PART XII

FISH PASSAGE DESIGN AND IMPLEMENTATION

This page left blank to help facilitate two-sided printing.

ADVISORY NOTE

This manual describes fish passage approaches and techniques used with varying degrees of success by passage and watershed restoration specialists. The approaches and techniques described here are not all-inclusive and represent only a starting point for project design and implementation. They are not surrogates for, nor should they be used in lieu of, a project design that is developed and implemented according to the unique physical and biological characteristics of the site-specific landscape and ecology.

The techniques and approaches described in this manual do not replace the need for services of professionals with the appropriate expertise, including but not limited to licensed professional engineers or licensed professional geologists, where such expertise is called for by the Business and Professions Code section 6700 et seq. (Professional Engineers Act) and/or section 7800 et seq. (Geologists and Geophysicists Act).

Part XII replaces "Human Induced Obstructions, Fishways and Culverts" (pages VII – 51 through VII – 61) in the February 1998 version of the *California Salmonid Stream Habitat Restoration Manual.*

This page left blank to help facilitate two-sided printing.

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

This page left blank to help facilitate two-sided printing.

ACKNOWLEDGEMENTS

The principle authors of Part XII, Fish Passage Design and Implementation are Michael Love and Kozmo Bates, Professional Engineers with extensive experience in fish passage engineering. Mr. Love, as the principal engineer for Michael Love & Associates, has designed, implemented, and learned from numerous fish passage and stream restoration projects throughout Coastal California. Mr. Love is a primary developer of the United States Forest Service FishXing software and learning systems. Mr. Bates is a consulting engineer with over thirty years of experience designing and implementing fish passage and habitat restoration. Together Kozmo and Michael regularly lead fish passage trainings, workshops, and field tours throughout California and beyond.

Contributing authors include Dr. Margaret Lang of Humboldt State University and Rachel Shea and Antonio Llanos of Michael Love & Associates. They provided invaluable technical, editorial, and artistic contributions to this document. Funding for the development of Part XII was from the California Department of Fish and Game (CDFG) Fisheries Restoration Grants Program through a grant to Pacific Coast Fish, Wildlife and Wetland Restoration Association.

Gary Flosi the CDFG grant manager and lead editor for Part XII wants to recognize the following individuals for their contribution to this project. Chris Ramsey and Barry Collins (CDFG) deserve special recognition for their assistance with editing and formatting. Marcin Whitman and Margie Caisley from the CDFG Fisheries Engineering Team were the lead reviewers concerning technical issues. George Heise and Kris Vyverberg from the Fisheries Engineering Team also contributed to this project. Additional CDFG reviewers included Scott Downie, Bob Coey, Margaret Paul, Mary Larson, and Mark Smelser. In addition the following people provided edits and comments: Richard Wantuck and Margaret Tauzer (NOAA); Conor Shea (USFWS); Bruce Swanger (CalTrans); and Ted Frink, Randy Beckwith and James Newcomb (DWR).

This page left blank to help facilitate two-sided printing.

INTRODUCTION

There are numerous barriers to the movement of fish and other aquatic organisms in streams and rivers in California. Barriers range from highways, flood control projects and large dams to small road crossings and water diversion dams. Such barriers can exclude species from tributaries, and often greatly fragment habitats and isolate populations of fish and other aquatic organisms.

This document provides technical guidance for the design of fish passage projects at stream crossings, small dams and water diversion structures. Options include, in order of preference, range from having no structure to constructing fishways.

Complex facilities at large dams are not included, though many of the principles apply. This document is intended to help guide the designer through the general process of selecting an appropriate design approach to improve passage for fish and other aquatic organisms (simply referred to as fish passage in the remainder of Part XII). It provides concepts, a design framework, and procedures to design stream crossings and fishways that satisfy ecological objectives.

This document is intended to be a guide for the designer through the general process of selecting a design approach for passage improvement. It provides concepts, a design framework, and procedures to design stream crossings and fishways that satisfy ecological objectives, including the passage of fish and other aquatic organisms.

These guidelines are meant to supplement existing state fish passage criteria (Appendix IX-A) and federal guidelines (Appendix IX-B). The designer should refer to those and other documents, standards and experts for structural, roadway, geotechnical, and other engineering and environmental considerations associated with the design.

Each site is unique, and conditions will often require individual solutions. These guidelines advocate a principle that the best fish passage design is the one that provides for all or most of the following ecological objectives:

- Efficient and safe passage of all aquatic organisms and life stages
- Continuity of geomorphic processes such as the movement of debris and sediment
- Accommodation of behavior and swimming ability of organisms to be passed
- Diversity of physical and hydraulic conditions leading to high diversity of passage opportunities
- Projects that are self-sustaining and durable
- Passage of terrestrial organisms that move within the riparian corridor.

A design that emulates natural systems is the one most likely to satisfy ecological objectives. Designs described here might at least partially accommodate for movement of terrestrial species, but these guidelines do not attempt to design specifically for this objective.

Figure XII-1 shows a range of project types, design approaches, and solutions in a spectrum of ecological value. This figure is a basic guide to this manual; it shows many of the tools discussed in this guide in more or less the order that they are presented.

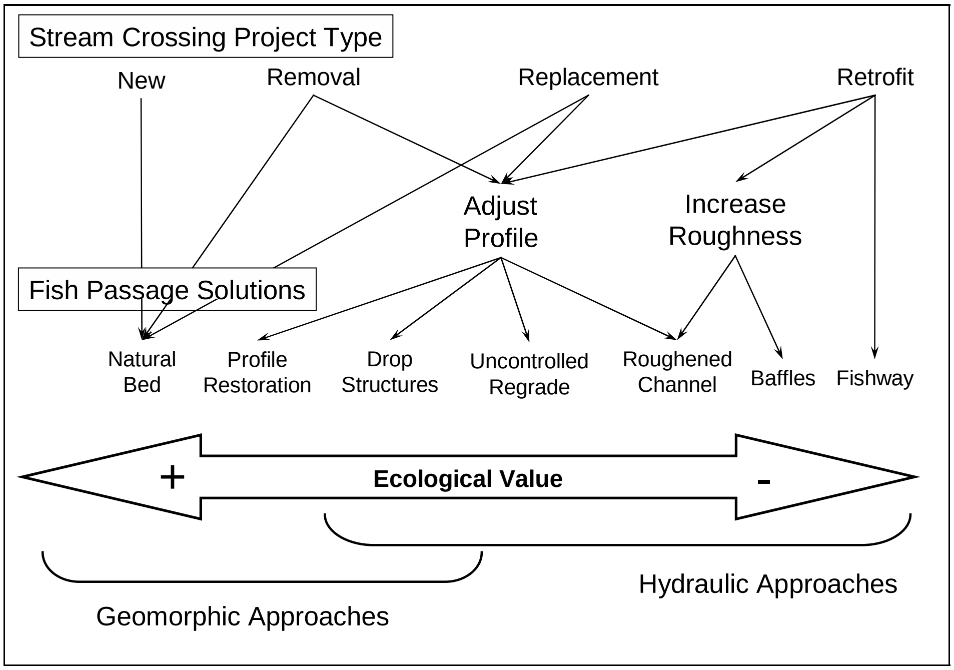


Figure XII-1. Spectrum of Ecological Solutions for Fish Passage.

Across the top of Figure XII-1 are examples of fish passage projects encountered. Projects range from the construction of a new stream crossing culvert to the retrofit of an existing culvert or dam. The type of project leads to one or several tools or solutions shown in the lower rows of Figure XII-1. The tools and solutions that are chosen and shown connected in the figure are generally based on the ecological principles described above. Profile adjustments and roughness are tools in the design process. These project types and the solutions presented in the figure are generally in order of ecological value with highest values to the left. For example, a natural bed solution has a greater ecological value than use of profile control, adding baffles to a culvert, or a constructing a fishway.

The solutions on the left are based on geomorphic principles; they mimic natural conditions and are flexible and resilient. The solutions on the right are based on structural and hydraulic principles and are more rigid. The terms geomorphic and hydraulic solutions are the basic classification of fish passage solutions used in this manual. A geomorphic solution is based on the premise that a channel that simulates characteristics of the natural channel will present no more of a challenge to movement of organisms than the natural channel. A hydraulic solution is based on the premise that a structure with appropriate hydraulic conditions will allow target species to swim through it. These approaches are further described in Select the Design Approach (page XII-15).

Some of the approaches and analyses described are more rigorous than is necessary for simple sites; an experienced design team will be able to streamline the process in many cases. Many sites however have unique challenges that can only be solved by applying an in-depth understanding of the biological, hydrologic, geomorphic, and structural components of the design. For complex sites, the use of an interdisciplinary design team is encouraged. To be successful, it is important to recognize where a higher degree of rigor is needed and to engage specialists in the design when appropriate. This document is not comprehensive for all situations. It refers to other guidance documents that have additional detail. This document does not cover passage at large dams that might require complex facilities such as trap-and-haul systems, auxiliary water systems, or multiple fishway entrances.

Figure XII-2 shows a general design process for fish passage projects. The layout of this guideline generally follows this sequence of steps.

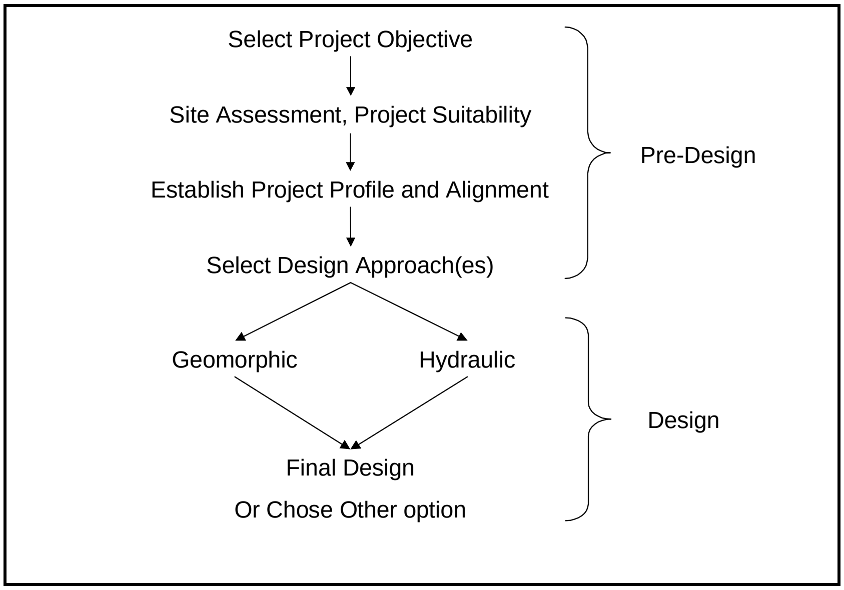


Figure XII-2. General Fish Passage Design Process.

The development of objectives, preliminary site assessment, and an understanding of potential project layout and profile are necessary before selecting the preferred design approach. These steps are considered pre-design, which are discussed in Pre-Design for Fish Passage Projects (page XII-3) and Stream Crossing Layout: Alignment and Profile (page XII-16). Additional pre-design steps might be needed depending on the design approach selected. The formal design process includes design criteria, the detail design, and steps specific to the selected design approach. These design steps are described in Geomorphic Designs at Stream Crossings (page XII-28 through Fishways (page XII-107). The final design comprises of final dimensions and details, structural elements, and construction considerations necessary to complete the project. Designs are often not as simple as implied here. Steps may be iterative as solutions or assumptions are selected, tested, and modified.

PRE-DESIGN FOR FISH PASSAGE PROJECTS

Pre-Design

Pre-design is a step in a stream crossing project that accounts for characteristics of the stream and inter-relationships of the road or dam, stream, and target species. It includes establishing clear project objectives and evaluating channel stability, alignment, and transitions. Watershed and site conditions, including geomorphic context are assessed. Through pre-design, a *project profile* and *planform* stream crossing alignment is developed (Note: words included in the Glossary page XII-139 are identified in the text by being italicized the first time they are used).

When a project fails to satisfy fish passage objectives, it is often because of an inadequate pre-design. This step is needed regardless of the ultimate fish passage design approach used; the design approach should be selected or confirmed at the conclusion of pre-design.

The design process is not necessarily linear. Iterations are needed to complete some parts and a previous phase may have to be re-visited if a satisfactory design cannot be completed with the current assumptions and design decisions.

The scale of project should be appropriate for the ecological resources at stake. Information needed and the process used to identify the appropriate fish passage design strategy for a site includes gathering information on site-specific issues such as the project objectives, site constraints, channel morphology, species, and existing and potential habitat characteristics and values.

The pre-design should provide a framework for designers and interested parties to make decisions requiring trade-offs regarding channel profile, self-sustainability and habitat issues.

Pre-Design Site Assessment

Any structure set into a dynamic stream channel should fit the context of the system without interrupting the geomorphic processes that define the system. For a project to fit the context of the watershed, reach, and site, relevant information is gathered and interpreted. Information requirements and level of detail will vary from site to site depending on the scale of the project, site complexity, project objectives, and the design approach used.

An inter-disciplinary approach is very helpful for this part of the design and the pre-design assessment is the most important stage for a range of disciplines to be involved. The inter-disciplinary team may include experts in aspects of biology, geomorphology, geology, hydraulics, sediment transport, hydrology, construction, structural design, and others. Characteristics that might lead to seeking additional expertise include failing banks, heavy debris loads, large amounts of sediment stored upstream of an existing crossing, *headcut* issues, channel instabilities, complex channel shapes, and unusual alignments or road configurations.

Aspects of a site assessment might include physical and habitat surveys, channel characterization, pebble counts, hydrologic correlations, geotechnical investigations, etc. Careful and thorough documentation of the various assessment procedures is essential. Assessment data needs will vary by project and will include many of the following parameters:

- A description of existing structures; dimensions, conditions, history, etc.
  - Stream, road, culvert alignments and road vertical alignment
- Recent flood history and flood evidence at the site
- Channel characteristics
  - Survey the longitudinal profile of the existing channel thalweg (long profile). Record survey points at unique and repeatable geomorphic features such as heads of riffles and step crests (see Harrelson et al. 1994).
  - The long profile should extend upstream and downstream further than the existing or new culvert might affect the channel. The survey length depends on the scale of the project, the vertical drop through the existing crossing, and the *mobility* of the streambed. A sand-bedded channel may mobilize for thousands of feet upstream; a steep boulder dominated channel may not be affected at all. Survey low and high-flow hydraulic controls, bed controls, and grade breaks. Note channel dimensions, key bed and bank features, bed material, and *floodprone width.*
  - For stream simulation design, consider what reach will likely be a *reference reach* and include it in the profile if it is contiguous with the project channel reach, or survey it separately if it is not.
  - Identify *key features*, observations of unique channel characteristics, and locations where channel characteristic were measured.
  - Measure representative *bankfull* channel, *active channel*, and/or *ordinary high water* width.
  - Survey channel cross-sections immediately upstream and downstream of any existing structure and two additional cross-sections upstream and two additional cross-sections downstream of the influence of any existing structure.
  - Identify general bed and bedform characteristics. Various channel classification systems are useful to describe the channel (see Montgomery and Buffington 1997 and Rosgen 1996).
  - Identify any features that might affect the long profile or channel alignment for the life of the project such as debris and sediment sources and current or likely bank erosion. Identify size, spacing, function (*profile control*, *roughness*, confinement, and bank stability), bed drop, and permanence (*mobility* and condition) of *key*

channel features and grade controls. Key features are permanent or semi-permanent structures such as bedrock outcrops, large woody debris, stable debris jams, boulder steps, and human made structures that control the channel shape and/or grade, *bedforms*, and bed material sorting.

- Representative floodprone width
    - Estimate conveyance of floodprone area using an assessment of floodplain characteristics such as width, elevation, and roughness.
- Geomorphic stage and evolution of the channel
    - Channel history (e.g., historical realignment, placer mining, splash dams, removal of large wood from channel, upstream dams and debris basins).
    - Assess the potential headcut impacts upstream of the crossing (see Headcut Issues page XII-25).
    - Establish the *vertical adjustment profiles*, estimating range of elevations the channel might experience through the reach in the lifetime of the new stream crossing. This is a key to setting the elevation of the culvert and/or profile control structures (see Channel Vertical Adjustment Profiles page XII-20).
- Channel stability
    - Identify the dominant controls of profile and alignment.
    - Determine the likelihood of channel *aggradation* or *incision* in the lifetime of the crossing. Consider the likelihood of changes to hydrology, sediment input, development, base level change, loss of major profile controls, etc. Roni (2005).
- Bed mobility
    - A mobile bed is characterized by bedforms that indicate recent deposition. General characteristics include sand to gravel bed material, steep faces on bars, no vegetation on bars, no moss on bed material, no *armor layer* or *imbrication*, and bed material loose rather than compacted.
    - An immobile bed does not move frequently compared to the life of the structure. Characteristics include cobble to boulder bed, exposed bedrock, *cascade* or *step-pool* channel, vegetation or other evidence of infrequent bed movement, well *armored* or imbricated bed. An immobile bed may be present with mobile bed material moving over it.

- Hydrology
  - Continuous flow gaging, peak flow gaging, basin correlations, hydrologic regressions
  - Qualitative hydrologic characteristics of basin
  - Expectations of future watershed conditions that might affect hydrology
  - Hydrology assessment products
    - Fish passage design flows
    - High structural design flow
- Other nearby infrastructure.

The key is to understand the potential use of each parameter or procedure and apply standard assessment protocols appropriately for that use. Detailed methods and protocols for these assessments are described in other parts of the *California Salmonid Stream Habitat Restoration Manual* and by USFS (2008) and Harrelson et al. (1994).

Results of the pre-design assessment should be adequate to inform another designer of enough detail of the watershed, site, and decision process that they can do an appropriate and independent design.

Design Data Forms

Several design data forms are included in Appendix XII-A to guide, document, and assist the design and review of stream crossing projects. There are two data forms, one for stream simulation design and a second for use with either of the hydraulic design approaches (baffles, profile control). The design data forms include only fish passage, geomorphic, and hydrologic design information; also document other aspects of the project (e.g., traffic, geotechnical, road characteristics) during pre-design. Attach a plan view sketch and a long profile to the design data form. See the design guide for background for all data and details recommended on sketches.

Summarize data to show design milestones, assumptions, and conclusions. The last step of the pre-design, as described here, is selection of the approach for fish passage design. It is important to document project milestone decisions such as how the design approach was selected.

Establishing Project Goals and Monitoring Objectives

The primary goal for fish passage projects is to obtain unimpeded fish passage; however, projects may have additional goals to meet the needs of particular interest parties. For example, instream crossing projects may also include road and transportation goals. There may also exist program (e.g., funding limitations), and environmental goals to accommodate as well. When the goals of the various interested parties appear to conflict, their basic needs and objectives need to be understood and addressed. A good project manager will recognize potential conflicts early in the process so they are resolved before they unnecessarily stall the project. Consider using an independent facilitator if differences are substantial.

Fish passage projects should include an expected and achievable level of fish passage as an objective. In addition, specific, measurable objectives need to be developed to address other project goals adopted. CDFG biologists, in consultation with NOAA Fisheries biologists, will evaluate needs for aquatic species passage and ecological considerations for in-channel structures on a case-by-case basis. Biologists will consider the following in determining the need for passage of aquatic organisms at a site:

- Presence/absence and health of aquatic species populations
- Aquatic species and life-stages currently or historically present and watershed goals for species or fish community restoration
- Potential habitat gain upstream
- Presence of exotic and/or invasive species; on occasions, passage may not be desirable at a stream crossing structure in order to maintain separation of aquatic species
- Condition and value of habitat upstream (and downstream) that might be affected by the project (i.e., is incision acceptable with regards to meeting project objectives)
- Movement needs of non-fish aquatic species
- Movement needs of terrestrial wildlife.

Clear project objectives are needed to ensure all project goals are achieved. They are the specific measures (e.g., construct a self-sustaining stream simulation bed) used to determine whether the project was successful in achieving the objectives.

Objectives are often stated as written quantitative design criteria, which should be referred to when making design and planning decisions. By clarifying expectations (e.g., how many, to what degree, under what conditions, etc.) specific objectives make it clear to all parties what is needed to achieve the project goals. Project objectives should become the basis of the monitoring plan. For example, an objective measure of “self sustaining” can be assessed by conducting an as-built survey then monitoring the project over time. A “stream simulation” can be evaluated by comparing the project to the reference reach.

Any of the following measurable objectives might be applied to a specific project:

- Design and construct a self-sustaining stream simulation streambed.
- Design and construct passage for the target species as per the CDFG fish passage criteria that requires no more than a single day of maintenance effort per year
- Entirely mitigate the loss of any riparian habitats and any sediment impacts of the project
- Design the road crossing to have a 50% probability of a longevity of 50 years.

Implementation Monitoring

Implementation monitoring helps to both ensure the project fulfils all of its design objectives, and to document as-built conditions. This requires establishing realistic objectives and developing a design appropriate for the site that is capable of meeting the project objectives and constraints, and then constructing the project as designed. Although Part XII focuses largely on design development, correct implementation of the design is an essential component of a successful project. Construction of fish passage and other in-stream projects frequently requires skills and expertise outside of those typically needed for standard civil construction projects. It is important for the project manager to ensure that those constructing the project have the required skills and fully understand the intent of the design. It is important someone knowledgeable about the specific and most critical elements of the design perform regular field inspections and provide on-site guidance during construction. Elevations and slope are critical elements to any fish passage design, and should be regularly checked during construction. Materials and sources should be approved before the material is produced and hauled to the site. Unanticipated site conditions encountered during construction often require making onsite modifications to the design, which must be documented. The best person to perform this task is usually the project designer, with approval coming from the project manager.

Implementation monitoring is conducted to determine if the project was constructed as designed. This includes an as-built survey and as-built drawings that document any modifications to the original design. Additionally, it is advisable to establish photo-points before construction. Take photos from the established photo-points regularly during and immediately following construction. Refer to Part VIII, "Project Monitoring and Evaluation", and Roni (2005) for more information on conducting implementation monitoring.

Effectiveness Monitoring

Monitoring the effectiveness of a project through time provides information that benefits future designs by identifying activities that are successful and activities that lead to unintended consequences. When effectiveness monitoring identifies problems, action can be taken to remedy the situation. Conducting effectiveness monitoring requires that pre-project objectives, expected project performance, and anticipated channel responses be well documented and implementation monitoring be completed.

The level of monitoring required depends on the type of project, the risk and uncertainty regarding its performance, and the consequences of it failing to meet project objectives. An effectiveness monitoring plan, at its simplest involves at least one post-project visit to make qualitative observations and retake photo-points. The initial post-project visit should occur the first year after the normal high flow period, with revisits occurring after large flood events. Monitoring activities requiring longer-term extensive physical and/or biological surveys might also be appropriate. Physical monitoring may include assessing geomorphic changes to the channel, or in the case of stream simulation, it may involve comparing the channel geometry and profile inside the culvert to those in the adjacent channel reaches. For hydraulic designs, physical monitoring may include measuring water depth, velocities, and hydraulic drops at specific flows to ensure the structure satisfies project criteria. Biological monitoring may include performing fish distribution, population abundance, or spawning surveys upstream and downstream of the crossing, or evaluating the success of revegetation efforts.

A number of the design approaches and techniques described in Part XII are relatively new and their long-term performance has yet to be assessed. Therefore, effectiveness monitoring of these types of projects will help develop a track record and improve guidance for design and construction. For more information on developing an effectiveness monitoring plan, refer to Part VIII, “Project Monitoring and Evaluation”, and Roni (2005).

Ecological Considerations of In-Channel Structures

The placement of artificial structures such as road-stream crossings and dams can result in impacts to aquatic habitats that should be avoided, minimized, or otherwise mitigated. These impacts may be associated with the structure itself or with channel modifications necessary to install, repair or retrofit a structure for passage of fish or other aquatic organisms.

This guideline focuses on passage of aquatic organisms at such structures. Other goals should not be ignored though. The general health of fish populations may be a broader goal and it may depend as much on other impacts as on passage at the structure.

Defining Ecological Connectivity

Connectivity is the capacity of a landscape to support the movement of organisms, materials, or energy (Peck 1998). It generally includes passage of aquatic organisms as described above, but also includes linkages of biotic and physical processes and materials between upstream and downstream reaches.

The health of fish populations ultimately depends on the health of their ecosystems, which includes processes and materials moving through the stream. Biotic linkages includes but is not limited to upstream and/or downstream movement of mammals, birds, and fish, and the upstream flight, and downstream drift of insects and other invertebrates. Physical processes include the movement and distribution of woody debris, sediment and migration of channel patterns.

It is important that woody debris and bed material pass unhindered through the stream crossing structure. When debris becomes trapped at the inlet of a structure, aquatic organism passage barriers are created, and habitat may be degraded both above and below the stream crossing.

Road fills, stream crossings, fords and dams that are small relative to the stream corridor may block some of these functions. These issues are difficult to quantify but can be significant to the health of aquatic ecosystems.

Passage of Fish and other Aquatic Organisms

Designing for passage of fish and other aquatic organisms is the primary focus of Part XII. Barriers whether dams, culverts or road fords that interrupt the movement of organisms may lead to the following impacts to aquatic communities:

- Loss of resident populations by preventing re-colonization of upstream habitats after disturbance events, such as fires, floods or droughts
- Partial or complete loss of populations of migrant species due to blocked access to critical spawning, rearing, feeding or refuge habitats
- Altered aquatic community structure (e.g., species composition, distribution)
- Reduced genetic fitness of aquatic populations making communities more vulnerable to changing or extreme conditions.

These biological impacts result from restricting the movement of aquatic organisms within the stream network. Many fish species move daily, seasonally, and/or during different life stages. Juveniles of many fish and salamander species will also move to disperse after hatching and to find suitable rearing habitat.

To maintain native fish assemblages at appropriate densities, all fish and other aquatic organisms should be free of human-caused barriers to movement. When designing for passage, consider more than just the large and strong adult salmonids. Other native fish may become extirpated from the watershed upstream during a disturbance event (drought, fire) and not be able to repopulate the area. This extirpation of non-salmonids may have adverse affects on salmonids (e.g., loss of food source).

In addition to adult salmon and steelhead moving during higher flows to access suitable spawning habitat in spring and fall, juvenile salmonids also move during and in anticipation of low flows. The moderating effect of groundwater on extreme water temperatures can also provide motivation for fish movement.

Many crossings may provide “partial” or “temporal” passage, i.e., passage for specific species or size classes, or only under certain flow conditions. In addition to excluding weaker swimming species and life stages, significant migration delays may occur for others (Lang et al. 2004), leaving fish vulnerable to predation, disease and overcrowding, and potentially affecting reproductive success. Fish on spawning migrations will often attempt to pass these structures under impassable conditions and unnecessarily expend critical energy reserves during a physiologically stressful period. Lang et al. (2004) observed adult salmon attempt nearly 600 leaps at one culvert with only five successful entries through the structure. Multiple partial barriers within a stream system can magnify these impacts.

Passage of Wildlife

A consideration for each project is the movement of non-aquatic and semi-aquatic wildlife in some situations, which may or may not be at streams. No specific guidance is given for passage of non-aquatic species. The focus of Part XII is passage of aquatic species but non-aquatic species can certainly benefit from application of some of the designs presented, such as stream simulation.

Many species of amphibians, reptiles, and mammals use riparian zones as travel corridors (Naiman et al. 1993) and the movement of these species may be impacted by certain crossings. Small animals will often use culverts and bridge openings to pass under roads. At some sites, keeping animals off the road can also be a significant public safety benefit. Replacing stream crossings can provide a great opportunity to address both fish and wildlife passage in a single project.

Direct Loss of Aquatic Habitat

Aquatic habitat includes all areas of the environment where aquatic organisms reproduce, feed, and seek shelter from predators and environmental extremes. Stream crossing installations often require some level of construction in the stream channel, which often replaces native stream material and diversity with a uniform concrete or steel surface. Sometimes habitat changes are due to hydraulic effects of the structure.

Each species salmonid, whether anadromous or resident, require specific spawning conditions related to the water velocity, depth, substrate size, gradient, accessibility and space. All salmonids require cool, clean water in which to spawn. Upwelling of groundwater is also important features of spawning habitat. A culvert or other structure placed in spawning habitat replaces the natural gravel used for spawning with a metal or concrete surface. Even if natural substrates are recruited within the structure, the spawning habitat might be shallow or unstable and it will be disconnected from groundwater influence. Spawning habitat loss is especially important because it is usually irreplaceable (Saldi-Caromile et al. 2004).

Juvenile salmonids use almost all segments of the stream environment during some stage of their freshwater residence. Habitat usage is highly variable depending upon the species, life stage and time of year. Pools with large woody debris are valuable habitat. Trees on the stream banks also provide important habitat features, serving as cover and a source of insects and large woody material, both of which critical to rearing fish. The food chain in the stream environment begins with leaves, seeds, branches, and large wood provided by nearby trees, shrubs and grasses. Aquatic invertebrates like mayflies, stoneflies and caddisflies feed on these organic materials and in turn provide an important food source for fish. In addition, mature trees along stream banks provide shade, overhead cover, a source of terrestrial insects and large woody material, which are critical to rearing fish. Removal of riparian vegetation for culvert placement and associated roadway fill impacts these organic inputs and aquatic habitat values. If undersized, stream crossings may also block the recruitment of woody debris to downstream reaches.

Crossings often cause changes to channel alignment, channel diversity, and hydraulic conditions, which may degrade habitats above and below the structure. The configuration and connection of the channel, floodplain, and side channels may also be altered. Mitigation for direct loss of fully functioning natural stream habitats may be difficult. Stream crossing designs that maintain natural stream substrates within the structure, and minimize disruption to the channel and riparian corridors are therefore encouraged.

Floodplain Flows

Floodplains are important components of the aquatic system. During floods, water, sediment, and woody debris may move across floodplains, creating and maintaining unique habitats. In many situations, it is important to maintain floodplain continuity. Floodplains can provide refugia for fish away from the high velocities in the channel. Side channels are often important habitats on active floodplains that provide aquatic organisms passageways to move upstream during floods. Inundated floodplains can connect to off-channel ponds and wetlands that can provide excellent foraging habitat for juvenile salmonids.

The stability of a stream channel depends on its connection to the floodplain. Active floodplains can convey a substantial portion of the total flow during floods and can become depositional areas for sediment and debris. Eliminating a floodplain and *constricting* flood flows to the channel increases scouring forces on the stream's bed and banks and can cause a channel to become unstable.

Road-fills at stream crossing approaches are often raised above the floodplain surface, constricting floodplain flows into the culvert. This causes a discontinuity in the floodplain and can change the erosion and depositional processes that maintain diverse floodplain habitats. Stream crossing design should consider the importance of maintaining flow conveyance on the floodplain and continuity of side channels and other important habitat features.

Risk of Structure Failure

When overwhelmed by high flow, often combined with debris and sediment, a stream crossing structure and roadway fill can act like a dam across the valley and can result in catastrophic failure and/or stream diversion. Structure failures can cause extensive damage to habitat that persists for many years. Failures can be a result of inadequate design, poor construction or maintenance, beaver damming, deterioration of the structure, or severe natural events. The process of evaluating, designing, and installing fish passage or road crossing structures should consider the risk of failure. Typical situations that might entail high risk include presence of large debris, high road fills, and presence of valuable habitat. Sizing a structure for passage of extreme flood events and associated debris and sediment can minimize this risk. Crossing structures should typically designed to accommodate a 100-year flood event. Designing to minimize consequences of failure, such as the consequence of road overtopping, also reduces risk.

Designing road-crossing structures for passage of aquatic organisms is not without risk of failure. There is an inherent risk of failure to provide passage of aquatic organisms with any culvert design. Some designs have more risk and uncertainties than others do. Structures that span the entire channel without constricting it are preferred, compared to engineered solutions described in Part XII that are narrower than that. In some cases, resource values and risk assessment may dictate that engineered solutions are not acceptable.

Other Water Quality Impacts

Storm water runoff from roadways can affect aquatic habitats at road crossings regardless of the type of crossing. Road ditches often drain directly into the stream at a crossing, potentially being a chronic source of sediment and other contaminants. The presence of the road can also increase the risks of slope failures directly entering the stream. Mitigate the quality and quantity of storm water runoff by applying best management practices (BMP's). In general, treat road runoff by minimizing direct discharge to the stream (see Part X).

Channel Maintenance

Undersized, poorly sited, or poorly aligned culverts can create chronic sediment and debris problems (Figure XII-3). Highways are often placed at the fringe of river floodplains and cross the alluvial fans of small streams entering the floodplain. These areas are natural depositional zones, where streams are prone to frequent lateral channel movement. Stream crossings in these locations tend to fill with bed material. To keep the structure from plugging and the water overtopping the road, periodic and in some cases annual channel dredging becomes necessary.

Figure XII-3. Poorly aligned culvert. Note log causing a blockage.

Dredging may affect channel stability, spawning and rearing habitat, and water quality for some distance upstream and downstream. The interruption of bed movement to downstream reaches may also trigger channel adjustments, which may lead to additional channel maintenance activities such as bank armoring.

Poorly designed culverts and bridges can also cause localized bed and bank scour of the upstream and/or downstream channel, which often leads to additional channel armoring.

Construction Impacts

Impacts during construction of a crossing might include the release of sediment or pollutants, the creation of temporary barriers to movement, stranding or killing fish and aquatic organisms, removal of stream bank vegetation, and the alteration of flow. Timing of construction, water, erosion and sediment control planning, and post-construction revegetation, can mitigate some of these issues (see Part IX pages 51-53 for detailed measures). Construction plans submitted for regulatory approval must include fish relocation, and sediment and erosion control plans.

Select the Design Approach

Types of Fish Passage Designs

The design for passage of fish and other aquatic organisms at culverts, fords and dams can be defined in two general categories, geomorphic and hydraulic.

<u>Geomorphic Designs</u>

The specific geomorphic design described below is Stream Simulation. The premise of this design approach is a channel that simulates characteristics of the natural channel will present no more of a challenge to movement of organisms than the natural channel. It is a natural channel design. There is no part of the design specifically directed at target species or their swimming capabilities. In the case of stream simulation in a culvert, the size of the culvert is specified by the stream simulation design. The approach is therefore used for new and replacement stream crossings. It is also used where a culvert is replaced with a bridge, a culvert is permanently removed, or for any new channel design. Details of stream simulation design are described in Geomorphic Designs at Stream Crossings (page XII-28).

> <u>Stream Simulation Design</u>: A channel that simulates characteristics of the natural channel, will present no more of a challenge to movement of organisms than the natural channel.

A simplified version of stream simulation is the Low Slope Approach. It is a conservative design applied only to low risk sites. It is intended for simple culvert installations and is based on the premise that the design of an oversized culvert in a low risk site can be simplified and built with little risk to passage, habitat, and the channel.

> <u>Low Slope Design</u>: the design of an oversized culvert in a low risk site can be simplified and built with little risk.

Details of low-slope design and its limitations including what is meant by "low risk" are described in Low-Slope Stream Simulation (page XII-41).

<u>Hydraulic Designs</u>

A traditional design for fish passage is the hydraulic design. It is based on specific fish passage design criteria that reflect the migration timing, swimming ability, and behavior of selected target species. It is based on the premise that a structure with appropriate hydraulic conditions will allow target species to swim through it.

> <u>Hydraulic Design</u>: a structure with appropriate hydraulic conditions will allow target species to swim through it.

The hydraulic design is used primarily for culverts that are retrofitted to improve fish passage, fishways, and flumes.

Details of the hydraulic design are described in Overview of the Hydraulic Design Approach (page XII-50) and for fishways in Fishways (page XII-107).

STREAM CROSSING LAYOUT: ALIGNMENT AND PROFILE

Project layout includes alignment and profile. Together, they describe the crossing, road, and adjacent channel in space. Alignment is the orientation of the crossing structure and the road relative to each other in plan view or to the adjacent stream channel. Profile can be thought of as the elevation of the channel thalweg at a series of points that describe the crossing and adjacent channel.

Alignment

Culvert alignment is designed concurrently with the *project profile*; which is the channel profile through a crossing that will be constructed or will initially develop following completion of the project. If either changes, the other is affected. In the simplest situation, a straight channel meets the road at right angles, and the upstream and downstream reaches are easily connected through a straight crossing. Alignments are often not so simple.

A culvert that is skewed relative to the upstream channel is hydraulically inefficient. A skewed alignment increases the risk of debris plugging and decreases the capacity of the culvert. It can cause upstream ponding, sediment deposition, and bank scour even if the inlet is not plugged. These risks are associated with high flows, so think of the flow patterns at those flows when considering alignment.

Risk is minimized when a culvert is aligned with the upstream and downstream channels and increased with the angle of the skew. Aligning the crossing structure with the upstream channel often results in a skewed alignment relative to the road however, requiring a longer structure or headwalls.

An objective of culvert replacement projects should be to improve the existing alignment if it is poor. The disturbance of realigning the culvert and channel might be balanced by the reduction of risks of culvert skew.

Due to existing alignments of the road and stream and to other site limitations, there is often no feasible perfect alignment; design alignment is a compromise among several variables. Change of road location and/or alignment might be the best solution. There are situations, such as steep channels controlled and/or confined by bedrock or other features, where realignment is not practical.

Culvert Length

The risk that fish or other organisms will be blocked increases with longer culverts. The likelihood of any erroneous design assumptions or construction inadequacies are increased by added length of culvert. Conversely, culverts are often installed off the channel alignment to minimize length of the culvert and save costs in materials. An objective should be to install the appropriate length of culvert in alignment with the stream channel while minimizing the risk of passage failure and keeping costs reasonable or in line with projected budgets.

A longer culvert is more likely to cut off channel bends, reducing overall channel length. This can have a significant effect on channel stability in the adjacent reaches of sinuous channels. If the meandering channel is in a wide floodplain, the crossing may have compounding risks of concentrating over-bank flow through the crossing. Minimize structure length to manage risk. In some locations, shifting the road location to avoid a bend can be a solution. Additional methods for shortening structures include adding wingwalls, lowering the road elevation, or steepening the road embankment.

These modifications may have inherent implications of cost, safety, and road fill stability. The risks associated with long culverts can also be partially mitigated by increasing structure width. This will allow additional lateral variability in the channel and provide some width for over-bank flows inside the culvert.

Skewed and Bend Alignments

Roads crossing streams at a skew and crossings at channel bends are common culvert alignment challenges. Some solutions for a skewed alignment are shown in Figure XII-4.

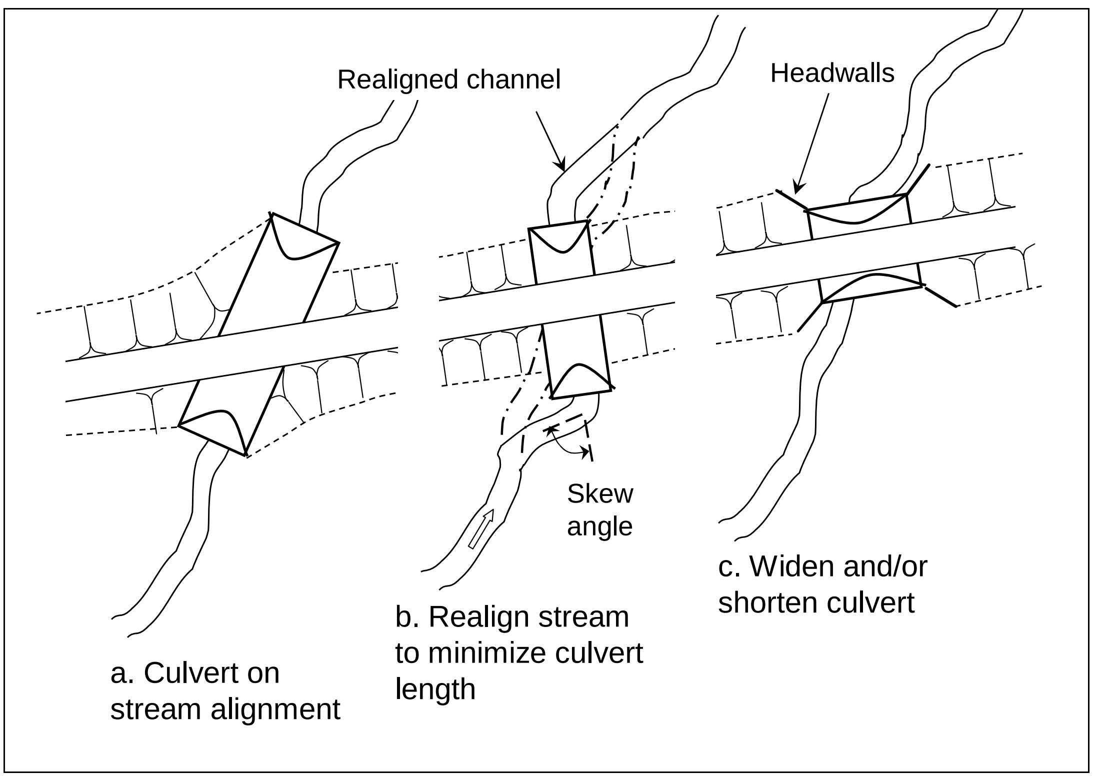


Figure XII-4. Alignment options at a skewed culvert and their trade-offs: (1) match the channel alignment, (2) realign the stream to minimize culvert length, and (3) widen and/or shorten the culvert.

Matching the channel alignment has the least risk of debris blockage and maximizes the capacity of the culvert. However, this may require a longer culvert, which results in additional direct loss of habitat.

Realigning the channel creates a skewed inlet and outlet, which increases the likelihood of debris blockage and reduces the culvert capacity. This option potentially disrupts more riparian and stream habitat, oversteepens the banks, and has a greater risk of bank erosion due to the skew and inefficient inlet.

Though technically the culvert is still skewed, widening and/or shortening the culvert can reduce or eliminate the effects of the skew. This option has the greatest capacity and the least likelihood of debris blockage. It might have a cost more than the other options if wingwalls are used to shorten the culvert.

Each option requires some level of design compromise. None of these options necessarily stands alone; a project will often combine aspects of the three options.

Crossings located at a bend in the channel are a second common alignment challenge. The three options described above for the skewed alignment should be considered.

In any case, consider also the road alignment and elevation. Investigate opportunities of changing the road alignment or lowering the road to reduce the culvert length and mitigate poor stream-to-road alignments. Depending on the road usage and floodplain characteristics, there may also be opportunities to add floodplain causeways, bridges, culverts, or high flow spillways over the road to diminish extreme velocities through the crossing. These opportunities might be important for protection of floodplain and in-stream habitats as well as passage through the crossing.

Consider how far the channel is likely to migrate laterally during the life of the project. This is especially important for a crossing on a bend. Options to accommodate expected changes include widening the culvert, offsetting the crossing in the direction of meander movement, and controlling the meander shift at the inlet with appropriate bank stabilization measures or training structures.

Transitions

Transitions from the upstream channel to the culvert and then from the culvert to the downstream channel should be designed to minimize abrupt changes in cross-sectional shape and channel alignment. Providing good transitions can reduce failure risks, eliminate effects of previous culverts, and affect performance, capacity and passage through the culvert.

An undersized culvert typically causes an hourglass shape in the channel (Figure XII-5). Channel widening upstream and downstream of the culvert are caused by deposition in the enter of the channel upstream and scour downstream. The upstream effects can further decrease the capacity of the culvert and increases the risk of debris blockage. Downstream effects can interrupt passage corridors and jeopardize a streambed in the culvert.

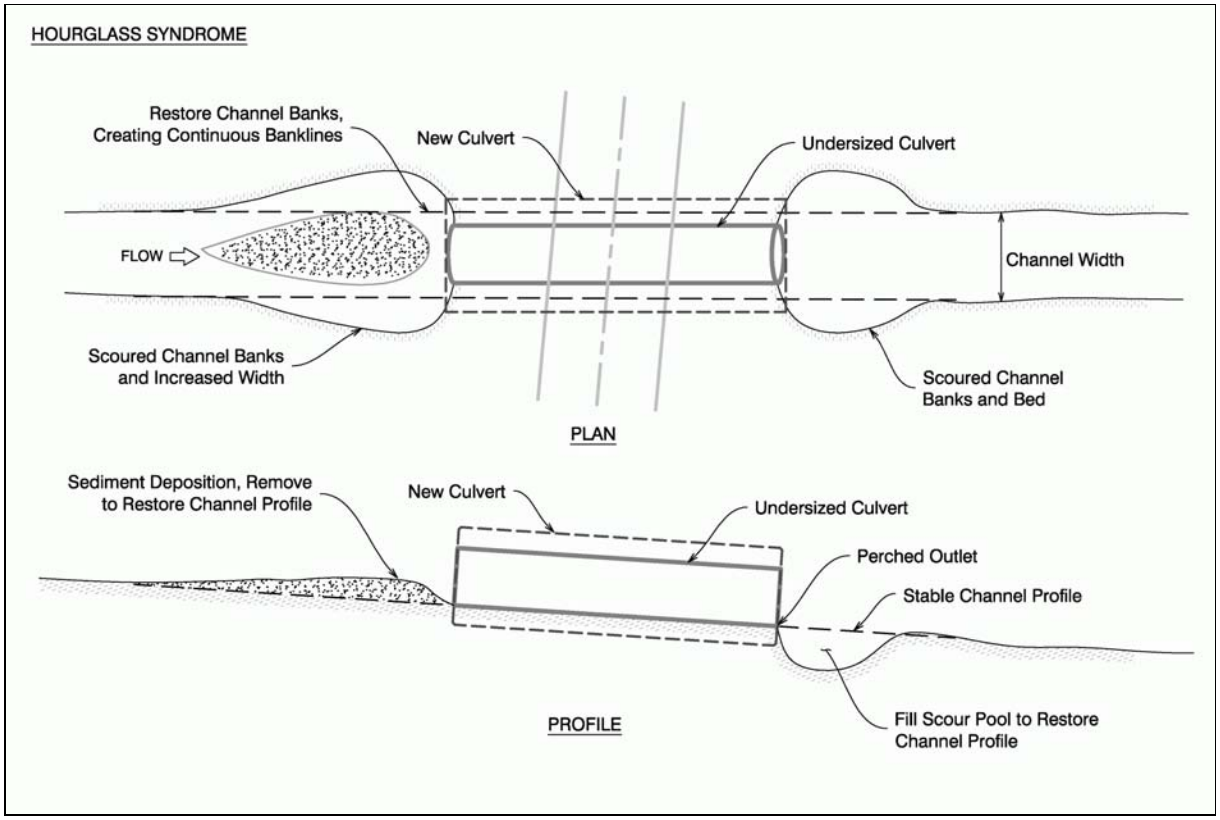


Figure XII-5. Hourglass syndrome at an existing culvert and with transitions to restore banklines.

To minimize these risks, the culvert dimensions and alignment should gradually transition into the natural channel cross section. This is especially true for banks on the outside of a channel bend. The ideal situation is for the culvert cross-section dimensions to equal the natural channel dimensions, forming a continuous channel through the project. For stream simulation designs, the upstream and downstream banklines should be restored to be continuous with the banklines within the culvert. Channel banks should be modified if necessary to restore the shape of the natural channel cross-section. Any unnatural mid-channel deposition should be removed to restore the entire cross-section.

A scour hole downstream of a culvert that is replaced with a stream simulation design should be filled so banklines can be restored and to provide a base for the stream simulation bed. If a scour hole is valuable rearing habitat, its loss may have to be mitigated by replacing it with other scour structures elsewhere. If there is a scour hole downstream of an existing culvert that is retrofitted internally for fish passage, consider leaving it in place as an energy dissipation feature to protect the channel further downstream. In the case of a retrofitted culvert (e.g., addition of baffles), consider the additional energy dissipation that might be required as a result of a raised hydraulic profile within the culvert.

Project Profile Design

Channel Vertical Adjustment Profiles

The final *project profile* represents the slope and elevation of the initial stable streambed through the project reach and is a primary tool for establishing the elevation of the crossing. It should seamlessly connect stable points in the upstream and downstream channel segments. It is based on the slope of the *reference reach* and will ideally fit between estimates of possible high and low channel profiles through the site.

The elevation of the culvert floor or footings may depend on the design method used and characteristics of the natural channel. If there is to be a streambed within the culvert, the floor or footings are somewhere below that bed. The intent is that the crossing *tailwater* elevation will match the normal water level exiting the culvert so there is no drop and no unnatural backwater. This condition should persist for the life of the project. Culvert elevation in stream simulation designs is discussed in Culvert Elevation and Height (page XII-39).

If a culvert is being replaced, the effect of the existing and new culverts on the profile must be understood. If the culvert is perched, the project profile may be long, perhaps including adjacent reaches that will be restored to natural grade, or where artificial profile controls will be installed.

The dimensions of natural alluvial channels vary through time and location. The slopes and elevations of unstable channels also raise (*aggrade*) or lower (*degrade* or *incise*) over time. Culverts can become either *perched* or plugged with sediment if they are not designed for vertical adjustments to the streambed that will likely happen during the life of the culvert.

The pre-design includes an estimate of the possible future channel profiles through the site; these are the estimated highest and lowest vertical adjustment profiles. The structure should be designed to satisfy design criteria when the bed is at any elevation within the range of vertical adjustment profiles as shown in Figure XII-6. For example, bed depth and channel width should be accommodated at the lowest potential profile and culvert capacity and debris passage should be accommodated at the highest potential profile.

There is no cookbook procedure for doing this assessment; it requires an understanding of channel characteristics and evolution and might require expertise beyond that in the design team. There is often uncertainty about what a future stable slope might be. A wide and conservative range of vertical adjustment profiles might be reduced with additional understanding of the channel. Seek additional information or expertise if needed to interpret the channel and predict future trends.

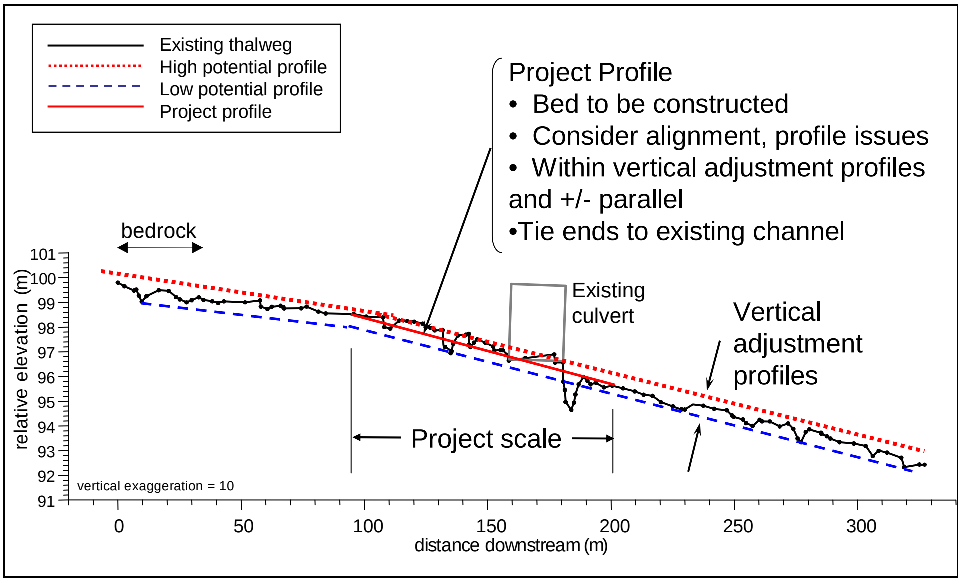


Figure XII-6. Possible project profile for a culvert replacement in a stable channel within range of vertical adjustment profiles (VAP) determined by site assessment.

Consider the following questions when developing vertical adjustment profiles:

- Is the channel profile controlled by temporary controls (e.g., beaver dam or debris jam) or permanent controls (e.g., bedrock or boulder channel)? Is the bed *mobile* or relatively immobile?
- What is the stage of the channel evolution and what will it look like in the future?
- Is the downstream channel incised or likely to incise? Investigate far enough downstream to identify a stable base level.
- Will land use practices affect the future channel profile by changing peak flow hydrology, sediment, and/or debris loads?
- Will channel changes in nearby reaches affect the channel profile?
- For culvert replacements, will replacement of the culvert affect the channel profile?

The resulting natural vertical adjustment profiles might not be acceptable. Headcut issues might affect this decision. In that case, a *forced profile* with profile control structures might be necessary. A forced profile is generally steeper than the otherwise stable slope of the channel constructed.

Scale of the Project

Generally, the scale of the project should reflect the scale of the problem. If an existing culvert is perched, the designer must determine whether the perch is due to local scour caused by the existing culvert, or whether the downstream channel has incised. Figure XII-7 shows the difference between the two conditions. Scour due solely to an undersized culvert in a *stable channel* is usually limited to a short distance below the culvert; the plunge pool is a local scour feature and the scale of the project can be local. The drop at the culvert outlet may be simply addressed by replacing the culvert with an appropriately sized culvert, filling the scour pool and allowing the accumulated sediment upstream of the culvert to scour and re-grade.

If the downstream channel is incised, the solution will be more complex and a solution of a comparable scale should be considered. The appropriate scale of the solution for an incised channel should consider the extent, status, and cause of the incision. Restoration of the incised channel will likely have the greatest overall benefit assuming it restores downstream habitats, protects upstream habitats, and is self-sustaining.

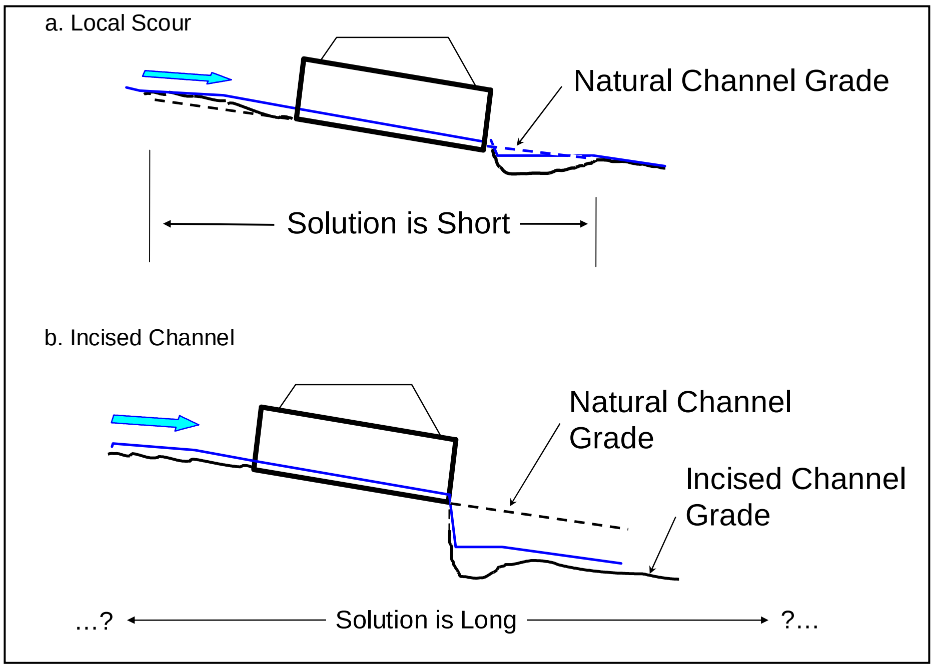


Figure XII-7. Comparison of a perched culvert caused by (a) local scour and (b) downstream channel incision.

Vertical Adjustment Profiles (VAP) in a Stable Channel

A stable channel is one that is neither *aggrading* nor *degrading* over time. For stream crossing design, channel stability is generally considered for the life of the crossing. At the very least, local streambed elevations can change due to local pool scour and fill, such as might occur during a flood.

Estimating the vertical adjustment range requires professional judgment, observation, and interpretation of natural channel conditions and evolution. Start with the surveyed longitudinal profile and characteristics of the channel. Evaluate any potential for downstream *base level* change, changes in incoming sediment loads, or other possible watershed changes that could affect vertical bed stability and elevation. Consider possible profile changes and stability of profile controls within the reach, such as loss or accumulation of debris, beaver dams, and other culverts or infrastructures that might be modified. Include limits of vertical changes such as soil and bedrock outcrops in the channel bed and floodplain elevations and locations and depths of any borings done for pre-design.

Any features or processes that may cause the channel to rise locally will affect the high adjustment profile. Debris accumulations can easily cause bed elevations to rise. In a depositional reach, natural aggradation should be considered. Sediment from a headcut, bank failures, or delivered from an upstream tributary may cause a streambed to aggrade.

Using that information, draw at least two profiles on the longitudinal profile drawing to show the range of vertical adjustment profiles (VAP's) through the site. The lower profile represents the lowest likely elevation of the streambed in the life of the structure and the upper profile is the highest likely profile. An example of a simple profile and vertical adjustment range is shown in Figure XII-6.

Draw the project profile considering the vertical adjustment range. The project profile is the stable profile that will be constructed or will initially develop. The project profile is ideally between the upper and lower vertical adjustment profiles and connects profile control features in the existing channel at the upstream and downstream ends of the project. It should extend at least as far upstream and downstream as the new culvert installation might affect the channel. If the culvert replacement will initiate an upstream headcut, the vertical adjustment profile should extend beyond the anticipated length of the headcut.

Profiles can be drawn in segments where a channel has distinct grade breaks. The high and low profiles might not be parallel where a feature will limit the possible channel elevation from going higher (e.g., floodplain elevation) or lower (e.g., bedrock). If it is uncertain how far the bed might move vertically (e.g., in a channel with a highly mobile bed and good potential for debris jam formation), the designer might increase the vertical adjustment range somewhat to offset the uncertainty and risk of error. If the designer is not confident predicting vertical adjustment range they should seek additional expertise and/or more assessment information. Additional assessments and/or expertise can reduce uncertainties. Design details, such as adding roughness elements, width, and bed depth, might reduce risk. Designers should document design assumptions with notes on the profiles.

Vertical Adjustment in Incised or Incising Channels

Construction or replacement of a culvert in an incised or incising channel is more complex. A channel incises when its bed scours and lowers over time either by natural process, by hydrologic changes in the watershed, by lowering of the *base level*, and/or by the lowering or removal of a control point in the channel. Figure XII-7(b) and Figure XII-8 show downstream channels that have incised so its profile is close to parallel to the upstream channel but it is offset at a lower elevation and the culvert is perched above.

Several project profiles should be evaluated in this case. In addition to considerations of the stable channel described above, it is necessary to understand the causes of channel incision, the sensitivity of the channel, and how it will evolve in the future. Consider how the condition of the upstream channel relates to project objectives.

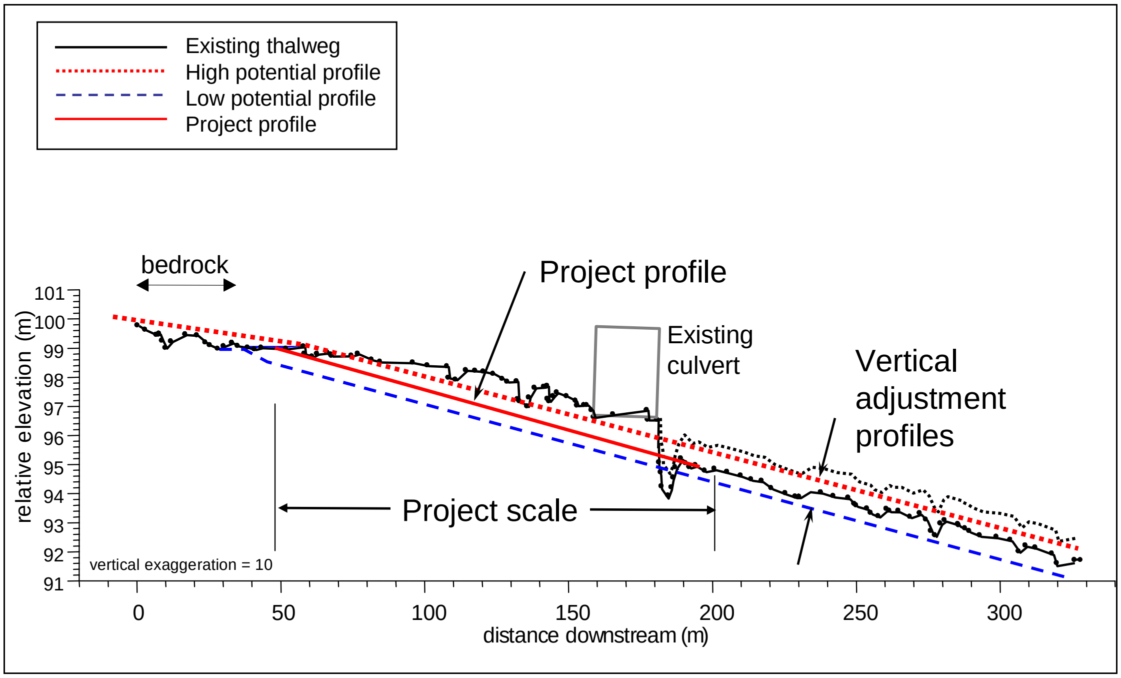


Figure XII-8. Possible project profile for a culvert replacement in channel with regional incision. Project profile is within the range of vertical adjustment profiles, which are based on the assumption of no culvert at the site.

A project profile to consider, and the ideal situation, is the stable profile that would be at the site if no culvert had ever been installed. The project profile should not be steeper than a natural reference reach in a similar setting in the same stream. If it is steeper, make sure the design will accommodate a lessening of the slope as the channel evolves.

To get that profile, the upstream channel might be allowed to incise or constructed at a lower elevation. There are significant risks that must be considered if a culvert is lowered and the incision is allowed to proceed upstream. A headcut profile might not be acceptable. Other considerations, such as construction limitations, other infrastructures, or protection of habitat might require limiting upstream headcutting. In these cases, the project profile might have to be located above or below the natural vertical adjustment range. If a *forced profile* with *profile control* structures is necessary, then immobile structures are needed to control the elevation and grade of the channel. A forced profile is shown in Figure XII-9.

Options for a forced profile are:

- Raise the downstream channel to a natural grade by rehabilitating it
- Steepen the downstream channel with profile controls
- Steepen the culvert
- Lower the culvert and steepen the upstream channel.

No single solution satisfies all situations and projects are often designed using a combination of two or more of these options. A general description of profile controls is included in Profile Control (page XII-54). The profile control strategy might be to permit a headcut to adjust the profile, but to control its extent with permanent profile controls, or limit its rate of migration using deformable structures. Temporary controls such as scattered, buried or temporary rock structures that are expected to fail over time mitigate some of the headcut impacts.

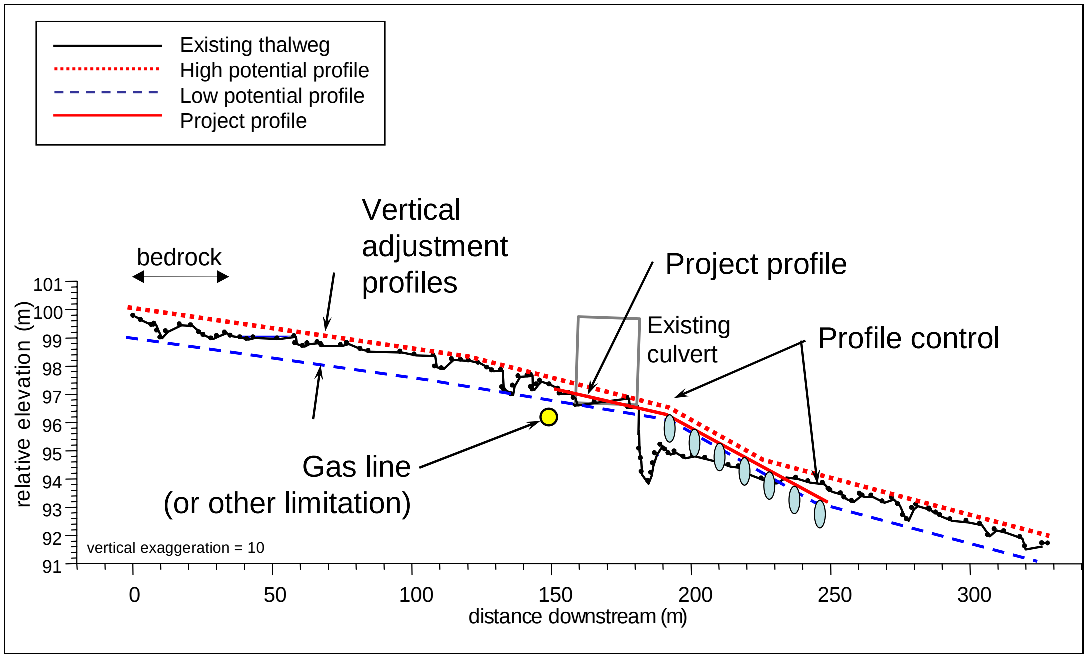


Figure XII-9. Possible project profile for a culvert replacement in a channel with regional incision and project limitations. Project profile is a forced channel using profile control structures due to site limitations.

Headcut Issues

Schumm (1977) described a channel evolution model, which is shown in a simplified version in Figure XII-10. During the initial stages of incision, the channel becomes deeper and narrower, the relative heights of the banks increase and the banks become steeper. Loss of floodplain connection and concentration of flows within the channel exacerbate the incision process. Reinforcement by root structure is decreased. Consequently, banks fail, and the channel then widens over a long period of time until the channel re-establishes its natural slope, floodplain, bankfull width and depth at the lower elevation (Schumm 1977). The entire process can take years, decades, or centuries (USFS 2008).

A channel may become incised locally by scour in response to the lowering or removal of a downstream culvert. The channel profile is often discontinuous and over-steepened where it transitions back to the unaffected channel upstream. That discontinuity is a headcut, which, as it erodes, migrates upstream and eventually incises the channel for some distance. The same situation occurs if an undersized culvert is replaced with a larger one, since the flood hydraulic profile is lowered by the reduction of the culvert constriction. The headcut in this situation is typically limited to the extent of the culvert influence.

Habitat impacts of channel incision can be extensive and prolonged. They can be mitigated by reconstruction of the channel either into a natural grade or steepened with hydraulic controls. Bates et al. (2003) and UFWS (2003) identified issues to consider when deciding whether to control a headcut or allow it to continue upstream when a culvert is removed or lowered and/or enlarged. The effects have to be weighed against other options, such as steepening a channel to artificially maintain the elevation of a culvert that is a *nickpoint*.

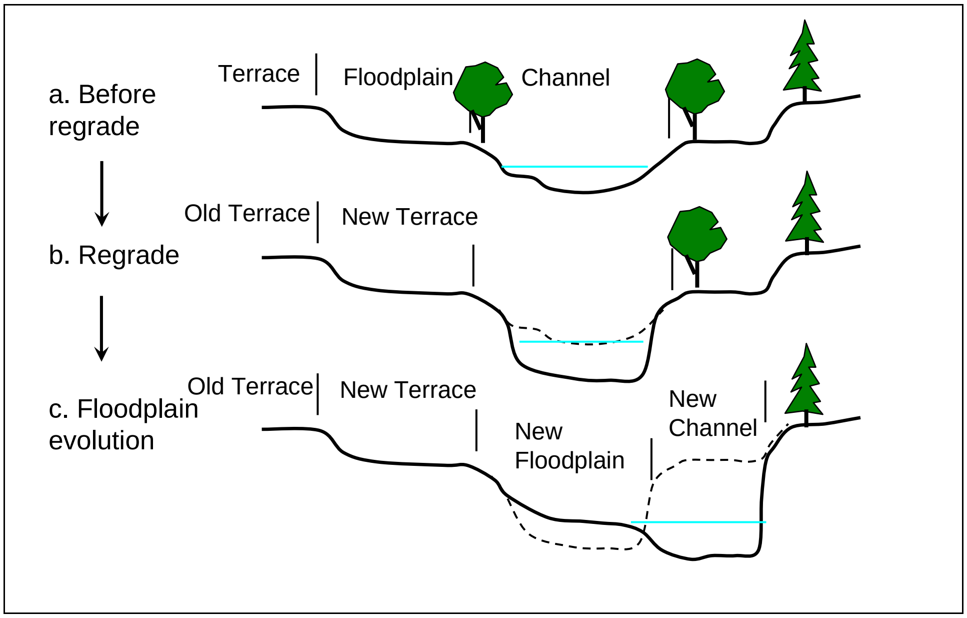


Figure XII-10. Channel evolution model based on Schumm (1977).

Extent of headcut - The distance a headcut can travel upstream depends on the channel slope, bed mobility, supply of sediment, and the presence of debris or other key features in the channel. The extent is usually less in armored or coarse-grained channels than in fine-grain beds. Sandy beds often headcut uniformly without increasing slope until they reach a grade control of debris or larger bed material. A headcut of just a foot can extend hundreds or thousands of feet upstream in a sand-bedded channel.

Condition of upstream channel and banks - If the upstream channel becomes incised, banks will become less stable as they are undermined. Banks that are already prone or are on the verge of failure are most vulnerable. A bank stability assessment can be used to identify this risk.

Habitat impacts of upstream channel incision - Allowing the headcut to travel upstream can have significant effects on aquatic and riparian habitats. As a channel incises it typically becomes confined and banks become vertical. Habitat diversity and channel stability are reduced because the stream cannot access its floodplain during high flows. The very habitat attempting to be restored for fish access might be impacted or lost.

The channel will eventually evolve back to a stable configuration, but it could take a long time, possibly a century. The evolutionary process is one of bank erosion as the channel widens and reestablishes a floodplain at a lower elevation, resulting in chronic discharge of sediment. Bedrock might become exposed if it is shallow, resulting in a loss of habitat. If no debris or sediment structure is left, sediment might not accumulate in which case recovery would be slow. The headcut can also cause enough downcutting to leave side channels perched and/or inaccessible.

Presence of fish or other organisms - A headcut can pose a short-term risk of loss of organisms that are in the bed or pools upstream of a culvert. The bed may scour at a lower flow than normal in a headcutting situation.

Habitat impacts to downstream channel from sediment release - The increased sediment released by a headcut will likely affect aquatic habitats downstream. In addition to the volume of sediment released, it will be released at flows lower than would normally transport that material so it might deposit in pools and other habitats.

Decrease in culvert and channel capacity due to initial slug of bed material - Allowing an uncontrolled headcut upstream of a culvert can mobilize a slug of material during a single flow event. As this material moves through the culvert and the downstream channel, it can accumulate and reduce the capacity of both. In a normal *bedload* regime, the material would transport through the reach, but in the case of a headcut, the bedload rate is high at lower flow. A loss of capacity can result in additional deposition and, in extreme cases, can fill the entire channel and plug the culvert.

The risk is highest where the upstream bed is mobile. Degradation should be controlled if the culvert and/or downstream channel cannot withstand much change in capacity, even for a short period of time. Similar limitations should be considered where structures downstream are at risk from a loss of channel capacity or where banks are at risk of erosion.

Utilities and structures - A headcut can jeopardize structures in the channel or on the banks. Be aware of utilities buried under or near the channel and the effects of increased bank erosion on structures near the channel.

Potential for fish passage barriers created within the degraded channel - Consider the risk of channel incision exposing passage barriers upstream. Buried logs, non-erodible materials, and infrastructure such as buried pipelines might be exposed by channel headcuts. Additionally, upstream culverts could become perched. As the channel headcuts to these features, they become the new *knickpoint* and fish passage barrier. Adding to the difficulty, these problems may occur where they are not visible from the project site, where access is more difficult, or on other properties.

Design Approach

The last task of the pre-design is to select the appropriate fish passage design approach or approaches. These approaches are discussed in Select the Design Approach (page XII-15).

The preferred choice, where applicable, is stream simulation. The low-slope design approach is a simplified version of stream simulation for low risk sites. Hydraulic designs, such as profile control methods, might be required in cases where stream simulation is not feasible or for retrofits of existing culverts. Baffling an existing culvert may be used in cases where replacement is not a feasible option. Fishways might be appropriate where site limitations are severe. They are designed by the hydraulic approach.

Figure XII-1 shows the types of stream crossing projects across the top and the range of passage solutions they might lead to across the bottom. Project objectives and limitations of the site the design approaches determine which line to track down and ultimately which approach can be used at a site.

GEOMORPHIC DESIGNS AT STREAM CROSSINGS

Stream Simulation

Stream simulation is a geomorphic approach for the design of culverts and open channels for passage of fish and other aquatic organisms. The objective is to create a natural channel (dimensions, slope, bed and banks) through the crossing to connect the channels above and below the crossing. Diverse hydraulic conditions, hiding and resting areas, and moist edge habitats that aquatic and semi-aquatic species might use are created at a wide range of flows.

The premise of the approach is that the stream simulation channel through the crossing presents no more of an obstacle to movement than the adjacent natural channel.

The intent is to set the stage so the simulated channel adjusts to accommodate a range of flood discharges and sediment/debris inputs and the channel evolves similarly to the natural channel it simulates. Bed material in the stream simulation channel is as mobile as the reference channel. Flows that transport sediment and debris and rework the channel should not be constrained or accelerated inside the crossing structure. Bed material sorting and distribution, and bedforms are therefore similar to the natural reach.

> Premise of stream simulation: A channel that simulates characteristics of the natural channel, will present no more of a challenge to movement of organisms than the natural channel.

The design is based on a natural reference reach near the crossing. Bankfull channel dimensions, channel slope, bed material, and *bedforms* are simulated. Bankfull flow is widely recognized as an index that represents channel-forming flows in alluvial rivers (Dunne and Leopold 1978; Leopold et al. 1964). Slope is recognized as a primary controlling factor of channel and bedform shapes (USFS 2008). Figure XII-11 shows an example of a stream simulation design with a bankfull channel width and banklines that mimic the adjacent channel and create diverse hydraulic conditions at all normal flows.

Natural stream channels are tremendously diverse and complex, and include some degree of randomness in their response to runoff events and land management. It is an art to “read” a stream in order to simulate it. Knowledge is continually expanding as more structures are built and tested by floods. Part XII represents the best set of methods at this time, but its limitations should be recognized.

Figure XII-11. Stream simulation culvert in Twenty-Six Mile Creek, Washington State.

A simplified stream simulation approach is the low-slope design. This design is limited to low-risk sites and the design is simplified to a culvert width and slope as functions of the natural channel width and slope. No reference reach is used in that case. A streambed is not necessarily built into the culvert though it can be. The application and design are further described in Stream Simulation Application (page XII-30) and Low-Slope Stream Simulation (page XII-41).

The difference between stream simulation and roughened channels (as described in Roughened Channels page XII-57) should be clear. Stream simulation channels mimic the natural channels near the crossing. It is as mobile as the reference channel. If the reference channel is immobile, the stream simulation channel is also immobile, though it resembles the characteristics of the reference reach. A steep roughened channel does not necessarily resemble any specific reach near the crossing.

Much of the stream simulation design process was initially developed by Washington Department of Fish and Wildlife (Bates et al. 2003) and has been expanded by USFS (2008).

Stream Simulation Application

Stream simulation can be applied to new and replacement culverts, but generally cannot be used in culvert retrofit projects since the culvert size is defined by the design process. Stream simulation is essentially a channel design. The approach can also be used to design other channels whether associated with a crossing or not.

Simulations of a channel placed inside a culvert are not exact replications of natural channels. Features like channel-spanning wood, embedded wood, bankline vegetation, cohesive soils, and floodplain functions cannot typically be created inside of crossing structures. These features usually reinforce the natural bed and provide roughness that slows flow and helps create a diversity of water depths and velocities needed for passage of aquatic species. Likewise, we cannot reproduce the roughness and diversity contributed by channel bends or the complexity of large features like debris jams inside of structures. Though they cannot be duplicated, some of these characteristics can be simulated with large rock, and sometimes with wood. Artificial banks constructed of rock sized to be immobile simulate banklines in the reference reach. The grade-stabilizing functions of embedded debris can also be simulated using permanent rock features.

There are occasions where the channel at the crossing is not connected to an upstream alluvial channel that can supply the size and volume of bed material needed to replenish the simulated channel. For example if a road fill creates a pond above the culvert, bedload will not be transported through the pond so the downstream culvert and channel reaches are not directly connected to a supply of bedload. Stream simulation may not be appropriate in such a case.

Low-slope designs are strictly limited to low risk sites; these are low gradient channels with short culverts. The premise of the low-slope design is if a culvert is installed in a low risk site and the culvert is large relative to the channel and an appropriate project layout has been established, it is a low risk, and the level of design can be reduced. The intended application of this design is for small private roads where the owner chooses not to invest in an engineered design but may be willing to, instead, oversize the culvert or crossing channel. The definition of a low-risk site, where a low-slope design can be applied, is a channel with slope of 1.0% or less and a culvert length of 75 feet or less. Use of the low-slope method does not preclude the need for a thorough pre-design and understanding of vertical adjustment potential and alignment issues. The design is described in Low-Slope Stream Simulation (page XII-41).

Stream Simulation Design Process

Each site will have a unique solution. There are many variables to consider in a design and no cookbook solution. The descriptions here are general. The designer should refer to more detailed design guidance such as USFS (2008).

The methods described here are more rigorous than are often necessary for simple sites. Other sites have unique challenges that can only be solved by applying an in-depth understanding of fluvial processes and how they relate to the crossing. Risky conditions such as a culvert that confines a floodplain or is steeper than the reference reach require the team to devote more time and care to the assessment and design effort and possibly to engage additional specialists in the design. There may be other methods of stream simulation analysis and design at specific sites.

Those methods are acceptable as long as the premise of stream simulation can be satisfied at least as well as it can by the methods described here.

Figure XII-12 shows the basic design steps for stream simulation. The first three steps in the design process are part of the pre-design, which was generally described in Pre-Design (page XII-4). They are revisited here because for the unique characteristics of this approach.

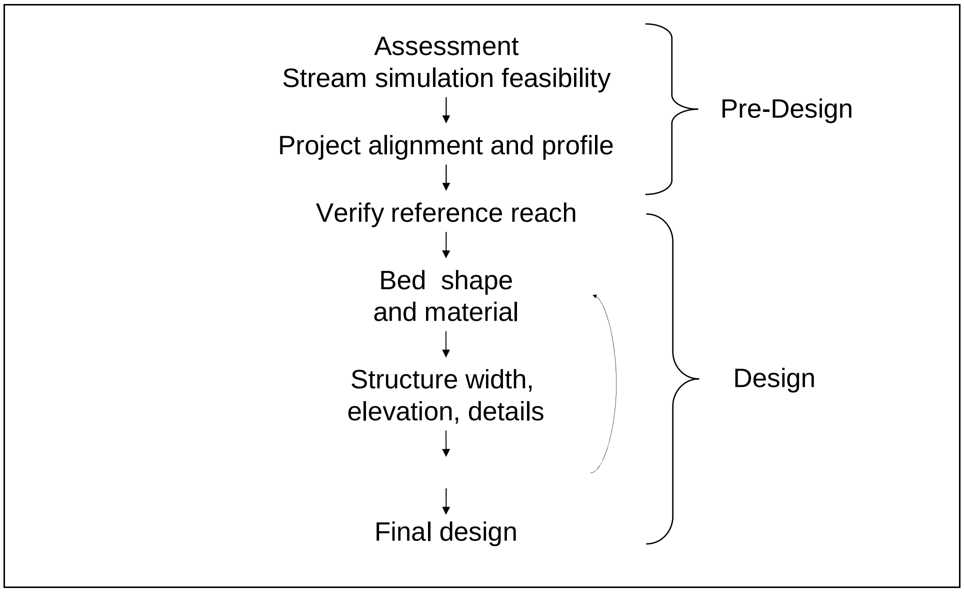


Figure XII-12. Stream Simulation Design Process Flow Chart.

A stream simulation design data form is provided in Appendix XII-A. It is intended to assist the designer in the design process and to document assumptions, data and their sources, and design conclusions.

Stream Simulation Site Assessment Needs

Site assessment has been described previously in general for culverts. There are some additional assessment needs for stream simulation. The stream simulation design is based on a specific reference reach near the crossing, which will be characterized in the assessment. In addition to the usual pre-design data needs, the following characteristics of the reference reach should be documented.

- Cross-section surveys including bankfull channel and floodprone area
- Floodprone width and characteristics to determine floodplain conveyance
- Bedforms and structure
- Bed material; pebble count and assessment of subsurface material or bulk bed material sample. Characterize colluvium, key features, debris, and bankline characteristics.

Specific techniques for doing these assessments are described further by USFS (2008).

Reference Reach

The reference reach is a specific identified length of channel near the crossing that serves as a template for the design of the stream simulation channel. To satisfy the premise of stream simulation, it must approximate the physical conditions, especially slope, of the project site and it must be self-sustaining when simulated inside a confined structure. This means that flows interacting with the bed and the structure walls will create and dynamically maintain streambed material sizes and patterns within the structure. In high flows, the simulated bed should mobilize, adjust and reform similarly to the natural channel; eroded material should be replaced by sediment transported from upstream. Setting the stage for this means establishing basic characteristics from the reference reach, such as gradient, bed and cross-section shape, bank configuration, and bed material size, key features, and arrangement.

The reference reach should have the following characteristics:

- Appropriate stage of channel evolution. Consider how the project reach is likely to change during the life of the structure before selecting a reference reach. What adjustments will occur when the existing structure is replaced by a continuous streambed?
- Near the project, ideally immediately upstream. Factors that control channel dimensions and structure (flow, debris, sediment) are then the same. If it is just upstream, it is the source of material that will replenish the project reach and it is continuous with the project reach.
- Outside of the influence of the existing structure.
- Channel gradient should be similar to the design gradient through the road-stream crossing.
- At least as long as the length of the road-stream crossing culvert or channel.
- Relatively straight. The roughness of bends must be simulated in a straight structure, usually using rock. This can increase turbulence and compromise the degree of simulation.

At new crossings, the undisturbed natural channel at the site is the reference reach.

Look at the longitudinal profile and consider the variability of slopes within the reach. There may be short punctuated steps that are steeper than the average gradient and that control the overall slope.

The slope of the reference reach should not be much different than needed for the project profile. If the channel is steepened too much the bed material must be so much larger than in the upstream reach that the material will not be replenished and the simulation will not be self-sustaining. Remember the premise of stream simulation is that the simulated channel is close enough to the natural one that organisms will move through it as easily. If the change of slope leads to a substantial change in channel shape or bed material character, that premise may not apply. While the design profile should approximate the stable slope connecting the upstream and downstream reaches, Bates et al. (2003) suggest the reference reach slope vary no more than 25% from the project profile slope. This a conservative suggestion; there are no data to support a specific criterion. A maximum *percent* change of slope is used, because a flatter channel is much more sensitive to a given absolute change than a steeper one.

Streambed Design

The simulated streambed is designed using the characteristics and dimensions of the reference reach. The following streambed elements are important to design of the stream simulation channel:

- Channel type; channel classifications as defined by Montgomery and Buffington (1997)
- Channel bankfull width, or active channel width if bankfull is not clear
- Channel slope
- Bed material size distribution
- Bedforms and cross-section shape
- Channel banklines, bank irregularities, margins, *key features*, floodplain
- Bed mobility.

Not all of these characteristics can be constructed. The framework and enough of the structure and materials are built so these characteristics will be developed and maintained by the hydraulic action of high stream flows.

The stream simulation bed material is a *well-graded* mix that approximates the reference reach particle-size distribution. It must include enough fines to prevent excess sub-surface flow. The simulation bed mix is specified based on the reference reach pebble count. Bunte and Abt (2001) and Harrelson et al. (1994) describe pebble count methods. Alternatively, a sieved bulk sample can be used if desired. Pebble counts are impractical for sand-bedded channels. A visual estimation of particle sizes is usually adequate in channels with dominant sizes of medium gravel and finer.

An essential component of stream simulation is bed mobility. Mobility here is the frequency of flow at which bed material is mobilized relative to the life of the crossing project. For example, a step-pool channel with key pieces that are mobile only at flows that occur once in 30 years is considered immobile. Chin (1998) and Grant et al (1990) show that step material moves only during infrequent floods, as infrequent as just during 50-100 year floods. The material of steps is expected to move so infrequently relative to the life of the project that it should be considered permanent and therefore designed as being immobile. At the other end of the mobility spectrum, the bed of a dune-ripple bed may be constantly mobile. The bed material might therefore be left to fill-in the culvert naturally since it is in constant supply and the risk of it not being initially installed is low.

As a framework for characterizing the reference, the channel classification system developed by Montgomery and Buffington (1997) is helpful. It focuses on the bedforms that control the functions and characteristics that are important.

Pool-Riffle and Plane Bed Channels

Channels characterized by an undulating bed with a sequence of bars, pools, and riffles are defined as *pool-riffle* channels by Montgomery and Buffington (1997). In contrast, they define channel beds without bedforms and with low width-to-depth ratios as *plane bed* channels. Designs for these two channel forms are the most basic. Design of the bed for these channel types is described below and will be the basis for design of other channel types.

The D_{95}, D_{84}, and D_{50} of the reference reach bed are used directly as the corresponding grain sizes of the stream simulation bed mix. The surface of the reference channel bed is therefore directly simulated. This means that, if the reference reach bed is armored, the large particle sizes will be over-represented in the rest of the mix below the surface. This is a safety factor for the simulated bed; if the bed scours, there is additional armor material below the surface and the resulting bed surface will become coarser and rougher. This is appropriate because the armored bed indicates a relatively low rate of bedload supply.

Pebble counts typically under-represent fines in the bed. However, the smaller grain sizes in the bed below the surface are very important for mobility and bed permeability. Mobility is affected by smaller particles that bind the bed together. A porous bed can allow substantial flow to move through it; the entire stream flow may go subsurface. The simulation bed mix must have enough fine sediment to fill the voids between the larger particles. Do not assume the stream will transport sufficient fines to seal an open-graded bed surface; it could take years to fill in the voids naturally. There are culvert situations in which the entire summer stream flow went subsurface for at least a decade after construction. The issue is especially critical in steep channels where the hydraulic slope can drive the flow subsurface and in spring-fed channels that do not experience frequent high flows or sediment transport. The smaller grain sizes are therefore sized based on the armor layer to create a dense mixture (see Sizing the Engineered Streambed Material page XII-67) for methods to size the material. USFS (2008) has additional detail on the technique.

Including fines in the bed mix commonly raises justifiable concerns about water quality and habitat impacts immediately after construction. Without special care, fine sediment in a freshly constructed bed will wash downstream during low or moderate stream flows that would not normally move the material. *Jetting* or *flooding* the fine material down into the bed during construction and/or placing a veneer of washed gravel over the surface can mitigate this.

Bed material is placed in the culvert with the expectation that subsequent flows will sort and distribute the material into a natural configuration. It is placed in a cross-section that includes a thalweg so there is some diversity and depth during initial flows.

When a bed of mobile material is recruited or placed in a culvert or other smooth-walled channel, the bed initially tends to flatten unnaturally. Then, because of the smooth walls, the flow often scours a trench along one or both walls. The streambed shown in Figure XII-13 is an example. Note the difference in character of the downstream channel and the channel within the culvert.

The bed is dominated by medium gravel and is quite mobile. The downstream bed has a diverse cross-section and is influenced by woody vegetation. The bed within the culvert is flat and shallow, and without character. It is also possibly a barrier to passage of adult fish at low flow. These effects can be prevented with banklines or other structures that create roughness and disrupt the flow along the culvert walls similar to natural banklines. They are equivalent to natural variations in stream banklines.

Figure XII-13. Deep Creek. Comparison of diverse bed created by woody vegetation that disrupts the flow and a flat shallow-flow bed within the culvert (Photo: Kozmo Bates).

Banklines in a low-slope design would be similar to the banklines described for stream simulation in Channel Cross-Section (page XII-37). Disrupters are single or groups of rock near the edges of the channel that create the bank diversity similar to natural banklines. If a bed is allowed to form naturally, disrupters should be large and high enough so they are exposed at the surface of the bed after it is deposited. The intent is to provide some disturbance so the stream will create bedforms naturally during the first freshets experienced by the project.

<u>Dune-Ripple Channels</u>

Dune-ripple channels are low gradient channels with sandy bed and bedforms as defined by Montgomery and Buffington (1997). The key to design of dune-ripple channels is the mobility of the fine-grained bed. Because the bed mobilizes and mixes during frequent moderate flows, a bed will readily form on its own. There may not be a need to place the bed material, except as needed to help maintain the initial channel cross-section shape and banklines. Pebble counts are impractical for sand-bedded channels. A visual estimation of particle sizes is usually adequate.

Step-Pool Channels

A step-pool channel is characterized by longitudinal steps formed by large clasts (cobbles or boulders) organized into discrete channel-spanning structures that separate pools as defined by Montgomery and Buffington (1997). Step-pool channels are more complex. Steps form when the largest particles in the bed congregate and support each other forming structures that are more resistant to movement than the individual pieces. Usually boulders form the framework of the steps, which support smaller bed material. In nature, step-pool bedforms can take decades to form so we cannot rely on step-pool features to form naturally in the lifespan of the project. Since they are critical for energy dissipation and channel stability, steps must be constructed. Steps should be designed to match those in the natural reference reach.

Likewise, it is not likely that steps would reform inside the culvert if the constructed steps are washed out. For this reason, steps made of large rock are designed with a bed stability model to be immobile. They are generally sized to be stable at the *stable bed design flow*, which is the flow at which the large rock forming the framework of the channel bed is sized to remain immobile. It might be the same as the *structural design flow* for the crossing (i.e., 100-year flow). The size of the large bed particles, width of the bed, and the size of the culvert all potentially affect stability. Immobile rocks placed in any streambed should be limited to banklines or be partially buried in the bed so the risk of them blocking movement of other material and creating a jam is minimized.

Except for the steps themselves, the step-pool channel bed is designed from a pebble count of the reference channel (see basic design process; Pool-Riffle and Plane Bed Channels page XII-34). Frequent high flows scour and replenish the material between steps as bedload moves through the system. The design of the steps can be approximated by a pebble count of the steps in the reference reach but it is then designed essentially the same as the engineered bed material of a roughened channel. The greatest difference is the channel shape, slope and spacing of key features of a stream simulation channel are based on the reference reach. Use the reference reach as a template and use the concepts described in Step-Pools (page XII-63).

Cascade Channels

Cascade channels are steep channels characterized by large roughness elements relative to the water depth and without repeating bedforms as defined by Montgomery and Buffington (1997). Cascade channels are steep and the largest bed particles are large relative to normal flow depths. Energy is dissipated by water flowing over and around individual rocks. Rocks that are key to bed structure and stability are immobile up to very high flows. Again, at these flows, shear stresses inside a pipe are higher than in an open channel. Bed stability would be critical in a simulation since, if the bed fails, the bare culvert would be unlikely to recover naturally. The channel is designed so individual rocks are stable up to the high *stable bed design flow*.

Like the step-pool channel, a cascade stream simulation is designed essentially the same as the engineered bed material of a roughened channel. Again, use the reference reach as a template and use the concepts described in Cascade and Pool (page XII-65).

Channel Cross-Section

A cross-section of the completed stream simulation channel is shown in Figure XII-14. The width of the stream simulation channel between the banklines is the same as the bankfull width of the reference reach. The culvert width may need to be greater than bankfull for several reasons discussed below.

The diversity, roughness, and shape of the channel and banklines are critical to satisfying passage objectives of some aquatic organisms. For example, weak swimmers and crawling species may need margins of slow, shallow water with eddies in which to rest. Channel edge diversity is necessary between low-flow and normal high-flow levels to accommodate the different movement capabilities of all aquatic species. Bankline diversity should be included in all stream simulation designs. Without root structure, cohesive soils, or the ability to scour into parent bed material, banklines will not form naturally inside the structure.

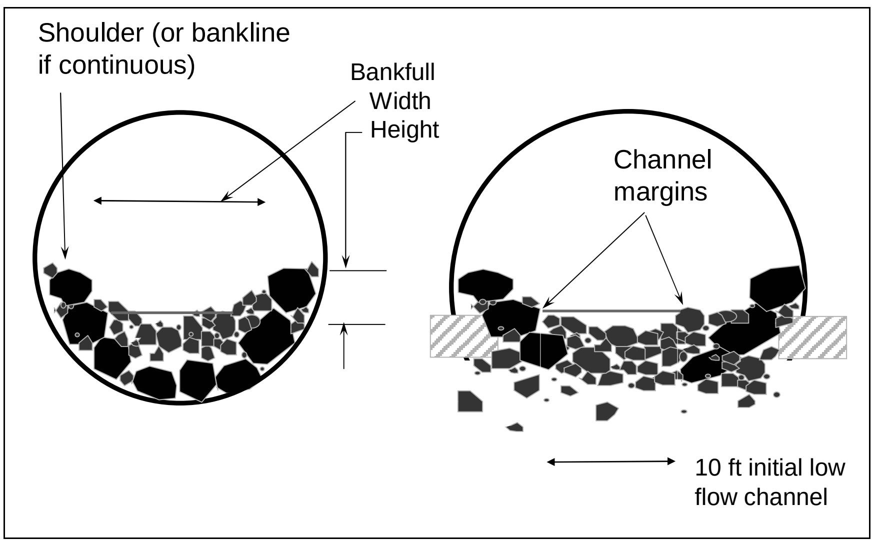


Figure XII-14. Stream simulation bed design with banklines or shoulders in round and bottomless pipes. Culverts span bankfull channel.

Features constructed on the margins simulate the reference channel banklines and edge diversity. Based on the complexity of the reference reach any of several structures might be added to the stream simulation bed. Use the reference reach bankline diversity, including frequency and size of wood or rock protrusions, as a guide to design the bankline/margin. The intent is to create a permanent bankline, so material large enough to be stable at the *stable bed design flow* is required (see Bankline Rock page XII-71).

Many streams have non-alluvial features such as large wood, embedded or jammed wood, and large boulders that may have fallen or slid into the stream or are glacial remnants. Woody debris in the reference reach might be in the form of small jams, buried wood that buttresses the bed and/or forms steps, or wood protruding from a bank. These features are often partially buried in the bed, they might block part of the channel cross-section, and then often play a significant role in the reference reach. Imitating the size and distribution of individual elements using large rock should simulate these functions. A cluster of rocks jutting out from the culvert wall can simulate a bank log in a natural stream. The cluster will provide some edge diversity, and will help prevent a low-flow trench being scoured next to the culvert wall. Figure XII-15 shows the cross-section, including *colluvial* boulders, in a stream simulation design. Note the similarity in channel shape and characteristics of the stream simulation channel within the culvert and the natural channel downstream.

Figure XII-15. Stream simulation channel in Stossel Creek culvert with natural shape, dimensions and key features.

In simple situations, bedform shapes (riffles and pools) are not constructed, but some temporary bed features are helpful to provide an initial thalweg and set the stage for channel margins to develop. In the simplest case, a V-shaped low-flow channel with a width up to about ten feet and lateral slope of 1:5 can be formed into the bed material that has been placed in the culvert. The V-shape is not intended to persist through flood events. High flows will redistribute the bed material naturally, constructing a diverse channel with a thalweg.

Structure Width

In the stream simulation design, the structure is sized by fitting it around the designed channel. It could be a culvert of various shapes or a bridge. Structure size might also be affected by stability, mobility, and/or flood capacity analyses.

The goal of stream simulation is that the simulated channel be self-sustaining and free to adjust similar to the natural channel. For the simulation bed characteristics to be self-sustaining, the hydraulic forces it experiences must be similar to the reference channel, especially at those flows that create and rearrange major bed structures. If the channel is constricted by the structure at those flows, the character of the bed will be changed; it may wash out, lose its structure, and/or become coarser. For these reasons the stream simulation channel has a width equal to the reference reach and has similar banklines and other key features that control channel and bed form. The bankfull cross-section or another similar parameter that represents channel-forming processes is used for this purpose. For this reason, *entrenchment* of the project reach is a critical parameter affecting culvert width. If a culvert is located in a channel within a wide active floodplain, over-bank flow will be forced laterally from the floodplain into the constriction of the culvert. The culvert may have to be wider so the bed simulates the reference reach that is affected by the floodplain.

> The first estimate of structure width is simply the width needed to span the channel.

The first estimate of culvert width is simply the width needed to span the bankfull channel. This is the minimum allowed culvert width for stream simulation. If the design includes banks, the culvert must be wide enough to span the bankfull bed plus the added width of bank material on both banks. Other considerations of culvert width are relative sizes of key pieces and their stability at high flows and construction and maintenance access.

Culvert Elevation and Height

The goal of setting a culvert elevation is to provide enough bed depth within the structure to avoid exposing the culvert floor or the footings, even in scour pools and when the bed profile is at its lowest potential elevation (lowest vertical adjustment profile). To set the elevation of the culvert invert or open-bottom arch footings, use these three parameters:

1. The low vertical adjustment profile (Project Profile Design page XII-20)
2. The depth of scour pools within that profile (Stream Simulation Site Assessment Needs page XII-31) and
3. A thickness of the bed so the material is well-integrated and able to structure itself.

The dimensions for setting a culvert elevation are shown in Figure XII-16. Start the sizing by setting the mid-point of the culvert rise or diameter at or above the high potential profile. If the culvert is any lower, the converging roof of the culvert will reduce the bed width. Then set the culvert floor elevation as if the bed is at the low potential profile. The required bed depth inside the pipe also depends on the size of the largest bed material. The minimum thickness of the bed over the culvert floor should be 1.5 times the diameter of the largest immobile particles in the bed or four times the size of the largest mobile material, whichever is greater. This is so the bed materials can form a mass and large particles do not have to set on the floor. For stream simulation beds with only small material, up to cobbles, the floor should still be buried by at least 20% of the rise of the culvert.

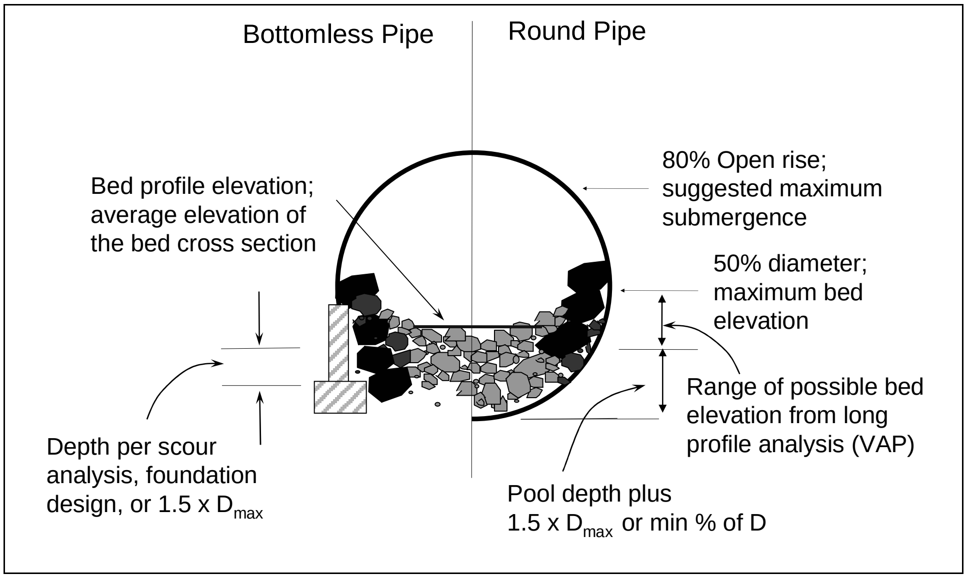


Figure XII-16. Stream Simulation Culvert Elevation.

Design of non-circular culverts will vary from this. Bottomless arches are typically built on stemwalls that are part of the footing. The elevation and design of the footing is determined by whichever is greater, depth needed for structural design of the foundation, the projected bed scour depth, or a burial of at least 1.5 times the diameter of the largest immobile particles in the bed as described above. The scour depth might be limited by bankline material if it is immobile. For an initial design bury the top of the footing two feet below the lowest expected channel profile. This should be verified in the final design. A thorough analysis is typically necessary (USDOT/FHWA 2001). FHWA describes scour methods and data (FHWA 2003). Where the consequences of failure are large, use a larger culvert or a deeper footing.

A second goal that affects culvert elevation is to maintain flood and debris capacity when the bed is at its high adjustment profile. This will determine the culvert height. The high bed design flow is the flow at which the any permanent features (key features, banklines, step structures) are stable and do not wash out of the culvert. The simulated bed is likely to fail if the culvert becomes pressurized during flood flows. Pressurized flow happens when the headwater depth is over the top of the culvert and there is substantial headloss (e.g., somewhat greater than the natural headloss in the reference reach of the same length) between the upstream and downstream water levels. For bed stability, and with a safety factor, the culvert inlet should not exceed 80% submergence during the stable bed design flow. The submergence is the distance from the bed, when at the high vertical adjustment profile, to the soffit of the culvert.

Select the bed design flow appropriate with the level of risk and consequences of failure of the bed. Consider bed mobility, the ability of the bed to restore itself, and equipment access for repair if necessary.

Bed Mobility and Stability Analysis

Mobile streambeds are designed so the reference reach stream simulation beds have "equal mobility." When the bed mobility's are equal, the bed shape, distribution of bed material, and bedforms are assumed to be similar and the goal of stream simulation is achieved. A mobility analysis is useful where the simulation differs somewhat from the reference reach (e.g., steeper or floodplain flow is confined into a culvert) and can also be used to help mitigate risks of pressurized pipe or of a long pipe. The mobility analysis is performed on the alluvial portion of bed; D_{84} is used as an index for bed mobility. USFS (2008) describes these risks further, including thresholds, methods, and background for the analysis. The goal is to have D_{84} as mobile in the stream simulation channel as in the reference reach. If the two channels have the same slope, size (cross-section), bed (bed distribution and bedforms), and confinement no analysis is needed.

Some stream simulation channel features such as banklines, steps, and rock clusters are intended to be permanent. A stability analysis is performed for those features at the stable bed design flow. Use the reference reach as a template and use the concepts described for roughened channels (Roughened Channels page XII-57) to size the stable bed and bank material.

Low-Slope Stream Simulation

Premise of low-slope: The design of an oversized culvert in a low risk site can be simplified.

The low-slope design is a simplified stream simulation design for use at low risk sites. Low risk sites are defined as short culverts in channels with low slopes. This approach is intended to simplify design and permitting for short crossings under residential driveways, farm roads, short public road crossings, and similar sites. The primary advantage of the low-slope approach to the culvert owner is to avoid surveying and engineering costs associated with fish passage design for other options. Special fish passage design expertise is not required. Accurate geomorphic interpretation of the channel profile (vertical adjustment potential) and layout (alignment) are still necessary though. The low-slope option requires few technical calculations for design of the culvert itself and results in a conservative but reasonable culvert size. The default dimensions do not guarantee culvert flood capacity, which still must be calculated.

The California low-slope option is defined by these criteria:

- The low-slope approach shall only be applied in low risk situations of low slope and short culvert length. Culvert length is limited to 75 feet and the natural channel slope is limited to no more than 1.0%.
- The bottom of the culvert is embedded 20% to 40% of the height of the culvert (diameter of a round culvert) when the bed is at any potential elevation during the life of the project (low to high vertical adjustment profile). Minimum footing depth is the critical dimension for bottomless structures in lieu of a culvert floor. A thorough pre-design is necessary, especially for culvert replacements.
- For culverts greater than 50 feet in length, the culvert and scour pool must be backfilled with material that has a similar gradation to the bed material in the adjacent channel. For culverts less than 50 feet in length the scour pool must be filled with bed material in the adjacent channel, but the bed can be allowed to from through natural recruitment inside the culvert.
- The width of the culvert at the streambed elevation must be at least 1.25 times the average natural channel bankfull width. This and the shape of the culvert determine the actual culvert structure width.
- The culvert and associated road fill must not constrict the active floodplain excessively such that frequent backwater affects the upstream channel or there is a risk of culvert or road failure.

Figure XII-17 shows the same definition of the low-slope design option.

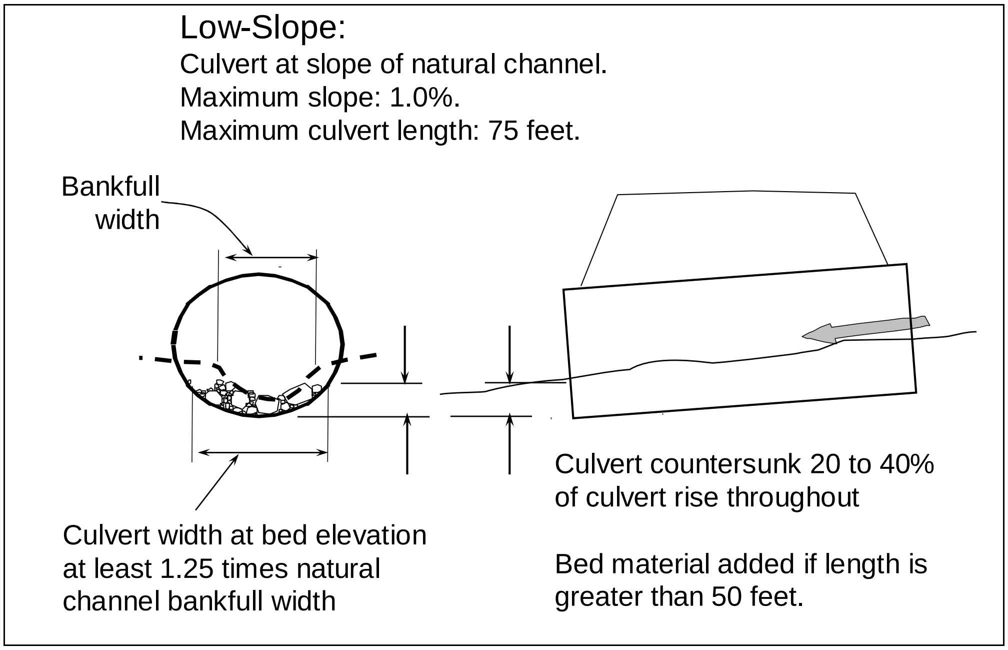


Figure XII-17. Graphic definition of low-slope design.

Low-Slope Application

This option is appropriate only for low risk situations with a low slope and short culvert length. The culvert height must be adequate to accommodate uncertainties of an unstable channel as aggradation or incision occurs. Because the application and design entirely depend on the future channel slope and elevation, a careful assessment of the potential channel elevation for the life of the project is essential (see Project Profile Design page XII-20).

It is anticipated that because the culvert bed is at least as large as the natural channel bed, material will deposit in the culvert. However, for culverts greater than 50 feet in length, there is increased risk of relying on material deposition, so material must be placed in the culvert to form a channel bed. The natural bed will allow a broad range of fish species and sizes to move through the culvert. This might not occur or might not be persistent in several situations. For example, a floodplain constriction can cause a culvert bed to be unstable or the naturally recruited streambed may be inadequate to meet the objectives of the project. The streambed in a culvert that is skewed significantly may not be stable as it is scoured by concentrated flow. A streambed or channel margins and banklines might not form immediately after construction but may be important for migration of aquatic organisms. The design might be modified to mitigate these issues or the designer may have to consider constructing the streambed as a stream simulation design.

The low-slope design option is usually only applied in new and replacement culverts. It can be used as a retrofit only in the unlikely situation that the culvert is already appropriately sized but the downstream channel has incised and left it perched. In this rare situation you may be able to use profile control or profile restoration to reestablish a downstream channel elevation that places the existing culvert at a suitable elevation for the low-slope approach.

Low-Slope Design Process

The low-slope design begins with the pre-design described in Pre-Design (page XII-4). From the pre-design the designer must understand the vertical adjustment range of the channel through the new culvert and be able to evaluate the effects of any headcut created by a culvert replacement, lowering, and/or enlargement.

From this information and the design criteria, the elevation of the culvert can be established and an initial estimate of the size of the culvert can be made.

The width of the culvert at the elevation where it meets the average elevation of the streambed at any cross-section is at least 1.25 times the average natural channel bankfull width. This and the shape of the culvert determine the actual culvert structure width. The floor of the culvert is embedded within the range of 20% to 40% of the culvert rise. If no bed is placed in the culvert, use the culvert width at the elevation equal to the lowest potential profile.

Bed material placed or naturally deposited inside the culvert may not be persistent if the culvert constricts the active floodplain too much. For example, consider a culvert designed in a channel with a bankfull width of 10 feet and a floodprone width of 100 feet. During a flood, flow from the floodplain will be constricted into the 10-foot culvert and will likely scour the bed. To design a culvert that will have a persistent bed, the culvert can be enlarged or additional culverts can be placed through the fill in the floodplain. The additional culverts in this case are not intended for normal flow conditions. They are intended to be active only during overbank flows.

If the low-slope culvert is 50 feet or less in length and built in a bed that is mobile, a streambed does not have to be constructed in the culvert. Bed material in a mobile streambed will quickly fill the culvert and form a natural bed.

If a scour pool exists downstream of a low-slope culvert that is replacing an undersized culvert, the pool should be filled as described for stream simulation culverts so the internal bed can develop.

Banklines in a low-slope design would be similar to the banklines described for stream simulation in Stream Simulation (page XII-28). Rocks should be scattered along the banklines to disrupt the flow and create some diversity in the hydraulics and the bed.

Finally, the flood capacity of the culvert must be verified, as it is for any culvert design. Capacity should be checked assuming the channel bed is at the highest vertical profile. The design should also meet or exceed other applicable local, state, or federal standards for hydraulic capacity, headwater depth, and other design parameters.

Geomorphic Considerations in the Design of Fords

This section provides an overview of the design considerations and elements essential for fords. A ford crossing is a road-stream crossing in which the drivable roadway is overtopped by stream flow anywhere from year-round to once every few years. Other common names for fords are low water crossings and Arizona crossings.

A traditional (un-vented) ford is built at the elevation of the streambed and places all of the stream's flow over the roadway. A vented ford has an opening under the roadway surface, such as a culvert, that provides conveyance of normal flows and keeps the roadway dry most of the time. Whether vented or un-vented, fords frequently create barriers to fish and other aquatic organisms and interrupt transport of sediment and debris. Additionally, they often require frequent maintenance and repair that cause repeated disturbance to the adjacent stream channel. For passage and maintenance, they are very sensitive to any changes of elevation in the natural streambed, especially un-vented fords.

Fords are typically used in channels with low banks and relatively high width-depth ratios. A key advantage to the use of fords is they can be designed to avoid interrupting flow conveyance across a floodplain because the approaches to a ford do not need to be raised. Other advantages are if a ford fails, little to no sediment is released to the downstream channel and they are designed to allow debris and sediment to pass over the roadway. Because of these advantages, fords are best suited for roads that are not maintained frequently.

Fords are poorly suited for highly entrenched channels because of the difficulty of constructing the approaches, which must be steep and require a large amount of excavation into the bank. Entrenched channels are often better suited for other types of stream crossing structures that freely span the flood prone channel width.

The following is a summary of the different types of fords and the design features that can make them suitable for passage of fish and other aquatic organisms. Refer to the US Forest Service (2006) publication, titled *Low-Water Crossings: Geomorphic, Biological, and Engineering Design Considerations* for more information. The USFS publication provides descriptions of types of fords and their suitability to provide aquatic organism passage and maintain channel stability.

Un-Vented Fords

Un-vented fords can be problematic for fish passage if vehicles must cross the stream at the same flows that fish are expected to move upstream. Vehicles crossing through flowing water as shallow as one foot are at substantial risk of being swept off the roadbed. This is also the typical minimum water depth required for upstream passage of adult anadromous salmonids. Therefore, use of un-vented fords on fish bearing streams should be limited to intermittent streams where vehicles do not need to cross during fish passage flows.

Un-vented fords can be classified as unimproved or hardened. Unimproved fords have a roadbed consisting of native streambed material. Unimproved fords typically create suitable fish passage conditions, but often fail to provide adequate safety for vehicular traffic. They are also susceptible to scour damage.

Hardened fords have a stable driving surface of rock, concrete, asphalt, concrete blocks, planks, gabions, geocells, or a combination of these materials. A scour hole often forms downstream of improved fords because the surface of the roadbed is rigid and smoother than the natural channel. The acceleration of flow across the roadbed causes scour immediately downstream and a drop may form off the downstream edge of the ford. The drop creates a shallow water depth on the ford, which, with the drop, may limit fish passage. Like a culvert, if the downstream channel incises, the ford is likely to function as a knick point and a drop will form across the downstream end of the ford that can block fish passage.

Preventing a drop from forming over an un-vented ford with an improved roadbed often requires use of one or several profile control measures downstream of the crossing. This can be in the form of rock weirs downstream of the anticipated scour pool or construction of a roughened channel to prevent a scour pool from forming (see Profile Control page XII-54). The grade control should backwater the road surface and provide sufficient depth and suitable water velocities during fish passage flows.

Vented Fords

Vented fords, if properly sited, designed and constructed, can provide aquatic organism passage and not jeopardize a geomorphically stable channel. The vent is typically constructed using one or more concrete or metal culverts. The size of the vent is relative to the bankfull width, depth and area, and the ratio of the open-area of the vent to the bankfull area is referred to as the Vent-Area Ratio (Figure XII-18).

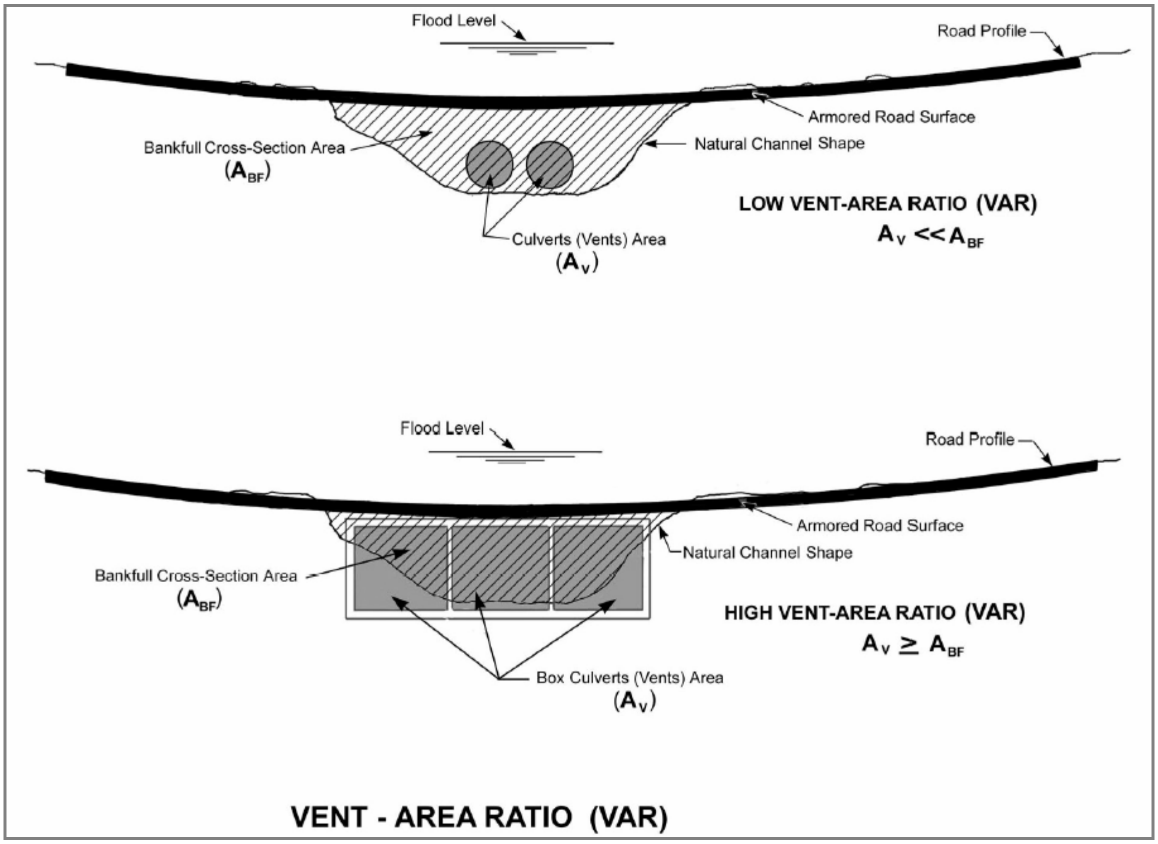


Figure XII-18. Definition sketch of the Vent-Area Ratio (VAR) for vented fords (USFS 2006).

A low vent-area ratio indicates that the crossing constricts the bankfull flow, leading to frequent overtopping and spill off the edge of the ford, typically forming a scour pool and a permanent drop downstream of the ford. Vented fords with low vent-area ratios frequently clog with sediment and debris. Once clogged, fish passage is blocked and the roadway becomes inundated even more frequently and at greater depths and the channel is affected.

To reduce clogging of the vent, the vent should be sized larger then the bankfull cross sectional area. The vent should span the bankfull channel width and the top (*soffit*) of the vent should be above bankfull depth (Figure XII-19). If multiple vents are required to achieve this, dividing wall thickness should be minimized and positioned away from the main flow path, which is often located near the thalweg. The wall separating multiple vents often catches debris and is a risk to fish passage and the structure. To reduce the risk of catching debris, the upstream edge of the wall should be adverse sloped to encourage debris to float up onto the crossing, and be rounded to eliminate sharp edges that are more likely to snag debris.

Once a vented ford creates a backwater, sediment may deposit and accumulate in the upstream channel. Reducing backwater at bankfull and higher flows can minimize this. In mobile bed channels, the headwater should not overtop the vent soffit until reaching a flow where the channel bed is fully mobile. This is generally above bankfull depth. The height of the roadway above the vent soffit should be minimized to reduce backwater effects and allow stream flow to overtop the road once the vent is at capacity. The flow blockage effect of guardrails and other flow obstructions should also be minimized.

Figure XII-19. A vented ford constructed with three embedded concrete box culverts that span the bankfull channel and convey the bankfull flow without overtopping (FishXing Case Studies 2008).

To maintain natural streambed substrate, the vent inverts should be embedded below the low potential streambed profile, as identified in the Pre-Design (page XII-3) and should be aligned with the approaching channel (Stream Crossing Layout: Alignment and Profile page XII-16). Rock banklines can be constructed along the edges to simulate the hydraulic roughness and diversity found along the banks of the adjacent channel. Rock used to form the banklines should be sized to be stable up to the stable bed design flow (e.g., 100-year flow). In mobile bed channels the bed within the vents can be formed by the natural recruitment of streambed material. Otherwise, it should be constructed within the vent. With these design elements, the design of bed within the vent is no different than other stream simulation designs.

Roadway Approaches

The roadway approaches to fords typically slope downward towards the stream. If left unpaved or if they drain into an unarmored ditch, they can become chronic sources of fine sediment to the stream.

Over time and use, the downstream end of an un-vented ford often subsides. When this happens the depth will increase, forcing vehicles to cross further upstream. This causes the approaches to widen, frequently leading to rutting and increased sediment delivery.

These problems can often be addressed by paving approaches, including best sediment management practices in drainage ditches, minimizing the length of the approach, and constructing the crossing as a vented ford to keep the roadway dry. Refer to Part X of the *California Salmonid Stream Habitat Restoration Manual* for more on reducing sediment inputs from road-stream crossings.

The road approaches should not be built up above the elevation of the floodplains, which would constrict the floodplain. Low road approaches is a basic advantage of using a ford.

Final Design and Construction Techniques

This section describes construction techniques and practices that are unique to stream simulation projects. They are primarily related to specification and construction of the streambed inside the culvert. Normal structural design, analysis of flood capacity, water management, excavation, and culvert placement practices are no different than other culvert installations and are therefore not described here.

Selecting the Style of Culvert

The stream simulation design up to this point has focused on design of the streambed and the overall dimensions of the culvert. The decision as to what style of culvert to use is part of the final design. A wide variety of structures may fit the project site and objectives; circular pipes, pipe arches, concrete or metal boxes, open-bottom concrete or metal arches, and many types of bridges. All have their specific advantages and disadvantages. Use the structure type that best fits the specific needs and objectives of the crossing.

While the design of a stream simulation structure is based primarily on accommodating natural stream function, other considerations that might affect product selection for the crossing are roadway geometry, failure risks, geotechnical considerations, construction limitations, cost, and others.

One-piece *embedded pipes* are usually used on small streams because of their low cost and generally simple installation. Actual width is limited to what can be manufactured and hauled to the site. There is large difference between embedded pipes and bottomless pipes. One-piece embedded pipes can be placed quickly as a single unit. Special equipment might be necessary to load bed material into it however or the means for placement of the material might limit the size of the pipe itself. Larger road-stream crossings may be constructed with a wide variety of structure types.

Bottomless pipes have the advantage that bed material can be placed from above before the culvert is attached to concrete footings and stemwalls. On the other hand, construction of those footings and delayed installation of the culvert structure result in other complications and a longer project duration and therefore possibly greater cost. A bottomless pipe might save excavation of bedrock and bottomless pipe footings can be placed to contour to bedrock.

A minimum depth of fill is generally needed over a culvert for structural purposes; it may vary from no fill (possibly for pre-cast concrete) to three feet or more. When fill heights are low, round and pipe-arch culverts may not allow sufficient cover over the structure. Consider using low profile and box structures, raising the fill height, or using a bridge.

Compared to culverts, channel-spanning bridges tend to have lower risks and higher longevity, and provide better passage for aquatic, semi-aquatic and terrestrial animals. Even with short spans they are often cost competitive with culverts. With increasing span, they become more economical than culverts. When they are close in cost to other structures, they are generally preferable. It is worth considering bridges in active flood plain locations and debris-flow or landslide-prone areas where high clearance is necessary.

Specifying Bed Material

An ideal bed mixture is based on the reference reach and may have to be modified for site conditions. The contract might specify a range of material sizes rather than specific sizes so there is some flexibility in procuring the material. Material might be specified that is within 5% larger and 5% smaller than the ideal gradation. For example, the rock intended to be the D_{84} in the streambed might be specified as being between the screen sizes that pass 79% to 89% of the mixture.

If possible, use standard rock sizes and mixtures that are commonly used in the area such as those commonly specified in local public works contracts. Mix portions of materials described by standard specifications to get the desired mixture. Samples of the bed mixture components should be inspected before material is hauled to the site or mixed. Specify the alluvial and key feature components separately so the key features are supplied and handled separately. For the alluvial material, a spreadsheet design can be used to combine various quantities of standard size materials until a plotted curve of the specified mix overlays a corresponding plot of the designed mix. USFS (2008) describes more detail for specifying bed material quality and mixtures.

Material in the original bed at the site might be suitable for at least a portion of the stream simulation bed. If the bed is removed for the placement of an embedded pipe, it will be mixed and loosened in the process. Compare the size of the material to the desired size distribution based on the analysis of a bulk sample. Additional material may have to be added to achieve the desired gradation.

Placing Bed Material

This section describes the hauling, sequence, and installation of bed material. Some of these practices differ greatly between a bottomless pipe and a full pipe, and, in fact the practice itself might be a determining factor in selection of the style of culvert.

Large cobbles and boulders should be hauled separately from small rock so the material does not get separated as it is hauled, stored, and loaded into the culvert. Haul it and store it at the site and mix each load to be carried into the culvert.

Backfill around the culvert before or concurrently with the placement of bed material so the culvert strength is developed before the bed material loading distorts the culvert. The exception to this is when bed material is placed against concrete stem walls in a bottomless pipe installation.

If possible, construct the bed entering from the upstream end and placing material starting at the downstream moving upstream. This helps pack the material as if it were sorted and placed by the stream. This is especially true for steeper channels; steps and other key features should always be built from the upstream side. A base of rock might be added on the floor of the culvert to protect it from any equipment used inside the culvert.

Key features should be embedded into the alluvial streambed. Place them individually over the first lifts of alluvial or base material and then place smaller material around them. Bankline rock should be placed into position rather than pushed. Bed material should be placed over and behind bank rocks to fill the gaps around them.

It is helpful to paint the bed profile on the inside of the pipe as guidance to the equipment operator as well as to see how the bed reacts after construction. Stable stream simulation beds typically loose about 20% of their depth due to consolidation and erosion of finer material when there is not substantial replenishment right away. Overfill the bed to account for any initial loss of depth.

Equipment used for installing streambed simulation material depends on the size of the structure and whether it is an embedded or bottomless pipe. Trail-building or garden equipment can be used for embedded culverts smaller than six feet high. A small loader or manual labor might be used for slightly higher culverts. Special materials conveyors and dump boxes mounted on rails have been used for mid-sized pipes. Be aware of air quality issues and safety regulations with gas-powered equipment operating in confined culverts.

Bed material should be placed rather than pushed so it does not separate and the structure is not damaged. Use rubber-tired equipment when possible. Material should be tamped in place. It generally does not have to be mechanically compacted. Form a thalweg in the bed to concentrate initial low flows. A thalweg formed with 5:1 side slopes and up to ten feet in width is generally adequate.

The final bed should be washed so the fines are pushed down into the bed. This can be done with a hose from a dewatering pump or with a wash of water from the bucket of an excavator. A veneer of washed gravel can be placed over finished bed to make it even cleaner.

USFS (2008) describes more details for placing bed material in stream simulation culverts.

OVERVIEW OF THE HYDRAULIC DESIGN APPROACH

Definition of the Hydraulic Design Approach

The hydraulic design approach has long been the standard fish passage design approach for culverts and *fishways*. Unlike stream simulation, the hydraulic design approach involves designing a structure for passage of targeted fish species and life stages by creating a hydraulic environment that is compatible with the fish's swimming and leaping abilities over a specified range of flows. The hydraulic conditions generally evaluated are water velocity, depth, turbulence, and drop height over weirs. The design objective is to achieve the desired hydraulic conditions at flows that the target fish are expected to move upstream. The range of stream flows is defined by the *low and high fish passage design flows*.

The hydraulic design approach focuses on providing passage of specific fish targeted species and life stages rather than providing unrestricted movement for the entire assemblage of fish and other aquatic organisms within the stream. This approach requires knowledge and understanding of the swimming and leaping abilities of the target fish and how they vary within the population, timing of upstream fish movement relative to season and stream flow, and behavioral issues that may affect passage. Because hydraulic designs have historically focused on passage of adult salmonids, there has been considerable research to guide development of design criteria for these fish. However, much less information is available for the hydraulic and hydrologic requirements for both juvenile salmonids and non-salmonid species.

Application of the hydraulic design approach is limited to situations where *ecological connectivity* is not a project objective. Some applications include:

- Retrofit of existing culverts with baffles
- Use of grade control structures, such as log weirs, rock weirs and roughened channels
- New or replacement culverts where physical limitations preclude use of other design options (i.e., stream simulation, bridges)
- Fishways, including fish ladders and roughened channels.

Although this design approach focuses on creating a suitable hydraulic environment for fish passage, considerations must also be given to the geomorphic impacts the design will have on the channel. Experience has found that culverts designed with the hydraulic design approach often fail to provide fish passage as intended due to unanticipated impacts to the downstream and upstream channel. For example, a culvert designed for passage of adult salmon or steelhead may still have outlet water velocities at high flows far greater than those found in the natural channel. As a result, a large scour pool may form that can cause the culvert to become *perched*, blocking fish.

Due to the shortcomings and limitations of the hydraulic design approach, it is generally not recommended for new or replacement culvert installations. When applying the hydraulic design approach to the retrofit of an existing stream crossing, it may not be possible to satisfy all fish passage design criteria. In these cases, fish passage improvements may be limited to a portion of the fish population.

Hydraulic Design Criteria

Projects that apply the hydraulic design approach for fish passage will often require, at a minimum, involvement of a fisheries biologist, hydrologist, and hydraulic engineer to establish appropriate design criteria and develop an acceptable hydraulic design. There can be significant errors and uncertainties associated with estimation of hydrology, hydraulics, and fish swimming speeds, which can be mitigated by making conservative assumptions in the design process. For example, a design based on the swimming abilities of the weaker individuals will improve passage for a greater portion of the population.

The design process begins with determining the fish species and life stages for which passage is desired. Once these target fish are identified, fish passage design flows and hydraulic criteria need to be established. For salmonids, these criteria should be based on the current CDFG criteria and NOAA Fisheries guidelines (CDFG 2002; NOAA 2001).

Fish Passage Design Flows

It is generally neither practical nor necessary to provide fish passage at all flows. For structures designed using the hydraulic approach, fish passage criteria should be satisfied within a range of *low and high passage design flows*. At the low passage design flow the objective is to provide sufficient water depth. At the high passage design flow the objective is to avoid excessive water velocities and turbulence.

When defining fish passage flows, the objective is to encompass the range of flows that fish typically move upstream based on an understanding of the life history of the target fish. For adult anadromous salmonids upstream movement is often associated with the timing of their spawning migration. For juvenile salmonids upstream movement may be associated with daily foraging or seasonal movement related to changing flow conditions, habitats and environmental stressors, such as overcrowding or declining water quality. The timing of movement may be seasonal or year-round.

CDFG (2002) criteria and NOAA (2001) guidelines recommend criteria for fish passage design flows for both salmonids and non-salmonids. Fish passage design flows should be selected with consideration for the hydrologic characteristics of the stream and sensitivity of the target fish to low-flow and high-flow delays in movement. The movement of some fish is more time sensitive than others. For example, adult salmon and steelhead often require higher flows to migrate upstream and spawn. If the fish encounters a culvert that presents a high-flow barrier, migration may be delayed for days. Such a delay can have a direct influence on the success of the fish to spawn, the location that it spawns, and the viability of its offspring. Conversely, a fish that moves daily to forage may only be minimally affected if upstream movement is blocked during high flows. Lang et al. (2004) discusses the considerations for developing fish passage design flows and explores the implications to migration delay when selecting design flows within the hydrologic regime of coastal northern California.

In coastal central and southern California, rainfall events are often more intense but less frequent than further north. The resulting flow patterns provide adult steelhead more limited opportunity to migrate up rivers and streams to spawn, warranting consideration of providing passage at higher flows than may be called for further north. A more appropriate high passage design flow for adult anadromous steelhead within these regions may be closer to the 2-year recurrence interval flow.

Water Velocity

Maximum cross-sectional average water velocity criteria for salmonids are provided in the CDFG (2002) criteria and NOAA (2001) guidelines. The water velocity criteria are conservative, and intended to provide passage for the smaller and weaker individuals within the population. The water velocity criteria are applied to the entire length of a culvert or other hydraulically designed structures that fish must swim through. The criteria generally do not apply to velocity over the crest of a baffle or weir because the distance over the crest is short.

Specific swimming performance data must be obtained when using the hydraulic design approach to provide passage of a non-salmonid species. The FishXing User Manual (USFS 2007) provides a well-referenced discussion on fish energetics and locomotion accompanied by a list of published studies on the swimming abilities of numerous fish species.

Hydraulic Drop Height

Whether a fish leaps over or swims up a hydraulic drop is based on physical and behavioral factors. The CDFG (2002) criteria and NOAA (2001) guidelines provide criteria for maximum hydraulic drop heights for passage of salmonids at culvert outlets. This is the vertical difference in water surface between the culvert outlet and downstream tailwater pool. Drops at culvert outlets should be avoided, but in cases of culvert retrofits, may be unavoidable. In these cases, the maximum hydraulic drop at a culvert outlet should not exceed the maximum drop heights listed in the CDFG criteria and NOAA Fisheries guidelines. To dissipate energy associated with the hydraulic drop and provide suitable conditions for salmonids to leap, depth of the receiving pool should meet CDFG criteria and NOAA Fisheries guidelines.

The hydraulic drop criteria also apply to drop structures. However, there is a distinct difference between drops at a culvert outlet and over a profile control weir. Unlike a culvert outlet, slower and deeper water is typically found both downstream and upstream of a weir, reducing the likelihood that the fish will be swept back downstream over the weir.

Boulder weirs create substantial hydraulic diversity (Ruttenberg 2007) resulting in better passage conditions than for more uniform profile control weirs. The diversity in drop heights, water velocities and depths, and flow patterns created by well-designed and constructed boulder weirs can provide good juvenile fish passage conditions. In some cases, they are allowed to have larger hydraulic drops than other types of weirs for juvenile salmonid passage.

For designs following the stream simulation approach the hydraulic drop criteria do not generally apply. Instead, the drop heights within the constructed channel should be similar to, but not exceed, those typically found in the adjacent natural channel.

For hydraulic designs that require passage of non-salmonid species, the leaping and swimming abilities of the target fish must be established. There are many non-salmonid species that do not leap and are unable to swim through steep hydraulic drops. If the leaping abilities of the target fish are unknown, hydraulic drops should be avoided.

Water Depth

Minimum water depth criteria are applied to culverts, roughened channels, and other hydraulically designed structures for fish passage. Water depth is the greatest depth in the channel or culvert cross section. Water depth criteria generally do not apply to depth over the crest of a baffle or weir because the distance over the crest is short. The CDFG (2002) criteria and NOAA (2001) guidelines provide minimum flow depth criteria for salmonids.

Minimum water depth criteria are generally intended to provide sufficient depth to fully submerge the fish (Powers and Orsborn 1985; Webb 1977). To ensure full submergence, water depth criteria is based on the body depth of the fish plus some additional depth to account for variability of fish within the population and other factors.

Examples of depth criteria for non-salmonids are given by the Vermont Department of Fish and Wildlife (VDFW 2007) and Maine DOT (MDOT 2002). Both recommend providing depths that are at least one and a half times the body depth of the fish. Minimum water depth requirements are typically based on the largest individual fish of the population. To estimate body depth, FishXing (USFS 2007) and FishBase (2008) provide relationships for body depth to total fish length for many species.

Turbulence

Turbulence is the rapid fluctuations in water velocity associated with energy dissipation and typically includes entrainment of air within the water column. Large amounts of turbulence can disorient and exhaust a fish, resulting in a passage barrier. Smaller fish, with their smaller mass and weaker swimming abilities, are more susceptible to turbulence. Although little research has been conducted regarding the effect of turbulence on juvenile salmonids, Powers (1997) documented a marked decrease in passage of juvenile coho salmon associated with increased turbulence along the walls of a corrugated metal culvert.

Avoiding excessive turbulence is generally a design consideration for pools below hydraulic drops, baffled culverts, and roughened channels. A common measure of turbulence in fish passage design is the Energy Dissipation Factor (EDF). This is the rate of energy dissipation within a volume of water. Although CDFG and NOAA Fisheries do no have specific EDF design criteria, this document provides some guidance and recommendations for evaluating turbulence in hydraulic design.

PROFILE CONTROL

Profile control covers techniques for steepening the channel profile. Approaches to controlling the channel profile can be used both downstream and upstream of replaced or removed barriers to control *headcutting* and channel *incision*, or to meet other channel and habitat restoration objectives. Profile control structures are also used to raise the downstream channel to the elevation of an existing culvert or other in-stream barrier to improve fish passage. See Project Profile Design (page XII-20) for examples of site conditions at stream crossings that warrant consideration of profile control in a *forced profile*.

Profile control options include one or a series of drop structures, roughened channels and profile restoration. Fishways can be considered an extreme example of profile control and are described in Fishways (page XII-107). Except in some cases of profile restoration, profile control involves constructing a length of channel steeper than its self-sustaining slope using *forcing features* constructed of materials that will remain stable. Saldi-Caromile et al. (2004) provide detailed description and design guidance for use of profile control structures.

Approaches for controlling the channel profile include:

- Profile restoration
- Roughened channels; rock ramps, mimicking natural steep channels
- Drop structures; rigid weirs, rock weirs and chutes, deformable drop structures.

These structures vary from semi-natural and diverse to rigid and uniform. They also vary in the hydraulic environment they create, the degree and certainty of passage provided, the range of applicable slopes, structural durability, and construction materials.

Siting of Profile Control Structures

When profile control structures fail, it is commonly by scouring either under or around the end of the structure. Keys to a good design include consideration of overall slope, planform and cross section geometry, embedment and bank keys, and ballasting of buoyant materials.

Profile control structures are best suited for relatively straight channel reaches. Placement of profile control structures within a meander or channel bend increases the risk of flanking, bank erosion, or scouring around the end of the structure. In un-entrenched channels and streams with erosive banks the elevated water level upstream of a profile control structure further increases the risk of channel migration and flanking. Lateral migration of the channel can lead to poor alignment with the structure, potentially creating adverse entrance or exit conditions for fish passage.

When placed in a reach containing a gradual bend, structures should be oriented and shaped to turn the flow away from the outside bank and towards the downstream channel. This can reduce erosion along the outside bank and decrease the risk of flanking.

Channel adjustment at the transition between the profile control structure and the downstream natural channel is an important and often overlooked part of the design. Extending the project past the last control structure will help prevent downstream scour and potential failure. Saldi-Caromile et al. (2004) and Mooney (2007) summarize methods and equations for predicting scour below various types of profile control structures.

Increased water depth, velocity and turbulence generated by the structure are often carried to the downstream channel, causing scour of the bed and banks. If not accounted for in the design, this scour can form an excessive drop at the end of the profile control reach, creating a fish barrier and increasing the risk of failure. A pool at the downstream end of the last structure is often needed to dissipate this energy and prevent downstream erosion. If no pool is available naturally below the profile control structure, it should be constructed or expected to develop. The profile control should be extended downstream to accommodate such a pool (Figure XII-20). In a stable channel, the downstream end of any profile control structure is often placed at or below the grade of the existing channel to accommodate a pool.

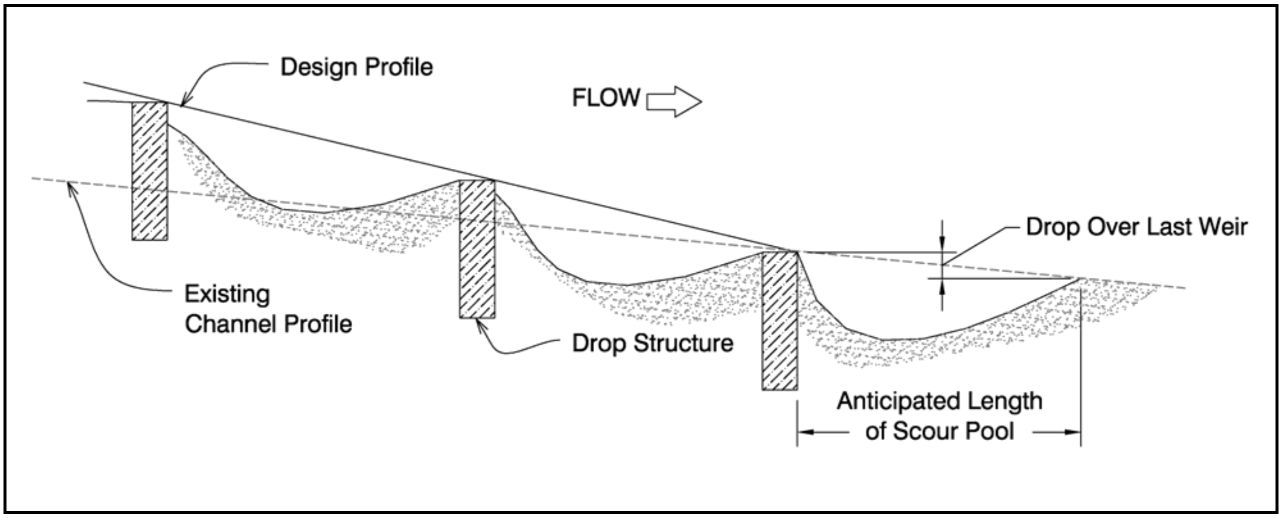


Figure XII-20. Downstream-most profile control structure is placed at or below existing channel grade to ensure the drop formed by the resulting scour pool does not become a barrier.

If the cross sectional shape of a profile control structure constricts flow more than the downstream channel, the drop at the downstream transition may increase with increasing flow. To account for this, the drop at the last structure should be less than the maximum drop for fish passage. A hydraulic analysis can assist in evaluating the drop height at the low and high fish passage flows.

If the channel is unstable with the potential for some downstream incision, the transition of the profile control structure should be designed based on the future bed elevation and the vertical adjustment potential. Identifying a downstream point in the channel that is stable and unlikely to experience future incision may assist in determining the ultimate stable channel profile. A geomorphic characterization of the downstream channel stability and potential for post-project channel incision should be conducted during the pre-design phase of the project (Pre-Design page XII-4).

Profile Restoration

The US Forest Service (USFS 2008) describes channel restoration as the re-establishment of structure, grade, and function to the stream with the goal of achieving a self-sustaining channel at an appropriate grade to meet fish passage and/or other objectives. Restoring the profile of the channel might include re-grading or realigning the channel to restore the historical profile, channel length, and meander pattern. Profile restoration, by definition is the most natural profile control approach. However, physical changes within the stream and watershed may prevent profile restoration from being self-sustaining.

Channel incision frequently leads to vertical drops at hard structures within the channel, such as culverts, bridge aprons, and pipeline crossings. Profile restoration should be considered for projects to address the effects of an incised channel. The opportunity for profile restoration should be identified in the pre-design phase. Benefits of this technique may go far beyond passage of aquatic organisms. Restoring the historic profile might restore in-stream, riparian and floodplain habitats, improve channel-floodplain interactions, reconnect side-channels, reverse bank erosion, and reduce sediment delivery from bank and bed erosion. It can also eliminate any effects of a headcut, if it were to be allowed to occur.

Profile restoration projects often need to extend a long distance downstream, requiring cooperation and involvement of multiple landowners. The larger project scale may slow implementation and make profile restoration the most expensive alternative. However, profile restoration is likely more self-sustaining than other options. Profile restoration might be accomplished over time by building structure and roughness into the channel as part of the project and then allowing natural sediment deposition to raise and reconstruct the channel.

There are a number of valuable design references for channel restoration. For an introduction to the process of channel restoration see FISRWG (2001). Specific details for design of channel restoration projects are included in Saldi-Caromile et al. (2004).

Roughened Channels

Roughened channels, sometimes referred to as nature-like fishways, are constructed channel reaches stabilized with an immobile framework of large rock mixed with smaller material. Roughened channels provide fish passage by controlling the channel profile and adding roughness and structure to it. By design, they create hydraulic diversity that emulates conditions found in steeper or confined natural channels. Unlike individual rock weirs used to control the channel profile, the bed framework forming a roughened channel creates a continuous stable channel structure that is able to flex and move slightly while continuing to function as intended. Unlike stream simulation, a roughened channel is designed with an immobile bed and is not necessarily based on a reference reach in the same channel. Roughened channels are designed using the hydraulic approach.

Roughened channels have a wide variety of fish passage applications. Most common are providing profile control in conjunction with existing or replacement stream crossings and passage over or around low-head dams and other types of drop structures.

They can be constructed inside or outside of culverts. When constructed inside culverts they are usually limited to replacement installations because existing culverts rarely have the necessary width and capacity to accommodate the additional bed material. A common application of roughened channels is where the channel has to be steeper than a reference reach so stream simulation cannot be used.

> Roughened channels should only be used at stream crossings when other more preferred approaches, such as stream simulation, are not feasible.

Common configurations of roughened channels include rock ramps spanning a part or the entire width of the channel, step-pool or cascade-pool sequences, and bypass channels around dams or drop structures. These are similar to the fishway layouts described in Fishway Layout (page XII-110). Although short segments may be steeper, overall slopes of roughened channels commonly range between 3% and 5%, which are within the range of channel slopes that salmonids traverse in natural systems.

When designed and constructed properly, the hydraulic diversity created by the bed and banks of a roughened channel creates a broad range of depths, velocities and turbulence within any given cross section and over a wide range of flows. This hydraulic environment provides many pathways for smaller and weaker swimming fish, including along the margins of the channel. Although roughened channels are treated as hydraulic designs aimed at passage of target fish (Calles and Greenberg 2005; Bates 2003), the hydraulic diversity allows for passage of weaker swimming non-target aquatic species. For example, studies of roughened channels in other regions have documented successful passage of minnow, chub, roach, larval stages of lamprey and a host of cyprinid species (Beatty et al. 2007; Calles and Greenberg 2007; Santos et al. 2005).

In addition to providing upstream and downstream passage of aquatic organisms, roughened channels are generally efficient at passing high flows, wood and sediment. Similar to stream simulation designs at stream crossings, roughened channels placed inside culverts can include banklines that provide a passage corridor for semi-aquatic and terrestrial animals.

Although roughened channels have been widely used in other regions for a number of years, they are relatively new to California, and the design methods outlined in Part XII have not been extensively tested. Implementation and effectiveness monitoring is especially important given the experimental nature associated with roughened channels. Through monitoring and experience, these design and implementation procedures will likely continually improve to better meet objectives.

Roughened Channels as Profile Control

Although many different types and configurations of roughened channels have been constructed, Part XII focuses primarily on design of full spanning roughened channels for profile control that mimic the morphology of natural channels with slopes similar to the designed project profile. Unlike stream simulation, a "nature-like" roughened channel has a different slope and morphology than the adjacent channel. Though the structural design of steep stream simulation channels may be the same as for roughened channels, roughened channel morphology is out of context with the adjacent channel, and not considered stream simulation.

While this section focuses on using roughened channels for profile control, the general design methods and procedures described may apply to other applications as well. Some of the methods described can apply to design of stream simulation crossings in naturally steep streams, as discussed in Geomorphic Designs at Stream Crossings (page XII-28). Other roughened channel applications, such as bypass channels around dams, are discussed in the Fishways (page XII-107).

Geomorphic Features and Channel Arrangements

The geomorphic characteristics of natural channel types, along with hydraulic fish passage design criteria for water depths and velocities, turbulence, hydraulic drops and minimum pool depths, can be used to guide design of a roughened channel. Montgomery and Buffington (1997) developed a channel classification system based partially on channel bed morphology. Based on their classifications, channels with slopes between 1.5% and 3% most frequently have a plane-bed morphology, which is characterized by a lack of repeating bedforms (i.e., pool-riffle). At the upper slope limit for plane-bed channels, the bed material is often cobble dominated mixed with large boulders, often referred to as a run or rapid.

Channel slopes between 3% and 6.5% are most likely to have step-pool morphology, with steeper channels having a cascade morphology. Both step-pool and cascade channels have bed and banks consisting of large material that is highly resistant to erosion. This large bed material forms structural diversity and governs geomorphic characteristics of step-pools and cascades, such as pool size and spacing and channel width and slope. The bed material in these high gradient streams is relatively immobile, with the largest bed material becoming mobile only during very infrequent (i.e., 50 to 100 year) flow events (Chin 1998; Grant et al. 1990).

A roughened channel can only approximate the characteristics of a plane-bed, step-pool or cascade channel. Individual rocks are expected to adjust position but the larger rocks are sized to be stable and not move out of the roughened channel reach. The bed material must remain fixed because, unlike stream simulation, if a rock within the roughened channel becomes mobile it will not be replaced by natural recruitment.

The *active channel* in a roughened channel lies between the banks, and is sometimes referred to as the channel bottom width. An active channel with gradually sloping triangular or trapezoidal cross sectional shape creates hydraulic diversity that persists with changes in flow and stage (Figure XII-21). These channel shapes concentrate lower flows to provide deeper water in the center, and shallow, slower flow along the margins that persists, even with changes in stage. This edge zone produces suitable conditions for smaller, weaker swimming fish such as juvenile salmonids and non-target aquatic species as well as a wet margin possibly for semi-aquatic and non-aquatic species. Trapezoidal channel shapes are generally used for larger streams because they have a greater capacity and require more flow than a triangular cross section at the same depth.

The active channel width should be similar to the width of the adjacent natural channel. Excessive concentration of flow towards the channel center can create an unstable channel bed. To maintain shallow flow along the margins for weaker swimming fish, it is best to design the active channel to become fully wetted at roughly the high passage design flow for resident trout (5% annual exceedance flow). Generally, a water depth of less than two feet deep is achieved when the active channel becomes fully wetted. Steep cross-channel slopes can cause an excessive concentration of flow, which can destabilize the bed material.

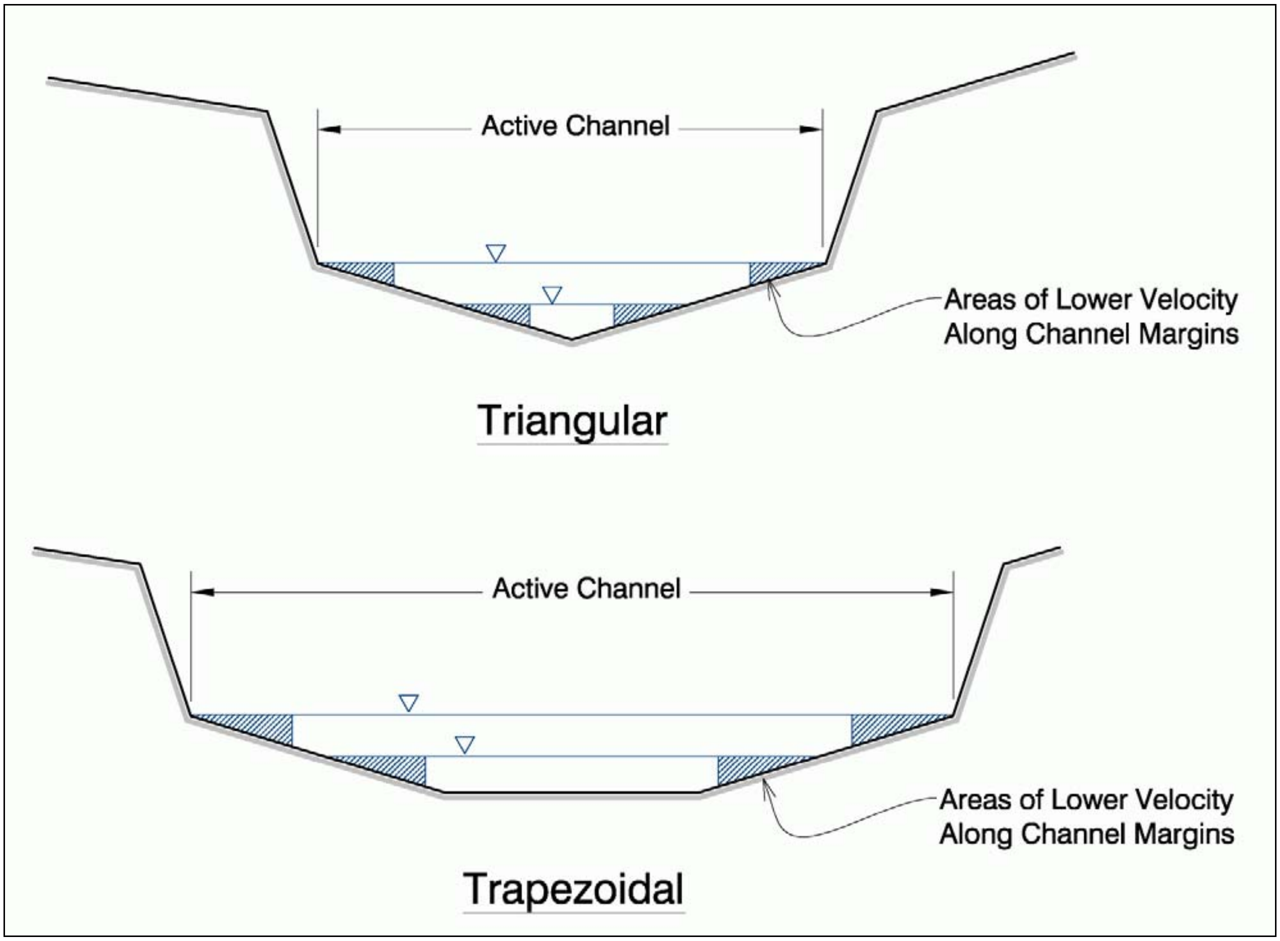


Figure XII-21. Triangular and trapezoidal shaped active channels provide slower water velocities and damp zones along the channel margins where smaller fish can swim through. A trapezoidal channel will require more flow to achieve the same depth as a triangular shaped channel.

Streambed Material

The bed material used in construction of a roughened channel is referred to as the *engineered streambed material* (Figure XII-22). Placed within the active channel, it consists of a *well-graded* mixture (diversified particle sizes) of material designed to be immobile up to the *stable bed design flow*, the flow threshold at which the large framework rock is designed to remain stable. When constructed as part of a new or replacement stream crossing, the stable bed design flow is frequently the same as the *structural design flow* for the crossing (e.g., 100 year flow). Unlike typical riprap sizing, engineered streambed material includes particle sizes ranging from large stable rock to fine sands and silts. The larger portion of rock ($\geq D_{50}$) is sized using standard riprap sizing methods for predicting stable particle sizes. Structure designed into the bed, such as steps, are built using the largest material in the gradation (D_{84} to D_{100}). Smaller material fills the voids between the larger rock and controls porosity to avoid excess subsurface flow. The bed mixture should include between 5% and 10% fines (sands and silts), similar to the bed material gradation in a natural channel. Sizing the Engineered Streambed Material (page XII-67) provides a suggested design procedure for developing the size, gradation, and thickness of the engineering streambed material, including the gradation of smaller particles ($\leq D_{50}$) in the mixture.

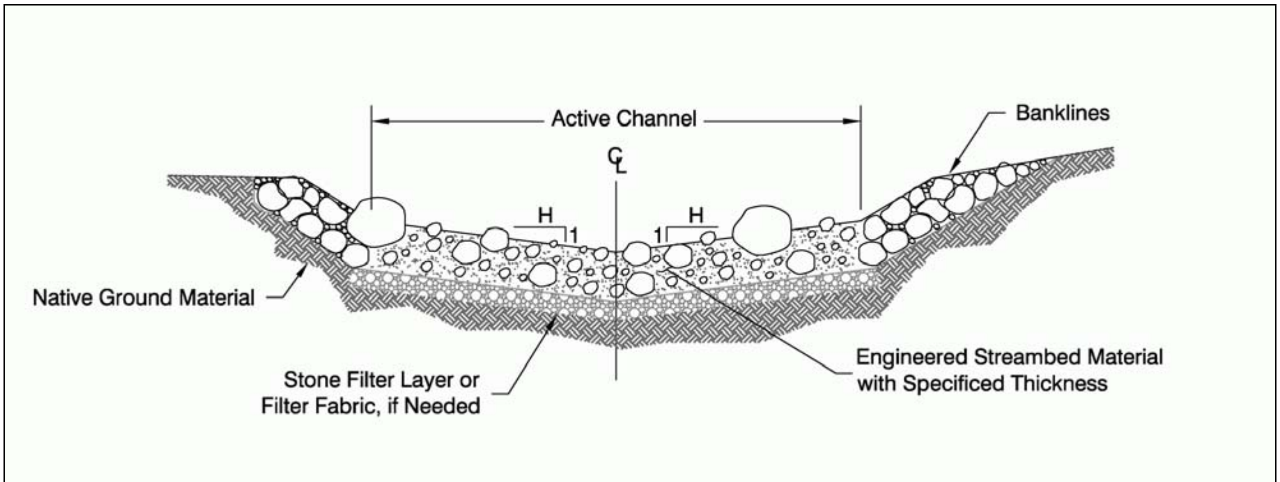


Figure XII-22. Typical cross section of a roughened channel with engineered streambed material and banklines.

Banklines

Banks of the roughened channel run along the edges of the active channel. As in natural step-pool and cascade type streams, banks are composed of material resistant to scour. The banks of the roughened channel should be well-graded, with both large immobile rocks as well as smaller material that fills the voids and prevents *piping*. Banklines should be irregular in shape to provide additional roughness and hydraulic complexity. Designs can include large rock embedded into the banks to create slight channel constrictions.

Banklines typically are composed of smaller rock than the active channel because the banks are subject to lower velocities. The toe of the bank typically experiences higher scouring forces than further up the bank. Therefore, the largest rock forming the bankline is often placed along the toe of the bank. Like naturally steep channels, banklines typically contain flows up to the 2-year flow, and often much higher flows. The height of armoring on the bankline should be adequate to prevent scour. This depends on site-specific factors, including water depth, velocities, shear stress on the banks, erosive potential of the native soils, *entrenchment* of the channel, and risk of flanking at the stable bed design flow. Bankline Rock (page XII-71) provides some guidance on sizing rock for banklines. Opportunities to use bioengineering techniques to limit the height of the bankline rock should be considered. Inter-planting the bank rock with vegetation should also be considered as a habitat mitigation feature (Fischenich 2001b) (McCullah and Gray 2005).

Bedform

The *bedform* morphology of the roughened channel profile can vary, depending on its length and slope, the characteristics of the adjacent natural channel, and project goals and objectives. In general, the more a roughened channel's slope and bed material diverges from the characteristics of the adjacent natural channel, the more risk and uncertainty involving channel stability and fish passage.

The following sections describe bedform morphology for different roughened channel types. They include rock ramps, chutes and pools, step-pools and cascade and pools. In general, when a roughened channel extends in length for roughly five or more channel widths, it is recommended that a large pool be added to break up the reach and aid in dissipating energy. Each reach of steep channel and pool combination is referred to as one sequence. Table XII-1 lists each channel type and their recommended slope ranges. There is not always a clear distinction among these bedforms in nature.

Bedform	Overall Roughened Channel Slope	Recommended Maximum Elevation Drop Across Roughened Channel
Rock Ramps	$\leq$4.0%	5 feet[1]
Chutes and Pools	$\leq$4.0%	2 feet per Sequence
Step-Pools	3.0-5%	5 feet per Sequence[2]
Cascade and Pool	4.0-6.5%	5 feet per Sequence

Table XII-1. Recommended range of overall design slopes and maximum elevation drops for various roughened channel bedforms.

[1] Larger drops across the roughened channel require breaking up the reach with large pools.
[2] A step-pool sequence may include multiple steps; four or five steps per sequence are common.

Much of the design guidance for roughened channels is based on the characteristics of natural channels. There is some risk in using a natural channel as a template for design of a channel that is intended to be stable, if not rigid. Natural channels have evolved over decades if not centuries and have been formed by a history of flow events likely including some extreme flows. Even the best design and construction practices cannot duplicate the structure and hydraulic sorting and particle done in nature. Consider the slope, spacing, and rock sizing describe as natural limits. Mitigate any risk and uncertainty by designing conservatively relative to those limits.

Rock Ramps

Rock ramps are continuous roughened channels constructed at a constant slope with no large structural bedforms (e.g., steps, pools). Rather, random large rocks (D_{50} to D_{100}) in the engineered streambed material create hydraulic roughness and diversity. Morphologically, rock ramps are similar to *plane-bed channels*, which lack repeating bedform patterns (Montgomery and Buffington 1997). The largest rocks are substantially smaller size than bankfull depth, which differentiates them from cascades. Rock ramps are often limited to slopes less than 4% and are best for overcoming elevation differences of 5 feet or less. Higher and longer rock ramps may be less stable due to the potential for increasing water velocities in the downstream direction. Additionally, the risk of creating an exhaustion barrier to fish increases as the ramp length increases. To overcome larger elevation differences, rock ramps can be interspersed with large pools to form a sequence of chutes and pools or small pools can be scattered within rock ramps.

Rock ramps and chutes rely on the swimming, rather than leaping, abilities of the fish, making them better suited for passage of fish species and life stages that have poor or no leaping abilities.

However, to achieve adequate water depth for fish passage, a sufficient amount of flow is required, which limits their application. In streams with very low base-flows, rock ramps and chutes may not be able to provide adequate water depth for fish passage during low flows. This concern is increased with increasing slope, channel width, and the likelihood of significant subsurface flow.

Chutes and Pools

A chute and pool channel consists of a short rock ramp subunit followed by an armored pool subunit. The bed structure of this repeating sequence dissipates energy through a combination of hydraulic roughness across the chute and the volume of the pool below the chute. Chutes and pools are recommended in lieu of rock ramps when the roughened channel is long or when the unit discharge (flow in channel divided by active channel width) is high. The recommended maximum overall slope for rock chutes and pools is 4% for small and moderate-sized streams, with the slope of the chutes greater than 4% and no slope across the pools. The drop across a ramp/pool sequence is typically limited to two feet to adequately dissipate the flow's energy. A small drop also typically causes each chute to submerge the crest of the next upstream chute during larger flows, drowning-out the lower portion of the chute. At high flows, greater than fish passage flows, the water surface slope across the chute becomes roughly equivalent to the overall slope of the chute-and-pool sequence rather than the steeper slope of the chute, thus reducing scouring forces on the chute.

The chute is typically constructed with a rock band at the upstream and downstream ends of the chute. A rock band consists of a row of large rock, two rocks deep, similar to a rock weir in design and construction (Rock Weirs and Rock Chutes page XII-83). Engineered streambed material (ESM) is placed between the rock bands. Both the bands and the ESM are V-shaped in cross section to concentrate flows towards the center of the channel and make for shallower and slower flow along the channel margins.

The bed of the pools typically consists of ESM, making them resistant to erosion and controlling the depth and length of the pool. Alternatively, the channel can remain unarmored between chutes, allowing pools to scour and form within the native ground. In this case, the chutes function as individual drop structures and the overall grade of the chute and pool sequence is typically limited to 2.5%. See Rock Chutes (page XII-88) for use of chutes as individual drop structures.

Step-Pools

A roughened channel can be designed to simulate a step-pool channel. Natural step-pool channels typically occur at channel slopes between 3.0% and 6.5%, but can be found in lower and higher sloping channels (Montgomery and Buffington 1997). Steps are ribs across the channel composed of boulders, logs, or bedrock. Water plunges over each step and into pools formed between steps. This bedform dissipates the stream's energy as water flows over the step and plunges into the receiving pool. The pools are armored and resistant to scour and erosion. Step-pool channels are generally highly confined and the stream banks are relatively rough and resistant to scour.

In design of a step-pool roughened channel for use as profile control, characteristics of natural step-pool channels should be emulated. For this application, focus on step-pool channels formed by boulders and large cobbles. Numerous studies have described spacing between steps or pools as exhibiting a rhythmic pattern related to channel width, slope, and particle size. These relationships, along with fish passage design criteria for hydraulic drops and minimum pool depths, can be used to guide design of a step-pool roughened channel. Figure XII-23 illustrates some common dimensions used to describe the step-pool bedform.

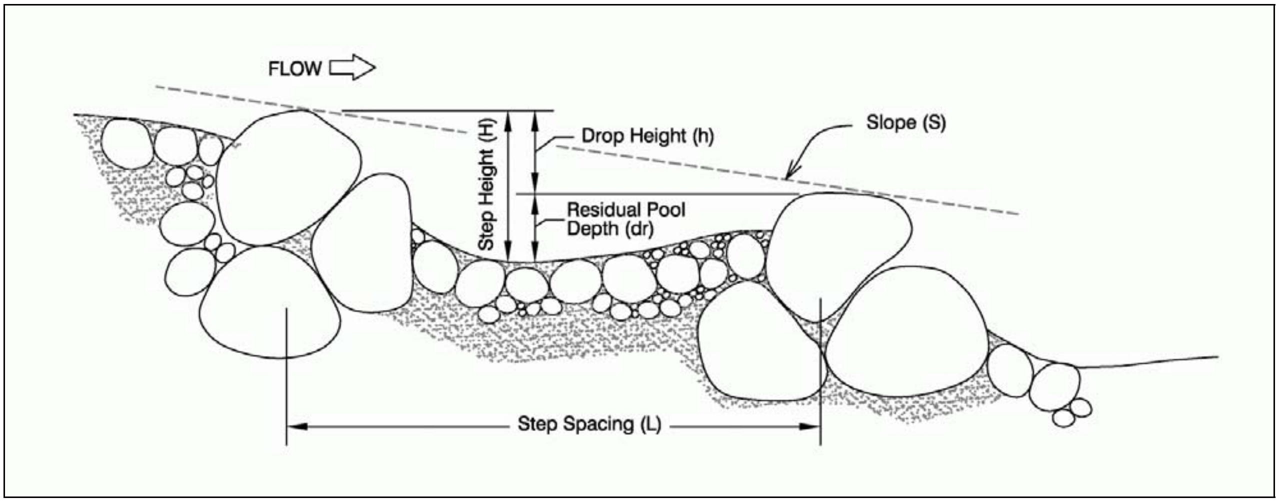


Figure XII-23. Dimensions used to describe a step-pool channel in profile.

Spacing between steps frequently ranges between 0.5 and 2 channel widths, with spacing becoming closer with increasing channel slope (Grant et al. 1990; Chin 1999; Chartrand and Whiting 2000). A relationship that is widely used to describe the rhythmic step-pool pattern, and that can be applied to the design of a step-pool roughened channel, is the ratio of H/L/S. The step height (H) is the sum of the drop between steps (h) and the residual pool depth (d_r). Zimmerman & Church (2001) reported that the ratio ranges between 1 and 5 for step-pool channels, and at slopes of 4% and less, generally between 2% and 5%.

The step height (H), as measured from the maximum depth of the pool to the top of the step, is closely related to the size of the particles forming the step (Chin 1999; Chartrand and Whiting 2000). Based on this work, the average or median rock size forming the step is roughly equal to the step height. Natural channels with steps composed of rocks on the order of one meter (3.3 feet) have been found to be extremely stable (Chin 1998). Additionally, the size of the larger rock forming the step is commonly between 0.5 and 1.0 times the bankfull channel depth, with bankfull depth measured at the step (Church and Zimmermann 2007; Montgomery and Buffington 1997).

The step-pool channel unit can be built at slopes between 3% and 5%. Because water often accelerates as it flows down this type of channel, the recommended maximum overall drop across a series of steps is 5 feet. If larger drops must be overcome, it is necessary to breakup steep step-pool reaches with large pools to dissipate accumulating energy.

<u>Use of Large Pools</u>: Grant et al. (1990) and others describe a step-pool channel composed of two subunits. One subunit is a series of tightly spaced boulder steps interspersed with small “pocket” pools (Figure XII-24). At the bottom of the series of steps is a large pool subunit. At high flows, water accelerates as it moves down the steps, and the large pool at the bottom of steps then

dissipates the flow's energy and slows the water. The large pool also provides holding habitat for fish during high flows, when the smaller pools are too turbulent.

Grant et al. (1990) found the spacing of the large pools, as defined in Figure XII-24, averaged between 2 and 4 channel widths, and the large pools with lengths of at least one channel width. The spacing between individual steps ranged between 0.4 and 0.8 channel widths, and the slope of steps subunit was between 5% and 6.5%. This type of channel sequence can be used to construct a roughened channel with an overall slope as steep as 5%. The large pool subunit should be constructed with no slope and the overall drop between the large pools should not exceed 5 feet. This repeating sequence of closely spaced steps with pocket pools followed by a large pool can aid in dissipating energy and should be considered when designing roughened channels that extend in length for five or more channel widths.

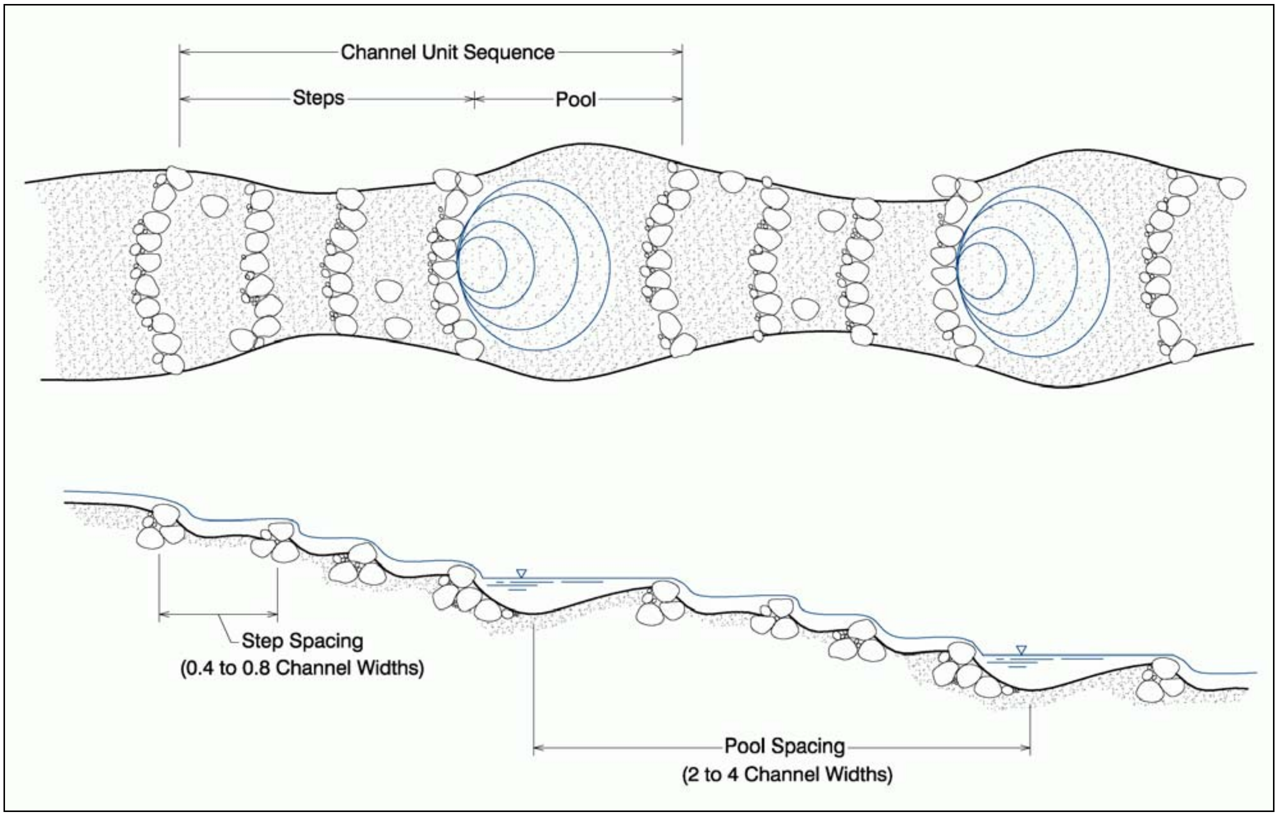


Figure XII-24. Step-pool channel sequence that includes larger pools every 2 to 4 channel widths, as described by Grant et al. (1990).

Cascade and Pool

Natural cascade channels are steep channels characterized by large roughness elements relative to the water depth and without repeating bedforms (Montgomery and Buffington 1997). They are most likely to have natural slopes greater than 6.5%, but have been observed in channels with slopes as low as 4.5%. Cascade channels contain small, partially channel-spanning pools spaced less than one channel width apart. The channel bottom is relatively flat. Large keystone rocks that are essentially immobile are found randomly throughout the active channel, with many of them located near the center of the channel. The size of the keystone rocks are close to or exceed the channel's bankfull depth. Their large size relative to the channel creates flow constrictions and retains smaller boulders and large cobbles to form complex steps at lower flows. The hydraulics of a cascade is characterized as jet-and-wake flow; water is constricted between, and flows over, the large bed material in the form of jets. The jet (supercritical flow) then enters the small receiving pool, forming a wake (hydraulic jump).

A cascade, as described above, can be used as bedforms for roughened channels. This type of bedform is best suited for profile control in stream reaches that are already steep (> 3%), and have relatively coarse bed material and confining banks.

> Constructed cascades are only suitable for relatively straight channel reaches that are highly confined, with floodplains that are small or nonexistent.

Given the steep slope and tendency for water to accelerate as it flows down a cascade, larger pools must be placed between short cascades to dissipate excess energy and provide holding areas for fish. The repeating cascade and pool sequence is very similar to the steps and pool sequence shown in Figure XII-24 and the unit sequence described by Grant et al. (1990). Pool spacing should not exceed 2 to 4 channel widths. To maintain suitable fish passage conditions, the cascades should not have a slope greater than 8% and the overall slope of the cascade and pool should not exceed 6.5%.

Unlike the channel spanning water surface drops created in a step-pool channel, the rocks in a cascade and pool roughened channel should create a complex series of smaller drops that effectively dissipate energy and provide fish with numerous pathways to swim upstream. Some approaches include creating constrictions with keystone rocks to create a hydraulic drop and backwater pool, or arranging rock structures to form multiple drops (Figure XII-25). During design and construction, care should be given to avoid creating situations where the drop criterion for fish passage is exceeded.

The cascade roughened channel is considered to be experimental. It is uncertain if young-of-the-year (YOY) salmonids will be able to ascend a constructed cascade, although a previous study found YOY coho ascending a 5.7% step-pool and cascade channel during summer low flows (Kahler et al. 2001). If passage of YOY or other weaker swimming fish species is a project objective, it may be necessary to develop a study plan to verify that adequate upstream passage is being provided.

At some sites there may also be concern for holding capacity for adults under low flows. If a cascade can not provide deep holding pools such an approach may not be appropriate for the site.

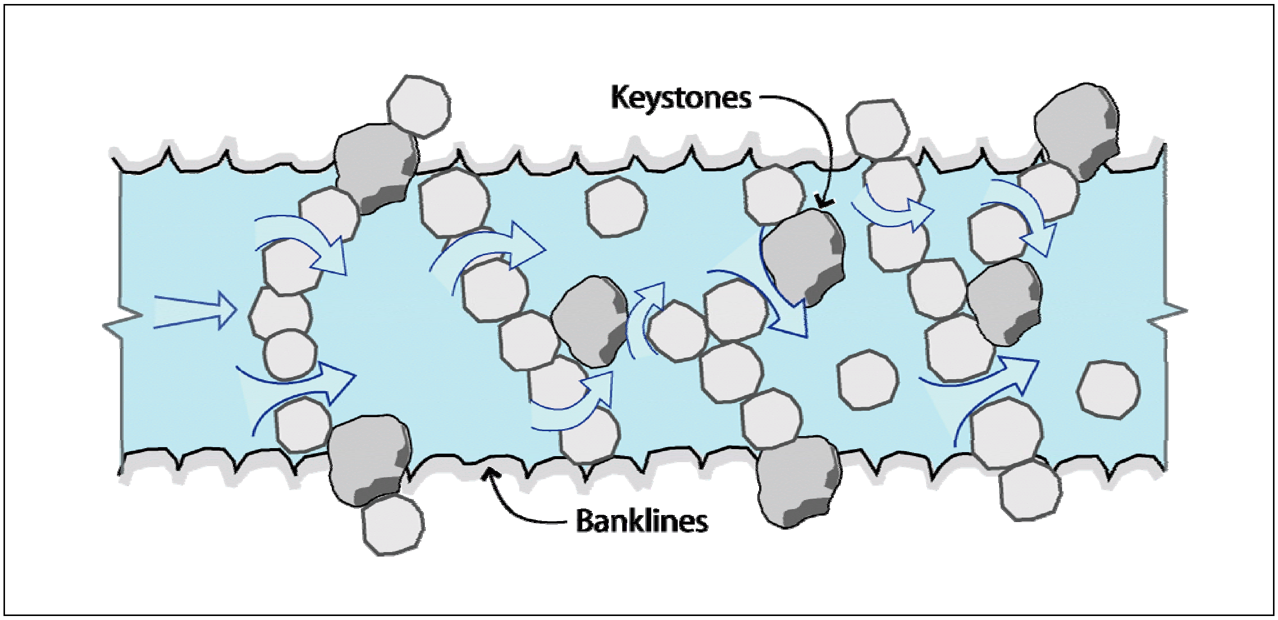


Figure XII-25. Cascade subunit of a cascade and pool channel. The cascade is a complex series of small steps form numerous pathways for fish to swim during lower flows while creating a rough cascade at higher flows.

Sizing the Engineered Streambed Material

Engineered streambed material that forms the bed of a roughened channel has two components: large rock that forms a framework and smaller material that fills the interstitial voids in that framework. The framework of larger rocks is the immobile component of the channel, and maintains the channel shape and profile. The framework rock is sized to be stable up to the *stable bed design flow*, with small adjustments in rock position expected at lower flows. Smaller interstitial materials fill the voids between the framework, minimizing the overall porosity of the streambed, maintaining surface flow, increasing stability and reducing the risk of *piping*. Together, they form a *well-graded* mixture with no gaps in the sediment gradation curve.

The following sections present a method for determining the size and gradation of both the framework and interstitial material that comprises the engineered streambed material. The bed sizing methods discussed applies to all types of roughened channels.

<u>Framework Sizing Equations</u>

This section presents a method for sizing the stable framework of the engineered streambed material (ESM). The framework is defined as the largest 50% of the ESM (D_{50} to D_{100}). There are numerous methods for sizing rock to remain stable in steep sloping channels (Mooney 2007; Maynord 1994; Abt et al. 1986; Abt et al. 1988; Abt and Johnson 1991; Ferro 1999; Costa 1983; Robinson 1998; ACOE 1994). These methods are primarily based on unit discharge in the channel, with many of them derived from shared data sets and yielding similar results. Differences among methods are primarily related to inclusion of coefficients for safety factors, rock thickness, gradation, angularity, and flow concentration.

The method described in this section uses the ACOE (1994) rock sizing equations as a foundation for developing the gradation of stable rock in a roughened channel design. The methods and equations for rock sizing provided in the *Hydraulic Design of Flood Control Channels* (ACOE 1994) are suitable for a wide range of applications and include sizing of rock for steep channels and chutes. It is important to review the original publication before applying methods outlined in this section.

ACOE (1994) presents the following equation for sizing rock for rock chutes with slopes greater than 2%:

$$D_{30-ACOE} = \frac{1.95S^{0.555}(1.25q)^{\frac{2}{3}}}{g^{\frac{1}{3}}}$$ **Equation XII- 1**

Where:

- $D_{30\text{-}ACOE}$ — D_{30} stable particle size based on rock gradation provided in ACOE 1994 (ft)
- S — Hydraulic slope (ft/ft)
- q — unit discharge within the active channel at the stable bed design flow (cfs/ft)
- g — gravitational acceleration (32.2 ft/s^2)

Included in the equation is a flow concentration factor of 1.25 to account for failures induced by concentration of flow between individual grains. The equation was derived in a conditions of low unit discharge in straight riprap channels with slopes ranging from 2% to 20%. The riprap was angular and had a relatively uniform gradation, a layer thickness of 1.5D_{100} and banks with side slopes of 2.5H:1V.

Unit discharge (q) used in predicting the stable rock size for the channel bed is defined as the amount of flow within the channel ($Q_{Channel}$) at the stable bed design flow divided by the width of the active channel (b) (Figure XII-26). Overbank flow ($Q_{Overbank}$), if present, should be subtracted from the total flow for calculation of unit discharge. This will require a hydraulic analysis. For the initial design, a uniform flow cross sectional analysis is generally sufficient. A backwater analysis (i.e., HEC-RAS) may be necessary to finalize the design.

For the stability and associated hydraulic analyses, the overall roughened channel slope is generally used in the initial analysis. For roughened channels with compound slopes of chutes and large pools, the chutes are typically drowned-out during large flood events. The result is a water surface slope that approximates the overall channel slope. However, the highest shear stress on the channel may not be at the stable bed design flow, but rather at a lower flow when the water surface slope over the chutes is steeper. Before finalizing the design, a backwater analysis should be performed to validate the water surface slope and unit discharge used for sizing of the engineered streambed material.

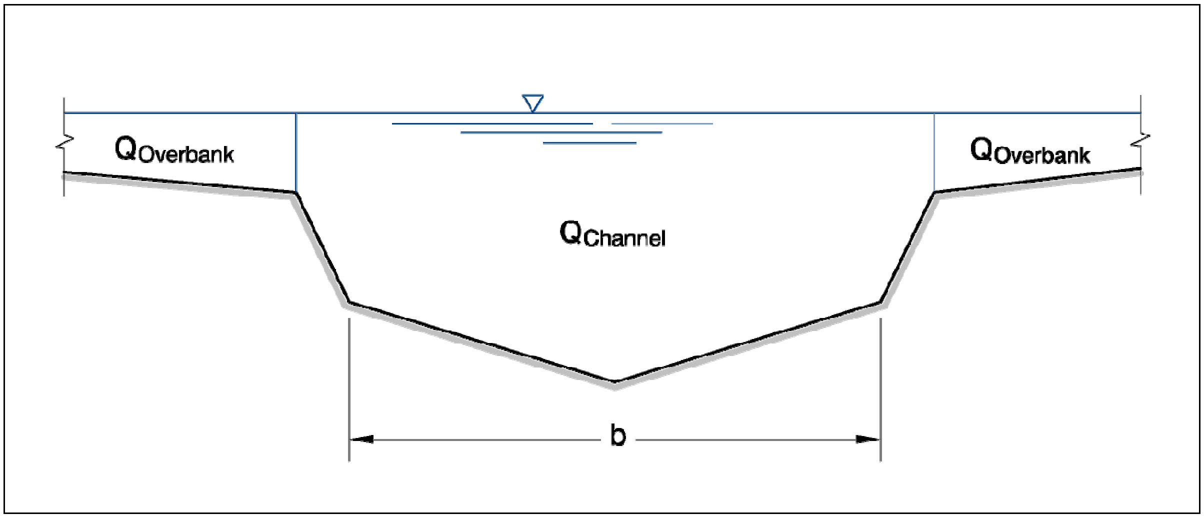


Figure XII-26. Unit discharge for analyzing particle stability is calculated using the flow within the active channel divided by the width of the active channel ($q = Q_{Channel}/b$). Overbank flow is not included.

The ACOE (1994) method produces a relatively uniform gradation, with D_{85}/D_{15} ratios ranging from 1.7 to 2.7. The result is a very porous mixture of similarly sized rocks, with voids composing as much as 30% to 35% of the volume (CalTrans 2006). The uniform gradation causes subsurface flow during low flows, creating unsuitable conditions for fish passage. Conversely, streambed material in a natural channel is characterized by a wide gradation of material sizes, with smaller material filling the voids between the larger particles. The ratio D_{85}/D_{15} in a natural steep channel is commonly between 8 and 14 (Bates et al. 2003; Montgomery and Buffington 1997; Grant 1990).

To achieve a stable bedform while filling the interstitial voids, Bates et al. (2003) recommends the $D_{30\text{-}ACOE}$ for a uniform riprap gradation be scaled by 1.5 to achieve a suitable D_{84} for the engineered streambed material (ESM) in a roughened channel:

$$D_{84\text{-}ESM} = 1.5\ D_{30\text{-}ACOE}$$

The $D_{50\text{-}ESM}$ (50 percentile particle in the ESM) and $D_{100\text{-}ESM}$ can then determined based on ratios derived from bed material within natural channels (Bates et al. 2003):

$$D_{50\text{-}ESM} = 0.4\ D_{84\text{-}ESM}$$

$$D_{100\text{-}ESM} = 2.5\ D_{84\text{-}ESM}$$

These ratios are within the ranges found in steep boulder and cobble bedded streams (Bathurst 1978, 1987, 1985; Thorne & Zevenbergen 1985; Jarrett 1984; Simons & Senturk 1992; and Limerinos 1970).

The ratios provided above for sizing the $D_{100\text{-}ESM}$ should be viewed as guidance, and may need to be decreased in some cases. In step-pool and cascade channels, as the D_{84} increases in size the D_{100} to D_{84} ratio has been observed to decrease. It is also important to avoid having rock that is disproportionately large relative to the channel width. Generally, the largest rock should not be greater in size than one-quarter of the active channel width. Otherwise, the channel may become constricted excessively, causing undesirable hydraulic conditions.

Filling Interstitial Voids to Control Porosity

The material smaller than D_{50} serves to fill the interstitial voids between the larger rocks. Material smaller than the D_{50} can be sized using a modified version of the Fuller-Thompson equation, as described in USFS (2008). This method is used to form a high-density mixture comprised of between 5% and 10% of fine particles (sands and silts) less than 2 mm in size to seal the bed and control permeability. The Fuller-Thompson equations rearranged to find the D_{16} and D_8 relative to the D_{50} are:

$$D_{16-ESM} = 0.32^{\frac{1}{n}} D_{50-ESM}$$ **Equation XII- 2**

$$D_{8-ESM} = 0.16^{\frac{1}{n}} D_{50-ESM}$$ **Equation XII- 3**

To develop the design particle-size distribution curve, an n value between 0.45 and 0.70 is recommended. These are standard values for high-density mixes. The n value selected should result in the $D_{8\text{-ESM}}$ to be approximately 2 mm. If it fails to, additional fines should be added to the mix to achieve the recommended 5 to 10% fines in the final mix.

Sizing of Rock Steps and other Large Rock Structures

For roughened channel steps, chutes or cascades, the larger rocks in the composite engineered streambed material, from $D_{84\text{-ESM}}$ to $D_{100\text{-ESM}}$ in size, are separated from the gradation and used to construct steps and other stable large rock features. The remainder of the material ($\leq D_{84\text{-ESM}}$) is used to form the bed between the steps. Although these large rock features are formed by material ranging in size ranging between the $D_{84\text{-ESM}}$ to $D_{100\text{-ESM}}$, the actual volume of material needed to construct these features should be calculated independently.

Thickness of Engineered Streambed Material

The framework ESM relies on the interlocking of the larger rocks for stability. It is recommended that the thickness of installed ESM be equal to the buried depth of the largest rock used in its construction. The thickness of the ESM between large rock features should be equal to the largest rock used in that section of channel, which is often the $D_{84\text{-ESM}}$. In a rock ramp, the largest rock is typically installed to protrude above the surface of the channel as much as one-third its height so it is effective hydraulically. In such cases, a suitable ESM design thickness is $0.67D_{100}$.

Many rock sizing methods have been found to be inappropriate for this application. Most rock sizing methods recommend a minimum material thickness of 1.5 to 2 times D_{50} or 1.0 to 1.5 times D_{100} of the installed rock. These methods use narrow gradations, with the D_{100} less than 50% larger than the D_{50}. However, the gradation of the ESM results in a D_{100} more than six times the size of the D_{50}, making these recommendations inappropriate for the ESM.

For constructed steps in a step-pool roughened channel, footer rocks are placed under the top rocks similar to the recommended design for rock drop structures (Footings of Rock Weirs page XII-84). This places the bottom of the footing rocks well below the bottom of the adjacent ESM (Figure XII-27).

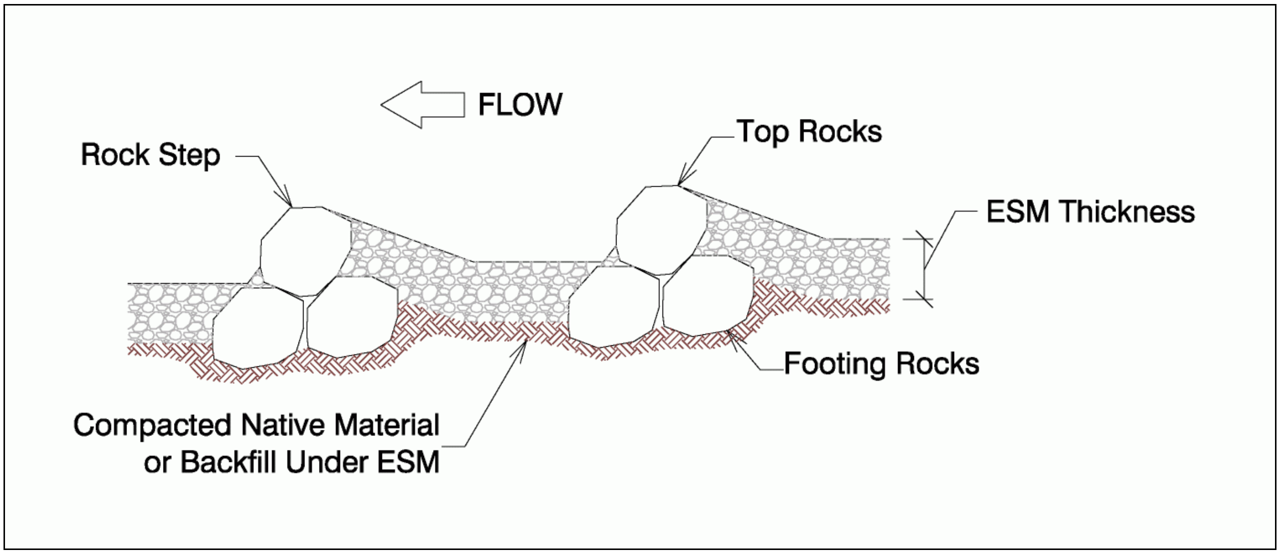


Figure XII-27. Typical thickness of ESM and rock steps in a step-pool roughened channel.

Bankline Rock

The banklines of a roughened channel should be resistant to scour and provide additional channel roughness. Observations of natural steep channels indicate that the composition of the banks is often similar to that of the channel bed materials. Material supplied to steep channels is typically from colluvial hillslope processes rather than the alluvial processes of channels with lower slopes.

The following methods for sizing bankline rock are based on sizing of rock for *riprap* revetments along waterways. Two methods are presented to allow for comparison of results. Both use average water velocity and side-slope of the revetment, but only one of them incorporates depth of flow. Both methods yield a D_{50} rock size that is substantially smaller than the D_{50} of the ESM, and should be viewed as a minimum rock size for the banklines. Rock must be stacked to achieve a steeply sloping bankline, which may necessitate larger rock than predicted with these equations. Rock angularity is important in this case.

Riprap revetments use a relatively uniform gradation, which results in large void spaces between the rocks. Roughened channel banklines use a wide gradation of material to fill these voids, which prevents piping and can accommodate revegetation. Using the calculated D_{50} for the banklines, the gradation of the bankline material is calculated using the methods outlined in Sizing the Engineered Streambed Material (page XII-67) for the Engineered Streambed Material (ESM).

CalTrans Stream Bank Rock Slope Protection (RSP)

The CalTrans Stream Bank Rock Slope Protection (RSP) Design Guidelines (CalTrans 2006) was developed to design rock slope protection along stream banks. The D_{50} rock weight is computed by the following equation:

$$W_{50} = \frac{0.00002 V_b^{6} SG}{\sin^3(\beta - \alpha)(SG - 1)^3}$$ **Equation XII- 4**

Where:

W_{50} weight of the D_{50} rock (lbs)

V_b channel velocity to which bank is exposed (ft/s)

=V_c x 0.67 for parallel flows

= V_c x 1.33 for impinging flows (bends, flow convergence, divergence)

V_c Average cross sectional velocity (ft/s)

SG Specific gravity of rock (Typically 2.65)

b Shape factor constant equal to 70° for broken rock

a Bank angle of RSP slope from horizontal (1.5H:1V slope = 33.7°)

The rock weight is then used to determine the standard CalTrans rock size class forming the outer face of the RSP. Rock weights should always be rounded up to the higher size class. The higher velocity multiplier should be used to account for turbulent flow within roughened channels. Based on the specific weight of the rock, convert the rock weight to a diameter to obtain the D_{50} for the banklines.

HEC-11 Design of Riprap Revetment

The HEC-11 (FHWA 1989) method of riprap revetment was developed to design riprap revetment along waterways. The D_{50} rock size is computed by the following equation:

$$D_{50} = C\frac{0.001V_{avg}^{3}}{d_{avg}^{1.5}K^{0.5}} \quad \textbf{Equation XII- 5}$$

Where:

D_{50} — D_{50} rock diameter (ft)

C — correction factor for flow stability (1.5-2.2 recommended for turbulent flow)

V_{avg} — average main channel velocity (ft/s)

d_{avg} — average flow depth (at design flow) in main channel (ft/s)

K — slope factor

$$K = \sqrt{1-\frac{\sin^2\theta}{\sin^2\phi}} \quad \textbf{Equation XII- 6}$$

Where

θ — bank angle (degrees) from horizontal, typically 1.5H:1V; slope = 33.7^o

ϕ — riprap angle (degrees) of repose, typically 40^o (ACOE 1994)

Fish Passage Design of Roughened Channels

The type of fish passage analysis required depends on the roughened channel type due to the type of hydraulics created. Generally, roughened channel reaches are analyzed by the hydraulic approach (depth, velocity, turbulence, and hydraulic drop).

Rock Ramps, Chutes and Cascades

The hydraulic variables used to assess fish passage in rock ramps, chutes and cascades are water depth, velocity, and turbulence. Analyze the channel hydraulics at the critical fish passage design flows, which are usually the low and high fish passage design flows. When backwater effects are present at the high passage design flow, water velocities may be higher at a lower flow. Generally, a uniform flow cross sectional analysis is sufficient to evaluate fish passage hydraulics in these types of roughened channel types. The cross section should represent the channel, not a pool. The slope should be that of the ramp, chute, or cascade. A depth dependent roughness coefficient should be applied, as presented in Appendix XII-B. Compare the maximum channel depth, cross sectional average water velocity, and EDF to the fish passage criteria.

At a low fish passage design flow the maximum water depth in the channel cross-section should satisfy the minimum water depth criterion. At low flows, water depth is predominately controlled by constrictions as water flows between the large rocks protruding form the channel bed. At these flows, the *relative submergence* is generally beyond the range of flows that the depth dependent hydraulic roughness equations were developed (Appendix XII-B). Approaches to analyzing low-flow conditions include extrapolation of a roughness coefficient (using sound judgment) or evaluating the hydraulics of various constrictions based on the shape of the cross-section and distribution of large rocks to estimate water depths between constrictions.

At the high fish passage design flows water velocities and turbulence should be evaluated one of two ways; using the average cross sectional water velocity or the water velocity within a subsection of the cross section.

Use of a cross sectional average water velocity neglects the hydraulic diversity created by a roughened channel. Conditions along the margins of the channel are often suitable for passage, even when the average cross sectional velocity exceeds fish passage criteria. With sufficient water depth and wetted width in the channel, it is possible to divide the cross section into subsections, evaluate the hydraulics in segments near the channel margins and compare it to fish passage criteria. This can be performed with some cross section models, such as WinXS Pro (Hardy 2005), or using a backwater model, such as HEC-RAS (ACOE 2008). The average water depth, water velocity and turbulence in this channel subsection should meet the design criteria for the target fish. The width of a subsection should be no less than 4 feet.

To evaluate turbulence, the energy dissipation factor (EDF) is calculated at the high passage design flow using the equation for sloping channels (see Turbulence page XII-54 for EDF discussion):

$$EDF = \gamma VS \qquad \textbf{Equation XII- 7}$$

where γ is the unit weight of water (62.4 lb/ft^3), V is the average water velocity (ft/s), and S is the hydraulic slope (ft/ft). Although there are no well-developed criteria for EDF in roughened channels, generally the EDF should not exceed 7 ft-lb/s/ft^3 for adult salmon and steelhead (Bates et al. 2003) within the entire channel, or channel subsection that fish may use for swimming upstream.

Insufficient depth, excessive velocity, and excessive turbulence can all be corrected by one or more of the following changes:

- Increase the cross-slope of channel to increase concentration of flow towards channel center
- Adjust the channel width
- Decrease the channel slope
- Increasing rock size in the ESM, thus increasing the hydraulic roughness.

Step-Pool Channels

The hydraulic variables used to assess fish passage in step-pool channels are the water surface drops over the steps, pool depths, and turbulence as EDF within the pools. In most situations, step-pool roughened channels maintain plunging flow conditions at fish passage flows. Hydraulics of the step pools are modeled assuming weir flow over each step. Generally, the hydraulics are modeled as sharp crested weirs. When the tailwater is above the crest of the step, the weir is partially submerged. Submergence should be accounted for in the analysis using the equation developed by Villemonte (1947), which is in Appendix XII-B, Equation XII-B-5.

If each step is constructed with the same crest-to-crest drop and the cross sectional shape of the steps is the same throughout the roughened channel, then the water surface drop will be the same over all of the steps. If the shape or crest-to-crest drop between steps varies, the water surface drops over the steps will differ. In such cases, the hydraulics of each individual step must be analyzed to determine if each water surface drop meets design criteria. For all step-pool roughened channels, the water surface drop over the last step should also be analyzed to ensure that it does not become excessive at the high fish passage flow. The last step is also affected by transitions (see Channel Transitions page XII-76).

At the low passage design flow the maximum pool depth should be compared to the minimum required depth. At the high passage design flow the EDF in the pool should be compared to the recommended EDF thresholds. EDF in the pool is calculated the same as for a pool and weir fishway (Turbulence page XII-54). For traditional pool-and weir fishways, a maximum EDF of 4.0 foot-pounds per second per cubic foot of volume is recommended for adult salmon and steelhead (Bell 1991) and 3.0 foot-pounds per second per cubic foot of volume for trout species (Larinier 1990). However, depending on the hydraulic diversity in the pool (i.e., bankline roughness), a step-pool roughened channel may provide fish passage at an EDF that is as much as 50% higher than these values (Bates pers. comm.). If the water surface drops vary from step to step or if pool size and shape varies, then the maximum pool depth and EDF in the pool must be calculated for each individual pool. Otherwise, the pool depth and EDF will be the same from pool to pool at a given flow.

Factors Influencing Longevity

In designing roughened channels and other types of profile control structures, it is important to recognize the potential mechanisms by which these structures can fail. Failure may be related to geomorphic or structural factors.

Geomorphic processes that can threaten a roughened channel or other types of profile control structures include downstream channel incision, insufficient supply of fine sediments, and lateral channel migration. Measures can be incorporated into the roughened channel design to address anticipated channel adjustments. A thorough geomorphic site assessment during the pre-design, as described in Alignment (page XII-16), will help identify and avoid these types of issues.

An insufficient supply of fine sediment can lead to long-term problems associated with the porosity of the roughened channel bed. When fines winnowed from the bed are not replenished by new fines, voids eventually form between the larger stable rocks. This results in piping and the subsequent loss of larger material – a process driven by the hydrostatic pressure created by the difference in head through the roughened channel. The loss of fines leads to excessive porosity and increased subsurface flow. This problem is most often associated with roughened channels at or around dams, within highly urbanized watersheds, or when the slope and size of the roughened channel bed material is much greater than the upstream channel.

Piping of the native material that underlies the engineered streambed material (ESM) can also cause structural failure. The risk of piping increases as the slope or the overall head differential through the roughened channel increases. Roughened channels constructed over fine-grained sandy substrates and/or without an adequate thickness of ESM are most susceptible. If piping is a risk at a project site, cohesive sediment may be added to the fines portion of the ESM, or the head differential minimized by over multiple roughened channel sections at an overall lower slope than originally planned. Finally, a granular filter blanket or geotextile fabric filter placed under the ESM can reduce the risk, but must be placed well below the potential scour depth. Based on the FHWA (1989) recommendations for riprap revetments, a filter may be considered beneath the ESM if the D_{15} of the ESM is more than five times the D_{85} of the native material. The wide gradation of material sizes in a well-designed ESM gives it similar characteristics to, and functionality of, a granular filter blanket. Because of the properties of the ESM, a granular filter blanket or geotextile fabric is rarely needed to control piping.

Structural failure can result from dislodging and the loss of large rock from the roughened channel or scour at the downstream end of the roughened channel that leads to rock movement and over-steepening of the channel. Proper sizing of the engineered streambed material and incorporation of transitions to dissipate energy at the top and bottom of the roughened channel will minimize the likelihood of failure by these mechanisms.

Channel Transitions

Adverse hydraulics at the transitions between the roughened channel and the natural channel or at slope breaks within the roughened channel can lead to poor fish passage conditions. Transition hydraulics at slope breaks and at the upstream and downstream ends of roughened channels should be analyzed using a backwater model. If the tailwater is too low, a drawdown in the water surface will develop. A drawdown causes water depth to decrease while increasing water velocities and turbulence in the downstream direction, potentially creating adverse fish passage conditions.

As flow enters a roughened channel there is often a drawdown and acceleration in water velocity, which can cause additional scouring forces. To reduce scour potential, an upstream transition should be included consisting of a gradual steepening and narrowing of the channel rather than an abrupt change in grade.

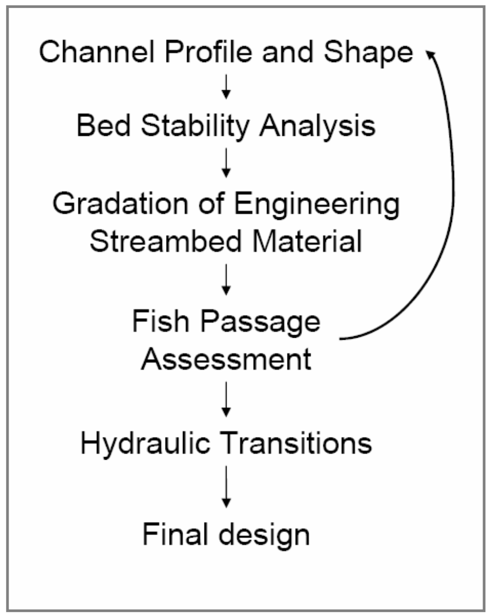
Roughened channels generally produce higher velocities than found in the adjacent natural channel. If close attention is not given to the transition between the roughened channel and the downstream natural channel, scour can occur in the channel at the downstream end. Downstream transitions are typically either a flat or reverse grade (forming a pool) section of roughened channel at the downstream end. The downstream end of the roughened channel can be buried into the downstream bed in anticipation that the channel may eventually scour and expose that part of the roughened channel.

Overview of the Design Process

The roughened channel design procedure involves an iterative process to develop channel shape, particle size, and hydraulic conditions for both stability and fish passage. The design begins with a project profile and a general cross sectional channel shape, followed by hydrologic and hydraulic calculations and a stability analysis to develop the gradation of the engineered streambed material. Fish passage conditions are then evaluated to ensure they meet design criteria. If fish passage criteria are not initially satisfied, the channel design will have to be modified and the previous steps repeated. Lastly, transitions at the upstream and downstream ends of the roughened channel should be designed.

Hydraulic geometry for the design cross-section and slope is determined for a range of flows including the stable bed design flow. A single cross section hydraulic analysis assuming uniform flow and assuming the water surface slope is equal to the overall slope of the reach is often adequate for the stability analysis.

Hydraulic roughness of a channel is directly dependent on the depth of flow relative to the size of the bed material. Appendix XII-B presents several depth dependent hydraulic roughness equations and their limits of application. Hydraulic roughness and the size of rock in the engineered streambed material are interdependent, requiring an iterative process to calculate a stable rock size.



Using the flow depth and hydraulic geometry, a stability analysis is conducted for the stable bed design flow. Particle stability is typically determined using standard riprap sizing methods based on unit discharge (flow rate in active channel/active channel width), as presented in Sizing the Engineered Streambed Material (page XII-67). The gradation of the engineered streambed material is determined from the stable rock size as predicted by the stability analysis. This rock size becomes the basis for determining the design gradation of the engineered streambed material. Material smaller than the D_{50} is sized using the Fuller-Thompson equation that was developed to achieve a low-porosity mixture.

Next, fish passage conditions are evaluated at the low and high fish passage design flows and at any other critical fish passage flows for each target species. For rock ramps, chutes and pools, and cascades, a single cross sectional analysis and depth dependent estimates of hydraulic roughness can be used to evaluate the water depth, velocity, and turbulence. The cross section should be representative of the roughened channel, and the slope of the chute, ramp, or cascade should be used for the analysis. Fish Passage Design of Roughened Channels (page XII-73) outlines the fish passage analysis for these channel types.

In step-pool roughened channels, the steps are assumed to maintain plunging flow conditions at fish passage flows. Fish passage conditions are evaluated assuming weir flow over each step, accounting for submergence when applicable. At each fish passage flow, calculate the water surface drop over each step, the maximum pool depth, and turbulence in the pool. Fish Passage Design of Roughened Channels (page XII-73) outlines the fish passage analysis process for step-pool channels.

Good judgment must be used when interpreting these results in terms of actual fish passage conditions. Additionally, depth, velocity, drops, and EDF in a roughened channel can be compared to those in the adjacent natural channel to understand how much more challenging passage of the roughened channel is compared to the natural channel. If fish passage conditions are not adequate, change the channel shape and/or slope to improve hydraulic conditions. The stability analysis and fish passage assessment must then be repeated.

Once the channel shape and engineered streambed material gradation have been determined, the gradation of the bankline material should be developed as described in Bankline Rock (page XII-71).

Next, the bed morphology should be developed. This includes determining the size, shape, and spacing of any rock structures, such as chutes, channel spanning steps, complex steps, or constriction rocks. These structures are composed of the largest of the engineered streambed material ($>D_{84}$).

Before finalizing the design, it may be necessary to complete a backwater analysis of the roughened channel at fish passage flows and the stable bed design flow to evaluate hydraulic transitions and the hydraulics at any other unique cross-sections.

Implementation of Roughened Channels

In general, construction of a roughened channel requires skilled equipment operators, a large quantity of rock and other imported material, and on-site construction guidance from persons familiar with design and construction of roughened channels. For the constructed roughened channel to be built and function as intended, regular guidance by the project designer is required during construction. Additionally, construction issues frequently arise that must be correctly addressed in a timely manner.

Construction of a roughened channel is typically done in the following sequence:

1. Excavate native material and/or backfill and compact material to the sub-grade elevations for installation of granulated filter blanket (if needed), banklines and ESM and material. Then excavate trenches for placement of steps, bands, or other rock structures that extend below the ESM or key into the banks.

2. It is typically best to work in sections, going from upstream to downstream so completed work does not backwater the current work area. If water is well controlled, working from downstream going up has the advantage of rock being placed against the downstream bed, which is closer to a natural condition of hydraulic sorting. Plan the sequence of construction so large equipment does not have to cross over completed structures or

bankline rock. If they do have to cross over existing structures, smaller fill material from the ESM can be used to protect the structures.

3. Place the footing row(s) and top row of rocks for steps, bands, or other rock structures.

4. Install bankline rock, including any keystone rocks that protrude from the bank. Individually place the larger rock in the bankline gradation. Use the smaller material to fill in the voids between the large rock. To compact the banklines, tamp in place followed by *jetting* or *flooding* to wash the finer material into remaining voids.

5. Install ESM in lifts across the active channel. The height of each lift should be greater than the D_{50} but less than the D_{84} of the ESM. Plan and specify the lifts and the large rock within each lift so the desired distribution of exposed rock is eventually achieved as described below.

    a. Begin each lift by individually placing the largest rocks in the lift (size greater than thickness of lift) throughout the channel bed in the proportions called out in the ESM gradation (Figure XII-28). This ensures the large rocks are positioned vertically and laterally throughout the ESM horizon. It also allows the large rocks to protrude above the finished grade to create hydraulic roughness and diversity. For stability, the rock should not protrude more than one-third of its height above the finished grade of the channel bed.

    b. Place the remaining material into the channel at a thickness equal to one lift. Mix in-place as necessary until the mixture is well-graded.

    c. Compact each lift by tamping, followed by jetting or flooding so fine material is worked into the lift. If water continues to rapidly infiltrate through the placed ESM, the bed is not adequately sealed. Add additional fine material to the top of the lift and then jet or flood the material into the bed. Repeat until the bed is adequately sealed. During final flooding of the top lift, an adequately sealed bed will maintain water flowing down-slope across the surface of the roughened channel.

The ESM is typically a mixture composed of different size classes of available material. The design gradation of the ESM can be achieved by mixing these materials in the correct proportions. The gradation of the different available materials may be available from the supplier. Otherwise, it can be verified by estimating with a pebble count (Harrelson et al. 1994) or a sieved bulk sample. Native streambed material excavated for the project can often be incorporated into the ESM mixture once the gradation of the material is established. In the end, a “recipe” is developed that describes the proportion of each material used in making the mixture.

If rounded rock is used for the construction of the engineered streambed material framework ($>D_{50}$) it should be adequately upsized during the design process. The ACOE (1994) equations were derived for angular rock. Experiments identified that when a riprap chute is comprised of rounded material, the stone begins to move at a flow about 40% lower than for angular rock (Abt et al. 1988; Abt & Johnson 1991).

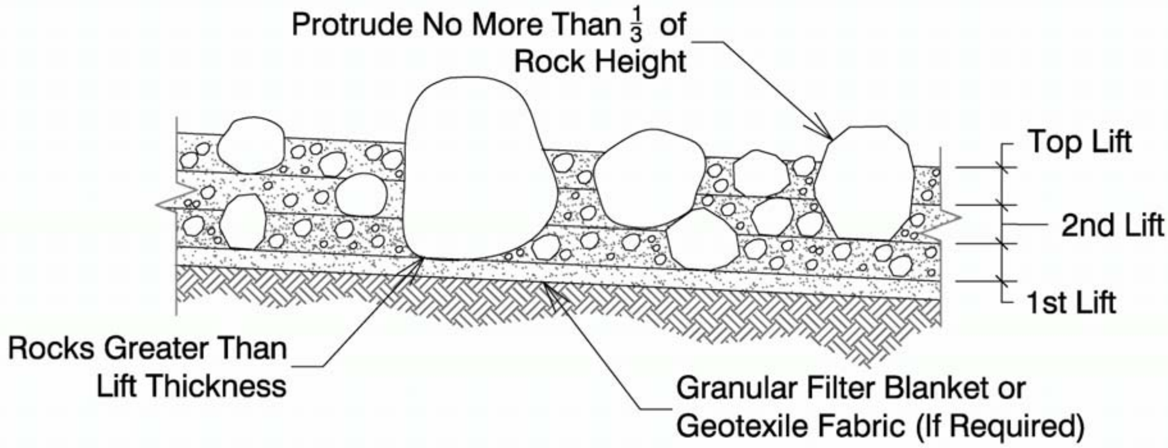


Figure XII-28. Placement of ESM in lifts. Begin each lift by individually placing rocks larger than the thickness of the lift, follow with placement and mixing of the remaining portion of the ESM.

Drop Structures for Controlling Channel Profile

Drop structures are individually constructed drops in the channel bed that span the entire channel to create a steeper profile than would naturally occur. They differ from roughened channels in that they are not a continuous structure throughout the project reach, but discrete individual structures with native streambed between. They are also referred to as weirs or sills. They are often constructed of rock or logs, but may be built with concrete, sheet pile, timber planks, or other types of construction materials. Some common uses of drop structures include improving fish passage at barriers such as perched culvert outlets, stabilizing the bed of an incising channel, raising the channel bed to restore the historical channel profile, or as a low dam to facilitate an in-stream water withdrawal.

Although a single drop structure is sometimes sufficient, a series of drop structures is generally required to meet fish passage project objectives. With a series of drop structures, the channel profile and water surface can be incrementally stepped-up to provide fish passage. When fish passage is required, each individual drop structure should comply with the maximum hydraulic drop criteria.

Unlike steps constructed in a roughened channel (see Roughened Channels as Profile Control page XII-58), each drop structure is typically independent from the next, with a distinct scour pool that forms between structures. The scour pool should be large enough to dissipate the energy of the drop and provide suitable conditions for fish to swim or leap over the structure. Shape of the drop structure, drop height, and competency of the streambed and banks all influence the width, length and depth of the receiving scour pool.

The longevity of drop structures depends on their structural integrity and the vertical and lateral stability of the channel. If one structure shifts or completely fails, the drop at the next upstream structure will increase, possibly creating a fish barrier. In some cases, failure of one drop structure can initiate a cascading failure of upstream structures.

Selecting the type of drop structure and construction materials is project specific. Influencing factors may include fish species and life stages requiring passage, slope of existing channel, stability of downstream channel, acceptable project length, construction work-window, site access for equipment and materials, availability of materials, level of construction experience and oversight, overall cost, and aesthetics.

Influence of Drop Structure Shape on Hydraulics

Drop structures generally function as weirs at most flows. The shape of a weir crest influences the flow patterns over the weir and the characteristics of the scour pool below the weir. Flow generally crosses perpendicular to the crest of a weir and is concentrated at any low point along the weir crest. The length and lateral slope of the weir crest governs the depth of water over the weir and the upstream backwater. Using these principles, the planform and cross sectional shape of a weir guides the flow patterns over the weir and the location and degree of downstream scour. A drop structure that is straight, perpendicular to the channel, and level across the channel tend to create a rectangular channel and a scour pool that spans the full width of the channel. A structure with a V-shape in plan view (pointing upstream) and/or in elevation across the crest (low in the center of the channel) tends to form a long and narrow scour holes in the center of the channel.

Slope and Spacing of Drop Structures

The slope of a design profile with drop structures is usually measured from crest to crest of the drop structures. Spacing of drop structures depends on drop height and design slope. As the slope of the design profile steepens, the spacing between drop structures must decrease to avoid exceeding the maximum drop criteria for fish passage. If the spacing of structures is too close, each scour pool will extend to the next downstream structure, thereby preventing deposition and formation of a pool tailout, as well as failing to adequately dissipate energy from the drop. When this occurs, it will be difficult to seal porous rock or log weirs, resulting in flow passing through the structure rather than over the crest. This can create a low-flow fish barrier and undermine the stability of the structure. Additionally, inadequate dissipation of energy in undersized pools can cause velocities and turbulence to increase, which may block fish passage, scour the channel bed and banks, and potentially cause failure of the next downstream drop structure.

For gravel and cobble bedded streams, drop structures should generally not be used to oversteepen the channel slope above 4% to 5% or they will become too closely spaced. In streams that do not experience large variations flows, such as spring-fed dominated streams, higher slopes may be sustainable.

Use of drop structures in low slope channels with fine-grain substrate (sands and silts) can be problematic due to the erosiveness of the streambed and banks and tendency for the structure to sink into the streambed. In these situations, a roughened channel (Roughened Channels page XII-57) may be a more appropriate method for controlling the channel profile. Roughened channels better control bed and bank scour and can be designed to withstand deformation while continuing to provide fish passage.

When using multiple drop structures in series, the drop height between structures is typically measured from crest to crest. This assumes that all of the structures have the same planform and cross sectional shape and dimensions. Variations in the structure can cause each to have different backwater characteristics, leading to differential drop heights and potentially creating a fish barrier at high flows. If drop structures have different shapes, a water surface profile should be developed for both the low and high fish passage design flows to evaluate the hydraulic drop over each structure.

If the bed between drop structures is erodible, the pools below each structure will generally scour to a sufficient size to dissipate the energy of the drop. Following the guidance for slope limitations and drop height will generally ensure that adequate pool volume is provided. However, in situations where the channel bed and banks are non-erodible (i.e., concrete, bedrock, or rock lined channel) the EDF for the pools at the high fish passage design flow should be checked to avoid creating a turbulence barrier. See Turbulence (page XII-54) for more information on evaluating turbulence in non-erodible pools below drops.

Upstream, Downstream, and Inside Culverts

Placement of drop structures within and around culverts should be done with extreme caution. When placed close to a culvert inlet, the hydraulic forces created by the drop can cause excessive scour at the inlet, sometimes resulting in scour of the bed through the entire culvert. Additionally, drop structures near a culvert inlet can decrease culvert capacity and increase the risk of debris plugging. As general guidance, avoid locating drop structures and their scour pools within the area of flow contraction upstream of a culvert inlet. HEC-RAS (ACOE 2008) provides guidance on determining the length of channel that experiences flow contraction. Provide a spacing that is greater than a long pool and tailout in the natural channel below a similar drop structure. Drop structures with a one-foot drop should be located at least 35 feet upstream of a culvert inlet (Bates et al. 2003) in a gravel-bedded channel.

When constructing a drop structure below an existing culvert, the structure should be placed at least 20 feet downstream of the outlet to maintain the outlet pool for energy dissipation. In cases where a new crossing is designed using stream simulation or low-slope approaches, no scour pool is expected and drop structures can be placed closer to the outlet.

Use of drop structures inside culverts is generally not recommended, unless the culvert is designed as a fishway (see Fishways page XII-107). A roughened channel is more suited for providing profile control inside new or replacement culverts. Rock weirs as part of a step-pool stream simulation channel can be placed inside culverts when applicable (see Stream Simulation page XII-28).

Keying into the Streambed and Banks

Keying drop structures sufficiently into the streambed and banks is essential for preventing undermining and flanking, or end-running (Figure XII-31). The crest of the weir at the banks should be placed high enough to concentrate flow towards the center of the weir. At the point that the weir intersects the stream banks, the top of the weir should be below bankfull elevation.

If flow plunges over the structure and towards the bank, the flow will tend to scour the bank and the structure key. A detail design for the treatment of this area is important to avoid erosion and over-steepening the bank, which can threaten structure support or sealing at the keys.

The structure extends into the bank in an excavated trench. The key typically extends at least as far into the banks as the banks are tall, or two foundation rock widths, whichever is greater but can be reduced where banks are not erosive because of armoring or competent native material. Cut-off walls of rock or logs buried into the stream banks and across over-bank areas and oriented perpendicular to the flow can be used in conjunction with the bank keys to further prevent flanking.

The key into the streambed should extend sufficiently below the predicted scour depth to prevent undermining of the structure and maintain the integrity of the structure. The scour depth increases with increasing drop across the structure and decreasing size of bed material in the channel. Fill any voids in or around the keys with high-density material and compact it to avoid seepage that can cause piping and failure.

Rock Weirs and Rock Chutes

Rock structures, which include rock weirs or chutes, can withstand small shifts of material and continue to function as intended. They are made of individual rocks stabilized by weight of the material as well as contact with other rocks. Because they can withstand small deformations and continue to provide fish passage, these types of drop structures are better suited than rigid weirs to withstand downstream channel adjustments.

Because of the inherent irregularities in the surface of rock structures, they generally provide increased hydraulic diversity and better passage performance in comparison to rigid weirs. They can also be easily adjusted by moving individual rocks by hand or with small equipment.

Rock structures are typically designed to maintain lower slopes than rigid weirs. Because of construction methods and the ability for the rock to shift, larger tolerances must be incorporated into the design of the shape and placement of rock structures. The gaps between rocks make them more permeable than rigid weirs, requiring additional care and consideration during design and construction to seal the weirs and provide suitable passage conditions during low flows. Sealing of rock structures is enhanced by providing sufficient spacing between successive structures so bed material accumulates upstream of each structure.

Shape of Rock Weirs and Chutes

Rock weirs can be shaped in both planform and in cross section to concentrate the flow towards the center of the channel and away from the banks, or to spread the flow relatively evenly across the entire channel width. Each pattern has advantages and disadvantages in terms of fish passage, structural stability, impacts to the adjacent channel, and overall design slope. The face of a rock weir can also be laid back in the stream-wise direction to spread the hydraulic drop over a longer distance. Laying back the face of the weir creating a chute rather than a distinct drop in the water surface, allowing fish to swim rather than leap over the structure.

Cross Sectional Shape of Rock Weirs

The crest of a rock weir should be shaped to concentrate low flows towards the center of the channel and away from the banks. Lowering the side-slope of the crest will decrease the backwater effect created by the weir. The side slope of the crest will depend on the channel width, shape of the weir, shape of the channel, height of the banks, and the desired backwater effect. Often it is preferable to have the weir crest closely resemble the cross sectional shape of the existing channel. To avoid excessive upstream backwater effects and downstream scour, side slope should not exceed 5H:1V, and should be less on wide streams (Figure XII-31). Weirs with relatively flat crests should include a low-flow notch for fish passage.

The ends of the weir should key sufficiently into the banks to prevent flanking. NRCS (2000) recommends that the rock extend at least four times the D_{100} rock size into each stream bank. If there is substantial over-bank flow during extreme high flows, the key may need to extend further.

Footings of Rock Weirs

Keying the weir sufficiently into the bottom of the channel can prevent undermining caused by scour; a common mode of failure for rock weirs. The rock must be stacked into at least two rows to key the foot of the weir below the potential scour depth. The bottom rocks are referred to as the footing rocks. The weir footing can be constructed with either one or two rows of footing rocks (Figure XII-29). Using two rows of footing rock can provide additional stability and better control for placement of the top rocks at the design elevation. Two rows of footing rocks are often used for stability when raising the elevation of the channel. However, to reduce materials one row of footing rocks below the row of top rocks may be used in situations where the new channel is cut into an existing channel bed. The footing rocks should be placed at the toe of the downstream slope so as not to prevent to formation of a jump pool. The top rocks should be carefully selected and individually placed with a minimum of voids. The upstream half of the top rock rests on the existing bed material rather than a second row of footing rock. Voids in the rock should be filled in lifts as the rock is placed. Material used to fill the voids should be washed into place and rodded into voids. After completion of the weir additional material should be spread and rodded into voids appearing after washing, and the process repeated until voids are filled.

Likewise, a chute should have a row of footing rocks and top rocks at the downstream end to buttress the material above it. Keep in mind that in a chute, the lower end is submerged at high flows.

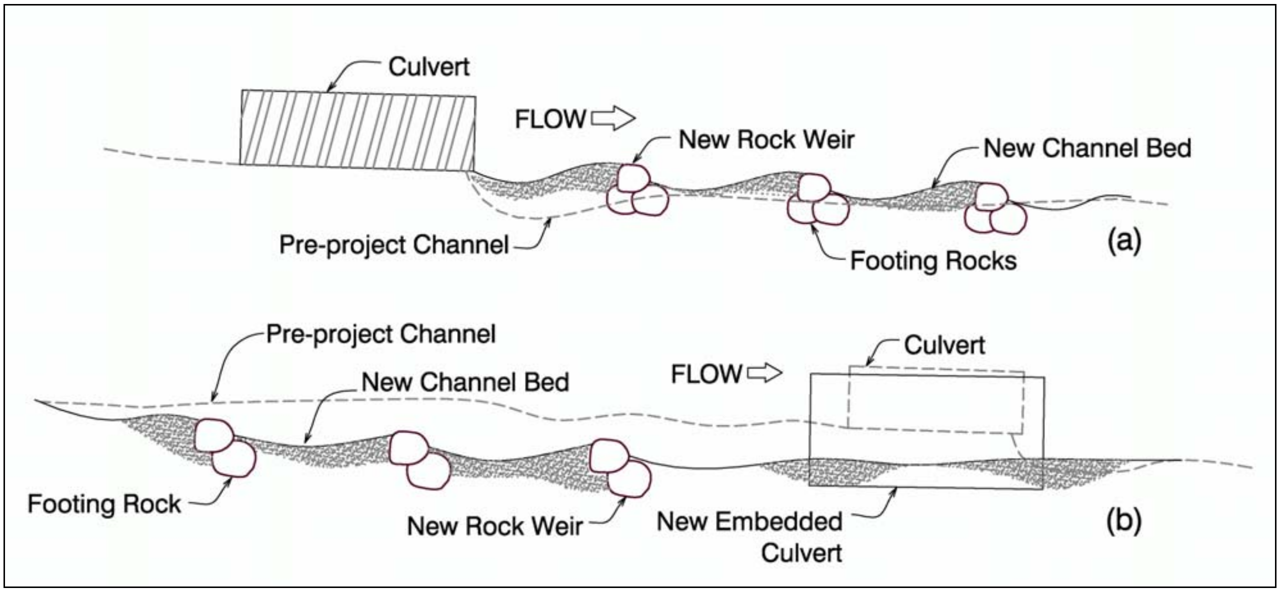


Figure XII-29. Examples of (a) using two rows of footing rocks for weirs that raise the existing channel bed below a perched culvert and (b) using a single row of footing rocks for lowering an existing channel profile to prevent headcutting upstream of a culvert replacement.

In lieu of a scour analysis, for gravel or cobble bedded streams, the largest rock size in the design gradation (D_{100}) can be used to determine the depth of the footing rock (see Rock Sizing for Rock Weirs and Rock Bands page XII-89). The bottom of the footing rock should be at least as deep as the D_{100} below the downstream weir crest or pool tail crest elevation (Figure XII-30). The depth of scour below a drop structure in a gravel-bedded stream is commonly two and a half times the drop of the weir (Saldi-Caromile et al. 2004).

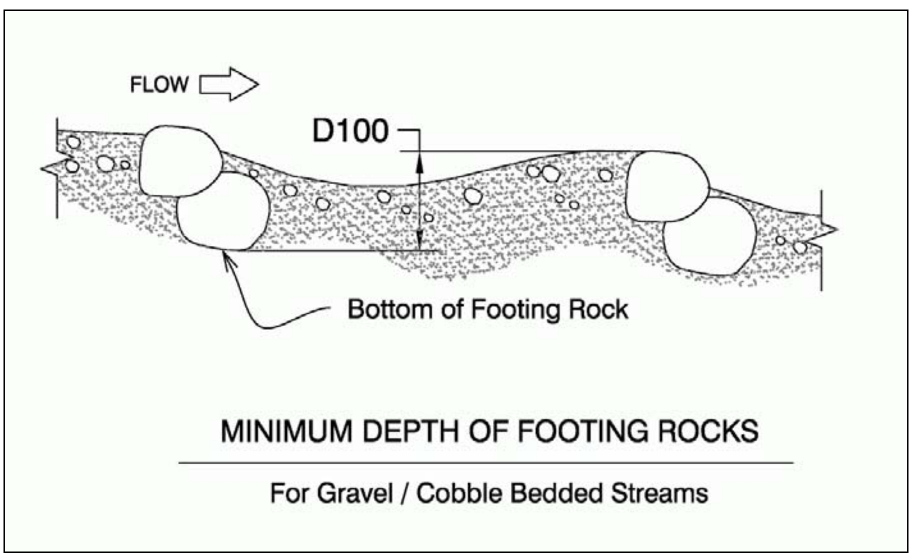


Figure XII-30. In lieu of a scour analysis, the minimum depth of the footing rock can be estimated from the D_{100}. The D_{100} is the largest rock size used to construct the weir, as determined from the rock sizing analysis.

If the rocks keyed into the bank are exposed due to bank scour, they may become an active part of the rock weir. For this reason, the rock keyed into the banks should have footing rock and be roughly the same size as the rock used in the channel portion of the weir.

Arch and Chevron Rock Weirs

Weirs in the planform shape of an arch or chevron, with the apex pointing upstream, concentrate flow towards the center of the channel (Figure XII-31). This shape of weir tends to scour a long and deep pool in the center of the channel while directing flow away from the downstream banks. A depositional area along the channel margins may be created, reducing the risk of bank scour.

To span a wide stream or river may require the use of W-shaped weirs, also referred to as labyrinth weirs. These are composed of two or more chevron shaped weirs placed together to span the channel. The weir shape will create a diverse channel bed in the downstream channel rather than a uniform, flat channel. The weir crests at the apex of each weir cycle in a labyrinth weir can be placed at different elevations to concentrate low flows into a single low flow notch rather than splitting it between multiple low flow notches.

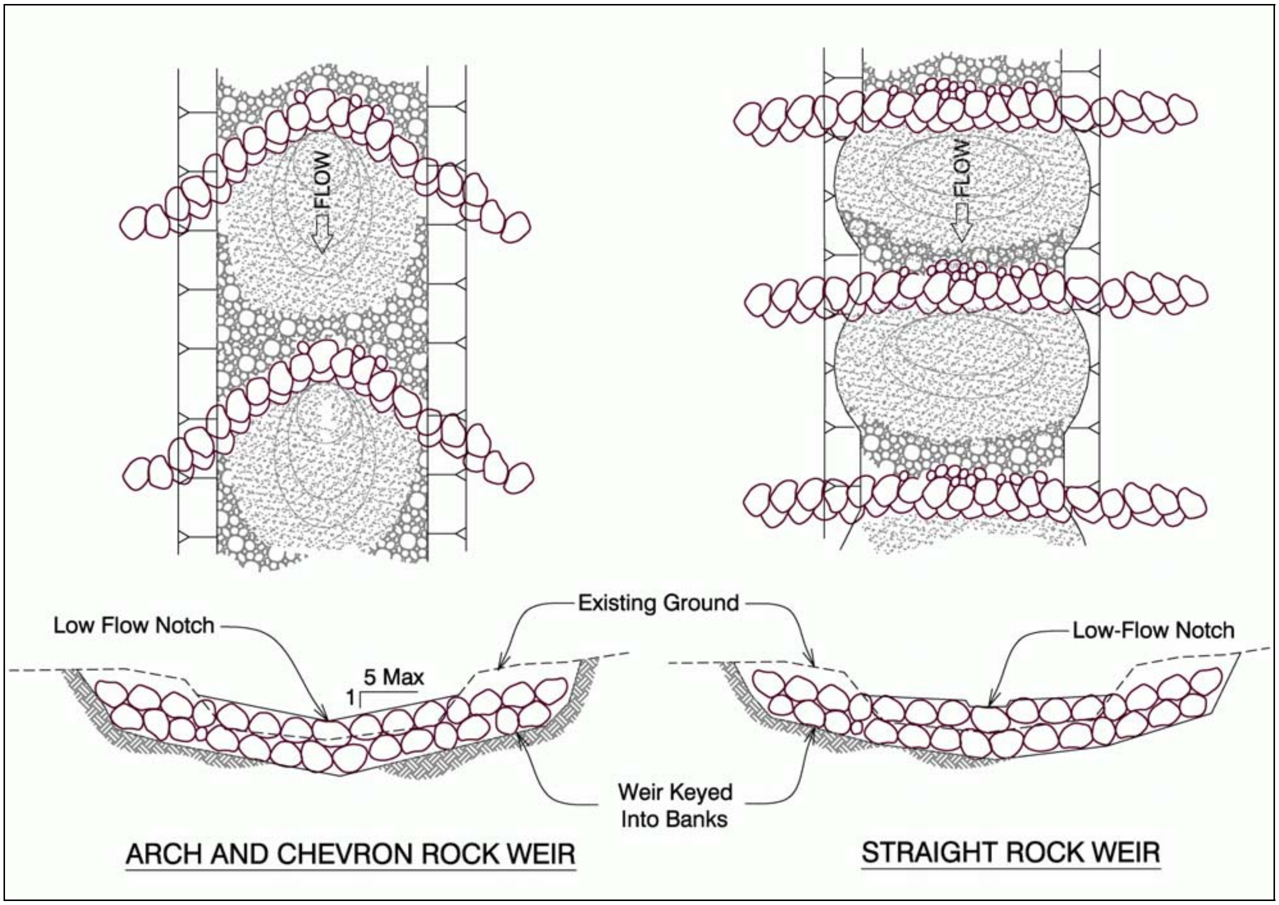


Figure XII-31. Examples of arch shaped rock weir and straight rock weir in planform and cross section.

These upstream pointing rock weirs gain strength through their arch shape (Figure XII-32). The forces exerted onto the weir by the stream flow pushes the rocks against each other, transferring the forces into the banks. The apex of the weir should have an angle between 90 and 120 degrees. The sharper the angle, the more flow is concentrated towards the center of the channel, creating a longer and deeper scour pool with an increased risk of undermining. Bates et al. (2003) suggests a maximum overall grade (measured from crest to crest) of 3% for sharply angled arch and chevron rock weirs. The crest elevation of the weir should slope down towards the apex to concentrate flow away from the banks and towards the center of the channel.

Straight Rock Weirs

Straight rock weirs span the channel perpendicular to the flow (Figure XII-31). The crest can be level or sloped. The more level the crest, the more flow is spread across the entire weir, limiting its backwater effect. By spreading-out the flow, the concentration of scour is reduced. The resulting scour pool below a straight weir is typically shallow and wide, spanning the entire channel. The stream wise length of the pool is relatively short. Because the weir does not direct flow away from the channel margins, bank erosion should be anticipated immediately downstream of straight weirs.

Figure XII-32. Arch-shaped rock weirs produce diverse hydraulics across the crest while concentrating flow towards the channel center. Photo courtesy of Rob Sampson.

To reduce the velocities along the banks, the crest should have a gentle side slope towards the center of the channel. Additionally, it should have a distinct notch near the center of the channel to concentrate low-flows for fish passage.

Because a straight weir lacks the inherent strength provided by the arch shape, the rock may need to be larger to remain stable. Additionally, achieving good rock placement during construction of straight weirs is essential, including ensuring excellent rock-to-rock contact.

Straight rock weirs with level crests can be placed at closer spacing than arch or chevron weirs because their scour pools are generally shorter in length. Bates et al. (2003) suggests a maximum overall grade (measured from crest to crest) of 5% for straight rock weirs.

Rock Chutes

A rock chute is a short, steep, semi-rigid section of constructed channel. They mimic chutes that occur in natural channels but are designed to be permanent. When the pool below a rock chute is armored with engineered streambed material (ESM), it is considered a chutes and pools roughened channel and the recommended maximum slope from chute to chute is 4%. When the pool is not armored below the chute, it is considered an individual drop structure, and the recommended maximum overall slope from chute to chute is 2.5%, but may be steeper in course bedded streams.

A chute has a sloping face of 5% to 10%. Because of their sloping face of the rock chute, they can be built with a larger overall drop than an individual weir. The maximum recommended drop through a rock chute is one foot. They are constructed in a series with the spacing between chutes sufficient to dissipate the energy within the pools.

The rock bands define the ends of the chute and are designed like rock weirs (Figure XII-33). They are constructed with a cross-sectional V-configuration to concentrate low flow in the center and to provide a diversity of hydraulic conditions at all flows. ESM is placed between the rock bands (see Sizing the Engineered Streambed Material page XII-67). The plan view shape is concave with the opening pointing downstream so flows are concentrated towards the center of the channel. Refer to Chutes and Pools (page XII-63) for details regarding design of the rock chutes.

The pool length and depth between chutes should be sufficient to dissipate any excess energy coming off the chute. A scour analysis can assist in estimating the appropriate pool depth. It may be prudent to excavate the pool to achieve the desired depth rather than allowing it to scour. Otherwise, the energy from initial high flows may not be adequately dissipated in the pool below the chute, potentially scouring and mobilizing the next downstream chute.

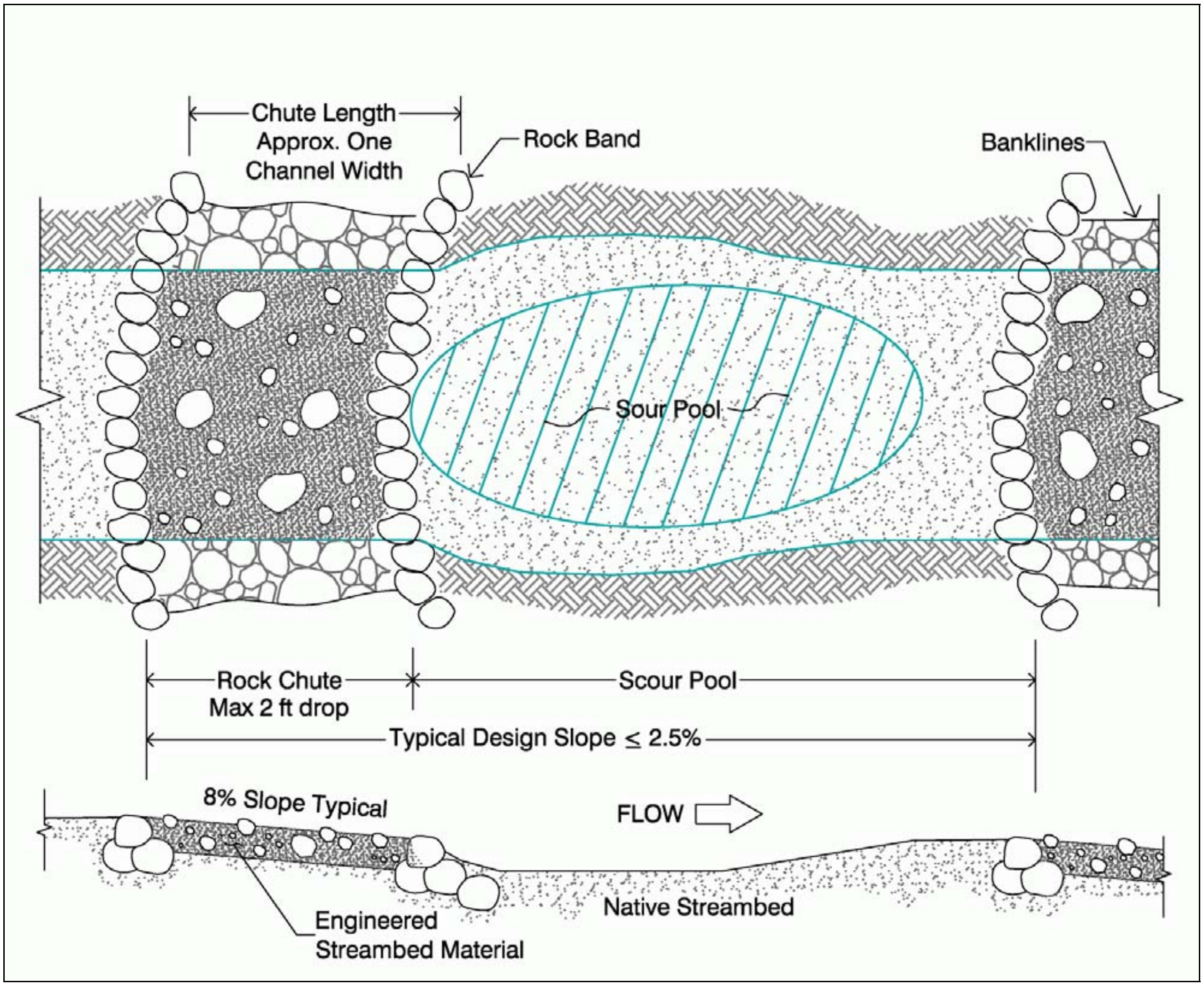


Figure XII-33. Typical chute with unarmored pool in plan and section.

Rock Sizing for Rock Weirs and Rock Bands

Rocks comprising a rock weir or the rock bands in a chute should be large. Larger rocks are less easily moved by flows, less prone to failure due to scour, and take less time to install. In general, guidelines recommend minimum rock sizes of 2 to 3 feet (NRCS 2000; FHWA 1979; Thomas 2000), and larger in streams with unit discharges greater than about 15 cfs/ft.

The size of rock should not be disproportionately large relative to the channel width. The weir should be comprised of a number of rocks to ensure that they interlock and voids are filled, thus increasing stability and impermeability. Avoid using any individual rock that is greater than one-third the channel width.

Stability depends on the size of the rock, the interlocking of the rock, and planform shape of the weir. Riprap sizing methods are based on a blanket of rock placed parallel to the flow, where the stability of the individual rocks relies largely on the interlocking created by the blanket-like placement. As a result, the stable rock sizes determined using standard riprap sizing procedures are too small for rock weirs.

NRCS (2000) recommends sizing rock for rock weirs by first computing the stable median rock size using the Far West States (FWS) Lane Method riprap sizing method (NRCS 1996) and then increasing the results by scaling factors to obtain an appropriate size of rock for the weirs. The FWS Lane Method for riprap is a follows:

$$D_{75-riprap} = \frac{3.5wDS}{CK}$$ **Equation XII- 8**

Where

$D_{75\text{-riprap}}$ D_{75} riprap size in inches

w channel top width at the design flow (feet)

D maximum depth of flow in channel (feet)

S channel slope (feet/feet)

C coefficient for channel curvature. Ranges from 0.6 to 1 with a value of 1 for straight channels.

K side slope coefficient. Typically ranges from 0.53 to 0.87 for installed rock slope revetments of 1.5H:1V to 3H:1V, respectively.

The FWS Lane Method yields a D_{75} riprap size in inches. The K side slope coefficient significantly changes the computed rock size. A value of 1.0 has been used by Fripp et al. (1998) because the rock is placed flat on the streambed.

The $D_{75\text{-riprap}}$ is then scaled to obtain the $D_{50\text{-riprap}}$ based on standard riprap gradation. A common scaling factor is (NRCS 1996):

$D_{75\text{-Riprap}} = 1.2D_{50\text{-Riprap}}$

To determine the rock gradation for rock weirs, the $D_{50\text{-Riprap}}$ is then modified as follows:

$D_{50\text{-Weir}} = 2 \text{ x } D_{50\text{-Riprap}}$

$D_{100\text{-Weir}} = 4 \text{ x } D_{50\text{-Riprap}}$

$D_{\text{min-Weir}} = 0.75 \text{ x } D_{50\text{-Riprap}}$

NRCS recommends that the rock be well graded between the D_{50} and D_{100} sizes, with the larger rock forming the surface of the weir and the smaller rock filling the voids between the larger rock.

Rock Selection and Placement

It is best to use angular rock due to its ability to lock tightly together and resist movement. Rounded rock can be used, but the size must be increased. Rock size should be measured as the average of the three dimensions (length, width, thickness). The least dimension of an individual rock should not be less than one-third the greatest dimension. Rock used in weirs should be uniformly sound, durable and free from cracks, seams, and other defects that can increase its deterioration.

Construction of rock weirs and other types of rock structures require a skilled equipment operator and an attention to details. Elevation of placed rocks should be regularly checked, and rock position should be adjusted to achieve the design elevation. All large rocks used in structures and in the channel should be individually placed by hand and/or machine and secured in desired position by machine tamping of rock and surrounding support material. Large rocks forming the rock weir should be placed tightly together to minimize gaps, and each rock should have a minimum of three contact points with adjacent rocks. When constructing, it is useful to hand select individual rocks that best fit. Fill all voids with smaller material in layers as the rock is placed to minimize permeability. After completion of the weir, fill material should be tamped further into place and material spread into any voids that appear. This process should be repeated until voids are filled.

Cabling Rock

The rock size used in rock weirs should be sufficient to resist movement at the design flow. If properly sized rock is not available, cabling smaller rocks may be necessary to create adequate mass. Cabling may prevent a semi-rigid rock weir from being able to adjust over time. Cables have been known to catch debris, which can cause rocks to move. The steel cables can also create a public hazard by forming a leg-trap for people in the water and by causing lacerations when frayed.

Cabling of rock in weirs may be appropriate in situations of limited site access, where sufficiently large rock or heavy equipment large enough to handle the rock cannot access the site. If smaller rock must be used, cabling can add stability and longevity to the weir (see *California Salmonid Stream Habitat Restoration Manual* Part VII Figure VII-3).

Sealing of Rock Weirs

To reduce the risk of flow passing through the weir rather than over the crest, and to add stability, spaces or voids between the large rocks should be minimized. During construction, rocks should be placed close together to minimize the size and number of voids. Voids should be filled with smaller rock specifically selected to fill niches and native bed material and tamped in place. Through time, deposition against the upstream face of the weir will keep the weir sealed. In some situations, clay packed into the spaces between rocks has been used successfully to provide a long-term seal. The additional effort of using clay to fill voids may be warranted in cases where there is an insufficient supply of bedload to maintain a sealed weir.

Deformable Drop Structures

Deformable drop structures are designed to provide temporary bed stability and where gradual channel incision is acceptable. Typically constructed of rock, and to a lesser extent large woody debris, this type of drop structure is allowed to deform through time by means of downstream scour and movement of individual rocks. The drop structure may begin as a rock weir, deforming into a chute and then a steep roughened riffle. In each transformation the drop height decreases and fish passage is maintained.

Deformable drop structures have been used successfully to slow channel incision upstream of culvert replacements. In certain cases, slowing upstream incision can be desirable to prevent a rapid sediment release that could degrade aquatic habitat, overwhelm the culvert or severely decrease downstream channel capacity. Slow channel incision may also provide an opportunity for vegetation to stabilize stream banks as they steepen in response to the channel bed lowering.

Design of deformable drop structures is done by sizing the rock to withstand relatively low design flows or by minimizing the depth rock is keyed into the streambed, or both. Avoid using rock sized much larger than the maximum drop height to reduce the risk of creating an excessive drop as the structure deforms. Because of variability and uncertainty of hydraulics, soils, and the structure, it is not possible to accurately predict the flow at which any structure will begin to deform.

Rigid Weirs

Rigid weirs are fixed non-deformable structures that cross the entire channel to create a series of small drops to permanently control the channel profile. Their rigidity is the primary difference between them and rock weirs. They are commonly made of logs, sheet piling, concrete, or other durable materials. A benefit of rigid weirs is that they can often be built at a steeper grade than roughened channels and rock weirs, thus minimizing the project footprint. They are easier to seal and can be designed to concentrate flows so they perform well even at very low flow.

A series of rigid weirs is commonly limited to slopes of 5% or less. At these slopes, bed material is naturally deposited on the upstream side of each structure, improving sealing and stability. Steeper slopes may necessitate a formal fishway with flow control.

Weirs commonly have distinct water surface drops. They should include variability in cross section to create diversity in hydraulic conditions at the weir and in the channel downstream. They have the advantage that the cross-section can be finely controlled. They can include a hydraulically designed notch to concentrate very low flows, which can be advantageous for low-flow passage.

Horizontal weirs tend to create pools that are trapezoidal and uniform in cross section. Weirs that dip toward the middle of the channel and have a V-shaped planform pointing upstream tend to concentrate the thalweg in the center of the channel and create more complexity and diversity than horizontal weirs perpendicular to the channel. Trade-offs include that V-shaped weirs are more complicated to build and may have to be built at a lower slope. If they are built of logs, any exposed portions of the logs will deteriorate more quickly than if submerged. An example of rigid V-shaped weirs is shown in Figure XII-34 at Goldsborough Dam removal project.

Poorly designed or constructed weirs commonly fail by scour either under or around the end of the structure. Keys to a good design include overall slope, planform and profile geometry, embedment and bank keys, and ballasting of buoyant materials.

Figure XII-34. Goldsborough Dam Removal Project. An example of V-shaped rigid weirs.

Concrete and Sheet-Pile Weirs

Concrete and sheet-pile weirs can be manufactured precisely with a varied cross-section similar to the natural channel, and a crest shape that is specifically designed for fish passage. Sheet-pile weirs might be effective where foundation conditions are poor. Sheet-pile weirs can be solid sheet-piles or H-piles with wood or pre-cast concrete lagging between them. Prefabricated structures can reduce construction time and are useful where excavation and access is difficult. Special equipment, such as cranes or pile drivers are typically needed for installation.

Weir crests can lack the variety of passageways found in rock structures but the diversity can be enhanced by adding variability to the crest. Boulders might be embedded in the crest or a weir can buttress additional boulders in the upstream channel to create structures similar to chutes. In this case, the weir itself replaces the footer boulders in a chute.

Concrete and sheet-pile weirs can be built at a steeper overall slope than log weirs when the structures are more deeply embedded into the streambed. In comparison to logs or rock, these materials can provide a good seal without relying on deposition along the upstream face of the weir. As the profile slope increases, the structure effectively becomes a fishway and those design criteria must be applied. Saldi-Caromile et al. 2004, describes additional details of rigid drops structures.

Log Weirs

Log weirs are unique within the category of rigid weirs. They span the channel instead of being buried vertically like sheet-pile and other structures, they deteriorate more quickly than steel and concrete structures, and they are buoyant. Slope limitations previously described are especially important for log weirs because they can fail by being undermined if placed on too steep a slope.

There are a variety of designs of log weirs: stacked logs in a horizontal weir, weirs angled in planform to direct flow, and V-weirs and X-weirs to concentrate flow. Simple, straight, double-log sills are the most secure and the easiest to construct. These require the least overall channel length and are often the least costly of the rigid weirs if large logs are available. At low flow, horizontal logs have a thin uniform sheet spill. Without a notch, they can block any fish that does not leap.

Weirs that dip toward the middle of the channel and have a V-shaped planform pointing upstream tend to concentrate the thalweg towards the center of the channel. This creates more channel complexity and diversity than horizontal weirs perpendicular to the channel. Trade-offs include that they are more complicated to build and may have to be built on at lower slopes. If they are built of logs, any exposed portions of the logs will deteriorate more quickly than if they are entirely and permanently submerged.

Log weirs designed and built well commonly survive extreme flow events. Keys to a good design, in addition to those described for drop structures in general, are to use two stacked logs with diameters of 16 to 30 inches so the bottom log is deeper than the expected scour hole. Scour holes below horizontal weirs in gravel beds are typically two to two and a half times the drop of the weir. The logs should be pinned and cabled together with the upper log slightly downstream of the lower one so the water spills clear of the lower log. Logs should be notched during low flow to create a chute for those flow conditions.

The logs should be ballasted from below by cabling to a buried anchor block rather than by depending on riprap stacked on the ends of the logs. The buried ballast will also allow the ends to be protected with bioengineering techniques rather than riprap. Figure XII-35 shows a series of log weirs with the banks entirely protected with large wood. The weirs are ballasted from below as described above. No riprap was used on the project. Design details, sketches, and various log configurations are described by Saldi-Caromile et al. (2004).

Figure XII-35. Schoolyard Creek bank protection with large wood. No riprap was used on the project. Constructed 2000.

BAFFLE RETROFITS OF STREAM CROSSINGS

The most effective solution for creating unhindered fish passage at a barrier culvert is to replace it with a new crossing structure designed for using the stream simulation approach, combined with profile control if necessary. In situations where replacements are not feasible or justifiable, retrofitting a culvert with baffles may be a practical approach to provide incremental passage improvements. Baffles are a series of flow obstructions placed inside of culverts to improve fish passage by increasing water depth at lower flows and decreasing water velocity at higher flows. In comparison to weirs, baffles are short relative to the depth of flow and hydraulic drops between baffles are small. Baffles can also be used in flumes and other structures that function hydraulically like culverts.

Overview of Baffle Hydraulics

Baffles are designed to function in two different hydraulic regimes: plunging and streaming. Most baffles function as weirs at lower flows. Water plunges over each discrete baffle into pools formed between the baffles, similar to a pool and weir fishway (see Pool and Weir Hydraulics page XII-113).

As the flow and depth over the baffle increases, the water begins to stream, or skim, across the baffles rather than plunge over each baffle. In streaming flow, the baffles function together as hydraulic roughness that dissipates energy through turbulence. This effectively reduces the average cross-sectional water velocity and increases water depth. Baffles may also provide areas of low velocity where fish may escape from higher velocities. The flow at which the regime transitions between plunging and streaming is discussed in Pool-and-Chute Fishways (page XII-121).

Turbulence, measured in terms of the Energy Dissipation Factor (EDF), is important in the design of baffles. At low flows water plunges over each baffle and energy is dissipated through turbulence within the receiving pool. At higher flows, baffles act as large roughness elements that slow water velocities and dissipate the flow's energy through turbulence throughout the culvert.

Refer to Appendix XII-C for guidance on analyzing baffle hydraulics and evaluating turbulence in a baffled culvert.

Limitations of Baffles

When retrofitting a culvert with baffles, it is important to understand their limitations. Baffles rarely provide fish passage conditions equivalent to a crossing designed specifically for passage. In addition, baffles obstruct flow through the culvert, creating hydraulic conditions favorable to fish but that may affect culvert performance. Important limitations and concerns with baffle installations include reducing hydraulic capacity, debris and sediment trapping, suitability for juvenile and weak swimming fish passage and the possibility for unstable hydraulics. After attempting a retrofit design, these concerns may lead to the necessity for a different design approach, such as culvert replacement.

Baffles have the potential to substantially increase the culvert's headwater depth and reduce the hydraulic capacity of the culvert. Measures that improve the hydraulic efficiency of the inlet, such as adding wingwalls or mitering the culvert inlet, can slightly reduce the impact of baffles on hydraulic capacity. In some cases, the height and placement of the first baffle downstream from the inlet can be designed to reduce its influence on headwater depth and hydraulic capacity.

Baffles are prone to catching and becoming clogged with debris, which may create a blockage to fish, impair the hydraulic performance of the culvert, and jeopardize the entire crossing. Contemporary baffle designs attempt to accommodate debris passage, but some increased level of debris trapping is inevitable. Regular inspection of baffled culverts is required. Debris within a baffled culvert must be cleared in a timely manner to minimize the duration of any blockage to fish passage and to prevent further accumulation of debris. Because debris problems generally arise during high flows, debris removal is often required during those higher flows when access and working conditions are difficult. This is especially important because many fish populations migrate at those same high flows.

The pools between baffles may also trap and become filled with sediment. This can reduce the roughness and negate the fish passage improvements intended by the baffles. It may not be possible to maintain the intended roughness in baffled culverts where large gravel and cobble bedload is present. In severe cases, sediment accumulation creates a hydraulically flat and smooth bed of sediment along the culvert floor that results in conditions similar to before the placement of the baffles but with reduced hydraulic capacity.

There is little data to guide baffle design for passage of juvenile salmonids and non-salmonid species. Passage of juvenile salmonids is likely limited to relatively low discharges with plunging flow conditions, during which the baffles function as low weirs. Under streaming flow conditions, the average cross sectional water velocity in a baffled culvert may be within the swimming abilities of juvenile salmonids or other weaker swimming fish, but the turbulence generated by the baffles is believed to present a passage barrier.

Baffles are generally not recommended for culvert slopes greater than three percent. At steeper slopes, it becomes difficult to achieve streaming flow, and unstable hydraulic conditions and excessive turbulence are likely to arise. If the culvert is large enough, retrofitting with a weir-type fishway may meet fish passage objectives on steeper slopes. Otherwise, culvert replacement could be the only solution capable of meeting fish passage objectives.

Baffle Design

Appropriate baffle designs vary with the shape, size, and material of the existing culvert and site constraints. Baffle design starts by identifying an appropriate baffle type and materials for the culvert of interest. The hydraulic design approach is then applied to arrive at a preferred baffle configuration (geometry, height, and spacing). This approach requires identification of target species and life stages to establish fish passage design criteria and design flows, as outlined in Hydraulic Design Criteria (page XII-51). Special hydraulic conditions at the culvert inlet and outlet transitions must be considered. The baffle configuration that best meets these criteria is selected as the preferred retrofit design. Culvert hydraulic capacity and risks of accumulating sediment and debris must be evaluated.

The hydraulics of baffles are complex and difficult to model numerically. As a result, baffle hydraulics are best evaluated using results from scaled physical models. Only a limited number of baffle shapes, sizes, and spacing have been evaluated using physical models. The majority of these experiments have considered only the hydraulic performance of the baffles; very few baffle configurations have been evaluated biologically (Ead et al 2002; Gregory 2004; Rajaratnam 1990; Shoemaker 1956). The development of turbulence and its effect on passage have not been studied. As a result, design of baffles requires considerable engineering judgment from someone with extensive experience or expertise in hydraulic engineering. Appendix XII-C provides specific design equations and procedures for use in design of baffle retrofits.

Types of Baffles

There are numerous types and configurations of baffles constructed of varying materials. Selection of the baffle type will often be determined or constrained by the culvert shape, size, material, capacity, and condition. Contemporary baffle types have evolved from experiences with earlier baffles. For many years Washington (offset) baffles were the recommended baffle type. However, field experience has shown these baffles are highly prone to clogging with debris and sediment and they are believed to create hydraulics unsuitable for passage of juvenile salmonids and other weaker swimming fish. They are also difficult to install in circular culverts.

Baffles containing narrow notches or slots are generally not recommended due to their susceptibility of plugging by debris or large bedload. Baffles with notches that alternate from side to side are also not recommended. At higher flows, the alternating notches can create undesirable hydraulics and smaller fish that swim in the slower water along the edges may be unable to escape the higher velocities created by this alternating flow pattern. Additionally, each change in direction of the main flow increases the risk that the baffles will capture debris.

Generally, baffles that create diverse hydraulic conditions at fish passage flows and that open upward, such as a V-shape, are recommended.

Circular and Pipe-Arch Culverts

Corner baffles and weir baffles are recommended for use in circular culverts (Figure XII-36). The dimensions shown in the figure are parameters in the hydraulic design and are defined in Appendix XII-C. Corner baffles are shaped to concentrate the majority of flow and floating debris towards the low side of the baffle while providing slower water along the opposite side of the culvert for fish to swim through. Weir baffles are for wider and steeper culverts with a shape that is a composite of two corner baffles with a V-shaped notch or a small horizontal weir plate in the middle.

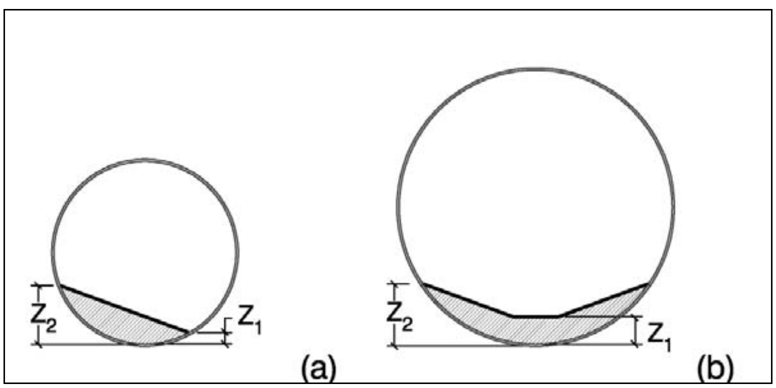


Figure XII-36. Cross sectional view of (a) corner baffles and (b) weir baffles for circular culverts.

Corner and weir baffles are typically constructed of steel. The metal baffles may be anchored or welded to the culvert or to a steel hoop wedged between corrugations. Baffles should fit snuggly against the culvert to prevent water from flowing under, rather than over, the baffle. The cross sectional shape of circular metal culverts is often deformed by loading and settling, requiring each baffle to be fitted individually. When concrete lining of the culvert invert is part of the project, the concrete can be used to secure and seal the baffles, but the concrete thickness must be accounted for in the baffle design.

Other baffle designs may be acceptable if shown to be as effective as corner or weir baffles in satisfying fish passage objectives.

Flat Bottom Culverts

The most common fish passage limitation in box culverts and other structures with flat floors is inadequate water depth. Considerable flow is required to achieve fish passage depth criteria. In these types of structures, correction of low water depth at lower flows often remedies excessive velocities at higher flows.

Angled baffles are recommended for retrofitting box culverts and other structures with flat floor (Figure XII-37). Angled baffles can be constructed of steel, wood or concrete and are anchored to the culvert floor. In plan view, the baffle is skewed 60 degrees relative to the direction of flow. The baffle is tapered so the upstream end is low. The baffle skew and tapered crest are designed to concentrate flow and promote debris passage along one side of the culvert while providing slower water for fish passage on the opposite side. The exact shape of the baffle crest is selected to provide sufficient water depth for each targeted fish species and life stage at its low passage design flow.

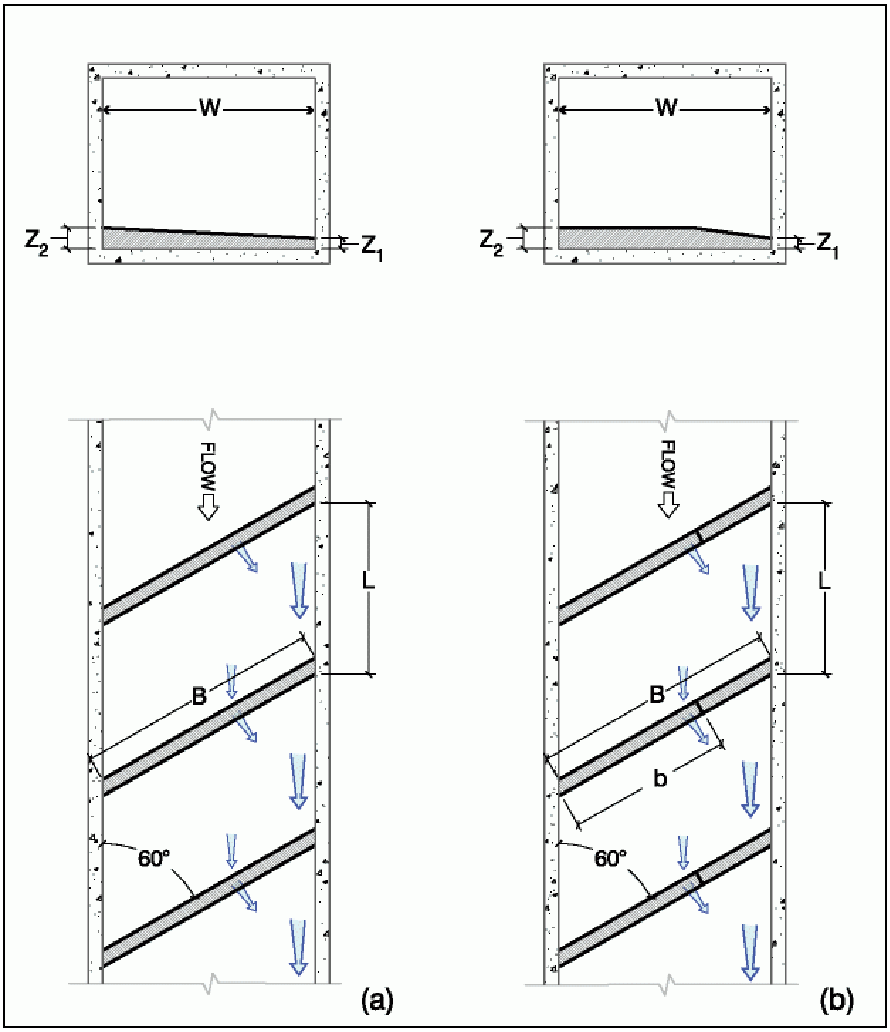


Figure XII-37. Section and plan view of angled baffles in a box culvert with (a) full tapered and (b) partial tapered crests.

Baffle Height and Spacing

For corner and weir baffles, the height of the notch above the culvert *invert* (Z_1 in Figure XII-36) and baffle spacing (L) are set to meet depth criteria at the low passage design flow and to provide sufficient roughness to satisfy velocity criteria at the high passage design flow.

In general, baffle spacing should be no less than 5 feet and should be set so there is at least 0.2 feet of drop between each baffle. Closer spacing or less drop increase the risk of sedimentation in a gravel-bedded stream. More drop would be required to scour larger bed material. Closer spacing may also fail to provide sufficient velocity shelter for fish to rest. In steeper culverts, taller baffles and closer baffle spacing might be required. In streams with large debris or sediment loads, goals associated with fish passage and structural risks may have to be compromised.

Water depth is always calculated between the baffles rather than on the baffle crest. At low flows, when baffles function as weirs, the minimum depth between two baffles occurs immediately downstream of each baffle. At higher flows, when water is streaming, the water surface slope matches the culvert slope and water depth is relatively uniform, though turbulent, between baffles. Like water depth, water velocity is calculated using the wetted area between the baffles rather than along the baffle crest.

For corner baffles and weir baffles, the high end of the baffle (Z_2) is typically set so the baffle is almost fully submerged at the highest fish passage design flow. The intent is to maintain a low-velocity and low-turbulence passage corridor along the edge of the culvert at fish passage flows.

For angled baffles the design usually strives to have the water depth just fill the notch and fully wet the baffle (water depth = Z_2) at the low passage design flow for the largest target fish, such as adult salmon or steelhead. This results in a minimum baffle height required to meet depth criteria.

Other Design Considerations

Adding baffles to a culvert requires attention to details beyond those addressed by the fish passage design criteria. These can include *hydraulic transitions* at the culvert inlet and outlet, providing sufficient *flow control*, minimizing sedimentation, and considering *fish attraction*.

Inlet Transition

An abrupt *drawdown* in the water surface as it enters the culvert may occur in situations where the culvert width is much narrower than the wetted width in the upstream channel, or the water velocity in the culvert is substantially greater than in the upstream channel (Figure XII-38). The overall drop in the water surface as it enters the culvert is the *inlet head loss*. The transition consists of a *flow contraction* followed by an expansion. In severe cases, this hydraulic transition can create a combined velocity and turbulence barrier to fish. Although there are no fish passage design criteria for maximum inlet head loss, it is recommended to avoid an inlet head loss exceeding 0.2 feet for juvenile salmonids and 0.5 feet for adult salmonids.

The inlet head loss can be calculated using standard methods associated with determining the headwater depth for a culvert (FHWA HDS-5 2005). The amount of head loss at the inlet is influenced by the water velocities in the upstream channel and in the culvert, the degree to which the culvert inlet constricts the approaching stream flow (relative size and alignment), and the shape of the inlet (i.e., projecting, headwall, wingwall, or mitered). In design of a baffle retrofit excessive inlet head loss can be corrected by further reducing the water velocity in the culvert or modifying the culvert inlet to make it more hydraulically efficient, such as adding wingwalls or other transitions.

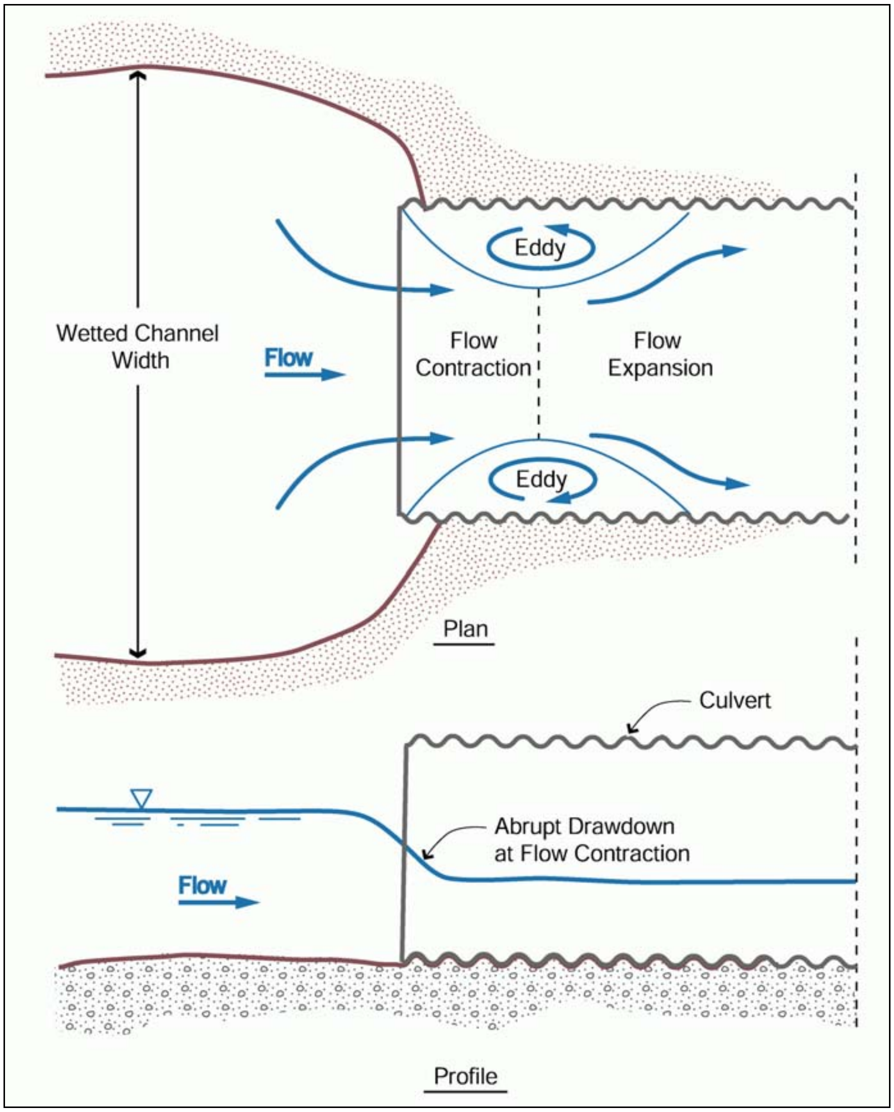


Figure XII-38. Contraction and acceleration of the stream flow as it enters a culvert can form a steep drawdown in the water surface. In certain cases, this drawdown may hinder fish passage due to excessive velocity and turbulence.

Outlet Transition

Designing a baffle retrofit requires attention to the hydraulic transition at the outlet at both the low and high passage design flows. Because baffles raise the water level within a culvert they will often create a hydraulic drop at the culvert outlet or increase the height of an existing drop. Even if there is no hydraulic drop at the outlet at low flows, a drop can form as flows increase and depth within the culvert increases more rapidly than in the *tailwater*. The result can be a substantial hydraulic drop at the culvert outlet during the high fish passage flow, creating a leap or velocity barrier, or both (Figure XII-39). Preventing a hydraulic drop at the outlet often requires adding weirs or other profile controls to the downstream channel to increase the tailwater level (see Profile Control page XII-54). If an outlet drop is unavoidable, the last baffle should be placed at the outlet and shaped like a notched weir to concentrate flow and provide good hydraulic conditions for fish to leap (see Weir Crests page XII-117). This last baffle may need to be taller than the other baffles to reduce the drawdown and acceleration in water velocity as flow approaches the freefall at the outlet. This may solve the drawdown and velocity effect but may create a leap barrier.

Figure XII-39. With increasing flow the water surface in the baffled culvert rises more than the tailwater pool, and a small hydraulic drop becomes much larger. The drop at high flow also causes water to drawdown and acceleration as flow approaches the culvert outlet, potentially creating a velocity barrier.

Dividing Walls for Wide Culverts, Multiple Culverts, and Aprons

In wide culverts, it may be necessary or desirable to baffle only one side of the culvert to achieve the desired hydraulic conditions for fish passage or minimize reduction in flow capacity due to the baffles. In these cases, a dividing wall running the length of the culvert separates the baffled and un-baffled sides (Figure XII-40a). Similarly, it may be necessary to use dividing walls on inlet and outlet aprons to confine the flow, especially at crossings with multiple culverts (Figure XII-40b).

Baffles in divided culverts frequently experience problems with excessive sedimentation. This problem can be due in part to concentration of high flows into the un-baffled section, leaving insufficient flow in the baffled portion of the culvert to scour the sediment. This is exacerbated when a dividing wall becomes overtopped at relatively low flows. Once the dividing wall is overtopped, the flow, water depth, velocity, and turbulence in the baffled section do not effectively increase with increasing stream flow (Figure XII-41a). If there is insufficient scouring forces, sediment will deposit and remain trapped between the baffles. To avoid this, a low-flow sill at the inlet of the un-baffled side might be needed to force sufficient flow into the baffled portion. The dividing wall should be high enough to contain flows that generate velocities and turbulence sufficient to scour and transport sediment (Figure XII-41b). In many cases this can be done be designing the wall height to prevent overtopping at flows less than bankfull flow. The low-flow sill might reduce the culvert capacity. The sill is often located at least one to two culvert widths downstream of the inlet to reduce the potential for debris clogging and minimize the effect of the sill on inlet control and culvert capacity.

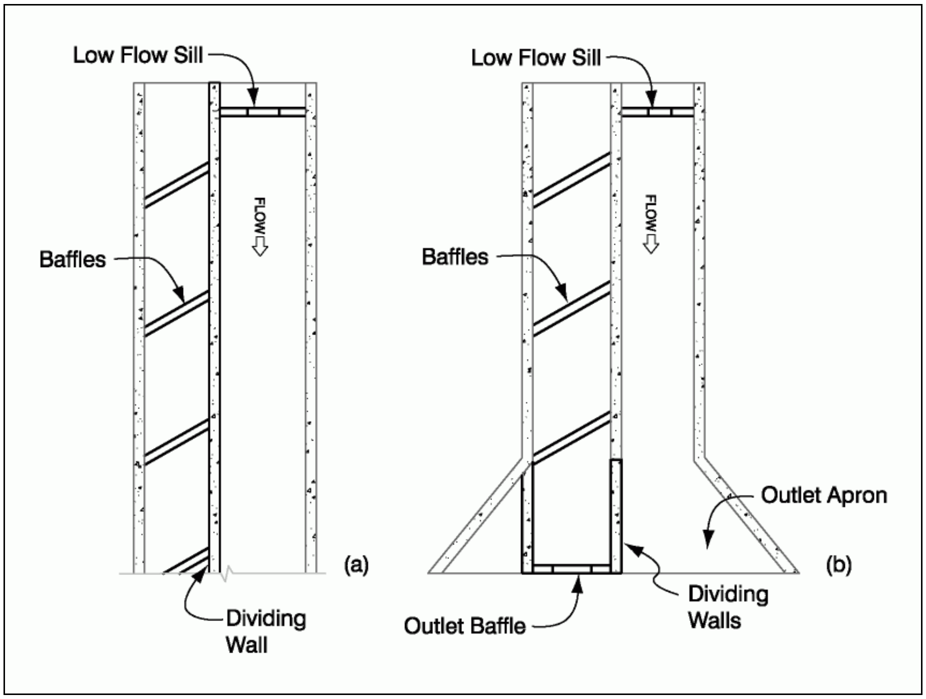


Figure XII-40. Dividing walls used (a) to baffle one side of a wide culvert and (b) to confine the flow on an outlet apron. The low-flow sill provides flow control to concentrate lower flows into the baffled section.

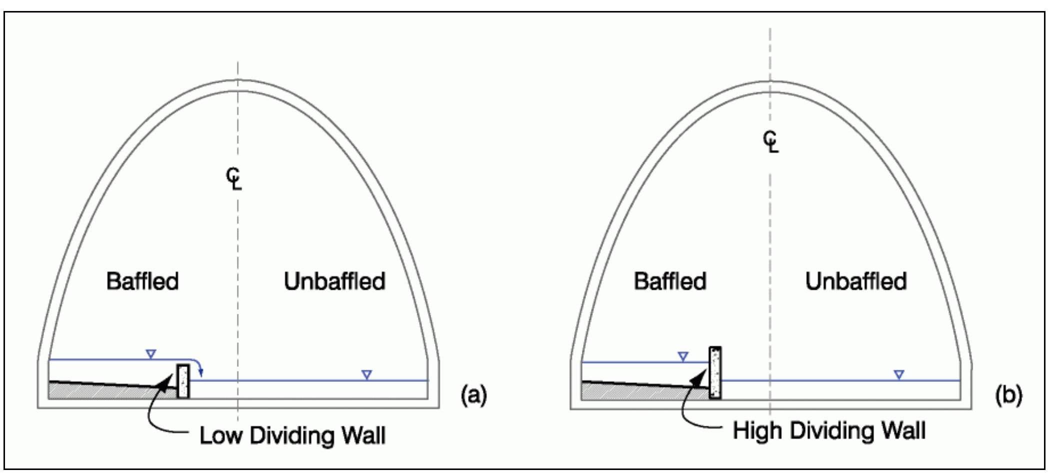


Figure XII-41. Section views of a wide culvert with (a) low and (b) high dividing walls that separate the baffled and un-baffled sections. Before overtopping the dividing wall, the baffled section should contain enough flow to generate sediment scouring forces.

Special attention is required at the downstream junction of the flows in the baffled and un-baffled sections. This junction should not create hydraulic conditions that may prevent fish from finding or successfully entering the entrance to the baffled section. Fish will be attracted to the un-baffled section if the flow is high. Refer to Fishway Entrance (page XII-111), for a description of conditions that aid in attracting fish to the entrance. In some cases, fish may swim through the un-baffled portion of the culvert. To help ease passage over the low-flow sill, the downstream face of the sill can be sloped and/or the sill can be notched.

Summary of Hydraulic Design Process

The hydraulic design of baffles in a culvert requires selection of the preferred baffle type and configuration that best satisfies fish passage criteria for the target species while meeting project constraints. The design process often requires several iterations before identifying a preferred baffle configuration. Due to site constraints and conflicting goals associated with retrofitting an existing culvert, it may not be possible to meet all design criteria and guidance. In such cases, it is important to have well defined project objectives that are acceptable to the reviewing agencies, weigh the impact of each decision on passage performance, and document the decision process. A design data form for hydraulic designs is included in Appendix XII-A and can be used for documentation of the process. In the end, the acceptability of the design relies on the degree to which it satisfies the project goals.

The design process begins with determining the target species and hydraulic design criteria and low and high passage design flows appropriate for them. Then select the baffle shape (corner, weir, or angled) appropriate for the culvert type. Next, determine the baffle configuration (height, spacing, and geometry) that meets minimum water depth criteria at the low passage design flows. Also, check the EDF at the transition from plunging to streaming flow to ensure the pools between the baffles are not excessively turbulent. Once a baffle configuration that satisfies minimum depth requirements has been determined, check that it satisfies maximum water velocity and EDF criteria at the high passage design flow. If not, velocity and turbulence can be reduced by increasing the baffle height or decreasing the baffle spacing, or some combination of the two. If only a portion of the stream flow will be conveyed through the baffled section, flow control and dividing walls need to be designed in conjunction with design of the baffles.

Once a preferred baffle configuration is selected, check that turbulence and scouring forces are sufficient to avoid excessive sedimentation between the baffles. This should be done at a flow when the upstream bed material begins to mobilize, which may be approximated in a natural stable channel using the bankfull flow. If sedimentation appears likely, increasing baffle spacing or lowering baffle height may reduce sedimentation risk.

Once the baffle arrangement is determined, the hydraulic drop at the inlet and outlet transitions should be evaluated at the low and high fish passage flows. Excessive inlet head loss may warrant changes to the baffle arrangement or modifications to the culvert inlet to improve entrance efficiency. Excessive drop at the outlet may be addressed with profile control measures (Profile

Control page XII-54) in the downstream channel. If an outlet drop at fish passage flows is unavoidable, an outlet baffle that creates a good hydraulic transition for fish to swim or leap into the culvert should be included. This baffle will function similar to a fishway weir (see Pool and Weir Fishways page XII- 113), for desirable weir shape characteristics for fish passage.

Once the culvert retrofit design has been completed, the hydraulic capacity of the baffled culvert needs to be evaluated. Determine the *structural design flow* for the culvert (e.g., 100-year flow), which is the flow that the maximum allowable headwater occurs. Check the hydraulic capacity of the baffled culvert to ensure it meets project constraints. If the baffled culvert is *outlet controlled* at the structural design flow, the baffles will likely reduce the culvert capacity. If the retrofit culvert lacks sufficient capacity, options are limited. It may be possible to increase incrementally hydraulic capacity by moving the first baffle downstream from the inlet, modifying the culvert inlet to improve hydraulic efficiency, or adding an overflow culvert. Meeting culvert capacity objectives may require reducing the baffle height and/or spacing, thus reducing the effectiveness of the fish passage design.

A step-by step design procedure for design of culvert baffles is provided in Appendix XII-C along with additional guidance, references, and equations for baffle hydraulics.

Final Design and Construction Techniques for Baffles

Once the hydraulic design of the baffle has been completed, the next step is to determine the baffle material and method of securing.

Materials for Baffles

Baffles are commonly constructed of wood, concrete, steel, plastic, and composites. The selection of baffle material is often governed by how the baffles will be attached, the culvert shape, material and condition, site access for construction, and the stream’s sediment and debris loads.

Wood has been used for baffles for a long time. Tight-grained redwood is preferable due to its resistance to rot associated with recurring wetting and drying. Although lumber is less resistant to abrasion than steel and concrete, redwood baffles installed in numerous culverts on high bedload streams still function more than 30 years after construction. With suitable redwood becoming difficult to obtain, the use of recycled plastic lumber and other wood-plastic composites is becoming more common.

Lumber is generally easy to hand-carry and place into a culvert, making it well suited for difficult to access culverts. Baffles can also be constructed using several smaller pieces of lumber bolted together. It can be cut on-site to conform to the culvert shape, making it well suited for use in metal culverts, which typically have a varied cross sectional shape due to loading and settlement.

A characteristic of redwood is that it swells when wet. This helps ensure a tight fit along the culvert floor and walls. If using synthetic lumber, it may be necessary use a rubber gasket or grout between the culvert and the baffle to achieve a watertight seal.

Reinforced cast-in-place concrete is often used in concrete culverts. Like wood baffles, the wooden forms can be cut to match the shape of the culvert floor. Concrete is susceptible to abrasion and impact from large bedload and debris. Angle iron can be placed on the upstream face of the concrete baffle to increase its durability and longevity. Additionally, higher strength concrete and other admixtures can increase strength and durability.

Baffles in circular culverts are frequently fabricated from steel. Steel baffles are highly durable but can be difficult to install. Because steel baffles are generally prefabricated, care must be made to measure the culvert cross section at each baffle location to ensure the each baffle fits snuggly against the culvert. A gasket or grout between the metal baffle and culvert is sometimes required to achieve a good seal.

Anchoring Baffles

In reinforced concrete culverts, baffles are most commonly attached to the culvert by bolting or doweling and into the floor and the walls of the culvert. Lumber and metal baffles can be secured into holes drilled in the concrete floor using long threaded rods or bolts embedded with epoxy or grout.

Baffles are commonly secured to metal culverts using “L” bolts or expansion bolts. The bolts travel through holes drilled through the culvert wall. Another method is welding the baffles to the metal culvert using gussets.

Another technique for securing baffles in corrugated metal culverts is to use prefabricated steel baffles welded onto expandable hoop-rings (Bates et al. 2003). The rings are expanded into the corrugation by an arrangement of nuts and threaded rings similar to turnbuckles. Each baffle should be fitted for its exact location due to the varied cross sectional shape of an individual culvert.

There are several approaches to addressing situations in which the strength of the culvert floor, whether concrete or metal, is inadequate to carry the lateral or pullout load exerted by the baffles. These include adding a reinforced concrete lining along the invert, slip-lining in circular culverts, and use of helical anchors that extend into the soils underneath the culvert. Pressure grouting the void exposed by a hole drilled through the culvert floor might provide reinforcement for an anchor bolt.

Adding a reinforced concrete lining along the culvert invert is a common practice for rehabilitating deteriorated metal culverts and box culverts with exposed rebar. The baffles can be installed at the same time the culvert is being concrete lined, using the reinforced lining to secure them in-place.

Slip-lining is another approach to rehabilitate deteriorated circular culverts. The liner should be a metal pipe rather than plastic when adding baffles. Corner or weir baffles can then be welded into the new metal pipe before installation.

Helical anchors that extend into the soils beneath the culvert invert have been used to secure baffles in both concrete and metal culverts. The anchors are designed to transfer lateral loads from the baffle to the soil rather than to the culvert. A geotechnical investigation may be required to determine the feasibility of using helical anchors at a specific site.

FISHWAYS

Common fishways used at culverts and low dams in California are discussed below. This is only intended to be an introduction to general concepts and application of various fishway styles. It is not intended to have sufficient detail to guide a final design. Other options such as lowering or removing a dam or other barrier should be considered but are not described.

Formal fishways are not the preferred fish passage solution at culverts and low dams. Solutions with diverse hydraulic conditions and passage corridors, such as stream simulation, roughened channels and boulder weirs, are preferred over formal fishways because they provide passage for a broader range of species, often over a broader range of flows.

Fishways are designed primarily based on hydraulic criteria such as flow, velocity, turbulence, and drop height. Figure XII-42 shows the layout of a typical bypass fishway, one of several fishway styles, and common components and nomenclature used for fishways. Other pool-style fishways would have a similar general layout.

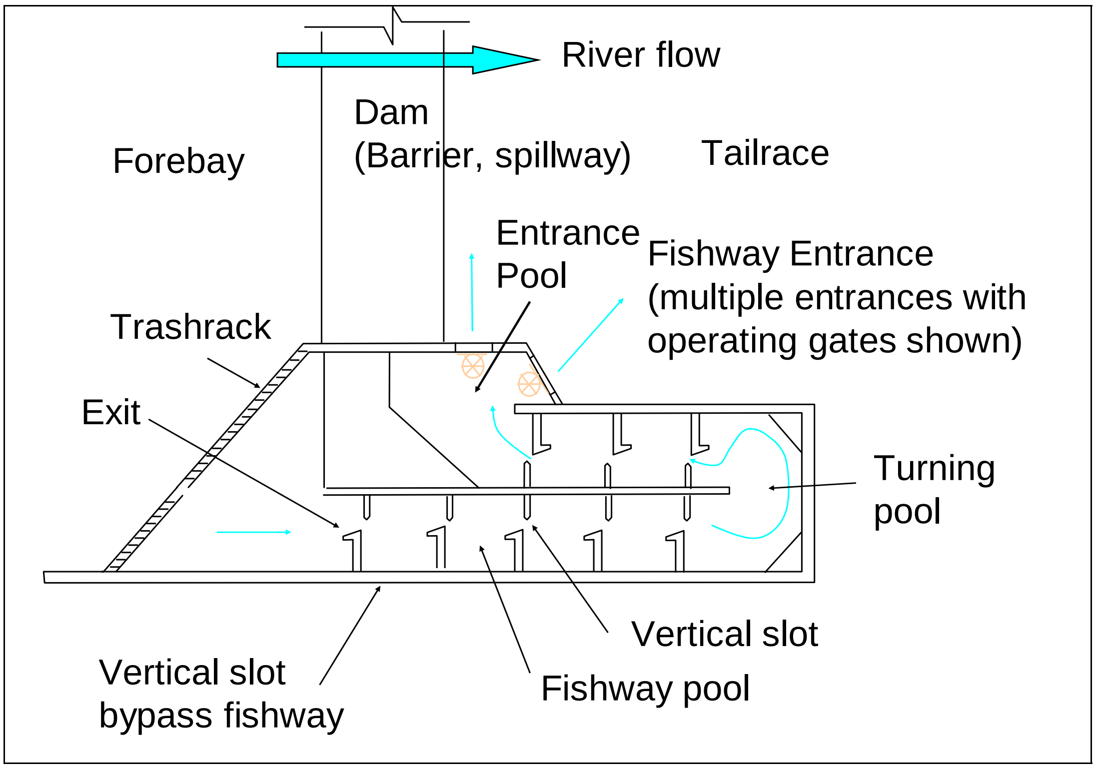


Figure XII-42. Vertical slot fishway with typical fishway nomenclature.

Entrances and exits refer to the fish entrances and exits as they move upstream. *Tailrace* and *forebay* (or *headwater*) are the areas downstream and upstream of the entrance and exit respectively. The entrance pool is the first pool inside the entrance. Auxiliary water systems supply additional water to the entrance pool to help attract fish to the entrance. *Flow control* is the system that controls the rate of flow to the fishway as the river flow changes.

Only fishways at culverts and low dams are discussed in Part XII. Concepts and details such as operating entrance gates, multiple entrances, auxiliary water systems, trap and haul systems, mechanical flow control systems, which are used in larger facilities are not described.

Six fishway styles are described:

- Pool style fishways
    - Simple pool and weir
    - Ice Harbor
    - Pool-and-chute
    - Vertical slot
- Roughened channel fishways
- Denil and Alaska steeppass fishways.

Most of these fishway styles can be used at a variety of locations - at dams, downstream of culverts, and within culverts. Specific applications and limitations are described with the descriptions of each style. The appropriate choice of a particular fishway style for a site depends on a number of variables including:

- Project goals including species and age classes to be passed
- Scale of system and project; dam height, channel, hydrology
- Degree of *flow control* available
- Dependability of operation and maintenance
- Debris, bedload, and ice considerations
- Capital, operation, and maintenance costs.

Fishway Pre-Design

Pre-design is a project step that accounts for characteristics of the stream and inter-relationship of the barrier, the stream, and the target species. It includes understandings of project hydrology, hydraulics, sediment, debris, target species, and fishway layout. Pre-design is generally described in Pre-Design (page XII-4). Additional elements of pre-design that are unique to fishways are described below.

A fishway might span the entire channel or be located adjacent to the channel and take only a portion of the flow. For full-spanning fishways, the project and fishway profiles are a primary focus of site assessment as it was for culverts. For bypass fishways, the fishway entrance and exit locations and hydraulic conditions are primary foci.

The pre-design should provide a framework for designers and interested parties to make decisions requiring trade-offs about fishway style, fishway flow and flow control, entrance and exit conditions, and maintenance and operational expectations.

Pre-Design Site Assessment

In addition to the general site assessment needs described in Pre-Design (page XII-4), these data are often necessary and unique to fishway designs:

- Document bathymetry of any scour or holding areas below the barrier.
- Develop continuous flow gaging, peak flow gaging, basin correlations, and hydrologic regressions. Accuracy of flow estimates for fishway design are important where flow control is required.
- Develop stage-discharge rating curves at the tailrace and forebay of the barrier.
- Document circulation patterns in the tailrace that might affect movement of fish for the range of fish passage flows. Videos are good for documenting flow patterns and flood conditions.
- Document observations of fish accumulating or leaping at the barrier.
- Detailed geotechnical information might be needed for more complex structures.
- Hydrology.

Fishway Layout

A fishway layout can be either full channel width, partial width, or a bypass. Figure XII-43 shows schematics of the three layouts for the example of roughened channel designs. These layouts apply to most fishways regardless of the style.

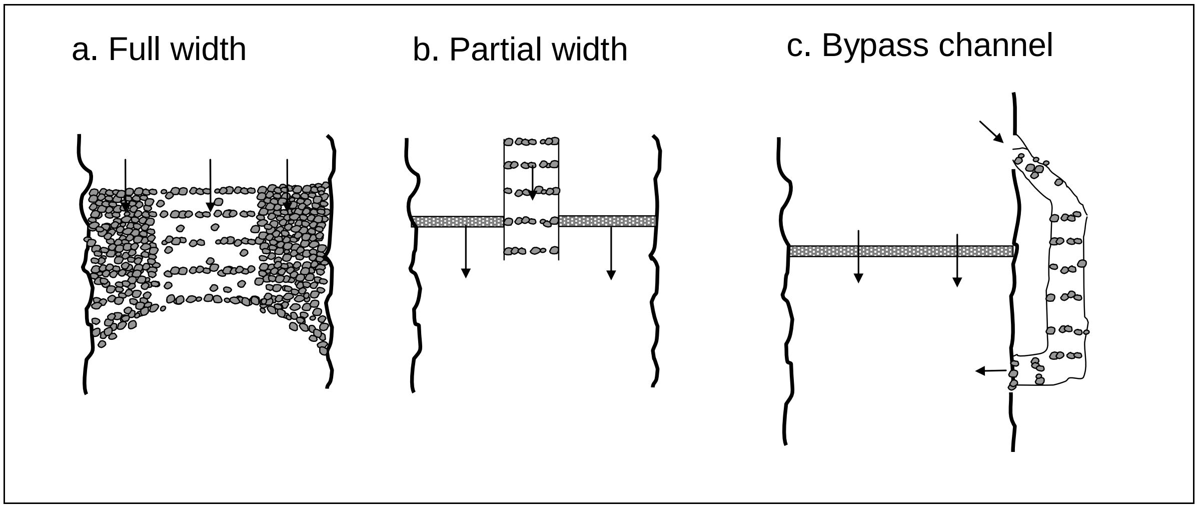


Figure XII-43. Fishway layouts (a) Full width, (b) Partial width, and (c) Bypass fishways.

A full width fishway (Figure XII-43a) has the advantage that it spans the channel so fish have no problem finding it. It normally has no flow control. *Flow control* is a system that meters the flow into a fishway and the hydraulic head and/or depth at the entrance, exit, or other locations as the stream flow changes. Full width fishways are limited in the width and slope of the channel in which it can be applied. It works well downstream of culverts and in incised channels. The fishway might consist of a roughened channel or independent weirs as described in Profile Control (page XII-54).

A partial width fishway, as shown in Figure XII-43b, can be applied to a wider channel. It might be on a bankline or in the center of the channel. The fishway shown in the figure has the disadvantage of being located mid-channel and thereby having poor access for maintenance and operations. On the other hand, the fishway entrance is more accessible by fish approaching from either side of the channel. It also has the disadvantage that, unless the fishway is constructed through the dam and partially upstream of the barrier as shown in the figure, the fishway entrance might be located downstream of the barrier. A basic principle of fishway design is to locate the fishway entrance near the barrier and not downstream of it, so fish are not forced to move back downstream to find it. If the fishway is moved upstream as in the figure, flow control is difficult because the upstream fishway walls might be overtopped at some high flow.

The bypass fishway is isolated from the channel (Figure XII-43c). It might be away from the dam as shown or built into the bank. A primary key to successful fish passage is attracting fish into the fishway, which can also be the greatest challenge in the design of a bypass fishway. The advantages of a bypass fishway are that it can be built and maintained in the dry and out of the channel, it has the smallest footprint, and the entrance can be located at the optimum location, such as at barrier. Fishway flow control devices and debris racks are easiest to include and operate in a bypass layout. A bypass fishway is generally smaller than other styles and the entrance can be hard for fish to find.

Fishway Entrance

Fishway entrances and entrance pools have several purposes. Complex hydraulic settings might require complicated entrance pool designs with multiple entrances equipped operating gates, attraction jets, and auxiliary water systems. The design of fishway entrances for small dams and culverts should consider, as appropriate, the functions and concepts described below. These apply to partial width and bypass fishways. In the case of full-channel fishways, the entire channel is the entrance.

The most obvious, and necessary, purpose of fishway entrance pools is to provide fish access to the fishway. Fishway entrance hydraulics are designed to attract fish. The jet of water leaving the fishway entrance is an extension of the fishway into the tailrace and serves to guide fish to the fishway. The further the entrance jet penetrates the tailrace, the further the path is carried.

As described previously for partial-width fishways, the location of the fishway entrance should be at the upstream-most point of fish passage. Take into account the locations where fish hold before attempting to pass the barrier, and routes by which they will approach the barrier and fishway. All of these hydraulic considerations can change through the range of passage design flows. Redundant entrances can be provided if the proper fishway entrance locations are not well identified. Be aware of eddies and local flow conditions, especially at high flows. "Upstream" to a migrating fish means swimming into the approaching flow. Fish that must approach fishway entrances located in an eddy, may have to swim downstream or across the direction of flow to get to it. A fishway that is built on a bankline can create eddies that make the entrance difficult to find.

Field observations, time-stamped photos and videos, and sketches of flow patterns above and below the barrier should be made, especially for high flows. Physical model studies might be required for complex tailwater conditions. Observations of fish location and orientation when attempting to pass a barrier are additional valuable information.

There are no specific fishway entrance flow criteria. For fishways at dams, the entrance flow must be adequate to compete with spillway or powerhouse discharge flow for fish attraction. Site conditions, especially tailwater hydraulics and channel width, determine entrance flow requirements. Ultimately, the fishway entrance flow may determine the scale or style of fishway used. The scale of the river setting gives some insight into requirements for entrance flow. Bates (1992) described entrance flows as typically three to ten percent of the stream flow at the high fish passage design flow. NOAA guidelines recommend a minimum of five percent.

The greater the momentum of the jet from the entrance, the further it reaches into the tailwater and the more successfully it can guide fish to the entrance. A fishway entrance jet is optimized when it has the following characteristics:

- Streaming, rather than plunging flow, plunging flow creates a boil, not a jet.
- Head differential is high but not so high that it creates a velocity barrier for the burst swimming ability of target species.
- Entrance jet is not dissipated by high-energy flow such as turbulence from a spillway or turbine.
- The entrance and entrance pool interior are well lit to ambient light levels.
- Jet is concentrated. A concentrated jet penetrates further than a thin jet of the same cross-section area and flow.

Optimum entrance conditions for adult salmonids are typically a barrier to juvenile fish.

The fishway entrance head differential should be maintained throughout the passage design flow range. An entrance head differential of one foot is commonly applied to fishways for adult salmonids and the flexibility to increase that to 1.5 allows optimization of entrance conditions. Large fishways typically have operating gates that are used to optimize the attraction jet as the stream flow changes. Fishways on small dams and culverts are designed to operate without intervention. In that case the design usually cannot be optimized for all flows, but should be optimized for the prevalent fish passage flow and while being passable through the entire range of fish passage flows. An entrance design might result in trade-offs between a narrow vertical slot or an orifice and a weir crest optimally shaped for a specific flow. The vertical slot or orifice maintain better hydraulic conditions through a wider range of flows and continue to operate even if tailwater elevations are lower than expected. The weir entrance is optimized for a narrow flow range, is less vulnerable to debris, and has surface flow, which is attractive to leaping fish. Bates (1992) describes additional details of fishway entrances.

Pool and Weir Fishways

Pool style fishways are a series of pools at consecutively higher elevations. Water flows from pool to pool either over a weir (e.g., pool and weir), through a slot (e.g., vertical slot), through an orifice, or a combination (e.g., pool-and-chute). Fish leap or swim from pool to pool to gain elevation. The energy of the flow entering each pool is entirely dissipated in each pool before it flows to the next.

Pool and weir fishways are the most common style used at culverts and low dams and are applied to all scales of fish passage. The fishway is an open channel with pools that are separated by weirs, sometimes with orifices in the weirs. The shape and elevation of the weirs control the hydraulics within the fishway.

Pool and Weir Hydraulics

A primary limitation of the pool and weir fishway is the narrow range of operating flow. Two hydraulic conditions are important in the design of pool and weir hydraulics: the flow regime (plunging or streaming) and turbulence, which apply to other fishway styles as well. At the high passage design flow, the fishway flow should be in plunging flow regime and turbulence should be limited. These characteristics as well as freeboard, and fishway bends are described for pool and weir fishways but apply to various degrees to other fishway styles as well. Any differences are noted with the description of the other fishway styles.

Plunging and Streaming Flow Regimes

The normal flow circulation in a pool and weir fishway is the plunging regime. Plunging flow is characterized by a circulation pattern of water flowing over the upstream weir creating a nappe that plunges downward towards the fishway floor, then moves downstream along the floor and rises along the face of the next downstream weir before either dropping over the weir or rolling back upstream along the surface of the pool (Figure XII-44). As flow increases in the fishway, the hydraulics transition through a range of transition conditions and eventually to streaming regime. In streaming, a continuous surface jet passes over the series of weir crests and skims along the surface of the pools. Shear forces create a circulation in the pool opposite to that in the plunging regime.

Hydraulic instability such as surging and oscillations in the water surface often occur in the transition between the upper range of plunging flow and the lower range of streaming flow (Bell 1991). This transition regime should be avoided. Passage studies have repeatedly shown that when fishway flows operate at the transition point, passage delays occur.

The streaming regime is the basis of the hydraulics of baffles in culverts and flumes. It should be used with caution in fishways because the energy is not dissipated in each pool and the streaming jet is difficult to control.

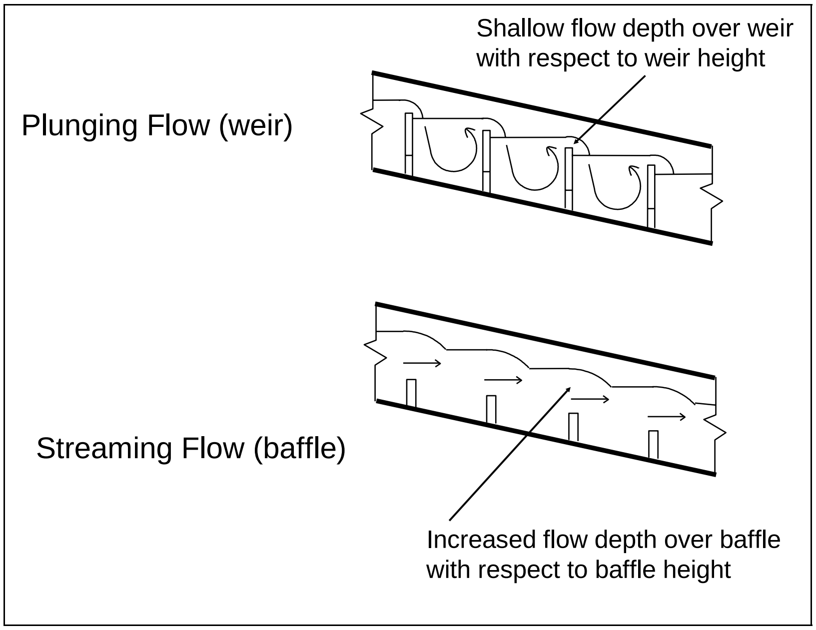


Figure XII-44. Plunging and streaming flow regimes relative to depth over the weirs or baffles.

The flow at which the regime transitions from plunging to streaming depends on the geometry of the pool, the flow, and the head differential between pools. Ead et al. (2004) describe these flow regimes and formulae for estimating the transition flow. Figure XII-45 is from Ead et al. and shows the relationship of plunging and streaming flows and pool geometry. The plot is non-dimensional, where:

Q_{t*} = Flow at which the transition occurs.
L = Length of fishway pool
p = Height of the weir

The equation reported by Ead et al. (2004) is rearranged to solve for the transition flow:

$$Q = Q_{t*}\sqrt{g}\,b_o S_o L^{3/2}$$ **Equation XII- 9**

Where:

Q Transition flow (cfs)

Q_{t*} Dimensionless transition flow (from Figure XII-45)

g Gravitational acceleration (32.2 ft/s^2)

b_o Width of fishway weir (ft)

S_o Slope of fishway (ft/ft)

L Length of pool (ft).

The original equation is non-dimensional but English units are provided as an example.

Figure XII-45 shows a wide range of flows in the band of transition between plunging and streaming conditions. Based on the flow characteristics described by Ead et al. for the purposes of fishway design, the upper limit of the plunging flow regime should be used. The work reported by Ead et al. is from horizontal weirs. The upper limit of plunging flow can be increased and the band of transition flows can be reduced with the shape of the weir crest as described in Weir Crests (page XII-117). Sloping weir crests can allow both plunging and streaming flow regimes to exist concurrently across the weirs. For sloping weirs, Equation XII-9 may be applied by approximating the weir shape as short segments with horizontal crests. Use the average elevation of a segment of the weir to determine the transition flow within that segment. This allows for estimating the portions of the weir section with plunging and streaming flows. Ead et al. also developed a formula for predicting the flow in streaming condition for pool and weir geometries.

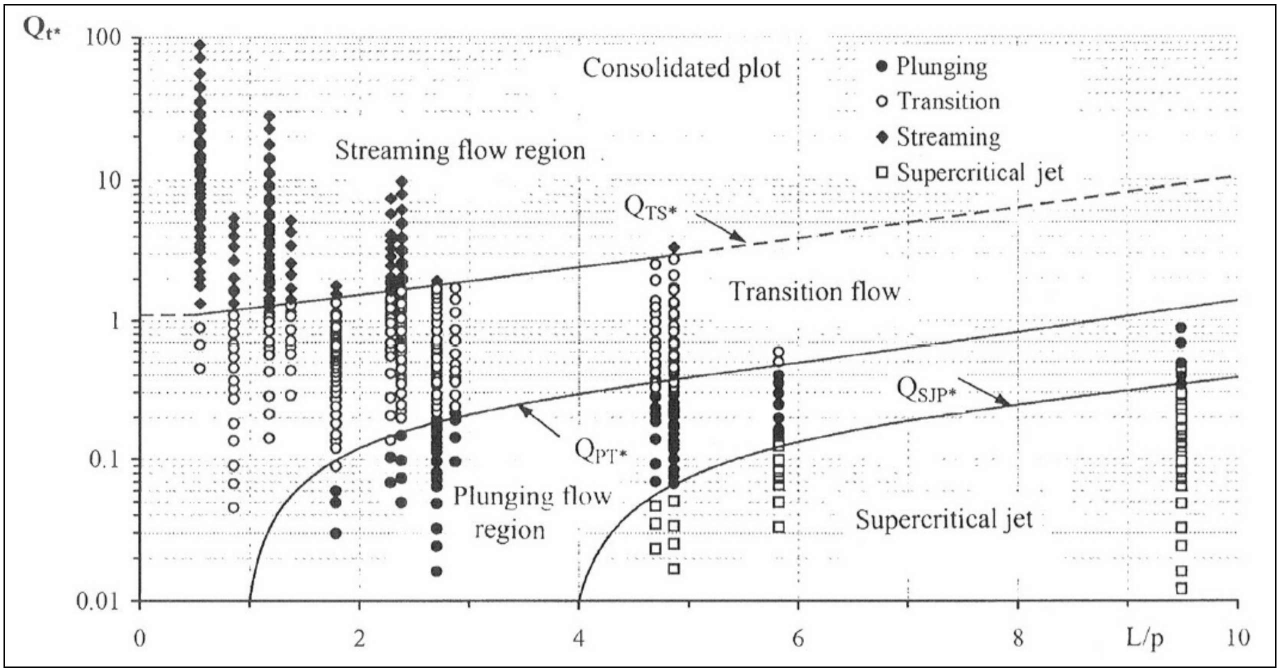


Figure XII-45. Plot of flow regimes in a pool and weir fishway, reproduced from Ead et al. (2004) with permissions from the publisher.

Turbulence

The volume in a fishway pool must be adequate to dissipate energy without being too turbulent for fish to hold and move through it. The rate energy is dissipated in a pool is described by the *energy dissipation factor* (EDF) and can be calculated with Equation XII-10. A maximum EDF of 4.0 foot-pounds per second per cubic foot of volume is recommended for adult salmon and steelhead (Bell 1991) and 3.0 foot-pounds per second per cubic foot of volume for shad and adult trout species, which would include resident rainbow and coastal cutthroat trout (Larinier 1990).

$$EDF = \frac{\gamma Q h}{V}$$ Equation XII- 10

V Effective volume of the pool for dissipating energy (ft^3)
γ Unit weight of water (lb/ft^3)
Q Flow entering the pool (ft^3/s)
h Head of the drop flow entering the pool (ft)

The head of the flow is the sum of the static head (drop in water surface) and kinetic head (function of velocity) entering the pool. The effect of kinetic head is generally negligible. This relationship shows that the greater flow and/or head entering a pool, the greater the volume needed to dissipate the energy without excess turbulence. Flow and/or head can therefore be controlled to manage energy dissipation (see Fishway Flow Control page XII-129).

Portions of the pool, because of its length or shape, may not be effective to dissipate energy. Most of the energy is dissipated near the plunge and, since fish have to pass through that area, the calculation of EDF should focus on that area. Pool lengths greater than eight feet or deeper than four feet should not be included in energy dissipation volume calculations.

Specific dimensions of fishway pools depend on the style of fishway, target species, scale of the river, and degree of flow control. Typical pool lengths and widths vary from four by six feet to eight by twelve feet. Pools as small as several feet wide and four feet long have been successful for smaller fish and with very precise flow control. The fishway depth should be enough so fish will not be stressed or reject the fishway. Typical depths required for large fish vary from three feet in streams and smaller rivers to eight feet or more in large rivers. Exposure and bright light may increase stress of fish and therefore require more depth.

Fish Behavior

Fish behavior and swimming abilities affect design concepts and the details of fish ladder design because various species move through fishways in different ways. Chinook and steelhead use weirs and orifices; early migrating Chinook tend to choose to swim through orifices rather than over weirs. Steelhead often reject fishways that are undersized, shallow, or cause the fish to be exposed. Shad use weirs exclusively and generally seek streaming flow conditions. They are wall-oriented, and can be trapped in dead-end corners. Sturgeon, suckers, carp, and many warm water species typically use orifices.

There are many additional species of interest in California though little is known about their behavior in fishways. If a fish passage project includes non-salmonid target species, advice should be sought from biologists familiar with the species regarding any typical behavior patterns.

Head Differential

Head differential is the difference in water level between two adjacent pools or at the fishway entrance. The allowable head differential depends on the species and age class of fish to be passed, the style and dimensions of the fishway, and the flow in the fishway.

Pool and weir fishways are intended to operate with plunging flow so energy is fully dissipated in each pool. As described in Turbulence (page XII-54), the flow condition depends partially on head differential. Too high a head differential and there will be too much turbulence in the pool and/or a leap barrier for some fish. Head differential should be limited to 1.0 foot for adult salmonids.

The head differential can be increased if it is contained in a chute without free falling flow and strong swimming fish (e.g., adult salmonids) are targeted for passage. The entrance might be operated with a differential that exceeds the criteria to enhance attraction to the fishway as long as target species can burst through the higher velocity and the flow is streaming.

Freeboard

Freeboard is the dimension from the water surface to the top of the wall. It should be enough so leaping fish cannot easily leap out of the fishway. A minimum of three feet is suggested for adult salmonids though more is required if there is upwelling or other hydraulic conditions that might induce a fish to leap somewhere other than at the weir. The freeboard in smaller fishways can be easily extended by constructing a fence or a wall on top of the fishway wall flush with the inside wall. Be aware of the effect of debris becoming snagged by fencing or of being damaged by high flows.

Fishway Bends

Long fishways are often laid out to switch back on themselves through a series of bends. The fishways in Figure XII-42 and Figure XII-46 include bends. Weaver (1963) reported significantly longer passage times through corner and bend pools. Regardless of the fishway style, details of the bends should be considered carefully to eliminate upwelling in corners and to maintain consistent flow patterns. An additional pool length at the bend might be needed to realign the flow to the downstream weir or slot. The outside walls of the turn should be shaped to carry the jet from an orifice around the bend without impacting a wall where upwelling could distract fish.

If the jet must follow the inside wall, the wall should be extended for a standard pool length downstream of the weir or a baffle should be added to disrupt the jet and deflect the flow into the center of the pool. For vertical slots, the baffle is essentially the same as the short wall forming a vertical slot. Fishway bends cannot be used in pool-and-chute fishways.

Weir Crests

The cross-section and longitudinal shapes of the weir crest are important features. The range of flows for which plunging flow persists is extended and the transition band is reduced or eliminated if the crest is rounded or chamfered on the downstream side. The value of Q_{t*} in Equation XII-9 can be increased by 25% by rounding the downstream side of the crest with a 6-inch radius. An orifice at the floor below the crest, such as an Ice Harbor Fishway (page XII-120) also extends the plunging regime.

The depth of flow over the weir crest should be at least the depth of target species that do not leap. A notch that is submerged by at least 6 inches by the backwater from next downstream weir works well. Notches should be V-shaped widening toward the top to help pass debris and to create a variety of hydraulic conditions for fish passage.

A minimum of 3 inches of depth over weirs in a fishways in small to moderate streams without flow control is reasonable for leaping fish. Depth at the crest can be somewhat controlled by the shapes of the weirs. For small applications, the width of a V-weir can be reduced by using half a "V" such as shown in the example of Little Fish Creek in Figure XII-46. The hydraulics of V-weirs can be analyzed by using standard V-weir equations or by analyzing them as short horizontal segments.

Design for Juvenile Salmonids

Juvenile salmonids (60 to 120 mm) can easily ascend a pool and weir fishway if the head differential, pool volume, and weir crest work together to create appropriate hydraulic conditions. Precise flow control is necessary to create passable conditions over more than a narrow range of flows. These fish can leap efficiently if conditions are good. First, to approach near the base of the weir, turbulence has to be low and not extend more than several feet downstream. To do that, the depth over the crest has to be shallow, no more than a few tenths of a foot deep and the flow has to plunge. A weir crest can be designed to gently slope across the fishway so there will always be a shallow depth at the water's edge at flows up until it is entirely submerged. The thickness of the weir should be minimized to less than four inches, so leaping fish more likely land in the pool rather than on the crest of the weir. If the wall thickness is greater than 4 inches, it is necessary to chamfer the downstream corner to reduce the thickness at the top of the wall to 4 inches or less.

Juvenile fish might be blocked at a fishway entrance that is designed with a high velocity to attract adult fish. There is no easy solution to this difference. A separate fishway entrance might be needed for juvenile fish. In an extreme situation, an entire second fishway might be needed.

Powers (1993) recommended that the head differential should not exceed 0.7 foot for sub-yearling coho. CDFG criteria and NOAA guidelines require a drop of 0.5 foot or less. Juvenile salmonids can leap higher than that but leaps become more erratic and less successful. Figure XII-46 shows an example of a fishway designed for juvenile coho with weirs as described above. A flow control weir just above the fishway exit controls flow to the fishway. An upstream migrant trap at the fishway exit has confirmed heavy use by the target juvenile coho.

Figure XII-46. Little Park Creek fishway design for juvenile salmonid passage. Baker Reservoir, WA.

Operation and Maintenance

Because hydraulics are critical to the performance of pool fishways, operations and maintenance are also critical. An important limitation of pool and weir fishways is that pool depth and volume are reduced if bed material accumulates there. Some gravel will be scoured from fishways that have plunging flow characteristics up to a relatively high flow. Gravel often reduces the pool depth to just a few feet and the entire pools will fill-in in the case of heavy gravel transport rates or cobble bedload.

Bedload bypasses and sediment sumps have been used to mitigate sediment accumulation but with only marginal benefits. Sediment bypasses have been built into the fishway exit so bed material is shunted over a spillway rather than into the fishway. The upper pool of a fishway could be designed as a sediment sump if there is a way to bypass the lower fishway pools with a sluice channel or to remove stop-logs to sluice the entire fishway channel. Sluicing at any but high flows may impact downstream habitats.

Sediment accumulation in the stream near the fishway exit can block low flow from entering the fishway or create a shallow condition that impedes fish exiting the fishway. The fishway design should include considerations of geometry of the dam or culvert and fishway that will affect sediment deposition and methods, access, and equipment needed for maintenance.

Debris is also a common problem in fishways. Small debris often blocks orifices and notches. Trash racks are commonly attached to the exits of bypass fishways but are not recommended if they will not be maintained regularly. A trash rack should be provided at the fishway exit when the fishway includes orifices or where pool dimensions are small relative to the size of debris present.

Written operating and maintenance plans should be developed for fishways so there is a good understanding of the maintenance effort expected by interested parties.

Ice Harbor Fishways

The Ice Harbor fishway is a specific pool and weir fishway with orifices, flow stabilizers, and a non-overflow section in the middle of each weir. It is built at a 1-on-10 overall slope (1 foot vertical to 10 feet horizontal). The half Ice Harbor fishway is, as the name implies, half of the Ice Harbor fishway, cut along the centerline. A schematic of a half Ice Harbor is shown in Figure XII-47. This configuration is recommended for moderate to large applications where good flow control is available. Wider non-overflow section and longer pools are acceptable.

A small half Ice Harbor fishway has a 3-ft weir crest and 15-inch square orifices and has a total flow of about 23 cfs with a foot of depth over the weirs. The flow must be consistent. The flow requirement is a limitation for the application of Ice Harbor fishways. To operate at a lower flow, the orifices would have to be equipped with sliding gates to close them off. Orifice dimensions as small as 12 inches by 15 inches have been used. The primary reason for not allowing smaller orifices is the increased risk of being plugged by debris.

There is little experience of sediment in Ice Harbor fishways since they are generally used at dams with flow control mechanisms that preclude the entry of bed material into the fishway. Small debris should not be a problem since the orifice at the floor will allow most of it to pass through.

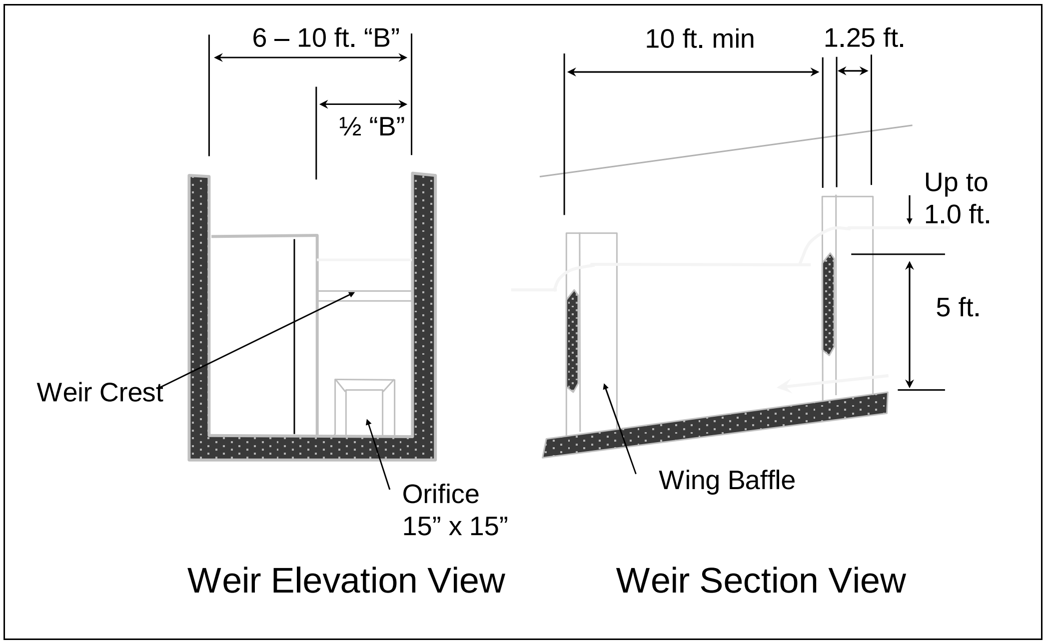


Figure XII-47. Half Ice Harbor fishway.

Pool-and-Chute Fishways

The pool-and-chute fishway is a hybrid fishway. It has a center notch or weir and sloping weirs that extend to the fishway walls. Parts of the fishway operate simultaneously in both plunging and streaming flow regimes at moderate to high flows. At low flow the fishway is essentially a pool and weir fishway as water spills over the center weir. At higher flows, water levels raise and flow spreads up the sloping weirs.

The fishway width is set so the high fish passage design flow does not quite cover the entire width of the sloping weirs. Shallow plunging flow exists at the flow margins so low-turbulence passage corridors are created along the sides of the fishway. Most of the flow streams down the center of the fishway at a high velocity and with high turbulence. If streaming flow is not achieved for the bulk of the flow in the center of the fishway, it will plunge and cause the entire pool to be turbulent. Figure XII-48 shows a pool-and-chute fishway at low flow. Figure XII-49 show a pool-and-chute fishway at low and high flow.

Figure XII-48. Fisher Creek pool-and-chute fishway at low flow.

(a)

(b)

Figure XII-49. Figure Silver Creek pool-and-chute fishway (a) high and (b) low flow.

The pool-and-chute design has some benefits over the traditional pool and weir fishway. For small tributary application, all of the flow can be contained in the fishway so attraction to the fishway is good and distraction caused by flow from a spillway is eliminated. Even when used as a partial-width fishway in a wide dam, the pool-and-chute fishway creates a strong jet, making it is very attractive to upstream migrants. Flood flows are contained within the fishway and can scour bed material and debris from the fishway, reducing maintenance. Diverse passage routes are available to fish moving upstream. Fishway pool sizes can be smaller than a traditional pool and weir fishway with the same range of operating flows.

It also has some disadvantages. Since there is a concentrated, high-velocity flow in the center of the fishway, it must be aligned in a straight line without bends. It therefore cannot normally be used in a bypass layout unless it has no bends and the entrance jet is directed into the stream. The entrance jet can cause erosion downstream if the channel is not wide enough or the fishway is not properly aligned with the channel.

Pool-and-chute fishways have not been extensively used or biologically evaluated. Hydraulics of the pool-and-chute are less certain than other fishways with more history. No more than five or six feet of head differential should be taken through a pool-and-chute because of the uncertainties of stability with the high energy in the fishway and the limited hydraulic verification done to date.

The fishway alignment in plan view must be straight with flow approaching from the upstream side parallel to the fishway walls. When used at the outlet of a culvert, the alignment must be parallel to the culvert flow, and be far enough downstream to allow the exiting flow to expand and achieve a low approach velocity before entering the fishway.

Pool-and-Chute Design

The basic layout consists of a center horizontal weir and two higher sloping shoulder weirs on the sides. Design of the pool-and-chute is complex. It requires a number of criteria be satisfied simultaneously and requires iterations among geometric and hydraulic parameters. The components used to define the pool-and-chute fishway are shown in Figure XII-50 pool-and-chute layout. Bates (1991 and 1992) developed the pool-and-chute concept and explained it more thoroughly.

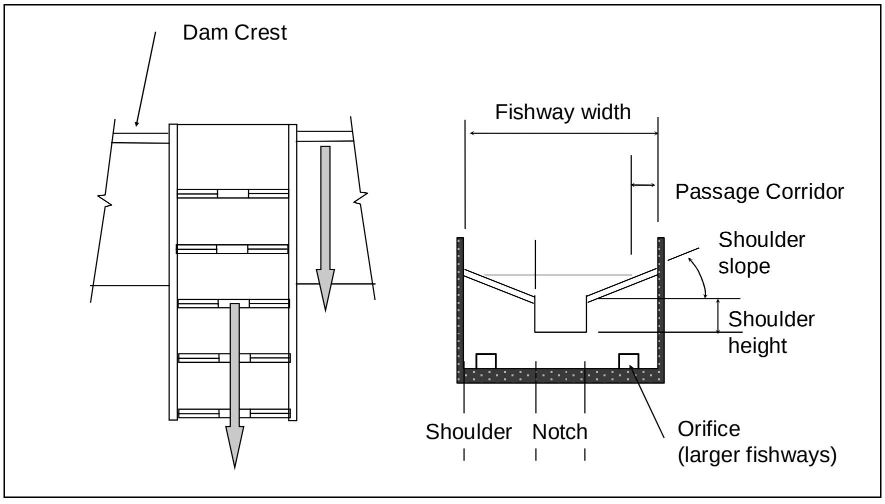


Figure XII-50. Pool-and-chute fishway layout with nomenclature.

Elevations of the horizontal notch weirs are based on plunging flow regime at low flow just as in a standard pool and weir fishway. The heights of the notch weirs control the pool depth at low flow.

The design of the sloping shoulder weirs is based on plunging and streaming flow regimes occurring simultaneously. There should be a corridor of plunging flow over part of the shoulder weirs when the flow over the horizontal weir transitions from plunging to the transition regime.

The depth over the edge of the shoulder weirs should be at least 6 inches when that transition occurs. See Plunging and Streaming Flow Regimes (page XII-113) for a description of plunging and streaming flow regimes and to estimate the transition flow at Q_{PT}* in Figure XII-45.

The drop per weir is based on fish passage criteria for a pool and weir fishway. The drops may also be affected by the hydraulic design in order to produce streaming flow at a given fishway flow. Streaming flow occurs at a lower flow when the head differential is reduced. Analysis of weir hydraulics must include velocity head within the fishway. The upstream weir has no approach velocity, and therefore should be 20% lower relative to the profile of the other weirs.

The maximum recommended fishway slope is 10%. At higher slopes, pool lengths have to be very short in order to get streaming flow over the notch weir. The pool lengths become inadequate to achieve the required energy dissipation factor over the shoulder weirs. Steeper slopes can be achieved if a narrow range fish passage flows is needed or of flow control is provided, which eliminates a great advantage of pool-and-chutes.

The sloping weirs slope up toward the fishway walls so at all flows, up to the high passage design flow, there is a shallow plunging flow regime at the water's edge. The outer edges of the shoulder weirs should be high enough so the outer two feet of the weirs are not submerged at the high fish passage design flow. Length and height of the shoulder weirs are set to maintain a fish passage corridor. A lateral slope of 1:4 or less is recommended. If low flows are high enough (about 30 cfs), orifices in the weirs and near the fishway walls can extend the plunging flow regime in that area. Orifices should be designed with considerations similar to the Ice Harbor design. As an added check, the energy dissipation factor (EDF) for the pool volume and plunging flow associated only with the shoulder weir portion of the width should satisfy the normal pool and weir criteria (see Turbulence page XII-54 for a description of EDF).

Once the geometry and high flow capacity of the shoulder weirs is set, the length of the notch weir is set to take the bulk of the fish passage design flow. The overall fishway width should be no wider than the channel because of the high velocity exiting the fishway.

Vertical Slot Fishways

Vertical slot fishways have distinct steps similar to pool and weir fishways, but hydraulic control is provided by narrow full-depth slots between the pools instead of overflow weirs Figure XII-51 is a schematic isometric view of a vertical slot fishway.

A great advantage of the vertical slot fishway is that it is entirely self-regulating. It operates without adjustment through the entire range of fish passage design flows. The difference and any change in elevation between the tailrace (entrance pool) and forebay (exit pool) is nearly equally divided among all of the fishway slots regardless of those water surface elevations and the river flow. Distributing the change throughout the fishway automatically compensates for any change in forebay and/or tailrace water surfaces.

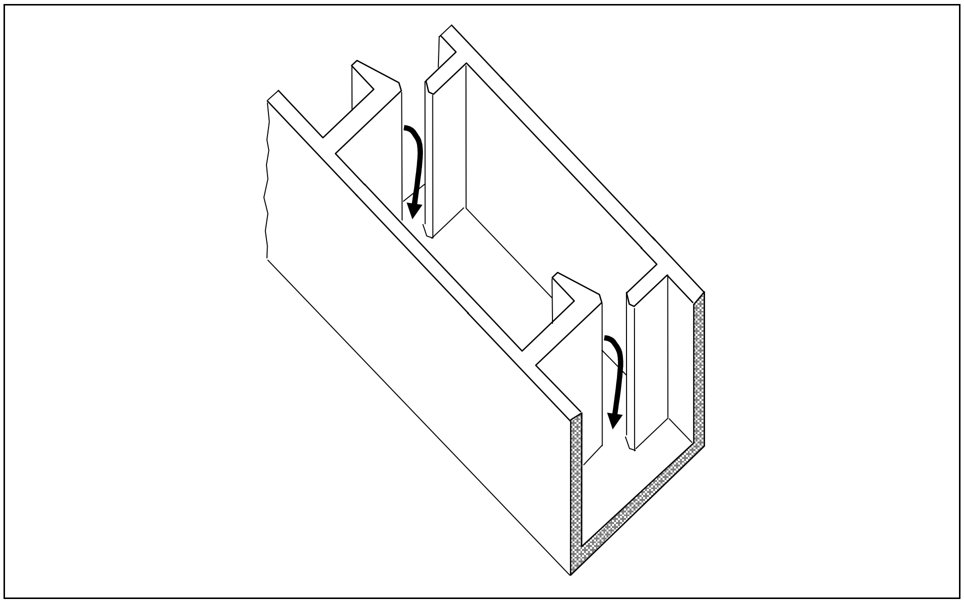


Figure XII-51. Isometric view of vertical slot fishway.

Energy is dissipated in each pool by the jet cushioning and mixing with water in the portion of the pool between the larger baffles. As additional flow passes through the fishway, the pool depths increase creating additional pool volume and maintaining appropriate levels of energy dissipation and turbulence. There is no need to calculate an energy dissipation factor as was described for pool and weir fishways as long as standard vertical slot fishway dimensions are used.

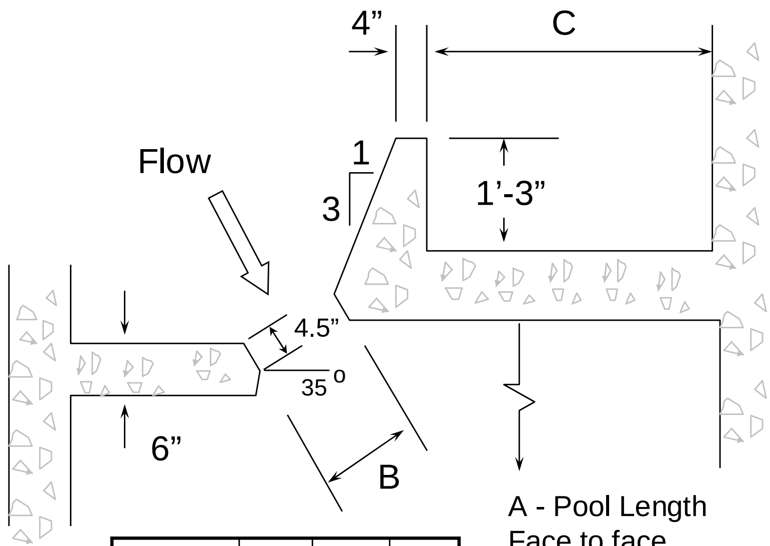
Passage

Another advantage of the vertical slot fishway is the full depth slots allow fish passage at any depth. Hydraulic studies by Rajaratnam et al. (1986) verified that the velocity through the slot is constant throughout the vertical profile.

The vertical slot is not usually suited for species that require overflow weirs for passage or that must orient to walls. For example, juvenile salmon can pass more successfully by leaping at a thin nappe over a weir than burst swimming though a high velocity jet. The vertical slot fishway gives those fish no opportunity to leap. Weak swimming fish may not be able to burst through high velocity jets in fishways designed for adult salmonids. Fish, such as lamprey and shad that orient to walls are often challenged and delayed by the tortuous pathway through vertical slots. Reducing the head differential and velocity through the slots can mitigate challenging conditions for these fish.

Dimensions

The dimensions of the vertical slot and pool are critical to the stability of flow. The dimensions shown in Figure XII-52 are described by Bell (1990) and should be adhered to unless specific experience or studies indicate that other configurations work. Generally, pools can be made larger in any dimension without a problem.



Ladder Width	A	B	C
8’	10’	12”	4’1”
6’	8’	9”	3’1”

Figure XII-52. Vertical slot fishway pool dimensions for 9” and 12” slots.

Any changes from the standard dimensions can result in unstable flow conditions and surging throughout the fishway. Surging oscillations as much as three feet have been experienced when the standard dimensions were slightly modified (Bates 1992).

Hydraulic conditions at shallow fishway depths are sensitive and most likely to be unstable. When the depth is too shallow, the jet exiting a slot tends to spread across the shallow floor rather than entering the cushioning pool and it tends to bypass the pool and move directly towards the next slot. Sills should be added if the slot is operated with a depth upstream of the slot less than about five feet or where the head differential may exceed the standard one foot. A sill is a short wall, generally 9-12 inches high in the bottom of a slot to make the slot shallower but still maintain minimum depth in the upstream pool. The sill allows the jet to occupy the same depths through and downstream of the slot and, therefore, stay more intact. Sills might also be used to ensure a minimum depth at low flow. Sills offer some benefit to the pool hydraulics at any depth but also incrementally diminish the fishway flow. Removable sills allow for easier cleaning at high sediment sites.

Standard widths of vertical slots are 9, 12, and 15 inches. Slots as narrow as 6 inches have been used for weaker swimming fish (Mallen-Cooper 2007). Other dimensions of the vertical slot, including the head differential between pools and therefore slot velocity, are reduced proportionately.

Flow

Flow through a vertical slot fishway is calculated as an orifice as in Equation XII-11.

$$Q = CwD\sqrt{2gh}$$ **Equation XII- 11**

Q = Fishway flow (ft^3/s)

C = Orifice coefficient (typically 0.75)

w = Slot width (ft)

D = Depth of water upstream of the slot (ft)

g = Gravitation constant (32.2 ft/s^2)

h = Head across the slot (ft)

The drop between successive pools is not always equal throughout the fishway. While the flow through each slot has to be identical, the depth of water in each slot may vary if the forebay and tailrace depths do not change equally as the river flow changes. This will create either a backwater curve in the lower pools (the tailwater level rising faster than the forebay with increasing flow) or a drawdown curve in the upper pools when the forebay rises faster than the tailwater.

Different design processes are required for the backwater or drawdown situations. However, in both cases, the floor elevations are based on minimum depth requirements at low flow. The number of slots is determined by the maximum forebay to tailrace head differential whether it is at low or high flow. The water surface profile is calculated for other flows to maintain a minimum head differential through the slots. A low head differential of 0.25 feet maintains an attraction velocity at the slot of about 3.0 fps. A normal minimum recommended depth, at the upstream side of a slot, is five feet though some vertical slot fishways are commonly operated as low as three feet.

Roughened Channel Fishways

Roughened channel fishways are as described for profile control in Roughened Channels (page XII-57). In addition to full-channel-width designs, as described in that section, they are often also designed with bypass layouts. Partial width roughened channel fishways might also work in some situations but the entrance usually has be located far downstream of the barrier and the structure itself takes up a large portion of the cross-section. The entrance can be located near the dam if the fishway can be built through the dam with most of its length upstream of the dam as shown in Figure XII-43b.

If low bank topography is available, a bypass layout can be routed around a dam so the entrance is near the base of the dam and the exit is some distance upstream of the dam. The fishway is a semi-natural channel excavated into the floodplain.

The design of a bypass roughened channel is a balance of flow control, stability design, and channel size. The stability of the channel, including slope of the channel and design of the bed, usually depends on good control of flow into the fishway so the fishway flow does not exceed a high structural design flow during high stream flow events. High fishway flow might be controlled for maintaining bed stability rather than for fish passage hydraulics, as it is for other fishways (see Fishway Flow Control page XII-129).

Flow control might be an orifice or gate built into a concrete or steel wall at the fishway exit. A similar device might be placed at the fishway entrance so some head differential is created for attraction of fish into the fishway. Figure XII-53 is a picture of a roughened channel bypass around a six-foot high dam on Spanaway Creek in Washington. Figure XII-54 is the orifice control at channel inlet. The flow control orifice in this example is equipped with adjustable plates so the flow control can be adjusted after monitoring.

One drawback of bypass roughened channels is that, in addition to the fishway flow being limited, the entrance is normally backwatered during high flows so there is no high velocity jet to attract fish to the entrance. Additionally, it is often difficult to design an entrance at an optimum location near the barrier since excavation of a channel near the base of a dam might be a structural risk. An orifice or slot similar to the flow control orifice, or at least a narrowed channel, might be provided at the entrance to enhance attraction. The scale of the project (width of the stream channel) in which the bypass roughened channel can be applied is therefore limited.

Figure XII-53. Spanaway Creek bypass roughened channel.

Figure XII-54. Flow control structure, Spanaway Creek bypass channel.

Roughened channels often depend to some degree on sediment recruited into the channel to replenish fine material that maintains a seal in the bed. If a bypass roughened channel exits into the forebay pool of a dam, that fine material may not be available naturally and may have to be added periodically as part a maintenance activity.

Denil and Alaska Steeppass Fishways

The Denil and Alaska steeppass fishways are fabricated flumes commonly constructed out of aluminum, steel, or wood with angled baffles to create enough roughness to control the velocity, even at high slopes. Both styles have been used extensively throughout the world but are not the first choice of fishway styles in settings where debris, sediment, and weak-swimming fish are to be passed. They have a limited headwater operating range and the baffles make them very susceptible to debris blockages. They are currently used in California primarily within trapping and evaluation facilities and for temporary fish passage during construction of other facilities. There are also some steeppass installations at small falls and dams.

Fishway Flow Control

Each of the various fishway styles described here has different ranges of flows through which they operate effectively. One extreme of operating ranges is the pool and weir fishway, which can only operate through a water level range of a fraction of a foot. A vertical slot, on the other hand, can operate through any water level fluctuations for which it is designed. The purpose of *flow control* is to extend the range of stream flows through which the fishway operates effectively by metering flow to the fishway. Flow control at the fishway exit may also be designed to maintain a specific head for a diversion. Regardless of the fish passage flow range, the fishway flow control might also be required to protect the fishway from damage during very high flows. This is especially true for roughened channel fishways.

There are five styles of flow control that can be used individually or in combination on any fishway. They are:

- Spillway control
- Self adjusting fishway
- Orifice or vertical slot flow control section
- Adjustable weirs
- Multiple level exit.

Spillway control is the most common and practical flow control method for fishways at culverts and small dams. Water is spilled over the spillway or dam to limit flow into the fishway. The geometries (length and opening dimensions) of the fishway and spillway act together to split and meter flows. Mechanical gates can be added to spillways to control water levels to within a very narrow range.

A vertical slot fishways is self-adjusting. No other flow control is needed. A vertical slot fishway can be used upstream of other fishway styles to control flow to them. Flow fluctuations in the fishway are reduced but not eliminated. If the upstream water level fluctuates only a small amount, the fishway flow may be within its design range. If it fluctuates greatly, the fishway design flow will be exceeded at some time. In that case, flow must either be added or taken out just upstream of the lower fishway as the forebay water level changes. For example, at low water levels a vertical slot segment can provide enough flow for a pool and weir segment downstream of it. At high water levels, additional water and headloss are taken through the vertical slot section and the excess water is bled off just upstream of the the pool and weir segment of the fishway so that segment has nearly a constant flow.

Flow control schemes that add water at low flow rather than bleed it off at high flow are also possible. They are not passive; they require water level sensors and automated gate operators and are therefore generally not preferred. An orifice flow control section is similar, but with submerged orifices rather than vertical slots. It is less preferred because fish are forced to sound and go through orifices, and the orifices may be difficult to inspect and maintain.

There are several mechanical flow control systems often used on large dams; they are not generally suitable for the scale of projects addressed in Part XII. Adjustable weirs and multiple level exits adjust the elevation of the fishway or fishway exit to the forebay elevation. Automatically telescoping or tilting weirs, in the upper portion of the fishway, can accommodate a small variation in forebay elevation. If a forebay is operated in more than one distinct operating range or if upstream water levels vary gradually, multiple level exits, together with other flow control measures, can be used. A low exit simply branches off of the fishway at the appropriate elevation and exits through a gated conduit in the dam. When not in use, the lower branch is closed. The switch between high and low exits is manual. When the flow is switched, the fishway must be inspected and any stranded fish removed.

REFERENCES (INCLUDING APPENDICES)

Abt, S.R. , R.J. Wittler, J.F. Ruff, D.L. LaGrone, M.S. Khattak, J.D. Nelson, N.E. Hinkle, and D.W. Lee. 1988. Development of Riprap Design Criteria by Riprap Testing in Flumes: Phase II Followup Investigations, volume 2. Colorado State University, Fort Collins, Colorado.

Abt, S.R., and T.L. Johnson. 1991. Riprap design for overtopping flow. Journal of Hydraulic Engineering 117(8):959-973.

Abt, S.R., J.F. Ruff, M.S. Khatak, R.J. Whittler, A. Shaikh, and J.D. Nelson. 1986. Environmental assessment of uranium recovery activities-riprap testing, Phase I, Report No. CER85-86SRA-JFR-MSK-RJW-AS-JDN24. Colorado State University, Department of Civil Engineering, Fort Collins, Colorado.

ACOE. 1994. Hydraulic Design of Flood Control Channels 1110-2-1601. U.S. Army Corps of Engineers, Washington D.C.

ACOE. 2002. SAM Hydraulic Design Package for Channels. Army Corps of Engineers, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center Vicksburg, MS.

ACOE. 2008. HEC-RAS, River Analysis System Hydraulic Reference Manual: Version 4.0, 4.0 edition. U.S. Army Corps of Engineers, Hydrologic Engineering Center. http://www.hec.usace.army.mil/software/hec-ras/hecras-document.html.

Bates, K. 1991. Pool-and-chute fishways. American Fisheries Society Symposium 10:268-277.

Bates, K. 1992. Fishway Design Guidelines for Pacific Salmon. Washington Department of Fish and Wildlife, Olympia, Washington.

Bates, K., B. Barnard, B. Heiner, J.P. Klavas, and P.D. Powers. 2003. Design of Road Culverts for Fish Passage. Washington Department of Fish and Wildlife, Olympia, Washington. http://wdfw.wa.gov/hab/engineer/cm/culvert_manual_final.pdf,

Bathurst, J. C. 1978. Flow Resistance of Large-Scale Roughness. Journal of the Hydraulics Division 104(12):1587-1603.

Bathurst, J. C. 1985. Flow Resistance Estimation in Mountain Rivers. Journal of Hydraulic Engineering 111(4):625-643.

Bathurst, J.C. 1987. Critical Conditions for Bed Material Movement in Steep, Boulder-Bed Streams. International Association of Hydrological Sciences Publication 165:309-318.

Bathurst, J.C. 2002. At-a-site variation and minimum flow resistance for mountain rivers. Journal of Hydrology 269(2002):11-16.

Beatty, S.J., D.L. Morgan, and A. Torre. 2007. Restoring ecological connectivity in the Margaret River: Western Australia's first rock-ramp fishways. Ecological Management & Restoration 8(3):224-228.

Bell, Milo. 1991. Fisheries handbook of engineering requirements and biological criteria. U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Bunte, K., and S. R. Abt. 2001. Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analyses in sediment transport, hydraulics, and streambed monitoring. General Technical Report RMRS-GTR-74 2001. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. http://www.fs.fed.us/rm/pubs/rmrs_gtr74.html.

Calles, E.O., and L.A. Greenberg. 2005. Evaluation of Nature-Like Fishways For Re-establishing Connectivity in Fragmented Salmonid Populations in the River Eman. River Research and Applications 21:951-960. .

CalTrans. 2006. California Highway Design Manual State of California Department of Transportation. http://www.dot.ca.gov/hq/oppd/hdm/pdf/chp0870.pdf.

CDFG. 2002. Culvert criteria for fish passage. Appendix IX-A in California Salmonid Stream Habitat Restoration Manual 3rd edition. California Department of Fish and Game. https://nrmsecure.dfg.ca.gov/FileHandler.ashx?DocumentID=3546,

Chartrand, S. M., and P.J. Whiting. 2000. Alluvial Architecture in headwater streams with special emphasis on step-pool topography. Earth Surface Processes and Landforms 25:583-600.

Chin, A. 1998. On the Stability of Step-Pool Mountain Streams. Journal of Geology 106:231-234.

Chin, A. 1999a. The morphologic structure of step-pools in mountain streams. Geomorphology 27:191-204.

Church, M., and A. Zimmerman. 2007. Form and stability of step-pool channels: Research progress. Water Resources Research, 43.

Costa, J.E. 1983. Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range. Geological Society of America Bulletin 94:986-1004.

Dunne, T., and L.B. Leopold. 1978. Water in environmental planning. W.H. Freeman and Company, San Francisco, California.

Ead, S.A., C. Katopodis, G.J. Sikora, and N. Rajaratnam. 2004. Flow regimes and structure in pool and weir fishways. Journal of Environmental Engineering and Science 3(5):379-390.

Ead, S.A., N. Rajaratnam, and C. Katopodis. 2002. Generalized Study of Hydraulics of Culvert Fishways. Journal of Hydraulic Engineering 128(11):1018-1022.

Ferro, V. 1999. Friction Factor for Gravel-Bed Channel With High Boulder Concentration. Journal of Hydraulic Engineering 125(7):585-590.

FHWA. 1979. Restoration of fish habitat in relocated streams, FHWA-IP-79-3. U.S. Department of Transportation, Federal Highway Administration.

FHWA. 1989. Design of Riprap Revetment: Hydraulic Engineering Circular. U.S. Department of Transportation, Federal Highway Administration.

FHWA. 1990. Highways in the River Environment Participant Notebook. U.S. Department of Transportation, Federal Highway Administration, Fort Collins, CO. http://www.fhwa.dot.gov/engineering/hydraulics/pubs/hire1990.pdf,

FHWA. 2001. Evaluating Scour at Bridges: Fourth Edition, HEC-18, 4th edition. U.S. Department of Transportation, Federal Highway Administration, Washington, D.C. & Arlington, VA. http://isddc.dot.gov/OLPFiles/FHWA/010590.pdf,

FHWA. 2003. Bottomless Culvert Scour Study: Phase I Laboratory Report. U.S. Department of Transportation, Federal Highway Administration.

FHWA. 2005. Hydraulic Design of Highway Culverts, Second Edition, Hydraulic Design Series No. 5 (HDS-5). U.S. Department of Transportation, Federal Highway Administration, Washington D.C. & Arlington, VA. http://isddc.dot.gov/OLPFiles/FHWA/012545.pdf,

FishXing Case Studies. 2008. US Forest Service. http://www.stream.fs.fed.us/fishxing/case.html

Fischenich, J. C. (2001b). Stability thresholds for stream restoration materials. EMRRP Technical Notes Collection (ERDC-TN-EMRRP-SR-29), U.S. Army Engineering Research and Development Center, Vicksburg, MS.

Fishbase. 2008. Fishbase, A Global Information System on Fishes. http://www.fishbase.org/home.htm.

FISRWG. 2001. Stream Corridor Restoration: Principles, Processes, and Practices. Federal Interagency Stream Restoration Working Group (FISRWG). General Website: http://www.nrcs.usda.gov/Technical/stream_restoration/

Fripp, J., C. Fischenich, and D. Biedenham. Circa 1998. Low Head Stone Weirs Draft, Technical Note EMSR 4-XX. U. S. Army Corps of Engineers.

Grant, G.E., F.J. Swanson, and M.G. Wolman. 1990. Pattern and origin of stepped-bed morphology in high-gradient streams, Western Cascades, Oregon. Geological Society of America Bulletin 102(3):340-352.

Gregory, S., J. McEnroe, P. Klingeman, and J. Wyrick. 2004. Fish Passage Through Retrofitted Culverts. Oregon Department of Transportation; Federal Highway Administration, Salem, Oregon.

Harrelson, C.C., C.L. Rawlins, and J.P Potyondy. 1994. Stream Channel Reference Sites: An Illustrated Guide to Field Technique. United States Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colorado. http://www.fs.fed.us/rm/pubs_rm/rm_gtr245.pdf,

Hey, R. D. 1979. Flow Resistance in Gravel-Bed Rivers. Journal of the Hydraulics Division 105(4):365-379.

Jarrett, R. D. 1984. Hydraulics of High-Gradient Streams. Journal of Hydraulic Engineering 110(11):1519-1539.

Kahler, T. H., P. Roni, and T.P. Quinn. 2001. Summer movement and growth of juvenile anadromous salmonids in small western Washington streams. Canadian Journal of Fisheries and Aquatic Science 58: 1947-1956.

Lang, M., M. Love, and W. Trush. 2004. Improving Stream Crossings for Fish Passage - Final Report. Humboldt State University and NOAA Fisheries, National Marine Fisheries Service. FINAL REPORT: http://www.stream.fs.fed.us/fishxing/NMFS%20Final%20Report%20(No%20Appx%20A).pdf,http://www.stream.fs.fed.us/fishxing/AppendixA_Final.pdf,

Lang, M. and E. Cashman. 2008. Influence of fish passage retrofits on culvert hydraulic capacity. Final report for California Dept. of Transportation (CalTrans). Contract No. 43A0068.10. 126 pages.

Larinier, Michel. 1990. Experience in fish passage in France: Fish pass design criteria and downstream migration problems. Proceedings of the International Symposium on Fishways 1990. Gifu, Japan.

Leopold, L.B., M.G. Wolman, and J.P. Miller. 1964. Fluvial Processes in Geomorphology. Dover Publications Inc., New York, New York.

Limerinos, J. 1970. Determination Of Manning's Coefficient From Measured Bed Roughness, Geological Survey Water Supply Paper 1898-B, volume 1989-B. U.S. Department of the Interior, Washington D.C.

Mallen-Cooper, M., and D.A. Brand. 2007. Non-salmonids in a salmonid fishway: what do 50 years of data tell us about past and future fish passage? Fisheries Management and Ecology 14:319-332.

Maynord, S.T. 1994. Streams Above the Line: Channel Morphology and Flood Control. U.S. Army Corps of Engineers, Waterways Experiment Station, Seattle, Washington.

MDOT. 2002. Fish Passage Policy & Design Guide. Maine Department of Transportation. https://maine.gov/mdot/interagency-meetings/iameet/april2004/documents/Fish_Passage_Policy_2004_Draft.pdf,

McCullah, J. and D. Gray. 2005. Environmentally Sensitive Channel- and Bank-Protection Measures (NCHRP Report 544), Transportation Research Board, Washington, D.C.

Montgomery, D.R., and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109:596-611.

Mooney, D.M., C.L. Holmquist-Johnson, and S. Broderick. 2007. Rock Ramp Design Guidelines. U.S. Department of the Interior, Bureau of Reclamation, Denver, CO.

Mussetter, R. 1989. Dynamics of Mountain Streams. Ph.D. Dissertation. Colorado State University, Fort Collins, Colorado.

NOAA. 2001. Guidelines for salmonid passage at stream crossings. NOAA Fisheries, NMFS SW Region. http://swr.nmfs.noaa.gov/hcd/NMFSSCG.PDF, www.h2odesigns.com/library/FishPassageDesign/Caltrans_FishPassageManual/Appendix-C-NOAA-Guidelines-for-Salmonid-Passage-at-Stm-Xngs-w-cover.pdf.

NRCS. 1990. Fish Passage and Screening Design, Technical Supplement 14N, Part 654, National Engineering Handbook U.S. Department Of Agriculture, Natural Resources Conservation Service.

NRCS. 1996. National Engineering Field Handbook, Part 650, Chapter 16 - Streambank and Shoreline Protection U.S. Department Of Agriculture, Natural Resources Conservation Service. http://directives.sc.egov.usda.gov/17553.wba.

NRCS. 2000. Design of Rock Weirs, Technical Notes Engineering No. 24, Engineering No. 24 edition. U.S. Department Of Agriculture, Natural Resources Conservation Service, Portland, OR.

Powers, P.D. 1997. Culvert Hydraulics Related to Upstream Juvenile Salmonid Passage. Washington State Department of Fish and Wildlife, Lands and Restoration Services Program.

Powers, P.D., and J.F. Orsborn. 1985. Analysis of barriers to upstream fish migration, an investigation of the physical and biological conditions affecting fish passage success at culverts and waterfalls. Washington State University, Department of Civil Engineering, Albroook Hydraulics Lab, Pullman, WA.

Rajaratnam, N., G Van der Vinne, and C. Katopodis. 1986. Hydraulics of vertical slot fishways. Journal of Hydraulic Engineering 112(10):909-927.

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

Rajaratnam, N., C. Katopodis, and A. Mainali. 1988. Plunging and Streaming Flows in Pool and Weir Fishways. Journal of Hydraulic Engineering 114(8):939-944.

Rice, C. E. , K. C. Kadavy, and K. M. Robinson. 1998. Roughness of Loose Rock Riprap on Steep Slopes. Journal of Hydraulic Engineering 124(2):179-185.

Robinson, K.M., C.E. Rice, and K.C. Kadavy. 1998. Design of Rock Chutes. Transactions of the ASAE 41(3):621-626.

Roni, P. 2005. Monitoring Stream and Watershed Restoration. Bethesda, Maryland: American Fisheries Society. 350 p.

Rosgen, D.L. 1996. A classification of natural rivers. Catena 22:169-199.

Ruttenberg, D. 2007. An Evaluation of Fish Passage at Rock Vortex Weirs. Master of Science Thesis. University of Idaho.

Saldi-Caromile, K., K. Bates, P. Skidmore, J. Barenti, and D. Pineo. 2004. Stream Habitat Restoration Guidelines: Final Draft. Co-published by the Washington Departments of Fish and Wildlife and Ecology and the U.S. Fish and Wildlife Service. http://wdfw.wa.gov/hab/ahg/shrg/.

Santos, J. M., M. T. Ferreira, F. N. Godinho, and J. Bochechas. 2005. Efficacy of a nature-like bypass channel in a Portuguese lowland river. Journal of Applied Ichthyology 21(2005):381-388.

Shoemaker, R.H. 1956. Hydraulics of Box Culverts with Fish-Ladder Baffles. Proceedings of the 35th Annual Meeting, Highway Research Board, Engineering Experiment Station, Report No. 53, Oregon State College, Corvallis, Oregon.

Simons, D., and F. Senturk. 1992. Sediment Technology, water and sediment dynamics. Water Resources Publication, Littleton, Colorado.

Thomas, D.B., S.R. Abt, R.A. Mussetter, and M.D. Harvey. 2000. A Design Procedure for Sizing Step-Pool Structures. Colorado State University, Fort Collins, Colorado. http://www.crwcd.org/media/uploads/reports_steppoolpaper.doc,.

Thorne, C. R., and L. W. Zevenbergen. 1985. Estimating Mean Velocity in Mountain Rivers. Journal of Hydraulic Engineering 111(4):612-623.

USFS. 2005. WinXSPRO, A Channel Cross Section Analyzer, User's Manual, Version 3.0, Gen. Tech. Rep. RMRS-GTR-147, 3.0 edition. U.S. Department of Agriculture, U.S. Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

USFS. 2006a. FishXing Users Manual. U.S. Department of Agriculture, U.S. Forest Service. http://www.fsl.orst.edu/geowater/FX3/FX3_manual.pdf.

USFS. 2006b. Low-Water Crossings: Geomorphic, Biological, and Engineering Design Considerations. USDA United States Forest Service National Technology and Development Program.

USFS. 2008. Stream simulation: an ecological approach to road stream crossings. USDA United States Forest Service National Technology and Development Program. http://www.stream.fs.fed.us/fishxing/aop_pdfs.html

USFWS. 2003. Geomorphic Impacts of Culvert Replacement and Removal: Avoiding Channel Incision. U.S. Fish and Wildlife Service, Oregon Fish and Wildlife Office, Portland, Oregon. http://library.fws.gov/Pubs1/culvert-guidelines03.pdf,.

VDFW. 2007. Vermont Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organisms. Vermont Department of Fish and Wildlife.

Villemonte, J.R. 1947. Submerged-weir discharge studies. Engineering News Record 2:866-869.

Weaver, C.R. 1963. Influence of water velocity upon orientation and performance of adult migrating salmonids. U.S. Fish and Wildlife Service, Fishery Bulletin 63(1):97-121.

Webb, P.W. 1977. Effects of size on performance and energetics of fishes. T. J. Pedley, editor. Scale Effects in Animal Locomotion. Academic Press, New York, New York.

Wolman, M.G. 1954. A Method of Sampling Course Riverbed Material. Transactions of the American Geophysical Union. 35(6): 951-956.

Zimmerman, A., and M. Church. 2001. Channel morphology, gradient profiles and bed stresses during flood in a step-pool channel. Geomorphology 40(2001):311-327.

This page left blank to help facilitate two-sided printing.

GLOSSARY

The terms in this glossary are defined relative to their use in Part XII. The first occurrence of each term is italicized in the document. The text in parenthesis following each definition is the initial location in the document where the term is used or other important uses of the term. They are included here for context.

Active channel – The portion of channel receiving sufficient and frequent enough flows to maintain cleanly scoured substrate. Margins of the active channel are located along the stream banks, often defined by *ordinary high water marks*. (Pre-Design Site Assessment)

Aggrade – Raising the level of a channel bed through general deposition of sediment. (Project profile design)

Armor – A surface streambed layer of bed material larger than that below it and that is rarely transported. This layer protects (armors) the underlying bed material from erosion and transport at flows that it would otherwise be mobilized. A well-armored bed suggests a supply-limited channel and low mobility. (Pre-design Site Assessment)

Attraction – Physical conditions that facilitate the fish finding the entrance of a fishway. (Fishway Entrance)

Baffle – Baffles are a series of flow obstructions placed in a culvert or flume to improve fish passage by increasing water depth at lower flows and/or decreasing water velocity at higher flows. (Overview of the Hydraulic Design Approach)

Bankfull – The location along the channel banks in which the channel flows full and a further increase in depth results in a rapid increase in width as flow spreads across the floodplain. It provides a consistent morphological index, which can be related to the formation, maintenance and dimensions of the channel as it exists under the modern climatic regime. (Pre-design, Stream Simulation)

Base level - The lowest level to which a stream can erode the channel through which it flows, locally equal to downstream bedrock, immobile feature or a larger water body. (Pre-Design Site Assessment)

Bedform – Features of the bed such as bars, steps, pools, etc. that are formed by high flows and are characteristics of the reach sediment supply and transport capability. (Stream simulation, Roughened channel)

Bedload – The part of sediment transport that is not in suspension, consisting of coarse material moving on or near the channel bed surface. (Project profile design, Stream Simulation)

Cascade channel – A channel classification of a steep channel characterized by large roughness elements relative to the water depth and without repeating bedforms as defined by Montgomery and Buffington (1997). (Stream Simulation, Roughened Channels)

Chutes and pools – Repeating bedform consisting of a short steep channel section (rapid or cascade) followed by a pool, used as profile control. (Roughened channels)

Colluvium – Rocks moved and introduced to a stream by gravity, such as by creep or slides, rather than being transported by the flowing water of the stream. Generally colluvium also includes soil material. (Pre-Design Site Assessment, Stream Simulation)

Contraction – A channel characteristic in which the width and/or depth of flow rapidly decreases, causing the flowlines to converge and the flow to accelerate. (Roughened Channels, Baffle Retrofits at Stream Crossings)

D_{xxx} - The size of a particle of which xxx% (e.g., 84%) of the particles of a mixture are smaller. For example, 84% of the particles in a specific mixture have median dimensions smaller than D_{84}. The median dimension of a particle is commonly used for this analysis. (Stream Simulation, Roughened Channels)

Degrade - Lowering of the level of a channel bed through general erosion of a reach. (Project profile design)

Deposition, sediment – Buildup of sediment within the channel, occurring when sediment transport forces become insufficient to keep the particle in motion. Deposition can be local due to a feature of the channel, or general as aggradation. (Pre-Design Site Assessment)

Drawdown – Decreasing depth of flow in the downstream direction due to an increase in water velocity (decrease in roughness or increase in slope), and/or change in the channel cross section. (Roughened Channels, Baffle Retrofits at Stream Crossings)

Dune ripple channel – A channel classification characterized by a low gradient channel with sandy bed and bedforms as defined by Montgomery and Buffington (1997). (Stream Simulation)

Ecological connectivity - The capacity of a landscape to support the movement of organisms, materials, or energy, including maintaining linkages of biotic and physical processes between upstream and downstream reaches. (Ecological Considerations of In-Channel Structures)

Embedded, culvert – A culvert with the floor below the channel profile. (Low-Slope Stream Simulation)

Energy dissipation factor (EDF) - The rate of energy dissipation within a volume of water, used as a measure of turbulence in the hydraulic design approach for roughened channels and fishways. (Roughened Channels, Fishways)

Engineered streambed material (ESM) – Streambed material for a roughened channel consisting of a well graded mixture of rock designed to be immobile up to the *stable bed design flow*. (Roughened Channels)

Entrenchment – The relative floodplain width, defined as the floodprone width divided by the bankfull width. (Stream simulation, Roughened channels)

Fish passage design flow, low and high - The range of flows (low to high) at which fish passage design criteria are satisfied in the hydraulic design approach. Water depth is usually primarily an issue at the low fish passage design flow. Water velocities and turbulence are commonly issues at the high passage design flow. Hydraulic drop criteria can be an issue at any flow between the low and high passage design flows. (Definition of the Hydraulic Design)

Fishway – A channel or structure specifically designed to produce suitable hydraulics for fish passage. (Overview of Hydraulic Design Approach)

Flanking - Erosion around the end of a structure causing the stream flow to flow around rather than over or through the structure. (Profile Control Structures)

Flooding, constructed streambed – Saturating the surface of the constructed channel bed or banks to consolidate and compact the material. (Roughened Channels)

Floodprone width – The width, measured perpendicular to the channel, susceptible to inundation during flooding, and commonly measured at twice the bankfull depth. (Pre-design Site Assessment)

Flow control – A system to meter the rate of flow into a fishway and the hydraulic head and/or depth at the entrance, exit, or other locations as stream flow changes. (Fishways)

Forebay – The impoundment of a dam just upstream of the dam or intake. (Fishways)

Forced profile - A channel profile that is controlled by flow obstructions (forcing features), whether natural or artificial. The obstructions cause the bedform to differ from the freeformed morphology for a similar sediment supply and transport capacity. (Project Profile Design, Profile Control Structures)

Forcing feature - Hard structure within the channel such as colluvium or large wood that controls the stream's elevation. (Profile Control Structures)

Headcut – A sudden unstable over-steepening in the channel profile located at the upstream extent of an incised channel. (Project profile design, Profile control structures)

Headwater – The water surface immediately upstream of a structure, such as a culvert. (Stream Simulation, Fishways)

Imbrication – Bed material particles in the channel overlay one another to form a pattern of shingles that shed water downstream. Imbrication suggest an armored bed and relative immobility. (Pre-design Site Assessment)

Incision - The process of channel bed lowering (degrading) and the resulting change in channel cross section shape and elevation. (Pre-design Site Assessment, Profile Control Structures)

Inlet control, culvert – The hydraulic condition in which the headwater depth at a flow is governed only by the geometry of the culvert inlet, and not by the hydraulics inside the culvert or the tailwater depth, which is *outlet control*. (Baffle Retrofits of Stream Crossings) (Milo 1991).

Inlet headloss – Dissipation of the flow's energy (potential and kinetic) as it enters a structure, such as a culvert. (Baffle Retrofits of Stream Crossings)

Invert, culvert – The elevation of the line that follows the lowest point along the inside bottom of a culvert or the floor of a flat-bottomed culvert. (Baffle Retrofits of Stream Crossings)

Jetting, constructed streambed – Washing the surface of the constructed channel bed or banks with water under high-pressure to consolidate and compact the material. (Implementation of Roughened Channels)

Key feature – Permanent or semi-permanent structures such as bedrock outcrops, large woody debris, stable debris jams, boulder steps, and human made structures that control the channel shape and/or grade and bed material sorting. (Pre-Design Site Assessment)

Knickpoint – Location along the profile of a stream at which a sudden gradient change occurs, often associated with a headcut. (Project Profile Design)

Mobility - The frequency of flow at which bed material moves. For example, key particles forming the steps in a step-pool channel might become mobile only at flows occurring once in 30 years. (Project Profile Design, Stream Simulation)

Nappe – A jet or sheet of water flowing over a weir or other drop. (Fishways)

Ordinary high water mark – Generally, the lowest limit of perennial vegetation. There are also legal definitions of ordinary high water mark that include characteristics of erosion and sediment. (Pre-design Site Assessment)

Outlet control, culvert - The hydraulic characteristic of a culvert in which headwater depth is governed at a flow by the tailwater depth, hydraulic conditions inside the culvert and the geometry of the culvert inlet. (Glossary)

Pebble count – A sampling method for characterizing the size of particles on the surface of a streambed. (Pre-design Site Assessment) (Wolman 1954).

Perch, culvert – A culvert characterized by an outlet elevated above the downstream channel forming a falls or cascade. (Project profile design)

Piping – The condition in which water flowing through substrate or under a structure erodes and carries fine particles from the material thus making it more porous and weaker. (Roughened channels)

Plane bed channel - A channel classification characterized by a channel bed without bedforms such as discrete bars, a low width to depth ratio and large values of relative roughness defined by Montgomery and Buffington (1997). Plane bed channels are dominantly gravel to cobble bedded and are in straight reaches. (Stream Simulation)

Planform – The layout of the stream, road, and other features as viewed from overhead looking directly down. (Pre-design Site Assessment)

Pool riffle channel – A channel classification characterized by an undulating bed that defines a sequence of bars, pools, and riffles as defined by Montgomery and Buffington (1997). (Stream Simulation)

Profile control – The use of structures, such as weirs, roughened channels or fishways, to steepen the channel beyond its naturally stable slope or to stabilize the bed of a degrading channel. (Pre-design, Profile Control)

Project profile – The channel profile through a crossing that will be constructed or will initially develop following completion of the project. (Pre-design)

Reference reach – A selected stream segment that represents a channel used to develop natural channel design criteria based on the reach characteristics, including stream channel dimensions, pattern and profile. (Stream Simulation)

Relative submergence – Used to describe the flow resistance imposed by the channel bed material, it is defined as the ratio of the hydraulic radius (R) or the average hydraulic depth (d) to the D_{84} particle size (R/D_{84} or d/D_{84}).

Riprap – Large, durable fractured rocks used to protect a stream bank or lakeshore from erosion. (Roughened Channels)

Rock ramps – A roughened channel that mimics a cascade or plane bed channel in that it is uniform without bedform features. (Roughened Channels)

Roughened channel – A constructed channel stabilized with an immobile framework of large rock mixed with smaller material. (Roughened Channels)

Roughness – An irregular surface or alignment such as boulders, baffles, or channel bends, that creates turbulence and therefore dissipates stream energy, increases water depth, and reduces average velocity. (Profile control, Stream Simulation, Roughened Channel, Baffle Retrofits of Stream Crossings)

Run – A plane-bed channel that lacks discrete bars found in relatively straight channels that may be either unconfined or confined by valley walls. Typically lack rhythmic bedforms and are characterized by long stretches of relatively featureless bed. (Ecological considerations)

Soffit, culvert – The inside top or ceiling of a culvert. (Stream Simulation)

Stable bed design flow – The flow at which the large rock forming the framework of the channel bed is sized to remain immobile. (Stream simulation, Roughened channels)

Stable channel (Stability) - A channel that is neither aggrading nor degrading over time. (Pre-Design Site Assessment, Project Profile Design)

Step pool channel – A type or classification of channel characterized by longitudinal steps formed by large clasts (cobbles or boulders) organized into discrete channel-spanning structures that separate pools containing finer material. (Stream Simulation, Roughened Channels)

Stream simulation – A natural channel design approach for stream crossings or elsewhere that includes construction of a channel that simulates characteristics of the natural channel. A stream simulation channel should present no more of a challenge to movement of organisms than the natural channel. (Stream Simulation)

Structural design flow – The flow at which a structure, such as a culvert, is designed to function without suffering damage. (Final Design and Construction)

Tailout, pool – Downstream end of a pool where bed material deposits causing a rise in the channel profile. (Ecological considerations)

Tailwater – Water surface downstream of a structure, such as below a culvert outlet or a dam. (Fishways)

Tailrace – The area of a channel just downstream of a dam. (Fishways)

Thalweg – The longitudinal line connecting the points of deepest water along a stream, which is located in the lowest point of a channel cross section. (Pre-design Site Assessment)

Transition, hydraulic – A change in the water surface slope caused by a change in channel geometry, slope, or roughness. (Roughened Channels)

Turbulence – Hydraulic condition characterized by rapid fluctuations in water velocity and flow direction and that dissipates kinetic energy. (Roughened Channels, Baffle Retrofits of Stream Crossings, Fishways)

Vertical adjustment profiles - The potential range of elevations the channel might experience throughout the lifetime of the project. (Project profile design)

Well-graded – A characteristic of a granular mixture in which the diversity of particle sizes is uniformly distributed from the smallest to largest. (Stream Simulation, Roughened Channels).

APPENDIX XII-A

CULVERT DESIGN DATA FORMS

Design data forms are provided to summarize the design process of a culvert. The purpose of the forms is to guide, document, and assist the design and reviews of culvert projects. There are two data forms, one for stream simulation design that includes the low-slope approach and a second for hydraulic design approach (baffles, gradient control). The design data forms include only fish passage, geomorphic, and hydrologic design information; other aspects of the project (e.g., traffic, geotechnical, road characteristics) should also be documented during pre-design.

Data is summarized to show design milestones, assumptions, and conclusions. The last step of the pre-design, as described here, is selection of the method for fish passage design. It is important to document project milestone decisions such as how the design method was selected.

A plan view sketch and a long profile should be attached to this design data form. See the design guide for background for all data and details recommended on sketches.

Not all sections will apply to any culvert; so chose the sections relevant to the specific culvert design process. There are two separate forms; one applies to culverts designed under the stream simulation option and the second applies to culverts designed under the hydraulic or low slope options.

Stream Simulation Design Data Checklist

This is a guide and summary for design and review of a stream simulation road - stream crossing including the Low-Slope design approach. Data is summarized to show design milestones, assumptions, and conclusions. This is not likely all of the data required for a complete design. Other design data sheets are available for other design methods.

A plan view sketch and a long profile should be attached to this design data form. See the design guide for background for all data and details recommended on sketches.

Describe any additional details necessary for the design on additional sheets.

Project

Project name and ID		
Stream		
Road, location		
Lat / Long (d/m/s)		
Interdisciplinary Design Team members		
Date		

Brief description of project ____

____

____

Project type (new, retrofit, replacement) ________________________________

Design approach (stream simulation, low-slope) __________________________

Does final design satisfy stream simulation design criteria? Explain deviations and limitations.

Y / N ____

Site characteristics (LS)

Is there an existing Culvert(s)? Y/N

Existing culvert perched: Y/N Height of perch ________________

Downstream channel incised Y/N Depth of incision _______________

Evidence of incision ____

____

Upstream backwater deposition Y/N

Evidence and extent ____

Project ________________ Project ID _______________

Date _______________

2 – BASIS OF DESIGN

ReferenceReach

Description of reference reach

Location of reference reach (e.g., "150' upstream from crossing)

____

Show location of reference reach on plan view sketch and profile.

Length of reference reach __________________________

Describe reference reach channel types (e.g., 75% pool-riffle, 25% plane bed)

____

____

Key bed features, function, and spacing (e.g., debris, steps, bends, etc.)

____

____

____

Bed mobility and how it was determined (e.g., observation, model applied, etc.)

Hydrology

Watershed characteristics

Area __________sq miles Mean elevation ______________ ft above sea level

Mean annual precipitation _____________________inches

Other hydrologic or flow characteristics (hydrologic province, area of lakes, northing, etc.)

____

Peak design flows	Derived flow (cfs)	Standard error (%)	Design flow (cfs)
2 - yr flow			
10 - yr flow			
25 - yr flow			
100 - yr flow			

Fish passage design flows

Species	Age class	High design flow (cfs)	Q7L2 (cfs)

Describe how hydrology was calculated and any assumptions (e.g., future conditions) made.

____

____

Project ________________ Project ID _______________
Date _______________

3 - BASIS OF DESIGN

Reference reach cross sections

Cross section labels			
Locations			
Channel type (M&B classification)			
Bankfull width			
Bankfull depth			
Floodprone width			
Elevation of high water mark			

Reference reach slope Average ________ Range______

Reference reach bed material

	Particle size (inches or mm)	How was particle size determined?
D_{95}		
D_{84}		
D_{50}		
D_{16}		
D_{5}		
Fines		

Reference reach key features

	Size (inches or mm)	Function	Spacing	Drop supported by feature	Permanence, mobility, condition
Debris and live wood					
Colluvium					
Bedrock					
Steps, clusters					

Function: Profile control, Roughness, Confinement, Bank stability

Project ________________ Project ID _______________
Date _______________

4 - DESIGN

Proposed Project Profile and Alignment

Proposed new channel within crossing Slope__________ Length __________
Upstream channel within project Slope__________ Length __________
Downstream channel within project Slope__________ Length __________

	Downstream end	Upstream end
Bed Elevation - project profile		
Bed Elevation - low potential profile		
Bed Elevation - high potential profile		

Stream simulation bed material

	Particle size (inches or mm)	How was particle size determined? (what model, observations)
D_{95}		
D_{84}		
D_{50}		
D_{16}		
D_5		

Additional features if included in the design

	Describe material, particle size (inches or mm)	Frequency, spacing
Disrupters, bands		
Banklines		
Key features		

High flow hydraulics

Event	Flow (cfs)	Tailwater elevation	Roughness (n)	Water surface elevation upstream	HW depth (HW/culvert rise)
2 - yr flow					
10 - yr flow					
25 - yr flow					
100 - yr flow					

Describe methods and sources of data high flow hydraulic calculations.

____

____

Project ________________ Project ID _______________
Date _______________

5 - DESIGN

Culvert Description

Dimensions, Elevations

	Existing Culvert	Proposed Culvert
Span	ft	
Rise	ft	ft
Upstream Invert Elevation		
Downstream Invert Elevation		
Culvert Length	ft	ft
Slope	%	%
Percent Embedded	%	%

Note: for bottomless structures, report elevations of tops of footings.

Description of proposed culvert; Choose one or more in each line

Shape: Round -Arch –Box

Other ____

Material: Corrugated metal -Smooth metal –Concrete

Corrugation dimensions: _________________________

Style Full pipe –Bottomless

Road and Alignment

Height of fill on upstream face: ___________ft.

Proposed culvert skew (parallel is 0 degrees)

Culvert to channel ________ degrees Road to culvert ________ degrees

Proposed alignment, transition changes_______________________________________

____

Describe permanent benchmark and elevation _________________________________

____

Other special considerations, recommendations _______________________________

____

____

____

____

Hydraulic Design Data Checklist

This is a summary for design and review of a road / stream crossing using the hydraulic design approach for fish passage at culverts. Data is summarized to show design milestones, assumptions, and conclusions. This is not likely all of the data required for a complete design. Other design data sheets are available for other design methods.

A plan view sketch and a long profile should be attached to this design data form. See the design guide for background for all data and details recommended on sketches.

Describe any additional details necessary for the design on additional sheets.

Project

Project name and ID		
Stream		
Road, location		
Lat / Long (d/m/s)		
Interdisciplinary Design Team members		
Date		

Brief description of project ____

____

____

Project type (new, retrofit, replacement) ____

Does this design satisfy hydraulic design approach criteria? If not, explain deviations and limitations. Y / N ____

____

Site characteristics

Is there an existing culvert(s)? Y / N

Is existing culvert perched? Y / N Height of perch__________________

Is downstream channel incised? Y / N Depth of incision_________________

Evidence of incision ____

____

Upstream backwater deposition Y / N

Evidence and extent ____

____

Project ________________ Project ID ________________
Date ________________

2 – BASIS OF DESIGN

Target Species

Species	Age class (Juv, Adult)	Fish length (in)	Hydraulic criteria		
			Max velocity (fps)	Min depth (ft)	Max turbulence (ft-lb/s/cuft)

Describe data sources ____

____

Hydrology

Watershed characteristics

Area ________________ sq miles Mean elevation ft ________________ above sea level

Mean annual precipitation ______________ inches

Other hydrologic or flow characteristics (hydrologic province, area of lakes, northing, etc.)

____

____

Peak design flows	Derived flow (cfs)	Standard error (%)	Design flow (cfs)
2 - yr flow			
10 - yr flow			
25 - yr flow			
100 - yr flow			

Fish passage design flows

Species	Age class	Movement seasons (months)	High design flow (cfs)	Low design flow (cfs)

Describe how hydrology was calculated and any assumptions (e.g., future conditions) made.

____

____

Project ________________ Project ID ________________
Date ________________

3 – DESIGN

Channel

	Downstream	Upstream
Average slope	%	%
Average bankfull width	ft	ft
Bed Elevation - project profile		
Bed Elevation - low potential profile		
Bed Elevation - high potential profile		
Channel type (M&B classification)		
Channel roughness (n)		
Elevation of downstream control		

How is profile controlled? ____

Culvert Description

Dimensions, Elevations

	Existing Culvert	Proposed Culvert
Span	ft	
Rise	ft	ft
Upstream Invert Elevation		
Downstream Invert Elevation		
Culvert Length	ft	ft
Slope	%	%

Note: for bottomless structures, report elevations of tops of footings.

Description of proposed culvert; Chose one or more in each line

Shape: Round - Arch - Box

Material: Corrugated metal - Smooth metal - Concrete

Corrugation dimensions: ____

Style: Full pipe - Bottomless

Project ________________ Project ID _______________
Date _______________

4 - DESIGN

Fish Passage Hydraulics

Flow (cfs)	Tailwater elev	Roughness (n)	Velocity (fps)	Depth (ft)	EDF (ft-lb/sec/cuft)	Passability (%)

Describe roughness (corrugation dimensions, bed material or roughened channel description, baffle geometry, etc.)

____

____

Describe methods and sources of data for fish passage hydraulic calculations.

____

____

High flow hydraulics

Event	Flow (cfs)	Tailwater elevation	Roughness (n)	Water surface elevation upstream	Headwater (HW/culvert rise)
2 - yr flow					
10 - yr flow					
25 - yr flow					
100 - yr flow					

Describe methods and sources of data high flow hydraulic calculations. ______________________

____

Road and Alignment

Height of fill on upstream face: ___________ft.

Proposed culvert skew (parallel is 0 degrees)

Culvert to channel ________ degrees Road to culvert ________ degrees

Proposed alignment, transition changes

____

____

Describe permanent benchmark and elevation ______________________________

____

APPENDIX XII-B

COMPUTING CHANNEL ROUGHNESS

Overview

To accurately predict water depths and velocities, especially at fish passage flows, estimation of hydraulic roughness, or flow resistance, is essential. Velocity, and therefore depth, is commonly predicted using the Manning equation (U.S. customary units):

$$V = \frac{1.486 R^{\frac{2}{3}} S^{\frac{1}{2}}}{n}$$ **Equation XII-B- 1**

Where *V* is the average water velocity, *S* is the water surface slope, *R* is the hydraulic radius and *n* is the Manning's roughness coefficient. The Darcy-Weisbach equation is also used to predict flow resistance. It is related to Manning equation by:

$$n = 0.0926 R^{1/6} \sqrt{f}$$ **Equation XII-B- 2**

Where f is the Darcy-Weisbach Friction Factor.

Selection of a flow resistance coefficient influences water velocity and flow depth predictions. Studies have found channel roughness depends on the depth of flow relative to the size of the bed substrate (Bathurst 1978, 1985 and 1987). This ratio of the hydraulic radius (R) or the average hydraulic depth (d) to the D_{84} particle size (R/D_{84} or d/D_{84}) is used to describe the *relative submergence* of the channel bed at a given flow. At shallower depths, flow resistance is very sensitive to changes in the depth of flow and substrate size. Flow around the larger bed particles causes additional roughness. Flow resistance becomes less sensitive to changes in depth as flows increase.

Numerous equations have been developed to estimate roughness coefficients. The equations presented in this document are those that are most applicable to steep channels and to roughened channels, where the grain size of the engineered streambed material is large relative to the water depth and therefore significantly impacts channel roughness. Each equation is applicable over a limited range of relative submergence, slope and substrate size. It is not uncommon to use one method for computing a roughness coefficient for fish passage flows and another one for estimating roughness at the structural design flow.

Methods to Compute Roughness

Definition of Variables

b — *Active channel* width

d — Average hydraulic depth (flow area divided by top with)

R — Hydraulic radius

D_n — Particle size, where the designated percent of particles in the gradation are smaller than n

W — Top width of flow

S — Water surface slope

n — Manning's roughness coefficient

f — Darcy-Weisbach friction factor

g — Gravitational acceleration

R/D_{84} or d/D_{84} — Relative Submergence

All equations presented are in US Customary Units.

Comparison of Methods for Predicting Roughness

Methods for predicting roughness coefficients are summarized in Table XII-B-1, accompanied by their range of application. Each equation is then discussed in detail in the following sections, along with recommended application.

Author	Slopes	Sediment Sizes (D_{50}) (feet)	Relative Submergence R/D_{84} or d/D_{84}	Data Origin
Mussetter (1989)	0.54-16.8%	0.1-2.1	0.2-3.7	CO mountain streams
Bathurst (1985)	0.2-4% (tested for slopes up to 9%)	0.2 - 1.1	0.4-11	gravel and boulder bedded rivers
Rice, et al. (1998)	1-33%	0.1-0.9	0.3-1.9	riprap on steep slopes in flume
Bathurst (1978)[1]	0.8-1.7%	0.6-0.8	0.4-1.3	Regulated river in Great Britain
Hey (1979)[1]	0.09-3.1%	0.1-0.7	0.7-17.2	Straight gravel bedded rivers
Limerinos (1970)	Not provided	0.02-0.8	0.9-69	CA rivers with coarse beds
Jarrett (1984)	0.2-4%	0.2-1.4	0.4-10.8	cobble & boulder streams
Bathurst (2002)	0.2-4%	0.4-2.5	0.4-11	compilation of stream data sets

Table XII-B-1. Methods to determine Manning's n and the range of conditions under which they were derived.

[1] Methods presented in Thorne and Zevenbergen (1985)

Note that all of the equations have considerable error associated with them. When estimating a roughness coefficient, it is important to select a method that is most suitable for the channel type, flow conditions, and range of flows and depths. It is helpful to compare results among equations, check the range of application, and understand how uncertainty in the roughness calculations can influence the design. Refer to the section on each individual method for the recommended conditions for application.

Figure XII-B- 1 presents Manning's n values predicted using the various methods presented in this document. For the figure, the equations were applied to dimensions of a typical roughened channel with a 1.5% slope and a D_{84} of 1.56 feet in a trapezoidal channel with a 10-foot wide bottom that had a 5H:1V side slopes and banks with 1H:1V side slopes. The estimates of Manning's n vary significantly depending on the methodology used.

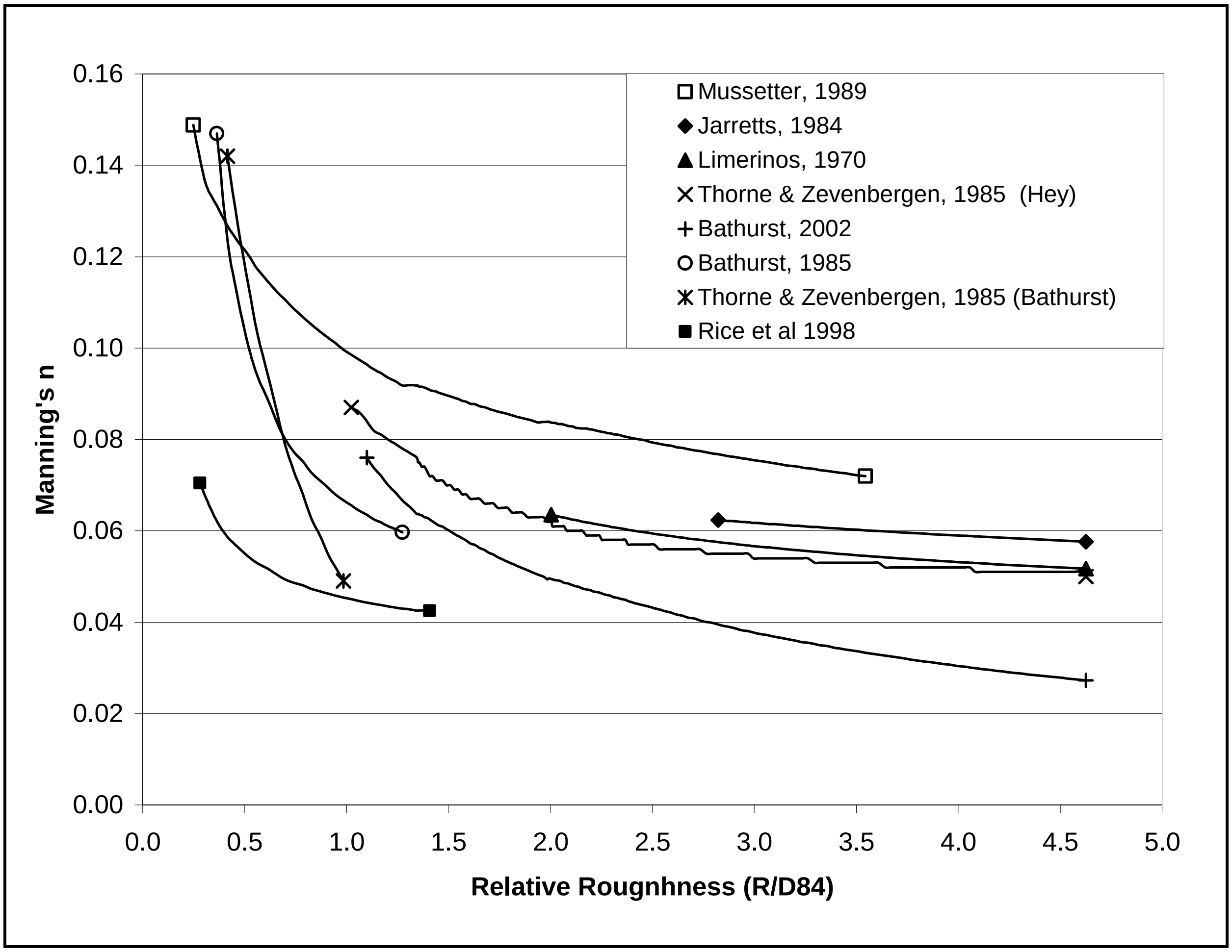


Figure XII-B- 1 Manning's n predicted using various methods for the same channel. Values are shown within their range of applicability.

Mussetter 1989

Mussetter (1989) combined several data sets encompassing a wide range of hydraulic conditions to develop the following equation:

$$\left(\frac{8}{f}\right)^{0.5} = 1.11\left(\frac{d}{D_{84}}\right)^{0.46}\left(\frac{D_{84}}{D_{50}}\right)^{-0.85} S^{-0.39}$$ **Equation XII-B- 3**

Mussetter developed this equation from a large dataset of Colorado rivers with slopes of 0.54-16.8%, d/D_{84} values from 0.24 to 3.72, and D_{50} sediment sizes from 0.1 to 2.1 feet. Most data points fall between d/D_{84} values of 1 and 2.

Mussetter found that Equation XII-B-3 underestimate channel roughness, with a mean error of 3.9% for channel slopes less than 4%, compared to measured field data. Simons & Senturk (1992) recommend use of this equation in steep gradient streams with large cobble and boulder sized bed material. Bates et al. (2003) noted that the equation's accuracy decreases when velocities are greater than 3 ft/s, and recommends limiting its use to determining velocities and depths for fish passage flows.

Bathurst 1985

Bathurst (1985) developed the following equation for predicting flow resistance derived from several high gradient gravel and boulder bedded streams:

$$\left(\frac{8}{f}\right)^{0.5} = 5.62\log\left(\frac{d}{D_{84}}\right) + 4$$ **Equation XII-B- 4**

This equation was derived from a compilation of data sets with slopes ranging from 0.2% to 4%, D_{50} sizes from 0.2 to 1.12 feet, and d/D_{84} values of 0.43-11.

Bathurst indicates the equation has the least error with low to moderate relative submergence; where d/D_{84} is less than two, it underestimates roughness by approximately 13%. For higher values of relative submergence the estimated error increases to $\pm$ 25-35%. When used for conditions with higher values of d/D_{84}, results should be compared with those obtained from other methods. Musetter (1989) found this equation to under-predict roughness in channels with slopes greater than 1.5% and relative submergence less than 4%.

Rice et al. 1998

Rice et al. (1998) derived a roughness equation from experiments of uniformly sloped rock chutes in flumes. Though derived for uniform slopes ranging from 2.8-33%, Rice compared results to data in Abt et al. (1988) for slopes between 1-20% and found similar accuracies.

$$\left(\frac{8}{f}\right)^{0.5} = 5.1\log\left(\frac{d}{D_{84}}\right) + 6$$ **Equation XII-B- 5**

This equation was derived specifically for shallow, uniform flows with an R/D_{84} range of 0.27-1.93 over rock chutes comprised of a relatively uniform gradation (D_{60}/D_{10} from 1.47 to 1.73) of material with a D_{50} ranging from 0.17-0.91 feet.

The equation predicts low roughness values when compared to other methods, likely due to the uniform gradation of the material and uniformity of the bed morphology. The equation is not recommended for application in natural channels, but may be suitable for predicting roughness of roughened channels with constant slope and no protruding boulders.

Thorne and Zevenbergen 1985

Thorne and Zevenbergen (1985) assessed several methods of computing roughness in mountain rivers with coarse bed material, steep slopes and shallow flow depths. They identified flow resistance equations developed by Bathurst (1978) and Hey (1979) as most accurately predicting roughness and mean velocity. The assessment was based on two field sites with slopes of 1.43-1.98%, a D_{50} sediment range of 0.43-0.53 feet, and R/D_{84} values of 0.89 to 1.56.

Thorne and Zevenbergen recommend a method that the use the Bathurst (1978) equation for large relative submergence ($R/D_{84} < 1$) and Hey (1979) equation for moderate to low relative submergence ($R/D_{84} \geq 1$). The authors recommend this method be used for determining roughness of riprapped channels and banks.

Thorne and Zevenbergen hydraulic roughness computations are included in the software package WinXSPRO (Hardy et al. 2005).

Bathurst 1978

Bathurst (1978) derived a flow resistance equation based on several field sites located on a single river with slopes of 0.8-1.74%, a D_{50} sediment size of 0.6 to 0.8 feet, and R/D_{84} values of 0.37 to 1.32.

$$\left(\frac{8}{f}\right)^{0.5} = \left(\frac{R}{0.365D_{84}}\right)^{2.34} \left(\frac{W}{d}\right)^{7(\lambda_E - 0.8)}$$

Equation XII-B- 6

where $\lambda_E = 0.039 - 0.139 Log\left(\frac{R}{D_{84}}\right)$

Bathurst recommends that this equation not be used when R/D_{84} exceeds 1.5. Thorne and Zevenbergen recommend applying Bathurst (1978) for situations with large relative submergence ($R/D_{84} < 1$).

Hey 1979

Hey (1979) developed the following equation from a large dataset from straight, gravel bedded rivers with slopes of 0.09-3.1%, R/D_{84} values of 0.7 to 17.23, and a D_{84} sediment size of 0.13 to 0.65 feet.

$$\left(\frac{8}{f}\right)^{0.5} = \frac{V}{gRS} = 5.62\log\left(\frac{a'R}{3.5D_{84}}\right)$$

Equation XII-B- 7

where $a' = 11.1\left(\frac{R}{d_{max}}\right)^{-.0314}$

For smaller relative submergence, where $R/D_{84} \geq 1$, Thorne and Zevenbergen recommend the equation by Hey for deeper flows. Grant et al. (1990) found the Thorne & Zevenbergen method best fit field data of high gradient boulder bed step-pool and cascade streams in Oregon. Bathurst (1985) found that Equation XII-B-7 over-predicted roughness, with greater error with deeper flows (R/D_{84} >6).

Limerinos 1970

Limerinos (1970) derived the following roughness equation from coarse bedded streams and rivers in California:

$$n = \frac{0.926R^{\frac{1}{6}}}{1.16 + 2\log\left(\frac{R}{D_{84}}\right)}$$

Equation XII-B- 8

The equation was derived based on data from numerous river channels in California with R/D_{84} values ranging from 0.9 to 69 and D_{50} sediment size ranging from 0.024-0.83 feet. The equation was found to have an error of $\pm$ 19%. The data used in the derivation of Equation XII-B-8 included a few sites with low R/D_{84} values, but most values were greater than 2.0, indicating the equation will better predict roughness for deeper flow and small relative submergence.

Equation XII-B-8 has been widely recommended for calculation of Manning's roughness values in streams, especially for higher velocity and larger flows (ACOE 1994; ACOE 2008; Richardson 1990; Thomas 2002).

Jarrett 1984

A flow resistance equation was derived by Jarrett (1984) based on data from 21 high gradient streams in Colorado with slopes ranging from 0.2-4%, sediment size D_{50} ranging from 0.2 to 1.4 feet, and R/D_{84} values from 0.4-10.8. The following equation estimates the average roughness through an entire stream reach, which may include multiple bedforms (e.g., steps and pools).

$$n = 0.39S^{0.38}R^{-0.16}$$

Equation XII-B- 9

Jarrett's hydraulic roughness computations are included in the software package WinXSPro (Hardy et al. 2005).

Jarrett found the equation overestimates Manning's n by as much as 30%, with the greatest error occurring at lower flows when $R/D_{50} <7$. Assuming $D_{84}= 2.5D_{50}$ for natural gravel rivers (Bates et al. 2004), Jarrett's equation is most applicable at deeper flows where $R/D_{84} >2.8$.

Bates et al. (2003) and Hardy et al. (2005) recommend using Jarrett's equation for bankfull and larger flows. Because the equation does not include a particle size, it is recommended that this equation only be used for roughness assessment of natural channels and channels designed using the stream simulation method. It is not recommended that it be used for assessment of constructed roughened channels.

Bathurst 2002

Bathurst (2002) combined previously published field data for mountain rivers to derive two flow resistance equations dependent on channel slope:

$$\left(\frac{8}{f}\right)^{0.5} = 3.10\log\left(\frac{d}{D_{84}}\right)^{0.93}$$ **for slopes > 0.8%** **Equation XII-B- 10**

$$\left(\frac{8}{f}\right)^{0.5} = 3.84\log\left(\frac{d}{D_{84}}\right)^{0.547}$$ **for slopes < 0.8%** **Equation XII-B- 11**

These equations were derived based on data from in-bank flows in channels with slopes ranging from 0.2 to 4%, D_{84} sediment sizes of 0.45 to 2.5 feet, and R/D_{84} values of 0.37 to 11.

Bathurst notes that these equations only consider the impacts of bed grain roughness with uniform flow, and neglect bed and bank form roughness and non-uniform flow conditions. Bathurst indicates that these equations correlate well with the field data and have less data scatter than other flow resistance relationships in the literature, but suggests the resulting roughness values should be considered minimum values. Figure C-1 indicates that during deeper flows (higher R/D_{84}) this equation predicts low values of n compared to other methods, which could result in under-prediction of flow depth and over-prediction of flow velocities.

APPENDIX XII-C

HYDRAULIC DESIGN OF BAFFLES

Baffles are added to existing culverts or flumes to increase water depths and decrease water velocities for fish passage. The material presented in this appendix supplements the discussion provided in Baffle Retrofits of Stream Crossings (page XII-95). Limitations of Baffles (page XII-96) discusses the use and limitations of baffles and should be reviewed before beginning a baffle retrofit design. This appendix first describes current methods used to perform the analyses needed to design baffle retrofits, and then summarizes the overall design process. The methods presented here represent current practice but ongoing research efforts and field assessments of retrofit installations continually improve our understanding of baffle performance. The aspects of baffle design covered in this appendix are:

- Selecting a baffle type and geometry
- Analyzing hydraulics to predict water depth, velocity, and turbulence at low and high fish passage design flows, and
- Evaluating the impact of baffles on the hydraulic capacity of the culvert.

These topics are followed by a step-by-step design procedure for baffles, which is provided at the end of this appendix. Though this section focuses on baffles in culverts, the same designs can be used in open flumes of comparable shapes.

Geometry of Baffles

Many types of baffles have been installed in culverts. However, the hydraulics of only a few have been studied or evaluated in detail. The following sections describe the most widely accepted baffle types for circular and flat bottom culverts. Studies of these baffle types have found they produce hydraulic conditions believed to be suitable for passage of adult salmonids, with the potential of providing passage for smaller fish at low flows. There have been no valid empirical biological studies to confirm passage through culverts at high fish passage design flows. Empirical equations have been developed to predict hydraulic performance for these baffle types based on culvert slope and size and baffle height and spacing. The baffles described below are the only types recommended at this time. Other types of baffles may be used in projects if their hydraulic behavior can be predicted and the baffles have been shown to produce suitable fish passage conditions.

Corner and Weir Baffles

Corner and weir baffles are the baffle configurations recommended for circular and pipe-arch (squashed) culverts (Figure D-1). Weir baffles are typically used for wider and steeper circular culverts. The choice between these styles becomes apparent in the design process.

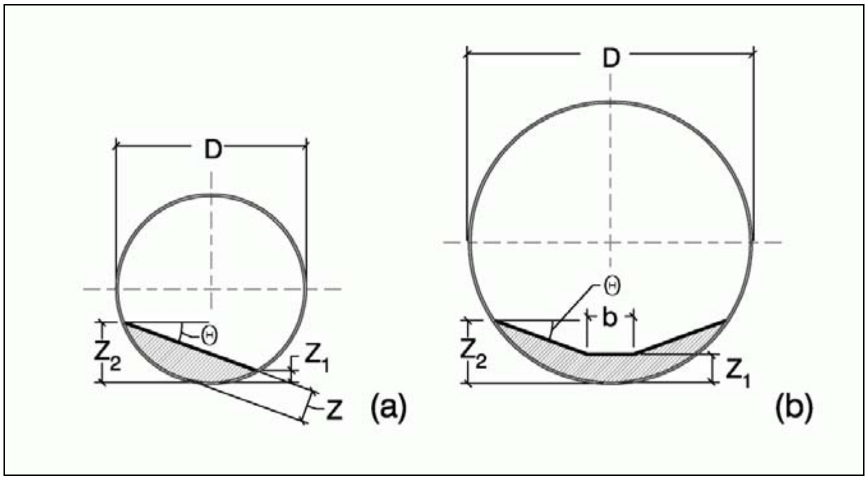


Figure XII-C-1. Design dimensions for (a) corner and (b) weir baffles.

For these baffle types the following variables are defined:

D = culvert diameter or span for pipe-arches (ft)
Z = baffle height normal to the crest of a corner baffle as shown (ft)
L = spacing between baffles (ft)
Θ = corner baffle side-slope (degrees from horizontal)
Z_1 = height of low end of baffle, measured from invert (ft)
Z_2 = height of high end of baffle, measured from invert (ft)
b = length of horizontal baffle crest

For corner baffles in round culverts circular, geometry and trigonometry are used to calculate Z_1 and Z_2 once Z and Θ are determined in the design process:

$$Z_1 = \frac{D}{2}\left[1-\cos(\phi+\theta)\right]$$
$$Z_2 = \frac{D}{2}\left[1-\cos(\phi-\theta)\right]$$

Equation XII-C- 1 and Equation XII-C- 2

Where:

$$\phi = \cos^{-1}\frac{(D-2Z)}{D}$$

Equation XII-C- 3

Typical angles for Θ are between 15^{o} and 25^{o}. The angle is adjusted by rotating the baffle but keeping Z_1 constant to satisfy minimum depth criteria at low passage flows while keeping the high part of the baffle dry at high passage flows. If this can not be achieved, Z may need to be increased.

Angled Baffles

Angled baffles are the baffle configurations recommended for flat bottom culverts, such as box culverts (Figure XII-C-2), and open flumes.

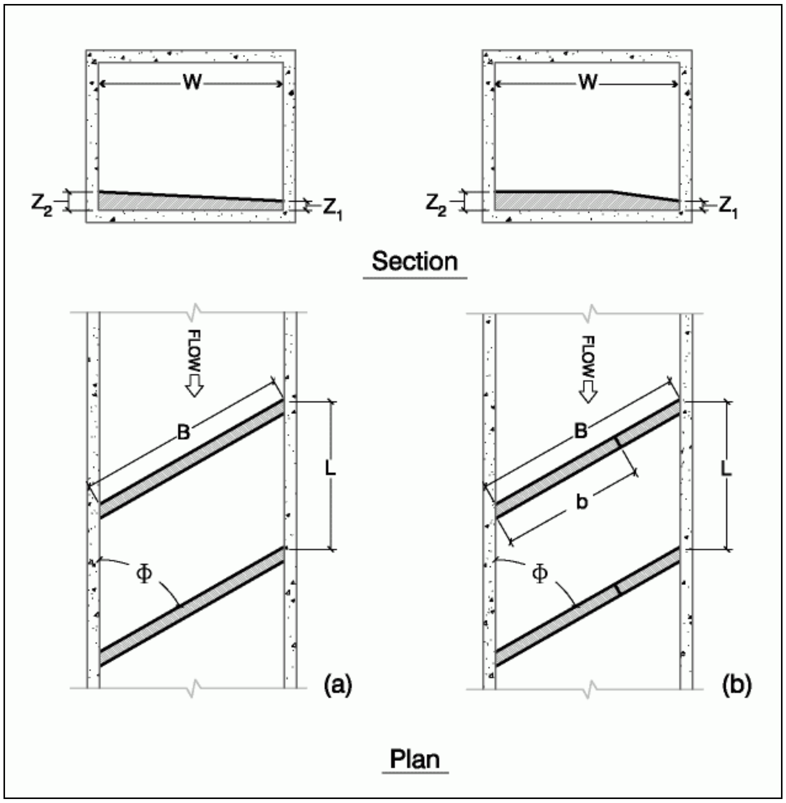


Figure XII-C-2. Design dimensions for (a) full taper and (b) partial taper angled baffles.

For angled baffles the following variables are defined:

W = culvert width (ft)
Z_1 = height of low end of baffle, measured from invert (ft)
Z_2 = height of high end of baffle, measured from invert (ft)
L = spacing between baffles (ft)
Φ = inside angle of baffle with wall in planform (degrees)
B = length of baffle (ft)
b = length of horizontal baffle crest (ft)

For angled baffles, the baffle length is:

$$B = \frac{W}{\cos(\Phi)}$$ Equation XII-C- 4

The recommended angle for Φ is 60^o. A smaller angle may create adverse hydraulic conditions. A large angle may reduce its ability to create slower and less turbulent water along the margin located at the high side of the baffle.

Baffle Hydraulics

At lower flows the corner, weir, and angled baffles produce plunging flow. At higher flows water begins to stream over the baffle. Ead et al. (2004) and Rajaratnam et al. (1988) provide some relationships for predicting the flow rate at which the transition from plunging to streaming flow occurs for pool and weir fishways. These can be applied to baffle arrangements if the baffle arrangement falls within the relationship's limits of application. Refer to Plunging and Streaming Flow Regimes (page XII-113) for more detail on plunging and streaming flow and determining the transition flow between them. Based on evaluation of these studies, a good assumption is that for baffles designed using the methods described below, plunging flow will occur at the low passage design flow, streaming flow will occur at the high passage design flow and all flows greater, including the culvert capacity flow, and there will be a transition between the regimes at a flow somewhere in between.

It is important to realize that all of the hydraulic calculations are for clear water, and do not account for affects associated with sedimentation or debris clogging within the baffles. Baffle Retrofits of Stream Crossings (page XII-95) and the design procedures outlined in Appendix XII-C Procedures for Baffle Hydraulic Calculations (page XII-C-10) provides guidance on means to reduce, but not eliminate, these risks.

Hydraulics of Plunging Flow across Baffles

Under plunging flow conditions, the baffle hydraulics can be approximated by modeling the baffles as sharp-crested weirs. The equation for a one-sided triangular sharp-crested weir is used to approximate plunging flow conditions over corner and angled baffles. Flow over weir baffles can be approximated using the equation for a sharp-crested trapezoidal weir. Note that while water depth criteria for fish passage are based on depth above the culvert bottom, the depth used in the weir equations is measured from the lowest point along the baffle crest. Plunging flow over other baffle shapes can by analyzed at a specified water depth by calculating weir flow in small segments across the crest length and then summing to obtain the total weir flow.

Weir submergence occurs when the water surface downstream of the weir becomes higher than any part of the weir crest. In plunging flow, submergence decreases the flow over the weir for a given depth, which can be accounted for using the equation provided by Villemonte (1947):

$$Q_s = Q\left[1-\left(\frac{h_d}{h_o}\right)^n\right]^{0.385}$$ Equation XII-C- 5

Where:

Q = weir flow over the baffle without accounting for submergence (cfs)
Q_s = weir flow over the baffle accounting for submergence (cfs)
h_o = upstream water depth above the weir crest (feet)
h_d = downstream water depth above the weir crest (feet)
n = coefficient equal to 1.5 for rectangular weirs and 2.5 for triangular shaped weirs

Hydraulics of Streaming Flow across Baffles

Under most streaming flow conditions, the water depth and velocity can be estimated using empirical equations for corner and weir baffles in circular culverts and angled baffles in box culverts. These empirical equations provide an estimate of normal depth in the baffled culvert at a given flow. Once a suitable baffle arrangement has been determined, it is often preferable to back-calculate a Manning's roughness coefficient based on the predicted normal depth. Because the roughness coefficient for a baffled culvert changes significantly with changes in flow, it must be calculated for each flow of interest, including the high passage design flow for each target species and the culvert capacity flow. The roughness coefficient can then be used in a backwater analysis of the culvert using standard hydraulic models to predict water surface profiles at a flow rate. The headwater depth and hydraulic conditions throughout the baffled culvert can be calculated, including the hydraulic transitions located at the inlet and outlet.

Corner and Weir Baffles

Based on flume studies and dimensionless analysis, Rajaratnam and Katopodis (1990) developed an empirical equation for predicting the hydraulics of weir baffles having a level crest. Lang (2008) modeled corner baffles in a flume at varying slopes. Results suggest that using the Rajaratnam and Katopodis coefficients for predicting hydraulics of corner baffles provides reasonable results. Due to a lack of available study of baffle hydraulics, the Rajaratnam and Katopodis results, combined with sound judgment, are considered suitable for design of both corner and weir baffles in circular culverts.

The Rajaratnam and Katopodis results can also be used to approximate the hydraulics of weir baffles in pipe arches (squashed pipes) by substituting the culvert span for the diameter. At higher flows this approach is not suitable. Instead, use the equivalent diameter of a circular pipe to model hydraulics of weir baffles in the pipe arch at capacity flows.

The equation provided by Rajaratnam and Katopodis has been rearranged to solve for average water depth in the culvert (Equation XII-C-6).

$$Y_o = D\left[\frac{Q}{C\sqrt{gS_oD^5}}\right]^{\frac{1}{a}}$$ **Equation XII-C- 6**

Where:

Y_o = water depth, measured from culvert invert (ft)
D = culvert diameter (ft)
S_o = culvert slope (ft/ft)
Q = flow in the baffled culvert (cfs)
g = gravitational acceleration (32.2 ft/s^2)
C = coefficient unique to baffle arrangement
a = exponent coefficient unique to the baffle arrangement

The baffle dimensions and their respective coefficients for Equation XII-C-6 are provided in Table XII-C-1. The coefficients were developed for culvert slopes from 1% to 5%. The first column lists the name of the baffle arrangement tested. Data for those ending with an '*e*' are extrapolated. It may be necessary to interpolate coefficients for other baffle height and spacing arrangements. The baffle height, Z, is measured as indicated in Figure B-2. For weir baffles $Z = Z_1$.

Baffle Arrangement	Z	L	C	a	Limits of Application
Weir Baffle D1	0.15D	0.6D	5.39	2.43	$0.25 \leq Y_o/D \leq 0.8$
Weir Baffle D2	0.15D	1.2D	6.6	2.62	$0.35 \leq Y_o/D \leq 0.8$
Weir Baffle D2*e*	0.15D	2.4D	8.5	3.00	$0.35 \leq Y_o/D \leq 0.8$
Corner Baffle	0.10D	0.5D	7.81	2.63	$0.20 \leq Y_o/D \leq 0.8$
Weir Baffle D3	0.10D	0.6D	8.62	2.53	$0.20 \leq Y_o/D \leq 0.8$
Weir Baffle D4	0.10D	1.2D	9.0	2.36	$0.20 \leq Y_o/D \leq 0.8$
Weir Baffle D4*e*	0.10D	2.4D	9.6	2.50	$0.20 \leq Y_o/D \leq 0.8$

Table XII-C-1. Baffle arrangements for circular culverts and resulting spacing, height, and hydraulic coefficients as a function of culvert diameter. Weir baffle data from Rajaratnam and Katopodis (1990). The corner baffle from Lang (2008).

The wetted area associated with Y_0 is needed to calculate water velocity. From simple geometry and trigonometry in a circular pipe, the flow area (*A*) between the baffles in a circular culvert is:

$$A = \frac{D^2}{8}(\phi - \sin\phi)$$

Where the angle of the circular sector, ϕ, is calculated in radians as:

$$\phi = 2\cos\left(\frac{D - 2Y_0}{D}\right)$$

For pipe-arch culverts, refer to tables of water depth verses wetted area, provided by manufacturers and also available in AISI (1994).

Angled Baffles

Lang (2008) developed empirical relationships for predicting the hydraulics of angled baffles in box culverts based on flume studies and dimensionless analysis. The angled baffles had a constant sloping crest and were skewed 60^0 relative to the culvert wall, as shown as ϕ in Figure B-2. The angled baffles were modeled in a square box culvert at slopes between 0.5% and 4%.

Based on Lang's work, Equation XII-C-7 predicts water depth for angled baffle arrangements:

$$Y_o = Z_2\left[\frac{Q}{C\sqrt{gS_oW^5}}\right]^{\frac{1}{a}}$$ **Equation XII-C- 7**

Where:

Y_o = water depth, measured from culvert invert (ft)
Z_2 = height of high end of baffle, measured from invert (ft)
W = box culvert width (ft)
S_o = culvert slope (ft/ft)
Q = flow in the baffled culvert (cfs)
g = gravitational acceleration (32.2 ft/s^2)
C = coefficient unique to baffle arrangement
a = exponent coefficient unique to the baffle arrangement

Angled Baffle Arrangement	L	Z_1	Z_2	C	A
Close-Spacing Tall Baffle Height	0.50W	0.132W	0.202W	0.122	1.85
Close-Spacing Medium Baffle Height	0.50W	0.092W	0.158W	0.123	1.70
Close-Spacing Low Baffle Height	0.50W	0.050W	0.112W	0.113	1.64
Intermediate-Spacing Tall Baffle Height	0.75W	0.132W	0.202W	0.139	1.82
Intermediate-Spacing Medium Baffle Height	0.75W	0.092W	0.158W	0.125	1.82
Intermediate-Spacing Low Baffle Height	0.75W	0.050W	0.112W	0.119	1.68
Far-Spacing Tall Baffle Height	1.00W	0.132W	0.202W	0.169	1.79
Far-Spacing Medium Baffle Height	1.00W	0.092W	0.158W	0.166	1.73
Far-Spacing Low Baffle Height	1.00W	0.050W	0.112W	0.180	1.64

Table XII-C- 2. Angled baffle arrangements in box culverts with specified baffle spacing and height as a function of culvert width. Hydraulic coefficients were developed by Lang (2008) and are applicable for water depths Y0 > 1.1 Z2 and Y0 < 0.80H, the culvert height.

Table XII-C- 2 lists the angled baffle arrangements that were tested and the corresponding values for coefficient used in Equation XII-C-7. Equation XII-C-7 and associated coefficients are applicable for water depths greater than 1.1 times the maximum baffle height ($Y_0 \geq 1.1 * Z_2$) but less than 0.80 the culvert height ($Y_0 \leq 0.80 * H$).

Turbulence

Baffles create *turbulence*, which is characterized by rapid fluctuations in water velocity and flow direction. Excessive turbulence can create a fish barrier. Insufficient turbulence during bedload transport flows can lead to excessive sediment deposition between baffles, reducing their effective roughness.

The measure of turbulence commonly used in fish passage design is the *Energy Dissipation Factor* (EDF). The EDF quantifies the rate energy is dissipated within a specific volume of water. Baffles function in plunging flow and streaming flow, and the EDF for these two flow regimes is calculated differently.

Turbulence for Plunging Flow

At low flows baffles typically function as weirs that create plunging flow. In plunging flow the energy is dissipated within the pool formed between the baffles. For plunging flow the EDF of the receiving pool is calculated as:

$$EDF = \frac{\gamma Q h}{V} \qquad \text{Equation XII-C- 8}$$

where γ is the unit weight of water (62.4 lb/ft^3), Q is the flow in the baffled culvert (ft^3/s). *V* is the effective pool volume between the baffles (ft^3), which is just the portion of the pool in which the energy is dissipated. Because the energy dissipation is concentrated within the upstream portion of the pool, in general the effective pool length for calculating EDF should not exceed 8 feet when baffle spacing is greater. The maximum EDF for plunging flow commonly used for adult salmon and steelhead is 4.0 ft-lb/s/ft^3, and 3.0 ft-lb/s/ft^3 for adult resident trout. Maximum EDF values for other species and life stages have not been determined. Refer to Pool and Weir Hydraulics (page XII-113) for a more through description of turbulence and EDF in pools.

The EDF for plunging flow conditions should be calculated at the flow estimated as the transition from plunging to streaming. With some baffle arrangements this can be estimated using equations provided by Ead et al. (2004) and Rajaratnam et al. (1988), but check the limitations of the equations. The equation by Ead et al. and its limitations are described in detail in Pool and Weir Hydraulics (page XII-113). Estimate the dimensionless transition flow using Ead et al. Figure XII-45 using the plunging transition, *Qpt**. Calculate the transition flow using Equation XII-9 and then the EDF using Equation XII-C-8. If there is excessive turbulence at flows within the plunging flow regime, the crest of the baffle may need to be raised to increase pool depth. Be aware that decreasing the EDF at the fish passage design flow might lower it at higher flows so sediment partially fills the pools.

In low slope culverts where baffles are often spaced far apart, the baffle arrangement may be beyond the limits of the empirical data for the plunging-streaming transition equation. In that case, EDF for plunging flow should be checked at the low fish passage design flow. Although it is difficult to predict the transition from plunging to streaming flow, it typically occurs at flows higher than the low fish passage design flow. Therefore, the calculated EDF at the low passage design flow should be less than the maximum recommended value.

Turbulence for Streaming Flow

In the streaming flow regime, baffles function as larger roughness elements and the EDF is calculated as:

$$EDF = \frac{\gamma QS}{A} \qquad \text{Equation XII-C- 9}$$

where γ is the unit weight of water (62.4 lb/ft^3), Q is the flow in the baffled culvert (ft^3/s), *A* is the wetted area between the baffles (ft^3), and S is the hydraulic slope (ft/ft).

There is little research available to determine the appropriate maximum EDF for fish passage in baffled culverts. For streaming flow in baffles, Bates (2003) recommends a maximum EDF of 5.0 ft-lb/s/ft^3 at the high passage design flow for adult salmon and steelhead. This recommendation is based on indirect measurements and observations of fish passage through a number of baffled culverts with various flows and values of EDF. A higher EDF is suitable for channels with more cross sectional hydraulic diversity than a culvert with simple baffles. The maximum EDF for passage of weaker swimming fish, such as juvenile salmonids, would be lower. However, additional data is needed to determine an allowable EDF for other salmonid life stages and other fish species as well as to confirm the EDF recommended for adult salmon and steelhead.

Bed Material Scour and Turbulence

Deposition of sediment between baffles can reduce their effective roughness, potentially eliminating the fish passage benefit of the baffles. Adequate water velocities and turbulence can reduce the risk of sedimentation. Generally, a drop of at least 0.2 feet between baffle crests should be maintained to provide sufficient scouring forces. A minimum EDF of 3.0 ft-lb/s/ft^3 is recommended in the baffled culvert at a flow in which the upstream bed material begins to mobilize, which may be approximated in stable channels as the bankfull flow. If the EDF is much less, the scouring forces associated with turbulence and water velocity may not be sufficient to avoid excessive sedimentation between baffles.

Culvert Capacity

By design, baffles increase the roughness of the culvert, which often decreases its hydraulic capacity. Normal depth of a baffled culvert at a capacity flow can be estimated using an appropriate empirical equation for the baffle arrangement (i.e., Equations XII-C-6 and XII-C-7). The limits of application should be noted when using this approach. These equations are often not applicable if the culvert barrel is flowing full.

Once the water depth is determined, the Manning's roughness coefficient should be back-calculated and then applied to the culvert in a backwater analysis using standard backwater models for culvert hydraulics (HY-8, HEC-RAS, FishXing). If the culvert is found to be inlet controlled at the capacity design flow, the influence of the baffles on culvert hydraulic capacity is minimal.

If the calculated capacity of the baffled culvert is not sufficient, the spacing and height of the baffles can be modified to decrease roughness. Moving the first baffle further into the culvert and lowering its height can also increase hydraulic capacity. In some cases these changes can keep a culvert flowing as inlet controlled at the capacity design flow. Obviously, these modifications have to be weighed against their effects on fish passage. It may be found that a baffle design cannot satisfy the project objectives and another design approach might be necessary.

The flood analysis should consider the effects of increasing the culvert backwater upstream of the inlet on over-bank flow, channel processes, and infrastructure. The design should also meet or exceed other applicable local, state, or federal standards for hydraulic capacity, headwater depth, and other design parameters.

Procedures for Baffle Hydraulic Calculations

This procedural summary is intended to provide general design guidance. Baffle design is an iterative process. When retrofitting an existing culvert there are numerous constraints to consider. For example, typically the culvert size and slope are predetermined and there is a little, if any, extra culvert capacity. As a result, it is frequently not possible to satisfy all of the provided guidance and criteria. In such cases, it is important to have clearly defined and accepted project goals, weigh the impact of each decision on passage performance, and document the decision process. In the end, a design's acceptability relies on the degree to which the project satisfies the goals and objectives.

1. Determine the low passage design flow (Q_{LP}), high passage design flow (Q_{HP}), sediment transport flow (Q_{BF}), and the depth, velocity and EDF (if available) criteria for each target fish.

2. Select an initial estimated baffle spacing (L) and height (Z_1 and Z_2) given the culvert diameter (D) or width (W) and culvert slope (S). Initial baffle spacing and height should be selected to satisfy the low flow depth criterion. Recommended maximum culvert slope where baffles should be applied is 4% and minimum baffle spacing is 5 feet.

3. Assume plunging flow with the baffles functioning as weirs at the low passage design flows for each target species, Q_{LP}:

   a. Use a sharp crested weir equation to calculate depth of flow over the baffles (Y_0) at the low passage design flow. Account for submergence, when present. To calculate Y_0 the baffle height (Z_1) needs to be added to the depth predicted from the weir equation.

   b. Calculate the minimum water depth (Y_{MON}) within the pools between the baffles at each Q_{lp}. The minimum depth occurs at the upstream end of the pool:

$$Y_{MIN} = Z_1 + Y_0 - L\,S$$

   c. Compare the minimum water depth to the depth criterion for each target fish.

      i. If there is insufficient depth at Q_{LP}, return to step 2 and increase the baffle height or decrease the baffle spacing, or both. The entire baffle may not have to be raised; increase the elevation of the lower edge of the baffle; Z_1.

      ii. If there is more than sufficient depth and EDF is low it may be desirable to return to step 2 to decrease the baffle height or increase the baffle spacing, or both to minimize the baffles' impact on culvert capacity.

iii. For angled baffles, the baffle should become fully wetted at approximately Q_{LP} for the largest design fish. This is intended to minimize impacts on culvert capacity while meeting minimum water depth criteria. To achieve this may require returning to step 2 to modify the baffle height or shape.

d. Calculate the EDF in the pools between baffles at the transition flow (plunging to streaming).

i. Calculate the transition flow using the equation by Ead et al. (2004). If the baffle arrangement is beyond the equation's limits of application, use Q_{lp} of each target species to evaluate EDF.

ii. Evaluate the EDF at the transition flow. If EDF is excessive, return to step 2 and increase the baffle height to increase the water depth. If using Q_{LP}, EDF should be well below the threshold for the target species.

4. Assume the flow is streaming and the baffles are functioning together as roughness elements at the high passage design flows (Q_{HP}). Under this assumption, use the appropriate empirical equation or an estimate of the hydraulic roughness coefficient to calculate water depth and velocity. Coefficients for the empirical equations may need to be interpolated to fit the baffle configuration. Note the limits of application of the equations and coefficients and apply sound judgment.

a. At Q_{HP} calculate the water depth (Y_o) for the selected baffle arrangement. Y_0 may be used to back calculate the Manning's roughness coefficient of the baffles, which can be use in a culvert backwater model.

b. Calculate the average cross sectional water velocity (V) for Q_{HP} using the relationship:

$$V = Q / A$$

The wetted cross sectional area (A) is measured between the baffles.

c. Calculate EDF for streaming flow in baffles using the equation:

$$EDF = \lambda QS/A$$

d. Compare the calculated water velocity and EDF to the velocity and EDF criteria for each target fish. If the velocities or EDF are excessive, return to step 2 to increase baffle height or decrease baffle spacing, or both.

e. In circular culverts the top corner of the baffle (Z_2) should be close to the water surface at Q_{HP}. To achieve this may require returning to step 2 to modify that dimension.

It may not be possible to simultaneously satisfy the velocity and turbulence criteria and the baffle height guidance. Velocity and turbulence levels greater than the target criteria may have to be accepted if additional roughness causes other criteria (e.g., culvert capacity) to be exceeded.

5. Calculate the EDF at a flow that the upstream bed material begins to mobilize, which is often assumed to be the bankfull or 1.5 year discharge in natural alluvial channels. Compare the EDF to the minimum EDF of 3 ft-lb/s/ft^3 for gravel-bedded streams to ensure sufficient scour between baffles. An acceptable level of turbulence is typically generated if the drop between baffles is 0.2 feet or more.

6. Evaluate the hydraulic transition between the culvert outlet and tailwater pool. Calculate a tailwater rating curve to obtain the tailwater elevation at the low and high fish passage design flows. For each design flow, compare the predicted normal water level within the culvert at the outlet (Y_o) to the level of the tailwater. The objective is to have the tailwater elevation be equal or greater than the water level in the culvert at each fish passage design flow. If the tailwater is lower than the water surface in the culvert outlet, there will be a hydraulic drawdown, or drop, and acceleration in water velocities near the outlet.

Possible modifications to the baffle arrangement to reduce or eliminate a hydraulic drop are limited because the culvert size, slope, and elevation are fixed. Baffles height may be reduced or spacing increased to lower the water surface in the culvert, but this may compromise fish passage. Alternatively, downstream gradient control measures, such as rock weirs, can be installed to raise the tailwater and eliminate the hydraulic drop. If site limitations prevent sufficiently raising the tailwater to match the water surface exiting the culvert outlet, it may be acceptable to have a drop or drawdown (M2 curve) in the water surface at the outlet. This can be evaluated with a backwater analysis. If a drawdown is allowed, check the water depth, velocity and EDF throughout the drawdown to ensure fish passage criteria are satisfied. To minimize the drawdown, a special outlet baffle should be installed (see Outlet Transition page XII-101). The resulting outlet drop should not exceed fish passage design criteria for hydraulic drops at culvert outlets.

7. Identify the structural design flow for the culvert (e.g., 100-year flow) and check the hydraulic capacity of the baffled culvert.

- **a.** Use the empirical equations to calculate the water depth at the structural design flow and then back calculate the corresponding Manning's roughness coefficient.
- **b.** Using the Manning's roughness coefficient, perform a standard culvert capacity analysis. Compare the headwater depth of the baffled to the unbaffled culvert to determine the impact of the baffles on capacity.
- **c.** Evaluate the risks of sediment or debris accumulations on fish passage and culvert capacity.