maine DOT general practice is to partially submerge the weir crest to facilitate passage of non-jumping species. Therefore, initial design will be for the downstream pool to be $h_2 = 4$ in (100 mm) above the weir crest.

Design Flow

Design flows can be based on field observations (actual depth/velocity measurements during the period of interest; minimum channel sections needed for movement) or median

flow equations for the periods of movement. Using the watershed data, monthly median flows were estimated using the U.S. Geological Survey regression equations. The September and October flows can be calculated using the equations in Appendix 2A, by look-up in the charts in Appendix 2A, or using the Maine DOT monthly median flow Excel worksheet.

By chart look-up, the average of the September and October medians is

$$\begin{aligned} Q &= (Q_{\text{Sep}} + Q_{\text{Oct}})/2 \\ &= 3.5 \text{ ft}^3/\text{s} = 0.100 \text{ m}^3/\text{s} \end{aligned}$$

This hydrologic design value will be adjusted for the specified submergence condition.

Weir Dimensions and Auxiliary Hydraulic Design Specifications

Recommended design values for water levels are

$$\begin{aligned} h_1 - h_2 &= 8 \text{ in (0.667 ft = 200 mm)} && \text{change in pool elevation across weir} \\ h_2 &= 4 \text{ in (0.333 ft = 100 mm)} && \text{downstream submerged depth on crest} \end{aligned}$$

It follows that the upstream depth on the weir crest is

$$h_1 = (h_1 - h_2) + h_2 = 12 \text{ in (1 ft = 300 mm)}$$

The height p_1 of the weir crest above the culvert invert is

$$p_1 = d_{\text{min}} - h_2 = 8 - 4 = 4 \text{ in (0.333 ft = 100 mm)}$$

and the pool depth d_1 just upstream of the weir is

$$d_1 = h_1 + p_1 = 16 \text{ in (1.333 ft = 400 mm)}.$$

The submergence ratio r_s is

$$r_s = \{1 - (h_2/h_1)^{3/2}\}^{0.385} = 0.921 = (Q/Q_{\text{free}})$$

The weir will actually be designed to accommodate a freely discharging flow of

$$Q_{\text{free}} = Q/r_s = (3.5 \text{ ft}^3/\text{s})/0.921 = 3.8 \text{ ft}^3/\text{s} (0.108 \text{ m}^3/\text{s})$$

Spacing Between Weirs

Spacing is calculated as

$$L_w = \Delta h/S$$

Where Δh = difference pool elevation across a weir and S is the culvert slope.

$$L_w = (0.667 \text{ ft})/0.02 = 33.35 \text{ ft (10.2 m)}$$

Calculate Notch Width

The notch width b_c is calculated with the K-C sharp-crested weir equation. The pipe is flowing partially full at flows characteristic of fish passage. The pool surface top width in a circular culvert just upstream of the weir is

$$B_1 = 2\{d_1(D - d_1)\}^{1/2} = 6.8 \text{ ft} = 2073 \text{ mm}$$

as calculated for a partially-flowing circular pipe. If a different culvert shape is used, then a different equation for B_1 should also be used.

The weir equation, rearranged for crest (notch) width b_c is

$$b_c = \{Q/r_s\} / \{C_e(2/3)(2g)^{1/2}h_1^{3/2}\}$$

The discharge coefficient C_e is determined using the chart in Appendix 2B. The depth ratio h_1/p_1 is $(12 \text{ in}/4 \text{ in}) = 3$. The width ratio b_c/B_1 is actually part of the solution for b_c and so an initial estimate must be made. Assume a b_c starting value $1/2$ of the upstream pool width B_1 , so initial $b_c = 3.4$ and $b_c/B_1 = 0.5$. By chart look-up, $C_e = 0.63$. Then

$$\begin{aligned} b_c &= \{3.8 \text{ ft}^3/\text{s}\} / \{0.63(2/3)(2 \times 32.2 \text{ ft/s}^2)^{1/2}(1 \text{ ft})^{3/2}\} \\ &= 1.13 \text{ ft} = 0.34 \text{ m} \end{aligned}$$

The assumed initial width ratio should be checked with this first iteration solution:

$$b_c/B_1 = 1.13 \text{ ft}/6.8 \text{ ft} = 0.17 \quad (\text{compare to initial value } 0.5)$$

Since this new value is so different from the initial assumption, the solution should be repeated. The new corresponding C_e value is 0.59 (for $h_1/p_1 = 3$, unchanged)

$$\begin{aligned} b_c &= \{3.8 \text{ ft}^3/\text{s}\} / \{0.59(2/3)(2 \times 32.2 \text{ ft/s}^2)^{1/2}(1 \text{ ft})^{3/2}\} \\ &= 1.20 \text{ ft} = 0.37 \text{ m} \end{aligned}$$

$$b_c/B_1 = 1.2/6.8 = 0.18 \quad (\text{compare to previous } 0.17; 5\% \text{ difference})$$

Given the uncertainty and approximation inherent in the various assumptions, this result is acceptable. Make the weir notch 1.2 ft (0.37 m) wide.

This same example is carried through in the worksheet that follows. This worksheet utilizes the additional correction K_b for the notch width. Designers can utilize the “manual” worksheet in Appendix 2C or the Maine DOT Excel worksheet for weir sizing calculations.

Design Example Fish Passage Weir-and-Pool Design Worksheet

Watershed Characteristics and Design Flow

1	Area (A)	12	sq miles
2	Sand & Gravel Fraction (SG)	0	Decimal fraction of area
3	Design Flow Q	3.5	ft ³ /s

Note: sand & gravel values only needed for monthly median flow equations; other design flow estimation methods may be used.

Weir, Culvert and Hydraulic Specifications

(perform all calculations in consistent units of feet or meters)

1	$h_1 - h_2$	8 in = 0.667 ft	W.L. drop across weir
2	h_2	4 in = 0.333 ft	Submerged depth on weir
3	d_{\min}	8 in = 0.667 ft	Min pool depth (downstream base of weir)
4	D	10 ft	Pipe diameter
5	S	0.02	Culvert slope
6	h_1	$4 + 8 = 12$ in = 1 ft	Upstream depth on weir $h_2 + (h_1 - h_2)$
7	p_1	$8 - 4 = 4$ in = 0.333 ft	Height of weir crest above invert $d_{\min} - h_2$
8	d_1	$4 + 12 = 16$ in = 1.333 ft	Upstream pool depth $h_1 + p_1$
9	r_s	$\{1 - (0.333/1)^{1.5}\}^{0.385} = 0.921$	Submergence ratio $\{1 - (h_2/h_1)^{3/2}\}^{0.385}$
10	B_1	$2\{1.333(10 - 1.333)\}^{1/2} = 6.8$ ft	Pool top width at weir $2\{d_1(D - d_1)\}^{1/2}$
11	L_w	$0.667 \text{ ft} / 0.02 = 33.35$ ft	Weir spacing $(h_1 - h_2) / S$
12	Q/r_s	3.8 ft ³ /s	Design flow adjusted for submergence Q/r_s

Calculations for Notch Width

Computation Constants

1	(Q/r_s)	3.8	from above
2	$(2/3)(2g)^{1/2}$	5.35	5.35 ft ^{1/2} /s; 2.95 m ^{1/2} /s
3	$h_1^{3/2}$	$1^{3/2} = 1$	h_1 from above
4	$A = (Q/r_s) / \{ (2/3)(2g)^{1/2} h_1^{3/2} \}$	0.71	Computation constant A
5	B_1	6.8	Pool width B_1 from above
6	h_1/p_1	$1/0.333 = 3$	Above crest-below crest depth ratio

Iteration for Notch Crest Width b_c

Iteration	0	1	2	3	4	5	6	7
b_c/B_1		0.5	0.16	0.18				
K_b		0.01	0.01	0.01				
C_e		0.63	0.58	0.58				
$b_e = A/C_e$		1.13	1.22	1.22				
$b_c = b_e - K_b$	3.4	1.12	1.21	1.21				

Notes:

- always use consistent units of [feet] or [meters] in hydraulic calculations
- set initial (iteration 0) b_c value = $1/2$ of B_1 ;
- get K_b and C_e by look-up in Appendix 2B;
- iterate until crest width b_c stops changing
- blank version of this worksheet in Appendix 2C

Energy Dissipation Factor (EDF) Calculation

The inter-weir pools should be checked for acceptable EDF ($\leq 5 \text{ ft-lb/s/ft}^3$; 250 J/s/m^3). When designing pool-and-weir systems, it is appropriate to assume that potential energy is to be dissipated. The equation for EDF is then

$$\text{EDF} = (\rho g)(Q\Delta y/V)$$

The flow Q is the fish passage design flow, the water level drop Δy is specified in the design, and the pool volume is determined from the calculated weir spacing, the design flow depths, and channel geometry.

The pool volume is difficult to calculate for a sloped, partially full circular pipe with level water surface. An acceptable approximation is to calculate the average water depth in the pool (i.e., average of upstream and downstream depths). From this average depth, calculate a cross-sectional wetted area A_w . Then volume is (approximately) the product of this area A_w and the length L between weirs. This general approach can also be used for other cross-section geometries.

At the upstream weir, depth $d_{\min} = 0.67 \text{ ft}$ (8 in or 200 mm); at the downstream weir, depth $(h_1 + p_1) = 1.33 \text{ ft}$ (16 in or 400 mm). Water depths and areas are calculated using the equations in Table 1, with wetted area analogous to embedded area. Calculations for pool volume are given in the following table in consistent units of (ft).

		Upstr	Downstr
Radius; diam; water depth	$R; D = 2R; d_b$	5; 10; 0.67	5; 10; 1.33
Water surf to pipe center	$D = R - d_b$	4.33	3.67
Water surf top width	$w_b = 2\{d_b(D-d_b)\}^{1/2}$	5.0	6.8
Flow Area	$A_b = R^2 \cos^{-1}(d/R) - dw_b/2$	2.18	6.19
Avg depth		1.0	
Water surf to pipe center		4.0	
Water surf top width		6.00	
Flow Area		4.09	
Length between weirs	L	33.35	
Pool Volume	$V = AL$	136	

Then EDF is calculated as

$$\begin{aligned} \text{EDF} &= (\rho g)(Q\Delta y/V) \\ &= (62.4 \text{ lbs/ft}^3)(3.5 \text{ ft}^3/\text{s} \times 0.67 \text{ ft}/136 \text{ ft}^3) = 1.1 \text{ (ft-lb/ft}^3/\text{s)} < 5 \end{aligned}$$

Since the calculated EDF is less than the upper limit of 5 (ft-lb/s/ft³), we conclude the pool-weir sequence provides adequate energy dissipation.