DESIGN OF FISH PASSAGE AT BRIDGES AND CULVERTS

HYDRAULIC ENGINEERING CIRCULAR – 26

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of CHRISTOPHER MICHAEL FREI find it satisfactory and recommend that it be accepted.

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Chair

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Abstract

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Development of guidelines for the design of bridges and culverts for fish passage began in January 2005 with an extensive literature review covering the topics of culvert design and assessment to ensure fish passage. A survey was posted online to gather input from design professionals across the country, and a Culvert Summit Meeting was held in Denver Colorado from February 15-16, 2006, to allow presentation and discussion of state-of-practice design and assessment techniques. Following the Summit meeting, a Technical Advisory Committee was developed with individuals specifically knowledgeable in the topics of interest. Members were crucial in shaping and reviewing the direction of these guidelines.

This document places current culvert design techniques into four categories based on design premise and objectives. These categories include: No Impedance techniques, which span the entire stream channel and floodplain; Geomorphic Simulation techniques, which create fish passage by matching natural channel conditions within the culvert crossing; Hydraulic Simulation techniques, which attempt to closely resemble hydraulic diversity found in the natural channels through the use of natural and oversized substrate; and Hydraulic Design techniques, which utilize roughness elements such as baffles and weirs to meet species specific fish passage criteria during periods of fish movement. Preliminary chapters covering the topics of fish biology and capabilities, culverts as barriers, fish passage hydrology, and design considerations aid in the selection of appropriate design techniques based on hydraulic, biologic, and geomorphic considerations. A further section presents examples of design techniques fitting the defined design categories. Design examples and case histories for a selection of design techniques are presented next, and are followed by a discussion on construction, maintenance, monitoring, and future research needs.

BACKGROUND

Development of these guidelines began in January 2005 with a literature review covering the topics of culvert design and assessment to ensure fish passage. In February 2005 a project website was posted to keep others apprised of progress, as well as to enhance contact with professionals interested in fish passage design and assessment.

In May 2005, a fish-passage survey was posted online to gather input from design professionals, non-governmental organizations, and other interested parties. Through February 2006 there were 67 respondents from 29 states representing biologists, fisheries managers, hydraulic engineers, bridge engineers, drainage engineers, and environmental managers. Of the states represented, only 5 reported fish passage to be of minor importance including New Hampshire, Florida, Oklahoma, Arizona, and Illinois. Furthermore, 13 states rated fish passage as an extremely important concern. Survey comments were used to shape the initial direction of HEC-26.

A Fish Passage Summit Meeting was held on February 15th – 16th, 2006 in Denver, Colorado. This comprised of 3 sessions – over one and a half days – covering the topics of culvert assessment, design and retrofit, and culvert replacement case histories. Speakers were selected, with design professionals known to be knowledgeable in each of our session topics, and care was taken to ensure that information was presented from regions that are under-represented in fish passage literature. Panel discussions were conducted at the conclusion of each session to invite audience participation and gain perspective on the topics presented. Overall, there were 110 people in attendance, including 16 speakers. Affiliation ranged from non-governmental-organizations to state departments of transportation.

A steering committee meeting was held at the conclusion of the Summit Meeting. Those in attendance are specifically knowledgeable in each of the topic areas, and were active in shaping the development of HEC-26. Members of the steering committee include:

Andy Kosicki	Maryland State Highway Administration
Marcin Whitman	California Department of Fish and Game
Mark Miles	Alaska Department of Transportation
Michael Furniss	United States Forest Service
Robert Gubernick	United States Forest Service
Scott Jackson	University of Massachusetts
Bryan Nordland	National Marine Fisheries Service

In addition to the Culvert Summit meeting, consultation with members of the Forest Service Technology and Development Center in San Dimas, California, as well as with Michael Love and Associates and Michael Furniss (key developers in

USFS's FishXing) were important in shaping project scope and direction. These meetings included site visits to inspect completed fish passage restoration projects and tide gates.

The following document represents the culmination of an effort to gather and share information necessary to understand the current state of bridge and culvert design for fish passage.

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GLOSSARY

Active Channel – A waterway of perceptible extent that periodically or continuously contains moving water. It has definite bed and banks, which serve to confine the water and includes stream channels, secondary channels, and braided channels. It is often determined by the “ordinary high water mark” which means that line on the shore established by the fluctuations of water and indicated by physical characteristics such as clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas.

Aggradation – The geologic process by which a streambed is raised in elevation by the deposit of material transported from upstream. (Opposite of degradation).

Apron – A flat or slightly inclined slab below a weir that provides for erosion protection and produces hydraulic characteristics suitable for energy dissipation or fish exclusion.

Anadromous Fish – Fish which mature and spend much of their adult life in the ocean, returning to inland waters to spawn. Examples include salmon and steelhead.

Armor – A surficial layer of course grained sediments, usually gravel or coarser, that are underlain by finer grained sediments.

Backwater – Water backed-up or retarded in its course as compared with its normal open channel flow condition. Water level is controlled by some downstream hydraulic control.

Baffle – Wood, concrete or metal mounted in a series on the floor and/or wall of a culvert to increase boundary roughness and thereby reduce the average water velocity in the culvert.

Bankfull Discharge – The discharge corresponding to the state at which the floodplain of a particular stream reach begins to be flooded. The bankfull discharge is a morphological indicator that is related to the formation, maintenance, and dimensions of a stream channel, as it exists under modern climatic conditions. The bankfull discharge, on average, has a flood frequency of approximately 1.5 years on the annual series, but the frequency can vary widely depending on the particular watershed and stream reach characteristics.

Bankfull Width – The point on a streambank at which overflow into the floodplain begins. The floodplain is a relatively flat area adjacent to the channel constructed by the stream and overflowed by the stream at a recurrence interval of approximately 1.5 years (see bankfull flow). If the floodplain is absent or poorly defined, other indicators may identify bankfull. These include the height of depositional features, a change in vegetation, slope or topographic breaks along the bank, a change in the particle size of bank material, undercuts in the bank, and stain lines or the lower extent of lichens and moss on boulders. Field determination of bankfull should be calibrated to known stream flows or to regional relationships between bankfull flow and watershed drainage area.

Bed – The land below the channel bed width.

Bedform – Elements of the stream channel that describe channel form (e.g. pools, riffles, steps, particle clusters).

Bedload – The part of sediment transport not in suspension consisting of coarse material moving on or near the channel bed.

Bed Roughness – Irregularity of streambed material that contributes resistance to streamflow. Commonly characterized using Manning's roughness coefficient.

Bridge – A crossing structure with a combined width (span) greater than 20 ft.

Burst Speed – See "Swimming Speed"

Cascade – A series of small vertical drops within a channel that may be natural or constructed.

Channel – A natural or constructed waterway that has definite bed and banks that confine water.

Channel Bed Slope – Vertical change with respect to horizontal distance within the channel (Gradient).

Channel-Bed Width – The distance from the bottom of the left bank to the bottom of the right bank. The distinction between bed and bank are determined by examining channel geometry and the presence/absence of vegetation. Common definitions include bankfull width and active channel width (OHW).

Channelization – Straightening or diverting a waterway into a new channel.

Countersink - Place culvert invert below stream grade.

Cruising Speed – See "Swimming Speed"

Critical Depth – The unique depth of flow in a channel that is characteristic only of discharge and critical slope. Often referred to as a flow control location.

Culvert – A conduit or passageway under a road, trail, or other obstruction. A culvert differs from a bridge in that it is usually constructed entirely below the elevation of the traveled way. It is usually consists of structural material around its entire perimeter and has a total width (span) of less than 20 ft.

Debris – Includes excess gravel, cobble, rubble, and boulder-sized sediments as well as trees and other organic detritus scattered about by either natural processes or human influences.

Degradation – Erosional removal of streambed material that results in a lowering of the bed elevation throughout a reach (opposite of aggradation).

Deposition – Settlement of material onto the channel bed.

Design Flood – The probabilistic estimate of a flood whose magnitude is equaled or exceeded within a given frequency.

Dewatering – Removal of water from an area.

Embedded Culvert – A culvert installation that is countersunk below the stream grade and filled with natural or synthetic material.

Entrainment –The process of sediment particle lifting by an agent of erosion.

Entrenchment – The vertical containment of a river and the degree to which it is incised in the valley floor.

Filter Fabric – A natural or synthetic fabric used to block sediment and water from flowing to a subsurface or surface area such as through a revetment of riprap along channel beds.

Fish Passage – The ability of fish to move both up and downstream through a bridge or culvert.

Fishway – A system that may include special attraction devices, entrances, collection and transportation channels, a fish ladder, exit and operation and maintenance standards to facilitate passage through bridges or culverts.

Fishway Weir – A term frequently used to describe the partition between adjacent pools in a fishway.

Flood Frequency – the frequency with which a flood of a given discharge has the probability of recurring. For example, a "100-year" frequency flood refers to a flood discharge of a magnitude likely to occur on the average of once every 100 years over a very long time span or, more properly, has a one-percent chance of being exceeded in any year. Although calculation of possible recurrence is often based on historical records, there is no guarantee that a “100-year” flood will occur at all within the 100-year period or that it will not occur several times.

Floodplain – The area adjacent to the stream constructed by the river in the present climate and inundated during periods of high flow.

Flow Duration Curve – A statistical summary of river flow information over a period of time that describe cumulative percent of time for which flow exceeds specific levels (exceedance flows), exhibited by a cumulative frequency curve that shows the percentage of time that specified discharges are equaled or exceeded. Flow duration curves are usually based on daily streamflow and describe the flow characteristics of a stream throughout a range of discharges without regard to the sequence of occurrence.

Fork Length – The length of a fish measured from the most anterior part of the head to the deepest point of the notch in the tail fin.

Geomorphology – The study of physical features associated with landscapes and their evolution. Includes factors such as stream gradient, elevation, parent material, stream size, valley bottom width.

Geomorphic Design – Culvert design to replicate or maintain natural stream geomorphic elements including gradient, width, bedform, bed material and key features. Fish passage requirements are assumed to be met when structures provide natural channel continuity.

Grade Stabilization or Grade Control – Stabilization of the streambed elevation against degradation. Usually a natural or constructed hard point in the channel that maintains a set elevation.

Head-Cutting – Channel bottom erosion moving upstream through a basin, which may indicate a readjustment of the stream’s flow regime (slope, hydraulic control, and/or sediment load characteristics).

Headwater – The water upstream from a structure or point on a stream.

Headwater Depth – The depth of water at the inlet end of a culvert.

High Passage Design Flow – The maximum river flow that fish can be expected to approach and pass a bridge or culvert.

Hydraulic Design – Design options utilizing natural or artificial flow control structures (including weirs, baffles, oversized substrate) to create hydraulic conditions passable for target fish species during specific periods of fish movement.

Hydraulic Jump – Hydraulic phenomenon in open channel flow, where supercritical flow changes to sub-critical flow. This will result in an abrupt rise in the water surface elevation.

Hydraulic Simulation – Design techniques that attempt to closely match natural stream flow characteristics by using embedded culvert structures, avoiding most channel constriction, and utilizing natural and oversized sediment in the barrel.

Incision – The resulting change in channel cross-section from the process of degradation.

Interstitial Flow – That portion of the surface water that infiltrates the streambed and moves through the substrate interstitial spaces.

Invert – The lowest point of the internal cross section of culvert or pipe arch.

Large Woody Debris (LWD) – Any large piece of woody material such as root wads, logs and trees that intrude into a stream channel. LWD may occur naturally or be designed as part of a stream restoration project.

Low Passage Design Flow – The lowest stream discharge for which upstream migrants are expected to be present, migrating, and dependent on the proposed facility for safe passage.

Manning's n – Empirical coefficient for simulating the effect of wetted perimeter roughness used in determining water velocity in stream discharge calculations.

Mitigation – Actions to avoid or compensate for the impacts on fish resulting from a proposed activity.

Normal Depth – The depth of flow in a channel or culvert when the slope of the water surface and channel bottom is the same and the water depth remains constant.

Ordinary High Water Mark (OHW) – Generally, the lowest limit of perennial vegetation. There are also legal definitions of OHW that include characteristics of erosion and sediment.

The OHW mark can usually be identified by physical scarring along the bank or shore, or by other distinctive signs. This scarring is the mark along the bank where the action of water is so common as to leave a natural line impressed on the bank. That line may be indicated by erosion, shelving, changes in soil characteristics, destruction of terrestrial vegetation, the presence of litter or debris or other distinctive physical characteristics.

Considerable judgment is required to identify representative OHW marks. It may be difficult to identify the mark on cut banks. In warm months grasses or hanging vegetation may obscure the OHW mark. Artificial structures (culverts, bridges or other constrictions) can affect the OHW mark by creating marks on the shore, which are consistent with OHW marks but above the elevation that is usually found in undisturbed river reaches.

Perching – The tendency to develop a falls or cascade at the outfall of a culvert due to erosion of the stream channel downstream of the drainage structure.

Pipe – A culvert that is circular (round) in cross section.

Pipe Arch – A pipe that has been factory-deformed from a circular shape such that the width (or span) is larger than the vertical dimension (or rise).

Plunging Flow – Flow over a weir, which falls into a receiving pool. Proportion of the flow at the receiving pool water surface is directed upstream.

Porosity – The percent of flow-through open area of a mesh, screen or streambed rack, relative to the entire gross area.

Reference Reach – A stable section of stream beyond the influence of the crossing of interest, with channel characteristics and geomorphology representative of the channel that would exist in the absence of the culvert crossing. This reach provides a template for design of Geomorphic Simulation structures.

Regrade – The process of channel adjustment to attain a new 'stable' bed slope. For example, following channel head cutting.

Resident Fish – Fish that are not migratory and complete their life cycle in fresh water.

Riffle – A reach of stream in which water flow is rapid and usually shallower than the reaches above and below. Natural streams often consist of a succession of pools and riffles.

Riparian – The area adjacent to flowing water (e.g., rivers, perennial or intermittent streams, seeps or springs) that contains elements of both aquatic and terrestrial ecosystems that mutually influence each other.

Riprap – Large, durable materials (usually rocks; sometimes broken concrete, etc.) used to protect a stream bank from erosion; may also refer to the materials used.

Scour – Localized erosion caused by flowing water.

Shear Strength – The characteristic of soil, rock and root structure on a parallel submerged surface such as the channel bed or channel bank.

Shear Stress – hydraulic force of water created by its movement on a parallel submerged surface such as the channel bed or channel bank.

Streaming Flow – See Plunging Flow

Substrate – Mineral and organic material that forms the bed of a stream. In an armored channel, substrate refers to the material beneath the armor layer.

Supercritical Flow – Occurs when normal depth is less than critical depth.

Swimming Speeds – Fish swimming speeds can vary from essentially zero to over six meters per second, depending on species, size and activity. Three categories of performance are generally recognized:

> **Cruising Speed** – The speed a fish can maintain for an extended period for travel without fatigue. Metabolic activity in this mode is strictly aerobic and utilizes only red muscle tissues.
>
> **Sustained (Prolonged) Speed** – The speed that a fish can maintain for a prolonged period, but which ultimately results in fatigue. Metabolic activity in this mode is both anaerobic and aerobic and utilizes white and red muscle tissue.
>
> **Burst (Darting) Speed** – The speed a fish can maintain for a very short period, generally 5 to 7 seconds, without gross variation in performance. Burst speed is employed for feeding, escape and negotiating difficult hydraulic situations, and represents maximum swimming speed. Metabolic activity in this mode is strictly anaerobic and utilizes only white muscle tissue.

Tailwater – Water that is ponded below the outlet of a culvert.

Thalweg – The longitudinal line of deepest water within a stream.

Toe – The break in slope at the foot of a bank where the bank meets the bed.

Upstream Fish Passage – Fish passage relating to upstream migration of adult and/or juvenile fish.

Upstream Passage Facility – A fishway system designed to pass fish upstream of a passage impediment, either by volitional or non-volitional passage.

Velocity – Time rate of motion; the distance traveled divided by the time required to travel that distance.

> **Average Velocity** - The discharge divided by the cross-sectional area of the flow in a culvert. Usually termed “average velocity”.
>
> **Boundary Layer Velocity** – Area of decreased velocity due to culvert boundary roughness. This region is restricted to only a few cm from the boundary.
>
> **Maximum Velocity -** The line of highest velocity encountered in all cross-sectional profiles in a culvert.

Weir – A short wall constructed on a stream channel that backs up water behind it and allows flow over or through it if notched. Weirs are used to control water depth and velocity.

Wetted Perimeter – Across a channel section, the length of the channel surface in contact with water.

GLOSSARY OF ACRONYMS

Acronym	Definition
ADFG	Alaska Department of Fish and Game
ADOT	Alaska Department of Transportation
CDFG	California Department of Fish and Game
CMP	Corrugated Metal Pipe
EDF	Energy Dissipation Factor
FHWA	Federal Highway Administration
GAO	General Accounting Office
NMFS	National Marine Fisheries Service
ODFW	Oregon Department of Fish and Wildlife
OHW	Ordinary High Water
SPP	Structural Plate Pipe
SPPA	Structural Plate Pipe Arch
WDFW	Washington Department of Fish and Wildlife
USFS	United States Forest Service

LIST OF SYMBOLS

Symbol	Definition
A	area (ft^2)
b_c	channel width across bars (ft)
C_d	discharge coefficient
C_e	dimensionless culvert exit head loss coefficient
C_0	dimensionless culvert head loss coefficient (C_e+K_e)
d	particle size of interest (ft)
D_i	particle size representing i% finer (Example, D_{16} is the particle size representing 16% finer)
f	dimensionless Darcy Weisbach friction factor
g	acceleration due to gravity (ft/s^2)
h	bank height (ft)
HW	headwater elevation above the culvert entrance invert (ft)
K_e	dimensionless culvert entrance head loss coefficient
L	Length (ft)
h_t	critical bank height (ft)
n	Fuller-Thompson coefficient for adjusting bed mixture gradation
n	Manning's roughness coefficient
Q	flow (ft^3/s)
q	unit discharge ($ft^3/s/ft$)
q_c	critical unit discharge ($ft^3/s/ft$)
Q_{100}	one hundred year flow (ft^3/s)
R	hydraulic radius (ft)
S	slope (ft/ft)
S_f	friction slope (ft/ft)
V	velocity (ft/s)
y	depth of water (ft)
Z	baffle height (ft)
τ	shear stress (lb/ft^2)
τ_c	critical shear stress (lb/ft^2)
γ	specific weight of water (lb/ft^2)
$\tau*$	dimensionless Shield's parameter
Φ	angle of repose (degrees)

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1 INTRODUCTION

1.1 PURPOSE AND SCOPE

This document is a design reference for the classification, design, or retrofit of a road-stream crossing to ensure **fish** passage, and has been formatted according to the requirements of a Federal Highway Administration Hydraulic Engineering Circular. It is the result of a comprehensive literature review completed to categorize national design procedures, case histories, and culvert assessment techniques. No particular set of passage criteria have been assumed; rather, a compilation of design options endorsed in different geographic regions are included to allow the user to select the most appropriate design method for their unique situation. A collection of design examples and case histories is intended to add clarity to the design methodology selection.

In order to provide stream reach connectivity for all wildlife, removal of road barriers or the installation of a bridge spanning the floodplain are ideal; however, this manual presumes that a narrower, fish-friendly, installation is both permitted and desirable for economical or logistical reasons. It is recognized that fish are not the only animals requiring habitat connectivity for long-term population viability, and future versions of this circular are intended to cover aquatic organism passage (AOP) in more detail. This manual is intended solely as a reference for the design, retrofit, or replacement of a road stream crossing to meet fish passage requirements.

The scope of this manual is also limited to culvert installations, which include bridges as defined by the Federal Highway Administration code:

> **Bridge.** A structure, including supports, erected over a depression or an obstruction, such as water, a highway, or a railway, having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 ft between undercopings of abutments or spring lines of arches, or extreme ends of the openings for multiple boxed; it may include multiple pipes where the clear distance between openings is less than half of the smaller contiguous opening.

In some situations, providing adequate width will require culvert installations spanning more than 20 feet, technically classifying them as bridges. For the purposes of culvert work, this includes installations with one or more contiguous openings, spanning a total distance of 20 feet or more. Examples include open bottom arches, pipe arches, circular culverts, and box culverts.

A logical progression is followed to guide the reader through the assessment and design process. Culvert analysis, design and retrofit techniques are then described, followed by case histories and design examples.

The increased biological, hydrological, and geomorphic sensitivity of a fish-passable structure requires that designers have access to a broad knowledge base. Proper assessment and design of a culvert installation or retrofit requires some expertise in hydraulic engineering, structural/geotechnical engineering, and hydrology; although, the level of experience needed varies depending on the preferred culvert installation/assessment method. Regional requirements for fish biology, hydrology, and geomorphology require that the design for fish passage be considered on a site-by-site basis, all but eliminating the possibility of a cookie-cutter design approach. Consultation with local engineers, stream ecologists and fish biologists will help ensure that the culvert selection, design, and alignment provide optimal stream reach connectivity, and that the most appropriate installation or retrofit strategy is selected based on ecological need, priority, cost, and site logistics.

1.2 FHWA HISTORICAL PERSPECTIVE

Waterway crossings, including bridges and culverts, represent a key and expensive element in our overall transportation system. The design of crossing structures has traditionally used hydraulic conveyance and flood capacity as the main design parameters. Hydraulic Design Series - 5 *Hydraulic Design of Highway Culverts* (HDS-5) specifies a culvert design procedure to maintain acceptable headwater depth during design floods; this ensures efficient conveyance of water, but normally does not include provisions for fish passage through the culvert (Normann et al. 1985).

Design for hydraulic efficiency necessarily overlooks the impact of a road-stream crossing on the aquatic ecosystem. Resulting structures often narrow the channel through the bridge opening or culvert barrel. Constricted reaches influence the characteristics of flow through and around the hydraulic structure, increasing velocities and scour potential (Johnson and Brown 2000). Augmented flow regimes may induce scour of the streambed through and downstream from the structure, and cause upstream progressing channel incision (Castro 2003). Table 1.1, from the Forest Service Stream Simulation Manual, lists a number of possible stream responses to altered hydraulic conditions caused by a traditionally sized crossing (Bates et al. 2006). In general, the effects of an undersized culvert can be described as a local destabilization of the stream channel (Johnson and Brown 2000).

Table 1.1. Possible Geomorphic Responses of a Stream Channel to an Undersized Culvert (adapted from Bates et al. 2006)

Geomorphic Response to Undersized Culvert
Downstream erosion of bed and banks
Downstream channel incision
Disconnected Floodplains
Direct habitat loss and degradation

Velocities resulting from traditionally sized culverts may exceed fish swimming ability, and scour at culvert outlets may prove too excessive for fish to leap into the structure (Venner Consulting and Parsons Brinkerhoff 2004). As a result, many bridges and culverts act as barriers to juvenile and adult fish movement (Flanders and Cariello 2000; Wilder et al. 2004; Browning 1990). For example, Figures 1.1 and 1.2 depict outlet scour resulting in perching – the development of a falls or cascade at the culvert outfall due to erosion of the stream channel downstream of the drainage structure (Bates et al. 2003) - while Figure 1.3 illustrates the impact of debris deposition. Often, high quality upstream fish habitat is disconnected from downstream river and stream corridors by structures that are impassable for native fish (Trombulak and Frissell 2000).

Figure 1.1. Scour downstream from culvert "perches" the barrel above the streambed, making it inaccessible to many fish species (United States Forest Service 2006b).

Figure 1.2. Multiple culvert installation located at a slope break where sediment is likely to deposit, creating a debris barrier. Flow is spread to thinly to allow fish passage (United States Forest Service 2006b).

Figure 1.3. Downstream scour caused this culvert to become perched, as well as presenting a low flow barrier to fish passage (Furniss 2006).

1.3 ECOLOGICAL PERSPECTIVE

River and stream corridors provide vital habitat for a wide range of animal species, many of which depend on the ability to move freely throughout their ecosystem in order to complete their life cycles (Jackson 2003). The importance of human transportation has led to roads that extend through much of the country, inevitably crossing over streams and rivers (Schrag 2003). Structures designed to pass water under a road frequently do not consider animal movement, causing fragmentation of many riverine systems (Trombulak and Frissell 2000). Recognition of the need to restore habitat connectivity has added ecological consideration to the design and retrofit of road stream crossings (e.g. Jackson 2003; Bates et al. 2006).

1.3.1 Importance of Animal Movement

As a dynamic environment, the habitat within riverine ecosystems is in a constant state of flux, begetting the need for animal movement (Amoros and Bornette 2005). The ability to move freely throughout a stream ecosystem allows wildlife to seek food and shelter, mating partners, escape predation, or move in response to extreme natural disturbances (Jackson 2003). While some animals can live their entire life under a single rock, others require substantial room to travel. For example, the Florida Black Panther has been shown to occupy home ranges up to 1182 square kilometers (Cramer 1999), and salmon can travel hundreds of miles up rivers and streams to make their return from the ocean to headwater streams to spawn (Groot and Margolis 1991).

Freedom of movement allows wildlife to seek out habitat suitable to their life stage. Salamanders, for example, utilize headwater streams as adults, but seek out environments with more stable hydrology when breeding. The resulting larvae are weak swimming, and could not survive in the more dynamic riverine system occupied by adults (Jackson 2003). Adult salmon migrate to the ocean to grow, but return to the headwater streams of their birth to spawn (Groot and Margolis 1991). It has been observed that smaller resident salmonids move upstream and downstream, relying on more than a small stream reach for survival (Young 1995; Young 1996; Kahler and Quinn 1998).

Population dynamics are linked to movement, allowing many subpopulations to interact to increase genetic exchange and enhance biodiversity. Just as roads convey traffic from one point to another, streams and rivers provide an avenue for animals to seek out the resources they need to survive and enhance their genetic biodiversity. Disturbances in river continuity force animals to utilize smaller areas - blocking off spaces that were once an integral part of their range.

1.3.2 Road Stream Interaction

Roads cover almost 2% of the landmass in the United States, leading to a seemingly unavoidable interaction of roadways and the environment (Schrag 2003). For example, a survey of Bureau of Land Management (BLM) and U.S. Forest Service land found 10,000 culvert crossings on fish bearing streams in Washington and Oregon alone (General Accounting Office 2001). And estimates of road and railroad crossing affecting Massachusetts streams are as high as 28,500 (Venner Consulting and Parsons Brinkerhoff 2004). Such crossings impact aquatic organisms and fish, potentially causing barriers to passage, fragmentation, and a loss of ecological connectivity (Trombulak and Frissell

2000). Many of the road-stream culverts that are currently in place were designed and installed with hydraulic conveyance as the main criteria (Normann et al. 1985). Natural stream processes were not considered in favor of relatively inexpensive culverts that could pass a design flow without roadway overtopping. This design methodology ignored issues such as sediment transport, fish and wildlife passage, and generally had a significant impact on the stream's natural hydrology (Jackson 2003). For example, over half of the 10,000 culverts surveyed on Forest Service and BLM land in Washington and Oregon are considered to be barriers to juvenile salmon passage (General Accounting Office 2001).

Although much recent focus has been on the passage of fish, many other organisms are affected by improperly designed culverts, from small aquatic organisms such as salamanders to large terrestrial animals such as deer (United States Forest Service 2006a; Schrag 2003). In general, a culvert that is impassable for fish will also pose as a barrier to weaker swimming semi-aquatic organisms (Bates et al. 2006).

As increasing human population leads to an expansion of our infrastructure, the role of roads in habitat decline and fragmentation is the subject of increased scrutiny (e.g. Spellerberg 1998; Trombulak and Frissell 2000). The long-term ecological effects of roads include loss and change of habitat, changes in biological makeup of communities, and fragmentation – leading to population isolation (Spellerberg 1998).

1.3.3 Effects of Population Isolation

The effects of isolation are most dangerous in smaller populations, although a variety of variables are involved in analysis of population vulnerability (Mace and Lande 1991). With a smaller isolated group there will be an increase in genetic homogeneity, as well as higher susceptibility to natural or chance events (Mace and Lande 1991). This can mean local extinctions due to drought or fire, and the results of inbreeding, including genetic weakness, which makes the population susceptible to disease, decreased reproduction, high mortality, and possibly to extinction (McKelvey et al. 2002).

For both aquatic and terrestrial organisms, negative impacts of roadway interaction are manifest through a loss of population connectivity. The species most vulnerable to isolation are those with large home ranges and low population numbers, including bears, wolves, mountain lions, Florida panthers, lynx, snakes and desert tortoises (Hass 2000). The removal of these predators can have a significant impact throughout the food web, and many attempts to increase connectivity have been undertaken in the United States, Canada and Europe, including underpasses and overpasses (Schrag 2003). Many of these wildlife-crossing case histories can be accessed through the U.S. Forest Services Wildlife Crossing Toolkit website at http://www.wildlifecrossings.info/beta2.htm.

Aquatic organism passage (AOP) was the focus of a short course developed by the U.S. Forest Service (2006b). To provide connectivity, road-stream crossings must provide a desirable passageway for aquatic organisms at a variety of flows. Culverts that mimic stream reach characteristics can provide favorable connectivity at a culvert crossing (Bates et al. 2006). Bridges, however, offer the most protection against habitat fragmentation (Robison et al. 1999). Organisms such as moles, salamanders, newts, and mussels depend on the ability to move between habitats at different life stages. For such organisms, the ability to reach vital rearing habitat is essential to survival, and fragmentation could spell the end of a localized population. With the recognition of the importance of ecological connectivity, limiting the disruption that road-stream crossings pose has received recent focus (e.g. United States Forest Service 2006a; Jackson 2003).

Without ecosystem connectivity, areas could remain void of species diversity, as new populations cannot move in to mitigate a local extirpation (e.g. Morita and Yamamoto 2002). The loss or disconnection of any portion of an ecosystem is undesirable but is not necessarily detrimental to a population (Farhig and Merriam 1985). Even in an undisrupted ecosystem individual animals are constantly in danger of death even as the larger population remains in tact. Persistence is the result of a constantly refreshing gene pool, which maintains genetic health. Connectivity ensures that wildlife is given the chance to move freely in order to complete life cycle functions and maintain long-term population viability.

1.4 NATIONAL LEGISLATION AND REGULATION

1.4.1 Laws

1.4.1.1 Clean Water Act

Objectives of the Clean Water Act (CWA) include restoring and maintaining the physical, chemical, and biological integrity of the waters of the United States. For culvert crossings, the USACE has the responsibility to interpret and implement this objective, requiring ecological connectivity, and the passage of fish both upstream and downstream through the structure.

Clean Water Act: Nationwide Roads Exemption BMP 40CFR 232.3 c(6)

> *"The design, construction and maintenance of the road crossing shall not disrupt the migration or other movement of those species of aquatic life inhabiting the water body."*

1.4.1.2 Endangered Species Act

The Endangered Species Act prohibits any activity that adversely impact threatened or endangered species, directly or indirectly. In the case of fish passage this includes a number of listed salmon, sturgeon, shiner, darter and perch species. The ESA is regulated by the Fish and Wildlife Service and NOAA Fisheries.

1.4.1.3 Rivers and Harbors Act of 1899

Section 10 of the Rivers and Harbors Act of 1899 regulates all construction work done in, over, or under navigable waters or that excavates or deposits material into what are deemed to be navigable waters in the United States *Navigable water* is defined as any water that has historically been used for or could possibly be used for transportation of interstate commerce. If this determination is made for a portion of a given body of water, the law applies to the entire body of water. This law can be applied even to water no longer considered navigable because of levees or other alterations that were permitted in the past. The enforcement of this law is overseen by the Army Corps of Engineers.

1.4.1.4 Fish and Wildlife Coordination Act

The Fish and Wildlife Coordination Act calls for comments and review by the Fish and Wildlife Service and by NOAA Fisheries (National Marine Fisheries Service), giving them authority over any federal program that could modify a natural body of water in the U.S., even those permitted by other federal agencies. Consequently, this law can be used to reject projects approved by the Army Corp of Engineers under Section 404 or Section 10.

1.4.2 State and Local Regulations

In addition to federal regulations, there may also be a number of local or state regulations that apply to the design and installation of road-stream crossing structures. Such regulations may dictate construction timing, allowable sediment levels, fish passage requirements, or preferred culvert design techniques. It is important to consult with local authorities before beginning any project.

1.5 MANUAL PREVIEW

Table 1.2. Manual Preview

Chapter	Description
2 Fish Biology	Fish biological abilities and requirements for successful movement.
3 Culverts as Barriers	Details the types of barriers presented by culverts that were not designed with a fish's biological capacities in mind.
4-6 Assessment/Inventory/Prioritization	Importance of the hydraulic assessment, inventory and prioritization of road stream crossing projects. Includes a discussion of commonly used techniques, as well as synthesis and recommendations for future prioritization
7 Hydrology	Discussion and comparison of hydrology used in the design of culverts for fish passage. Available techniques and recommended methods are included.
8 Design	Necessary considerations for the design or retrofit of a new or existing road-stream crossing installation.
9-11 Current Design Procedures	Details the current state of fish passage design, including design scenarios from across the country. Covers new installations, culvert replacements, and retrofits.
12 Case Studies/Design Examples	Case studies and/or basic examples of culvert design, installation and retrofit have been included to clarify the design process.
13 Construction/Maintenance	Common scenarios and recommendations for culvert construction and maintenance.
14 Monitoring	Suggested monitoring considerations to ensure long term success of culvert installations, replacements or retrofits.
15 Future Research Needs	Recommendations based on literature review and perceived gaps in current knowledge.

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2 FISH BIOLOGY

The capacity of fish to traverse physical obstacles will dictate the appropriate design of a culvert crossing. An understanding of resident fish biology and swimming ability will allow culvert designers to create a culvert design suitable for local conditions. This information is most commonly used when assessing fish passage at an existing culvert (Chapter 5), retrofitting an existing culvert for fish passage (Chapter 11), or designing a new culvert using the Hydraulic Design technique (Chapter 11). The following discussion outlines fish biology, swimming abilities, and requirements, providing a basic understanding of what fish need to successfully move throughout their environment.

2.1 ANATOMY

Fish possess two muscle systems to accommodate different modes of travel: a red muscle system (aerobic) for low-intensity activities and a white muscle system (anaerobic) for shorter, high-intensity movements (Webb 1975). Extensive use of the white muscle system causes extreme fatigue, requiring extended periods of rest.

2.2 CAPABILITIES AND ABILITIES

2.2.1 Swimming and Jumping

Fish movement can be divided into three categories based on speed and muscle use: cruising, sustained or darting speeds (Bell 1986). A fish at cruising speed uses the red muscle system exclusively, allowing extended periods of travel at low speeds. Sustained speed involves the use of both red and white muscle tissue, and allows the fish to reach quicker speeds for minutes at a time. Darting speed allows the fish to reach top speeds for a few seconds by exclusive utilization of white muscle tissue, requiring a significant rest period. Table 2.1 summarizes the muscle system use as it relates to fish movement.

Table 2.1. Movement type as it relates to muscle system utilization (Bell 1986).

Movement Type	Description	Muscle System	Period
Cruising	Also known as prolonged swimming, used for long periods of travel at low speeds.	Red (purely aerobic)	Hours
Sustained Swimming	Short periods of travel at high speeds	Red and White	Minutes
Darting	Maximum swimming speed or jumping, inducing fatigue.	White (purely anaerobic)	Seconds

Fish can fail to pass a culvert for a variety of reasons. An outlet drop or high velocity zone will act as a barrier when it exceeds the fish's darting ability, while a continuous section of culvert with relatively low velocity may require sustained swimming speeds to be maintained beyond a fish's natural ability. It is important to note that these criteria are not cumulative, and a fish that reaches exhaustion in any category will require a period of rest before continued movement.

A number of studies have been completed to ascertain the swimming and jumping ability of different fish species (e.g. Jones et al. 1974; Bainbridge 1959; Stuart 1962; Hinch and Rand 1998; Rand and Hinch 1998; Ellis 1974; Toepfer et al. 1999). Before designing a particular culvert crossing using a Hydraulic Design approach (Chapter 11) it will be necessary to check local conditions including fish species present and time periods/flows at which movement is required.

2.2.2 Species and Life Stages

Swimming and jumping capabilities can vary greatly between species. For example, Figure 2.1, taken from Bell's Fisheries Handbook, depicts the relative swimming abilities of adult fish. Darting speeds reaching 26 ft/s give adult steelhead a velocity potential more than twice that of an adult brown trout, and almost four times that of an adult herring (Bell 1986).

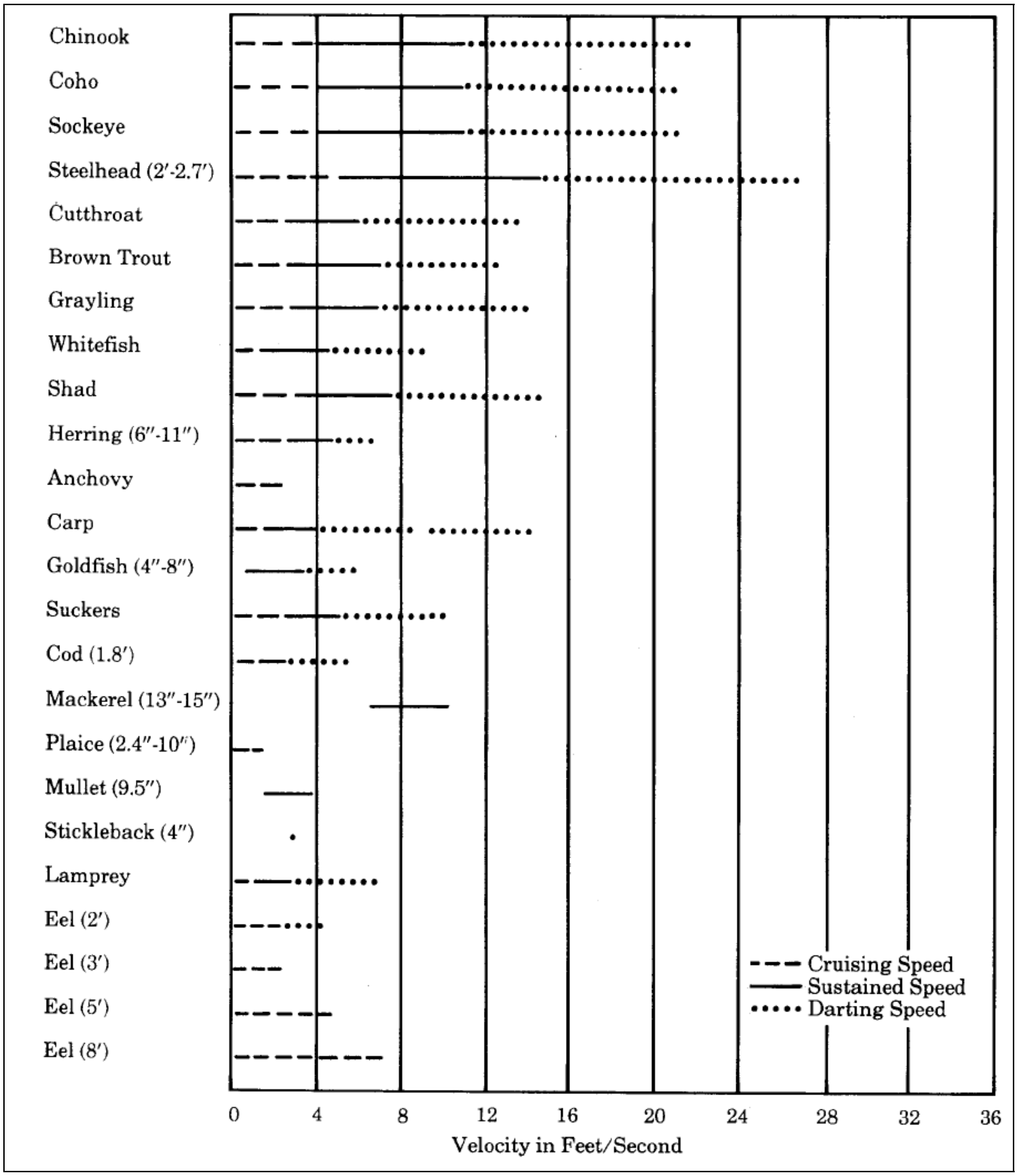

Figure 2.1. Relative Swimming Abilities of Adult Fish. From Fisheries Handbook of Engineering Requirements and Biological Criteria (Bell 1986)

Even within a given species, there can exist a large variation between individual capabilities. This can be the result of life stage, or individual prowess. Figure 2.2 depicts a similar collection of swimming abilities for young fish. If passage for these life stages is required, velocities thresholds drop significantly. For example, a young Coho salmon can reach sustained speeds up to 2 ft/s, while an adult is able to sustain almost 11 ft/s (Bell 1986). Individual fish will also exhibit dissimilar swimming capabilities, resulting in the velocity ranges depicted in Figures 2.1 and 2.2. This has serious ramifications for the selection of velocity criteria. Design for maximum swimming speed may create passage for the strongest swimmers, while maintaining a barrier to average or weak swimming individuals. Design for the weakest swimming fish will create a structure that is quite conservative, and possible over-designed.

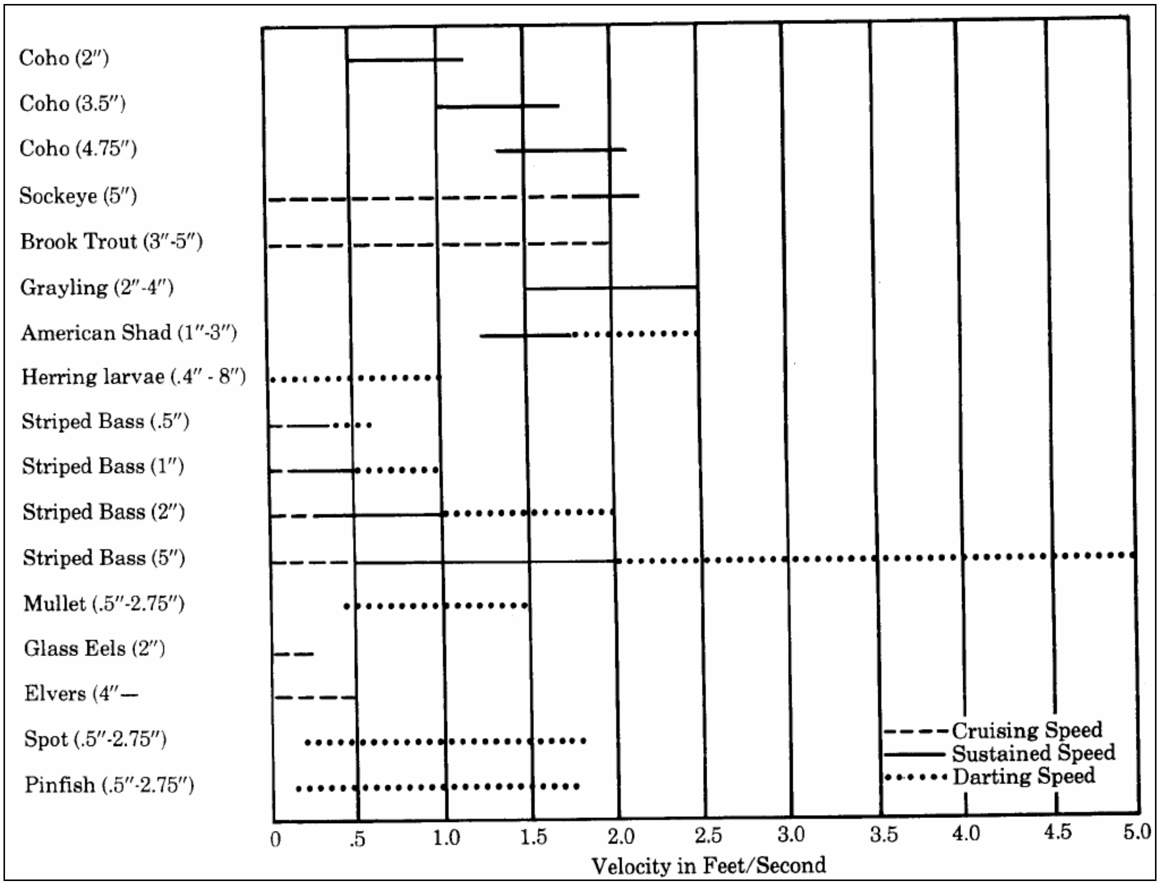

Figure 2.2. Relative Swimming Abilities of Young Fish (Bell 1986).

2.2.3 Depth Requirements

Fish require a minimum depth of flow to allow them to reach swimming potential (Dane 1978). Total submergence eliminates a fish’s risk of oxygen starvation, allows the fish to create maximum thrust, and lowers the risk of bodily injury through contact with the culvert bottom (Forest Practices Advisory Committee on Salmon in Watersheds 2001). For example, Table 2.2 from Everest et al, summarizes depth requirements for a variety of salmonid and trout species from the Pacific Northwest (1985).

Table 2.2. Minimum Depth criteria for successful upstream passage of adult salmon and trout (Everest et al. 1985). Note – fish may not be able to migrate long distances at the depths listed. Information is based on species found in Washington and Oregon.

Fish Species	Minimum Depth (ft)
Pink Salmon	0.59
Chum Salmon	0.59
Coho Salmon	0.59
Sockeye Salmon	0.59
Spring Chinook	0.79
Summer Chinook	0.79
Fall Chinook	0.79
Steelhead Trout	0.79

Specific depth requirements vary with species and life stage of concern, and are generally much more conservative than studies suggest. Alaska requires that depth be greater than 2.5 times the depth of a fish's caudal fin, as depicted in Figure 2.3 (Alaska Department of Fish and Game and Alaska Department of Transportation 2001). The Washington Department of Fish and Wildlife specifies a minimum depth of 0.8 ft for Adult Trout, Pink and Chum Salmon, and a depth of 1.0 ft for adult Chinook, Coho, Sockeye or Steelhead (Bates et al. 2003). Maine employs a depth requirement of 1.5 times body thickness (Maine Department of Transportation 2004).

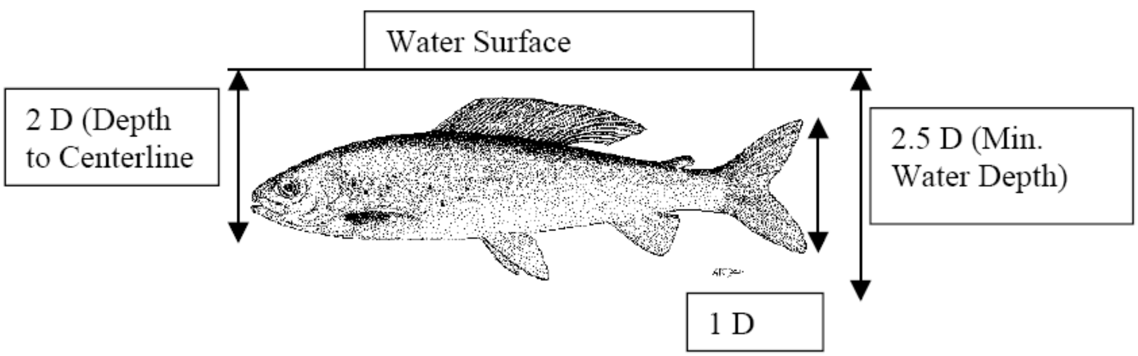

Figure 2.3. Minimum water depths for fish passage in Alaska (D = height of caudal fin). (Alaska Department of Fish and Game and Alaska Department of Transportation 2001).

2.2.4 Example of Fish Criteria

Exhaustion criteria have been experimentally derived for a variety of fish species, allowing the development of culvert velocity thresholds. Table 2.3 from Washington's Fish passage manual demonstrates how exhaustion and swimming speed criteria can be used to create relationships between allowable length and velocity based on fish species. In Washington State, adult trout represent a conservative lower design threshold, and are considered the species of concern in any area where specific fish species presence has not been determined (Bates et al. 2003). Further discussion of culvert criteria is included in Chapter 3.

Table 2.3. Fish-passage design criteria for culvert installations (Bates et al. 2003). Greater culvert lengths require lower velocity thresholds, while the increased swimming ability of larger fish (Adult Chinook, Coho, Sockeye and Steelhead) allows larger hydraulic drops and barrel velocities, but require a larger minimum depth.

	Adult Trout >6 in. (150 mm)	Adult Pink or Chum Salmon	Adult Chinook, Coho, Sockeye or Steelhead
Culvert Length	**Maximum velocity (fps)**		
10 - 60 feet	4.0	5.0	6.0
60 - 100 feet	4.0	4.0	5.0
100 - 200 feet	3.0	3.0	4.0
Greater than 200 feet	2.0	2.0	3.0
	Minimum water depth (ft)		
	0.8	0.8	1.0
	Maximum hydraulic drop in fishway (ft)		
	0.8	0.8	1.0

2.3 FISH MOVEMENT

2.3.1 Migration

Anadromous fish, such as salmon, migrate to the ocean to feed and grow, and return upstream as mature adults to spawn (Groot and Margolis 1991). Upstream movement is triggered by time of year, flow events and a number of environmental factors. For example, the upstream migration of spawning salmon is hypothesized to be in response to maturation, the changing length of days, and temperature regimes (Groot and Margolis 1991). Recognition of the importance of seasonal spawning runs to anadromous fish persistence led to the development of early fish passage guidance documents (e.g. Baker and Votapka 1990; Gebhards and Fisher 1972; Evans and Johnston 1972).

2.3.2 Resident Movement

Of more recent concern is the migration of resident and juvenile fish (e.g. Bates et al. 2003; Bates et al. 2006; Robison et al. 1999; Admiraal and Schainost 2004). Previous knowledge held that resident populations remained fairly stationary throughout the year (Gerking 1959); however, movement of both juvenile salmon and resident trout has been observed in response to a variety of environmental factors (Gowan et al. 1994). This includes up and downstream movement in response to extreme flows, stream temperatures, predation, lower population densities or search for food or shelter (Robison et al. 1999; Kahler and Quinn 1998; Schaefer et al. 2003).

Design to meet the needs of a spawning salmon will not necessarily guarantee that a culvert will allow passage of weaker swimming juveniles or resident fish. Although fish are capable of specific swimming energies, it does not mean that fish will choose to expend maximum swimming energy when confronted with specific obstacles (Behlke et al. 1991). This is consistent with observations of fish moving through culvert boundary layers, and holding in areas of low velocity between corrugations (Powers et al. 1997).

2.4 LOCAL FISH REQUIREMENTS

The distribution of fish species, life stage and migration timing is available from sources such as State and Federal Agencies, Tribal governments, commercial landowners and non-profit organizations. Note that studies to ascertain fish presence may focus on larger waterways, providing low-resolution distribution maps that neglect smaller streams (Clarkin et al. 2003).

It may be pertinent to conduct site visits to check for fish presence, and regional fish presence criteria may be useful (i.e. fish are assumed absent in streams with gradients above 20%). To ensure that fish presence is adequately understood, some guidelines begin with the default assumption that passage is required for the weakest swimming fish contained in their criteria (i.e. Bates et al. 2003; Robison et al. 1999). In Oregon, designers must contact a local biologist, or prove that fish passage is not required at a site, before less conservative design requirements can be utilized (Robison et al. 1999).

Although fish may not appear during a survey, it doesn't mean they don't inhabit the reach at some times of the year. Fish are often in areas where biologists do not expect them, and it is likely desirable to provide passage for native migratory fish that are or were historically present at the site (Clarkin et al. 2003).

2.5 CONCLUSIONS

A "successful" fish crossing will ensure passage for the weakest swimming fish species of concern. Before beginning the design process, it will be necessary to ascertain all fish species for which passage is desirable, including swimming ability and timing of fish migration. Many studies have been completed to understand the swimming abilities of particular fish species, and values or formulas can be found in fish passage literature, through collections of data such as those provided for FishXing www.stream.fs.fed.us/fishxing/, or through online sources such as FishBase www.fishbase.org. It is important to check with local fisheries biologists to understand the needs of fish in your area.

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3 CULVERTS AS PASSAGE BARRIERS

3.1 STREAM FRAGMENTATION

Culvert installations can significantly decrease the probability of fish movement between habitat patches (Schaefer et al. 2003). Figure 3.1 depicts the possible results of ineffective road-stream culverts on fish populations. In the undisturbed case, fish are free to use the entire stream system as habitat. After a road interrupts stream continuity, fragmented populations are forced to survive independently. Over a short time, smaller populations are more likely to die of chance events (Farhig and Merriam 1985), but over the long-term, genetic homogeneity and natural disturbances are also likely to extirpate larger populations (Jackson 2003). Figure 3.1 shows this process sequentially from top left to bottom right.

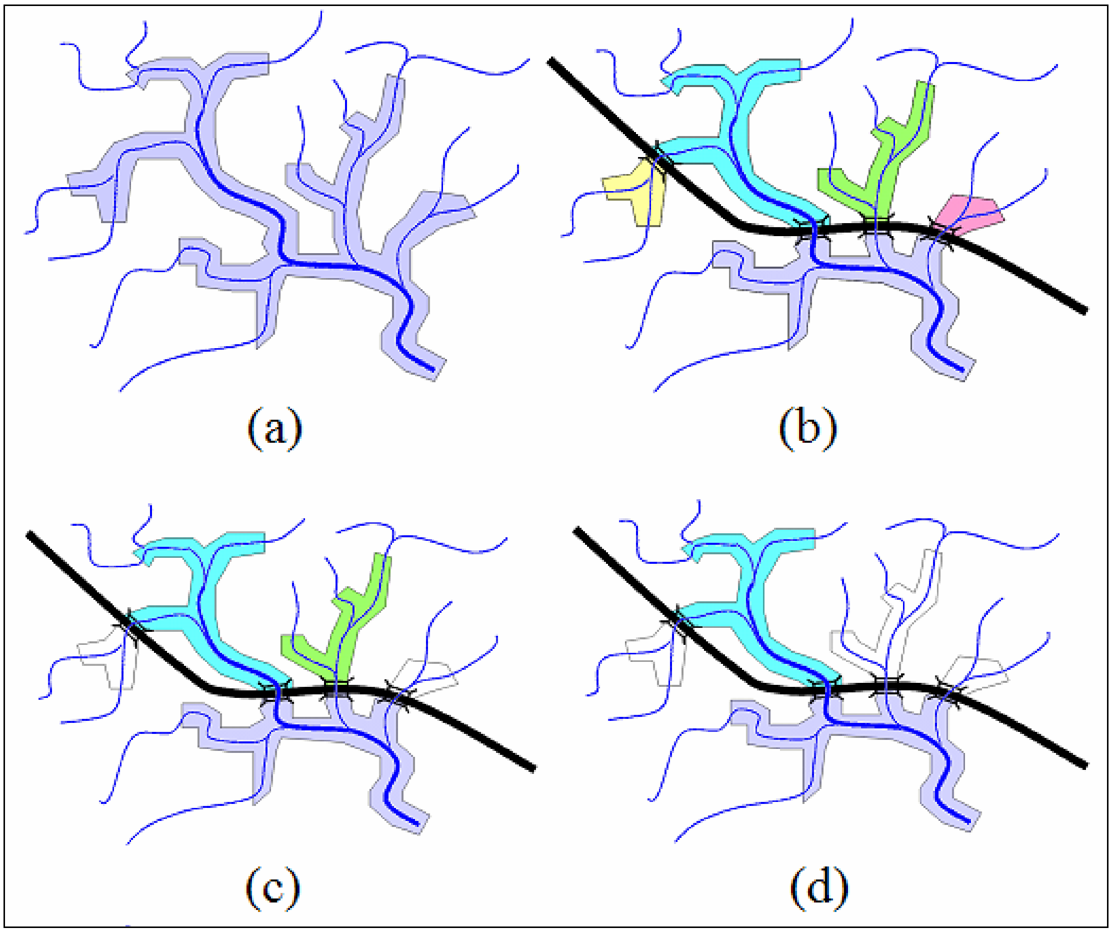

Figure 3.1. Changes in fish habitat use over time after roadway fragmentation. From top left to bottom right: (a) undisturbed habitat, with fill representing habitat in use; (b) habitat with ineffective culverts causing fragmentation; (c) fragmented system after a few years (areas with no fill represent population extirpation); (d) fragmented system after many years (Jackson, S., Personal Communication).

3.2 LONGITUDINAL BARRIERS

A culvert becomes a barrier to fish passage when it demonstrates conditions exceeding fishes' biological ability. Common obstructions to fish passage include excessive water velocities, drops at culvert inlets or outlets, physical barriers such as weirs, baffles, or debris caught in the culvert barrel, excessive turbulence caused by inlet contraction, and low flows that provide too little depth for fish to swim. Figure 3.2, from Baker and Votapka, depicts an early rendition of four common barrier types (1990).

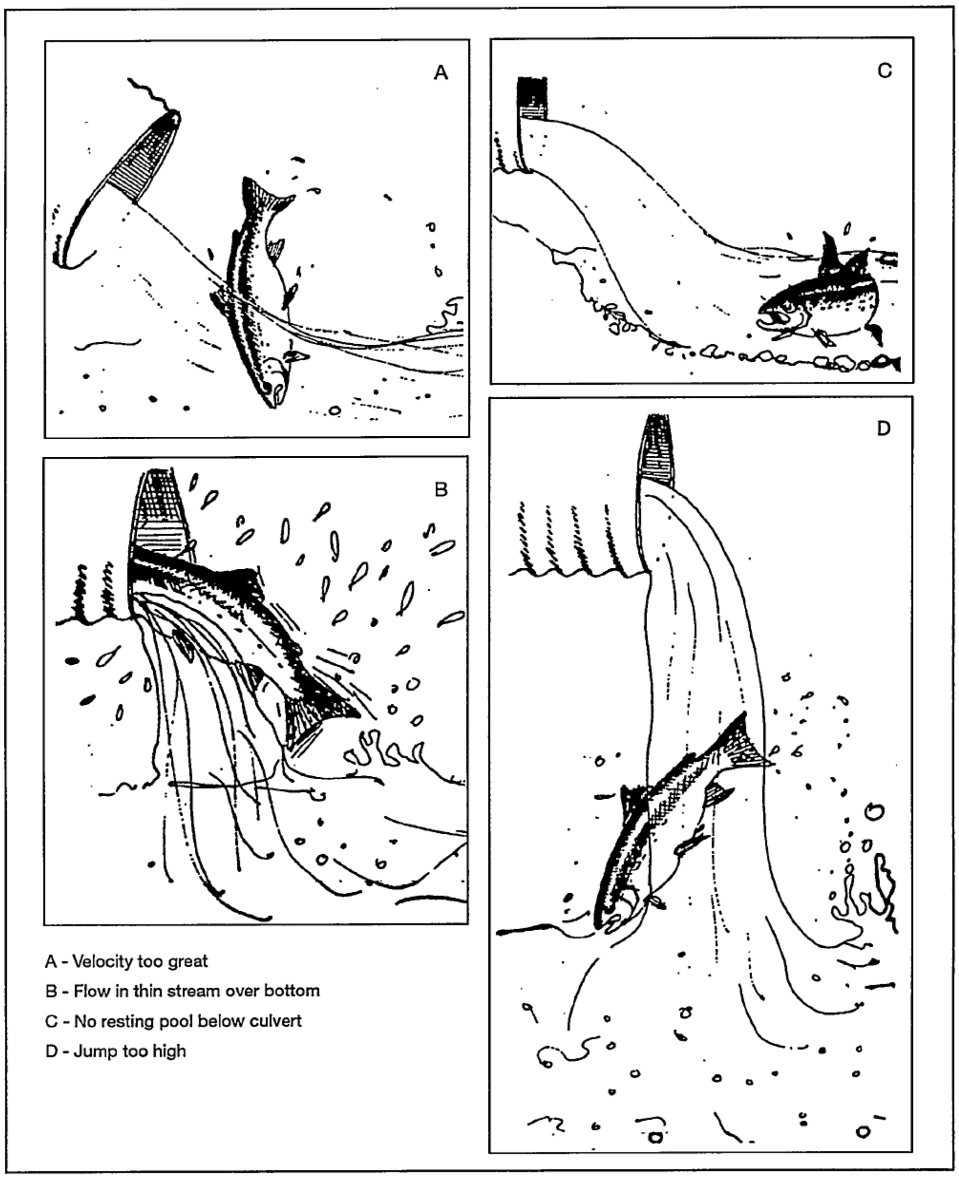

Figure 3.2. Barriers to fish passage (Baker and Votapka 1990).

The severity of obstacles to fish passage compounds when a series of obstacles cause fish to reach exhaustion before successfully navigating the structure. For example, fish have been observed successfully passing an outlet drop, but having insufficient white muscle capacity to traverse a drop at the culvert inlet (Behlke et al. 1989). As noted in Chapter 2, fish swimming abilities are not cumulative, and a fish that reaches exhaustion in any category of muscle use will require a period of rest before continued movement (Bell 1986).

3.2.1 Drop at Culvert Outlet

Drops in water surface will create passage barriers when they exceed fish jumping ability. Drops can occur at any contiguous surface within the culvert, but they are most commonly seen at the culvert outlet (see Figure 3.3), where scour and downstream erosion leads to culvert perching (Forest Practices Advisory Committee on Salmon in Watersheds 2001). At existing sites, drops will need to be addressed through culvert replacement, retrofit, or channel modification, such as backwatering the culvert outlet.

Figure 3.3. Perched outlet, leap barrier
(Alaska Department of Fish and Game 2005)

Fish require a jump-pool to gain the momentum necessary to jump into the structure. Early field observations suggested that successful fish passage at falls occurs when the ratio of drop height to pool depth is 1:1.25 (Stuart 1962). Aaserude and Orsborn later correlated fish passage to fish length and the depth that water from the falls penetrates the pool (1985). For practical application, jump pool requirements are generally specified based on a ratio of drop height to pool depth. Oregon, for example, uses 1.5 times jump height, or a minimum of 2 ft depth (Robison et al. 1999). An adequate jump-pool neither guarantees that a fish has the ability to make the required leap, or once in the culvert, has the energy to overcome the water velocity in the culvert barrel.

3.2.2 Excessive Velocity in Barrel

Figure 3.4 depicts a culvert outlet presenting a drop and velocity barrier to fish passage. There are many categories of velocity that impact fish passage within a culvert crossing. These include boundary layer velocity, maximum point velocity, average cross sectional velocity, and inlet transition velocity. The importance of each is discussed below.

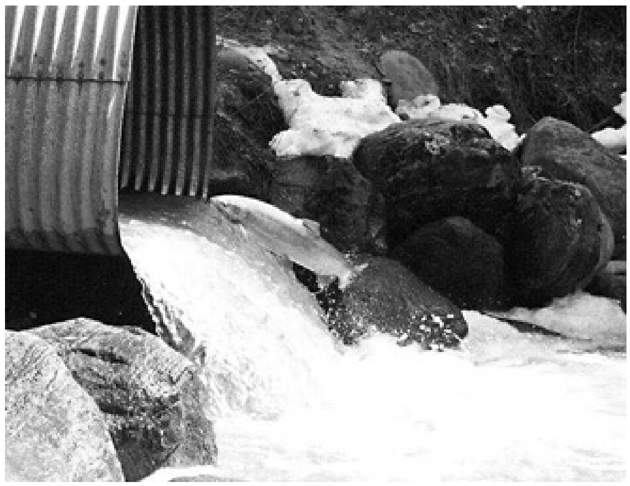

Figure 3.4. Drop and Velocity Barrier (Alaska Department of Fish and Game 2005)

3.2.2.1 Boundary Layer Velocity

Roughness caused by corrugations creates areas near the culvert edges with what is termed a boundary layer velocity. Fish have been observed to use this area to hold and rest, or swim upstream through culverts (Behlke et al. 1989; Powers et al. 1997). Investigation of the development of low velocity zones has quantified velocity reduction in round culverts for use in fish passage design (Barber and Downs 1996). However, variability in flow patterns and fish utilization are likely too great for this phenomenon to be consistently accounted for in design standards (Lang et al. 2004). To ensure passage, Powers recommended that design be based on velocity - without considerations of roughness (1997). Although the impacts of roughness have not been directly correlated to fish passage success in the field, using corrugated pipe and large corrugations is still common practice to increase roughness and decrease boundary layer velocity (e.g. Maine Department of Transportation 2004; Bates et al. 2003; Robison et al. 1999).

3.2.2.2 Average Velocity

Average cross sectional velocity is the most common velocity parameter used in culvert design. Although the characteristics of a fish's chosen path may not be well represented by average velocity (Powers et al. 1997; Barber and Downs

1996), little is understood about the utilization and development of boundary layers within a culvert, and average velocity represents a conservative design parameter (Lang et al. 2004).

3.2.2.3 Maximum Point Velocity

Points of maximum velocity will also occur within the culvert as water flows over or around constrictions such as weirs or baffles. While average velocity will likely be based on a fish's prolonged swimming ability, fish may be required to use their white muscle tissue to burst through zones of maximum velocity (Rajaratnam et al. 1991).

3.2.2.4 Inlet Transition Velocity

A culvert inlet that constricts channel flow width can increase velocity and potentially flush bed material out of the structure. This constriction could cause unanticipated flow patterns such as turbulence that may disrupt fish passage (Bates et al. 2003). The inlet requires special consideration, as it is the last barrier for a fish traversing a culvert. Inlet conditions are especially important in long installations, or when successful navigation through a series of other obstacles has required significant use of fishes' white muscle tissue. The addition of tapered wingwalls may significantly reduce the severity of an inlet transition (Behlke et al. 1991).

3.2.3 Insufficient Depth

Insufficient depth can be a barrier within the culvert or on any continuous flow area before or after the culvert installation. Insufficient depth will impair fishes' ability to generate maximum thrust, increase fishes' contact with the channel bottom, and reduce the fishes' ability to gather oxygen from the water (Dane 1978). Combined, these effects reduce a fish's swimming potential and increase the risk of bodily injury and predation. Criteria for sufficient depth vary from state to state, and although species specific depth requirements can be found, it may also be desirable to provide a "fish factor of safety" (Gebhards and Fisher 1972). State criteria for fish passage depth are included in Table 3.1, and comparison with literature values will show that most criteria are quite conservative.

Table 3.1. State Fish Passage Depth Requirements.

State	Depth Criteria
Maine	1.5 times fish thickness
Alaska	2.5 times caudal fin height
Washington	0.8 ft adult trout, 1.0 ft adult salmon and steelhead
California	0.5 ft juvenile salmonids, 0.67 ft adult non-anadromous salmonids, 1.0 ft adult anadromous salmonids.
Oregon	12 inches adult steelhead and Chinook salmon 10 inches other salmon, sea run cutthroat trout and trout over 20 inches in length 8 inches for trout under 20 inches, Kokanee and migrating juvenile salmon and steelhead.

3.2.4 Excessive Turbulence

Treatments used to reduce culvert velocity or increase depth may also increase turbulence, and dissuade fish from entering or traversing the structure or confuse their sense of direction. Although little is understood about the effects of turbulence on fish passage, recent studies at University of Idaho have found that fish prefer to hold in zones of low turbulence (Smith and Brannon 2006). Washington and Maine design guidelines specify fish turbulence thresholds, quantifying turbulence with an Energy Dissipation Factor (EDF) (Bates et al. 2003; Maine Department of Transportation 2004):

$$EDF = \gamma QS/A$$

Equation 3.1 (Bates et al. 2003)

where

EDF= Energy Dissipation Factor (ft-lb/ft^3/sec)
γ = unit weight of water (lb/ft^3)
Q = fish-passage design flow (ft^3/sec)
S = dimensionless slope of the culvert (ft/ft)
A = cross-sectional flow area at the fish-passage design flow in square feet. (For baffled installations flow area is taken between baffles, and for roughened channels large roughness elements are excluded.)

Washington State requires the EDF to be less than 7.0 for roughened channels, 4.0 for fishways, and 3.0-5.0 for baffled culvert installations. These criteria are based on experience in Washington, and will be modified with future research and evaluations (Bates et al. 2003). Maine DOT has similar requirements (Maine Department of Transportation 2004).

3.2.5 Excessive Length

Longer culvert installations require fish to maintain speed for extended periods of time, leading to increased energy expenditure. For this reason, maximum allowable velocity thresholds decrease with increasing culvert length (Bates et al. 2003; Robison et al. 1999).

Extreme length can also cause a culvert to be dark. Research has noted behavioral differences in light vs. dark passage of fish species (Welton et al. 2002; Kemp et al. 2006; Stuart 1962), suggesting that darkness may dissuade certain fish from entering a structure (Weaver et al. 1976). This theory has yet to be accepted as common knowledge (Gregory et al. 2004), but deserves consideration when installations require long structures. NMFS, for example, requires consideration of lighting in culverts exceeding 150ft in length (National Marine Fisheries Service Southwest Region 2001). It is important to consult with the appropriate natural resource agency before considering the addition of lighting to a culvert installation.

3.2.6 Debris Accumulation

Culverts with baffles, large roughness elements, or small diameters may have a high propensity to collect debris. This debris can include natural materials such as Large Woody Debris (LWD) and warrants specific consideration in areas where anthropogenic or natural debris accumulation is likely. A program of monitoring and maintenance will ensure that debris is removed before it causes a barrier to fish passage (Forest Practices Advisory Committee on Salmon in Watersheds 2001).

Table 3.2 summarizes the impact of each of the aforementioned barriers on fish.

Table 3.2. Description of longitudinal barriers to fish passage and possible effects.

Barrier Type	Description	Impact
Drop	Drop at culvert exceeds fish jumping ability, or jump pool is insufficient to generate sufficient thrust.	Fish cannot enter structure, or will expend too much energy entering the structure to traverse other obstacles.
Turbulence	Turbulence within culvert dissuades fish from entering, or confuses sense of direction	Fish do not enter culvert, or are unable to successfully navigate the waterway.
Velocity	High velocity, at any contiguous surface, exceeds fish swimming ability.	Fish tire before passing the crossing.
• **Boundary Layer Velocity**	Lower velocity zone at edges of culvert	Fish may be able to utilize in order to pass a structure even when average velocities exceed their ability.
• **Maximum Point Velocity**	Highest velocity zone within a culvert	Fish may be able to burst through this section.
• **Computed Average Velocity**	Average flow velocity	Used in analysis, but may not be representative of a fishes travel path.
Debris	Caught within a culvert, debris can block flow, or portions of flow.	Fish may not be able to pass by debris, or constricted flow may increase velocity within the culvert.
Length	Culverts is longer than 100-150 ft.	Fish may not enter structure due to darkness. Fish may fatigue before traversing the structure.
Depth	Low flow depth causes fish not to be fully submerged.	Fish will be unable to swim efficiently, or pass the structure.

3.2.7 Conclusions

Culverts can act as barriers to fish passage by presenting any number or combination of impassable obstacles. Treatments designed to treat one barrier must ensure that another is not created in the process. Localized treatments, such as moderately sloped aprons, may eliminate a drop, but can present a low flow or velocity barrier (Whitman, M., Personal Communication). Rock weirs designed to backwater a culvert may create a drop or debris barrier if not properly installed. Successful installations will consider all possible obstacles in terms of local fish requirements and crossing context.

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4 CULVERT INVENTORY

4.1 OVERVIEW

A culvert inventory can provide knowledge of location, adequacy, and potential cost of replacement/retrofit of road-stream crossings within a watershed context. With such knowledge, planners can begin to prioritize and plan for fish passage restoration on a watershed scale. A robust inventory will be invaluable in planning efforts, and many assessment schemes have been created to collect information necessary for the prioritization of crossing replacement (i.e. Clarkin et al. 2003; Taylor and Love 2003; Washington Department of Fish and Wildlife 2000).

4.1.1 Knowledge of crossing location

The first step in a program of fish passage restoration is awareness of the problem, including location and condition of waterway crossings. An inventory can be as simple as a listing of the locations of existing road-stream crossings, and will ideally include basic survey information. There are two standard methods for completing a culvert inventory, including road- and stream-based approaches.

4.1.1.1 Road based inventory

A road based inventory follows a particular road system to identify and evaluate all road stream crossings. This type of inventory is useful to managers requiring knowledge of highway impact on fish passage, and will allow highway dollars to be efficiently spent on the mitigation of fish passage barriers. For example, known barriers can be addressed in conjunction with routine road maintenance.

Road based approaches can be very complete, although following a road will invariably miss a number of barriers that exist on side streams or barriers created by minor roads, man made dams, or diversions (Washington Department of Fish and Wildlife 2000)

4.1.1.2 Stream based inventory

A stream based inventory follows the entire fish bearing system within a watershed or ownership, noting all constructed obstacles (e.g. dams, culverts, water diversions). Further evaluation of these structures provides an understanding of fish passage barriers in a watershed context. This type of inventory will allow analysis of the amount of stream habitat that can be opened up by repairing/replacing a particular culvert. This knowledge will help ensure that program dollars are spent for maximum ecological benefit.

4.1.2 Inventory Goals

To allow prioritization for replacement, more specific site information will be required. A national inventory process created by the Forest Service was designed to answer two questions (Clarkin et al. 2003):

- Does the crossing provide adequate passage for the species and life-stage of concern?
- What is the approximate cost of replacement?

Such knowledge allows a basic understanding of fish impediments, as well as the requirements/plausibility of replacement. Additional information, such as environmental risk, may also be beneficial to planners attempting to prioritize corrections of road-stream treatments. Risk assessments may be coupled with fish passage assessment and inventories, but will require additional time and expense. Methods for determining environmental risk are outlined in *Methods for Inventory and Environmental Risk Assessment of Road Drainage Crossings. Rep. No. 9877 1809P - SDTDC*, U.S.D.A. Forest Service (Flanagan et al. 1998).

4.1.3 Assessment and Prioritization

Assessment is an important step in understanding the adequacy of road-stream crossings and their relation to other culverts. Basic surveys are used to evaluate a number of factors that potentially impact fish passage. These surveys allow the crossing to be understood in terms of influence on the stream system and estimated cost of replacement. Assessment surveys are not detailed enough for design, but can provide planners with the information necessary to prioritize crossings for replacement. Assessment topics are covered in more depth in Chapter 5 Assessment.

Prioritization of crossings will generally involve a number of factors including barrier status and the cost of replacement for a culvert crossing. Planners may also want to know the ecological significance of replacement, the future impact of doing nothing, along with answers to other regionally specific questions. These topics are covered in more depth in Chaper 6 Prioritization.

4.2 DATA COLLECTION

An initial survey of the culvert and adjoining stream reach will allow a basic understanding of current crossing conditions. This survey will cover a number of site characteristics including culvert and channel measurements and classification, flow data, and watershed conditions. Specific culvert characteristics of interest may include those listed in Table 4.1 from Coffman 2005. It will be useful to have a standardized survey collection method that incorporates collection of all pertinent parameters.

Table 4.1. Specific culvert characteristics useful in assessment, including possible barrier types (Coffman 2005).

Culvert Characteristic	Possible Barrier
Outlet drop and outlet perch	Jump barrier
Culvert slope	Velocity barrier
Culvert slope times length	Exhaustion barrier
Presence of natural stream substrate	Depth barrier
Relationship of tailwater control elevation to culvert inlet elevation	Depth and velocity barrier

Basic survey techniques are included in *Stream Channel Reference Sites: An Illustrated Guide to Field Technique* (Harrelson et al. 1994). Examples of fish passage survey application, including forms, explanations of survey points, and data collection are included in Appendix E of *National Inventory and Assessment Procedure* (Clarkin et al. 2003), which is based on information in Chapter IX of *California Salmonid Stream Habitat Restoration Manual* (Taylor and Love 2003). Figure 4.1 depicts some typical longitudinal survey points used in a culvert survey.

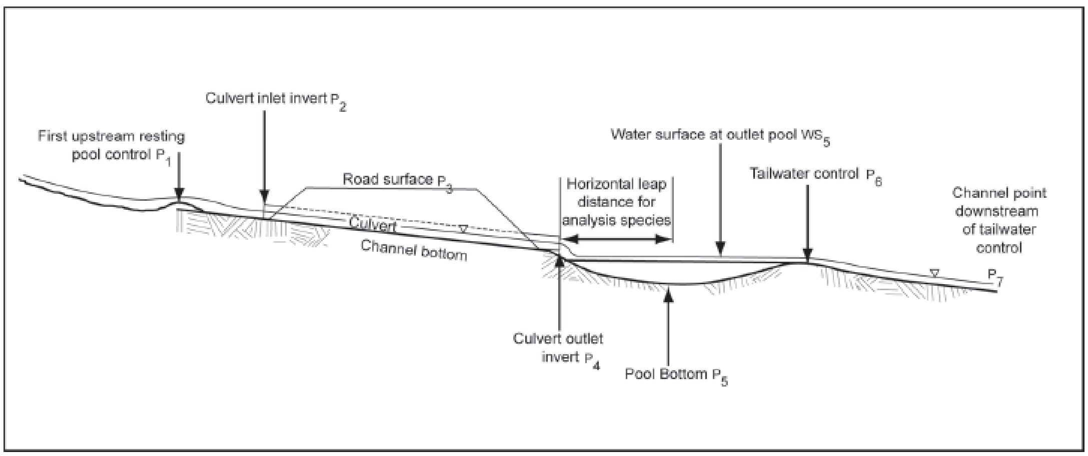

Figure 4.1. Longitudinal Profile Survey Points (Clarkin et al. 2003).

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5 CULVERT ASSESSMENT

5.1 OVERVIEW

5.1.1 Criteria

Before crossing assessment can begin, it is necessary to have a clearly defined set of assessment criteria. Much like culvert design criteria, assessment criteria show regional variability, and generally consider the following elements in order to determine fish passability:.

- Depth of flow
- Flow velocity
- Drop heights
- Pool depths
- Culvert length
- Substrate

5.1.2 Development

Development of procedures and criteria for culvert assessment should be done by a group of knowledgeable individuals, recognizing program/project goals. Properly designed culvert assessment will provide adequate knowledge of a crossing location and ultimately lead to a robust inventory that will aid in crossing prioritization.

Agreements between State DOTs and Resource agencies can greatly expedite the design and assessment procedure, ensuring that the requirements of all parties are met satisfactorily through a common vision. For example, Alaska and Oregon currently have agreements between their respective resource agencies to epedite permit applications for culvert installations. They also have a shared priority of replacement/repair of fish passage barriers (Venner Consulting and Parsons Brinkerhoff 2004).

5.2 CRITERIA

Assessment criteria will vary depending on fish species present as well as the timing and duration of fish movement. Criteria for adult salmon, for example, will be significantly different from that used for juveniles or trout species (e.g. Robison et al. 1999; Washington Department of Fish and Wildlife 2000). Development should be done by a group of knowledgeable professionals with project or program goals in mind.

It is recommended that assessment criteria be developed separately from design criteria (Lang et al. 2004). Typically, design criteria are quite conservative, so as to provide passage for the weakest swimming individual during a range of design flows. Assessment criteria however, seek to determine the degree to which a crossing is a barrier to fish passage. Crossings that would be labeled inadequate by design standards may only provide a partial barrier to fish passage. As a result, criteria for design and assessment are slightly different, and generally not interchangeable.

5.2.1 Degree of Barrier

5.2.1.1 Passable, Impassable, Indeterminate

Assessment allows crossings to be grouped into categories of adequacy such as “Passable”, “Impassable”, and “Indeterminate”. Category definitions are expounded to clearly place barriers within a matrix. In California, a culvert that can pass all salmonids during the entire migration period earns a “green” classification, while a culvert that does not meet requirements of strongest swimming fish and life stage present over the entire migration period is classified as “red” (Taylor and Love 2003). Culverts that cannot be placed in these categories remain in the “gray” area, where the crossing may present impassable conditions to some species and life stages at some flows. Further analysis is required in order to ascertain the extent of the barrier.

It is likely that initial surveys will show many culverts to be “indeterminate”, where adequacy cannot be determined without a detailed hydraulic analysis (Clarkin et al. 2003). Furthermore, a great number of “impassable” crossings typically ensure that “indeterminate” crossings are never properly analyzed (Furniss 2006).

5.2.1.2 Temporal, Partial, Total

Culverts falling into the “indeterminate” area are likely barriers to some fish species and life stage. The extent of this barrier incorporates further categorization. Table 5.1 shows barrier categories endorsed in California (Taylor and Love 2003). Assessment criteria are used to prioritize culvert crossings for future replacement, and the degree of barrier is one of many factors used to determine the urgency of culvert replacement/retrofit. Most culverts will present a partial or temporal barrier to fish passage, and an understanding of the culvert “barrierity” (portion of the time, or degree to which, a crossing disrupts fish passage) is useful in assessing the impact of a culvert on the surrounding ecosystem, and in determining the need and urgency of culvert replacement (Furniss 2006).

Table 5.1. Fish passage barrier types and their potential impacts (Taylor and Love 2003)

Barrier Category	Definition	Potential Impacts
Temporal	Impassable to all fish at certain flow conditions (based on run timing and flow conditions)	Delay in movement beyond the barrier for some period of time
Partial	Impassable to some fish species, during part or all life stages at all flows.	Exclusion of certain species during their life stages from portions of a watershed
Total	Impassable to all fish at all flows	Exclusion of all species from portions of a watershed.

5.3 EXISTING PROCEDURES

In most situations, site survey and inspection alone will not determine barrier status. While drop heights, substrate, inlet contraction, and slope can be examined, hydraulic analysis will likely be required in order to ascertain flow velocities, flow-depth and pool-depths during design conditions. Assessment is therefore broken into a series of “screens” or “filters”, using regionally or locally defined criteria.

5.3.1 Coarse Filter

A first pass or “coarse filter” can be used to determine the transparency of the crossing to fish in the natural reach. The basis of this analysis is the presumption that crossings successfully replicating the surrounding natural stream channel conditions will exhibit similar hydraulic conditions, allowing passage for all fish at the flows at which they would be traveling in the natural stream reach. A passable culvert will match natural stream reach characteristics including width, substrate and slope. The coarse filter may also be used to quickly identify obvious barriers such as excessive perching or extreme slope.

5.3.2 Regional Screen

If a culvert cannot be clearly categorized as adequate or inadequate using a coarse filter, a subset of regionally defined criteria is used to further clarify culvert adequacy. At this level of analysis, specific fish species criteria are examined to understand culvert impact on the local biota.

5.3.3 Examples of Regional Screen Criteria

California’s Salmonid Stream Habitat Restoration Manual contains a culvert categorization scheme covering adult and juvenile anadromous salmonids (Taylor and Love 2003). This method combines coarse filter and regionally defined criteria. A flow-chart model (Figure 5.1) helps surveyors place culvert passability into one of three categories: green, gray, and red.

• Green: Condition assumed adequate for passage of all salmonids and lifestages during the entire period of migration.

• Gray: Conditions may not be adequate for all salmonid species or life stages presumed present. Additional analyses are required to determine extent of the barrier for each species and lifestage.

• Red: Conditions fail to meet passage criteria over the entire range of migration flows for even the strongest swimming species and lifestage (adults) presumed present.

5.3.4 Flow Chart Filters

Flow-chart categorization has the advantage of providing a simple step-by-step method with variables that are easily interchangeable to meet program needs (Clarkin et al. 2003). Although California addresses all culverts and fish in one chart, additional charts could easily be created to address different species and lifestages of concern. The simplicity of this type of analysis may create a propensity for culverts to fall into the “gray” area (Clarkin 2003).

It should also be recognized that other characteristics not covered in the filter may cause culverts to pose potential barriers, and need to be examined. Examples include breaks in slope, inlet and outlet aprons, crushed inlets or damage to the crossing invert (Taylor and Love 2003).

5.3.5 Matrix Filters

Alaska and Oregon compile regional criteria and coarse filter information into a set of criteria that depend on installation type and culvert embedment (Robison et al. 1999; Flanders and Cariello 2000). Alaska’s filter for juvenile coho Figure 5.2 for example, provides a matrix of criteria depending on structure type. This added level of scrutiny may ensure that fewer culverts fall into the “indeterminate” area of passability (Clarkin et al. 2003).

5.3.6 Hydraulic Analysis

When barrier status of a culvert cannot be determined after a coarse filter or regional screen, a hydraulic analysis, including a field study, mathematical modeling or direct observation should be completed. This may include situations where baffles or weirs are present. The goal of these studies will be to determine if culverts meet the requirements of target fish species.

5.4 RECOMMENDED TEMPLATE

Most of the existing criteria were developed from studies focusing on one or two target species, or anadromous species such as Pacific salmon (Bunt et al. 1999; Belford and Gould 1989). This resulted in species-specific guidelines tailored to local fish populations, and resulting inventories and criteria are only truly applicable for the region in which they were developed. For national applicability, a general guidance document has been created to aid in the development of regionally specific inventories.

A *National Inventory and Assessment Procedure* was produced by the United States Forest Service San Dimas Technology and Development Center (Clarkin et al. 2003). This included a review of current State procedures and a synthesis of techniques into a standardized, and generally applicable method for assessment and prioritization development. Figure 5.2 depicts a flow chart of a culvert assessment technique. Although the specifics of each level of assessment change slightly depending on regional guidance, the general sequence remains the same. In the first stage, conditions within the culvert are compared to conditions in the undisturbed natural channel. If the culvert does not sufficiently maintain natural reach characteristics, a second pass is conducted, in which surveyors analyze the crossing based on regionally defined passage criteria. If the passability is still not determined, a hydraulic analysis of the crossing is employed.

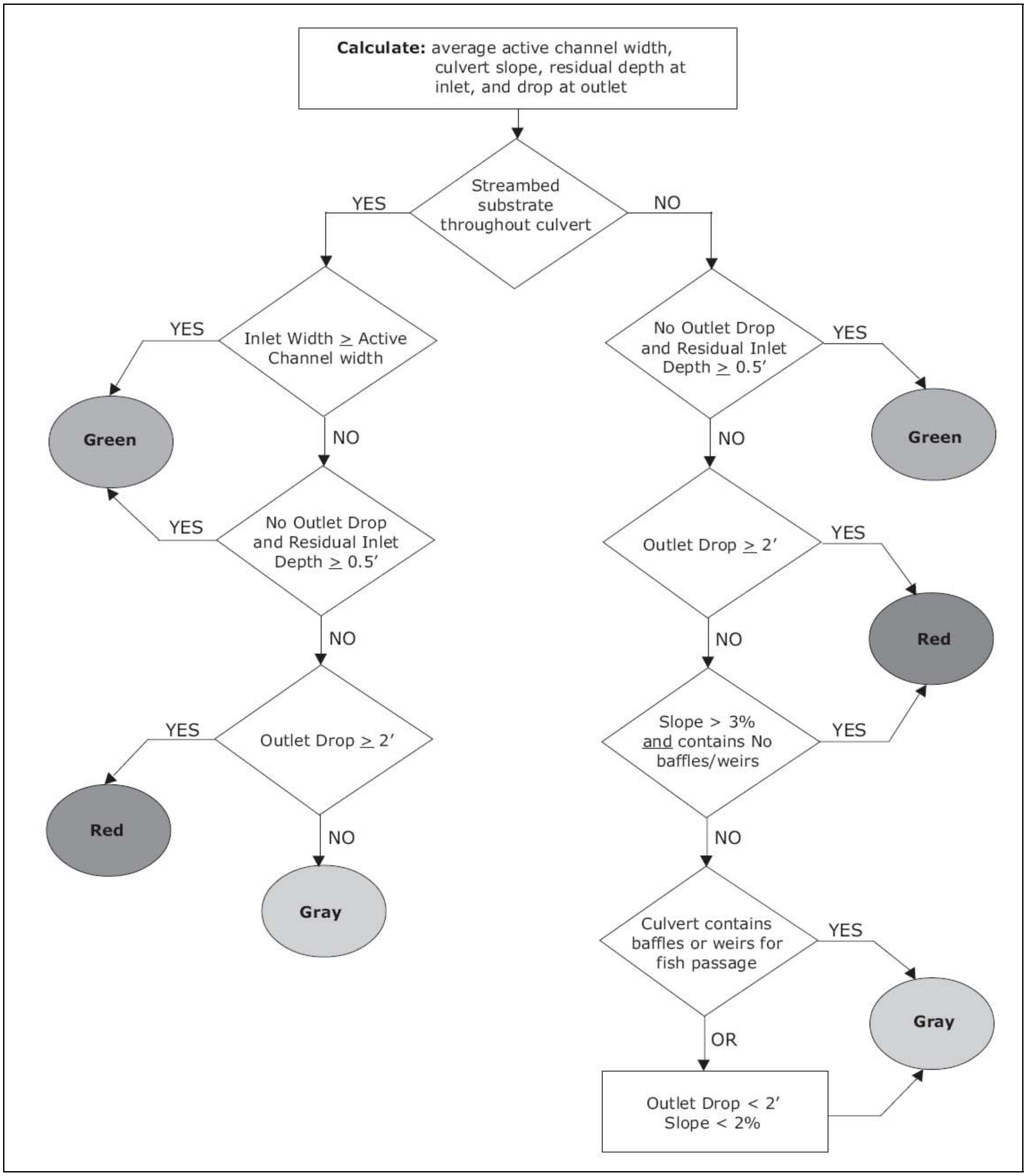

Figure 5.1. Example of a coarse filter and regional screen. Green-Gray-Red screen developed for California's anadromous adult and juvenile salmonids (Taylor and Love 2003). (Figure from Clarkin et al. 2003).

	Structure	*Green1*	*Grey2*	*Red3*
1	Bottomless pipe arch or countersunk pipe arch, substrate 100% coverage, invert depth greater than 20% of culvert rise.	Installed at channel grade (+/- 1%), culvert span to bankful width ratio of 0.9 to 1.0, no blockage.	Installed at channel grade (+/- 1%), culvert span to bankful width ratio of 0.5 to 0.9, less than 10% blockage.	Not installed at channel grade (+/- 1%), culvert span to bankful width ratio less than 0.5, greater than 10% blockage.
2	Countersunk pipe arches (1x3 corrugation and larger). Substrate less than 100% coverage, invert depth less than 20% of culvert rise.	Grade less than 0.5%, no perch, no blockage, culvert span to bedwidth ratio greater than 0.75.	Grade between 0.5 -2.0%, less than 4" perch, less than 10% blockage, culvert span to bedwidth ratio of 0.5 to 0.75.	Grade greater than 2.0%, greater than 4" perch, greater than 10% blockage, culvert span to bedwidth ratio less than 0.5.
3	Circular CMP 48 inch span and smaller, spiral corrugations, regardless of substrate coverage.	Culvert gradient less than 0.5%, no perch, no blockage, culvert span to bedwidth ratio greater than 0.75	Culvert gradient 0.5 to 1.0%, perch less than 4 inches, less than 10% blockage, culvert span to bedwidth ratio of 0.5 to 0.75.	Culvert gradient greater than 1.0%, perch greater than 4 inches, blockage greater than 10%, span to bedwidth ratio less than 0.5.
4	Circular CMPs with annular corrugations larger than 1x3 and 1x3 spiral corrugations (>48" span), substrate less than 100% coverage, invert depth less than 20% culvert rise.	Grade less than 0.5%, no perch, no blockage, culvert span to bedwidth ratio greater than 0.75.	Grade between 0.5 -2.0%, less than 4" perch, less than 10% blockage, culvert span to bedwidth ratio of 0.5 to 0.75.	Grade greater than 2.0%, greater than 4" perch, greater than 10% blockage, culvert span to bedwidth ratio less than 0.5.
5	Circular CMPs with 1x3 annular corrugations (all spans) and 1x3 spiral corrugations (>48" span), 100% substrate coverage, substrate depth greater than 20% of culvert rise.	Grade less than 1%, no perch, no blockage, culvert span to bedwidth ratio greater than 0.75	Grade 1.0 to 3.0%, perch less than 4 inches, less than 10% blockage, culvert span to bedwidth ratio of 0.5 to 0.75.	Culvert gradient greater than 3.0%, perch greater than 4 inches, blockage greater than 10%, culvert span to bedwidth ratio less than 0.5.
6	Circular CMPs with 2x6 annular corrugations (all spans), 100% substrate coverage, substrate depth greater than 20% of culvert span.	Grade less than 2.0%, no perch, no blockage, culvert span to bedwidth ratio greater than 0.75	Grade 2.0 to 4.0%, less than 4" perch, less than 10% blockage, culvert span to bedwidth ratio of 0.5 to 0.75.	Grade greater than 4.0%, greater than 4 inch perch, greater than 10% blockage, culvert span to bedwidth ratio less than 0.5.
7	Baffled or multiple structure installations		All	
8	Log stringer or modular bridge	No encroachment on bedwidth.	Encroachment on bedwidth (either streambank).	Structural collapse.

Figure 5.2. Alaskan fish-passage evaluation criteria. United States Forest Service Region 10 (Flanders and Cariello 2000).

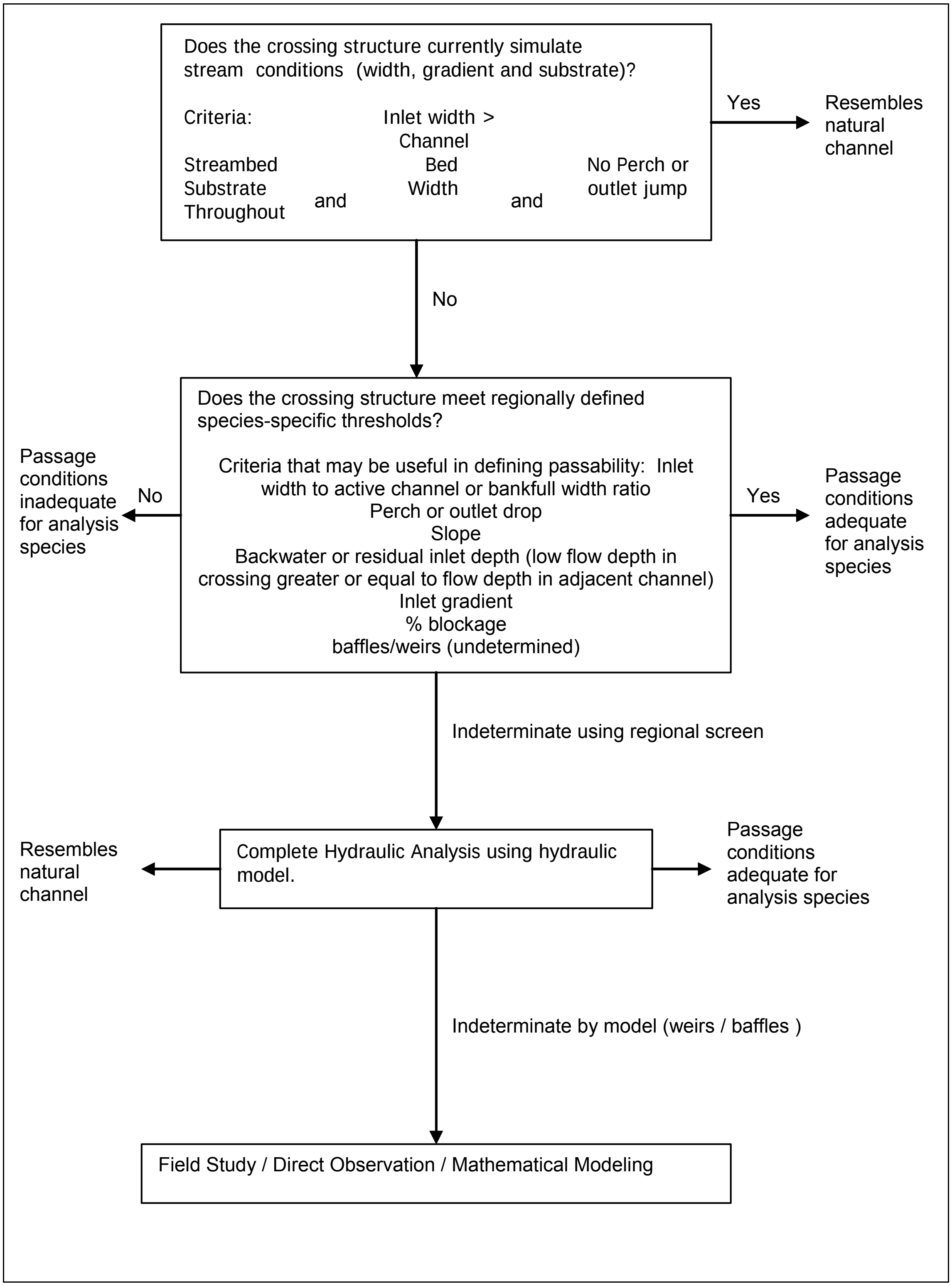

Figure 5.3. Flow chart for Culvert Assessment (adapted from Clarkin et al. 2003). Coarse filter determines if the culvert matches stream reach characteristics, if not, regionally defined criteria determine whether the culvert is appropriate for the fish species and life-stage of concern. If not, hydraulic modeling software is utilized.

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6 PRIORITIZATION OF ROAD CROSSING TREATMENTS

6.1 OVERVIEW

6.1.1 Objectives

The objective of a prioritization inventory is not necessarily to rank fish barriers in the order that they should be addressed. However, a basic understanding of culvert barrier location, status, and cost estimates will allow culverts to be addressed in an efficient manner. The following section outlines common criteria, and provides a good starting point for the development of a regionally specific prioritization scheme.

6.1.2 Funding Source

Funding source may impact the way that project prioritization is best utilized. Highway dollars may be most efficiently spent by performing a road based inventory and assessment to understand how a particular highway impacts fish passage. With an understanding of culvert barriers in context, fish passage can be addressed in conjunction with other road maintenance, ensuring efficient spending of highway dollars. In the case of project based funding, money may be most efficiently spent on culverts with the greatest ecological impact, and a watershed based inventory may ensure efficient spending.

6.2 CRITERIA

Prioritization criteria should be developed by a group of knowledgeable individuals, and regional criteria will likely vary slightly. Some factors to consider at each crossing include: amount and quality of habitat blocked, fish species present and species status, proximity to other barrier structures, cost of replacement, possibility/cost of crossing failure, and degree of barrier (total, partial, temporal). There may also be unique characteristics to consider, such as barriers that serve to keep out invasive species, and existing barrier structure that have created habitat upstream. The benefit of replacement will need to be weighed against the possible consequences or no action. An explanation of possible considerations follows.

6.2.1 Cost

Cost of replacement/retrofit includes:

- Diversion
- Traffic control
- Design
- Installation

- Maintenance

Crossings may be less costly to replace as roadwork or maintenance occurs near the crossing site, or when other crossings are repaired in the same area.

6.2.2 Ecological Significance

6.2.2.1 Species Significance

The ecological significance of a crossing will include consideration of species present, as well as amount and quality of habitat blocked. A culvert that is blocking an endangered species will require more attention than a comparable barrier that impedes the passage of non-listed species. On the other hand, a barrier culvert might be acting to keep invasive species or diseases from reaching undisturbed native populations.

6.2.2.2 Current Ecological Function

It is important to understand potential costs and benefits before removing a barrier to connectivity, as impassable crossings may occasionally provide a beneficial function. A culvert that presents a barrier to fish passage may also have ecological function that outweighs the benefits of replacement. For example, culverts in a vertically unstable channel may provide elevational control by creating a rigid boundary past which channel incision cannot progress. Removal of a grade control culvert could allow channel incision to progress upstream, possibly affecting fish passage at the structure and habitat quality throughout the reach (Castro 2003).

6.2.3 Habitat Blocked

The quantity of habitat blocked by a particular crossing will be combined with considerations of habitat value to understand the benefits of a potential replacement or retrofit. A culvert blocking access to critical spawning habitat, for example, may require urgent consideration.

6.2.3.1 Degree of Barrier (Barrierity)

The degree of barrier (partial, temporal, total) will also determine the urgency of replacement. All other considerations being equal, a culvert that poses a complete barrier will require more urgent attention than a culvert providing a partial or temporal barrier.

6.2.3.2 Barriers Upstream/Downstream

In a situation where anadromous fish spawning access is a concern, a culvert replacement opening 10 miles of high quality spawning habitat will be made ineffective by a single barrier culvert downstream. In general, it is recommended that culvert replacement progress from downstream to upstream, although in some situations benefits may still be significant for resident fish populations.

A series of partial barriers may combine to effectively block fish from reaching their final destination. Although a culvert that presents a short duration barrier during fish migration may seem like a small problem, a series of delays may mean that spawning fish cannot reach their destination. Regional experience must be used to determine acceptable delay. When prioritizing retrofit and replacement projects, it will be important to establish a crossings context within the watershed.

6.2.4 Risk/Significance of Failure

A culvert that is in disrepair or that is severely undersized may have large ecological or hydraulic significance associated with failure. For example, a culvert in Oregon became plugged with debris, causing water to wash out fill, run parallel the road, and eventually scour out an entire valley wall as it found its own path to the river below (Furniss 2006). Figure 6.1, from Furniss et al, depicts this type of failure, know as diversion (1997).

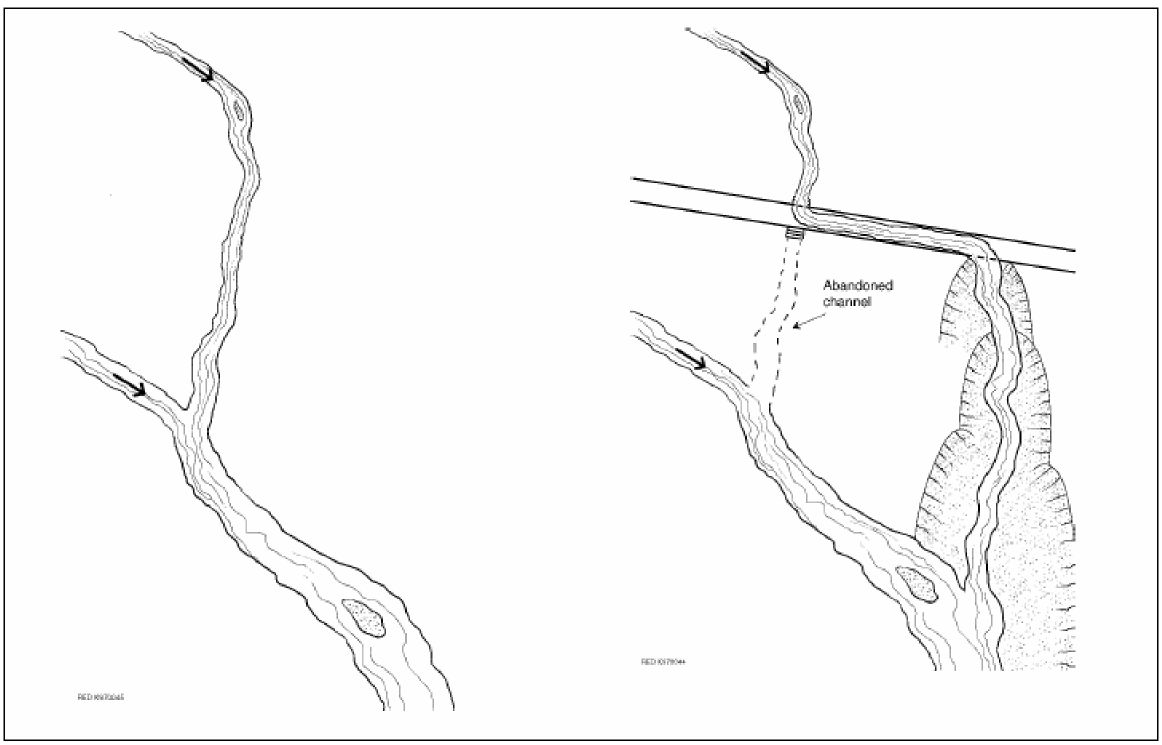

Figure 6.1. The erosional consequences of diverting stream flow onto non-stream slopes. Often landslides of debris flows can be triggered by the loading of non-stream slopes with excess water and undermining of slope support by gully erosion (Furniss et al. 1997).

An understanding of environmental risk requires additional analysis. *Methods for Inventory and Environmental Risk Assessment of Road Drainage Crossings* (Flanagan et al. 1998), provides a discussion of the potential environmental impacts of culvert failure. This includes a review of past assessment procedures including recommended assessment procedures.

The economic cost of doing-nothing can be calculated by many methods including:

- *Some Applications of Flood Frequency and Risk Information in Forest Management* (Hansen W.F., 1987)

- *Evaluation of Uncertainty of Flood Magnitude Estimation on Annual Expected Damage Costs of Hydraulic Structures* (Bao et al. 1987)

In addition to monetary expense, culvert failure can have significant impacts on habitat quality, possibly allowing a sediment slug to progress downstream, covering spawning habitat or useable areas with fines or silt. Studies of the response of road stream crossings to large flood events in the Pacific Northwest showed that additional failure mechanisms include debris flow, woody debris lodgment, and hydraulic exceedance (Furniss et al. 1998).

6.3 EXISTING PRIORITIZATION PROCEDURES

6.3.1 California Department of Fish and Game

California employs a ranking system for determining the priority of road stream crossings. Points are awarded to a crossing based on species diversity, extent of barrier, habitat value, risk of failure and current conditions. For example, priority based on species diversity is broken into the following rankings:

- Endangered Species – 4 points
- Threatened or Candidate – 2 points
- Not listed – 1 point

Barrier status is responsible for up to 5 points, high habitat value can result in up to 10 points, and risk of failure up to 5. The result of this prioritization is not intended to provide a list and order of culverts to be addressed (i.e. 30 points fixed first, 28 points fixed second), but gives a list of severity and spatial distribution of crossings to aid planning decisions (Taylor and Love 2003).

6.3.2 Oregon Department of Fish and Wildlife

Oregon uses degree of fish blockage and risk of crossing failure to group culverts into one of five categories of prioritization. This allows a general categorization of crossing from Type 1 culverts - which block passage of coho salmon habitat, or have high risk of catastrophic failure, to Type 5 installations - which are on non-fish bearing streams with moderate to high risk of failure (Robison et al. 1999).

6.3.3 Washington Department of Fish and Wildlife

Washington Department of Fish and Wildlife's *Fish Passage Barrier and Surface Water Diversion Screening Assessment and Prioritization Manual* (2000) outlines a Priority Index (PI) ranking system similar to California. Values are assigned to various factors affecting barrier severity, including potential benefits of replacement. Priority is based on barrier status, production potential, habitat blocked, condition of fish stock, projected project cost, and species-specific values. Information is input into a database where prioritization is calculated and culvert inventories are ranked and stored. Since 1991, Washington has inventoried over 2500 miles of state routes, and opened up 369 miles of habitat once blocked by barrier culverts (Wilder et al. 2004).

6.4 RECOMMENDED TEMPLATE

The Forest Service's *National Inventory and Assessment Procedure* (Clarkin et al, 2003) has an in-depth discussion of culvert assessment, inventory and prioritization that provides adequate guidance for the development of regional criteria, and this is the recommended reading for those wishing to develop a regional fish passage inventory or culvert assessment procedure. A blank template from Clarkin et al, has been included (Figure 6.2) that allows regional criteria to form a simple coarse filter and regional screen (based on Taylor and Love 2003) (2003).

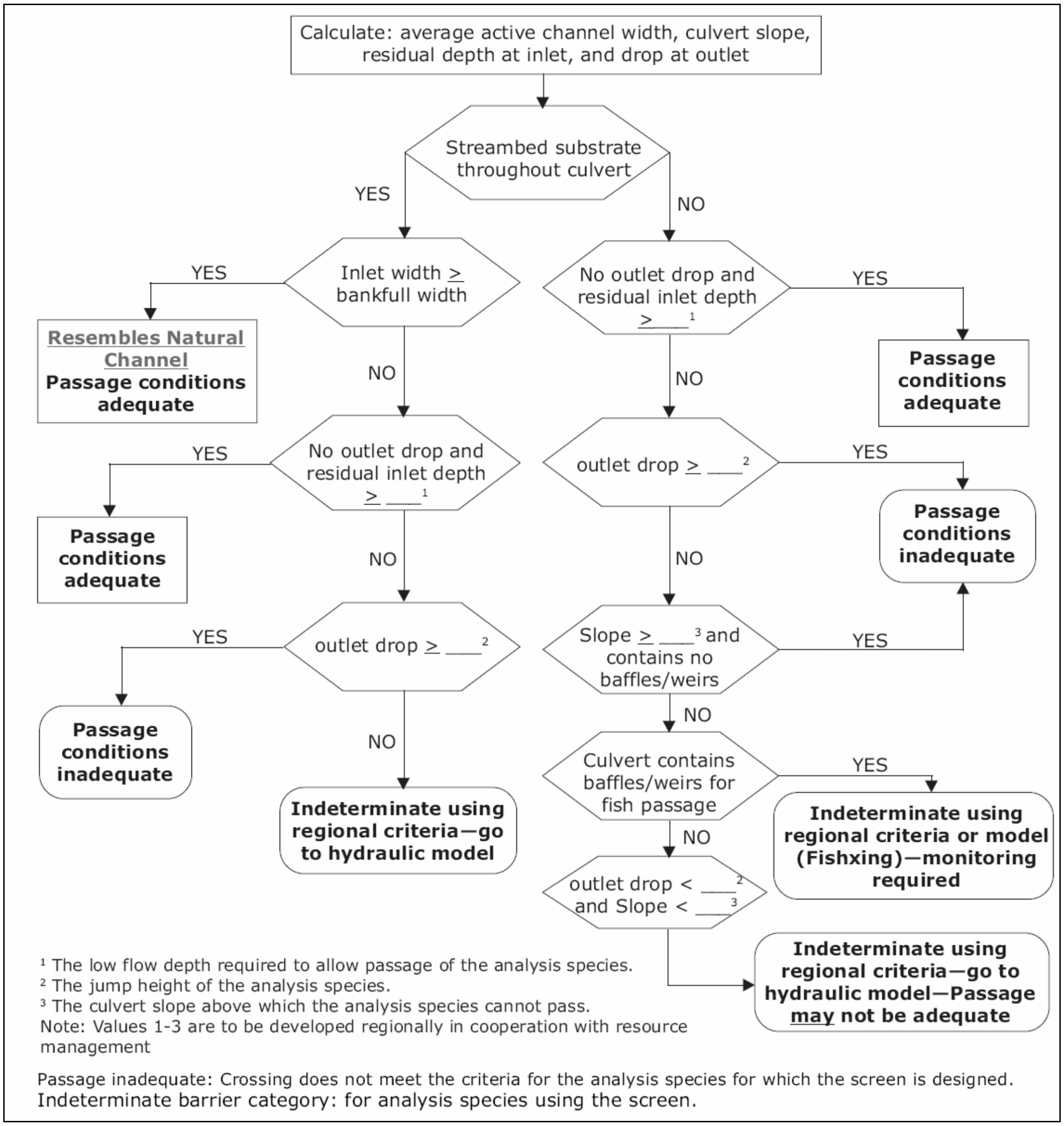

Figure 6.2. Fill in the Blank Regional Screen based on the California Model (Clarkin et al. 2003)

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7 FISH PASSAGE HYDROLOGY

7.1 OVERVIEW

Crossings should allow fish passage at a range of flows corresponding to the timing and extent of fish movement within the channel reach. The use of design techniques tailored to specific fish species and life-stages requires knowledge of fish swimming ability and site hydrology in order to create a passable structure. This process necessitates a more thorough understanding of site flow characteristics than is provided by a typical hydraulic analysis for structure stability. The following discussion details typical design requirements, including state-of-practice hydrology.

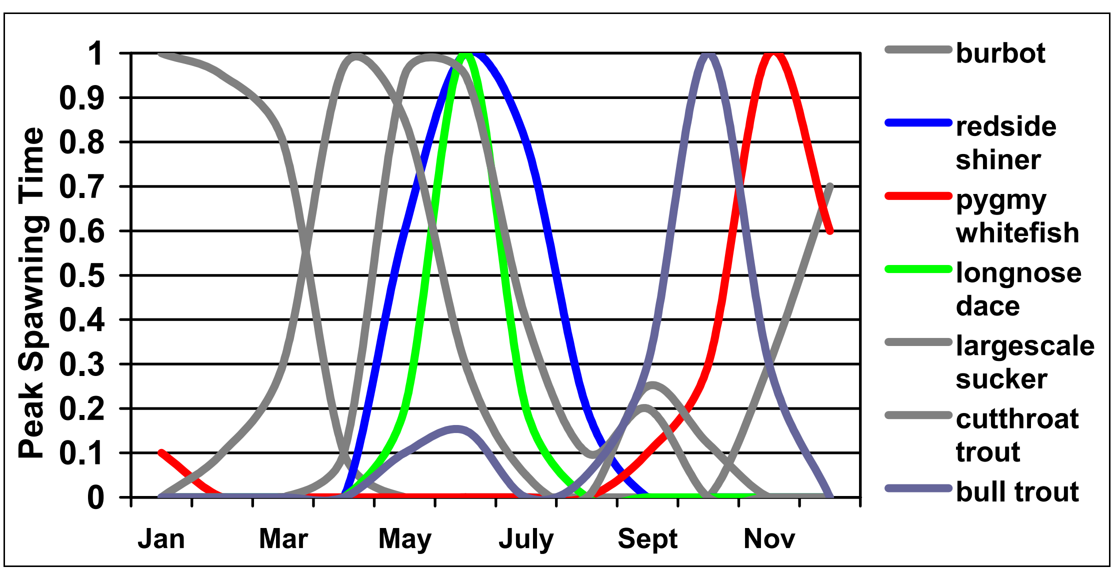
7.1.1 Seasonality

7.1.1.1 Timing and Extent of Fish Presence

The timing of fish presence and migration must be considered when determining appropriate hydrology for fish passage design. Fish presence can vary from watershed to watershed (Scott and Crossman 1973), and in-stream flows may show great disparity with timing of fish migration .

In addition, the presence of multiple fish species can quickly convolute evaluation of fish passage hydrology. Figure 7.1 depicts the general timing of fish spawning migrations for a number of freshwater species in Virginia. Determining species presence and sensitivity within a stream reach requires site-specific knowledge, and consultation with a local fisheries biologist is advisable.

Figure 7.1. Peak Spawning periods for a selection of freshwater fish in Virginia, based on Biological data in (Scott and Crossman 1973). (Adapted from Hudy 2006)



7.1.1.2 Species and Life Stage

Timing and movement of regional fish populations will depend on fish species and life stage. In the Pacific Northwest, for example, adult salmon and steelhead migrate in the fall and winter months, while juvenile salmon migrate in the spring as fry and in the fall as fingerlings (Bates et al. 2003). Culverts designers in Maine must consider spawning movement of Atlantic salmon from May to November (Maine Department of Transportation 2004). In addition, resident fish may require movement at any time of the year (Kahler and Quinn 1998; Gowan et al. 1994). Due to variable abilities and periods of migration, each fish species and life stage may necessitate a different set of hydrologic constraints.

7.1.1.3 Annual Variation

An understanding of annual fluctuations in hydrology will ensure that crossings present acceptable conditions from year to year. The flow duration curves (FDC) used in analysis of fish passage flows, see Figure 7.2, represent averages and fail to account for annual variations in hydrology. A study in Northern California found a culvert using specified low-flow criteria (90% migration period exceedance) created a one day migration delay in WY99 (a "wet" year) but a ten day delay in WY2001 (a "dry" year) (Lang et al. 2004).

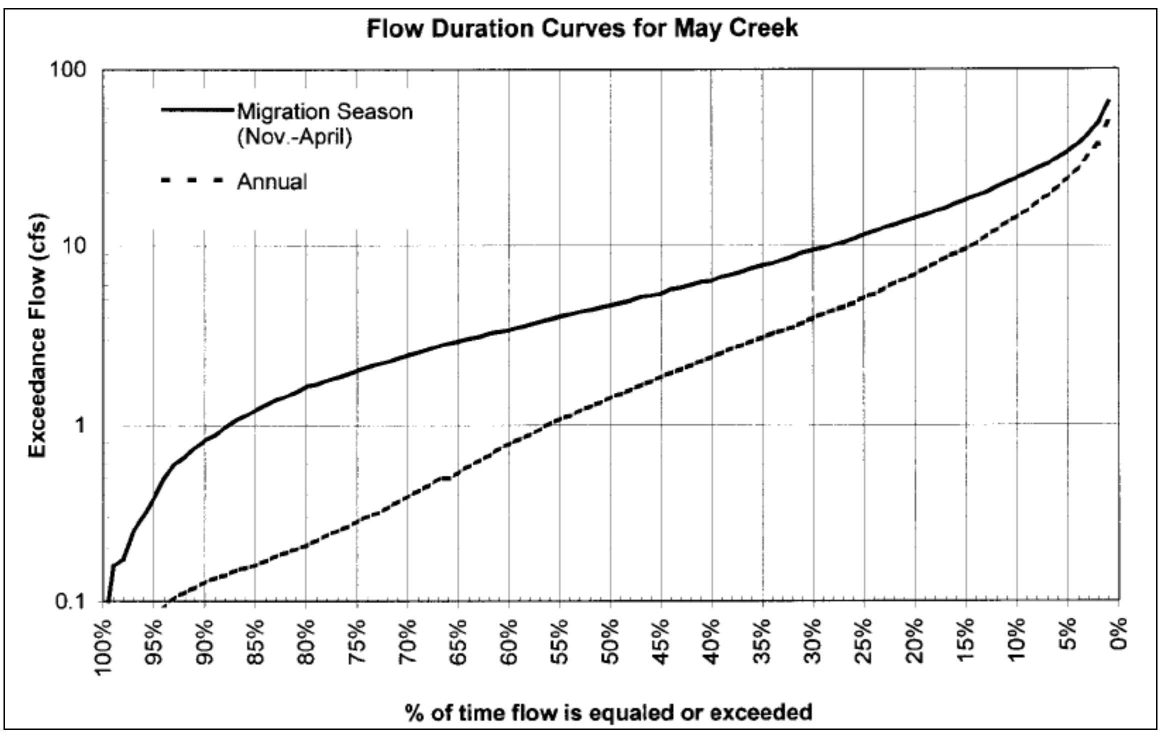


Figure 7.2. Synthetic flow duration curves from May Creek, based on flows occurring from November through April (Migration Season) and October through September (Annual). Curves were created using the regional flow duration curve. The annual flow (Qave) for May Creek was estimated to be 5.9 cfs (Lang et al. 2004).

7.1.2 Extreme Events

7.1.2.1 Fish Response

Even within a period of fish migration, design is not intended to provide fish passage at all flows. In a natural stream reach, fish respond to high flow events by seeking out shelter until passable conditions resume (Robison et al. 1999). During extreme low flows, shallow depths may cause the channel itself to become impassable (Clarkin et al. 2003; Lang et al. 2004). Generally, upper and lower thresholds bound the flow conditions at which fish passage must be provided.

7.1.2.2 Allowable Delay

Fish may be able to handle a short interruption to upstream migration without negative consequences. The extent of this "allowable delay" depends of the timing and motivations for fish movement. A resident fish may be able to tolerate a short delay without extreme consequences, while a delay of a few days may be detrimental to spawning salmon, whose migrations involve significant physical changes, including a rapid depletion of fat and protein reserves (Groot and Margolis 1991). The delay caused by a single culvert can be compounded by a series of culverts that present short delays, making it imperative to understand a crossing's place in the overall watershed context. Delay has a number of negative consequences including stress and physical damages, susceptibility to disease and predation, and reduction in spawning success (Ashton 1984).

7.1.2.3 Migration Flows

As discussed in Chapter 2, fish movement is triggered by time of year, flow events and a number of environmental factors. For example, the upstream migration of spawning salmon is hypothesized to be in response to maturation, the changing length of days, and temperature regimes (Groot and Margolis 1991). Consultation with local fisheries biologists will help ensure that hydrology is properly matched to requirements of local fish populations.

7.2 DESIGN REQUIREMENTS

7.2.1 High Fish Passage Flows

A high fish passage flow captures the upper bound at which fish are believed to be moving within the stream. Fish passage requirements should be met at all discharges up to and including the high fish passage flow. This may exclude flows falling below a lower threshold, known as the low fish passage flow.

Table 7.1 shows a comparison of state and agency guidelines for high fish passage flows. Many states use an exceedance flow between 1 and 10% of the annual flow duration curve (a 10% exceedance flow is met or surpassed 10% of the year).

Table 7.1. State and agency guidelines for high fish passage flows, (adapted from Clarkin et al. 2003). Q_2 refers to the 2-year flood.

Alaska	Washington	Oregon	NMFS SW Region	California Dept of Fish and Game	NMFS NW Region	Idaho
Q_2d_2: the discharge 24 hours before the 2-yr flood.	10% exceedance flow during migration period - species specific	10% Exceedance flow during migration period: species specific. Approximate by $Q_{10\%} = 0.18*(Q_2)+36$ where $Q_2 > 44$ cfs. Where $Q_2 < 44$ cfs, use Q_2.	For adult salmon and steelhead 1% annual exceedance flow or 50% Q_2. For juveniles, 10% annual exceedance flow.	Standards vary from 1-10% exceedance flow for various groups of fish.	5% exceedance flow during period of upstream migration	<2 day delay during period of migration

+High flows are for Hydraulic Design Approaches only, with the exception of Alaska and Idaho.

7.2.2 Low Fish Passage Flows

Low fish passage flows define the lower bound at which fish passage is desired. This flow condition is used to ensure that depth and velocity barriers are not created within a crossing. Flows below this threshold may cause the channel itself to present a depth barrier to fish movement (Clarkin et al. 2003).

Specific depth requirements vary with the species and life stage of concern. Alaska requires that depth be greater than 2.5 times the depth of a fish's caudal fin (Alaska Department of Fish and Game and Alaska Department of Transportation 2001). For example, a 60-mm juvenile Coho Salmon requires a water depth of approximately 48mm or 1.9 inches. Washington State specifies a minimum depth of 0.8 ft for Adult Trout, Pink and Chum Salmon, and a depth of 1.0 ft for adult Chinook, Coho, Sockeye or Steelhead (Bates et al. 2003).

Table 7.2 depicts available current state guidelines for low flow analysis of fish crossings. It has been suggested that spawning adults should be delayed no more than 3 days during the average annual flood, or 7 days during the 50-yr flood (Ashton 1984). Many current design manuals specify design based on a 2-yr 7-day flood, roughly corresponding to the 95% exceedance flow.

Table 7.2. State and agency guidelines for low fish passage flows (adapted from Clarkin et al. 2003).

Alaska	Washington	Oregon	NMFS SW Region	California Dept of Fish and Game	NMFS NW Region
None	2-yr, 7-day low flow (WAC 220-110-070) Natural bed culverts must be maintained to ensure low flow channels are ok	2-yr, 7-day low flow or 95% exceedance flow for migration period: species specific	Adult Salmon - Greater of 3 cfs or 50% exceedance flow Juveniles - Greater of 1 cfs or 95% annual exceedance flow	Standards vary from 50-95% exceedance flow for various groups of fish.	95% exceedance flow during months of upstream migration

+ Low flows are for Hydraulic Design approaches only, with the exception of Alaska.

7.2.3 Bankfull Flow

Bankfull flow is the discharge at which flow from the main channel begins to spill over into the floodplain. Generally, this discharge is referenced as the 1 to 2-yr flood event (Leopold and Wolman 1957), although this does not always correspond to field observations (Mussetter 1989). Bankfull is an important parameter in alluvial channels, as it is the discharge that effectively transports the most sediment, impacting long-term channel form, function, and stability (Harrelson et al. 1994). Although bankfull-flow is rarely calculated for fish passage analysis, the concept of bankfull-width is an important design parameter for fish passable structures. This concept will be discussed further in Chapter 8.

7.2.4 Streambed Stability and Crossing Capacity

Although design for fish passage will generally control structure size, culverts must still comply with flood flow conveyance requirements. At any road crossing, structure stability must be maintained up to and including a design flood (Normann et al. 1985). An outline of the hydrologic cycle, and methods for determining extreme flows are included in HDS-2 (Federal Highway Administration 2002).

Occasionally, design methods will also require that streambed material be sized for stability during a specific design flood (e.g. Alaska Department of Fish and Game and Alaska Department of Transportation 2001; Bates et al. 2003). Generally, this stability analysis corresponds to the discharge used to check culvert capacity – on the order of a 50 year event. Table 7.3 includes design flows used for streambed stability in fish culverts.

Table 7.3. Flows used in determining adequate structure stability. (Adapted from Clarkin et al. 2003). Q_{50} and Q_{100} refer to the 50-year and 100-year floods, respectively.

Alaska	Washington	Oregon	NMFS SW Region	California Dept of Fish and Game
Q_{50} or Q_{100} *	Q_{100} with Debris *	Q_{100}	Q_{100} at headwater/depth = 1	Q_{100} at headwater/depth = 1.5

* Streambed stability check required

7.2.5 Tidal Influence

The hydrology of culverts in tidal areas requires consideration of both upland flow and tidal impact (Zevenbergen et al. 2004). Methods for determining culvert outflow with changes in tidal elevation must account for stream flow as well as tidal outflow as an ebbing tide causes water to return to the ocean. Successfully meeting fish passage provisions may require tidal data in appropriate time increments and a continuous hydrologic simulation model for tidal elevations and stream flow. Examples include the U.S. Environmental Protection Agency’s

Hydrological simulation Program – Fortran (HSPF) or Storm Water Management Model (SWMM) (Bates et al. 2003). Observed and predicted tidal elevations, including information on benchmarks for tidal stations, are available on NOAA's internet site at http://tidesandcurrents.noaa.gov/.

A detailed discussion of tidal patterns, influence, and references are provide in Hydraulic Engineering Circular 25, available at http://www.fhwa.dot.gov/, and the Army Corps of Engineers has a number of publications on construction in coastal areas, available at www.usace.army.mil.

7.3 RECOMMENDED HYDROLOGY APPROACH

In determining flow criteria, consultation with local experts will ensure that fish requirements are met. After determining fish presence and allowable delay, hydrologic conditions should be selected to allow fish passage to meet project goals. Once desirable criteria are developed, there are a number of methods available for determining site hydrology. Although state and agency guidelines for fish passage flows differ, a number of approaches are available for ascertaining site hydrology. Depending on availability, the following approaches can be used in determining fish passage design flows (Bates et al. 2003; Lang et al. 2004):

- Stream Gaging
- Continuous-flow simulation model
- Local Regression equation
- Regional Regression equation
- Flow Duration Curves

7.4 OTHER CONSIDERATIONS

Other considerations include the hydrology of the basin in which the crossing is located, the target species for which passage must be provided, and future watershed conditions.

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8 DESIGN CONSIDERATIONS

8.1 INTRODUCTION

Many factors will determine the suitability of any particular set of fish passage design criteria for a culvert installation, replacement, or retrofit. Besides economics, site logistics, regulatory requirements, and roadway characteristics are all examples of issues that may dictate particular design procedure. The following design categories have been developed to aid in the classification and selection of design approaches based on project goals. These goals are based on biological, geomorphic, and hydraulic considerations.

8.2 DESIGN APPROACHES

8.2.1 No Impedance

DEFINED - No Impedance – Crossing design produces no impedance to aquatic organism passage by spanning both the channel and floodplain.

Aside from road removal or relocation, bridges provide optimum biological, geomorphic and hydraulic connectivity (Robison et al. 1999). Often bridges will be more expensive to install and have shorter effective lives than culverts (Venner Consulting and Parsons Brinkerhoff 2004). The No Impedance procedure will not be described further.

8.2.2 Geomorphic Simulation

DEFINED – Geomorphic Simulation approaches are based on recreating or maintaining natural stream reach geomorphic elements including slope, channel-bed width, bed materials, and bedform.

The basis of these methods is the presumption that crossings matching natural conditions will readily pass fish that are moving in the natural channel. For this reason, analysis of fish passage flows is not required. Such techniques could be considered the “gold-standard” of fish passage, and provide a substantial degree of conservativeness. Geomorphic Simulation techniques are mostly a product of the Pacific Northwest, arising out of trial and error and experience within the region (Bates et al. 2006).

8.2.2.1 Biological Characteristics

Successful installations should pass fish, debris, and sediment at rates very closely resembling the natural stream reach. Geomorphic Simulation assumes passage for all fish species and life stages moving through the natural channel for all flows at which they are moving. Culverts spans wider than the bankfull width can provide dry bank margins that can serve to provide passage for aquatic and terrestrial organisms.

8.2.2.2 Geomorphic Characteristics

To allow natural processes to occur within the culvert, the crossing slope must remain close to that of the natural channel. A review of such culverts in Washington State found that installations remaining within 25% of natural channel slope successfully replicated natural channel conditions (Barnard 2003). New open bottomed installations can be placed to minimize disturbance of bed material, or laid below grade and backfilled with natural material to maintain natural channel grade.

Geomorphic Simulation creates wide spanning culverts that exceed channel bed width. In Washington, Barnard found that these structures should be 1.3 times the channel bankfull width in order to replicate stream processes (2003). In new installations, wide spanning culverts allow crossings to maintain natural bed material. In replacement installations, a designed bed mix is based on analysis of local bed materials including a pebble count or sieve analysis. Substrate continuity is maintained through the culvert by creating a natural channel bed structure, or by allowing the channel to form naturally within the crossing. Successful crossings transport sediment at rates similar to the natural channel.

The wide-spanning culverts and open bottom structures needed to meet such requirements will have high costs associated with materials and installation, but will allow a slight buffer against lateral and vertical stream adjustments (Bates et al. 2006). Although success has been achieved in high gradient situations, methods simulating the natural stream have been limited to gravel and cobble beds. No applications have yet been found in low gradient areas with fine sediments, cohesive soils, or dense vegetation (Bates et al. 2006).

8.2.2.3 Hydraulic Characteristics

Geomorphic Simulation avoids the need for consideration of target species/life-stage, timing of fish migration, or fish passage hydrology. Since crossings are generally much larger than culverts designed for hydraulic capacity alone, Geomorphic Simulation will typically control design (hydraulic capacity must still be checked to meet the required headwater-flood policy).

8.2.2.4 Data Requirements

Depending on the specific design methods used, Geomorphic Simulation requires the following information.

- Channel type (Section 8.6)
- Channel longitudinal profile
- Channel cross sections
- Reference reach characteristics

- Channel geomorphic characteristics
- Bedforms
- Bed and bank material

Adjustment potential (vertical and horizontal) and alignment
Peak flow for culvert flow capacity

8.2.3 Hydraulic Simulation

DEFINED - Hydraulic Simulation techniques utilize embedded culverts, natural or synthetic bed mixes, and natural roughness elements such as oversized rock, to provide hydraulic conditions conducive to fish passage. These techniques operate on the assumption that providing hydraulic diversity similar, but not identical, to that found in natural channels will create a fish passable structure without checks for excessive velocity or turbulence. Many techniques are based on regional design experience.

Regardless of specific criteria, Hydraulic Simulation will generally have the benefit of creating smaller spanning structures that have a reduced cost when compared to Geomorphic Simulation.

8.2.3.1 Biological Characteristics

By creating a crossing that resembles natural stream slope and substrate, passage is assumed adequate for fish in the stream reach. This assumption is often based on regional experience and project monitoring (Alaska Department of Fish and Game and Alaska Department of Transportation 2001; Maryland State Highway Administration 2005; Robison et al. 1999; Miles, M., Personal Communication; Browning 1990). Although structures aren't specifically oversized to provide stream bank margins, low flows may provide dry bank areas that will allow aquatic organisms to pass (Miles, M., Personal Communication).

8.2.3.2 Geomorphic Characteristics

Hydraulic Simulation creates hydraulic roughness, low flow paths, and resting areas conducive to fish passage by utilizing natural bed material (Robison et al. 1999; Browning 1990), or oversized substrate that remains stable during design floods (Alaska Department of Fish and Game and Alaska Department of Transportation 2001). Bed structures and key pieces are used to create flow diversity and resting areas, ideally matching bed characteristics of the natural channel.

Geomorphic continuity is maintained fairly well through structures designed for Hydraulic Simulation. Culvert width is generally close to or slightly less than bankfull (Alaska Department of Fish and Game and Alaska Department of Transportation 2001; Bates et al. 2003; Browning 1990; Robison et al. 1999; Maryland State Highway Administration 2005), allowing sediment and debris flow to continue through the crossing at flows up to bankfull. Substrate does not necessarily mimic stream reach substrate and form as in Geomorphic Simulation. Smaller, more rigid structures may have the tradeoff of a shorter design life than Geomorphic Simulation structures (Browning, M., Personal Communication).

Some Hydraulic Simulation approaches create a stable channel within the culvert (i.e. Alaska Department of Fish and Game and Alaska Department of Transportation 2001; Bates et al. 2003). In such a case, bed load and suspended load still move through the culvert, but bed material is not scoured out at high flows (i.e. a 50yr event). This requires less floodplain relief, as higher flows can pass through the culvert without scouring the bed material (Miles, M., Personal Communication).

In situations where a mobile bed is created, or allowed to develop within the crossing, sediment and debris movement is similar up to bankfull flows. Bed material can be washed out during a flood event, leaving a bare culvert and leading to upstream progressing channel incision. Recruitment may replace material that is scoured out. Regardless of bed stability, fines must be part of the bed material mixture to seal voids and avoid flows going subsurface, which would create a low flow barrier.

8.2.3.3 Hydraulic Characteristics

Culverts designed for Hydraulic Simulation are generally very close to, or slightly less than, bankfull width. Methods that call for increased bed sizing and roughness will decrease flow velocity but increases turbulence.

Culvert sizing will generally be controlled by design for desired span rather than hydraulic capacity. Hydraulic capacity must still be checked to ensure adequacy.

Fish passability is not specifically checked except in the WDFW Roughened Channel technique (Bates et al. 2003). In Alaska, experience has found that culverts following their Hydraulic Simulation "Stream Simulation" criteria adequately pass fish, and permitting has been expedited (Alaska Department of Fish and Game and Alaska Department of Transportation 2001). Techniques developed by Maryland State Highway Administration (2005) and Browning (1990) check channel velocities for compliance with local stream flows.

8.2.3.4 Data Requirements

Channel type (Section 8.6)
Channel longitudinal profile
Channel cross sections
Reference reach characteristics (mainly applies to replacements)
  - Channel geomorphic characteristics
  - Bedforms
  - Bed and bank material

Adjustment potential (vertical and horizontal) and alignment

8.2.4 Hydraulic Design

DEFINED - Hydraulic Design techniques create water depths and velocities that meet the swimming abilities of target fish populations during specific periods of fish movement. General considerations include the effect of culvert slope, size, material, and length. Flow control structures such as baffles, weirs, or oversized substrate are commonly utilized to create adequate hydraulic conditions.

Hydraulic Design is applicable to retrofits, new, and replacement culverts. This technique generates a smaller diameter culvert that keeps cost of materials and installation to a minimum while still meeting fish passage criteria including average cross sectional velocity, flow depth, and drop height. Hydraulic Design is specifically tailored to meet target fish species requirements, but produces a less conservative design than Geomorphic or Hydraulic Simulation. These designs are applicable in areas where stream grade is at or near bedrock, and at slopes up to 5% (Robison et al. 1999; Bates et al. 2003; Katopodis 1992). Fishway design may be applicable up to a 25% slope depending of fish species and life stages present (Katopodis 1992).

8.2.4.1 Biological Characteristics

Hydraulic Designs have been shown to aid in upstream migration by providing resting pools, low velocities, and deep flow (Gregory et al. 2004). These techniques utilize the swimming abilities of target fish populations in order to develop hydraulic criteria necessary to ensure fish passage. The target fish species and lifestage should be determined through consultation with fisheries biologists, and will generally focus on the weakest swimming fish known to require passage during specific periods of fish movement. Designs to meet specific hydraulic criteria are likely to constrict flow, disrupt ecosystem connectivity, and require a more rigorous design and permitting process than geomorphic or Hydraulic Simulation (i.e. Alaska Department of Fish and Game and Alaska Department of Transportation 2001; Bates et al. 2003). Hydraulic Design does not account for ecosystem requirements or the movement of non-target species.

8.2.4.2 Geomorphic Characteristics

Hydraulic Design is applicable over a range of slopes. Installations on mild slopes may create fish passable conditions without grade control structures, while moderately sloped (1-3.5%) installations and retrofits may require weirs or baffles to attain fish passable conditions (Bates et al. 2003; Alaska Department of Fish and Game and Alaska Department of Transportation 2001).

The structures created by Hydraulic Design are more likely to affect flow through and around the structure than those designed by Geomorphic- or Hydraulic Simulation. Localized aggradation and degradation due to channel constriction may have to be addressed (Castro 2003), and regular debris maintenance is generally required for Hydraulic Design culverts. This can be especially important in retrofit situations where structure modifications, such as baffles or weirs, have the propensity to catch and hold debris, increasing the risk of debris clogging (Bates et al. 2003).

8.2.4.3 Hydraulic Characteristics

Low and high fish-passage flows must be determined to ensure that hydraulic criteria are met during periods of fish movement (Chapter 7). This requires knowledge of the times of the year and flow regimes at which fish move within the natural channel. In new installations, fish passage considerations will generally control structure size, but flood conveyance must still be checked. Smaller diameters, especially when combined with the effects of baffles, or other roughness elements, can restrict passage of water and debris through the culvert, decreasing the flood flow capacity while increasing the likelihood of plugging and culvert failure.

8.2.4.4 Data Requirements

Channel longitudinal profile
Target fish species and requirements
Channel cross sections
  Channel geomorphic characteristics
  Bed and bank material
Adjustment potential (vertical and horizontal) and alignment
Low fish passage flow
High fish passage flow
Structural design flow

8.2.4.5 Further Considerations

This design approach is often recommended as a last alternative, when other possibilities are found to be unfavorable (Alaska Department of Fish and Game and Alaska Department of Transportation 2001; Bates et al. 2003; Flosi et al. 1998; Robison et al 1999; Maine Department of Transportation 2004). In Washington for example, design guidelines recommend that use of Hydraulic Design be limited to culvert retrofits, producing inexpensive, short-term, benefits until the crossing can be replaced (Bates et al. 2003).

Baffles have a much larger failure rate than other techniques. They are prone to clogging, and are difficult to prefabricate as settling may cause the baffles to pop out leading to damage to the culvert itself and to culvert failure (Robison et al. 1999; Gardner 2006). Hydraulically designed structures will have a shorter design life, increased maintenance needs, and a more intensive permitting process than Geomorphic or Hydraulic Simulation culverts.

8.3 CONSTRAINTS

Other than biological, geomorphic, and hydraulic considerations, a number of project and site constraints will help determine the appropriateness of a particular design technique. These include, but are not limited to, funding, cost, right-of-way, and physical, environmental, and regulatory issues.

8.3.1 Funding

8.3.1.1 Source

The funding agency will influence which design procedure is selected. In situations where a small amount of funding must be stretched out to accomplish optimum results, smaller, less expensive installations will likely be best suited to providing fish passage at the most locations possible. This may increase maintenance needs and decrease design life, but allow current dollars to provide the most benefit. If funding is provided on a project basis, designers may want to consider creating a structure that offers increased design life, and provides passage for all fish.

It must be noted that significant disagreement exists regarding design objectives and the responsible allocation of funds. Geomorphic Simulation will create wide spanning culverts that provide a very conservative design with respect to fish passage but come with a large associated cost. Exclusive installation of these structures would allow fewer crossings to be completed, which may be considered a poor allocation of public funds. Conversely, installations focused on target fish passage may be considered overly narrow in focus. Larger culverts likely provide broader ecosystem connectivity, allowing natural stream processes to occur and minimize the impact of the stream crossing on organisms over time.

Many design techniques are still considered experimental, and long term monitoring is still required to understand the true impacts and implications of a selected method (Chapter 14). Careful consideration of goals and requirements should be taken before selecting design criteria.

8.3.1.2 Costs

Cost considerations include design, construction, and life cycle costs such as maintenance. Costs of road-stream crossings will increase with the higher material, excavation and construction costs of large fish passage structures associated with Hydraulic and Geomorphic Simulation. Conversely, channel-spanning structures will require less maintenance and have a greater design life than smaller fish passage structures. Wide culverts may also have less impact on the surrounding reach including impact on stream ecology, structure, and function.

8.3.2 Right of Way

Right of way will determine the ability of designers to modify the channel outside of the culvert structure. Some design situations will require hydraulic control structures to ensure adequate backwatering, or to control channel slope, scour, and incision. Clear communication with local landowners will provide an understanding of right of way.

8.3.3 Physical Constraints

In addition to right of way, a number of physical barriers or obstacles could force the designer to consider the costs of moving those obstacles vs. a change in design direction. Examples include utility crossings, extreme gradient changes, and incised or degrading channels. An open bottom structure in a vertically unstable reach might allow the channel to adjust out of control, and a rigid structure may be necessary to maintain habitat upstream and gradation through the reach.

8.3.4 Environmental Constraints

Environmentally sensitive areas will require a high degree of design consideration. For example, at a new crossing in a salmon spawning area, it may be pertinent to design an open bottom structure that allows natural substrate to remain relatively undisturbed through the crossing. For example, a culvert barrier replacement in northern California utilized natural substrate, and experienced salmon spawning within the structure only two years after installation (Furniss, M., Personal Communication).

8.3.5 Regulatory Constraints

Regulatory requirements, like those discussed in Chapter 1 may reduce design options. For example, the presence of endangered or threatened fish species will require specific and immediate consideration, and if passage for weak swimming fish is required, Hydraulic or Geomorphic Simulation may be the best option.

8.3.6 Alignment

Proper culvert alignment requires consideration of channel shape, morphology, and culvert length. Installations that run perpendicular to the road will allow the shortest installations. Flow exiting a culvert at an angle, however, is likely to induce scour (Baker and Votapka 1990; White 1997), requiring wider culverts or channel treatments to protect against stream movement (Bates et al. 2006). Highway alignment should avoid sharp stream bends, severe meanders, confluences or other areas of converging and diverging flow (Maryland State Highway Administration 2005). When situations require installation at a bend, Figure 8.1 depicts a series of alignment options. Following the current channel form will require a longer culvert. Straightening the channel will shorten the crossing but require channel protection.

Creating a wider crossing will provide a slight buffer for channel migration but may also significantly increase material and construction costs (Bates et al. 2006).

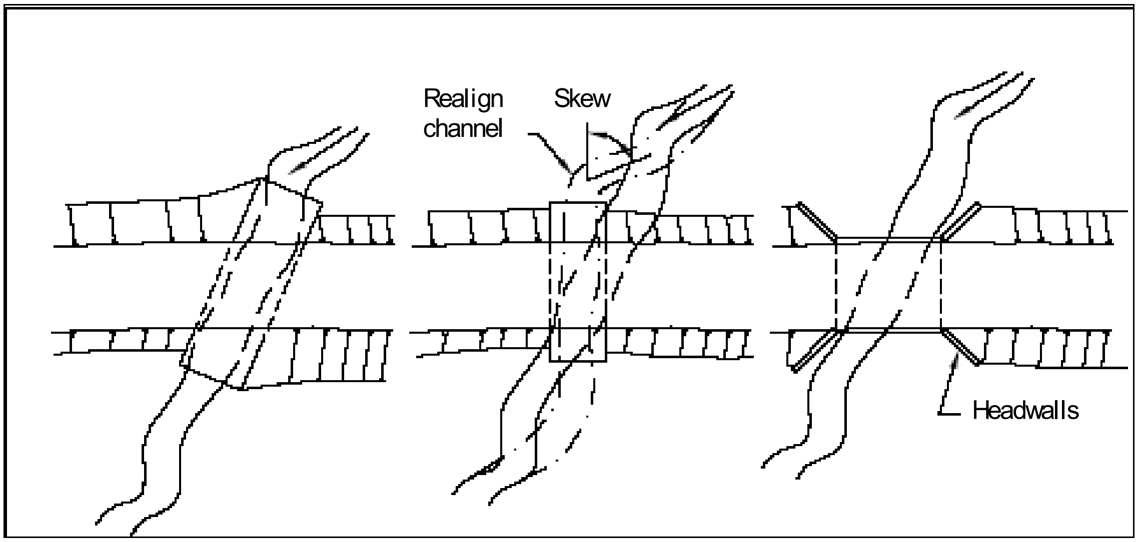

Figure 8.1. Alignment options for a skewed road-stream crossing (Bates et al. 2006).

Treatments recommended for minimizing culvert length include the addition of headwalls, steepening embankments, and narrowing the road (Bates et al. 2003; Maryland State Highway Administration 2005). Specifications for such options are included in HDS-5 (Normann et al. 1985).

8.4 STREAM MORPHOLOGY

As a rigid structure in a dynamic environment, culverts must be designed with channel processes in mind. Effective designs consider the channel and watershed context of the crossing location. Channels are continually evolving, and an understanding of stream adjustment potential must be addressed. Without consideration, well intended plans could have detrimental or completely ineffective results/impacts on the stream system and related habitat (Castro 2003; Furniss 2006)

8.4.1 Gradient

Past channel degradation can require channel modification, or considerations of the impact of increased slope on channel stability, substrate, and future conditions (Robison et al. 1999; Bates et al. 2006; Bates et al. 2003). A true Geomorphic Simulation can only be completed when culvert bed slopes very closely match the slopes of the adjacent stream channel. Oversized sediment utilized in Hydraulic Simulations provides more leeway with regards to stream slope, but also require that crossing slopes be close to the adjacent channel.

8.4.2 Bed Material and Embedded Culverts

The benefits of natural streambeds and embedded culverts are widely recognized in fish passage applications (e.g. Venner Consulting and Parsons Brinkerhoff 2004; Bates et al. 2003; Taylor and Love 2003; Clarkin et al. 2003). Bed material provides barrel roughness, which provides areas of low velocity that may be conducive to fish passage (White 1997).

8.4.3 Key Roughness Elements

In order to provide fish migration paths and resting areas many design techniques utilize key roughness elements to create diversity in flow velocity, depth, and energy dissipation (Robison et al. 1999; Bates et al. 2006; Browning 1990). Key roughness elements describe any number of materials that can be used to provide hydraulic roughness and diversity to a crossing including oversized substrate, constructed channel features including banks, stone sills, boulder clusters, log sills, and baffles. Such features are intended to increase bed stability and provide resting areas and hydraulic diversity conducive to fish passage.

8.4.4 Subsurface Flows

Crossings that are filled with a coarse simulated bed mix may allow low flows to seep between rocks – and move in the subsurface - until interstitial spaces have been sealed with fine particles. To limit streambed permeability, an appropriate proportion of fine material must be included in the bed mix (5-10%) (United States Forest Service 2006a; Bates et al. 2006). During channel construction, placement of a sediment barrier fabric (Browning 1990), or washing fines into the streambed during construction can effectively seal the voids (Bates et al. 2006).

8.5 CHANNEL GEOMETRY

8.5.1 Channel Width

The correct determination of channel width is an important prerequisite for many of the design techniques described in this manual. Width measurements should describe normal straight channel conditions between bends and outside the influence of a culvert, artificial, or unique constriction (Bates et al. 2003). Two common design parameters include bankfull width and active channel width. In entrenched and non-adjustable systems bankfull and active channel width may be very similar, while evaluation in other areas, such as meandering valley streams, might show great discrepancies (Bates et al. 2006).

8.5.1.1 Active Channel Width

The “active channel” describes the stream width at current and recent discharges, beyond which permanent features such as terrestrial vegetation begin to dominate

(Hedman and W.M.Kastner 1977). For engineering purposes, the active channel can be distinguished by the ordinary high water (OHW) mark - the elevation delineating the highest water level that has been maintained for a sufficient period of time to leave evidence on the landscape (Taylor and Love 2003). Representations may also include erosion, shelving or terracing, change in soil characteristics, a break or destruction of terrestrial vegetation, moss growth on rocks along stream margins, vegetation changes from predominantly aquatic to predominantly terrestrial, or the presence of organic litter or debris (Taylor and Love 2003; Bates et al. 2003).

8.5.1.2 Bankfull Width

Bankfull width describes stream characteristics during channel forming events. Bankfull flow marks the condition of incipient motion, with impacts on long-term form, function and stability of the channel (Williams 1978). This is typically recognized as a 1 to 2 year event, when flow within the channel just begins to spill over into the active floodplain (Leopold et al. 1964). When floodplains are absent or difficult to ascertain, as in entrenched mountain streams, markers used to determine bankfull and active channel show little variation (Bates et al. 2003). Difficulty in determining bankfull flow in the field prompts some guidelines to call for estimation of bankfull width based on a surveyed cross sections and return period flow (i.e. Maine Department of Transportation 2004). This type of estimation may show great disparity when compared with field observations of channel-bed width (Mussetter 1989).

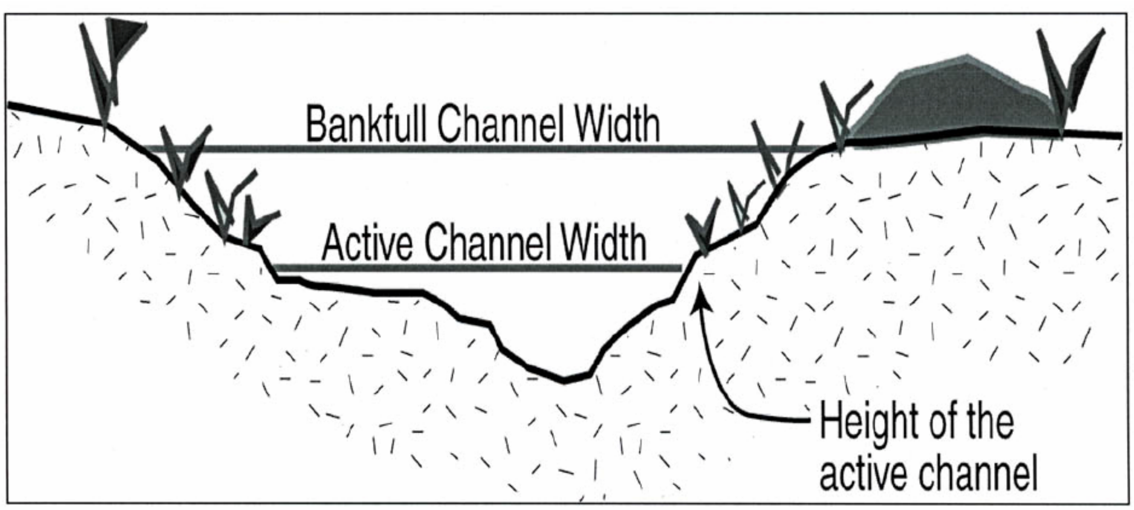

Figure 8.2. Depiction of Bankfull Channel Width compared to Active Channel Width (Taylor and Love 2003). Note that in certain systems bankfull and active channel can be very similar, and active channel indicators are often used to describe bankfull flow when a floodplain is not present as in entrenched systems.

Constricting channel width has many negative impacts that will need to be considered. Constricting flow can cause increased scour at the culvert outlet, increasing the risk of streambed erosion and downstream channel incision, and a constricted inlet can force backwatering of the upstream channel, leading to aggradation (Castro 2003). This phenomenon should be recognized at existing crossings, where removal of a culvert may allow incision to progress upstream unchecked (Castro 2003).

8.5.2 Channel Profile

It is extremely important to understand structure impacts on the channel over time including incision, scour, headcut and regrade (Bates et al. 2006). This requires an accurate survey of the longitudinal profile (River and Stream Continuity Partnership 2004). A longitudinal profile should include the culvert site and 20 channel widths or a minimum of 200-300 feet up- and downstream of the structure (Castro 2003; Bates et al. 2003). This will allow an understanding of the final channel bottom elevation as a result of the replacement structure ensuring proper invert elevations, embedment, and slope. A good survey is also useful in assessing the potential for downstream flooding, alteration of upstream and downstream habitat, potential for erosion and headcutting, and stream stability in general (River and Stream Continuity Partnership 2004).

8.5.2.1 Channel Evolution

Figure 8.3 depicts channel evolution after an initial channel incision moved the stream from a stable state. Although a crossing may seem stable, there are various levels of stability, and it is important to examine upstream and downstream channel condition to understand the current channel condition.

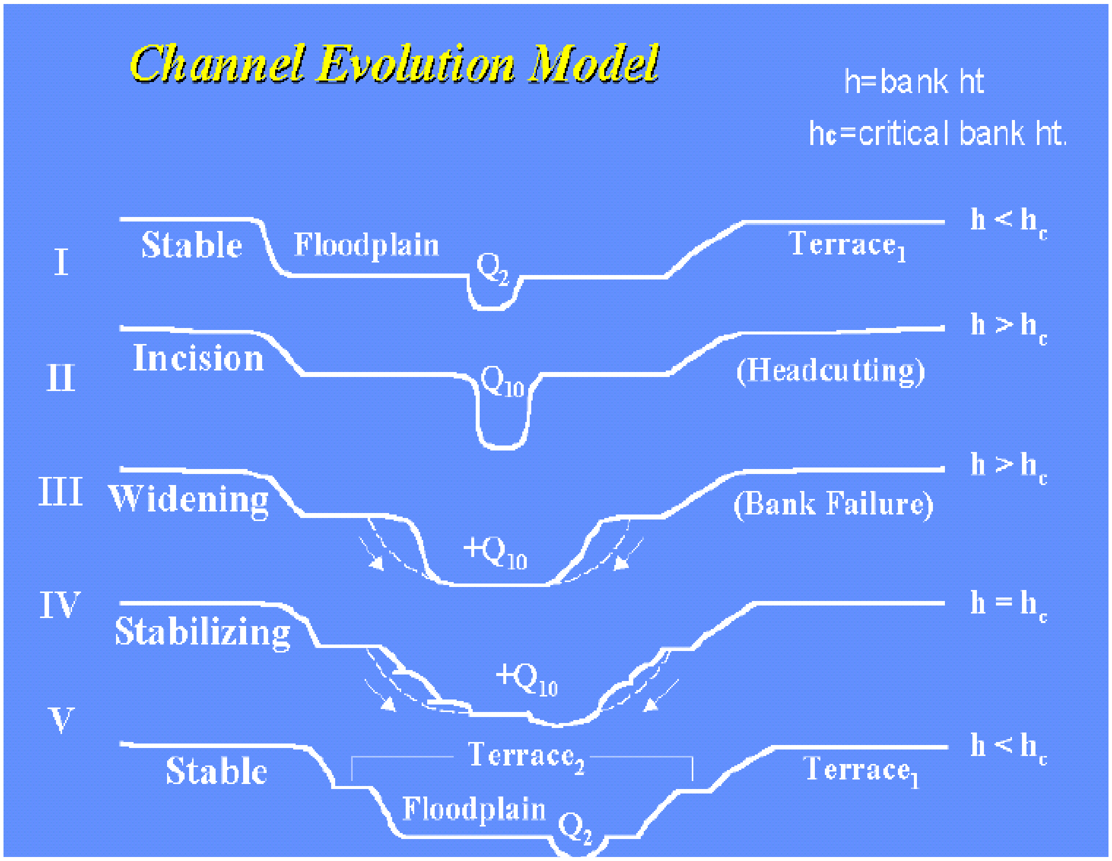

Figure 8.3. Channel evolution model (Castro, 2003). Critical bank height is inherently unstable and will result in bank failure and stream widening.

8.5.2.2 Channel Incision, Headcut and Regrade

As channels continually evolve and migrate, channel adjustment can lead to structure failure. Installations that fail to recognize channel processes may compromise fish passage and alter quantity and quality of stream corridor habitat (Castro 2003).

In situations where a current culvert installation is acting as a control point, removal, replacement with a larger structure, or lowering may allow channel incision to progress upstream uncontrollably, or until another control point is reached. Regrade will be more immediate and pronounced in sand bed streams and channels with low rates of bed load transport (Bates et al. 2003). Stream reaches with high degradation potential will cause Geomorphic Simulation culverts to be ineffective, and Hydraulic Design or Simulation incorporating channel grade controls (Section 8.7.4) may be more suitable.

8.6 STREAM CLASSIFICATION

Systems for stream classification are a useful tool in building awareness of stream form and function. Methods describe the channel in terms of cross-sectional shapes, morphological parts of the stream and interactions between flow and sedimentation (Bunte and Abt 2001). The following discussion of stream classification is intended to introduce the user to popular methods in stream classification and geomorphology, but is not sufficient for structure design. Coordination with a local geotechnical engineer and gemorphologist is necessary for ensuring structure performance. For more information it will be useful to examine references included below.

8.6.1 Montgomery and Buffington

Montgomery and Buffington created a stream classification system to describe channel systems in the Pacific Northwest. Their methodology follows changes in channel morphology as steep headwater streams run through steep valleys and hillslopes, gentle valleys, and eventually low gradient valleys (Bunte and Abt 2001). As water flows to the ocean, channel types generally transition from cascade, step-pool, plane bed, pool-riffle and dune-ripple. Channel bedform is described by the type and size of sediment, sediment transport capabilities, and hydraulic conditions within a stream reach. Table 8.1 from Bunte and Abt summarizes this classification system with respect to channel geomorphic and hydraulic conditions.

Table 8.1. Stream Classification by Montgomery and Buffington, (after Montgomery and Buffington 1997 1998). (Adapted from Bunte and Abt 2001).

Stream gradient, range and mode (m/m)	Stream type	Typical bed material	Dominant sediment source	Dominant sediment storage	Typical pool spacing*
0.03 - 0.20 (0.08 - 0.20)	Cascades	Cobble-boulder	Fluvial, hillslopes, debris flows	Around flow obstructions	< 1
0.02 - 0.09 (0.04 - 0.08)	Step-pool	Cobble-boulder	Fluvial, hillslopes, debris flows	Bedforms	1 - 4
<0.02 - 0.05 (0.02 - 0.04)	Plane-bed, forced pools	Gravel-cobble	Fluvial, bank failure, debris flows	Overbank	None
<0.001- 0.03 (0.01)	Pool-riffle	Gravel	Fluvial, bank failure	Overbank, bedforms	5 - 7
< 0.001	Dune-ripple	Sand	Fluvial, bank failure bedforms	Overbank,	5 - 7

*Values in parentheses are the modes of the observed stream gradient distribution; * in terms of channel widths*

8.6.2 Source, Transport and Response Reaches

A reach-scale categorization allows streams to be categorized based on relative positions within the watershed, and sediment transport characteristics. This type of analysis is useful in understanding the potential response of a channel reach to a crossing installation. Montgomery and Buffington define reach level morphologies as source, transport and response reaches (Montgomery and Buffington 1993).

Transport reaches are high gradient supply-limited channels, which are unlikely to respond quickly or severely to disturbance. This includes bedrock, cascade and step-pool channels. Response reaches are lower gradient transport-limited channels with a high potential for morphological adjustment in response to sediment input. This general classification covers plane-bed, pool-riffle and braided channels. The transition from transport to response reach is where the impacts of increased sediment supply will have the largest impact, as sediment supplied by the transport reach will readily settle out at the first reach that cannot maintain sediment transport capacity (Montgomery and Buffington 1993).

A crossing location within a particular reach, as well as the proximity of other reaches will help a designer ascertain the potential impacts and geomorphic response of the stream. Crossings that fall at the intersection of two different channel types, for example, could indicate channel incision, or that the crossing is located at a point of geomorphic transition (Bates et al. 2006). Crossings placed in a response reach may require extra consideration of channel processes and morphological impacts.

8.6.3 Rosgen Stream Classification

Rosgen channel classification is based on five morphometric parameters of the channel and its flood plain including entrenchment ratio, width-depth ratio at bankfull flow, sinuosity, stream gradient and mean bed particle size (Bunte and Abt 2001). These characteristics are used to distinguish seven stream types, represented by capital letters A to G. Table 8.2 lists the morphological characteristics of Rosgen’s stream types.

Table 8.2. Morphological characteristics of the major Rosgen stream types (Bunte and Abt 2001)

Stream Type	Morphological characteristics
A	**Step-pool, or cascading**: plunge and scour pools, high energy, low sediment storage, stable;
B	**Riffles and rapids**: some scour pools, bars rare, stable;
C	**Pool-riffle sequences**: meandering, point bars, well developed floodplain, banks stable or unstable;
D	**Braided**: multiple channels, shifting bars, scour, deposition, high sediment supply, eroding banks;
DA	**Anastomosing**: multiple channels, pool-riffle, vegetated floodplain, adjcnt. wetlands, stable banks;
E	**Meadow meanders**: well-developed floodplain, riffle-pool, relative high sediment conveyance;
F	**Valley meanders**: incised into valleys, poor floodplain, pool-riffle, banks stable or unstable;
G	**Gullies**: incised into hillslopes and meadows, high sediment supply, unstable banks, step-pool.

Channels can be further distinguished using numbers to represent bed material and particle size, and lower case letters to represent deviation from expected channel slopes. For example, a stream classified as C4b is a C –type stream with a gravel bed and gradient within the range of 0.02-0.039 more typical of a B-type stream (Rosgen 1994). Accurate classification requires longitudinal and cross sectional channel survey and sediment sample analysis.

8.6.4 Summary of Channel Classification

All stream classification systems are useful in understanding basic channel reach geometry and dominant geomorphic processes. This can be valuable in predicting channel response to modification or culvert replacement. Certain channel types can carry specific design challenges. For example, risk of floodplain constriction and/or lateral adjustment is associated with Rosgen C, D and E channels (Bates et al. 2006). As mentioned above, plane bed, pool-riffle, and dune-ripple channels are associated with response reaches, and are likely to show the most dramatic response to disturbance (Montgomery and Buffington 1993).

For further discussion of stream classification and applicability to channel crossing design, it is useful to review the original documents by Rosgen (1994), Montgomery and Buffington (1993; 1998), Bunte and Abt (2001), and Bates (2006). It is important to note that these design techniques or classification systems are not well tested outside the regions for which they were created. Installations in low gradient, highly mobile sand bed streams may require special consideration.

8.7 CHANNEL MODIFICATIONS

As a rigid structure in dynamic environment, culverts require consideration of riprap and channel modification to address scour and channel degradation or incision

(Bates et al. 2003; Robison et al. 1999; Maryland State Highway Administration 2005). An undersized culvert will destabilize the adjacent stream reach. A number of alternatives are available to protect the impacted. Modification of the channel both up- and downstream of the structure can decrease the slope required at the culvert installation, helping to meet velocity, gradient and embedment requirements.

8.7.1 Erosion Control

8.7.1.1 Riprap

Riprap refers to oversized rock strategically placed within the channel to control scour and erosion. Application of riprap for energy dissipation is outlined in Hydraulic Engineering Circular 14 – Hydraulic Design of Energy Dissipators for Culvert and Channels (Thompson et al. 1983). Figure 8.4 depicts improper use of riprap for a fish passage situation. When utilized, voids in riprap should be filled with fines to prevent flows from going subsurface (Maine Department of Transportation 2004).

Figure 8.4. Downstream riprap will dissipate energy and reduce scour, but must be placed with fish utilization in mind. Riprap at this culvert exit effectively blocks fish passage (United States Forest Service 2005).

8.7.1.2 Energy Dissipation Pool

The state of Maine requires an energy dissipation pool at culvert outlets (Maine Department of Transportation 2004). These pools allow fish to rest before attempting to enter a structure, ensuring proper culvert outlet hydraulics and backwatering. General requirements include a pool width greater than or equal to 2 times the culvert span, and a pool length greater than or equal to 3 times the culvert span. Weirs are used to maintain the appropriate flow elevation and flow capacity. If the pool does not backwater the culvert outlet during the design period, the Energy

Dissipation Factor (Section 3.2.4) is checked to ensure that it is less than or equal to 4ft-lb/ft^3/s (Maine Department of Transportation 2004).

8.7.2 Channel Modifications

Downstream channel modifications may be necessary to ensure proper culvert backwatering or to control crossing slope. Upstream channel modification can include erosion or grade control structures (detailed below), or a tapering of channel banks to smooth out the impacts of an inlet constriction (Robison et al. 1999). A number of techniques for channel modification are included in Table 8.3.

Table 8.3. Comparison of channel profile design structures used to control grade either upstream or downstream of a culvert. (Adapted from Bates et al. 2003) with additional comments from other sources.

Grade Control	Advantages	Disadvantages	Limitations
Log Sills	Downstream bed-elevation control	Limited to <5% final gradient (affects length to catch channel grade)	Minimum spacing of 15 ft. Limited to <5% gradient. Allowable drop depends upon fish requiring passage.
Baffles	Increase hydraulic roughness	Turbulence, hydraulic profile raised, debris problems. No small fish passage.	Slope less than or equal to 3.5%.
Plank Sills	Hand Labor	Less durability	Limited to <5% gradient streams, small streams.
Roughened Channel	Natural appearance, flexible, can provide passage for all fish.	Technical expertise required. Technical fish-passage analysis required.	Limited to <3% gradient streams, moderate streams.
Boulder Controls	Flexible, allowing channel to regrade slowly	Not recommended downstream of culverts. Will degrade over time.	Maximum drop of 0.75 ft.
Fishway	Can provide passage for most fish	Expensive. Technical expertise and site-specific, flow-regime data required. Debris and bedload problems.	Narrow range of operating flow. Difficult to provide passage for all fish, all of the time.

8.7.3 Roughened Channel

Roughened Channels can be constructed within the natural channel to control channel shape, slope and form. This may be especially pertinent in areas where past degradation causes a culvert installation to be placed at a severe slope. Methods and equations used in the design of roughened channels can be found in Chapter 11.

8.7.4 Grade Control Structures

Grade control structures may be necessary upstream or downstream of a culvert to control longitudinal profile and water surface elevations. Downstream of a culvert these installations typically backwater the culvert and stabilize steepened reaches. Figure 8.5 depicts the placement of downstream grade control. Such structures have been shown to cause problems with fish passage (Browning 1990), and a clearance of 20 ft between the culvert outlet and the first downstream control is recommended (Bates et al. 2003; Robison et al. 1999). Upstream of a culvert, grade control is used to stabilize a reach and protect against current or future headcutting. This type of structure, depicted in Figure 8.6, should end no closer than 35-50 ft from the culvert inlet (Bates et al. 2003).

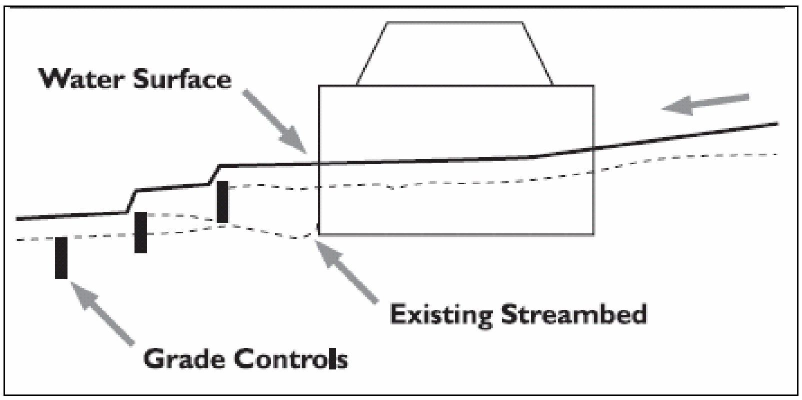

Figure 8.5. Downstream grade control (Bates et al. 2003).

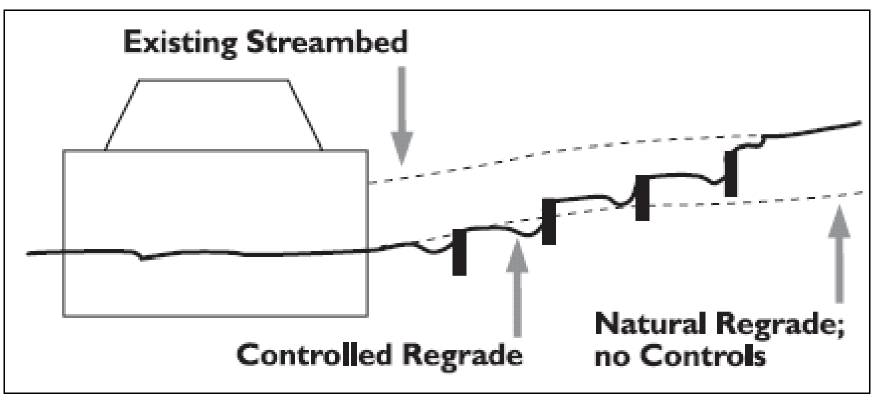

Figure 8.6. Upstream Regrade Channel-steepening options (Bates et al. 2003)

8.7.5 Tailwater Control

It may also be necessary to raise the tailwater elevation in order to backwater the culvert and provide minimum flow depths. Many methods are available including:

- Weirs
- Sills

- Constructed tailwater pools
- Full or partial channel restoration
- Riffle grade control structure/Roughened Channel

Flow over weirs can create velocity and depth barriers, and it may be necessary to design a series of weirs to provide fish passage and backwatering the culvert.

8.7.6 Broad Crested Weirs

The Maine Department of Transportation describes the following method for the design of a rectangular notch weir **-** Broad Crested Weir (Maine Department of Transportation 2004) This is a channel-spanning structure at the culvert outlet, which can be used to ensure proper water surface elevation and backwatering. When the drop over a weir will create a barrier to fish passage, it will be necessary to include further control structures to create a series of manageable step pools while maintaining adequate culvert backwater. A series of notch weirs is depicted in Figure 8.7.

Figure 8.7. Notch weirs downstream of a culvert installation, acting to properly backwater the culvert, while maintaining manageable drops (United States Forest Service 2005).

Design Procedures are as follows:

At first pass, the weir height can be set at the desired water height (ignores the depth of flow over the weir).

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

Equation 8.1

where

- C_d = discharge coefficient (0.9 assumed)
- b_c = channel width across the bar, ft
- h_1 = water elevation upstream of the bar (referenced to bar elevation), ft

Solving for h_1

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

Equation 8.2

(note the assumption 0.9 is in view of the uncertainty and variability in the weirs contemplated here)

Flow over the weir will be critical, and velocity (v_c) must be checked for fish swimming ability:

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

Equation 8.3

Channel regrade promoted by an undersized culvert installation can be a concern with culvert replacement or removal. Grade control structures can be used up and/or downstream of the structure to help protect against catastrophic channel regrade.

8.8 DESIGN CONSIDERATIONS

As mentioned above, design selection should be based on project goals and site biological, geomorphic, and hydraulic considerations.

8.8.1 Biological Considerations

8.8.1.1 Fish Passage Requirements

Crossing designs create different levels of stream reach connectivity. In general, Geomorphic Simulation creates the greatest connectivity, followed by Hydraulic Simulation and Hydraulic Design. A few pertinent questions can significantly narrow design option selection based on project goals.

What is the weakest swimming fish species and life stage for which passage required?

Example: Adult Salmon; Juvenile Salmon; resident trout; benthic fish; all species and life stages present.

All techniques are designed to ensure fish passage; however, geomorphic and Hydraulic Simulation approaches will allow passage for a wider variety of fish species and life stages.

For what fish species and life stage is passage desirable?

Hydraulic Designs can be completed to cater to a particular fish species and lifestage; however, such a structure may provide a barrier to weaker swimming fishes at some or all flows.

At what flows, and time periods are these fish migrating? What is the allowable delay?

Design may depend on the timing of fish migration and relative flows. Delay impacts may be less crucial for resident fish than a spawning salmon. This problem can be compounded, for example, by a series of culverts that provide passage only after short delays.

8.8.1.2 Ecological Significance

Further consideration should be paid to ecological significance of the area. The only way to truly maintain habitat is a bridge or open bottom structure, and, unless culverts are designed with waterway functions in mind, a loss of habitat will result within the culvert. Figure 8.8 shows a representation of the range of ecological solutions available at a road-stream crossing. Extremes ends of the spectrum include traditional design for flood capacity, and bridges or road removals that will permit valley and floodplain process.

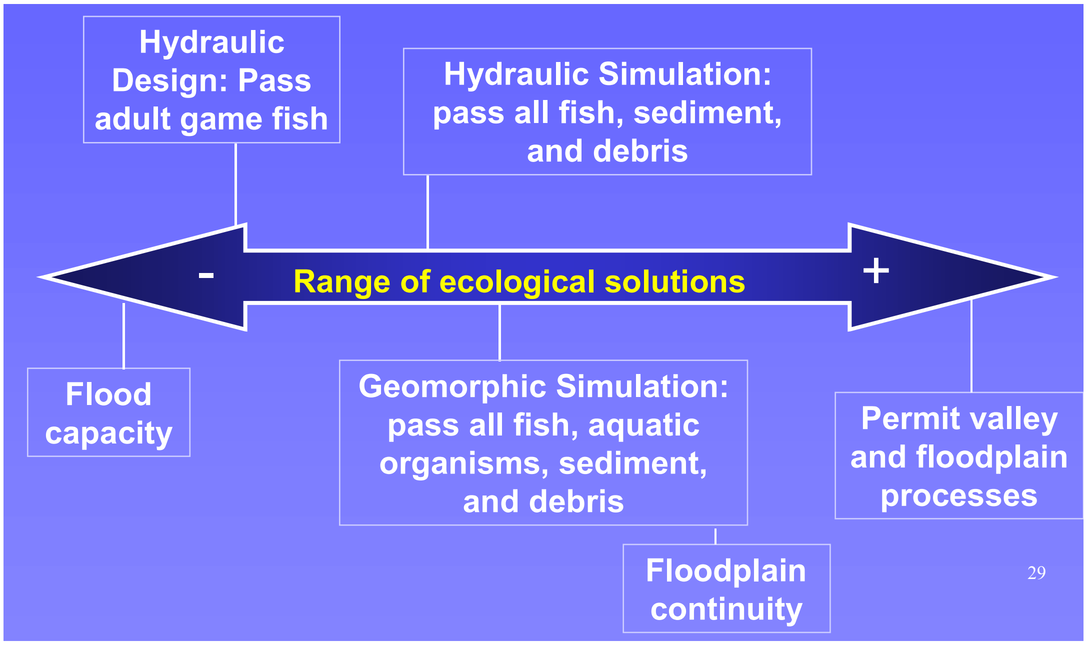

Figure 8.8. Range of ecological solutions at culvert installations (adapted from Gubernick 2006).

8.8.2 Geomorphic Considerations

Site geomorphology is another important consideration in design for fish passage. Slope, channel location, channel stability, and bed material are all example of geomorphic elements that affect design selection. For example, installations located at slope breaks or in sediment sensitive areas may have a high propensity to degrade or elicit a change in channel conditions, eventually creating another barrier or destroying valuable habitat (Bates et al. 2006).

8.8.2.1 Form and Key Features

Channel form and key features can aid in understanding channel processes including sediment transport, channel stability, and channel migration (Bunte and Abt 2001). Key features describe stream elements such as large woody debris (LWD), rock, vegetation, or channel confinement, all of which can play a large part in channel form and stability (Montgomery and Buffington 1998). While features such as LWD may be prominent in some channels, exact placement and development of such influences, and associated features, may be fairly unpredictable (Montgomery and Buffington 1993), and an understanding of overall influence and importance will be essential.

8.8.2.2 Stability

Channel stability refers to the likelihood that channel will retain its current placement, gradation, shape and form over time. Channels in highly entrenched mountain streams will be less likely to show lateral or vertical changes over time, while meandering valley streams may show great variation both laterally and vertically in response to minimal inputs (Montgomery and Buffington 1993; Rosgen 1994).

8.8.2.3 Morphological Adjustment Potential/Ability

A crossing can be built to buffer for slight lateral and vertical channel adjustments. Although this increases the size and cost of a structure, benefits can include decreased maintenance requirements and increased design life.

8.8.2.4 Rigid Structure in Dynamic Environment

All culvert act as rigid structures in a dynamic environment, remaining at a specific location and elevation and preventing channels from maintaining their natural processes (Bates et al. 2006). By attempting to understand the possible impacts of a crossing on the channel, it is possible to select design options that provide optimum fish passage while ensuring acceptable design life and maintenance requirements.

8.8.3 Hydraulic Considerations

8.8.3.1 Flood Flow Conveyance

Flood flow capacity must be considered at all road-stream crossings. Each state has established flood flow requirements for culverts as a function of roadway category. Typical values of required flood capacity range from the 4% chance flood (25-yr) to the 1% chance flood (100-yr). In culvert sizing, fish passage will generally control culvert design rather than flood capacity; however, hydraulic capacity must still be checked to ensure adequate flow flood conveyance.

8.8.3.2 Culvert Flow Characteristics

Slope and width will have a large impact on culvert flow characteristics. Crossings that are designed to create passage for specific fish and lifestages may require additional hydraulic considerations such as low and high fish passage flows and induced turbulence.

8.8.3.3 Targeted Fish Passage at Design Flows

Hydraulic Design options require detailed hydrologic information in order to ensure fish passage at specific periods of fish migration, while Geomorphic and Hydraulic Simulation methods attempt to match (or closely mimic) natural stream reach characteristics, and require little to no additional hydrologic information.

8.8.3.4 Passage for All Fish

Hydraulic and Geomorphic Simulation techniques are intended to provide passage for all fish species within the reach through any period during which they are moving. It may be difficult, or very costly, to provide passage for all fish by designing for specific hydraulic conditions.

8.8.3.5 Sediment Transport

Culverts that maintain a natural bed will be sized to retain natural reach sediment transport properties (Bates et al. 2003; Bates et al. 2006; National Marine Fisheries Service Southwest Region 2001). If crossings constrict flow, there will likely be associated impacts on sediment transport including aggradation upstream and increased velocities, scour and degradation downstream from the structure (Castro 2003).

8.8.3.6 Outlet Control

For fish passage velocities and depths to be met, it is recommended that flow remain subcritical through the culvert and at the outlet, requiring that culverts be designed to maintain outlet control (Alaska Department of Fish and Game and Alaska Department of Transportation 2001; Behlke et al. 1991; Bates et al. 2003). Characteristics governing outlet control include culvert inlet area and shape, barrel area and shape, barrel slope, barrel length, barrel roughness, and water surface elevation at the culvert outlet (Normann et al. 1985). Depressed inverts, or artificial roughness created by weir baffles, and deep corrugations can also be used to slow velocities within the culvert barrel (Behlke et al. 1991). Figure 8.9 from Hydraulic Design Series 5 depicts a culvert under outlet control.

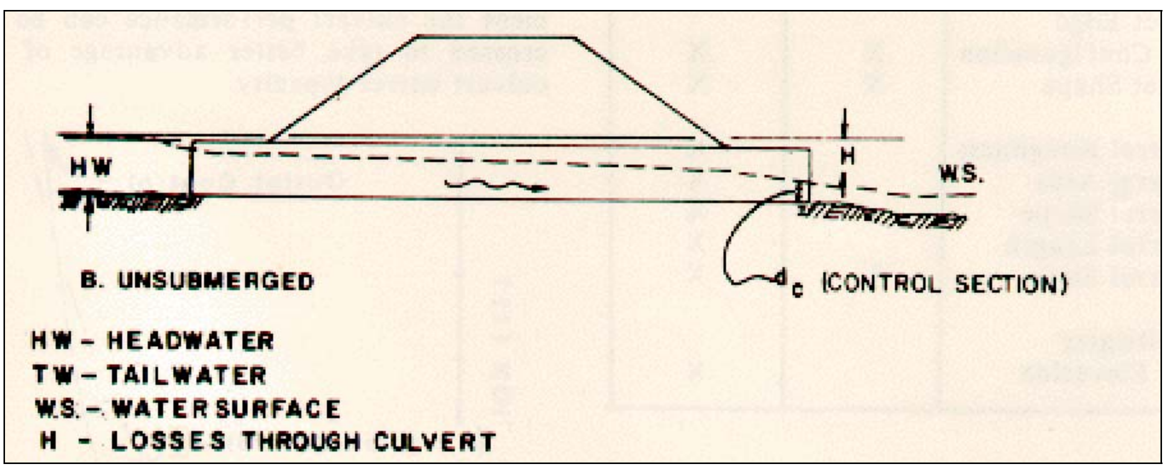

Figure 8.9. Culverts under outlet control. Hydraulic Design Series -5 (Normann et al. 1985).

8.8.3.7 Infrastructure Safety and Service Life

Culverts must also be built with consideration of safety and service life. Larger spanning culverts will have a greater cross sectional area for passing flood events, and a correspondingly longer design life (Browning, M., Personal Communication). Hydraulically designed culverts will have a smaller initial cost, but require additional maintenance and monitoring to avoid debris accumulation (Bates et al. 2003).

8.9 CULVERT SHAPES

A number of culvert shapes are available to meet the specific needs of a culvert site. Selection will be the result of site conditions including depth of cover, limited allowable headwater elevations, clogging potential, need for natural stream bottom, or structural and hydraulic requirements (Ballinger and Drake 1995). Common shapes for fish passage design include round and elliptical pipes, box culverts, and open-bottom arches. All types of culvert shapes have been used for fish passage, and selection is likely the result of site conditions and personal preference (Bates et al. 2003). Table 8.4 is a collection of noted advantages and disadvantages of culvert shapes and materials.

Table 8.4. Advantages and Disadvantages of different culvert shapes for fish passage installations. (Information from White 1997; Normann et al. 1985; Bates et al. 2003; Robison et al. 1999).

Shape	Advantages	Disadvantages
Bridge	Usually the best alternative for fish passage.	Cost
Circular	Structurally and hydraulically efficient. Greater depth of fill allowable for given span, and easier installation (in reference to Arch or Pipe Arch installations).	More prone to clogging at high flows. Flexible walls in large culverts require special care during backfill construction.
Pipe-Arch and Elliptical	Wider section available for low flows with less height.	For buried culverts, installation can be difficult.
Arch	Very good fish passage when sized adequately. Allow natural streambed material to be maintained in new installations.	Expensive installation. Not practical when stable footings cannot be created.
Structural plate (Round or Arched)	Can be placed on the bedding and partially backfilled with top plates left off.	Distortion during compaction can lead to problems joining final pieces.
Box	Easily adaptable to a variety of situations.	Not as structurally and hydraulically efficient as other shapes due to angled corners.
Multi Cell	Allow adequate capacity in low profile situations. Lower road bed elevation.	Prone to clogging due to area between the barrels and smaller individual culvert size.

Corrugated metal culverts are commonly used in fish passage design. These structures provide boundary roughness that may be conducive to fish passage (Powers et al. 1997; Barber and Downs 1996; Behlke et al. 1989), as well as aiding in retention of bed materials (Bates et al. 2003). Culvert embedment is also commonly called for, with some exceptions in hydraulically designed culverts. When new installations utilize natural bed material, bottomless structures have the advantage of allowing natural substrate to remain in place.

8.10 DESIGN SELECTION

The selection of an appropriate design technique will be the result of project goals and the design techniques applicable to a particular situation. In Chapters 9-11, design techniques from across the country are explained within the context of the design categories listed above. Design examples are included in the Chapter 12 to further clarify the design process.

Selection of method(s) and criteria should weigh achievable objectives against potential risk. A cost/benefit analysis, including risk analysis, may be pertinent in large culvert installations (Normann et al. 1985) like those associated with fish passage.

A first step in the decision process is to understand the necessity of a road crossing. Abandonment or removal of a crossing may be a plausible and desirable solution to fish passage problems, especially on forestland where road use is intermittent or logging and fire traffic can be rerouted with little consequence (Robison et al. 1999). A basic selection flow chart is shown in Figure 8.10.

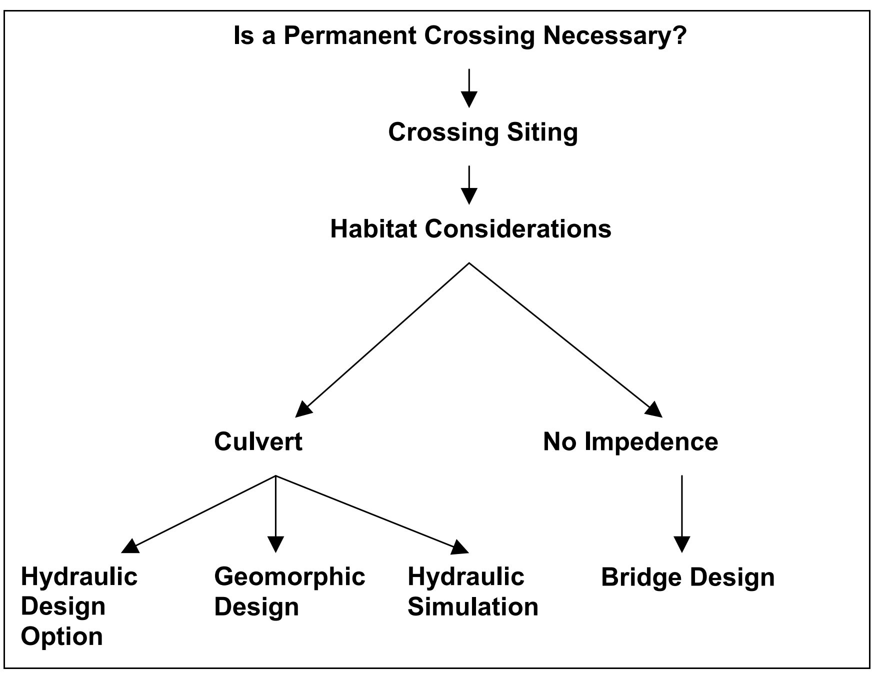

Figure 8.10. A generalized approach to culvert selection (adapted from Bates et al. 2003)

8.10.1 Agency Collaboration

Agreements between State Departments of Transportation and Resource agencies can greatly expedite the design and permitting process, ensuring that the requirements of all parties are met satisfactorily through a common vision. For example, Alaska and Oregon currently have agreements between their respective resource agencies aimed at more timely approval of permit applications for culvert installations, and recognizing the priority of replacement/repair of current fish passage barriers (Venner Consulting and Parsons Brinkerhoff 2004).

8.10.2 Summary Matrix of Design Options

Table 8.5. Summary of geomorphic, biologic and hydraulic characteristics of various crossing options.

Category	Relative Cost	Description	Characteristics		
			Biological	Geomorphic	Hydraulic
1	$$$$	No Impedance	No Impact	Unconstrained	Q_{100} Unconstricted
2	$$$	Geomorphic Simulation	Fish and AOP	Natural Substrate; Mobile Channel	Stability Check Required; Possible Relief Required
3	$$	Hydraulic Simulation	Some Fish and AOP	Oversized Substrate; Vertical Movement Controlled	Stability Design Required; Possible Relief Required; Hydraulic Target Check Required
4	$	Hydraulic Design	Target Fish	Artificial Channel	Hydraulic Target Design

8.11 ANALYSIS TOOLS AND SOFTWARE

Analysis tools and computer software can be useful in the design of fish passable structures. The following programs/websites are recommended or specified for use by many design/assessment documents.

8.11.1 FishXing

FishXing (pronounced “fish crossing”) is a fish passage analysis tool developed by the United States Forest Service. According to product description, FishXing provides the following features (United States Forest Service 2006a):

- Allows for comparison of multiple culverts designs within a single project
- Calculates hydraulic conditions within circular, box, pipe-arch, open-bottom arch, and embedded culverts
- Contains default swimming abilities for numerous North American fish species
- Contains three different options for defining tailwater elevations

- Calculates water surface profiles through the culvert using gradually varied flow equations, including hydraulic jumps
- Outputs tables and graphs summarizing the water velocities, water depths, outlet conditions, and lists the limiting fish passage conditions for each culvert

This software is free and available for download at http://www.stream.fs.fed.us/fishxing/

Noted limitations include:

- Inability to model crossings with multiple structures
- Incomplete fish swimming ability data (although the program does provide the option for user input of swimming values)
- Roughness coefficient selections limited and not always practical
- Steep learning curve
- Validation issues

This program has been recommended as a first cut analysis tool, but for concrete prioritization, design or analysis site visits and analysis should be completed (Cahoon et al. 2005). Analysis with field assessment and study has found FishXing to match results between 71 and 100 percent of the time (Rajput 2003; Cahoon et al. 2005). A powerful use for FishXing is in a culvert assessment of “indeterminate” designated crossings. The software may be able to move a designation to “passable” or “impassable”.

8.11.2 HY8

The HY8 Culvert Analysis program was developed by FHWA in order to automate the information contained within HDS-5, "Hydraulic Design of Highway Culverts," HEC-14, "Hydraulic Design of Energy Dissipaters for Culverts and Channels," and HEC-19, "Hydrology." It is intended for hydraulic capacity design, but is useful in evaluating design flood stability, scour potential, and culvert barrel velocity. Maryland suggests the use of other programs for the calculation of tailwater rating curves (Maryland State Highway Administration 2005).

This software is free, and available for download at:
http://www.fhwa.dot.gov/engineering/hydraulics/software/softwaredetail.cfm
Research at Brigham Young University is currently converting HY8 to a windows based program, with intentions of completion in spring of 2007 (Rowley et al. 2006).

8.11.3 HEC-RAS

The Hydrologic Engineering Center River Analysis System (HEC-RAS) is a river modeling program developed by the U.S. Army Corps of Engineers. HEC-RAS can be used to perform hydraulic calculations for a full network of natural and constructed channels. Users have the ability to place culverts within channel context and perform analyses of one-dimensional steady and unsteady flow. The steady flow component is capable of modeling subcritical, supercritical, and mixed flow regimes, while the unsteady flow component was developed primarily for subcritcal flow calculations.

HEC-RAS is free and available for download at:
http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html

8.11.4 FishBase

FishBase is a searchable relational database catering to different professionals including research scientists, fisheries managers, zoologists and many more. It contains information on over 28,500 fish species, including pictures, data on swimming speeds, distribution, biology, and references. It is available on CD or on the web at http://filaman.ifm-geomar.de/home.htm.

8.11.5 Commercial Programs

There are many commercial programs available for analysis and design of culverts, but their applicability has not been evaluated for this publication. A short discussion of many of these programs is available in *Environmental Stewardship Practices, Procedures, and Policies for Highway Construction and Maintenance*. Final Report for NCHRP Project 25-25, Task 4, National Cooperative Highways Research Program Transportation Research Board (Venner Consulting and Parsons Brinkerhoff 2004).

8.11.6 FishPass

The FishPass list-serve is a sponsored project of the Bioengineering Section of the American Fisheries Society with support from Oregon State University. FishPass is an un-moderated mailing list for professional discussion of the biological and engineering science of upstream and downstream fish passage. Areas of discussion include fish passage technologies, projects, swimming capabilities and behavior and biological and engineering studies and events.

Collections of previous discussion are available at
http://lists.oregonstate.edu/pipermail/fishpass/

Subscription details are available at
http://lists.oregonstate.edu/mailman/listinfo/fishpass

8.11.7 AASHTO Standards

Standards for Bridges, culverts, foundations and backfill can be found in "Standard Specifications for Highway Bridges, 17th edition" (AASHTO HB-17, AASHTO, 01-Sept, 2002)

8.12 INTRODUCTION TO EXISTING DESIGN METHODS

The design methods summarized in chapters 9, 10, and 11 represent the spectrum of techniques that are currently available to meet fish passage. Variability is in part due to the conditions under which criteria were developed, and applicability may be limited to specific geomorphic and hydraulic conditions. Careful attention should be paid to applicability and limitations, and engineering judgment is required.

Equations provided are based on the recommendations of design manuals for local situations. Designers should be familiar with the source, derivation, and limitations of these equations before using them. A review of method applicability was not conducted as part of the development of HEC-26, and engineering judgment must be used when applying state-of-practice technologies, remembering the importance of monitoring in the future refinement of these methods.

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9 GEOMORPHIC SIMULATION

As defined in Chapter 8, Geomorphic Simulation approaches are based on recreating or maintaining existing channel geometry. These design techniques attempt to mimic (or maintain) natural stream reach characteristics including slope, channel-bed width, bedform, and bed materials. The basis of these methods is the presumption that crossings matching natural conditions will readily pass fish that are moving in the natural channel.

The four examples of Geomorphic Simulation included in this chapter represent the spectrum of design techniques available. The USFS takes a stream reference reach approach, Washington State utilizes a specific set of general culvert width criteria, and Washington's No Slope and NMFS's Active Channel technique provide a simple and conservative design approach that is applicable in very limited situations. A summary of design approaches is included in Table 9.4 at the conclusion of this chapter.

Although maintaining stream continuity through the structure is the goal, these techniques are subject to the constraints of existing channel conditions including slope and available bed material. There may be very limited situations when an actual "Geomorphic Simulation" is achieved. The USFS and WDFW criteria for stream simulation provide equations that allow for adjustment for bed stability if the situation requires a Hydraulic Simulation be completed (Chapter 10).

9.1 U.S.F.S. STREAM SIMULATION – DRAFT MANUAL

Source
Bates et al 2006

Applicability
New and replacement installations
Passage required for all fish and aquatic organisms

Limitations
Slope of crossing resembles slope of natural channel or representative reach
Limited applicability in cohesive soils

The United States Forest Service recently produced a draft manual of their "Stream Simulation" design technique. This methodology utilizes a reference reach approach to understand bed material, channel morphology and structures found within the natural channel. A crossing structure is then designed to match reference reach characteristics. This ideally creates a crossing that is self-sustaining and free to adjust similarly to the natural channel.

This approach is simplest for new installations, where open bottom structures can be placed to span the stream channel, leaving natural bed material and bedforms in place. In replacement installations, past channel degradation may require a culvert to be steeper than the natural channel.

Although the following discussion summarizes design procedures, adequate understanding of channel processes and site characteristics is necessary to complete a viable fish passage culvert. The draft manual is quite comprehensive, but appropriate designs will require a skilled group of design professionals with breadth of knowledge covering engineering, hydrology, biology, and geomorphology. For further details refer to Bates et al 2006. Note - many criteria, such as slope, width, and applicability are largely left to the discretion of design professionals.

9.1.1 Basic Channel Design Procedure

1. Determine project alignment and profile
2. Verify reference reach
3. Design bed material and arrangement
4. Select structure size and elevation
5. Verify mobility / stability of simulated streambed

Table 9.1 depicts a number of design recommendations based on channel type. Channel types are based on Montgomery and Buffington (1997).

Table 9.1. Design Recommendations based on channel types (Bates et al. 2006).

REFERENCE CHANNEL TYPE	TYPICAL CONDITIONS					RECOMMENDED DESIGN STRATEGIES
	Bed Material	**Dominant roughness & structural elements**	**Slope**	**Entrenchment**	**Streambed mobility**	
Dune-ripple	Sand to medium gravel	Sinuosity, bedforms, banks. Small debris may provide structure	<0.1	Slight	Termed "live bed"; significant sediment transport at most flows	• Simulated bed can be native bed material or imported dense mix based just on D_{100} of reference reach. • Bands or clusters of material added to simulate diversity from wood. • Banklines designed to be immobile
Pool-riffle	Gravel, often armored	Bars, pools, grains, sinuosity, banks	0.1-2	Slight	Armored beds usually mobilize near bankfull	• Simulated bed D_{100}, D_{84}, D_{50} and D_{max} same as reference reach. • Material smaller than D_{50} is dense mix based on D_{50}. • Bands or clusters of material added for diversity. • Key features, banklines designed to be immobile.
Plane-bed	Gravel to cobble, usually armored	Grains, banks	1-3	Slight to entrenched	Near bankfull	• Simulated bed D_{100}, D_{84}, D_{50} and D_{max} same as reference reach. • Smaller material size distribution is dense mix based on D_{50}. • Key features, banklines designed to be immobile.
Step-pool	Cobble to boulder	Steps, pools, banks. Debris may add significant structure	3-10	Moderately entrenched to entrenched	Fine material moves over larger grains at frequent flows depending on size; often $>Q_{30}$	• Steps are spaced same as reference reach • Step-forming rocks are sized to be immobile. • Smaller material size distribution is dense mix based on D_{50} of material other than steps in reference reach • Banklines designed to be immobile.
Cascade	Boulder	Grains, banks	8-30	entrenched	Small bed material moves at moderate frequencies (floods higher than bankfull). Larger rocks are immobile in flows smaller than $\sim Q_{50}$	• Simulated bed D_{100}, D_{84}, D_{50} and D_{max} same as reference reach. • Smaller material size distribution is dense mix based on D_{50}. • Key features, banklines designed to be immobile.
Bedrock	Rock with sediment of various sizes in transport over rock surface	Bed and Banks	any	any	Bedload moves over bedrock at various flows depending on its size. May be thin layer of alluvium over bedrock. Wood can strongly affect sediment mobility.	• Stream simulation bed is bedrock. • Banklines and roughness elements are important but difficult to design as stable. • Condition, extent, and shape of bedrock are important. • Bottomless structure reduces rock removal compared to full pipe and can be anchored and shaped to rock.
Channels in cohesive material	Silt to Clay	Sinuosity, banks, bed irregularities	any	any	Fine sediment moves over immobile bed at moderate flows depending on its size. May be thin layer of alluvium over immobile bed.	• Stable cohesive bed and banks cannot be constructed in culvert. • Culvert walls may simulate smooth natural clay banks. • Bottomless structure might leave clay bed undisturbed.

9.1.2 Project Alignment and Profile

To ensure that the project layout is properly aligned with the eventual channel profile, a two-dimensional plan view, connecting the upstream and downstream channels, must be combined with a streambed profile, connecting vertically stable points upstream and downstream of the crossing. This will provide insight into channel degradation and eventual channel elevation.

9.1.3 Simulated Streambed Design

When natural bed material cannot be used, a well-graded mix of materials should be created to closely approximate the particle size distribution of the reference reach. The most important elements of a constructed bed are large particles to provide bed structure, and fines to limit bed permeability and bind the bed mix together. Analysis of bed material can be done through a sieve analysis, but is most commonly done through a pebble count.

When distribution is calculated by a pebble count, D_{100}, D_{84}, D_{50} of the reference reach are taken directly from the surface pebble count, and smaller grain sizes are determined through use of the Fuller Thompson equation (equation 9.1). This is based on D_{50}, and creates a simulated bed mix. (This application has not been field tested, and professional judgment is recommended).

Fuller-Thompson equation:

$$P=(d/D_{100})^{n}$$

Equation 9.1

Where:

- d = particle size of interest, mm
- P = percentage of the mixture smaller than d
- D_{100} = largest size material in the mix, mm
- n = parameter that determines how fine the resulting mix will be. A value of 0.5 produces a maximum density mix when particles are round

This equation can be rearranged to find any particle size, for example:

$$D_{16} = 0.32^{1/n}D_{50}$$

$$D_5 = 0.10^{1/n}D_{50}$$

The following procedure is included for designing a particle size distribution based on the Fuller-Thompson equation:

1. Use n values between 0.45 and 0.70 (standard range for high-density mixes)
2. Select an n value that results in 5-10 percent sand and finer materials. This material is very important for reducing permeability and locking larger pieces together.
3. If the resulting D_5 is larger than 2mm, adjust the mixture so that fines comprise 5 percent.
4. In cases where field estimates of fines are higher than 5-10%, the mixture can be adjusted to approximate field values.
5. Ensure that bed material specification is as well graded as the reference reach, without gaps in particle classes.

Figure 9.1 shows a representation of bed mix as compared to pebble count. The variability of bed gradation based on the selected n value allows the mix to be adjusted to meet permeability requirement.

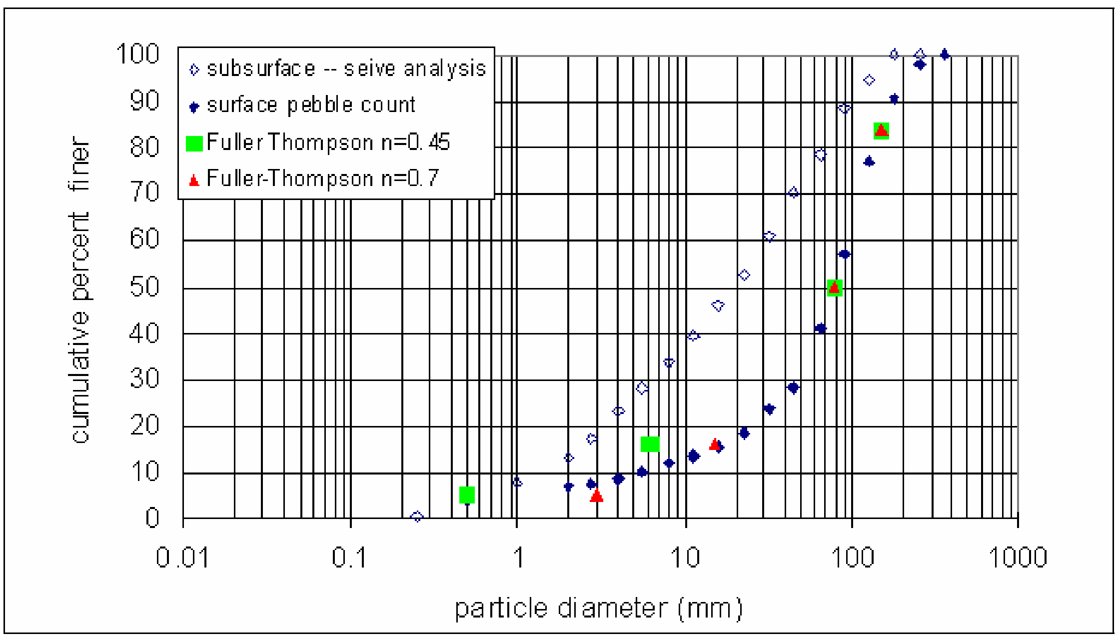

Figure 9.1. Surface and Subsurface Material Particle Size Distributions - South Fork Poudre River with Fuller-Thompson distributions. Field data from Kristin Bunte (figure from Bates et al. 2006)

Additional notes –

Washing fines into the bed surface with high-pressure water, or placing a veneer of washed gravel over the surface will mitigate the effects of fine sediments on downstream habitat quality.
Bed material should be at least as angular as local material to exhibit similar mobility. Rounded material may be more mobile than intended. Ideally, local

material can be used, increasing the likelihood that a constructed bed will represent the natural bed material.

When large wood controls or influences channel form in the reference reach, angular rock may be used to simulate structures and channel features.

9.1.3.1 Channel Width

Considerations of channel width will affect the culvert sizing and material selection. Channel width should consider channel entrenchment, key features and incision. In general, it is recommended that channel width be greater than or equal to:

1. Bankfull width of the reference reach, or
2. Four times the diameter of the largest particle in the simulated bed.

In situations where the channel is incising, culverts should be designed to accommodate anticipated widening or narrowing.

9.1.4 Bed Structure

At a minimum, a basic V-shaped low flow channel should be constructed within the culvert barrel (Figure 9.2), providing a continuous channel thalweg. Temporary bed structures can also be used to provide channel form until natural processes can shape the channel. Recommended structures include rock bands and clusters (to replicate the shape of dune-ripple and pool-riffle channels), marginal features to simulate the reference reach banklines and edge diversity, and key features to simulate specific structural features in the reference channel. Specific design of these features is included in the Stream Simulation Manual.

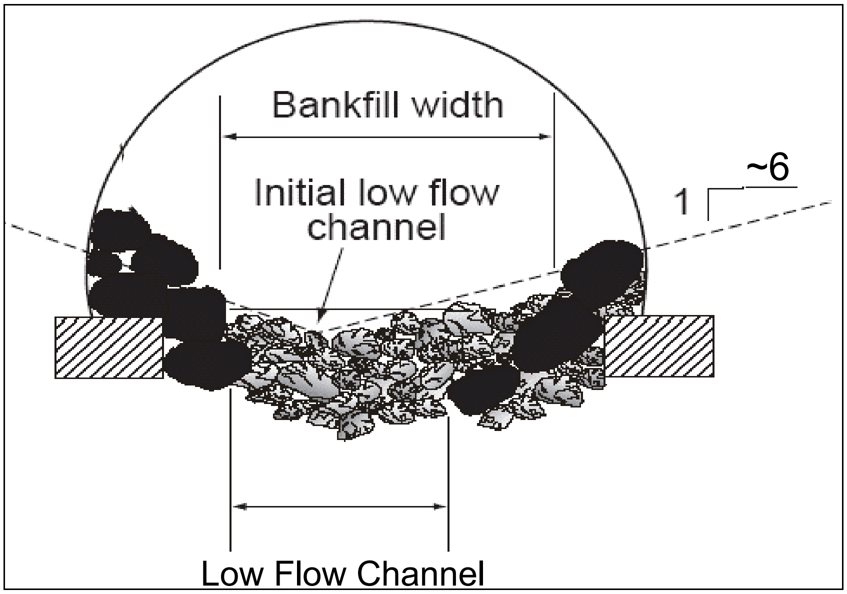

Figure 9.2. Low flow channel in an open bottom structure (Bates et al. 2006).

9.1.5 Crossing Structure Dimensions

Culvert Width - Culvert width is determined through a combination of bankfull width calculations and provisions for banklines and overbank surfaces. This should also incorporate channel width considerations. If banklines are desirable, an initial estimate of culvert width could be bankfull width plus 2 to 4 times the diameter of the largest mobile particle in the bed is suggested.

9.1.6 Bed Mobility and Stability Analysis

Checks can be made to ensure that bed material is mobile when channel material is mobile, and that banklines and key features remain stable at high design flows.

Typically, analysis is conducted on the particle size that provides structure (D_{84}). When this particle is mobile, most of the bed will also be mobile. The goal of this analysis is to ensure that the constructed channel will exhibit similar sediment transport characteristics to the reference reach channel. Flows typical of channel formation in the natural channel should be considered, ensuring that the constructed bed behaves similarly to the natural reach.

Bathurst's unit discharge equation, the modified Shield's equation, and U.S. Army Corps of Engineers riprap-sizing equation are recommended for this analysis. Designers should have a thorough understanding of the source, derivations, and limitations of these equations before use (Bates et al. 2006). Further discussion of these methods is included in the Stream Simulation Manual Appendix E, summarized below.

9.1.6.1 Modified Shield's Equation

Applicability
Riffles and plane-bed channels with channel-bed gradients less than 5%
Sand and gravel bed streams with low relative roughness (flow depth considerably greater than streambed particle size)
Poorly graded streambed (particles represent a narrow range of class sizes)

Limitations
D_{84} between 10 and 250 mm (2.5 to 10 inches)
Particle size of interest ≤ 20-30 times D_{50}.

The modified Shield's equation is used to determine particle stability based on critical shear stress. Particle stability is compromised when boundary shear stress in the channel is greater than a critical stress threshold. Boundary shear stress is calculated using equation 9.2.

$$\tau = \gamma RS$$

Equation 9.2

where:

- τ = average boundary shear stress, lb/ft^2
- γ= specific weight of water, lb/ft^2
- R= hydraulic radius, ft (Cross Sectional Area of Flow divided by Wetted Perimeter – calculated at design flow)
- S= slope, ft/ft

Once boundary shear stress has been calculated, a critical stress threshold is calculated using equation 9.3.

$$\tau_{ci} = \tau^*_{D_{50}} (\gamma_s - \gamma) D_i^{0.3} D_{50}^{0.7}$$

Equation 9.3

where:

- τ_{ci}= critical shear stress at which the sediment particle of interest begins to move (lb/ft^2)
- τ^*_{D50} = dimensionless Shields parameter for D_{50} particle size. This has been experimentally derived for a number of particle sizes (See Table 9.2).
- D_{50} = diameter (ft) of the median or 50th percentile particle size of the channel bed

D_i = diameter (ft) of the particle size of interest. (Typically D_{84} or D_{95} for stream simulation)

Table 9.2. Angle of repose, Shield's parameter and critical shear stress values for gravel-, cobble-, and boulder sized particles (Bates et al. 2006).

Particle size classification	Particle size, D_i (mm)	Angle of repose (Φ), f (degrees)	Shield's parameter [a], τ^*	Critical shear stress, τ_c (lb/ft^2)
very large boulders	> 2048	42	0.054	37.37
large boulders	1024-2048	42	0.054	18.68
medium boulders	512-1024	42	0.054	9.34
small boulders	256-512	42	0.054	4.67
large cobbles	128-256	42	0.054	2.34
small cobbles	64-128	41	0.052	1.13
very coarse gravels	32-64	40	0.05	0.54
coarse gravels	16-32	38	0.047	0.25
medium gravels	8-16	36	0.044	0.12
fine gravels	4-8	35	0.042	0.057
very fine gravels	2- 4	33	0.039	0.026

[a] equation used to determine Shield's parameter for gravel-, cobble-, and boulder-sized particles: $\tau^* = 0.06 \tan\Phi$

9.1.6.2 Critical Unit Discharge Approach

Applicability
Channels with gradients exceeding 10%
Flow depth is shallow with respect to channel-bed particle diameter (situations where discharge is much easier to determine than depth).

This approach is based on unit discharge, and a value of critical unit discharge will be compared to channel unit discharge to determine particle entrainment (particle lifting into flow).

Equation 9.4 is used to calculate channel unit discharge.

$$q = Q/w$$

Equation 9.4

where:

q= Unit discharge (ft^3/s/ft)
Q= Discharge (ft^3/s)
w= the width of the channel at a given cross section, defined by active channel width.

Equation 9.5 is used to predict the entrainment of the particle size of interest.

$$q_{c-D_{50}} = \frac{0.15 g^{0.5} {D_{50}}^{1.5}}{S^{1.12}}$$

Equation 9.5

where:

q_{c-D50}= the critical unit discharge to entrain the D_{50} particle size (ft^2/s)
D_{50} = the median or 50^{th} percentile particle size (ft)
g= gravitational acceleration (ft/s^2)
S= slope (ft/ft)

More generally,

$$q_{ci} = q_{cD50} \left(\frac{Di}{D_{50}} \right)^{b}$$

Equation 9.6

where:

q_{ci}= the critical unit discharge to entrain the particle size of interest (ft^2/s)
D_i= the particle size of interest
D_{50}= the median or 50^{th} percentile particle size (ft)
b= measure of the range of particle sizes that make up the channel bed. Quantifies the effects on particle entrainment of smaller particles being hidden and of larger particles being exposed to flow.

$$b = 1.5 \left[\frac{D_{84}}{D_{16}} \right]^{-1}$$

Equation 9.7

where:

D_{84}= the 84^{th} percentile particle size
D_{16}= the 16^{th} percentile particle size

Steps:

1. Equation 9.4 is used to calculate the unit discharge for bankfull flow
2. Equation 9.5 is used to find the critical unit discharge (q_{c-D50}) needed to entrain the D_{50} particle size at the given cross section.
3. Equation 9.7 is used to calculate the sorting of the channel bed (b).

4. Equation 9.6 is used to calculate the critical discharge (q_{ci}) needed to entrain the particle of interest at any given cross section.
5. Compare the critical unit discharge (q_{ci}) to the unit discharge (q) in the channel at the specified flow. If the unit discharge is less than the critical discharge the particle size of interest will not be entrained (particle will remain immobile). If unit discharge is greater than critical discharge the particle size of interest will be entrained.

9.1.6.3 Boundary Shear Threshold Analysis

Source
Williams 1983 (as discussed in Bates et al 2006)

Applicability
Williams equations indicate the upper and lower thresholds in boundary shear stress required to initialize movement of a given particle size.

Limitations
Equation 9.8 was developed from particles between 15 to 900mm (0.05 to 2.73ft).
Equation 9.9 was developed from particles between 10 to 3300mm (0.03 to 10ft)

$$\tau_{ci-u} = 0.0814 D_i$$

Equation 9.8

$$\tau_{ci-i} = 0.00355 D_i$$

Equation 9.9

where:

τ_{c-u} = is the upper critical shear stress value (lb/ft^2) for determining particle mobility and immobility for the particle size of interest.
τ_{c-l} = are the upper and lower critical shear stress values (lb/ft^2) for determining particle mobility and immobility for the particle size of interest, respectively.
D_i = is the particle size of interest (mm).

Steps:

1. Calculate the average boundary shear stress using equation 9.2 for the flow of interest (e.g. bankfull).
2. Using equations 9.8 and 9.9, calculate the upper and lower critical shear stress values for the particle size of interest at any given cross sections (e.g. D_{84}).

3. To determine if the particle will be immobile, mobile, or potentially mobile, compare the average boundary shear stress for a particular flow to the upper and lower critical shear stress values for the particle size of interest.

If the average shear stress (τ) is greater than the upper critical shear stress (τ_{c-u}), the particle will be mobile at this flow. If the average boundary shear stress (τ) is less than the lower critical shear stress (τ_{c-i}), then the particle will be immobile for these flow conditions. If the average boundary shear stress is between the upper and lower critical shear stress values, then the particle has potential to move at these flow conditions.

9.1.6.4 U.S. Army Corps of Engineers Riprap

Applicability
D_{84}/D_{15} ratio typically less than 3-7 in practice
Sizing immobile key pieces

Limitations
Considers angular rock (not specifically applicable to round rock)
Rock may move as smaller rocks surrounding key pieces move. Similar-sized rock should be used to support key pieces.

The U.S. Army Corps of Engineers has developed two riprap models for designing riprap bank protection. These were developed through laboratory and analytical work, and consider angular rock, which is resistant to sliding and rolling. Note that round rock may have to be significantly larger than angular rock to achieve similar levels of stability [Abt, 1988].

Manuals are available at http://www.usace.army.mil/publications/eng-manuals/em1110-2-1601.

9.2 WDFW STREAM SIMULATION

Source
Bates et al 2003

Applicability
New and replacement installations
Passage required for all species

Limitations
Stream grades ≤ 6%
Culvert slope does not exceed 125% of channel slope

In new installations, it is desirable to use open bottom structures placed at stream grade to allow natural bed material and form to remain undisturbed. In replacement installations, culvert slope should be within 125% of the upstream channel slope. In the case that natural bed material must be disturbed during construction, Washington's manual considers two design scenarios – outlined in section 9.2.1.

9.2.1 Design Procedure:

Washington State has developed a preliminary design process for stream simulation design based on local experience. Because of the relatively small amount of field experience, there is risk involved in its use, and this procedure should be applied conservatively.

9.2.1.1 Determine Site Suitability

- Sites less than 6% slope are considered within the scope of stream simulation in Washington. Higher slopes require special consideration.
- The ratio of culvert bed slope to channel slope (slope ratio) must be less than 1.25. Channel slope is generally taken as the upstream channel slope, but downstream slope can be used if it is representative of channel slope.
- The culvert itself should be placed as flat as possible to reduce shear stress between the culvert bottom and the bed material. Long installations will likely require the culvert to be placed with slope.
- Channel susceptibility to vertical changes should be assessed, and taken into account with culvert size and countersink elevation. Larger culverts will be required if material is likely to aggrade, and a lower countersink will be required in situations where channel degradation could undermine culvert stability.

9.2.1.2 Assessment of Adjacent Stream Reach

This step is not necessary for new installations, as natural bed form and material can be left undisturbed using an open-bottom structure. For replacement installations, a representative reach will be used to determine the proper bed sizing and culvert width. This reach is typically found upstream, with considerations of slope ratio mentioned above ($S_{culvert}/S_{channel} \leq 1.25$).

Two design scenarios are considered for these structures. The first scenario is applicable in low-gradient alluvial channels matching pool-riffle channel forms, or exhibiting the characteristics of Rosgen C, E or F-type channels. A second scenario applies in higher gradient streams with step-pool or cascade-type channels that are likely to be more stable - corresponding to Rosgen's stream classifications of A, B, F or G. In Washington, a somewhat arbitrary 4% threshold is used to divide these two methods.

9.2.1.3 Culvert Type and Size

Minimum bed width in any culvert should be determined by:

$$W_{culvert\ bed} = 1.2W_{ch} + 2 \text{ (in feet)}$$

Equation 9.10

where:

W_{ch} = the width of the bankfull channel, ft

Future channel widening (of an incised channel) should be taken into account. A full discussion of reasoning for this width criteria is included in the WDFW manual, and should be addressed before deviating from equation 9.10.

9.2.1.4 Culvert Bed Configuration

The decision to use a particular slope scenario (Figure 9.3 and 9.4) is based on channel assessment. Channel-bed composition should be described by a sample of the bed material or by a surface pebble count. In situations with large wood or roots dominate the reach, a representative reference reach (exhibiting similar slope and width) should be used as a design template.

The first design scenario, depicted in Figure 9.3, is utilized when slopes are less than 4% in the natural reach. Natural bed material is interspersed with bands of coarse material (1 to 2 times D_{100}) to control initial grade and cross-sectional shape. This provides a low flow channel desirable for fish passage, and addresses the likelihood of excessively slow channel formation in low-gradient streams with a large proportion of fine sediments. This also ensures that the channel thalweg forms towards the culvert center, reducing the probability of channel formation along culvert boundaries. In wider, low-gradient culverts, the low flow channel should meander.

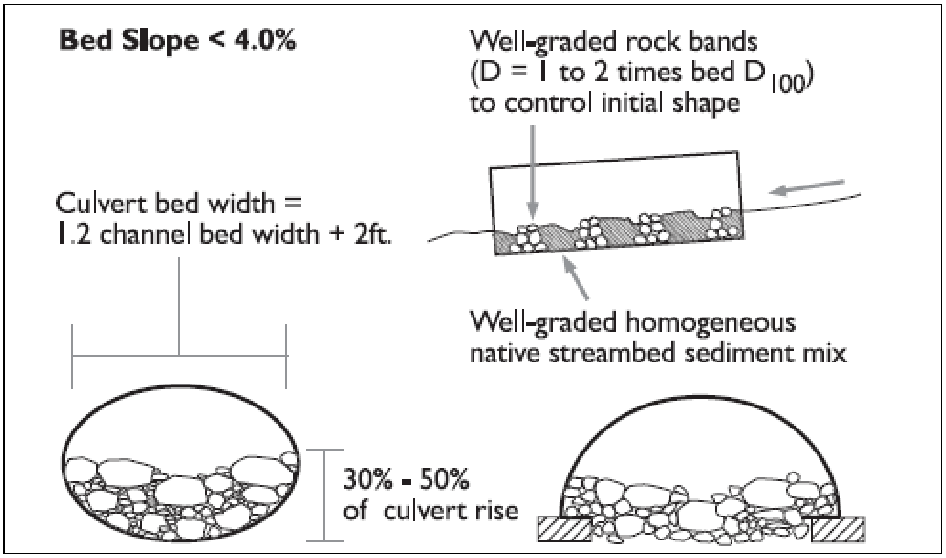

Figure 9.3. Washington Department of Fish and Wildlife Stream Simulation approach for low slope situations, where bed slope < 4.0%. Structure is filled with native streambed material and bands of well-graded rock to control initial shape of the culvert bed (Bates et al. 2003).

Spacing and Sizing of Rock Bands:

The distance between rock bands should be the lesser of five times channel width or the distance necessary to provide a drop between creates bands of less than or equal to 0.8ft. The first and last rock bands in the structure should be the greater than 2 channel widths, or 25 ft (whichever is less) from the culvert inlet and outlet.

For slopes greater than 4%, native or engineered bed material is used without bed-control structures. Coarser sediment found in streams is assumed adequate to control bed stability and create paths for fish passage. Figure 9.4 depicts this culvert configuration.

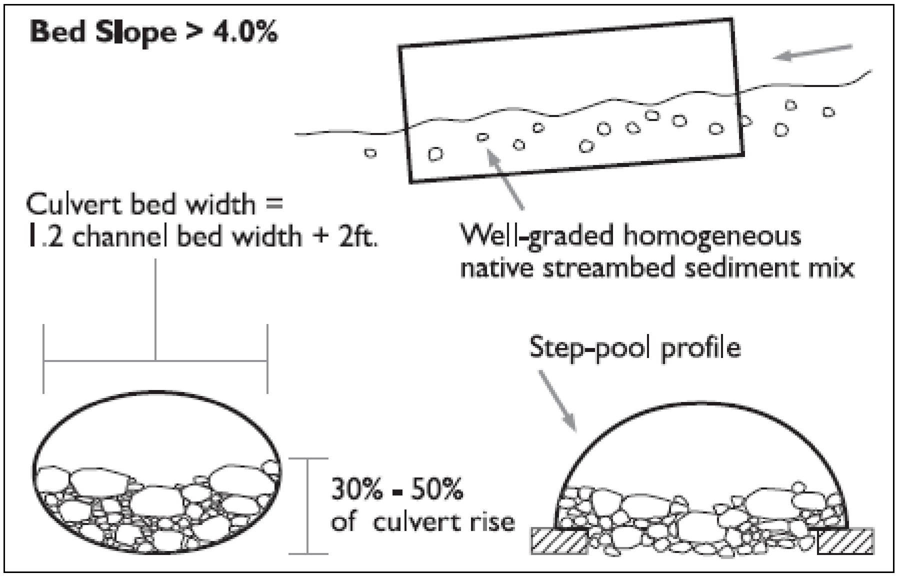

Figure 9.4. Washington Department of Fish and Wildlife High-Slope Stream Simulation Approach. Width and embedment criteria remain the same, but bed material consists of native sediment mix (Bates et al. 2003).

9.2.1.5 Culvert-Bed Design

Bed mix requirements vary with slope considerations:

- When culvert bed slope matches natural channel slope, sediment supplied to the structure will allow the bed in the culvert to rebuild after large flood events. Appropriately sized culverts will have bed material matching that found in the natural channel.

- When the slope ratio approaches the limits of stream simulation (1.25), coarse bed material required to maintain the slope will not be recruited, and finer materials will be lost over time. In this situation, a number of approaches are described below to aid in bed stability design. When stability requires bed material to be greatly oversized, it will no longer look or respond like the natural channel, and the resulting design may be more appropriately classified as Hydraulic Simulation.

9.2.1.5.1 Reference Reach Approach

Maximum particle size and appropriate sediment size distribution can be determined by examining reaches directly upstream from the culvert, or nearby reaches with similar characteristics to the design channel (e.g. unit discharge, slope, geometry and relative stability).

9.2.1.5.2 Unit-Discharge Bed Design

J.C. Bathurst developed the following equation to predict the size of D_{84} particles that would be on the threshold of motion for a given critical discharge in high gradient streams with heterogeneous beds (1987).

$$D_{84} = 3.45S^{0.747}(1.25q_c)^{2/3}/g^{1/3}$$

Equation 9.11

where:

D_{84} = Intermediate axis of the 84th percentile particle in the sediment distribution (ft)
S = energy slope of the proposed channel.
q_c= the critical unit discharge (total design discharge divided by the width of the bankfull channel) at which incipient motion of D_{84} occurs (ft^3/s)
g = The acceleration due to gravity (ft/s^2).

This is recommended as a starting point for development of sediment mixes in high gradient streams. Two design categories are recommended based on slope.

1. If channel slope is less than 4%, bed-changing flows may vary greatly. J.E. Costa's paleohydraulic analysis (described below) may be used to determine the magnitude of the bed changing flow for a given particle size.
2. If channel slope is greater than 4%, 100-year flood is used for design flow. This will closely predict the same size particle as that found in natural channels with similar Q_{100} and W_{ch}. This is the goal of stream simulation

These methods generally agree, but should both be checked. These are mobile or nearly mobile particles at these flows. If it is advisable to create a bed that is more stable, particle sizes should be increased. If bed slope approaches or exceeds 1.25 times the natural reach slope, it may not be possible to simulate stream conditions, and a Hydraulic Simulation design approach such as Roughened Channel may be considered.

9.2.1.5.3 Bed Design by Paleohydraulic Analysis

Paleohydraulic analysis uses the maximum particle size and flood depth to determine the discharge of flash floods. An equation developed by Costa (1983) to understand velocity based on particle size is useful in substrate sizing for stream channel design.

For determining depth, velocity (ft/s) is given by:

$$V = 9.57(D_{84})^{0.487}$$

Equation 9.12

where:
D_{84}= is arrived at by an iterative procedure (ft)

Steps:
1. D_{84} is assumed, allowing velocity to be calculated by equation 9.12
2. Divide design flow by velocity to get cross sectional area of flow
3. Find depth from proposed channel cross section
4. Use Table 9.3 to find the associated particle size.
5. When the resulting particle size agrees with the initial estimate, the particle design is considered suitable for design.

Table 9.3. Prediction of water depth for a given maximum particle size that has been moved. Data has been converted to English Units; some values are log-interpolated (Bates et al. 2003).

Slope ->	0.005	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
Particle Size, ft	**Depth, ft**										
0.2	1.2	0.9	0.6	0.5	0.5	0.4	0.4	0.4	0.4	0.4	0.4
0.5	3	2.1	1.5	1.3	1.2	1	1	0.9	0.9	0.9	0.8
1	6	4.1	2.9	2.5	2.2	1.9	1.8	1.8	1.7	1.6	1.5
1.5	8.8	5.9	4.1	3.6	3.1	2.7	2.6	2.5	2.4	2.2	2.1
2	11.3	7.4	5.2	4.5	3.9	3.4	3.2	3.1	2.9	2.8	2.7
2.5	13.6	8.9	6.2	5.4	4.7	4.1	3.9	3.7	3.5	3.3	3.2
3	15.6	10.2	7.1	6.1	5.3	4.6	4.4	4.2	4	3.8	3.6
3.5	17.6	11.4	7.9	6.9	6	5.2	4.9	4.7	4.5	4.3	4.1
4	19.5	12.6	8.7	7.5	6.6	5.7	5.4	5.2	4.9	4.7	4.5
4.5	21.3	13.7	9.4	8.2	7.2	6.2	5.9	5.7	5.4	5.1	4.9
8.1	36.4	23.1	15.6	13.5	11.7	10.1	9.6	9.1	8.6	8.2	7.8
10.5	45.6	28.9	19.4	16.7	14.4	12.5	11.8	11.2	10.6	10	9.5

At higher slopes, the Costa equation predicts smaller particle sizes than the Bathurst equation, all other conditions being equal (Bates et al. 2003).

9.2.1.6 Bed-Material Gradation and Specification

Once the largest material (D_{84}) has been sized, the rest of the bed mixture should well graded to minimize permeability. If material is imported, a synthetic streambed mix should be used. Relations for gradation are given as a starting point, and may be refined according to the availability of materials. Typical relations for gradation include:

$D_{84}/D_{100} = 0.4$
$D_{84}/D_{50} = 2.5$
$D_{84}/D_{16} = 8.0$

Note – When ratios indicate impractical sizing, the adjacent channel should be looked at for guidance. For example, a D_{84} of 1.8 ft requires a D_{100} of 4.5 ft that is likely not represented in the natural channel (Bates et al. 2003).
Gradations are not overly restrictive so as to be practical and economical.
Bed material comprised entirely of fractured rock is inappropriate for stream simulation, as jagged edges will interlock and dissuade appropriate migration of channel bed material.

9.2.2 Bed Retention Sills

Although WDFW does not consider this a desirable option, the application of bed retention sills can be considered (as a last resort) to hold bed material within the culvert. These sills can be steel or concrete placed at the bottom of the culvert to hold bed material within the barrel.

If desired, the crest of bed-retention sills should be V-shaped with a 10:1 slope laterally. These are placed at 20 percent of the culvert diameter below the streambed as constructed in the culvert. The maximum drop between sills should not exceed 0.8 ft, ensuring that each sill backwaters the next in the case that the bed material is scoured out.

9.3 NO-SLOPE DESIGN

Source
Bates et al 2003

Limitations
Stream reach slope <3%
Culvert length <100 ft, or product of slope times length < 0.2D
Embedment requirements can be met

Applicability
New and replacement installations
Passage required for all species

The No-Slope design specifies a culvert that is installed flat, and sized sufficiently large to allow natural movement of bed material and the formation of a stable bed within the barrel. This method avoids the need for detailed survey information or fish passage hydrology.

9.3.1 Design Considerations

Channel Slope – Natural stream channel slope should not exceed 3%. For replacement installations, future channel elevation and slope should be predicted using unaffected stream reaches both up and downstream.
Culvert Width - Structure width is 1.25 times channel bed width† (minimum 6 ft). WDFW recommends that this be taken as the average of at least 3 typical cross sections (Bates et al. 2003). Pipe, pipe-arch, and elliptical culverts are applicable for this design. Round culverts have the advantage of providing additional vertical clearance for a given width.
Embedment - The bottom of the culvert is buried no less than 20% and no greater than 40% of the culvert height. If bottomless structures are used, footings are designed for the largest anticipated scour depth, and the culvert should be placed so as not to disturb the natural bed.
Culvert Length – Due to embedment requirements, the product of slope times length must be less than or equal to 20% of the culvert diameter. In general, installations should not exceed 100 ft in length.
Culvert Slope - Culvert is laid flat within the stream reach.

† Washington uses bankfull-width as a design standard.

9.3.2 Additional Considerations

Evaluation of upstream headcut potential and impacts should be completed.

9.3.3 Design Procedure

No detailed design procedure is provided by the guidelines, but this method is intended for simple design situations, avoiding detailed survey information or high and low fish passage flow data. The No-Slope design option, depicted in Figure 9.5.

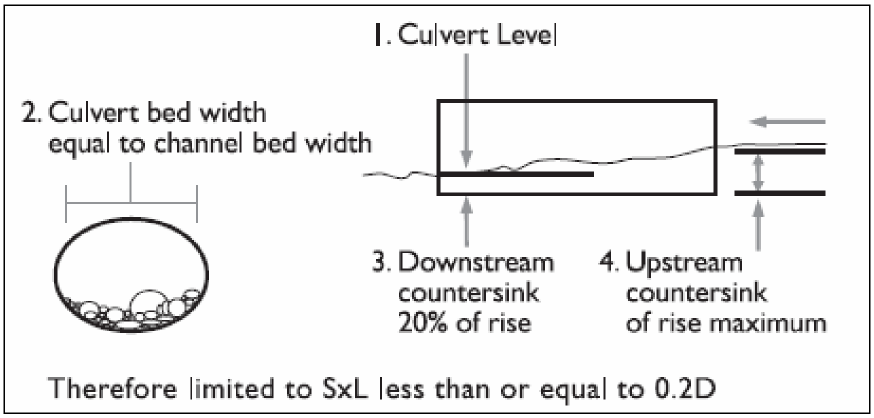

Figure 9.5. WDFW No-Slope Option (Bates et al. 2003).

9.4 ACTIVE CHANNEL

Source
National Marine Fisheries Service Southwest Region 2001

Aside from width requirements, NMFS's Active channel design is almost identical to WDFW's No-Slope design. In Washington's guidelines, the culvert width must exceed 1.25 times channel bankfull width, while NMFS recommends 1.5 times active channel width. California guidelines suggest that the active channel is generally less than bankfull width (Taylor and Love 2003). Entrenched streams in Washington may show little variation between active channel and bankfull widths (Bates et al. 2003). Discrepancies in regional manifestation of bankfull and active channel indicators likely lead to a similarly sized structure, although it would be conservative to take the larger of bankfull and active channel width.

Table 9.4 provides a summary of Geomorphic Design Techniques.

Table 9.4. Comparison of Geomorphic Design Techniques

Criteria	USFS	Washington	Washington	NMFS
	Stream Simulation	**Stream Simulation**	**No Slope**	**Active Channel**
Culvert Width	Bankfull, or bankfull + 4 times diameter of largest mobile particle (depending on desire for bank margins)	≥1.2 times Bankfull + 2ft	≥1.25 times Bankfull	1.5 Active Channel Width (Bankfull)
Culvert Slope	When channel degradation requires slopes greater than natural channel, find representative reference reach or consider channel restoration.	Slope ratio ≤1.25 Culvert may be installed flat or at grade.	Culvert Placed at 0% Slope	Culvert placed at 0% Slope.
	No slope limitations provided.	Gradients up to 6% recommended. Installations as high as 10% have been completed.	Suitable for streams ≤3% slope	Suitable for streams ≤3% slope
Bed Material	A Reference reach, representative of ~average stream conditions is template for design of crossing.	<4% slope, natural bed material with bands of coarse material (D = 1 to 2 times D_{100}). Culvert embedded 30-50% rise.	Culvert is buried into the streambed ≥20% of culvert height at outlet, <40% at inlet	Culvert is buried into the streambed ≥20% of culvert height at outlet, <40% at inlet
	Simulate the natural substrate found in the stream.	≥4% slope, native or engineered material without bed control structures. Culvert embedded 30-50% rise.	Uses natural substrate	Natural substrate is used
Bank Considerations	Designer can increase culvert width if bank margins are desired.	Culvert is wide enough to allow some bank margins to form.		
Culvert Shape		All types of culverts (box, round, concrete, CMP) have been used. Open bottom structures are desirable because they allow natural substrate to be maintained.		
Hydrology Required	Design Flood for culvert stability	Design Flood for culvert stability	Design Flood for culvert stability	Design Flood for culvert stability
Geomorphic Elements	Constructed bedforms match those found in reference reach. Low flow channel constructed in replacement installations.		Low flow channel constructed in replacement installations.	
Length			Slope times Length less than or equal to 0.2D.	Not suitable for lengths >100ft due to embedment requirements.
Reference	Bates et al, 2006	Bates et al, 2003	Bates et al, 2003	NMFS, 2001

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10 HYDRAULIC SIMULATION

As defined in Chapter 8, Hydraulic Simulation techniques utilize embedded structures, natural or synthetic bed mixes, and roughness elements to create hydraulic conditions conducive to fish passage. Structure design is optimized to provide and sustain existing substrate. These techniques represent the middle-ground between Geomorphic Simulation, which precisely matches natural channel geomorphology, and Hydraulic Design, which sizes a culvert for specific fish species. Table 10.3 (end of chapter) provides a summary of Hydraulic Simulation techniques.

10.1 OREGON DEPARTMENT OF FISH AND WILDLIFE STREAM SIMULATION

Source
Oregon Department of Fish and Wildlife (Robison et al. 1999)

Limitations
Moderate gradients: 1.5 – 8%
Stream width ≤ 15 ft
Valley fill must be adequate to allow adequate countersinking

Applicability
New and replacement installation
Fish passage required for all species

10.1.1 Watershed Information

Channel slopes must be between 1.5-8%. Bridges are suggested if stream width is greater than about 15 ft. Valley fill should be adequate for sinking the culvert into the streambed. The barrel should be sunk more than 20% of the culvert rise, or 18 inches for pipe arches and box culverts, and a minimum of 40% of the diameter (or 2 ft) for round culverts.

10.1.2 Culvert Sizing

The culvert width should match that of the channel bed width (defined as active channel width). Multiple measurements should be made above and below the culvert, as well as areas outside the influence of the culvert installation. This width should represent stream reach conditions prior to the impacts of the existing structure. Table 10.1 aids in the selection of appropriate structure so that the span or diameter matches that of the stream channel. For pipe-arch culverts not covered in Table 10.1, approximations of culvert area can be found using Equation 10.1.

$$\text{Area (ft}^2\text{)} = \text{Rise (inches)} * \text{Span (inches)} * 0.005472$$

Equation 10.1

Table 10.1. Flow capacity for non embedded circular and pipe-arch culverts (Robison et al. 1999). If culvert embedment is considered, oversizing is completed as detailed below.

CICULAR CULVERTS			PIPE ARCH CULVERTS		
Diameter (inches)	Cross Sectional Flow Area Culvert (ft^2)	MAX FLOW in Culvert (cfs)	SPAN times RISE (feet and/or inches)	Cross Sectional Area Culvert (ft^2)	MAX FLOW in Culvert (cfs)
15	1.2	3.5	22 in x 13 in	1.6	4.5
18	1.8	5	25 in x 16 in	2.2	7
21	2.4	8	29 in x 18 in	2.9	10
24	3.1	11	36 in x 22 in	4.3	16
27	4	15	43 in x 27 in	6.4	26
30	4.9	20	50 in x 31 in	8.5	37
33	5.9	25	58 in x 36 in	11.4	55
36	7.1	31	65 in x 40 in	14.2	70
42	9.6	46	72 in x 44 in	17.3	90
48	12.6	64	6 ft 1 in x 4 ft 7 in	22	130
54	15.9	87	7 ft 0 in x 5 ft 1 in	28	170
60	19.6	113	8 ft 2 in x 5 ft 9 in	38	240
66	23.8	145	9 ft 6 in x 6 ft 5 in	48	340
72	28.3	178	11 ft 5 in x 7 ft 3 in	63	470
78	33.2	219	12 ft 10 in x 8 ft 4 in	85	650
84	38.5	262	15 ft 4 in x 9 ft 3 in	107	930
90	44.2	313			
96	50.3	367			
102	56.7	427			
108	63.6	491			
114	70.9	556			
120	78.5	645			
132	95	840			
144	113.1	100			

Countersink -Appropriate countersink depth should be created according to the following criteria:

(a) Circular culverts: 0.4 times diameter or 2 ft, whichever is greater
(b) Pipe-arch culverts: 0.2 times rise or 18 inches, whichever is greater
(c) Box culverts: 0.2 times width, or 18 inches, whichever is greater

For channel slopes 0-4% the outlet and inlet inverts are sunk at the same depth

For channel slopes 4-8%: Use circular and pipe-arches only. Countersink the outlet according to the above criteria (a and b). Determine the outlet invert elevation relative to some datum, and determine the depth to countersink the inlet using Equation 10.2.

Elevation inlet invert = (culvert length)*[(channel slope-1.5%)/100] + elevation outlet invert. Note - use the inlet countersunk values in calculating the effective cross sectional area.

Equation 10.2

Effective Cross Sectional Area (ECSA) - Calculate "effective cross sectional area" and the flow capacity of the culvert using equation 10.3 and Table 10.2.

ECSA = [Culvert cross sectional area for chosen culvert]*[% loss in cross sectional area/100].

Equation 10.3

Table 10.2. Comparison of percent of culvert diameter or rise with baffles or embedding and corresponding cross-sectional area loss for the culvert (Robison et al. 1999).

Percent of rise or diameter with baffle or embedding inside culvert	Percent loss in cross sectional area	
	Round culvert	Pipe arch culvert
10	5	8
15	9	14
20	14	20
25	20	26
30	25	33
35	31	39
40	37	45
45	44	51
50	50	57
55	56	63
60	63	69
65	69	74
70	75	79

Flow capacity is determined by comparing the cross-sectional area to the corresponding maximum flow in the culvert on Table 10.1. It may be necessary to interpolate to find cross-sectional areas for odd-sized culverts.

Culvert Capacity – Culvert capacity must also be checked to ensure that it passes the 50-yr flood in order meet Oregon Department of Transportation standards for culverts.

Consideration of channel impacts - Hydraulic controls may be required to:

- improve structure entrance and exit conditions (beveled inlet configuration; providing resting pools at entrance and exit, etc…)
- concentrate low flows

- prevent erosion of the streambed and banks
- allow passage of bedload material. This provision is designed with ODFW consultation.

10.1.3 Bed Material Specification

The following bed mix is recommended based on local experience:

> 30% fines (silt; intended to seal the voids to avoid sub-surface flow)
> 30% small rock (0.5-6 inches)
> 30% large rock (6 inches - D_{100})
> 10% shadow rock (D_{100} - D_{200}, intended to simulate undercut banks, large wood and boulders, and to remain stable during flood events)

D_{100} is the diameter of the largest rock found naturally in the stream. D_{150}-D_{200} is 50-100% larger than the largest rock found naturally in the stream. Shadow rocks are placed to protrude 30-50% above the final streambed elevation. Large rocks, small rocks, and fines should be mixed before placing, and the final surface should be washed into interstitial spaces to ensure a good seal.

10.2 MAINE

Source
Maine Department of Transportation 2005

Bed Material - Eliminate hanging outlets where practical, and allow installation to fill with natural material. Allow streambed characteristics to be maintained as much as practical.
Culvert Material – Use corrugated elliptical pipe arches with largest feasible corrugations to maximize roughness.
Culvert Slope – Culvert slope is not to exceed natural gradient.
Culvert Embedment –

a. When culvert diameter is less than 48 inches the culvert should be embedded 6 inches into the stream bottom.
b. When culvert diameter is greater than 48 inches the embedment should be embedded 12 inches into stream bottom

Culvert Width – Culvert capacity is checked using Q_{50}, and the culvert should match natural stream depth and width at $Q_{1.5}$.
Two Pipe Installations (designed only by hydraulic engineer)

Design one pipe as above
Design a second pipe to pass flood flow

Fish Passage Check - Check flow depth during species-specific periods of movement
Capacity Check - Check 100-year flood

10.3 ALASKA DF&G AND DOT STREAM SIMULATION

Source
Alaska Department of Fish and Game and Alaska Department of Transportation 2001

Limitations
Natural channel slope ≤ 6%
Culvert slope is within 1% of the natural channel slope
Stable channels

Applicability
New and replacement installations
Passage required for all fish species present

When the following criteria have been met, fish passage is assumed to be adequate without further hydraulic calculations. This design methodology has worked well in Alaska, and fish have been observed successfully passing structures that have been in place (Mark Miles, Personal Communication). A memorandum of agreement between ADOT and ADF&G ensures that permitting goes quickly, and structures are designed to be smaller than Geomorphic Simulation, resulting in smaller initial cost.

Design Procedure

Although no specific design procedure is provided, fish passage is assumed when the following criteria are met.

- Stream gradient less than or equal to 6%
- Culvert width greater than or equal to 0.9 Ordinary High Water stage
- Culvert slope is within 1% of the natural channel slope (i.e. 4% channel slope, 3% - 5% culvert slope)
- Bed material is sized to be stable up to and including the 50-yr flood. (possibly requiring sediment retention baffles)
- Circular culverts should be buried at least 40% of the culvert diameter, while pipe arches must be buried 20% of the culvert rise.

Note - In situations where the channel slope is less that 1%, culverts may be installed at slopes less than 0.5%, with a span of at least 0.75 times Ordinary High Water stage.

10.4 BROWNING ET AL. 1990

Limitations
Slope ≤2-5% (see discussion below)
Stable Stream Systems

Applicability
New and Replacement
Passage required for all species

In a 1990 survey of culverts in Oregon had the primary goals of determining which type of culvert had the best fish passage, and if current design practices would have determined these culvert as providing that passage. It was also hoped that results would resolve current disagreements surrounding fish passage requirements. This study included collection of field data and hydrologic and hydraulic analysis of each of the sites. A comparison was made between culvert velocities and velocities present in the natural channel during the 2-yr and 50-yr flood events.

Adult salmon passage was a main concern at many sites, although trout were included as important species in many cases (Browning 1990). Study sites were largely located in stable stream systems that had reached dynamic equilibrium (Browning, M., Personal Communication). Based on the results of this survey, Browning recommends a design procedure that utilizes Hydraulic Simulation to create a fish passable structure.

This method is unique in that it does not require determination of channel bed width. Channel bed width is difficult to measure consistently, and boundary roughness in slightly constricted culvert installations may actually aid in slowing velocities during fish movement (Browning, M., Personal Communication).

10.4.1 Design Procedure

Culvert Width Headwater to depth ratio at the 50-yr flood should not exceed 1.0. This is intended to ensure that that culvert does not excessively constrict the stream reach.
Bed Slope – Although no specific limitations are given for slope applicability, recommendations were based on installations on grades of 1-2%, with limited sites approaching 5%.
Embedment - Culverts less than 10 ft diameter are buried a minimum of 0.5 to 1.0 ft below the natural stream slope. Culverts with diameters less than 10 ft are buried a minimum of 1/5th the culvert rise. In situations where system wide degradation is possible, the installation may require lowering to match the anticipated stream surface lowering.

Barrel Velocity – Barrel velocity remains within 25% of the natural stream velocity during discharges less than the 2-yr flood.
Outlet Scour - Outlet scour depth of less than 0.5 ft during 2-yr event.
Bed Material - Bed material should be similar to the natural stream reach placed to match stream reach conditions. Cohesive soils should be replaced with fine gravels since cohesion will likely be disrupted during installation. To keep flows from going subsurface, placement of a non-permeable barrier between the culvert bed materials and foundation materials can be considered. Over time, fines will wash into the voids to seal interstitial space, and more recent procedures recommend washing fines and silts into the streambed to seal voids (Bates et al. 2003).
Culvert Slope - The culvert barrel should be placed on as flat a slope as possible. (in general less than 2%). Culverts placed on a slope greater than 2% may require consideration of bed retention baffles.
Roughness – In situations where the installer cannot match velocity and scour conditions, small boulders can be included in the bed mix to increase roughness, and reduce downstream scour. These should be embedded, and not protrude more than 12 inches.
Capacity - Culvert headwater to rise ratio is not to exceed 1.0 (i.e. during 100-yr event).

10.4.2 Barrel Velocity and Depth

When stream gauges were not available at sites, U.S.G.S. regression equations were used to determine 2 and 50-yr flows for hydraulic analysis. Manning's equation was used to compute velocities in a typical section of the stream and compared to culvert cross section. Stream channels were approximated by using topographic data of the stream site to create a representative trapezoidal cross section. Slope was based on typical slopes in the vicinity of the culvert and a roughness value (n) is based on local streambed materials. For the study, Manning's "n" values were taken from:

Chow, V. T. (1959). "*Open-Channel Hydraulics*." McGraw-Hill Book Company, Inc, York, PA.

Barrel velocity calculations should be done for a number of flows, ideally covering the range of flows at which fish are moving. This includes analysis of depth and velocity in the culvert and natural channel at each discharge.

10.4.3 Outlet Scour

Outlet scour should be limited to 0.5 ft during the 2-yr event. Analysis was conducted based on the method in "Hydraulic Engineering Circular No. 14" (Thompson et al. 1983), with specific methods depending on the bed-material present. It is recommended that outlet scour potential be computed at each of the discharges used for velocity analyses.

If it is determined that outlet scour is likely to be a problem, boulders can be placed just downstream of the culvert outlet to reduce stream energy and potential scour depth. It should be noted that improperly placed structures could also pose a barrier to fish passage (see section on Rip Rap 8.7.1.1).

10.5 MARYLAND

Source
Maryland 2005

Maryland culvert design incorporates the use of a main channel culvert to maintain stream characteristics during bankfull flow, with floodplain culverts to handle overbank flows when practicable. Rather than creating "standard" design methods, Maryland addresses considerations surrounding the culvert design process.

10.5.1 Design Procedure:

Determine Bankfull Flow – When available, gauging station records should be used to estimate bankfull flow. Bankfull width should also be verified with field observations. In the absence of gauging records, flood-frequency plots can be used to estimate bankfull discharge corresponding to a return period between one and two years.
Design of Main Channel Culvert – A main-channel culvert should accommodate bankfull flow with minimum change in the hydraulic characteristics of unit discharge, width, depth, and velocity. When applicable, bankfull flow should be accommodated in a single pipe (up to 16 ft span) or a single box culvert cell (up to 20 ft).

> **Two Cell Installations** – When two culverts are required, box culverts are suggested to minimize the distance between spans. "W" weirs may be included upstream of a multiple cell installation to reduce bar deposition and scour, increase competence of bed material transport and reduce debris accumulation at the center wall.
> **Depress Culvert –** Culverts should be depressed a minimum of 20% below the existing channel bed, and allowed to fill naturally with bed material. In two culvert installations, the stream is expected to form a natural thalweg in one of the cells to accommodate low flows -minimizing fish passage problems.
> **Adjust Slope, Type, Roughness, and Dimensions –**
> Determine a composite "n" value based on bankfull flow, streambed materials, and culvert material above the streambed. Use HEC-RAS to run water surface profiles while attempting to match continuity of bankfull flow widths, depths, and velocities through the culvert. Plot bankfull depths in channel and adjust culvert invert elevations to maintain selected depression.
> **Main Channel Culvert Outlet** – minimize impacts to the downstream channel and stabilize flow conditions for fish passage. When bankfull flow velocities are significantly higher in the culvert than in the channel, or the

channel bed may be swept out, modifications such as baffles or downstream grade control structures may be considered.
Upstream Transition – The upstream transition section should be designed to achieve continuity of flow and maintain sediment transport characteristics of velocity and shear - avoiding deposition and scouring. This transition is likely less important for stable stream systems such Rosgen type B, C, and E, but may be very important for A, D, DA, F or G channels. Special considerations are covered in more detail in Maryland's design manual. When Right of Way is an issue, culvert width should be sized to match depth and velocity.

10.5.2 Floodplain Culverts

Floodplain culverts can be added in situations where a single culvert would overly constrict flow, and lead to effects on downstream morphology. Floodplain culverts can be installed to collect and convey flood plain flows, reducing the impact of the main channel culvert. This may exclude situations where the culvert is on a small ephemeral stream, short culvert installations, locations where fish passage is not required, crossings on streams will small floodplains that convey little flow and crossings where a larger main channel crossing is desirable for debris passage.

Floodplain culverts should be positioned on the floodplain, well beyond the influence of the main culvert. This will avoid channel undermining, degradation or migration into the area of the floodplain culvert. It will also avoid clogging due to debris carried in the main channel.

10.5.3 Culvert Sizing

Sizing should be done by a trial and error solution using HEC-RAS and HY8 to aid in the iterative design process. HY8 is used to select efficient culvert sizes, with downstream tailwater elevations taken from the water surface (HEC-RAS) hydraulic model. Results of culvert selections should be reviewed to ensure that they are reasonable.

10.5.4 Culvert Silting

Maryland addresses culvert silting but design guidelines were not available for this document.

10.6 ROUGHENED CHANNEL DESIGN

Source
Washington Department of Fish and Wildlife (Bates et al. 2003)

Applicability
Over steeped channel sections (as in replacement installations with past channel degradation)
Slopes up to 10% (according to design charts)
Passage required for target species
Limited work area or right-of-way

Limitations
Washington State still considers the Hydraulic Simulation "Roughened Channel" an experimental technology requiring more research and monitoring to be a viable design option.
Velocity and turbulence checks are required to ensure that they do not exceed fish thresholds.
This technique requires special design expertise, hydrology, and survey information.

Overview
The 2003 Washington Department of Fish and Wildlife fish passage guidelines include criteria for the creation of a roughened channel, either within or upstream of a culvert. Oversized substrate is designed for stability during the 100-year flood, allowing installation on over-steepened channel sections and moderate to high slopes. Roughness elements control depth and velocity, providing passage conditions adequate for the targeted fish species. Average cross sectional velocity and turbulence are checked against species-specific allowable value.

Culverts designed using this technique are reported to have mixed results in Washington, and are considered experimental at this time, requiring special design expertise, hydrology and survey information (Bates et al. 2003).

10.6.1 Design Procedure:

Roughened channel design consists of the following steps:

1. **Culvert Width** - Assume a culvert span, beginning with bankfull width. Considerations of debris and sediment transport, habitat, and passage requirements of non-target species should be included. According to WDFW, culvert width should be at least the width of the natural stream channel.
2. **Bed Material Stability** - Size the bed material for stability based on unit discharge for the 100-yr event (Q_{100}), as outlined in Step 3.

3. **Bed Material Size Check** -Check to see that the largest bed-particle size, as determined by stability, is less than one quarter the culvert span. If not, increase the culvert width, which decreases the unit discharge and, in turn, the particle size.
4. **Bed Material Gradation** - Create a bed-material gradation to control porosity (see WDFW Stream Simulation Design)
5. **Check Turbulence and Velocity** - Calculate the average velocity and EDF at the fish-passage design flow on the basis of culvert width and the bed D_{84} from gradation in Step 4 above. If the velocity or EDF exceed the criteria, increase the culvert span.
6. **Culvert Capacity** - Check culvert capacity for extreme flood capacity (i.e. 100-yr event).

Note - As gradient and unit discharge increase, WDFW recommends an increase in culvert width as the best way to achieve stability and passability, while reducing the risk of scour and extreme hydraulic conditions.

Steps 2-3 can be completed using a variety of recommended methods/equations. Included are The U.S. Army Corps of Engineers Riprap Design, the Critical-Shear Stress Method.

There also exist a number of alternatives for sizing bed material, including those covered in WDFW section on Stream Simulation Design (Section 9.2).

10.6.2 Bed Stability

For roughened channel design, bed material should remain in the culvert as placed. Bed material may shift slightly, but should not move an appreciable distance or leave the culvert. For this reason, bed material stability should be calculated before consideration of fish passage velocity. Unlike Stream Simulation design, roughened channels increase hydraulic forces due to increased slope. WDFW considered four methods for sizing bed material for stability (Bates et al 2003), two of which are discussed below.

10.6.2.1 U.S. Army Corps of Engineers Riprap Design

For slopes from 2-20%

$$D_{30} = \frac{1.95S^{0.555}(1.25q)^{2/3}}{g^{1/3}}$$

Equation 10.4

where:

D_{30}= dimension of the intermediate axis of the 30th percentile particle, ft

S= the bed slope, ft
q= the unit discharge, $ft^3/s/ft$
g= acceleration due to gravity, ft/s^2

1.25 is a safety factor that may be increased, and designers are cautioned against using this method for rock sizes greater than 6 inches.

The U.S. Army Corp of Engineers recommends angular rock with a uniform gradation (D_{85}/D_{15} = 2). This is not preferred for fish passage situations due to porosity issues. An approximate factor for scaling D_{30} of a uniform riprap gradation to one that is appropriate for stream channels is 1.5, so that:

$$D_{84} = 1.5 D_{30}$$

Equation 10.5

where:

D_{84} = dimension of the intermediate axis of the 84^{th} percentile particle, ft

10.6.2.2 Critical Shear Stress Method

Critical shear stress methods are used to estimate the initial movement of particles. Particles movement occurs when the maximum shear stress, $\tau_{0max,}$ within the channel exceeds a calculated critical shear stress, τ_c. Critical shear stress is the shear stress required to cause movement of a given particle size (see 9.1.6.1 and 9.1.6.3). The maximum shear stress is 1.5 times γRS, where γ is the unit weight of water, R is the hydraulic radius, and S is the slope. Data used to derive these equations are largely from low-gradient situations, although design charts show slopes up to 10 percent and particle sizes up to 1.9ft (Bates et al. 2003).

10.6.3 Fish Passage Velocity

Three equations are used to find roughness and velocity in order to calculate fish passage velocity. The three equations were derived from data in natural streams and account for roughness characteristics of natural channels. Constructed channels must be designed in such a way to maximize channel roughness and emulate natural channel planform and profile, otherwise the following equations will likely overpredict roughness and lead to an ineffective approximation of constructed channel velocities.

In general the relationship between velocity and roughness is given by:

$$V/(gRS_f)^{1/2} = 1.486R^{1/6}/ng^{1/2} = (8/f)^{1/2}$$

Equation 10.6

where:

- V = the average velocity, ft/s
- g = the acceleration due to gravity, ft/s^2
- R = the hydraulic radius, ft
- n = dimensionless Manning's roughness factor
- f = dimensionless Darcy-Weisbach friction factor
- S_f = the friction slope of the channel

The use of *n* or *f* depends upon convention, but the Darcy-Weisbach equation accounts for the reduction in roughness with increasing depth, whereas Manning's equation does not (Bates et al. 2003).

10.6.3.1 Limerinos equation

Source
Limerinos 1970 (as discussed in Bates et al. 2003)

Applicability:
Experience shows a more accurate prediction in higher-velocity situations

Limitations:
Equation is based on data where $0.9<R/D_{84}<6.9$ and $0.02<n<0.107$
The error range for $n/R^{1/6}$ is +42.9 percent to -33.7 percent

$$n = \frac{0.0926R^{1/6}}{1.16 + 2\log(R/D_{84})}$$

Equation 10.7

where:

D_{84} = the dimension of the intermediate axis of the 84th percentile particle, ft

10.6.3.2 Jarrett's equation.

Source
Jarrett 1984 (as discussed in Bates et al. 2003)

Applicability
Average velocity is less than 3 ft/sec
Based on data where slope is between 0.2% and 4%
May be applicable up to an 8.25% slope where $0.4<R/D_{84}<11$ and $0.03<n<0.142$

Limitations
Error range of *n* on the test data is wide, +44 percent to +123 percent
It is implied that, as slope increases, sediment size increases and so does roughness.

$$n = .32S_f^{0.38}R^{-0.16}$$

Equation 10.8

where:

S_f = the friction slope of the channel
R = hydraulic radius of the channel, m

10.6.3.3 Mussetter's equation

Source
Mussetter 1989 (as discussed in Bates et al. 2003)

Applicability
Derived from data in Colorado mountain streams, with sediment distributions similar to those recommended by WDFW guidelines.
Fish passage velocity calculations

Limitations
Derived from data where slope is between 0.54% and 16.8%, $0.25<R/D_{84}<3.72$, and $0.001<f<7.06$ ($0.036<n<4.2$)
Error range is between +3.8% to +12%
Accuracy decreases when velocity is greater than 3 ft/s

$$(8/f)^{1/2} = 1.11(y/D_{84})^{0.46} (D_{84}/D_{50})^{-0.85} S_f^{-0.39}$$

Equation 10.9

where:

y is the mean depth, ft

10.6.4 Turbulence Check

Washington State quantifies the impact of turbulence through the calculation of an energy dissipation factor (EDF), see Equation 3.1 for the EDF equation. For roughened channels, the EDF must be less than 7.0. This is based on experience in Washington, and will be modified with future research and evaluations (Bates et al. 2003).

10.6.5 Fish Rocks and Bed Retention Sills

In practice, installation of roughened channels has included bed retention sills and engineered substrate filling the culvert to 30% of the rise. Large boulders are then added to provide shadow as a safety factor for fish passage. The sills act to keep bed material in place. Further field experience is expected to eliminate the need for these structures (Bates et al. 2003).

A downstream control structure should be constructed to ensure that the lowest point of the bed elevation at the culvert outlet matches the elevation of a downstream control point. The control structure can be a stable natural feature or a permanent constructed control placed no closer than 20 ft from the culvert outlet. This protects against the creation of an outlet drop by ensuring that sills do not become exposed.

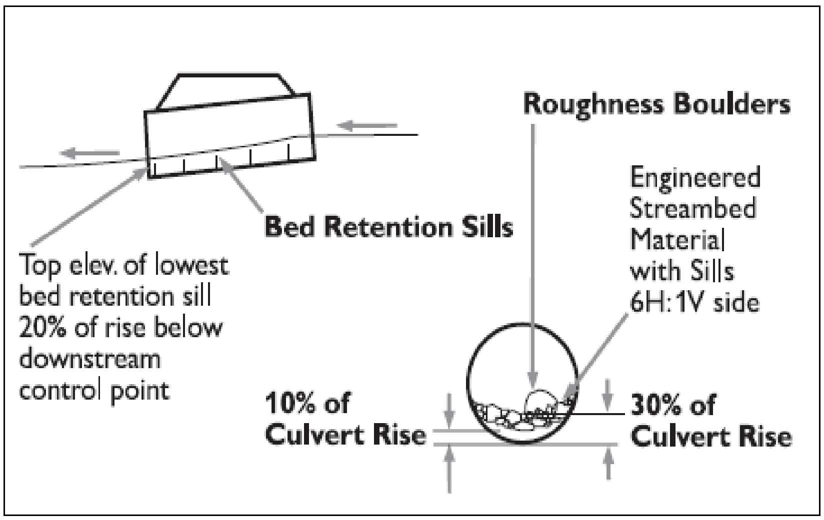

Figure 10.1. Roughened-channel culverts using fish rocks and bed-retention sills (Bates et al. 2003).

Bed Retention Sills – Bed retention sills are typically made of the same material as the culvert, and are attached directly to the culvert.
Bed Material – In low gradient situations, bed material creates the primary source of roughness, and is included to act as a factor of safety. In high gradient situations, the specified bed material may contain elements that will act as boulders.
Fish Rocks/Boulders – Rocks should be no greater than one quarter the culvert span to prevent overly constricting the flow. Boulders are embedded one third of their diameter (measured along the intermediate axis).
Depth of Flow – The water depth at the fish passage design flow should be less than or equal to two thirds of the exposed height of the boulders. The combination of these constraints should lead to a boulder diameter that is roughly twice the depth of water.

Table 10.3. Comparison of Hydraulic Simulation design techniques.

Criteria	Maine Hydraulic Geometry Matching	Alaska Stream Simulation	Browning WFLHD Recommendation	Maryland Culvert Design Procedure	Washington Roughened Channel
Width	Match pipe and stream flow geometry. Flow depth and width at 1.5-yr event.	≥90% Bankfull (OHW), for culverts on slopes up to 6%	Culvert inlet should not excessively constrict the stream	Match stable bankfull width of the upstream approach channel	Start with Bankfull width and iterate
	No inlet constriction at the range of design flows. If constricted, in-culvert weirs can control water level.	≥75% Bankfull (OHW) is allowed for culverts on slopes <1%, installed at slopes ≤0.5%		Single culvert for main channel flows, Floodplain culverts for floodplain flows.	
Slope	Place culvert at 0% slope, or as close as possible	Gradients up to 6%	Culvert placed as flat as possible, generally <2%		Applicable at high slopes and situations where inlet contraction will cause scour
Substrate	Embed pipe 6 inches if pipe D<48 inches, 12 inches if D>48in	Sized to be stable up to and including the 50-year design flood.	Similar to natural channel substrate, placed to match natural reach conditions.	Allow culvert to fill with natural substrate	Stable up to and including the 100 year flood event. Largest particles are less than 25% culvert span.
	Allow embedded pipe to fill with natural substrate.	Gravel retention baffles may be used. They should be 0.5 times the culvert invert burial depth.	Culvert <10ft diameter buried min 12-24 inches below natural stream slope	Culvert Depressed 1 to 2 ft.	Bed retention sills may be placed at 10% culvert height. Downstream control point ensures that sills are not exposed.
			Culvert >10ft diameter buried min 1/5 culvert rise below natural stream slope.	Transition section may be required between upstream channel and culvert. Riprap may be needed.	Fines must be used to control porosity.
			(cohesive soils replaced with fine gravels)		Culvert embedment of 30% -circular, 20% bottomless.
Hydrology Required	50 yr (L<10 ft) or 10-yr (L>10 ft) flood for culvert stability. Flow during periods of fish passage.	50-yr Flood for substrate stability	Headwater to Rise Ratio not to exceed 1.0 during design event (I.e. 50-yr)	1.5-yr to 500-yr flood frequency plot for crossing site.	Design Flood for culvert stability, Fish passage flows for velocity and turbulence check.
Hydraulic Considerations	Depth, velocity, and turbulence during fish passage flows.		Barrel velocity is within 25% of the natural stream velocity during discharges less than the 2-yr flood.	W - weirs suggested upstream of 2-cell box culvert installations.	Check velocity within the culvert to ensure that it is adequate for fish passage. Check Turbulence (EDF)
Geomorphic Elements			Small boulders included to increase roughness and reduce downstream scour		Large Boulders can be included to increase diversity. Stable low-flow path must be provided.
Reference	Maine DOT 2004	ADOT & ADF&G MOA, 2001	Browning 1990	Maryland 2004	WDFW 2003

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11 HYDRAULIC DESIGN

Hydraulic Design creates water depths and velocities that meet the swimming abilities of target fish populations during period of fish movement. General considerations include the effect of culvert slope, size, material and length. Hydraulic Design can include adding baffles to a culvert, adding sediment or sediment catching devices inside the culvert, backwater through crossing by installing downstream weirs, or modification of the culvert inlet or inlet approach to remove a constriction (Robison et al. 1999). Figure 11.1, from Robison et al, depicts the general flow of hydraulically designed structures (1999).

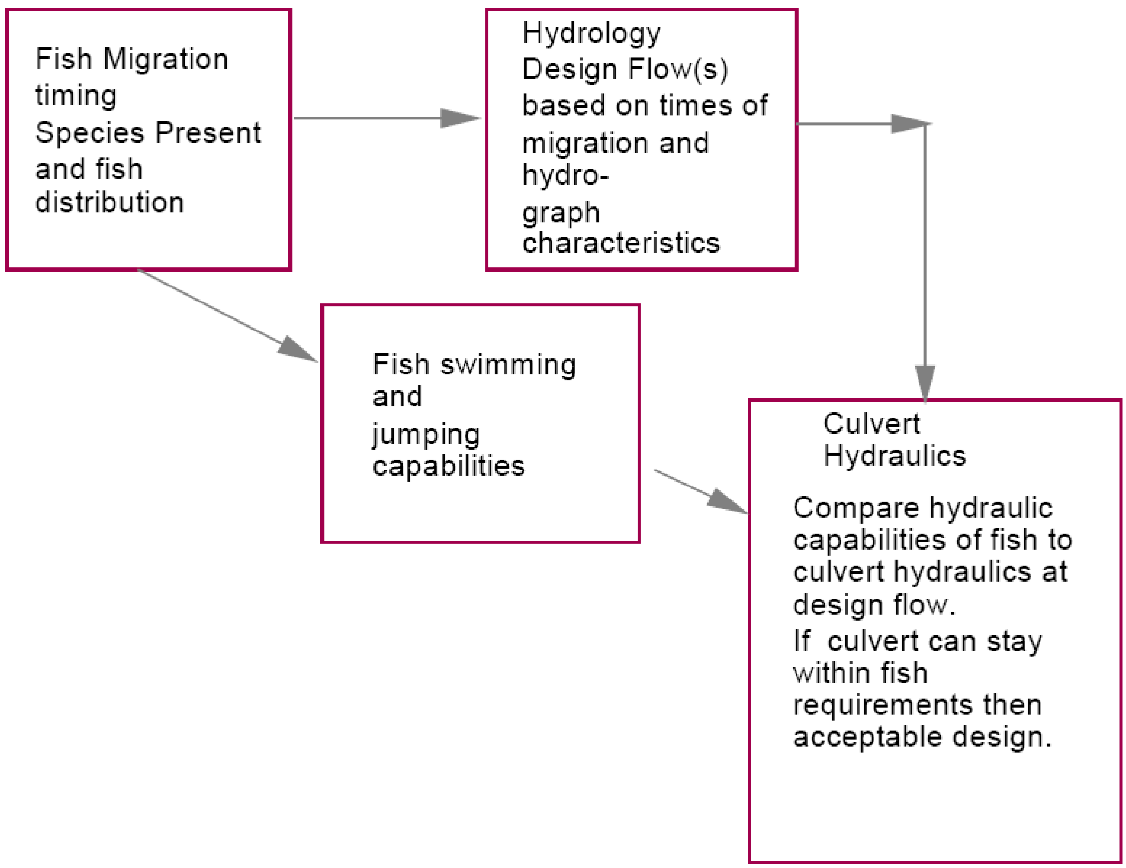

Figure 11.1. Steps in Hydraulic Design (Robison et al. 1999).

11.1 WEIRS VS. BAFFLES

Weirs act as small dams which controlling water depth within a culvert, while still passing the necessary design flow. Multiple weirs can create a series of drops and pools, allowing fish passage through a steeper structure (Zrinji and Bender 1995). A series of baffles work together to increase the hydraulic roughness of a culvert, thereby reducing the cross sectional velocity (Bates et al. 2003).

11.2 GENERAL HYDRAULIC DESIGN

The Washington Department of Fish and Wildlife (WDFW) provides a general design procedure for Hydraulic Design that will be described below (Bates et al. 2003). Additional weir/baffle configurations and culvert methodologies are included to expand upon the WDFW method. A generalized installation is show in Figure 11.2.

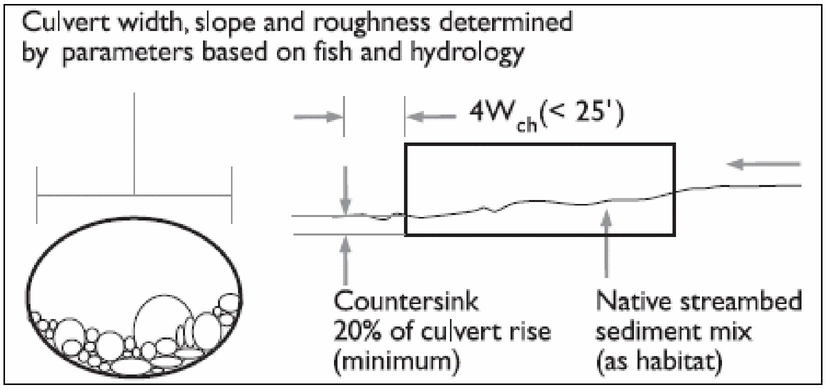

Figure 11.2. Hydraulic Design Option (Bates et al. 2003).

Applicability
New and Replacement Installations (when other options are precluded)
Retrofit
Fish passage required for target species

Limitations
Requires knowledge of fish movement timing and swim speeds
Requires additional monitoring due to propensity for roughness elements to catch debris
The addition of baffles will decrease culvert capacity (especially important in retrofit situations).

11.2.1 Design Procedure

1. **Length of Culvert -** Find the length of culvert based on geometry of the road fill
2. **Fish Passage Requirements** - Determine the target species, sizes and swimming capabilities of fish requiring passage. Use this to determine allowable barrel depth and velocity.
3. **Hydrology** - Determine fish passage design flows at which the fish-passage criteria must be satisfied.
4. **Velocity and Depth** - Determine size, shape, roughness and slope of the culvert to satisfy velocity criteria, assuming open channel flow and a bare culvert bottom. Verify that the flow is subcritical through the range of fish passage flows.

Velocity and depth requirements can be met through a number of alternative including baffles or channel modifications, weirs, sediment catching devices, or roughened channels.

5. **Channel-Backwater Depth** - Determine backwater elevation at the culvert outlet for fish passage at both low and high fish passage design flows.
6. **Culvert Elevation** - Set the culvert so that channel backwater elevations are at least as high as the water surface in the culvert.
7. **Flood Flow Capacity** - Verify that the flood-flow capacity of the culvert is adequate.
8. **Channel Profile** - If necessary, adjust the upstream and/or downstream channel profiles to match the culvert elevation. Channel modifications (as discussed in chapter 8) may be appropriate to control backwater elevation.

Several iterations of steps 4 through 8 may be required to achieve the optimum design.

Acceptable velocity and depth are determined through appropriate selection of culvert size, material and slope. Many types of analysis are acceptable, but the simplest is Manning's equation:

$$Q = \frac{1.49 A S^{1/2} R^{2/3}}{n} = VA$$

Equation 11.1

where:

Q = Channel discharge, ft^3/s
S = Channel slope, ft/ft
R = Hydraulic radius (cross-sectional area/wetted perimeter), ft
A = Cross-sectional area, ft^2
V = Average channel velocity, ft/s
n = Manning's "*n*" (channel roughness coefficient)

11.2.2 Channel Backwater

The downstream culvert invert elevation at the outlet is determined by matching the water-surface profile at the culvert outlet to the backwater elevation of the downstream channel. Downstream water surface elevation can be determined by observation of the water surface at flows near fish passage design flow, or by calculating the water surface profile in a uniform flow condition. This may require several iterations, and modifications may be required to establish the culvert slope and roughness to match the profile to the downstream channel backwater.

Backwatering may also be accomplished by using structures to raise and steepen the channel to an appropriate elevation.

11.2.3 Calculated Backwater

Channel backwater can be calculated using a open-channel flow calculation such as Manning's equation. WDFW recommends that this be calibrated with at least one high water-surface observation or high water mark (Bates et al. 2003). Selection of the appropriate Manning's *n* is very significant because it affects calculated water depths. The '*n*' value depends on a number of variables including surface roughness, vegetation, channel irregularities, channel alignment, scour and deposition, obstructions, the size and shape of the channel, stage and discharge, suspended material, and bedload. Methods for combining these variables are included in

Chow, V. T. (1959). "*Open-Channel Hydraulics*." McGraw-Hill Book Company, Inc, York, PA.

In situations where the project will affect the downstream channel, either as part of the design, or as the channel evolves after installation, the new channel slope, roughness and cross-sectional shape should be used for backwater calculations.

11.3 BAFFLE CONFIGURATIONS

Baffles are intended to create allowable velocities during fish passage flows, while not exceeding fish turbulence thresholds. Baffles devide the culvert into a series of cells and bays, creating resting areas between the baffles, and points of high velocity at the baffles (Ead et al. 2002). Fish are assumed to use their prolonged swimming speed along lower velocity areas and in between baffles, and use their burst speed to navigate around baffles (Rajaratnam et al. 1991).

Some of the most comprehensive baffle information available comes from a number of studies completed at the University of Alberta at Edmonton, Canada. The hydraulics of six fishway baffle configurations were analyzed, resulting in a series of five papers completed by Rajaratnam et al (Rajaratnam et al. 1988; Rajaratnam et al. 1989; Rajaratnam and Katopodis 1990; Rajaratnam et al. 1990; Rajaratnam et al. 1991). Figure 11.3 depicts tested baffles including offset baffles, slotted weir baffles, weir baffles, spoiler baffles, Alberta fishweirs, and Alberta fishbaffles.

Tests were conducted on slopes from 0.5-5% covering baffle heights (h/D), where h is baffle height and D is culvert diameter, of 0.1 – 0.15, and baffle spacing up to 1.2 culvert diameters. Spacing wider than one culvert diameter was found to decrease velocity while increasing depth (Ead et al. 2002). Culvert material in the majority of these tests was smooth, with the exception of tests conducted on the Alberta fishweir and Ablerta fishbaffle, when corrugated pipe was used.

From the baffle systems analyzed, weir and slotted weir baffles are recommended based on effectiveness and simplicity (Ead et al. 2002). Figure 11.4 shows the general layout of these two alternatives.

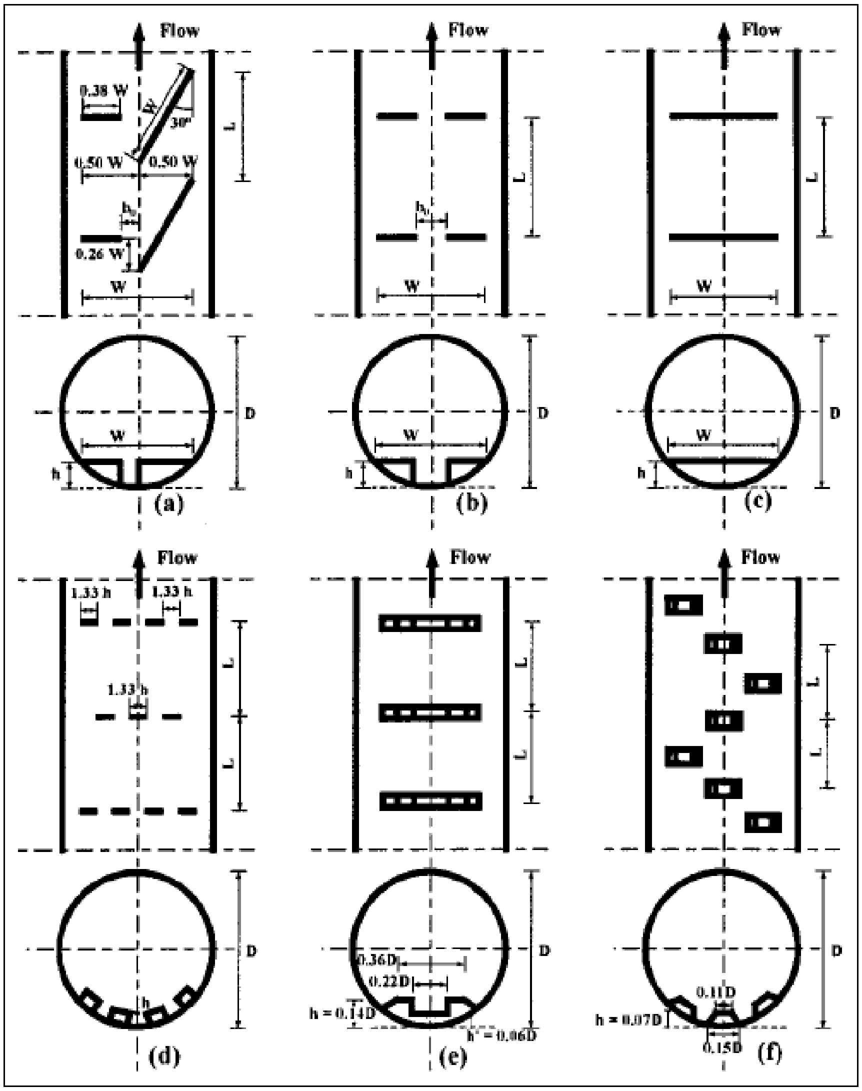

Figure 11.3 (a) Offset baffle; (b) slotted weir baffle; (c) weir baffle (d) spoiler baffle; (e) Alberta fishweir; and (f) Alberta fishbaffle (Ead et al. 2002).

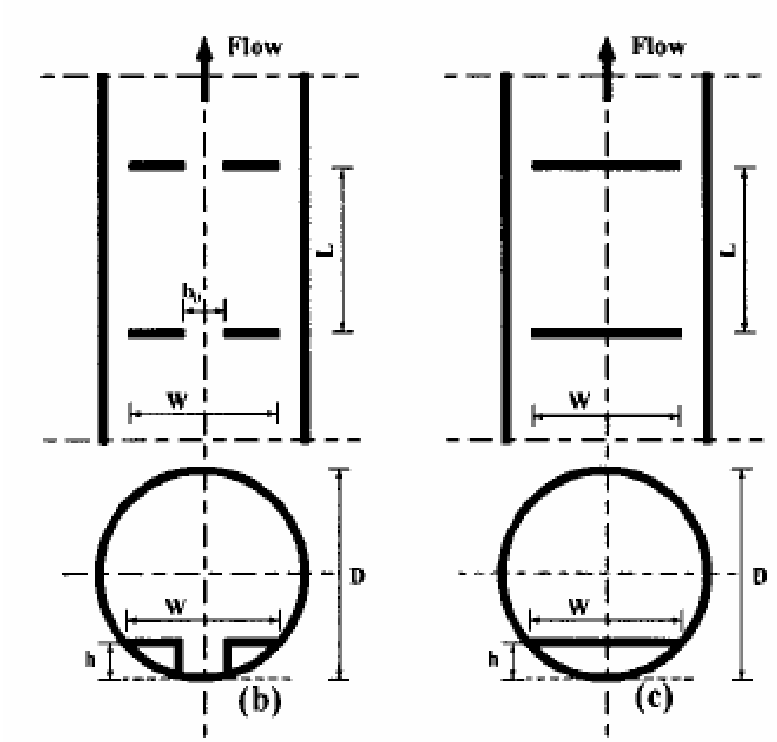

Figure 11.4. Culvert options (b) slotted weir and (c) weir baffle configurations. These are recommended for installation in fish passage situations due to simplicity and effectiveness (adapted from Ead et al. 2002).

Design techniques may be found in the Introduction to Fishway Design (Katopodis 1992).

11.3.1 WDFW Baffles

Washington Department of Fish and Wildlife has three recommended baffle configurations - two for circular culverts, and one for box culverts (Bates et al. 2003). In each case, notches are aligned to allow an uninterrupted line of fish passage along one or both sides. The continuously sloped baffle configuration in box culverts is generally used for juvenile fish passage in culverts 6 ft wide or less. Corner baffles are recommended for use on slopes between 1 and 2.5%, with notched baffles being used between 2.5-3.5%. Direct observation of baffle systems have lead to the recommendation that they not be used on slopes greater than 3.5%, with steeper slopes requiring stream simulation or fishway design (Bates et al. 2003).

To avoid inlet contraction that can lead to reduced culvert capacity, the upstream baffle should be placed at least one culvert diameter downstream of the inlet, and be high enough to ensure subcritical flow at the high design flow. It is also recommended that the designer use a mitered end or wing walls to improve hydraulic efficiency.

11.3.2 Baffles in Round Culverts

Velocity is calculated by the flow equations developed by Rajaratnam and Katapodis (Rajaratnam et al. 1989; Rajaratnam and Katopodis 1990). Washington utilizes sloping baffles, and although weir baffles from the studies were horizontal, they provide the most reliable information for predicting roughness of baffles. Data within these papers were simplified to create Equation 11.2 and Table 11.1, aiding in WDFW's baffle design procedure.

$$Q = C(y_0/D)^a(gS_0D^5)^{1/2}$$

Equation 11.2

where:

C	=non-dimensional coefficient that depends on baffle configuration
D	=diameter of the culvert, ft
a	=exponent depending on baffle configuration
Q	=discharge, ft^3/s
y_0	=depth of water, ft
g	=gravitational acceleration ft/s^2
S_0	=non-dimensional slope
Z_0	=height of the baffle (as depicted in Figure 11.5)

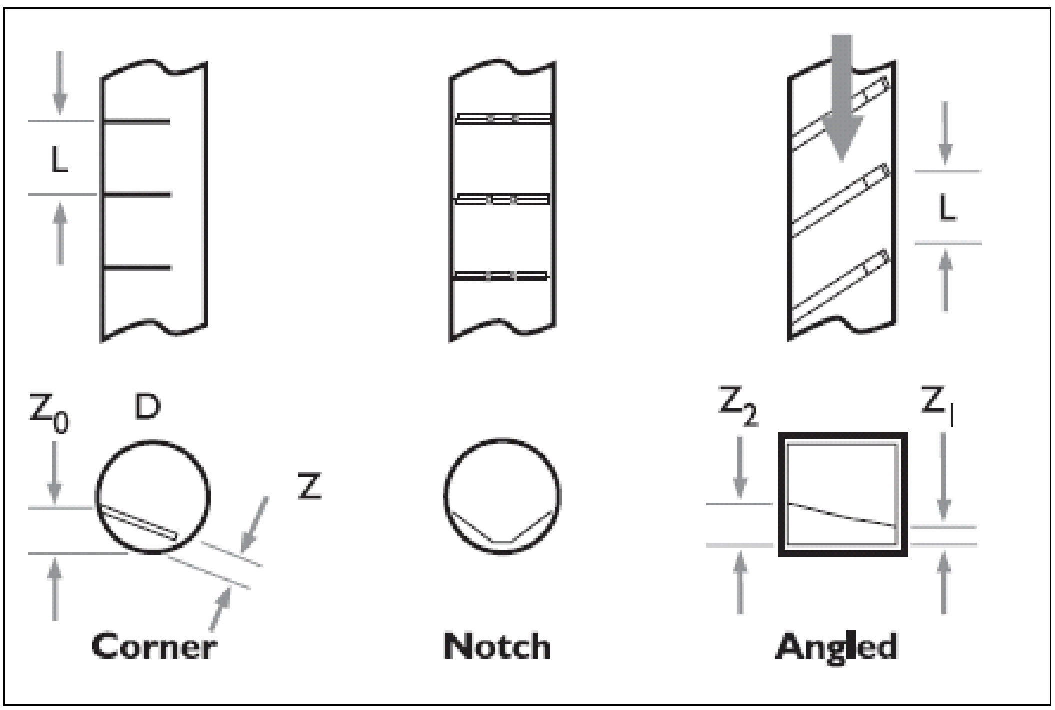

Figure 11.5. Recommended styles of baffles for round and box culverts in Washington (Bates et al. 2003).

Table 11.1. Baffle hydraulics (Bates et al. 2003). Limits shown are the limits of experimental data or valid correlation for the coefficients and exponents.

	Z_o	L	C	a	Limits
WB-2	0.15D	0.6D	5.4	2.43	0.25 y0/D < 0.8
WB-1	0.15D	1.2D	6.6	2.62	0.35 y0/D < 0.8
	0.15D	2.4D	8.5	3.0	
WB-3	0.10D	0.6D	8.6	2.53	0.35 y0/D < 0.8
WB-4	0.10D	1.2D	9.0	2.36	0.20 y0/D < 0.8
	0.10D	2.4D	9.6	2.5	

Equation 11.2 should be used to calculate the depth of flow, allowing velocity to be found by dividing the flow by the resulting cross sectional area.

11.3.3 Box Culverts

The hydraulics of baffles in box culverts are described by Shoemaker (1956). This study utilized the Darcy-Weisbach friction equation as a hypothetical model for culverts with baffles (Equation 11.3).

$$HW = (K_e + C_e + fL_c/D)V^2/2g+P-S_0L_c$$

Equation 11.3

where:

- f =dimensionless friction coefficient
- L_c =length of the culvert, ft
- D =the diameter of the pipe (four times the hydraulic radius of noncircular pipes), ft
- $V^2/2g$ =the gross cross section velocity head in the culvert where V is the average velocity, ft
- S_0 =dimensionless slope of the culvert
- K_e =dimensionless culvert entrance head loss coefficient
- C_e =dimensionless culvert exit head-loss coefficient
- HW =headwater elevation above the invert at the culvert entrance, ft

In Shoemaker's model, baffles were full width and level, with rounded leading edges at a radius equal to one tenth of the culvert height. Baffles heights of 0.10, 0.20 and 0.30 times the culvert rise and spacings of 1.0, 2.0, and 4.0 times the culvert rise were studied. The culvert had inlet and outlet aprons extending 2.5 times the culvert width, and wing walls flared at 34 degrees from the culvert sides, mitered at a 2:1 slope. The baffle furthest downstream from the culvert entrance was placed at the edge of the apron.

Shoemaker's variation of the Darcy-Weisbach friction factor is depicted in Figure 11.6.

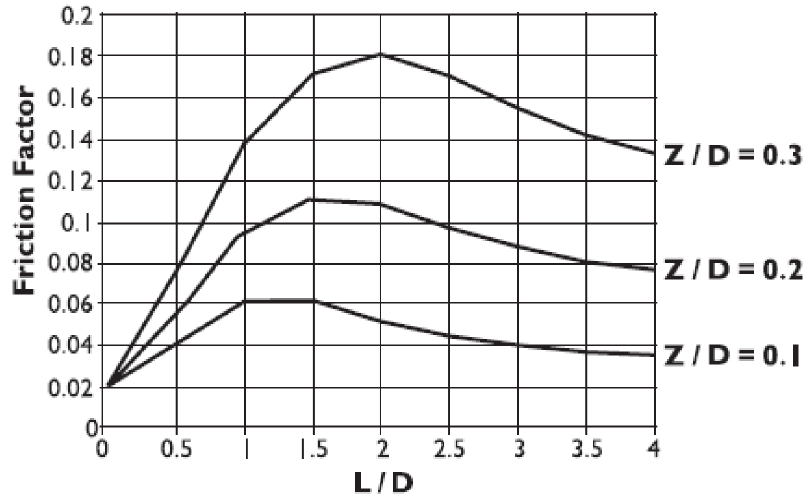

Figure 11.6. Variation of Darcy-Weisbach friction factor. L is the baffle spacing and Z is the baffle height (Bates et al. 2003).

Culvert capacity analysis assumes that entrance, outlet and friction losses are proportional to the velocity head. Equation 11.3 can be used with $C_0=K_e+C_e$ (from Figure 11.7), and other parameters as previously defined. According to Shoemaker, P can be approximated as the distance from the culvert invert to the center of the flow at the opening above a baffle (Shoemaker 1956).

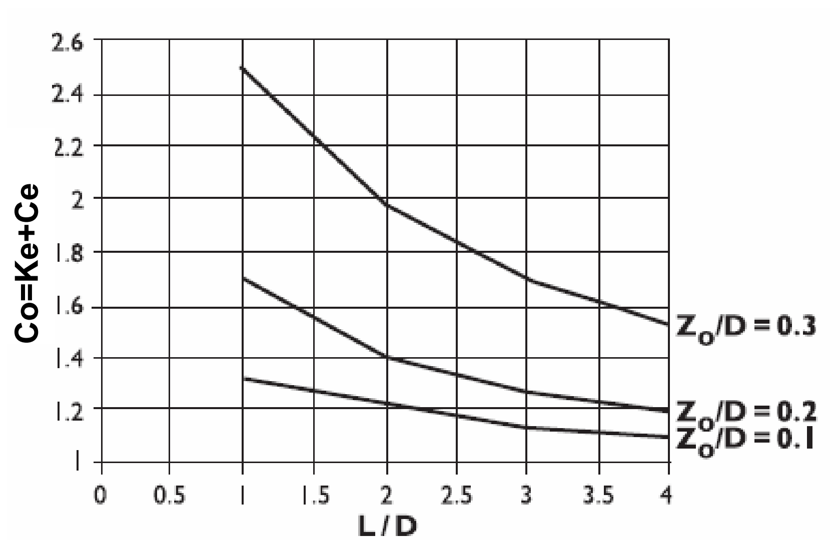

Figure 11.7. Energy coefficients for various baffle arrangements. K_e and C_e have been combined into a single head loss coefficient C_0, depicted here as a function of baffle spacing and height (adapted from Bates et al. 2003).

11.3.4 Energy Dissipation

In order to ensure that turbulence does not prevent fish passage ability, an energy-dissipation factor (EDF) is calculated (see section 3.2.4). For baffled fishways, WDFW recommends a value of 5 (ft-lb/ft^3/sec). It is further specified that the EDF should remain above 3 ft-lb/ft^3/sec at the high fish passage design flow to ensure that sediment deposition does not make the baffles ineffective or create a direct fish passage barrier.

The energy-dissipation factor is calculated as follows:

$$EDF = \gamma QS/A$$

Equation 11.4 (Bates et al. 2003)

where

EDF= Energy Dissipation Factor, ft-lb/ft^3/s
γ = unit weight of water, lb/ft^3
Q = fish-passage design flow, ft^3/sec
S = dimensionless slope of the culvert, ft/ft
A = cross-sectional flow area at the fish-passage design flow, ft^2
(For baffled installations flow area is taken between baffles, and for roughened channels large roughness elements are excluded.)

11.4 OREGON DEPARTMENT OF FISH AND WILDLIFE HYDRAULIC DESIGN

Source
Oregon Department of Fish and Wildlife (Robison et al. 1999)

Design Flows - See Hydrology Section

Water Velocity

Table 11.2. Water velocity requirement for culvert installations in Oregon (Robison et al. 1999).

Culvert Length (ft)	Salmon & Steelhead	Adult Trout (>6")	Juvenile Salmonids
Under 60'	6.0	4.0	2.0
60-100'	5.0	4.0	2.0
100-200'	4.0	3.0	*see Note below*
200-300'	3.0	2.0	*see Note below*
Over 300'	2.0	1.0	*see Note below*

Note – Hydraulic Design is not allowable in culvert installations larger than 100 ft when juvenile salmonids require passage.

Minimum Water Depth - Minimum water depth is specified by species and lifestage. For example,

- 12 inches for adult steelhead and Chinook.
- 10 inches for salmon other than Chinook, sea-run cutthroat trout, or other trout over 20 inches.
- 8 inches for trout under 20 inches, Kokanee, juvenile steelhead and salmon.

Maximum Jump Height –

- 12 inches adult steelhead and salmon,
- 6 inches trout, Kokanee, juvenile steelhead and salmon

Jump Pool Depth – Greater of 1.5 times jump height or 24 inches

Slope of Structure –

- Less than 0.5% if not embedded, baffled, or backwatered
- Up to 5% if baffled.
- 5-12% if installed with a fish ladder or integral weirs

Width of Structure - N/A
Length of Structure - Less than or equal to 100 ft if juvenile passage is required.
Flood Capacity - 100-yr flow

Oregon Baffle configurations are shown in Figure 11.8-11.10

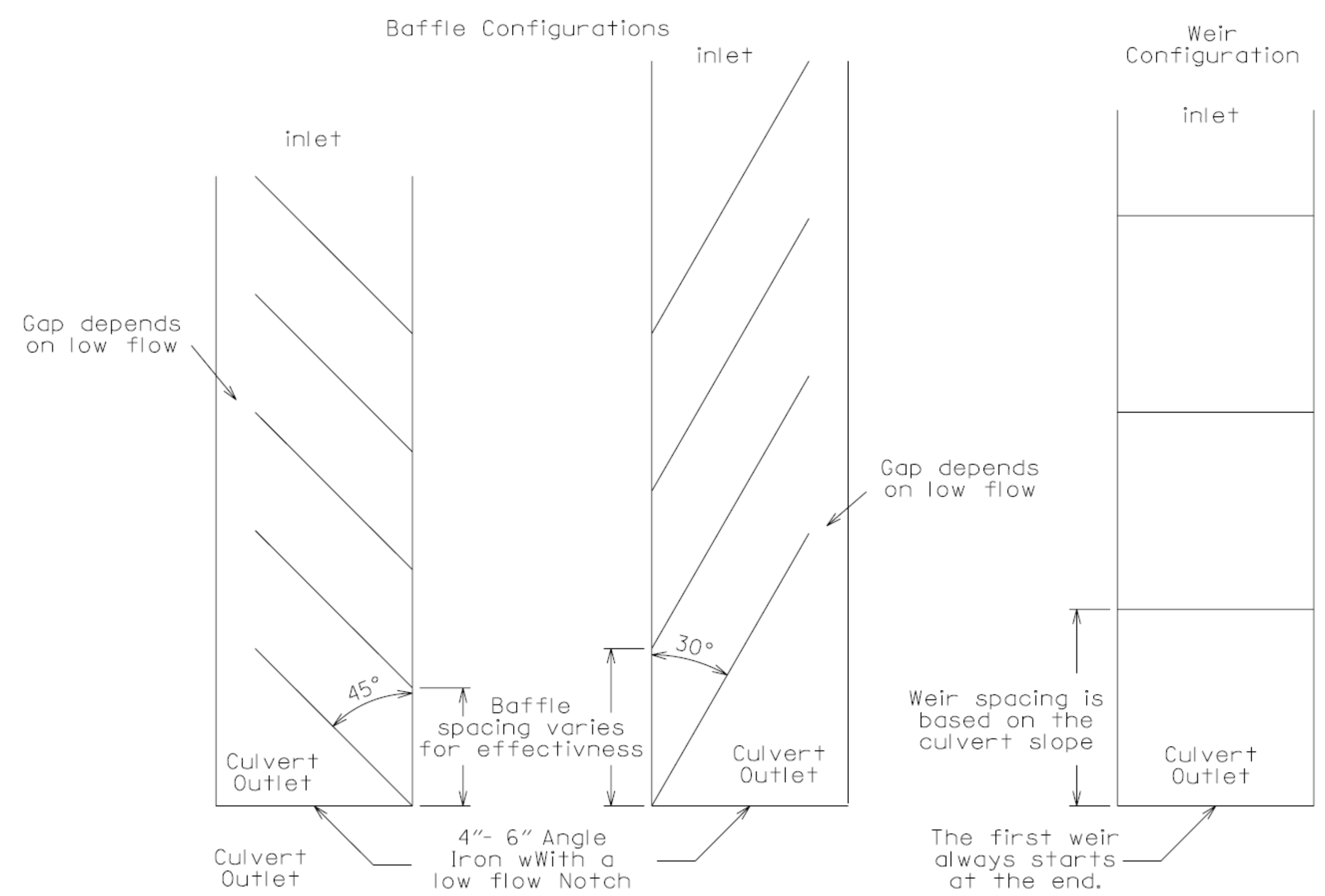

Figure 11.8. Baffle configurations endorsed in Oregon (Trevis, Personal Communication)

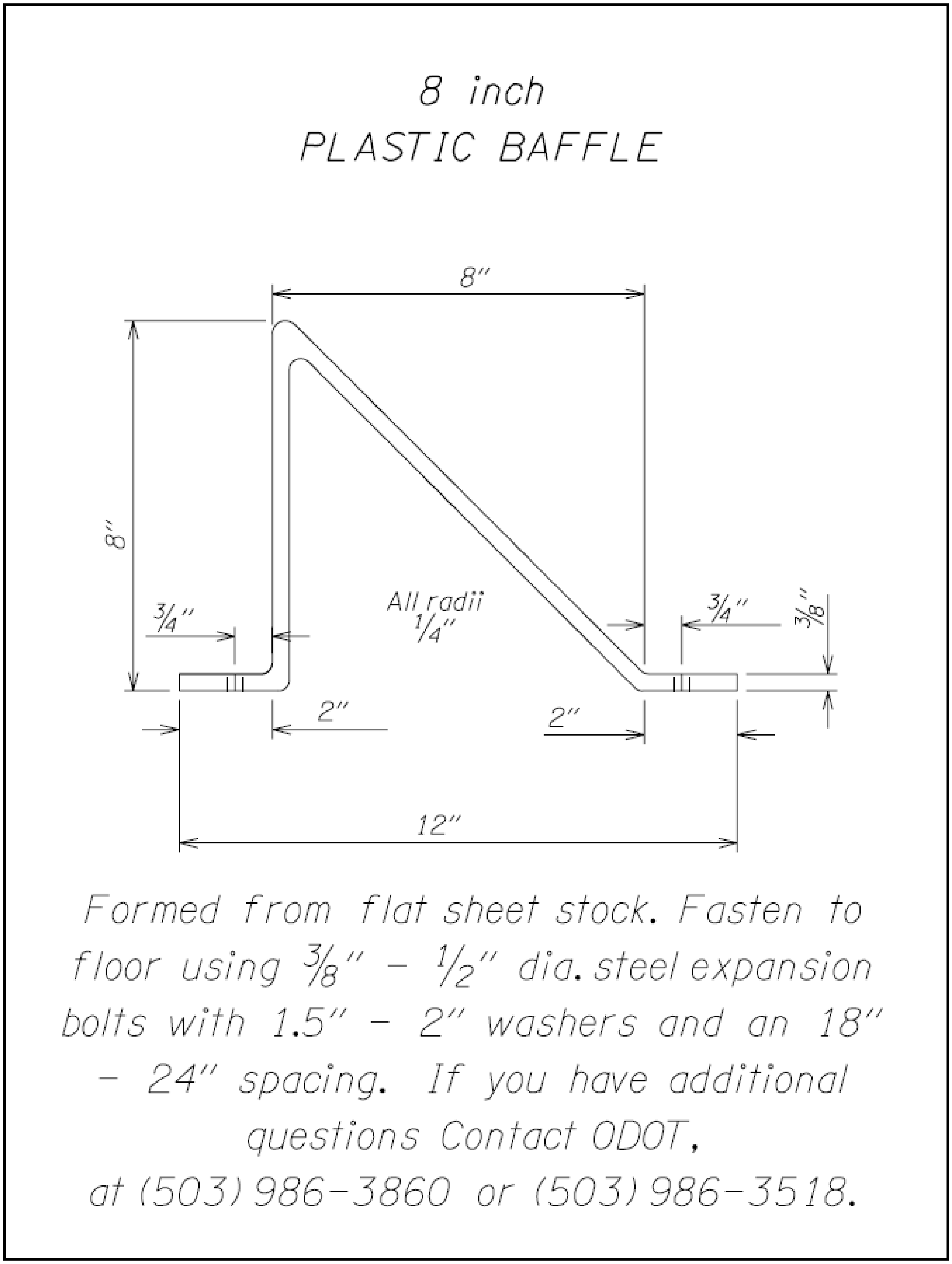

Figure 11.10. 8 inch plastic baffle used in Oregon (Trevis, Personal Communication)

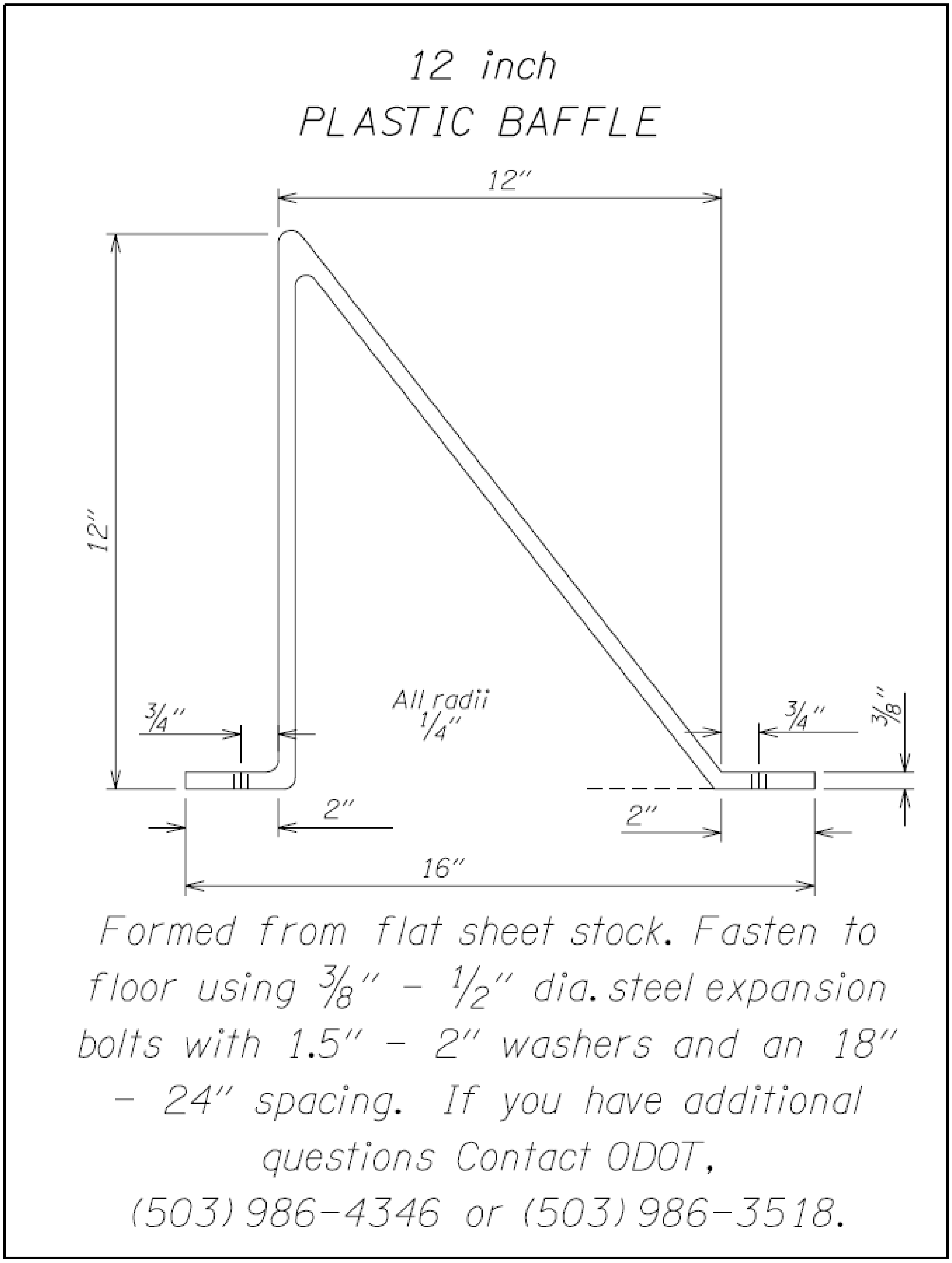

Figure 11.11. 12 inch plastic baffle used in Oregon (Trevis, Personal Communication).

11.5 MAINE DOT CULVERT DESIGN FOR REHABILITATION

Source
Maine Department of Transportation 2004

For culvert rehabilitations, the following objectives are desirable

- Eliminate hanging outlets
- Preserve minimum flow depth during critical periods of species-specific movement.
- Do not exceed maximum flow velocity during periods of species-specific upstream movement.

When species specific criteria are not available, generic design standards are provided including:

- Design for fish passage during low flow period
- Maintain at least 8 inches of water depth throughout the length of the culvert at design low flows
- Limit flow velocity to no more than 2 ft/s
- Limit drop in water surface elevation at the outlet to 2 inches
- Use average of median September and October flows as design flow
- Limit water level drop across grade control structures to 8 inches.
- When weirs are employed, weir notches should be at least 8 inches wide by 8 inches deep. Calculated dimensions should be rounded to the nearest 2 inch increment.

11.6 A DETACHABLE FISHWAY FOR STEEP CULVERTS

Source
Clancy 1990

Applicability
Culverts with widths close to that of the natural channel
Successfully used in culverts with slopes of 4.4% and lengths of 148 ft
Culvert capacity is adequate to withstand a reduction in cross sectional area without compromising design flood flow conveyance.

Limitations
Culvert capacity must be adequate to buffer the impact of added sediment, which was shown to reduce culvert capacity by approximately 15%.

A detachable fishway for culvert retrofits was designed to be inexpensive and easily constructed in the field. Hand placed rock is held in place by steel crossbars, creating a roughened channel that provides resting areas and low velocity paths within the culvert. The total cost of this retrofit (in 1990 dollars) was $2200 for a culvert that was 148 ft long and 6.2 ft in diameter. Fish passage was observed within the first year. A site visit eight years after culvert installation showed that fish passage remained in tact and that bed material had washed in-between large roughness elements.

Design Process:

1. Angle iron and reinforcing bar (as shown in Figure 11.12) is prefabricated in segments and assembled on site.
2. The upstream end of the fishway is anchored to the concrete headwall.
3. Downstream sections are bolted together
   Cross members welded in place every 4 ft
   Rock holder and hold-downs are angled upstream so that water pressure holds structure in place.
   Large rocks are hand placed on the upstream side of each cross member.

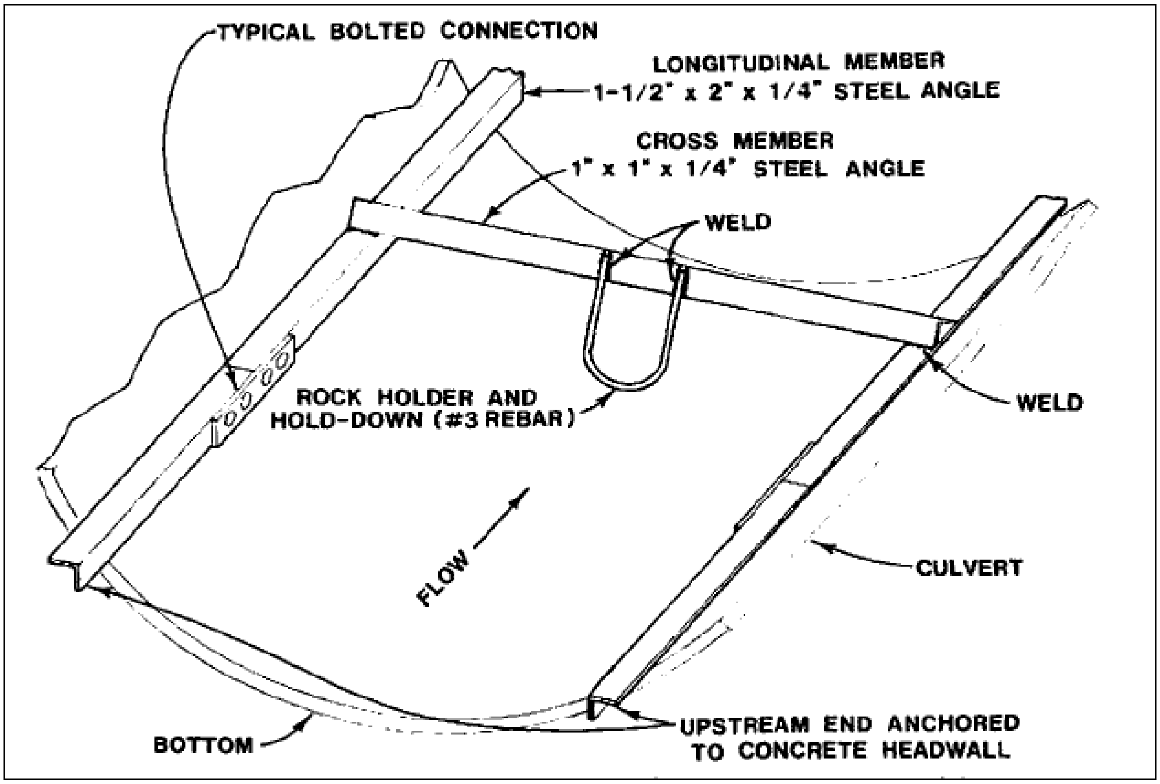

Figure 11.12. Detachable fishway design for culvert retrofit (Clancy 1990).

11.7 FISHWAYS

Applicability
Excessive drop at outlet cannot be mitigated by downstream grade control.
Right-of-way is unavailable for developing downstream grade control.
Steep culvert slope would require numerous closely spaced internal weirs.
Slopes from 10-25% depending on fish species and lifestage requiring passage.

Limitations
Long-term maintenance obligations.

Occasionally, weirs and baffles will be either be unfeasible, or will not produce the hydraulics conditions necessary for fish passage (Maine Department of Transportation 2004). Fishways such as the Vertical Slot Fishway, Denil Fishway, and Steeppass Fishway are structures consisting of a sloping channel partitioned by flow control devices such as baffles, weirs or vanes with openings to allow fish to swim through. Further discussion of such devices is in *Introduction to Fishway Design* (Katopodis 1992).

11.8 FLOODPLAIN CULVERTS

As described in Chapter 10, Maryland design guidelines contain specification for floodplain culverts in situations where a single culvert would overly constrict flow (Maryland State Highway Administration 2005). Floodplain culverts can be installed to collect and convey flood plain flows, reducing the impact of the main channel culvert. Floodplain culverts should be positioned on the floodplain well beyond the influence of the main culvert to avoid channel undermining, degradation or migration into the area of the floodplain culvert. This position also avoids clogging due to debris carried in the main channel.

11.9 TWO CELL INSTALLATIONS

Two cell fish culverts provide one cell for fish passage and another to ensure flood capacity. Maryland and Maine utilize two cell Installations as described in Chapter 10 (Maryland State Highway Administration 2005; Maine Department of Transportation 2004), and North Carolina has criteria for two cell culvert installations, Figure 11.13, utilizing a lowered fish passage culvert that creates a sinuous low flow travel path in the lower culvert (Twisdale, J. W., Personal Communication). Lang et al discourages two-cell installations due to the likelihood of debris collecting on the area between spans (Lang et al. 2004)

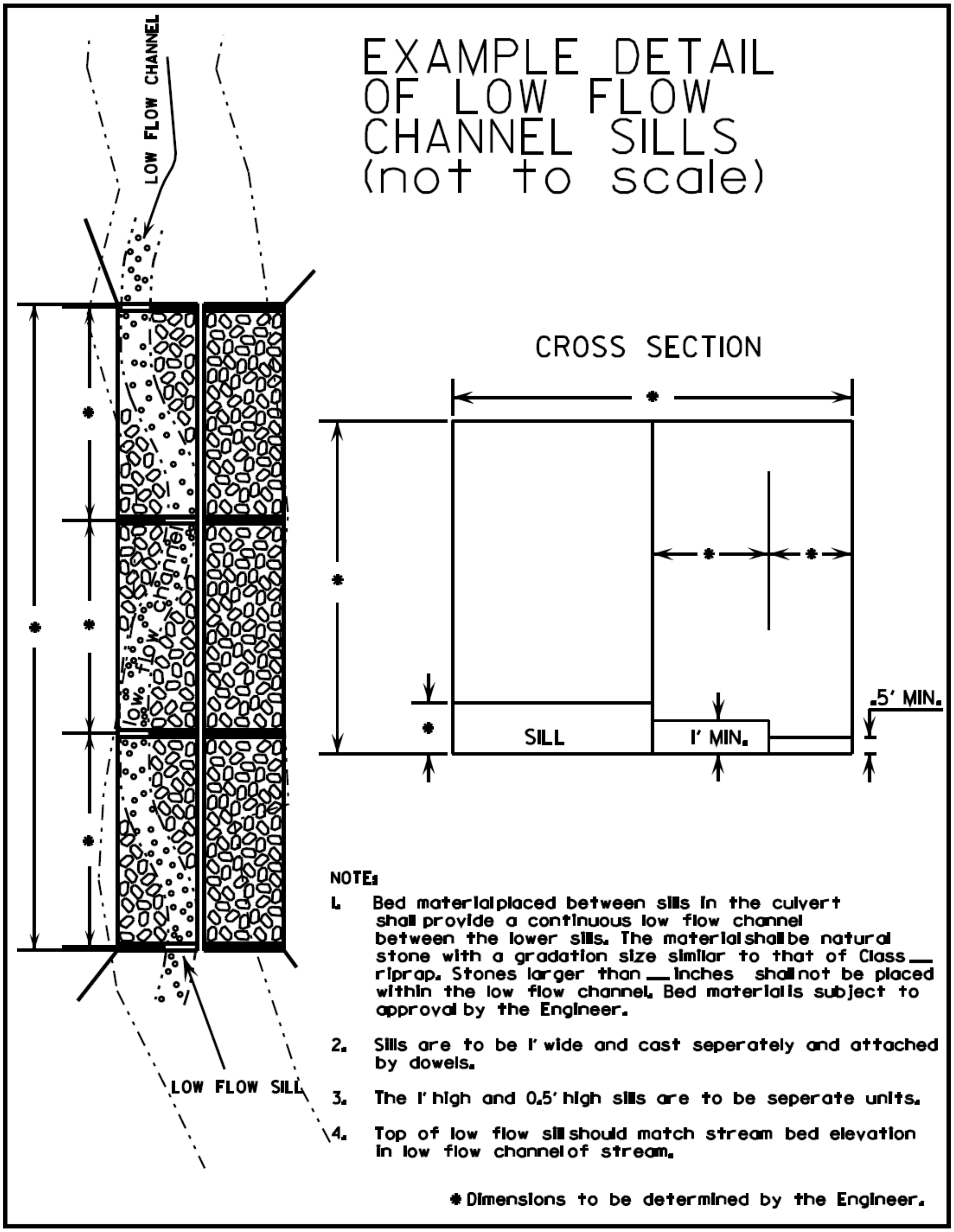

Figure 11.13. Example detail of low flow channel sills (Twisdale, J. W., Personal Communication).

11.10 DESIGN IN TIDAL AREAS

11.10.1 State Guidelines

Because of the difficulty in creating fish passage criteria in tidal areas, Washington Department of Fish and Wildlife promotes removal of tidal culverts as the preferred restoration technique (Bates et al. 2003). Maryland culverts are commonly designed for low tide conditions, ensuring that the culvert is accessible in a worst-case scenario (Andrzej Kosicki, Personal Communication).

11.10.2 Tide Gates

In tidal situations, tide gates are used to allow freshwater to flow into estuaries while ensuring that brackish waters are kept from moving upstream. Such structures have been part of a system of dikes used to allow the drainage and development of marshland (Giannico and Souder 2005).

Tide gates (or Tide flaps) are attached to culvert outlets as depicted in Figure 11.14, and are controlled by the elevational difference of water levels on either side of the culvert. In a process shown sequentially in Figure 11.15, culverts open as ebbing tides allow fresh water to flow to the estuary side of the culvert, and close as flood tides attempt to bring tidal waters upstream and upland. Fish passage at tide gates is focused on extending the period of time that tide gates remain open, thereby increasing the range of flows over which a fish will be able to pass the structure.

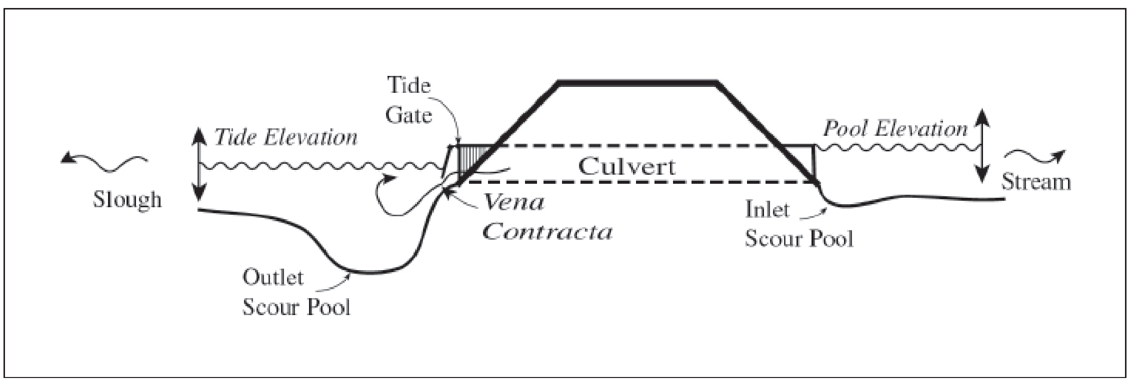

Figure 11.14. Lateral schematic of a culvert with a top-hinged tide gate attached to downstream end of culvert (Giannico and Souder 2005).

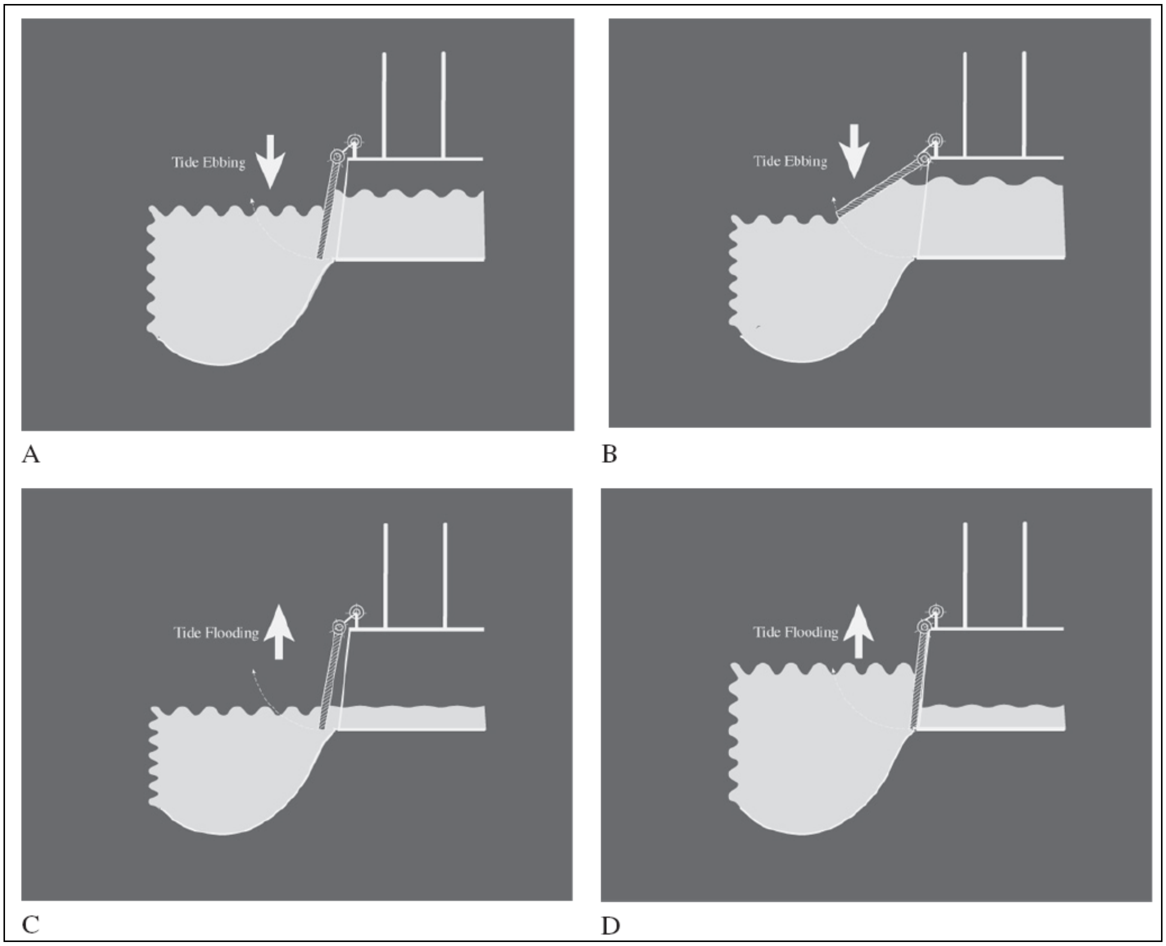

Figure 11.15. Tide gate operation cycle (Giannico and Souder 2004). (A) Tide gate begins to open when water pressure in culvert overcomes pressure of water on downstream side during ebb tide. (B) Tide gate is wide open during ebb tide. (C) Tide gate begins to shut when upstream water level drops and tide begins to rise. (D) Tide gate is shut during flood tide.

Advances in tide gate technology include gates with permanent holes, aluminum or plastic gates, fiberglass doors, side hinged gates, rubber gates, and fish passage appurtenances such as "pet doors" (Figure 11.16). These technologies are largely unvalidated, and have questionable effects on fish passage and stream ecology (Giannico and Souder 2004).

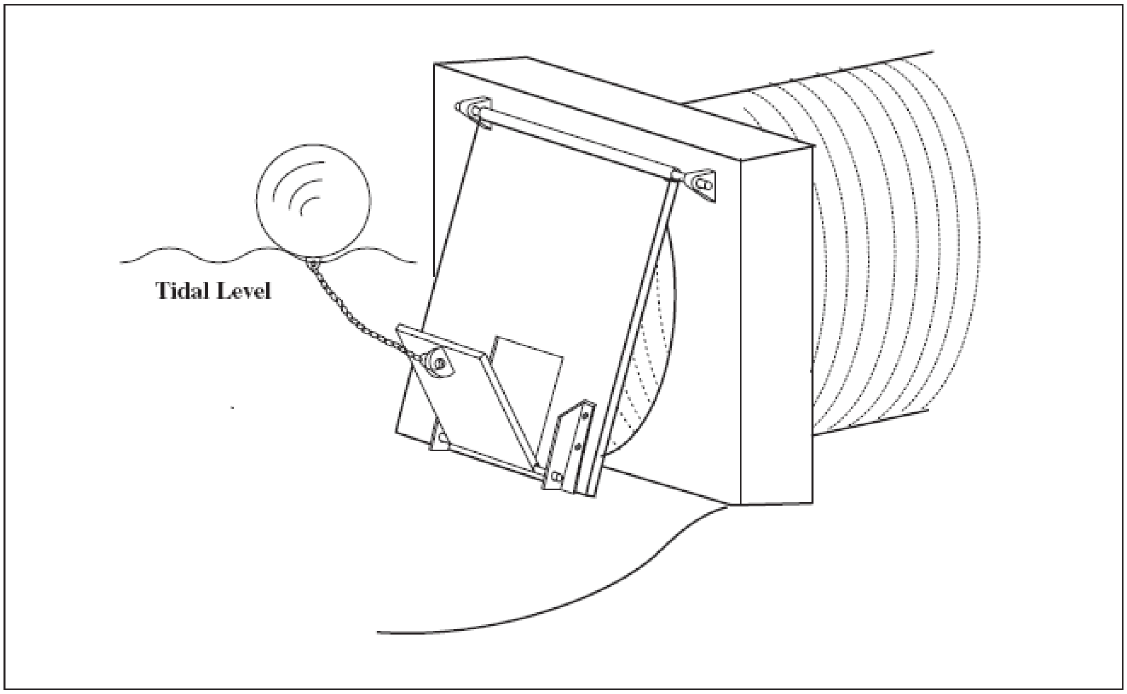

Figure 11.16. Bottom-hinged pet door (Giannico and Souder 2005). The floater allows a small area of the gate to open during periods when water elevations would keep the gate closed. This is intended to allow a longer period of fish movement.

Tide gates impact freshwater/brackish water interaction, and can have a profound effect on channel characteristics including flooding and water flow, channel geometry, water temperature, Ph, salinity, plant communities and fish and fish habitat (Giannico and Souder 2005). The authors warn that there is no such thing as a fish friendly tide gates, only a “fish friendlier” tide gate.

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12 CASE STUDIES AND DESIGN EXAMPLES

12.1 GEOMORPHIC SIMULATION

12.1.1 USFS Stream Simulation Design Example

A survey of the exiting channel, and a surface pebble count conducted on a representative reference reach, determined the following channel characteristics:

Channel width (W_{ch}) = 6.4 ft
Channel slope (S_{ch}) = 2.0%
Culvert length (L_{culv}) = 100 ft
D_{100} = 180 mm (0.591 ft)
D_{84} = 85 mm (0.279 ft)
D_{50} = 50 mm (0.164 ft)

The culvert is sized assuming that bank margins are desirable

Culvert bed width (W_{culv}) = $W_{ch} + 4*D_{100}$
W_{culv} = 8.76 ft

The culvert should span a minimum of 8.8 ft, which would rounded up to 9 ft

Bed mix gradation includes D_{100} – D_{50} determined from the surface pebble count, with D_{16} and D_5 determined by the Fuller-Thompson equation (9.1).

$$P = \left(\frac{d}{D_{50}}\right)^n \quad \textit{(Equation 9.1)}$$

The Fuller-Thompson 'n' value can be varied between 0.45 and 0.7 to control gradation until an appropriate proportion of fines (5-10%) has been attained. To start, compare the effects of an n value of 0.7 vs. and n value of 0.45. The results of these calculations have been plotted in Figure 12.1.

Using n = 0.7

$$D_{16} = 0.32^{1/n} * D_{50}$$
$$D_{16} = 0.32^{1/(0.7)} * 0.164 ft$$
$$D_{16} = 0.032 ft$$

$$D_5 = 0.10^{1/n} * D_{50}$$
$$D_5 = 0.10^{1/(0.7)} * 0.164 ft$$
$$D_5 = 6.1x10^{-3} ft$$

Using n = 0.45.

$$D_{16} = 0.32^{1/n} * D_{50}$$
$$D_{16} = 0.32^{1/(0.45)} * 0.164\,ft$$
$$D_{16} = 0.013\,ft$$

$$D_5 = 0.10^{1/n} * D_{50}$$
$$D_5 = 0.10^{1/(0.45)} * 0.164\,ft$$
$$D_5 = 9.8x10^{-4}\,ft$$

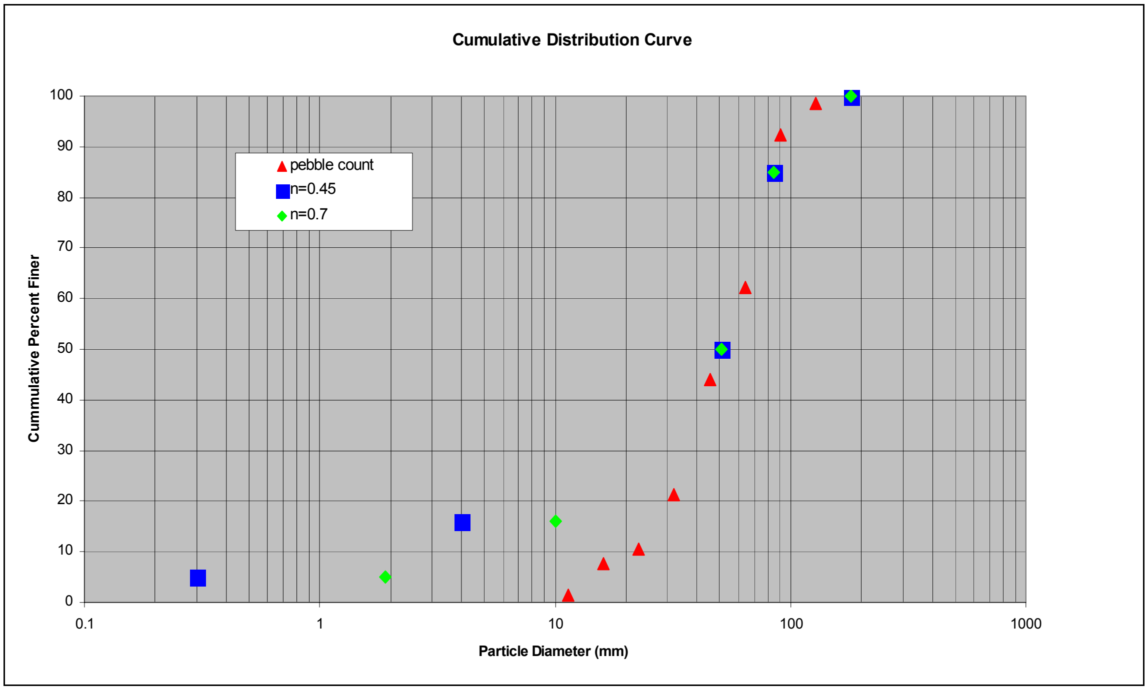

Figure 12.1. Example cumulative distribution curve for bed mix gradation using Fuller-Thompson method using n = 0.7 and n = 0.45.

It can be seen that an n value of 0.45 will lead to gradation of approximately 12-13% fines (2mm or less).

Refining further, using n = 0.55

$$D_{16} = 0.32^{1/n} * D_{50}$$
$$D_{16} = 0.32^{1/(0.55)} * 0.164\,ft$$
$$D_{16} = 0.021\,ft$$

$$D_5 = 0.10^{1/n} * D_{50}$$
$$D_5 = 0.10^{1/(0.55)} * 0.164\, ft$$
$$D_5 = 2.493x10^{-3}\, ft$$

This distribution is plotted in Figure 12.2

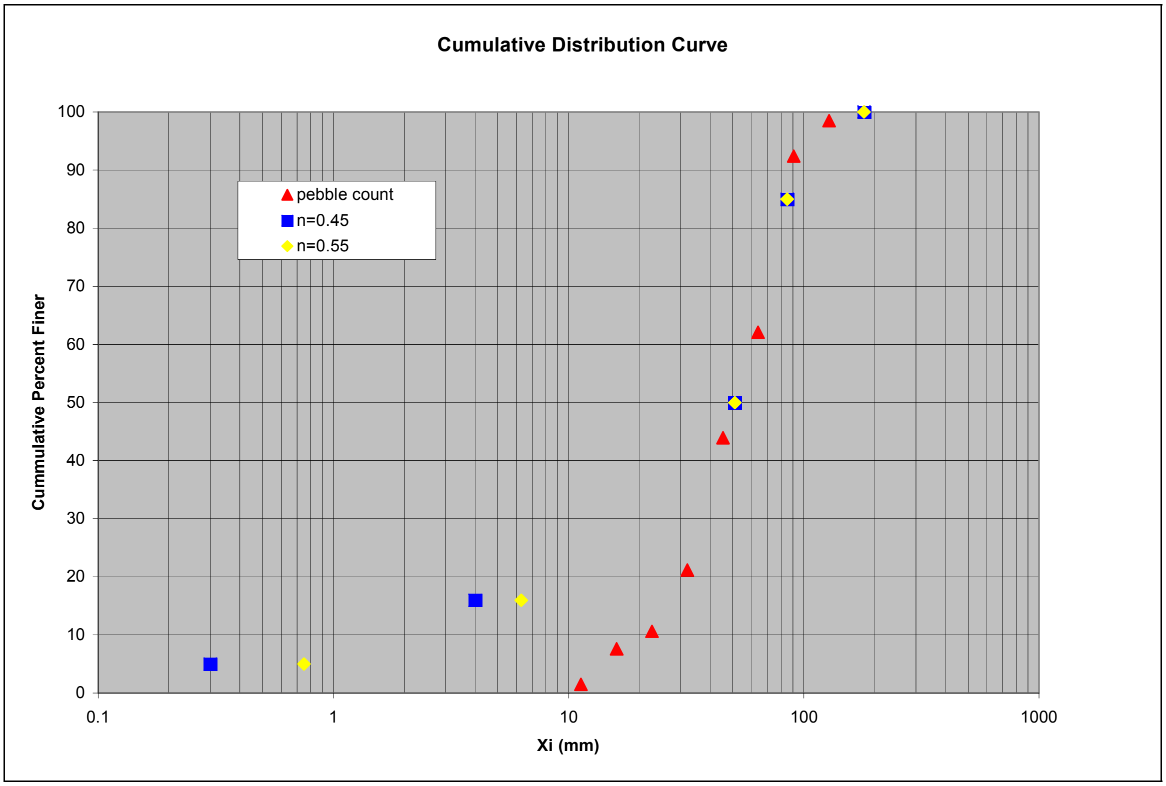

Figure 12.2. Example cumulative distribution curve for the Fuller-Thompson method using n=0.55 and n = 0.45.

An n value of 0.55 leads to a bed mix gradation with between 5-10% fines (smaller than 2 mm). The following gradation should be used for design

$D_{100} = 0.59\, ft$
$D_{84} = 0.28\, ft$
$D_{50} = 0.164\, ft$
$D_{16} = 0.021\, ft$
$D_5 = 2.5\, x10^{-3}\, ft$

12.1.2 USFS Stability Check Design Example

The following stability check example is taken (almost verbatim) from Bates et al. 2006. It is included here for clarification of the USFS Stream Simulation Design.

Determining if D_{84} moves at bankfull flow (Example from Bates et al 2006)

Channel Parameters are as follows:

> *D_{100} = 120 mm*
> *D_{84} = 52 mm*
> *D_{50} = 27 mm*
> *Bankfull flow (Q_{bf}) = 106 cfs*
> *Bankfull width (W_{bf}) = 18.7 ft*
> *Active channel width (W) = 15.3 ft*
> *Slope (S) = 0.0142 ft/ft*

Determine whether the D_{84} particle moves at bankfull flow in the stream using the **modified critical shear stress** equation for D_{84} (Equation 9.3)

$$\tau^*_{D50} = 0.050 \quad \textit{(From Table 9.2)}$$

$$\tau_{cD84} = 102.6(0.050)(0.39\,ft)^{0.3}(0.17\,ft)^{0.7}$$

$$\tau_{cD84} = 1.12\ \text{lb/ft}^2$$

Find the average boundary shear stress in the reference reach at bankfull flow (τ_{bf}) using equation 9.2.

$$\tau_{bf} = \gamma RS \quad \textit{(Equation 9.2)}$$

$$\tau_{bf} = \left(62.4\frac{lb}{ft^2}\right)(1)(0.0142)$$

$$\tau_{bf} = 0.886\frac{lb}{ft^2} < 1.12\frac{lb}{ft^2}$$

Therefore, the D_{84} particle size is stable bankfull flow

How well does the modified critical shear stress equation apply here?

- *D_{84}/D_{50} = 2.3, which is much less than 30*
- *Slope < 5%*
- *Channel unit is a riffle*
- *D_{84} particle size of 120 mm is between the range of 10 and 250 mm.*

Conclusion: The modified critical shear stress equation is applicable to this stream

Critical unit discharge equation
Find the critical unit discharge for D_{50} (q_{cD50}) using equation 9.5:

$$q_{cD50} = \frac{0.15 g^{0.5} (0.17 ft)^{1.5}}{0.0142^{1.12}} = 7 \frac{cfs}{s}$$

calculate b (which quantifies the range in particle sizes) using equation 9.7:

$$b = 1.5 \left(\frac{0.39 ft}{0.089 ft} \right)^{-1} = 0.342$$

Find critical unit discharge for D_{84} (q_{cD84}) using equation 9.6

$$q_{cD84} = 7 \frac{ft^3}{s} \left(\frac{0.39 ft}{0.17 ft} \right)^{0.342} = 9.3 \frac{cfs}{s}$$

$$q = \frac{Q_{bf}}{W} = 6.93 \frac{cfs}{s \cdot ft}$$

Both D_{50} and D_{84} are stable at bankfull flow in this example. These results argree with those of the modified critical shear stress equation.

Is the Bathurst equation appropriate for this stream?

Slope > 1%
D_{84} is small cobble
R_{bf}/D_{50} = 5.9, which is < 10 (low relative submergence)

Predicting the range of potential particle movement
Find the average boundary shear stress in the reference reach at bankfull flow (τ_{bf}) using equation 9.2.

$$\tau_{bf} = \gamma RS \text{ (Equation 9.2)}$$

$$\tau_{bf} = \left(62.4 \frac{lb}{ft^2} \right) (1)(0.0142)$$

$$\tau_{bf} = 0.90 \frac{lb}{ft^2}$$

Find the upper critical shear stress for the D_{84} particle size using Equation 9.8.

$$\tau_{cD84.u} = 0.0814 \cdot (120 mm) = 9.77 \frac{lb}{ft^2}$$

Find the lower critical shear stress for the D_{84} particle size using Equation 9.9

$$\tau_{cD84.l} = 0.00355 \cdot (120mm) = 0.426 \frac{lb}{ft^2}$$

τ_{bf} =0.90 lb/ft^2 is less than τ_{cD84-u} = 9.77 lb/ft^2 and greater than τ_{cD84-l} = 0.426 lb/ft^2, indicating that the D_{84} particle has the potential to be mobile at bankfull flow.

12.1.3 WDFW Stream Simulation Design Example

Stream properties are determined from a channel survey and analysis of multiple representative cross sections.

Channel width (W_{ch}) *= 6.4 ft*
Channel slope (S_{ch}) *= 2.0%*
Culvert Slope (S_{culv}) *= 2.2%*
Culvert length (L_{culv}) *= 100 ft*

Check Applicability

$$S_{ch} = 2\% < 6.0\%$$

$$Slope\ Ratio = \left(\frac{S_{culv}}{S_{ch}}\right) = 1.1$$

Channel has been assessed to have little susceptibility to vertical changes

Conclusion: WDFW Stream Simulation is applicable in this situation

Culvert width is determined according to equation 9.10

Culvert bed width (W_{culv}) *=* $1.2\ W_{ch} + 2\ ft$
$W_{culv} = 9.68\ ft$

Culvert should span a minimum of 9.68ft, which would likely be rounded up to 9.75 ft

Culvert bed configuration is based on slope scenarios. Since slope is less than 4%, design scenario I is employed, meaning that rock bands will be used to control the initial channel shape. This creates a situation that may be more adequately described as Hydraulic Simulation.

Bands spacing should be the lesser of:

$$5 \cdot W_{ch} = 32\,ft$$

$$\frac{0.8\,ft}{S_{culv}} = 36.4\,ft$$

Therefore, spacing will be 32ft

Bands are separated from the entrance and exit by the lesser of:

$$2 \cdot W_{ch} = 13\,ft \quad \text{or} \quad 25ft$$

Therefore, spacing should be at least 13ft from culvert inlet and outlet. With a 100ft structure this leaves room for 3 rock weirs at a spacing of 32 ft apart, and 18ft from the culvert entrance and exit.

Sizing of rock band material is based on a surface pebble count of the reference reach.

D_{100} = 180 mm (0.591 ft)
D_{84} = 85 mm (0.279 ft)
D_{50} = 50 mm (0.164 ft)

Rock bands are comprised of well-graded material within the following range:

$$D_{100} = 0.59\,ft \quad \text{to} \quad 2 \cdot D_{100} = 1.2\,ft$$

Since channel slope is less than 4%, Paleohydraulic Analysis can be used to check the bed changing flow, ensuring that bed mix gradation is adequate.

D_{84} = 0.279 ft (from above)

$$V = 9.57 \cdot D_{84}^{\;0.487} \quad \text{(Equation 9.12)}$$

$$V = 5.14 \cdot \frac{ft}{s}$$

Using Table 9.3, slope (2.2%) and particle size (0.28ft) are used to find depth of flow

Depth = 0.849 ft

With known depth, cross sectional area can be computed from the proposed triangular cross section with 6:1 side slopes. (Area of a triangle is 0.5*base*height)

$$Area = 0.5 \cdot Depth \cdot (12 \cdot Depth)$$
$$Area = 4.24 ft^2$$

Using the proposed cross sectional area, this corresponds to a flow of

$$Q = A \cdot V$$
$$Q = 21.8\ cfs$$

12.1.4 Unit Discharge Design Example

When slopes are greater than 4%, the Unit-Discharge method is suggested for finding a stable bed material gradation. Necessary parameters include:

100 year exceedance flow (Q_{100}) = 125 cfs
Culvert slope (S_{culv}) =5.0 %
Channel width (Wch) =8.0 ft

Solving for Critical Discharge (q_C):

$$qc = \frac{Q_{100}}{W_{ch}}$$

$$qc = 15.6 \frac{ft^2}{s}$$

Using the Critical Discharge equation (9.11) to solve for D_{84}:

$$D_{84} = \frac{3.45 \cdot Sculv^{0.747} \cdot (1.25 q_c)^{2/3}}{g^{1/3}} = 0.84 ft$$

So a D_{84} of 0.84 ft will create the necessary stability, and a gradation can be created based on D_{84}. This can also be checked using the Paleohydraulic analysis shown above.

12.1.4.1 Paleohydraulic analysis

$$D_{84} = 0.84 ft$$

$$V = 9.57 \cdot D_{84}^{0.487}$$ *(Equation 9.12)*

$$V = 8.79 \frac{ft}{s}$$

Using Table 9.3, find flow depth

Depth = 1.6 ft

Using the proposed channel dimensions (6:1 side slope, triangular channel)

Area = 0.5·Depth·(12·Depth)
Area = 15.4 ft^2
Q=V·A
Q=135.0 cfs

This is consistent with the trend of Costa's equation to predict smaller particle sizes than Bathurst's equation at higher slopes (Bates et. al 2003). Both equations show this D_{84} to be stable at Q_{100} (125 cfs).

12.1.5 WDFW No-Slope Design Example

Stream Properties Needed

> *Channel width* (W_{ch}) *= 6.4 ft*
> *Channel slope* (S_{ch}) *= 2%*
> *Culvert Slope* (S_{culv}) *= 2.2%*
> *Culvert length* (L_{culv}) *= 100 ft*

Channel Type and Size

> *Culvert bed width* (W_{culv}) $= 1.25 \cdot W_{ch}$
> $W_{culv} = 8$ *ft*

Culvert should span a minimum of 8ft

To check the applicability of No Slope Design, ensure that the product of channel slope times length is less than 0.2D

> $L_{culv} \cdot S_{culv} = 2.2$ *ft*
> $0.2 \cdot D = 1.6$ *ft*

Since slope times length is > 0.2D (2.2 ft > 1.6 ft) No-Slope method is not applicable in this situation due to the inability to meet embedment requirements.

12.1.6 Embedded Pipe Case History

The following example of stream simulation is taken from the USFS FishXing website (United States Forest Service 2006b), maintaining the format and content developed by the authors. It is reproduced here with permission from Mike Furniss of the USFS.

Location
Mad River Basin, Northern California
Mather Creek

Project Type
Embedded Structural Plate Pipe
Geomorphic Simulation

Pre-Project Barrier
Undersized Corrugated Metal Pipe (Overtopped at 5-yr flow)
6 ft (1.2 m) diameter CMP
135 ft (41.1 m) long at 0.4 % slope
Cascade over rock apron at outlet

Figure 12.3. Pre Project Barrier Culvert (United States Forest Service 2006b)

Channel Characteristics
100-year Flow: 570 cfs (16.1 cms)
Drainage Area: 1.7 mi^2 (4.4 km^2)
Bankfull Width: 11 ft (3.4 m)

Ecological Value
Provide access to 2.6 mi (4.2 km) of rearing habitat for coho salmon, steelhead and cutthroat trout. Upstream habitat is low gradient, marshy, and maintains good year-round flows.

Project Characteristics
Culvert Diameter: 16 ft (4.9 m)
Length: 130 ft (32.0 m)
Depth Embedded: 2-2.5 ft (0.6-0.9 m)
Slope of Bed in Culvert: 0.75 %

Figure 12.4. Replacement Culvert (United States Forest Service 2006b)

Challenges
Protecting buried water line
Stabilizing side slopes during excavation to set culvert at desired depth for embedding

Project Funding
Humboldt County
California Dept. Fish and Game

Completion Date
October, 2002

Total Project Cost
$234,544

Project Description
When installed in the 1970's, the downstream channel was realigned and channelized. Subsequently, a rock apron spanning the channel had been placed below the culvert outlet. A fish passage assessment conducted in 1999 found the sloping rock apron created a complete barrier to juvenile salmonids and a low-flow barrier to larger fish. The original culvert also had inadequate flood capacity and was in poor condition, with the bottom rusted-through.
An embedded 16 ft (4.9 m) diameter culvert was selected as the replacement crossing. The new culvert is designed to pass a 100-year flood at Headwater-to-Diameter ratio (HW/D) of 0.6 and is 145 % wider than the upstream bankfull channel. The appropriate slope and elevation for constructing the streambed within the culvert was determined from a 450 ft (137 m) long channel profile. Since the road was closed and no traffic bypass was needed during construction, the project took only four weeks to complete.

This project experienced many construction challenges. Although originally designed to be embedded 6 ft (1.8 m), problems with buried utilities, groundwater, and slope stability during excavation resulted in only embedding the culvert approximately 2.5 ft (0.9 m).

12.2 HYDRAULIC SIMULATION

12.2.1 Culvert with Floodplain Relief Case History

The following case history was provided by Andrez Kosicki of the Maryland State Highway Administration.

Location
MD Route 25 over Beaverdam Run, Baltimore County, Maryland, USA

Project Type
Main channel Structure Plate Pipe Arch (SPPA)
Floodplain culverts (one SPPA. and on SPP)
Hydraulic Simulation

Pre-Project Barrier
Single span slab bridge with a 20 ft long invert which was paved in the 1960s due to scour and poor structural condition. A single 10 ft diameter structural plate pipe was added in 1972 after hurricane Agnes washed away a roadway approach on the north side. See Figures 12-5 – 12.7.
Fish blockages included an upstream earth and debris dam, a 6 inch drop at the downstream outlet, and a 1-2 inch flow depth under low flow conditions
No aquatic life has been observed within 50 ft upstream of the bridge.

Channel Characteristics
100-year Design Flow: 2482 cfs
High Flow Velocity: 10 ft/s
Mannings n: 0.034
Drainage Area: 5.9 mi^2
Low Flow: 7cfs
Low Flow Velocity: 1.9 ft/s
Mannings n: 0.030

Ecological Value
Department of Natural Resources stream classification is a Class III (Natural Trout Stream)

Project Characteristics
2-12’4”x7’9” Structural Plate Pipe Arches (SPPA)
1-10’0” Structural Plate Pipe (SPP) with end walls
culvert length: 35.5ft
culvert slope: 0.56%

One of the two SPPAs was placed in the channel 2.0 ft below the existing stream invert (low flow cell). The other SPPA and the round pipe placed at bankfull elevations (approximately 3.0 ft higher than the low flow cell.)

Buried rip-rap aprons, each 25 ft long were placed at both upstream and downstream ends.

Post Project Observations and Lessons Learned

No formal monitoring program was set up since monitoring was not required by the permitting agency. Periodic field trips showed beneficial changes in the channel and within the structure:

- Aquatic life that was not seen before
- Various water bugs and good sediment movement resulting in clear water, whereas the pre-1994 structure passed water that was dark and murky.
- Side cells have displayed wildlife tracks (probably small mammals)

Figure 12.5. Pre-project channel condition (1992).

Figure 12.6. Upstream of pre-existing structure looking downstream.

Figure 12.7. Downstream of pre-exiting structure looking upstream.

Figure 12.8. Downstream of culvert, shortly after project completion in 1994.

Figure 12.9. Upstream of current crossing in 2005.

Figure 12.10. Upstream of current crossing during high-flow event.

12.2.2 WDFW Roughened Channel Design Example

Stream Properties Needed

Channel width (W_{ch}) = 7 ft
Channel slope (S_{ch}) = 1.7%
Culvert slope (S_{culv}) = 2.3%
Culvert length (L_{culv}) = 90ft
100 year exceedance flow (Q_{100}) = 125 cfs

Slope Ratio

$$Slope\ Ratio = \left(\frac{S_{culv}}{S_{ch}}\right) = 1.35$$

This is a situation where slope ratio exceeds 1.25 (typical upper range for Stream Simulation Design in Washington.

Culvert width is an iterative parameter beginning with channel bed width

Width of Culvert Bed (W_{culv}) = W_{ch}=7 ft

Culvert Bed Configuration by U.S. Army Corps of Engineers Riprap Design, requiring computation of unit discharge as follows:

$$q = \frac{Q_{100}}{W_{ch}}$$
$$q = 17.9 cfs$$

This allows the D_{30} particle size to be calculated by Equation 10.4 for rip rap sizing (other methods, such as those included in WDFW Stream Simulation design can also be used for bed sizing, and may be preferable over Equation 10.4, however, 10.4 is used here for illustrative purposes):

$$D_{30} = \frac{(1.95 \cdot Sculv^{0.555}) \cdot (1.25 \cdot q)^{2/3}}{g^{1/3}}$$
$$D_{30} = 0.60\, ft$$

Note - it may be pertinent to increase the factor of safety (1.25) since rock sizing in greater than 0.5ft.

Use D_{30} to find D_{84}, using the approximate scaling factor provided:

$$D_{84}=1.5 \cdot D_{30}$$
$$D_{84}=0.90\ ft$$

This particle size is checked to ensure that it does not exceed 1/4 of the culvert width

$$4 \cdot D_{84}=3.584 < 7ft$$

A gradation can now be created based on D_{84} = 0.9ft

12.2.2.1 Fish Passage Velocity

Fish passage velocity is now calculated to ensure that fish are able to traverse the structure. In this case, design is for juvenile Coho Salmon, and velocity cannot exceed 4 ft/s according to WDFW Hydraulic Design criteria (based on 90ft structure). Additional parameters required include fish passage velocity and hydraulic radius:

Allowable Velocity (V_{fish}) = 4 ft/s
Hydraulic Radius (R) = 0.35 ft

For use with Limerinos and Jarrett's equations, Velocity will be based on a Manning's n value, and will be calculated according to Equation 10.6:

$$V = \frac{1.486 \cdot R^{1/6}}{(n \cdot g)^{0.5}} \cdot (g \cdot R \cdot S_{culv})^{0.5}$$

Limerinos equation is solved as follows (Equation 10.7)

$$n = \frac{0.0926 \cdot R^{1/6}}{1.16 + 2log\left(\frac{R}{D_{84}}\right)} = 0.12$$

which can be used into Equation 10.6 to solve for velocity

$$V_l = \frac{1.486 \cdot R^{1/6}}{n \cdot (g)^{0.5}} \cdot (g \cdot R \cdot S_{culv})^{0.5}$$

$$V_l=1.20\ ft/s < 4.0\ ft/s$$

So, according to the Limerinos equation, this would be an acceptable velocity

Jarrett's equation is solved as follows

$$n = 0.32 \cdot S_{culv}^{0.38} \cdot R^{-0.16}$$
$$n = 0.10$$

Using n to solve for Velocity

$$V_j = \frac{1.486 \cdot R^{1/6}}{n \cdot g^{0.5}} \cdot (g \cdot R \cdot S_{culv})^{0.5}$$
$$V_j = 1.42\ ft/s \ < 4.0 ft/s$$

Mussetter's equation utilizes the Darcy-Weisbach friction factor, and is solved according to Equation 10.9.

$$\left(\frac{8}{f}\right)^{0.5} = 1.11\left(\frac{depth}{D_{84}}\right)^{0.46}\left(\frac{D_{84}}{D_{50}}\right)^{-0.85} \cdot (S_{culv})^{-0.39} \quad \text{(Equation 10.9)}$$

For this equation D_{50} is needed, and can be solved for according to the relations provided in Washington's Stream Simulation Design.

$$\left(\frac{D_{84}}{D_{50}}\right) = 2.5$$
$$D_{50} = \left(\frac{D_{84}}{2.5}\right) = 0.36\, ft$$

Channel depth is also needed, taken from analysis based on a 6:1 triangular channel at the fish passage design flow.

$$depth = 1.1\ ft$$
$$R = 0.52\ ft$$
$$\left(\frac{8}{f}\right)^{0.5} = 1.11\left(\frac{depth}{D_{84}}\right)^{0.46}\left(\frac{D_{84}}{D_{50}}\right)^{-0.85} \cdot (S_{culv})^{-0.39}$$
$$V_m = 1.11\left(\frac{depth}{D_{84}}\right)^{0.46}\left(\frac{D_{84}}{D_{50}}\right)^{-0.85} \cdot (S_{culv})^{-0.39} \cdot (g \cdot R \cdot S_{culv})^{0.5}$$

$V_m = 1.48\ ft/s < 4.0\ ft/s$, which is acceptable for fish passage

12.2.2.2 Turbulence

Turbulence is then checked through the calculation of channel EDF

$$EDF = \frac{\gamma Q_{fp} S_{culv}}{A} \quad \textit{(Equation 3.1)}$$

$$\gamma = 62.4 \frac{lb}{ft^3}$$

$$S_{culv} = 0.023$$

Q_{fp}=9.7cfs

A=6.53 ft^2 *(based on a triangular low flow channel with 6:1 side-slopes)*

$$EDF = 2.13 \frac{ft \cdot lb}{ft^3 \cdot s} < 7.0, \textit{ and is acceptable for fish passage design}$$

12.3 HYDRAULIC DESIGN

12.3.1 John Hatt Creek Case History

Source
FishXing Case Studies (United States Forest Service 2006b)
Study from Sebastian Cohen P.E., California Dept. of Transportation

Location
Navarro River Watershed, Northern California, USA

Project Type
Culvert Rehabilitation with Metal Insert
Corner Baffle Retrofit
Hydraulic Design
Placement of Concrete Weirs Below Outlet

Pre-project Conditions
5.5 ft (1.7 m) diameter CSP, 172 ft (52.4 m) long, at 2.4% slope
Culvert distorted (out of round) and deteriorating
Culvert bottom lined with concrete
Concrete drop structure at culvert inlet

Pre-Project Barrier
Insufficient depth, high velocities, excessive leap (Figure 12.11)
Partial barrier to adult steelhead trout
Total barrier to juvenile salmonids

Hydrologic Characteristics
Drainage Area: 0.6 mi^2 (1.6 km^2)
2-year Peak Flow: 60 cfs (1.7 cms)
Design Capacity (100-year Flow): 266 cfs (7.5 cms)
Headwater-to-diameter ratio at 266 cfs (7.5 cms) = 2.5
Adult Steelhead Passage Design Flows:
Upper = 30 cfs (0.85 cms), 50% of 2-yr peak flow
Lower = 3 cfs (0.08 cms)
Juvenile Salmonid Passage Design Flows:
Upper = 6 cfs (0.17 cms), 10% of 2-yr peak flow
Lower = 1 cfs (0.03 cms)

Channel Characteristics
100-year Flow: 2,100 cfs (59.47 cms)
2-year Flow: 415 cfs (11.8 cms)
Drainage Area: 3.61 mi^2 (9.3 km^2)

Ecological Value
Provide access to 0.6 miles (0.9 km) of upstream spawning and rearing habitat for steelhead trout

Project Characteristics
Insert a 3/8 inch (0.9 cm) thick welded steel pipe, 5 ft (1.5 m) diameter and 172 ft (52.4 m) long into existing culvert
Weld 43 steel corner baffles into pipe insert
Baffles 8.3 inches (21 cm) tall at center and spaced 4 ft (1.2 m) apart
3 precast concrete weirs with wooden low-flow notches below culvert outlet
9 inch (23 cm) drops between concrete weirs

Challenges and Lessons Learned
Bedrock surrounding culvert made "jacking" a larger pipe through the fill impractical
Existing culvert was out-of-round so smaller culvert had to be inserted
Only 25 ft (7.5 m) right-of-way available below culvert outlet for grade control weirs
Lack of rock armoring, and weirs not sufficiently keyed into banks resulted in flanking
Wooden low flow notch in center of concrete weir causes plunging water to strike concrete lip at low flow.
Need for inspection by personnel familiar with fish passage design concepts and objectives

Project Description
The existing 5.5 ft (1.7 m) diameter corrugated steel pipe (CSP) was deteriorated and identified as a depth barrier at low flow and a velocity barrier at high flow for adult and juvenile steelhead. The culvert required rehabilitation due to its deteriorated conditions. Retrofitting involved inserting a 5 ft (1.5 m) diameter, 172 ft (52.4 m) long, welded steel pipe (WSP) into the existing culvert at a 2.4% slope. This design was selected after removing the fill to replace the culvert was deemed too costly.

Baffles were designed to satisfy, as best as possible, State and Federal velocity and depth criteria for fish passage while avoiding excessive turbulence. Hydraulics of corner baffles at fish passage flows were modeled using empirical equations developed by Rajaratnam and Katopodis (1990) and provided in WDFW (2003). The energy dissipation factor (EDF) was calculated as a measure of turbulence.

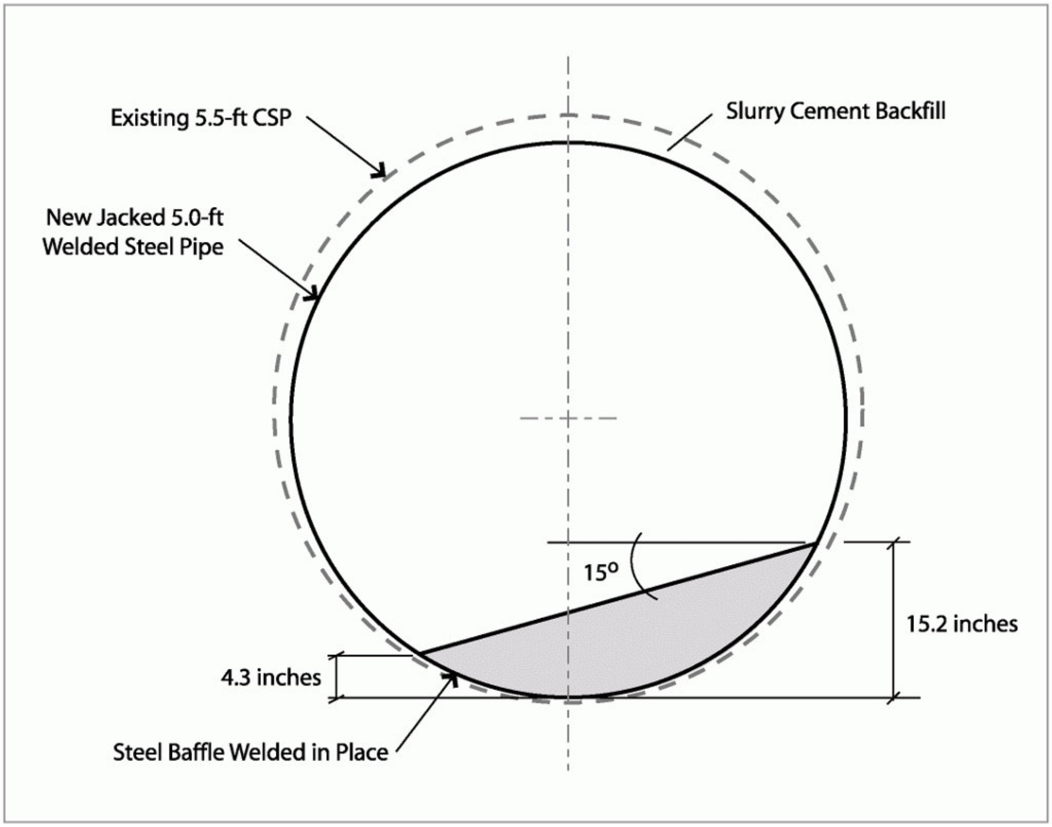

Figure 12.11. Top of the 9 in tall baffles were placed at 15 degrees to horizontal. The left and right edges are 4.3 in and 15.2 in above the invert, respectively.

Table 12.1. Modeled hydraulic conditions at fish passage design flows for John Hyatt Creek.

Species/Lifestage:	**Juvenile Salmonids Passage Flows**		**Adult Steelhead Passage Flows**	
Fish Passage Flow:	Lower	Upper	Lower	Upper
Flow:	1 cfs	6 cfs	3 cfs	30 cfs
Water Depth:	0.6 ft	1.1 ft	0.8 ft	2.0 ft
Ave. Water Velocity:	0.9 ft/s	1.9 ft/s	1.4 ft/s	4.1 ft/s
Turbulence (EDF):	1.5 lb-ft/s/ft^3	3.0 lb-ft/s/ft^3	2.2 lb-ft/s/ft^3	6.0 lb-ft/s/ft^3

A total of 43 corner baffles were welded into the pipe prior to insertion. Baffles constructed of 3/8 inch (0.9 cm) thick steel and spaced 4 ft (1.2 m) apart. The 9 inch (23 cm) tall baffles were rotated 15 degrees from horizontal, resulting in the low and high sides of the baffle located 4.3 and 15.2 inches (11 and 39 cm) above the invert, respectively. The gap between the existing and new pipes was filled with concrete slurry to prevent seepage.

The existing culvert outlet was perched nearly 1.5 feet (0.5 m) above the downstream water surface and the channel below the culvert was steep. To improve fish passage conditions at the outlet, three precast concrete weirs were installed within the 25 ft (7.5 m) right-of-way below the outlet. The concrete weirs were spaced 8 ft (2.5 m) apart with 9 inch (23 cm) drops. The weirs were keyed into the bank approximately 2 feet (0.6 m). Although facing class rock was to be placed on both banks between the weirs for scour protection, the contractor only placed rock on the left bank.

Post Project Observations and Lessons Learned
The baffles appear to be effective at reducing water velocities and increasing water depth within the pipe. The weir crest elevations below the outlet were placed within design tolerances.
Rock was only placed on the left bank below the outlet which allowed for rapid bank erosion, resulting in flanking of the weirs. The bank was rocked later to prevent further erosion. Placing rock along both banks, as designed, and keying the weirs further into the banks may have prevented flanking.
A design problem with the wooden low-low notch was also discovered. The wood is not set flush with the downstream edge of the weir. Instead of plunging directly into the downstream pool at low flows, the water strikes the lip of the concrete weir. Installing a steel low-flow notch flush with the downstream edge of the concrete weir would create the desired plunging conditions at low-flow.
A steep slab of existing concrete at the culvert inlet was to be removed as part of the project. However, it was left in place. Using inspectors familiar with the project's fish passage objectives may have avoided some of these problems.

Completion Date
October 2003
Total Project Cost
Construction: $140,000

Figure 12.12. A 5 ft diameter welded steel pipe was inserted into the pre-existing culvert, concrete slurry was used to fill the gaps.

Figure 12.13. Outlet of John Hyatt Creek culvert perched at 1.5 ft, block migrating steelhead.

Figure 12.14. Steel corner baffles welded to the pipe and spaced 4 ft apart. Baffle height provides 6 in of water depth at the juvenile low flow passage design flow of 1 cfs.

Figure 12.15. At high flows, baffles slow water velocities while producing minimal turbulence. Along the low side of the baffles, velocities are swift, improving passage of debris and sediment, while the high side of the baffle experiences slower velocities suitable for both adult and juvenile fish.

Figure 12.16. Culvert outlet after installation. Weirs below outlet were precast and lowered into place. Weirs were keyed into the bank roughly 2 ft and the contractor neglected to rock the left bank. The inspector failed to enforce this oversight.

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13 CONSTRUCTION AND MAINTENANCE

13.1 CONSTRUCTION

The following construction topics have unique applications in culverts designed for fish passage. Topics are not covered in-depth; however, links to pertinent references are included.

13.1.1 Timing

Timing of in-stream work will need to correspond to specific periods allowable by resource agencies. An in-stream work permit will be required.

13.1.2 Constructability

It is important to consider constructability of any culvert installation. The successful construction of culverts utilizing natural bed material is contingent on the ability of crews to place rock within the structure. In general, this leads to the requirement that culverts span a minimum of 6 ft (i.e. Bates et al. 2003). Depending on size of pipe and bed materials, placement has been done by a number of methods including Dingo Loaders, rock chutes, wheel barrows and trail building equipment. Due to the difficulty involved with mixing bed materials on site, it is also recommended that material be mixed prior to placement. Rock bands and banks must be placed by hand (United States Forest Service 2006a).

13.1.3 Bed Mix Specification

When specifying engineered bed material, the design engineer should ensure that materials and compositions are appropriate for the design. This should include a "pit run" where the design engineer examines the composition of rock piles to ensure adequacy.

When a pit cannot specifically guarantee the composition of a pile, it will be necessary to verify the adequacy of the material. WDFW recommends the following techniques:

- Count and measure all of the particles within a pile or a random sample (similar to a stream pebble count).
- Measure the largest and smallest particles present, and gage the distribution of intermediate sizes by eye to ensure that the mix is well graded.

The following example from Washington Department of Fish and Wildlife is intended to help clarify the process of material gradation for stream simulation (Bates et al. 2003).

The required bed gradation has been determined to be:

D_{100} = 1.25 ft.
D_{84} = 0.5 ft
D_{50} = 0.2 ft
D_{16} = 0.06 ft

What this means is that 16 percent of the material is less than three quarters of an inch, including roughly equal proportions of small gravel, sand and silt. Sixteen percent is between 0.5 to 1.25 feet, which, when viewed from above, will compose 1/6th of the channel surface. The remaining 68 percent is basically well-graded gravel and cobble. If a gravel pit is making up this mixture, then piles of material need to be assembled in proportions that approximate the desired gradation. One approach is to use parts or "scoops" of a given component. For the example mixture here, a very simple recipe could be: four scoops of six-inch-minus pit run with fines, plus one scoop of eight- to 15-inch rock.

13.1.4 Sealing Voids

In culverts with placed sediments, especially those involving the use of oversized sediment mixes, it is important to limit permeability. Without such considerations, a significant portion of flow may seep through interstitial voids, causing the stream to go subsurface. Methods to limit permeability include placement of filter fabric (Browning 1990), and including an adequate proportion of fine sediments in bed mixes (Bates et al. 2003; Bates et al. 2006). During construction, fines can be power-washed into voids to ensure, and expedite, bed sealing. This will also decrease the sediment concentration entering the stream system after the first flow event.

13.1.5 Compaction

For constructed bed culvert installations, bed material is placed in thin layers, compacted, and covered with filler material to be washed into voids (United States Forest Service 2006a). Smaller material should be well compacted around larger elements (Bates et al. 2006).

13.2 MAINTENANCE

Maintenance is advisable at regular intervals and after flood events. This may be especially important at installations in areas with significant amounts of LWD, or at crossings with a propensity to collect debris (baffled culverts, fishways). Standard culvert problems and treatments are listed in the Federal Highway

Administration *Culvert Repair Practices Manual Volume I* (Ballinger and Drake 1995). Properly designed and constructed fish passage culverts will still require regular maintenance and monitoring to ensure continued performance.

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14 MONITORING

Although much research has been done to understand the requirements of fish passage gaps in knowledge, nuances in fish behavior, and lack of adequate hydraulic and hydrological data result in criteria that are likely quite conservative (Furniss 2006). A monitoring program will help ensure that structure impact on fish passage is more clearly understood, allowing future criteria for assessment and design to be more effective, and aiding in reducing future expenditures for fish passage (General Accounting Office 2001)

14.1 PURPOSE AND SCOPE

The three types of monitoring listed in Table 14.1 can be carried out on a fish passage project (Collins 2003).

Table 14.1. Types of monitoring (Collins 2003).

Type of Monitoring	Description
Implementation	Determination of whether culvert is installed as planned, providing a baseline for future monitoring.
Effectiveness	Evaluation of whether a proper installation is having the desired effects.
Validation	The evaluation of a model's ability to predict events or performance.

For the purposes of fish passage monitoring, implementation and effectiveness monitoring are the most pertinent consideration (Collins 2003). Barnard's study of stream simulation culverts in western Washington is an example of effectiveness monitoring, and has allowed a better understanding of variables (i.e. width ratio and slope ratio) leading to successful stream simulation (2003).

For fish passage installations, implementation and effectiveness monitoring protocols might be used to answer the following questions (Collins 2003):

- Are restoration projects being carried out as proposed?
- Are restoration projects having the intended results?
- Are fish and other aquatic organisms responding in a positive way to the restoration treatments?

14.2 METHODS

Monitoring should begin with clear project goals that will allow the development of measurable parameters to allow "success" to be quantified (Committee on Restoration of Aquatic Ecosystems 1992). Ideally, monitoring might include direct observation of fish movement and utilization, but should at least focus on project compliance with design specifications such as substrate retention and the ability to maintain fish passable conditions (Furniss 2006).

Beginning with project goals in mind, parameters and field methods should be aimed at comparing current physical conditions to design performance criteria. Building upon this type of analysis, Harris (2005) developed the following criteria (Table 14.2) for fish passage installation effectiveness monitoring in California.

Table 14.2. Monitoring Questions, Parameters, Effectiveness, Criteria and Field Methods (adapted from Harris 2005).

Monitoring Question	Effectiveness Criteria	Parameters	Field Methods
1. Is the project still functioning as designed?		Fish passage restoration project is within DFG passage guidelines	
a. Is there still a sufficient jump pool depth for targeted species and life stages?	Residual pool depth at downstream outlet (if culvert outlet is perched or has entry leap).	If there is a jump, pool depth is appropriate for leap height. (Not required for no entry leap)	Thalweg profile through culvert plus water depths
b. Are leap heights still within jumping ability for targeted species and life stages?	Leap height (residual pool water surface elevation to passage outlet.)	Leap height is below critical heights for targeted species and life stage. (Not applicable for no entry leap.)	Thalweg profile through culvert.
c. In stream velocity in critical flow areas still within the swimming ability of the target species and life stages?	Stream velocity	Stream velocity is equal to or less than swimming ability of target species and lifestage.	Stream velocity/discharge measurements.
d. Is upstream inlet of the passage area/structure still at grade or below the channel bed?	Bed elevation at inlet and inlet elevation	Difference between natural channel bed and inlet is 0.	Thalweg profile through culverts
e. Is the passage area/structure still at grade?	Slope	Passage structure is at specific designed slope or the slope relative to the natural channel.	Thalweg profile through culvert
f. Can sediment bed load still pass through the restored area?	Slope (top riffle to opening), active channel width, hydraulic capacity.	Passage inlet shows no signs of clogging or deposition.	Thalweg profile through culverts, Cross section surveys
g. Can the structure pass 100-yr flows and debris	Hydraulic capacity	Passage passes 100-yr flows and watershed products.	Cross section surveys.
h. Does the passage project show signs of imminent failure?	Structural integrity	Structure shows no signs of collapsing	Thalweg profile through culverts, Cross section surveys
2 . Have channel or bank adjustments impaired the function of the passageway?	Slope, head-cutting, sediment deposition.	Channel adjustments have not impaired passage or habitat values.	Thalweg profile through culverts
3. Did the project have adverse effects on upstream or downstream habitat?	Bank erosion, channel incision/head-cutting, debris accumulation or sediment deposition.	Passage project has not adversely affected up and downstream habitat.	Thalweg profile through culverts, Cross section surveys
4. Is upstream habitat still suitable for the targeted fish species and life stages?	Habitat types and quality in upstream reaches.	Area is still suitable for targeted species and life stages.	Habitat monitoring.

14.2.1 Inventory and Assessment

Inventory and assessment, as outlined in Chapters 4-6 is a form of effectiveness monitoring that will allow designers to gain design experience through an understanding of the impact that structures have on a stream reach and fish populations. Many design techniques, such as those described in Browning's survey of culverts in Oregon (1990), were derived from field observations of existing structures, and can continue to be modified as monitoring provides insight into the sustainability and impact of specific culvert design elements.

14.2.2 Surveying and Field Inspection

Monitoring, surveying, and field inspection should focus on many of the same elements described in Chapters 4-6. This can include consideration of channel slope and elevation, culvert slope, crossing inlet and outlet conditions, existing bed material, and debris accumulation. Photos, benchmarks, monumented cross sections, and floodplain and terrace elevations can be useful in determining the culvert impact on the surrounding stream, and to determine if channel incision has occurred (Castro 2003). A major question to ask while in the field is - Is this culvert functioning as intended? (Furniss 2006).

14.3 FREQUENCY

All culverts with a span greater than 20 ft (bridge) must be inspected on a two year cycle in order to comply with National Bridge Inspection Standards (Ballinger and Drake 1995). For smaller culverts, it is recommended that culvert monitoring should be conducted at regular intervals to determine the effectiveness of crossing methods and installations. Pre and post project monitoring (implementation monitoring) should be followed by regular evaluation (effectiveness monitoring). These may be performed in response to large flow events or at specific intervals corresponding to regular maintenance or inspection. An effective monitoring plan will ideally be factored into the cost of any fish passage structure.

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15 FUTURE RESEARCH NEEDS

15.1 FISH MOVEMENT AND RESPONSE

To allow specific engineering of fish passage structure, further studies of fish response to turbulence, darkness, and velocity are necessary.

15.2 MONITORING

Monitoring of current installations is an important step in understanding the impact of state-of-practice design techniques on stream structure, function, and biology. Development of case histories will allow others to learn from the successes and failures of current fish passage installations.

15.2.1 Hydraulic Simulation Structures

As fish swimming capabilities and movement requirements are better understood, it will be possible to better engineer these structures. However, variations in local hydrology and dynamic stream systems will ensure that a conservative approach is required.

15.2.2 Hydraulic Design Structures

Gregory (2004) recommends the incorporation of before and after studies at hydraulically designed structures. This could include field and test bed experimentation with live fish, or comparison of fish passage within the natural reach to passage through retrofitted culverts (Gregory et al. 2004).

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