Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organisms in Vermont

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STATEMENT OF PURPOSE

This document is intended to provide technical guidance in the design and construction of stream/road crossings where the need for passage of aquatic organism passage has been identified. This guide is neither a cookbook nor a manual. Each site is unique, and conditions will lead to individual solutions. The methods and analyses described here are more rigorous than is necessary for simple sites and experienced design teams 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. We therefore encourage that an interdisciplinary team approach be used for these designs. To be successful, it is important to recognize where this higher degree of rigor is needed and to bring in specialists when appropriate.

These guidelines are not intended for use as a regulatory document. They are informative and do not impose any legal or regulatory requirement on the owner/designer of the project.

PREFACE

Stream crossings by transportation systems have had a profound influence on the movement and distribution of populations of aquatic species in Vermont. These impacts range from exclusion of species from tributaries of the White River and Connecticut River associated with the development of railroads and the interstate highway system, to highly fragmented habitats associated with town and private road development adjacent to stream networks. Vermont's Wildlife Action Plan (Vermont Department of Fish and Wildlife, 2005) identifies a large number of aquatic species threatened by such habitat fragmentation including 15 "species of greatest conservation need." The Vermont Department of Fish and Wildlife (VDFW) and the Vermont Transportation Agency (VTrans) have formally recognized this threat in a 2005 Memorandum of Agreement. The agencies developed a common goal "*to improve accommodation of wildlife and aquatic organism movement around and through transportation systems and to minimize habitat fragmentation resulting from the presence of transportation infrastructure".*

The *Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organism in Vermont* was developed by VDFW in collaboration with the Vermont Department of Environmental Conservation and VTrans as a major step toward meeting this goal. The contents of this guideline are based upon current knowledge of aquatic biology, fluvial geomorphology, hydrology and engineering and required the assistance of many experts in these areas of study. This document is presented with the intent of fostering improved design, installation, and maintenance of stream crossing structures to provide aquatic organism passage (AOP), aquatic habitat connectivity, and fluvial geomorphic functions in Vermont streams and rivers.

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Jonathan L. Wood, Secretary, Vermont Agency of Natural Resources

Wayne A. Laroche, Commissioner, Vermont Department of Fish and Wildlife

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Mission Statement
The mission of the Vermont Fish and Wildlife Department is the conservation of all species of fish, wildlife, and plants and their habitats for the people of Vermont. To accomplish this mission, the integrity, diversity, and vitality of their natural systems must be protected.

Guidelines for the Design of Stream/Road Crossings
for Passage of Aquatic Organisms in Vermont

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1. INTRODUCTION

There are numerous barriers to the movement of fish and other aquatic organisms in streams and rivers in Vermont. Though some of these barriers occur naturally, such as bedrock falls, many, such as culverts and dams, are human-created. Culverts in particular are a daunting challenge; there are thousands of them in Vermont's landscape and more are being installed every year as Vermont continues to develop. A study by the Vermont Department of Fish and Wildlife of culverts throughout the state provides some sobering results. Of 465 culverts assessed, less than 2% were rated as fully passable by aquatic organisms (Milone and MacBroom 2009).

VDFW presents these guidelines with the intent of fostering improved design, installation, and maintenance of stream crossing structures to provide and maintain aquatic organism passage (AOP), aquatic habitat connectivity, and fluvial geomorphic functions in Vermont waters.

This document provides concepts, design framework, and procedures to design road-stream crossings that satisfy ecological objectives including the passage of fish and other aquatic organisms.

These guidelines are not meant to replace existing standards and do not include all of the information necessary for a complete design of a stream crossing. The designer should refer to other documents, standards and experts for structural, roadway, geotechnical, and other engineering and environmental considerations associated with the design.

Passage of fish and aquatic organisms at road crossings is a complex issue. We strongly encourage that an interdisciplinary team approach be used for these designs. There are technical issues that should be considered by a range of expertise including biological, engineering, geomorphologic, geotechnical, structural, and hydrologic. We also encourage the design team to consult with VDFW Fisheries Biologists early in the project planning to ensure project objectives and biological considerations are appropriately defined.

Regulatory Obligations

These guidelines are not intended for use as a regulatory document, but as technical guidance for the design road-stream crossings where aquatic organism passage needs have been identified. There are several existing state and federal regulations that address the passage of fish and aquatic organisms in Vermont:

- U.S. Army Corps of Engineers, Vermont General Permit
    - Condition #17: Waterway Crossings
- Clean Water Act
    - National Roads Exemption BMP 40CFR 232.3 c(6)
- V.S.A.Title 10: Conservation and Development
    - Chapter 41: Regulation Of Stream Flow
    - Chapter 111. § 4607. Obstructing streams
    - Chapter 151. State and Land Use Development Plans (Act 250)
- Vermont Water Quality Standards
    - Section 1-03. Anti-Degradation Policy
- Natural Resources Conservation Service - Conservation Practice Standards

- Fish Passage Code 396.

Relevant sections and jurisdiction of these regulations and recommended practices are provided in Appendix F – Existing Regulations and Recommended Practices.

Other Standards

The design should also meet or exceed other applicable local, state, or federal standards for hydraulic capacity, headwater depth, and other design parameters. Other standards might include VTrans Hydraulics Manual, project environmental documents, VTrans Structures Manual, and AASHTO Specifications for Highway Bridges. For example, the VTrans Hydraulics Manual requires culverts to have flood capacities that vary from a 25-year flood to a 100-year flood by road class. These criteria may be more or less than what would be prudent for protection of passage facilities and habitat.

2. ECOLOGICAL ISSUES OF ROAD-STREAM CROSSINGS

The placement of road-stream crossings often results 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 aquatic organisms.

The following considerations may affect the siting, sizing, and design of stream crossing structures and/or passage improvements:

- Fish and other aquatic organism passage
- Direct loss of aquatic habitat
- Water quality impacts
- Upstream and downstream channel impacts
- Ecological connectivity
- Channel maintenance
- Construction impacts

VDFW District Fisheries Biologists should be consulted on the potential occurrence of these habitat concerns and to identify appropriate mitigation measures.

2.1 Passage of Fish and other Aquatic Organisms

Allowing movement of fish and aquatic organism is the primary focus of this guideline. Barriers to movement and migration may lead to the following impacts to aquatic communities:

- Loss of resident populations by preventing recolonization of upstream habitats after catastrophic events, such as floods or toxic discharges;
- 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 that allow communities to survive changing or extreme conditions.

These biological impacts result from restricting the movement of aquatic organisms within the stream network. Many fish species that live in Vermont's streams 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.

Studies in Michigan and Vermont have documented daily movement of adult brown trout, which leave daytime resting areas and travel upstream or downstream overnight, sometimes over a mile or more, presumably to forage, and then return to daytime home sites (Diana, 2004; Kenneth Cox, VDFW, personal communication). A recent study on Vermont's Batten Kill documented an adult brown trout moving over nine miles from the mainstem to a small tributary during its spawning period (Kenneth Cox, VDFW, personal communication). While brown trout and rainbow trout are well known for their migratory tendencies, brook trout also rely on regular seasonal movements to maintain viable populations. Gowan and Fausch (1996) documented brook trout summer seasonal movements of over a mile and shorter distances traveled regularly by resident brook trout. Movement occurs even in high gradient streams, as evidenced by Adams et al. (2000) who observed upstream movement of brook trout in slopes as high as 22%.

In addition to moving during higher flows to access suitable spawning habitat in spring and fall, trout and salmon also move during summer low flows and in anticipation of winter low flows. Peterson and Fausch (2003) observed peak movement of brook trout in the summer and fall, with nearly 80% of recaptured fish moving upstream and up to 2km away within a summer.

The moderating effect of groundwater on extreme water temperatures can also provide motivation for fish movement. Brook trout often spawn in areas of groundwater inflow (Webster and Eiriksdottir 1975, Witzel and MacCrimmon 1983, Curry and Noakes 1995, Waters 1995), and have been observed to overwinter in pools in proximity to groundwater discharges (Cunjak and Power 1986). Access to groundwater upwellings and tributary confluences is also important for thermal refuge for trout and other species during summer months (Baird and Kruger 2003).

Freshwater mussels commonly attach to fish hosts during their larval stage as a method of dispersal. In Vermont, the eastern pearlshell mussel can be found in small streams where culverts may be used. Since salmonids (trout and salmon) serve as the primary host for the larval stage of the eastern pearlshell, culverts that block juvenile salmonid movement also likely block pearlshell movement. The eastern pearlshell is known to occur in the upper Winooski and Dog River mainstems and the watersheds of Lewis Creek, West River, Passumpsic River, and Nulhegan River (Fichtel and Smith 1995).

Many crossings may provide “partial” or “temporal” passage, i.e. passage for specific species or size classes, or under certain flow conditions. In addition to excluding weaker swimming species and lifestages, significant migration delays may occur for other species (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 access 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 barriers within a stream system will serve to magnify these impacts.

Streams in Vermont that can be crossed with culverts are typically cold-water habitats. There are exceptions such as smaller waters in the Lake Champlain Valley where sensitive species such as the northern brook and American brook lamprey may reside. In general, however, most of the impacts associated with culverts in Vermont will affect coldwater fish populations – salmonids (trout and salmon), cyprinids (minnows), catastomids (suckers), osmerids (smelt), and cottids (sculpin). Aquatic salamanders associated with these habitats may include spring, two-lined and dusky salamanders.

2.2 Ecological Connectivity

C*onnectivity* 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 it 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 might include upstream and/or downstream movement of mammals, birds, and fish, and the upstream flight, and downstream drift of insects. 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 be allowed to pass unhindered through the stream crossing structure. When debris is trapped at the inlet of a structure, aquatic organism passage barriers are created, and habitat may be degrade both above and below the stream crossing.

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

2.3 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. In most cases, for every foot of culvert installed, a foot or more of stream habitat is lost.

Aquatic organisms utilize almost all segments of the stream environment during some stage of their lives. Habitat usage is highly variable depending upon the species, life stage, and time of year. For example, brook trout fry and fingerlings tend to often use stream margin habitats, while adults use deeper pools and runs. Brook trout require cool, clean water and clean, sorted *substrate* for spawning and incubation of eggs. As described earlier, groundwater upwellings through spawning substrates are also important features of brook trout spawning habitat. A culvert placed in these areas replaces the natural gravel used for spawning with a metal or concrete surface. Even if natural substrates are recruited within the structure, this habitat will be disconnected from groundwater influence.

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 the streambank 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.

Culverts 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. Culvert designs that maintain natural stream substrates within the structure, and minimize disruption to the channel and riparian corridors are therefore encouraged.

2.4 Water quality impacts

Roadway stormwater runoff can affect aquatic habitats regardless of the type of crossing. Quality and quantity of roadway stormwater runoff should be mitigated as determined appropriate by the Vermont Department of Environmental Conservation Water Quality Division.

2.5 Upstream and downstream channel impacts

An undersized stream crossing can lead to substantial bank erosion, flooding of adjacent property, or failure of the structure. At high flows, an undersized structure backs water upstream and bed material deposits in the channel above the structure. With receding flows, the bed and/or banks erode through or around the deposition. The result is either a chronically unstable channel bed or increased bank erosion and the need for bank clearing and protection. The additional input of sediment from increased bank erosion may further degrade aquatic habitat, potentially impacting fish reproduction and aquatic invertebrate populations.

Increased velocity from an undersized structure can cause *scour* that threatens the structure's soundness, as well as damages adjacent properties with excessive bank erosion and bank collapse. The risks and costs of structure maintenance, damage to adjacent property, failure of structures and the resulting road damage and public safety hazards, and loss of recreational fisheries should be considered in evaluating the cost of stream crossing structures.

Channel migration across the floodplain is a natural geomorphic process that varies with channel type and geomorphic conditions. When channel migration is halted by placement of a structure, risk of road failure, channel armoring and maintenance are often a result.

Use of the design processes described in this guideline generally mitigates these impacts. Typically, the size and elevation of stream crossing structures described in this guideline are such that velocities leaving the structure are not excessive. Sites with banks or beds susceptible to erosion may require special consideration.

2.6 Channel maintenance

The need for channel maintenance created by poor siting of road-stream crossings can be a significant problem. 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 excursions and avulsions. Stream crossings placed 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. Bed material removal 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.

2.7 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 streambank 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. Construction plans submitted for regulatory approval should include a sediment and erosion control plan covering these items.

2.8 Risk of structure failure

A stream crossing structure in combination with the roadway fill can act like a dam across the valley. Ice or debris jams may exacerbate the effect, in some cases resulting in catastrophic failure. 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 extreme natural events. The process of evaluating, designing, and installing stream crossings should consider the risk of dam formation and failure. Appropriately sizing the culvert for passage of debris and extreme events can minimize this 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/or uncertainties than others. Structures that span the entire channel without constricting it are preferred, followed by engineered solutions described in this document. In some cases, resource values and risk assessment may dictate that engineered solutions are not acceptable.

3. Culvert Pre-Design

The design of any stream-road crossing project includes three basic steps.

> The ***pre-design phase*** includes verification of project objectives, assessment of the site, selection of project alignment and profile, and an initial choice of type of project that will be designed.
>
> The ***fish passage design*** is the design of the structure itself to achieve the objectives of passage of fish and/or other aquatic organisms. The design might be done with a low-slope, hydraulic, or steam simulation design process.
>
> The ***final design*** includes verification of flood capacity, details of the structure, profile controls outside of the crossing, construction practices, and contract documents.

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 Pre-design phase should be applied regardless of the method selected for the design of the crossing. It should be applied in fact to the design of many other structures built in rivers or streams.

3.1 Aquatic Resource Objectives

In addition to the transportation objectives of the project, aquatic resource needs should also be defined prior to the design process. VDFW Fisheries Division will evaluate the aquatic organism passage needs on a case-by-case basis. Biologists will consider the following in determining the need for aquatic organism passage at a site:

- Presence/absence of aquatic species populations;
- Aquatic species and lifestages currently or historically present and watershed goals for species or fish community restoration;
- Distance from site to a permanent, natural migration barrier;
- Presence of exotic and/or invasive species;

  On occasions, passage may not be required at a stream crossing structure in order to maintain separation of aquatic species.
- Movement needs of non-fish aquatic organisms;

  Where the movement of non-fish aquatic species is of concern (e.g., mussels, amphibians) the project proponent may be asked to consult with VDFW's Wildlife Division.
- Movement needs of terrestrial wildlife.

  There is certainly interest in addressing the movement of non-aquatic and semi-aquatic wildlife in some situations, which may or may not coincide with streams. These guidelines in themselves are not driven by consideration of other than aquatic and semi-aquatic species.

VDFW Wildlife Division has an ongoing initiative with VTrans to identify key wildlife crossing areas and resolve existing wildlife/transportation conflicts. In certain instances, design for terrestrial wildlife movement along the stream margin may be requested in design. Where the movement of terrestrial species is of concern the project proponent may be asked to consult with VDFW's Wildlife Division.

3.2 Pre-Design Site Assessment

Site assessment is the gathering and interpretation of relevant information from the watershed, reach, and site. Information requirements and level of detail will vary from site to site depending on the scale of the project, site characteristics, project objectives, and design method used.

An inter-disciplinary approach is especially important for this part of the design process. 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 very important.

3.2.1 Pre-Design Assessment Data

Most of the site assessment parameters and procedures recommended here are defined in the Vermont Stream Geomorphic Assessment Protocols published by Vermont Department Agency of Natural Resources (VANR 2003, VANR 2005a, VANR 2005b) and available through the Agency's website.. The handbooks use methods and practices utilized by scientists and resource managers worldwide.

The procedures within these handbooks are not intended specifically for assessment or design of road-stream crossings so modifications to those procedures are expected in many situations. The key is to understand the utility of each parameter or procedure and apply the Vermont assessment protocols appropriately. They are particular to Vermont streams. They will guide the designer through an assessment and provide the essential pre-design data needed for a prudent crossing design.

It's best to have a design method in mind and do the assessment with the method in mind. Additional assessment parameters that might be necessary for stream simulation designs are described in Section 6.3.1, Stream Simulation Site Assessment Needs.

The following parameters should be observed or measured as part of the pre-design for any of the design procedures described in this guideline:

- Description and dimensions of existing structures; dimensions, conditions, history, etc.
  - Stream, road, culvert alignments. See VANR, 2003; Appendix G.
- Recent flood history and evidence at the site
- Characteristics of key features and channel grade controls
  - What key channel features (debris, live wood, colluvium, bedrock, steps) are present?
  - What effect do key features have on the channel?

        - Describe size, spacing, function (profile control, *roughness*, confinement, bank stability), bed drop, and permanence (mobility and condition).
        - See VANR, 2005b; Phase 2 Step 1. Pay attention to wood and permanence of grade control.
    - Bed material characteristics; amount, size, mobility
        - How mobile is the bed material? See Sections 3.2.2-Pre-design Assessment Interpretations, and 6.3.3, Streambed design.
        - See VANR, 2003; Phase 3, Steps 2 and 6.2. See also Section 3.2.2, Pre-design Assessment Interpretations.
    - Channel profile
        - Surveyed natural channel *thalweg*. See Section 3.2.3, Pre-design Assessment Products.
        - Describe channel slope, continuous or in segments
        - See VANR, 2003; Phase 3, Step 2.
    - Measured representative *bankfull channel* and/or *ordinary high water* width
        - See VANR, 2005b; Phase 2, Step 2.
        - Correlate bankfull and/or ordinary high water width with the Vermont regional hydraulic geometry curves developed by the River Management Program. See VANR, 2005a; Phase 1, Step 2.
        - Include cross-section surveys immediately above and below any existing structure.
    - Representative floodprone width
        - See VANR, 2005b; Phase 2, Step 2 and VANR, 2003 Phase 3, Step 2.
        - Estimated conveyance of floodprone area
    - Hydrology
        - Develop continuous flow gauging, peak flow gauging, basin correlations, hydrologic regressions. See VANR, 2005a; Phase 1, Step 1.
        - See *Basin Characteristics* feature of the USGS Vermont Streamstats interactive map http://water.usgs.gov/osw/streamstats/Vermont.html.

3.2.2 Pre-design Assessment Interpretations

- Hydrology
    - Qualitative hydrologic characteristics of basin
    - Expectations of future watershed conditions that might affect hydrology
    - High structural design flow
- Channel stability
    - Is the channel likely to aggrade or incise in the lifetime of the crossing? Consider likelihood of changes to hydrology, sediment input, bankline development, base level change, loss of major profile controls, etc.

  - General bed and bedform characteristics.
  - 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, *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.
  - Channel geomorphic stage and evolution.
  - Dominant profile and lateral controls. See VANR, 2005b; Phase 3.
  - Assessment of potential *headcut* impacts upstream of the culvert. See Section 3.4.5, Headcut issues.
- Bankfull channel and/or ordinary high water dimensions.
- *Vertical adjustment range*, the range of elevations the channel might experience through the reach in the lifetime of the new culvert. This is a key to setting the elevation of the culvert. See Section 3.4.1, Channel vertical adjustment range.

These interpretations are described in the following sections.

3.2.3 Pre-design Assessment Products

The following products should be developed in the pre-design assessment:

<u>Annotated plan view sketch</u>

The plan view sketch is a graphical interpretation of visual observations of the site showing the channel form, existing structures and their relationship to the channel, dominant channel hydraulic controls, and channel lateral movement characteristics. It is useful to initially describe the site before a topographic survey is completed during design.

Locations and orientations of photo points used, cross-sections, and survey reference points should be included.

The road alignment and characteristics, other infrastructures, potential construction access routes, project limitations such as rights-of-way and property lines should be shown.

Plan view sketches are generally described in the Vermont assessment protocols Phase 2, Step 1 though for the purpose of this guideline they are commonly done by field observation.

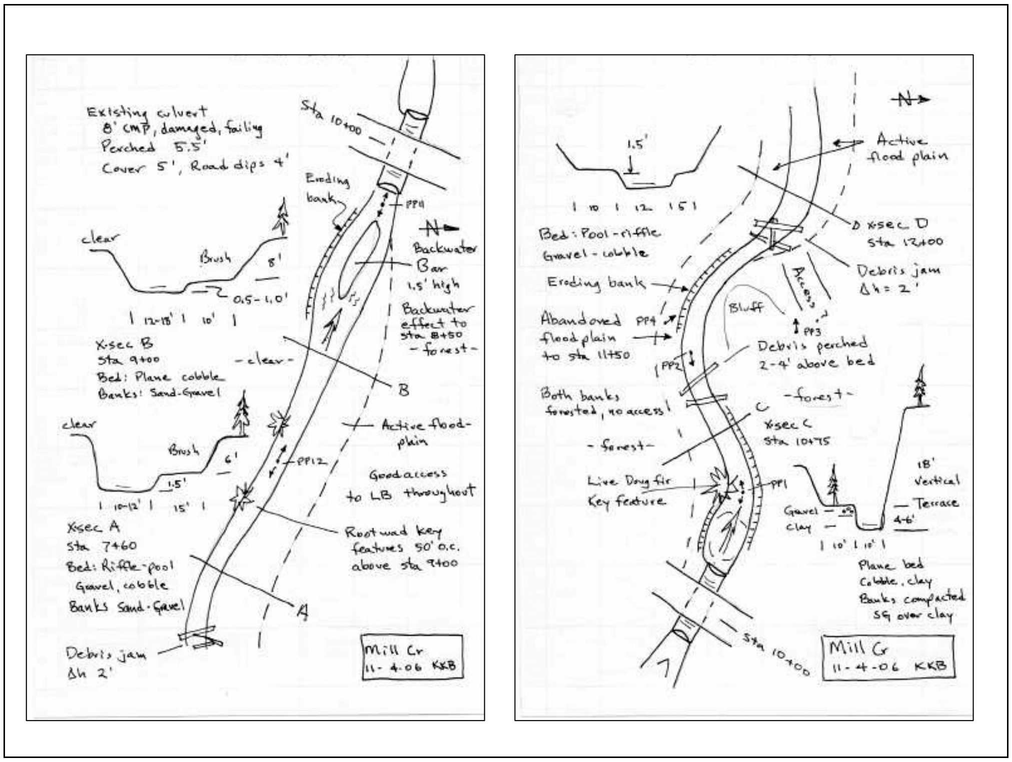

Figure 3-1. Example of a site assessment sketch.

<u>Annotated longitudinal channel profile</u>

The profile is a survey of the existing channel thalweg. Survey points are recorded at unique and repeatable geomorphic features such as heads of riffles and step crests.

The long profile should extend upstream and downstream further than the existing or new culvert might affect the channel. Survey length depends on the scale of the project, the vertical drop through the existing culvert, and the mobility of the streambed. A sand-bedded channel might be mobilized for thousands of feet upstream; a steep bouldery 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. USDA Forest Service (in press) has a thorough description of site assessment methods.

The profile should show dominant and temporary grade controls from beaver dams to bedrock, hydraulic control features, bed and gradient variability, and existing structures.

Identify the locations of surveyed cross-sections. It is also helpful to plot the bankfull elevations in the profile. Identify any features that you believe might affect the long profile or channel alignment in the next fifty years such as debris and sediment sources and current or likely bank erosion.

If you are doing a stream simulation design, consider what reach will likely be a reference reach and include it in the profile.

Channel profiles are generally described in the Vermont assessment protocols, Phase 3, Step 4. An example of a longitudinal profile is shown in Figure 3-2. Scale of the project is described in Section 3.4.2, Scale of the project.

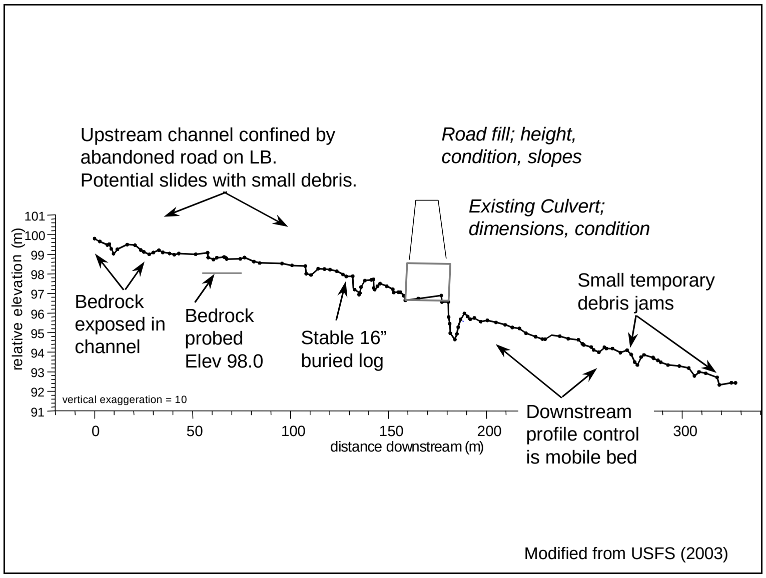

Figure 3-2. Example long profile sketch.

Channel cross-sections

Surveyed channel cross-sections are helpful for interpretation of the long profile. They, together with the profile and the site sketch, are a complete three-dimensional description of the site. Other than general interpretation, cross-sections can document the channel shape for any of the design methods. Specific cross-section measurements will be needed for the stream simulation option and are described in Section 6.3.2, Reference Reach.

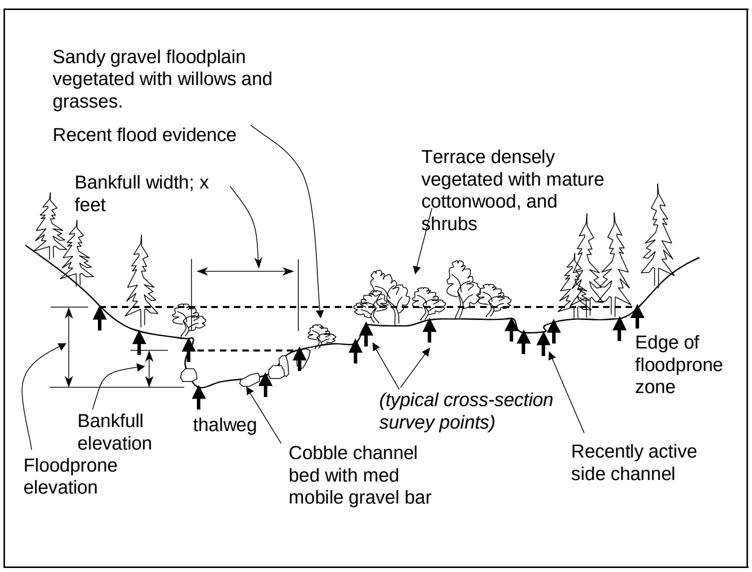

Figure 3-3. Example channel cross-section with annotations.

Pre-design Documentation

The plan view sketch and profile are the primary documentation of pre-design observations. Prepare documentation with the expectation that somebody other than you might design the project.

A good photographic record is very important for the design and to document pre-project conditions. Photo records are generally described in the Vermont assessment protocols. See VANR, 2003, Phase 2.

3.3 Project layout

The first step in the design is to establish the project layout in three dimensions:

- The generalized two-dimensional plan view with the new project connecting the upstream and downstream channels, and
- The streambed project profile, connecting vertically stable points upstream and downstream of the crossing.

Ideally, the project layout approximates the natural channel alignment and slope at the site. Since slope depends on crossing length and alignment, these must all be considered concurrently.

Consider the channel alignment, channel profile, and road alignment, how they affect each other, how they might vary for the life of the project, and any practical limitations to them. Consider the vertical adjustment range of the channel. What is the range of potential channel profiles that might be present at the site during the life of the project? The project should be designed to accommodate that range. A similar range can be applied to lateral channel movement.

The simplest situation is where the crossing is a new installation, the channel is stable, and the road alignment is perpendicular to the stream. In that case, the design alignment and profile are simply the existing channel. At more complex sites, the designer must consider trade-offs associated with the site layout. It may be useful to evaluate the pros and cons of several profiles and alignments to find the most reasonable combination.

3.3.1 Alignment

Culvert alignment is the orientation of the culvert structure relative to either the road or the stream channel. 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. Poor structure alignment with respect to the stream is a common source of passage and structural problems.

A skewed inlet (see Figure 3-4b) is hydraulically inefficient. It increases the risk of debris plugging and decreases the ultimate capacity of the culvert. It can cause upstream ponding and sediment deposition even if the inlet is not plugged. That deposition further exacerbates the poor alignment. A skewed inlet can also cause local scour of a stream simulation channel inside the culvert by forcing flow to one side. A skewed outlet can also cause bank erosion downstream by directing the flow at erodible banks. These risks are associated with high flows, so think of the flow patterns at those flows when considering alignment.

These risks increase with the skew angle and are minimized when the culvert is aligned with the upstream and downstream channels. However, aligning the crossing structure with the channel often results in a skewed alignment relative to the road (see Figure 3-4c), requiring a longer structure or headwalls.

Do not reduce culvert length by realigning the channel normal to the road without evaluating the trade-offs associated with the altered alignment relative to the channel stability and habitat loss.

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 risk.

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.

3.3.2 Culvert length

The longer the culvert the greater the risk that fish or other organisms will be blocked. The likelihood of any erroneous design assumptions or construction inadequacies are increased by the added length.

A longer culvert is more likely to cut off channel bends, reducing 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 two compounding risks: one associated with concentrating overbank flow through the crossing, and one with the longer culvert.

Always consider minimizing structure length to manage risk. In some locations, shifting the road location to avoid a bend can be a solution. Structures can also be shortened by:

- Adding wingwalls.
- Lowering the road elevation.
- Steepening and/or narrowing 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 will provide some width for overbank flows inside the culvert.

3.3.3 Skewed and bend alignments

A common culvert alignment problem is shown in Figure 3-4 where the road is aligned at an acute angle to the stream.

Three alignment options, each of which requires some level of design compromise, are:

a. Match the channel alignment;

b. Realign the stream to minimize culvert length;

c. Widen and/or shorten the culvert.

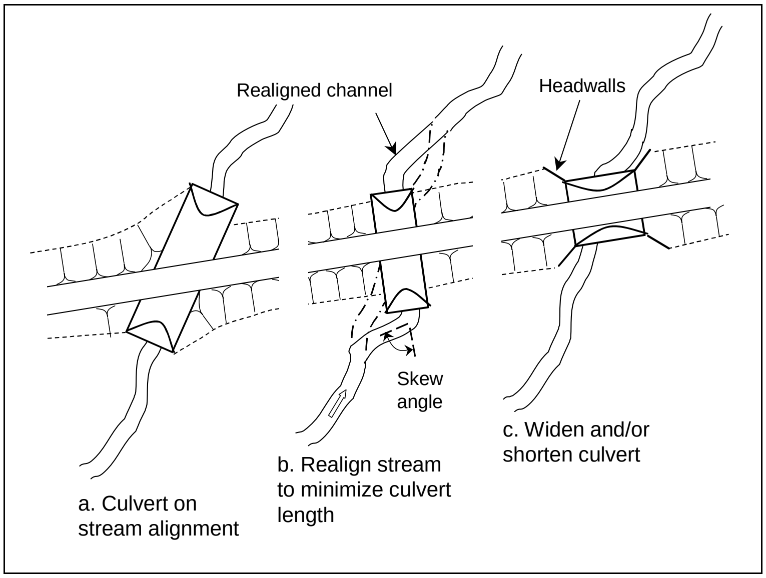

Figure 3-4. Alignment options for culvert on a skew.

None of these options necessarily stands alone; a project will often combine the three options.

Matching the channel alignment has the least risk of debris blockage and does not reduce 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.

Widening and/or shortening the culvert can reduce or eliminate the effects of skew as shown in Figure 3-4c. It has the greatest capacity and the least likelihood of debris blockage. It may require the longest construction period and might cost more than the other options if wingwalls are used to shorten the culvert. Precast concrete products can minimize those effects.

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.

Consider how far the channel is likely to migrate laterally during the life of the project (especially important for a crossing on a bend). Options to accommodate expected changes include

- Widen the culvert and offset it in the direction of meander movement
- Control meander shift at the inlet with appropriate bank stabilization measures or training structures.

If banklines are constructed within the culvert, the rocks used to construct the outside bank might need to be bigger to sustain the higher *shear stresses*. See Section 6.3.8.2, Bed stability analysis.

For long pipes with severe alignment issues, a curved pipe might be an alternative solution. A curved pipe is a series of culvert sections formed into a bend that preserves the inlet and outlet channel alignments, as well as channel length and slope. Curved pipes might be used, for example, in ravine channels where alignment cannot be changed, or where property boundaries limit alignment options. They require special culvert design, special product, and care in construction and may have cost and project duration implications.

3.3.4 Transitions

Special treatments might be necessary at the ends of a culvert where it transitions from stream channel to structure. Transitions can reduce failure risks, eliminate effects of previous culverts, and affect performance and capacity of the new structure. Risks of debris blockages is minimized at a good transition.

A common malady of existing culverts is called the “hourglass syndrome” characterized by a widened channel just upstream and downstream of the culvert. See Figure 3-5. An undersized culvert typically causes the hourglass syndrome. The over-widened channel just upstream from an undersized culvert can cause debris to rotate normal to the channel and plug a culvert.

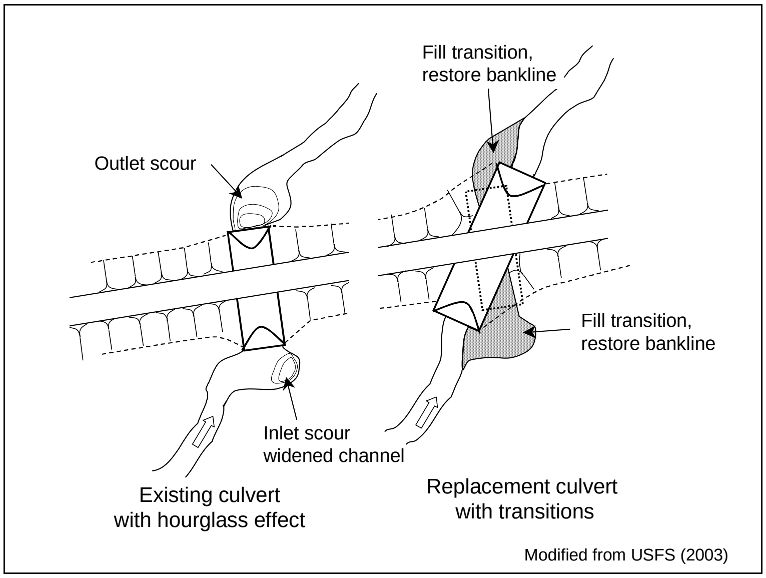

Figure 3-5. Transitions and "hourglass syndrome."

To minimize the probability of debris blockage and to maximize the capacity of the culvert, the culvert inlet dimensions should gradually transition into the upstream natural channel cross section. This is especially true for outer banks where the culvert is located on a channel bend. The ideal situation is for the culvert cross-section dimensions to equal the natural channel dimension. For stream simulation designs, the upstream and downstream banklines should 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

A scour hole below 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 there is a scour hole downstream of an existing culvert that is retrofitted for fish passage, consider leaving it in place as an energy dissipation feature to protect the channel downstream.

Efficient transitions mimic the natural channel. Transition modifications require work in the channel beyond the culvert but are often essential to success of the culvert.

3.4 Project profile design

The project profile represents the slope and elevation of the initial streambed through the project reach. It establishes the elevation of the crossing. It should seamlessly connect stable points in the upstream and downstream channel segments.

The floor of the culvert itself is below the elevation of the project profile. Its elevation may depend on the design method used and characteristics of the natural channel. The floor elevation is described in each of the three design methods.

For new culvert installations, assuming the road is aligned well to the stream, the existing stream profile is the project profile.

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

For now, in order to select a project profile, the designer should at least be aware of what profile control techniques are available, how they support project objectives, and what their limitations are. Artificial grade controls are described in Section 9, Profile Control.

Structures have a risk of becoming *perched* or plugged during their life that if they are not designed for vertical streambed adjustments that are likely during their life. The profile design starts by estimating the range of possible future bed profiles through the project reach and a design project profile and alignment are selected.

3.4.1 Channel vertical adjustment range

Natural channels vary over time. The elevation of the streambed at a road crossing may rise or lower over the life of the structure due to natural channel evolution, fluxes of sediment, debris accumulations, hydrologic changes, or other influences. The *vertical adjustment range (VAR)* is the range of elevations and slopes that the channel might experience in the life of the structure being designed. The designed structure should accommodate those changes.

The initial VAR is established with the assumption that no culvert or other artificial control is present. This would return the channel to a natural profile. If that VAR is not acceptable, a forced profile will be necessary to change the VAR.

A high adjustment profile is the estimated highest elevation the channel will be in the project reach; the crossing should accommodate flood flows and debris when the channel is in its high profile.

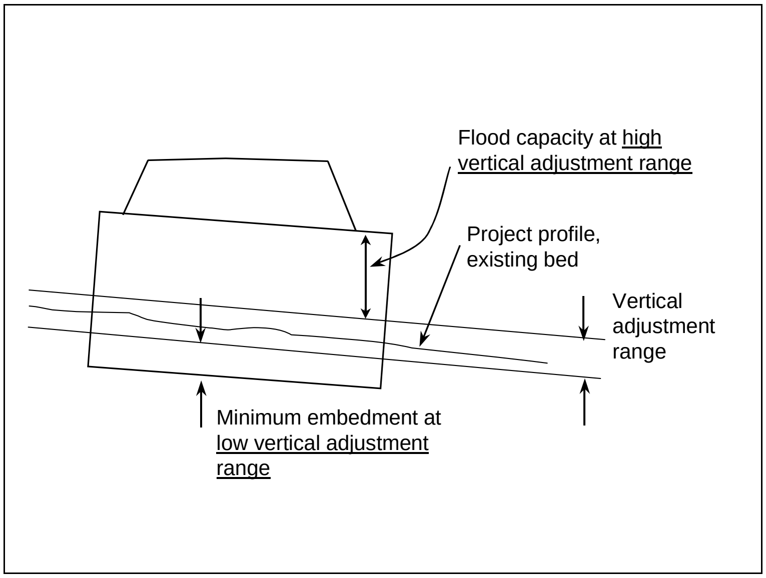

Figure 3-6. Flood capacity and embedment relative to vertical adjustment range.

The low adjustment profile is the lowest expected elevation of the channel. The elevation of the culvert floor will be below that profile and will depend on which design option is used. It should also accommodate large bed material (if stream simulation design) and the normal depth of scour in the channel (if stream simulation or low-slope design). See the appropriate design method to determine the final culvert floor elevation.

3.4.2 Scale of the project

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*. The scale of the problem should determine the scale of the solution. Scour due solely to an undersized culvert on 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. In the simplest cases, the restoration project may be nothing more than replacing the culvert with an appropriately sized culvert, filling the scour pool and allowing the accumulated sediment to naturally regrade.

If the downstream channel is incised, it is a problem of a larger scale and requires a more complex solution on that large scale. Grade control measures or channel restoration work some distance downstream and/or upstream of the culvert might be appropriate. Issues that should determine the scale of a solution for an incised channel include the extent of the *incision*, whether the incision is continuing, and the cause of the incision. An additional important considerations is whether the incision should be allowed to progress upstream as a *headcut* or whether it should be corrected by restoring the natural channel profile and elevation.

3.4.3 General procedure for profile design in a stable channel

A stable channel is one that is neither generally aggrading nor degrading over time - in this case, generally for the life of the crossing. It is important to estimate the permanency of grade controls upstream and downstream of the culvert and how much the elevation of the streambed might change in the culvert lifetime. At the very least, local streambed elevations can change due to local pool scour and fill, such as might occur during a flood.

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 watershed changes that could affect vertical bed stability and elevation. Consider possible profile changes and stability of grade 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 bedrock outcrops in the channel bed and floodplain elevations.

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 vertical adjustment range through the site. An example of a simple profile and vertical adjustment range is shown in Figure 3-7.

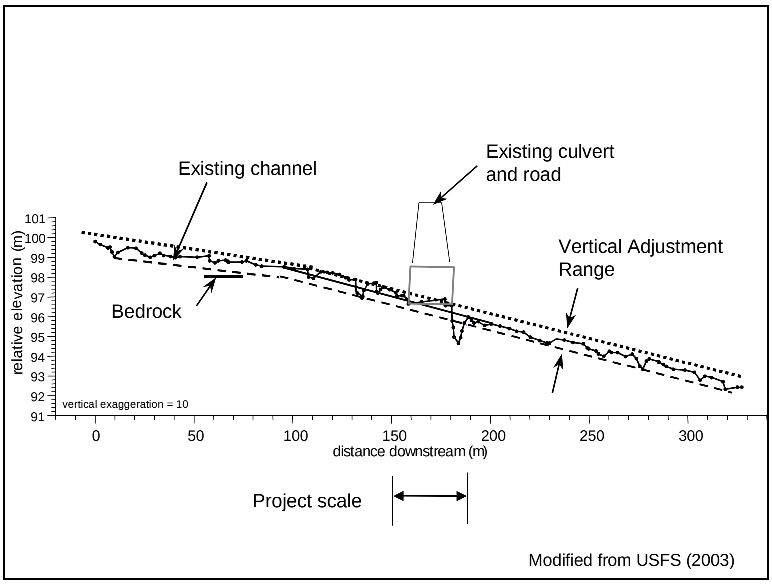

Figure 3-7. Project profile and vertical adjustment range.

The lower profile represents the lowest likely elevation of the streambed in the life of the structure and will lead to selection of the culvert floor elevation. The upper profile is the highest likely profile and will be used to ensure that the culvert is large enough to accommodate the high design flow when the streambed is at its highest likely elevation.

Estimating the vertical adjustment range requires professional judgment, observation, and interpretation of natural channel conditions and evolution.

Draw the project profile considering the vertical adjustment range. The project profile is the profile that will be constructed or will initially develop. The project design profile is ideally within that vertical adjustment range and connects grade control features in the existing channel. It should extend at least as far upstream and downstream as the new culvert installation might affect the channel.

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) as shown in Figure 3-7. If it is uncertain how far the bed might move vertically (for example, 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 risk of error. Document your assumptions with notes on the profile.

The extent of aggradation in the channel upstream of the existing culvert may affect the scale of the project. See 3.4.5 Headcut issues.

This section has covered simple installations in stable channels. Situations that are more complex are described in the next sections.

3.4.4 Incised or incising channels

Construction or replacement of a culvert in an incised or incising channel is more complex. In this case, the downstream channel has 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 it as shown in Figure 3-8.

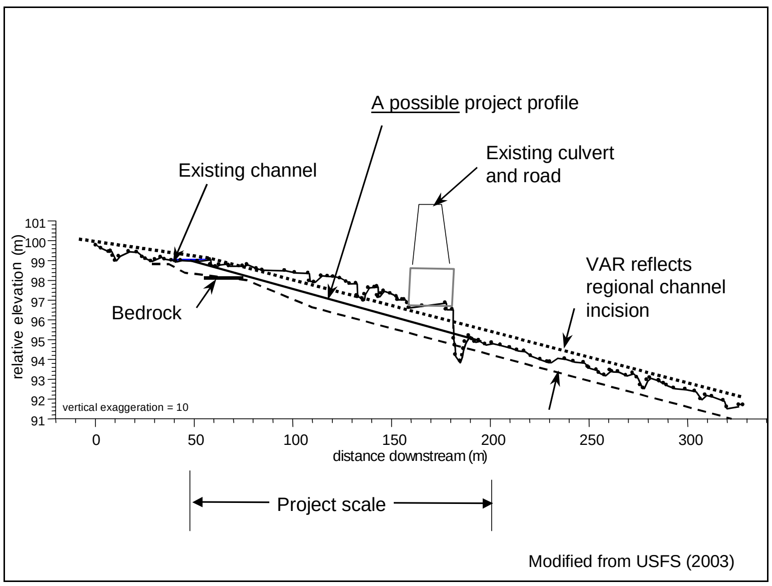

Figure 3-8. Vertical adjustment range with channel incised downstream.

Several project profiles should be compared in this case. Possible project profiles connect the upstream and downstream channels and the range of potential profiles is estimated based on final selected profile.

In addition to considerations of the stable channel described above, it is necessary to understand the causes of existing channel conditions, the sensitivity of the channel, and how it will evolve in the future.

A project profile to consider is the profile that would be at the site if no culvert had ever been installed. To get that profile, the upstream channel might be allowed to incise or new channel might be constructed at a lower elevation. Such a project profile is shown in Figure 3-8. There are significant risks that must be considered if a culvert is lowered and the incision is allowed to proceed upstream. Review Section 3.4.5, Headcut issues, describing issues associate with potential headcuts. On the other hand, such a design would allow the channel to return to a natural profile.

A headcut profile might not be acceptable. Other considerations, such as construction limitations, other infrastructures, or protection of habitat might limit the profile. In these cases, the project profile might have to be located above or below the natural vertical adjustment range. A forced profile with profile control structures is necessary; structure is needed to control the elevation and grade of the channel. A forced profile is shown in Figure 3-9. Options for a forced profile are:

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

A general description of profile controls is included in Section 9, Profile Control.

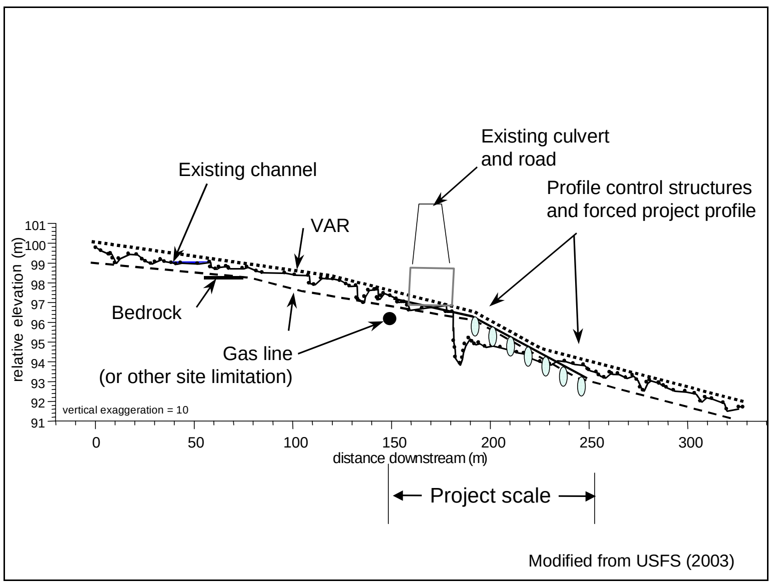

Figure 3-9. Project profile with forced profile.

No single solution satisfies all situations. Projects are often designed as a combination of two or more of these options.

The profile control strategy might be to permit a headcut to adjust the profile, but to control its extent with permanent grade 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.

If any of the last three options (steepened downstream channel, steepened culvert, or steepened upstream channel) are used, the project profile is first established and then a revised vertical adjustment range is estimated based on that project profile.

Channel rehabilitation should be considered as an option in any project associated with an incised channel. Channel rehabilitation is the restoration of planform, structure, and grade of the stream with the goal of achieving a stable and self-sustaining channel, rather than forcing the culvert into an artificially oversteepened profile. It is the most elegant and durable way to correct a large elevation drop caused by channel incision. Rehabilitation might mean building the channel bed back to its natural elevation and/or realigning the channel to restore the meander pattern and channel length.

If channel incision has been caused by a change in the hydrology of the watershed, perhaps due to land use changes, it may not be possible to restore the channel to historic predisturbance condition. Design the channel for the current and future hydrologic regime.

Channel rehabilitation can extend a considerable distance downstream, and may be the most expensive option. Its benefit is that it may have habitat restoration values that go far beyond passage of aquatic organisms; for example, such a project can restore in-stream, riparian and floodplain habitats and channel-floodplain interactions. Side-channels previously blocked by the existing culvert or roadfill can be reconnected. It can also reverse bank erosion, and is likely to be more self-sustaining than other options.

Channel rehabilitation may or may not be feasible for many reasons, and the decision to recommend it should be made by experienced team members. Details of channel design are beyond the scope of this guide. For more information on channel restoration, see Federal Interagency Stream Restoration Working Group (1998).

3.4.5 Headcut issues

Bates et al. (2003) identified eight issues to consider when determining whether to control a headcut or allow it to occur when a culvert is removed or lowered and/or enlarged. Castro (2003) described headcut issues to be recognized during the planning phase of a culvert replacement or removal project. These are primarily negative effects though they have to be weighed against other options such as steepening a channel to artificially maintain the elevation of a culvert that is a *nick point*.

<u>Extent of headcut</u> The upstream distance a headcut can travel depends on the channel slope, bed composition and mobility, sediment supply to the reach, and the presence of debris and/or colluvium in the channel.

The extent is usually less in armored or coarse-grained channels than in sand and fine-grain channels. 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 a thousand feet upstream or more in a sand-bedded stream.

A channel with a high sediment supply and a large amount of mobile bed material is generally affected less by a headcut and will reach an equilibrium more rapidly than a channel with a low rate of sediment supply.

<u>Condition of upstream channel and banks</u> If the upstream channel incises, 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.

<u>Habitat impacts of upstream channel incision</u> Allowing the headcut to travel upstream can have significant effects on aquatic and riparian habitats. As a channel incises it typically becomes narrow and confined; Habitat diversity and channel stability are reduced because the stream cannot access its floodplain during high flows.

Eventually, the channel may evolve back into its initial configuration, but substantial bank erosion and instability may persist for a long time. 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.

Wetlands have formed upstream of many undersized or perched culverts. Although they are artificial, they may create unique and valuable habitats and perform important functions in the riparian ecology. Their fate should be carefully considered when replacing culverts. Evaluation of tradeoffs of wetlands versus passage of aquatic organisms is beyond the scope of this document.

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. With a normal *bedload* regime, the material would transport out of the reach but in the case of a regrade, 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. Less immediate degradation should be allowed where the culvert and/or channel have even a short-term risk of loss of capacity. 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 degradation creating additional passage barriers upstream. Buried logs, nonerodible materials, and infrastructure such as buried pipelines are commonly exposed by channel headcuts. Additionally, upstream culverts could become perched. As the channel headcuts to these features, they become the new nick point 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.

3.4.6 Aggraded or aggrading channels

Construction or replacement of a culvert in an aggraded or aggrading channel may also be complex. In this case, the channel has been raised by accumulation of sediment through the reach.

In addition to considerations of the stable channel described above, it is critical to understand the causes of existing channel conditions, the sensitivity of the channel, and how it will be affected by future hydrologic changes and sediment inputs.

If the aggradation is just a local deposition upstream of an undersized culvert, it shouldn't be considered as part of the project profile. See the previous section regarding headcut issues.

4. DESIGN FOR PASSAGE OF FISH AND OTHER AQUATIC ORGANISMS

In most cases, the preferred stream crossing design to accommodate AOP is an open bottom bridge or arch. These structures generally provide the least risk of becoming a barrier over their lifetime as vertical bed adjustment is allowed to occur within the structure. However, it is recognized that costs and other constraints often make a closed structure (e.g. box, pipe, pipe arch, etc.) the preferred alternative. There are three primary culvert design options commonly used and described in this document: the low-slope, hydraulic, and stream simulation options. The basic concepts and definitions are the same here as generally accepted elsewhere in many parts of North America and the world though some of the specific criteria are modified to apply to ecosystems and aquatic organisms in Vermont. Other design methods might be developed in the future and are appropriate if they meet the same objectives.

The stream simulation and low-slope methods are preferred since they provide passage for a wider range of organisms and channel processes.

Passage for fish and other aquatic organisms is designed within the profile that was defined in Section 3.4, Project profile design. The designer may find that a reasonable project cannot be designed using one or any of these methods and within the desired profile. In that case, a new profile may have to be selected or perhaps a culvert is not suitable for the site.

Which design method is applied depends primarily on objectives of the project and ecological concerns. Briefly, these are situations where each option can be applied.

- Low-slope option
    - New culvert installation
    - Low risk sites (low gradient channel and short culvert)
    - Where passage of weak aquatic species is required
- Stream simulation option
    - New culvert installation
    - Any channel slope
- Hydraulic option
    - Retrofit of existing culvert
    - Where other options cannot physically be applied (e.g. a steep stream simulation channel is usually not feasible below a pond or road-impounded wetland that must be protected.)
    - Low to moderate channel slopes
    - Where target species biological criteria (e.g. swim speed) information is available.

The following sections describe each of the options in more detail. Background, limitations, appropriate applications, and criteria are described.

This guide is neither a cookbook nor a manual. Each site is unique, and conditions will lead to individual solutions. The methods and analyses described here are more rigorous than is necessary for simple sites and experienced design teams may 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. To avoid expensive mistakes, it is important to recognize where this higher degree of rigor is needed and to bring in specialists when appropriate.

This is an evolving science. Other new and alternative designs may be considered if they apply the design concepts and considerations provided in these methods and meet the overall project objectives.

5. Vermont Low-Slope Design

5.1 Definition of Low-slope Design

The low-slope design is a simplified design for use at low risk sites. It is intended to simplify design and permitting for private landowners with short crossings under residential driveways, farm roads and similar sites, so that channel slope and/or culvert length are limited. The low-slope option requires few technical calculations for design of the culvert itself and results in a conservative but reasonable culvert size.

> **Premise of low-slope:**
>
> *The design of an oversized culvert in a low risk site can be simplified and built with little risk.*

The low-slope option is defined by these criteria:

- The low-slope method shall only be applied in low risk situations of stable but mobile bed, low slope, and short culvert length. Culvert length is limited to 50 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 *rise* of the culvert (diameter of a round culvert; equivalent for other shapes) for the expected bed elevations over the life of the project. The elevation of the minimum scour cover over the footings is used in place of the culvert invert for bottomless structures.
- The width of the culvert at the elevation where it meets the streambed 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 does not constrict the active floodplain excessively.

Figure 5-1 shows the same definition of the Vermont low-slope design option.

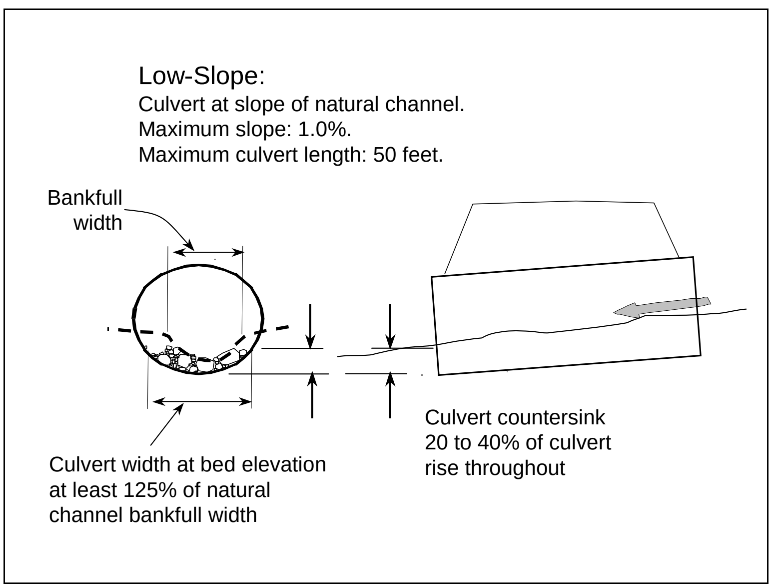

Figure 5-1. Definition of Vermont low-slope option.

5.2 Low-slope Application

This option is appropriate only for low risk situations with a stable but mobile bed, low slope, and short culvert length.

Since the culvert is embedded within a 20% range of the culvert rise, the culvert height must be enlarged to accommodate uncertainties of an unstable channel. An unstable channel might be one that will experience aggradation or incision such as when the downstream channel has incised.

Since 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 Section 3.4, Project profile design.

> *A careful assessment of the potential channel elevation for the life of the project is essential to the low-slope design.*

It is anticipated that since the culvert bed is at least as large as the natural channel bed and the bed is mobile, material will deposit in the culvert. The natural bed will allow a broad range of fish species and sizes to move through the culvert. This might occur or might not be persistent in several situations. For example, a floodplain constriction can cause a culvert bed to be unstable. The naturally recruited streambed may also be inadequate to meet the objectives of the project. For example, a streambed may be desired immediately or channel margins may be important for migration of aquatic organisms. The design might be modified to mitigate these issues or the designer may have to consider other culvert or road crossing design options.

The low-slope design option might be applied in new and replacement culverts. Since the bed profile assessment is complicated for an existing pipe that is perched, this option is best applied to replacements of pipes that are not perched or new installations. An existing culvert cannot be retrofit to comply with the low-slope design.

Consider bed mobility. Will the culvert fill and be persistent? Consider the channel profile and the impact of headcut discussed in pre-design. See the discussion on bed mobility, Section 3.2.2, Pre-design Assessment Interpretations.

The primary advantage of the low-slope option to the culvert owner is the avoidance of additional surveying and engineering costs required for other options. No special fish passage design expertise or survey information required.

5.3 Low-slope Design Process

The low-slope design follows the pre-design described in Section 3, Culvert Pre-Design. 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 the 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.

5.3.1 Low-slope culvert size and elevation

The width of the culvert at the elevation it meets the streambed 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 low potential profile.

Bed material placed or naturally deposited 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 placed through the fill in the floodplain. The additional culverts in this case are not intended for normal flow conditions. They are place in the floodplain and become active only during overbank flows.

Finally, the flood capacity of the culvert must be verified as it is for any culvert design.

The design should also meet or exceed other applicable local, state, or federal standards for hydraulic capacity, headwater depth, and other design parameters.

5.3.2 Low-slope culvert bed

If the low-slope culvert is 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.

When a bed of mobile material is recruited or placed in a culvert, the bed initially tends to flatten unnaturally. Then, because of the smooth culvert walls, the flow often scours a trench along one or both walls. These effects can be prevented with disrupters, banklines or other structures that disrupt the flow along the culvert walls. They are equivalent to natural variations in stream banklines.

Disrupters are single or groups of rock near the edges of the channel that create the bank diversity similar to natural banklines. Banklines in a low-slope design would be similar to the banklines described for stream simulation in Section 6.3.3.3, Banklines and margins.

If a bed is placed in the culvert, the disrupters can be clusters of rock larger than the largest particle in the natural channel. If a bed is allowed to form naturally disrupters should be large or 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.

6. **Stream Simulation Design**

6.1 Definition of Stream Simulation Design Option

Stream simulation is a geomorphic approach to designing for passage of fish and other aquatic organisms. It is a continuation of the natural channel dimensions, slope, bed and banks through the crossing to connect the channels above and below the crossing. The stream simulation creates the diverse water depths and velocities, hiding and resting areas, and moist edge habitats that different species need to move. The simulated channel inside the crossing should present no more of an obstacle to movement than the adjacent natural channel.

The goal is to set the stage so that the simulated channel evolves and adjusts to accommodate a range of flood discharges and sediment/debris inputs. For the simulated streambed to maintain itself through a wide range of flows, stream processes that control sediment and debris transport and maintain hydraulic diversity have to function as they do in the natural channel. This means that flows that transport sediment and debris and rework the channel should not be constrained or accelerated inside the crossing structure.

Premise of stream simulation:

A channel that simulates characteristics of the adjacent 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 channel near the crossing. Stream simulation design starts with a channel inside the structure at least as wide as bankfull width and with a slope close to that of the reference reach. Bankfull flow is widely recognized as an index for the full range of channel-forming flows in alluvial rivers. Slope is recognized as a primary controlling factor of channel and bedform shapes.

It is not always clear where the boundaries of “stream simulation” should be drawn. How far can we deviate from truly natural conditions and still depend on the premise stated above? Since we are unable to verify free mobility for all aquatic organisms at a site, success is likely to remain somewhat subjective. Stream simulation has some variability just as does the channel that is being simulated. The design requires professional judgment and expertise in a variety of professional fields.

Real stream channels are very diverse and complex, and there is randomness in their response to runoff events and inputs from land management. It is an art to “read” a stream in order to simulate it. There are no definitive quantitative methods that can ensure a simulated streambed will be sustainable through the full range of flows. Knowledge is continually expanding as more structures are built and tested by floods. This guide represents the best set of methods we have at this time, but its limitations should be recognized.

6.2 Stream Simulation Application

Stream simulation applies to new and replacement culverts. It does not apply to retrofits.

Simulations are not exact replications of real stream channels. Features like channel-spanning or embedded wood, bankline vegetation, cohesive soils, and floodplain functions cannot be recreated inside crossing structures. These features usually stabilize the bed and some provide roughness that slows flow and helps create depth and velocity variations needed for aquatic species passage. Likewise, we cannot reproduce the roughness and diversity contributed by channel bends or the complexity of large features like debris jams. 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 might simulate banklines in the reference reach. The grade-stabilizing functions of embedded debris can also be simulated using rock.

Stream simulation may not work in some situations. Stream simulation or any other design may not work in a channel that is rapidly changing such as after a major flood, where there is no stable reference reach. Other examples are inherently unstable landforms subject to frequent disturbances, such as alluvial fans, and debris torrent-prone channels.

These are not only poor choices for reference reaches; they may be poor sites for any road crossing. Where feasible, the most prudent solution may be to relocate the crossing and/or the road. Where this is impossible, the design team must predict potential channel adjustments for the life of the structure and design for them.

The same applies to channels that are actively migrating across floodplains. These streams present challenges to stream simulation not only because the channel may shift rapidly across the floodplain, but also because the structure cannot accommodate the highest flows that naturally spread across the entire floodplain. Concentrating floodplain flows through the structure can exert pressure on the simulated streambed that a reference reach connected to the floodplain never sees. Design solutions for wide floodplains are discussed in detail in Section 6.3.8, Bed mobility and stability analysis.

There are also occasions where the channel at the crossing is not connected to an upstream alluvial channel that can supply the size and volume of sediment needed by 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 culvert reach and downstream reaches are not directly connected to an upstream reach that would normally replenish bedload to the stream simulation reach.

Although this guideline focuses primarily on the design of culverts, the stream simulation design process can be readily applied for the design of channels to replace culverts that are removed.

6.3 Stream Simulation Design Process

As mentioned previously this guide is neither a cookbook nor a manual. Each site is unique and will have a unique solution. The methods and analyses described here are more rigorous than is 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. To avoid expensive mistakes, it is crucial to recognize where this higher degree of rigor is needed and to bring in other specialists when necessary.

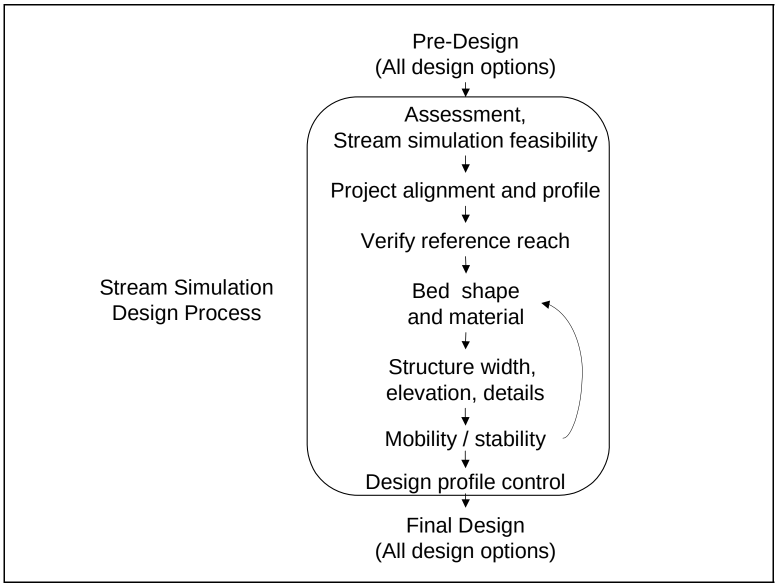

Figure 6-1. Stream simulation design process

There may be other and better methods of analysis and stream simulation design at specific sites. Those methods might be acceptable as long as the premise of stream simulation can be satisfied at least as well as it can by the methods described here.

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 USDA Forest Service (in press). The USDA Forest Service document also includes a thorough discussion of site assessment in preparation for a stream simulation design.

6.3.1 Stream Simulation Site Assessment Needs

An initial site assessment was described in pre-design, Section 3.2, Pre-Design Site Assessment and a project profile was selected. Additional site assessment data are needed for the stream simulation method. Many assessment protocols for these data are described by VANR, 2003 and are cited here. Other data and products listed here are described further in following sections.

- Reference reach characteristics
    - Floodprone width (VANR, 2005b; Phase 2, Step 2)
    - Characteristics of floodprone width (roughness, flood swales, etc.) to determine general floodplain conveyance (VANR, 2003; Phase 3, Step 2)
    - Characterize bed forms, structure (VANR, 2005b; Phase 2, Step 2)
    - Characterize depth of normal alluvial scour
    - Characterize colluvium, debris, banklines (VANR, 2005b; Phase 2, Step 2)
    - Pebble count and visually characterize subsurface material or bulk bed material sample (VANR, 2005b; Phase 2, Step 2)
- Products
    - Plan view sketch (if reference reach not included in pre-design data) (VANR, 2005b; Phase 2, Step 1)

  - Profile survey (if reference reach not within pre-design profile)
  - Cross-section surveys including bankfull channel and floodprone area (if not in pre-design data) (VANR, 2003; Phase 3, Step 2)
    - Location of reference reach, channel plan form, channel classification of segments, locations of cross-sections
  - Bed material size distribution
    - Pebble count should be stratified to separate key features including steps from more mobile bed material
  - Size and distribution of key features
  - Identify and measure alluvial pools on long profile
  - Documentation of design
- Interpretations
  - Feasibility of stream simulation
  - Selection and verification of reference reach
  - Reference reach interpretations
    - General floodprone area conveyance (may have to be quantified in design)
    - Bankfull and/or ordinary high water width correlated with prediction of bankfull channel width calculated from the Vermont regional hydraulic geometry curve. The River Management Program (VANR, 2005a; Phase 1, Step 2) has developed hydraulic geometry curves for bankfull discharge, and channel cross sectional area, width, and depth. If there is a large discrepancy between the measured and predicted bankfull widths, it should be a warning to understand what causes the difference. Additional geomorphic expertise might be needed for the design.
    - Bed mobility
    - Scour depth

6.3.2 Reference Reach

The reference reach is a template for the design of the stream simulation channel. To satisfy the premise of stream simulation the new structure must satisfy 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 similar 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 and arrangement.

Where no suitable reference reach can be found, it might be necessary to use another design method, such as the hydraulic method, use a bridge or possibly relocate the crossing.

An initial reference reach might be selected during the site assessment so it is included in the profile survey. The reference reach is confirmed after the project profile is designed so the desired project and reference reach slopes are known. A preliminary selection of the reference reach is made during the site assessment simply to minimize surveying effort. Later in the design, the chosen profile and reference reach may prove to be not appropriate and a new profile and reference reach should then be selected.

The reference reach should ideally have the following characteristics:

- Stable, meaning that is neither aggrading or degrading. Always consider how the project reach is likely to change over the structure lifetime 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's just upstream, it represents 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 road-stream crossing.
- 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. Ideally, the crossing would be built over the stream without disturbing it. However, if the natural channel is unconfined, consider the effects of confinement by the culvert on the hydraulics and bed of the stream simulation channel.

A structure length nearly equivalent to the length of a straight reference reach is likely safe. Risk can be reduced by shortening or widening the culvert or by locating the crossing to avoid channel bends. Alternative structures, such as bridges, should be considered when the culvert greatly exceeds the length of the reference reach.

Where the site has a concave or convex profile shape, reference reaches representative of both upstream and downstream reaches should be measured, because it may be necessary to construct a transition inside the pipe to connect the two sections.

If the selected project profile includes regrading a long reach to accommodate the new structure, the reference reach survey should be done not only for the simulated streambed inside the crossing structure, but also for a channel restoration project.

It may be impossible to identify a reference reach on very unstable channels where the system is in a state of change. This would be an undesirable site for any road crossings. If there is no other alternative, a reach-scale restoration effort might be necessary. A stable stream in a basin with similar characteristics might be used as a reference, but it would remain uncertain whether it could be transferred to the changing, unstable channel. Expect long-term maintenance.

For streams undergoing system-wide channel incision, if the headcut will be allowed to progress through the crossing site, use downstream reaches that have already stabilized as the reference reach.

The incised channel is one of several situations where the crossing may have a steeper grade than the adjacent reaches. Project objectives (e.g., preserve wetland habitat above crossing) or constraints (e.g., right of way, property boundaries) may dictate the steeper grade. In these cases, it may or may not be possible to achieve stream simulation, depending on whether reference reaches at the necessary grade exist. Generally, steeper reaches can be found, although they may be distant from the project site. The further away from the site, the more risk exists that the proposed reference reach's characteristics are not directly transferable. Until better information is available about how much of a difference is sustainable, a reasonable rule of thumb is to keep the simulated channel within 25% of the slope of the reference reach.

Look at the longitudinal profile and consider the variability of reach slopes. There may be short punctuated steps that are steeper than the average gradient that could serve as a reference reach. If necessary, investigate beyond the surveyed profile.

How much steeper can we go? The slopes of the stream simulation and the reference channel should not differ greatly. At some increase, the bed material must be so much larger than in the upstream reach that the upstream reach cannot replenish bed material eroded from the simulated streambed. This means 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.

Bates et al (2003) suggest a slope increase of no more than 25 percent of the natural or reference reach. The suggestion is a conservative rule of thumb; 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. A mobility/stability analysis should be conducted for any change in slope greater than the reference reach, even if it is within the 25 percent change guideline (see 6.3.8, Bed mobility and stability analysis).

6.3.3 Streambed design

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

- Channel type
- Channel width
- Streambed material
- Bedforms and cross-section shape
- Channel banklines, bank irregularities, margins, and key features
- Bed mobility.

Bed design objectives

- Bed shape
- Diversity
- Roughness
- Mobility
- Forcing features
- Control permeability

We cannot design and construct all of these characteristics. We will construct the framework and enough of the structure and materials so these characteristics will be developed and maintained by the hydraulic action of the culvert, channel, and input.

Characteristics like vegetation and channel bends also have important effects on the structure and hydraulics of the reference channel and should be considered in the design.

First, the basic procedure for designing a simulated bed is described, including banklines and key features. This "basic" procedure applies to pool-riffle and plane-bed channels with bed material of medium gravel or coarser. Special considerations for other channel types are described in the sections that follow.

As a framework, we use the channel classification system developed by Montgomery and Buffington (1997) because it focuses on the bedforms that control these functions and characteristic. Table 6-1, adopted from USDA – Forest Service (in press), summarizes important channel characteristics and recommendations for each channel type and ways to simulate them. Channels in cohesive soil are added to the Montgomery and Buffington channel types as a special design case.

Table 6-1. Channel types and stream simulation design strategies

Channel type	Bed material	Bed mobility *	Recommended design strategies
Dune ripple	Sand to medium gravel	Mobile at most flows. Termed "live bed"	Simulated bed can be native or imported material mix based only on D_{100} of reference reach.
Pool riffle	Gravel; may be armored	Usually mobile near bankfull. Armoring implies lower mobility	Simulated bed D_{100}, D_{84}, and D_{50} and D_{max} same as reference reach. Material smaller than D_{50} is dense mix based on D_{50}.
Plane bed	Gravel to cobble, usually armored	Mobile near bankfull.	Simulated bed D_{100}, D_{84}, D_{50} and D_{max} same as reference reach. Smaller material size distribution is dense mix based on D_{50}.
Step pool	Cobble to boulder	Step-forming rocks move at higher flows depending on size; often >Q_{30} Fine material moves over larger grains at frequent flows.	Steps are spaced same as reference reach Step-forming rocks are sized to be immobile. Smaller material size distribution is dense mix based on D_{50} of material other than steps in reference reach
Cascade	Boulder	Channel-forming rocks mobile at high flows; possibly greater than ~Q_{50} Smaller bed material moves at moderate floods (higher than bankfull).	Simulated bed D_{100}, D_{84}, D_{50} and D_{max} same as reference reach. Smaller material size distribution is dense mix based on D_{50}.
Bedrock	Rock with sediment of various sizes in transport over rock surface	Bedrock immobile. Bedload moves over bedrock at various flows depending on its size. May be thin layer of alluvium over bedrock. Wood can strongly affect sediment mobility.	Stream simulation bed is bedrock. Banklines and roughness elements are important but difficult to design as stable. Condition, extent, and shape of bedrock are important. Bottomless structure reduces rock removal compared to full pipe and can be anchored and shaped to rock.

Channel type	Bed material	Bed mobility *	Recommended design strategies
Channel in cohesive soil	Silt to clay	Immobile. Fine sediment moves over immobile bed at moderate flows. May be thin layer of alluvium over immobile bed	Stable cohesive bed and banks cannot be constructed in culvert. Culvert walls may simulate smooth natural clay banks. Bottomless structure might leave clay bed undisturbed.
Forced channels	Large rocks or debris forces channel	Forcing features are immobile	Key features are designed to be immobile. Function of key debris is simulated with rock.

Notes:
Banklines should be included in all stream simulation designs.

Banklines and other key features in all channel types are designed to be immobile.

For definition of nomenclature of D_{100}, D_{84}, and D_{50}, see the glossary under "Dxxx".

The design strategies listed in Table 6-1 are the basis for design. The information in the table can be an initial guide to important design and construction elements. For example, bed material is not sorted during construction and bedforms are not constructed in pool-riffle channels.

These channel types are not necessarily clearly separable; instead, they are a continuum. Characteristics and recommendations should be used as general guidance to help define a specific design strategy for each project.

The following sections describe the design of a stream simulation bed. The description is written with the assumption that the bed will be constructed. Alternatively, the bed might be allowed to fill naturally. Three issues might determine whether a bed should be constructed rather than allowed to fill naturally.

- Is the risk of headcutting acceptable? See Section 3.4.5, Headcut issues.
- What is the time expected for natural filling?
- Are key features such as steps, banklines, or other key features necessary?

A key feature described in Table 6-1 is bed mobility. Mobility here is the relative flow at which bed material is entrained. It is defined as a frequency relative to the life of the crossing project. For example key pieces in a step-pool channel that are mobile only at flows that occur once in 30 years are considered immobile. The material in the steps is expected to move so infrequently during the life of the project that it should be considered permanent. It can therefore be designed as being immobile. On the other hand, the bed of a dune-ripple bed may be constantly mobile. It may therefore just fill in naturally since it is in constant supply and the risk of it not being initially installed is low.

Is the upstream bed mobile enough to fill the culvert within an acceptable length of time? There are examples of culverts that have not filled and sealed even for a decade after construction. On the other hand, mobile beds will supply material quickly but the headcut risk might be greater.

Banklines, steps, and key features in all channel types are designed as permanent features. Some beds are made of composite materials. They may consist of small mobile material mixed with larger immobile rocks or debris. In those cases, each of the materials is designed separately with its appropriate mobility. Key features should be embedded into a base of other bed material for stability.

6.3.3.1 Stream simulation bed material

The design of a simple bed is described in this section. This will apply to most pool-riffle and plane bed channels. Following sections deal with special issues associated with other channel types and more complex issues such as channel steepening and floodplain constrictions.

Sorting of the bed material and formation of bedforms are controlled by hydraulics during high flow events and the bed material composition. Bed material in pool-riffle and plane bed channels is generally in the gravel-cobble range. For design purposes, this category consists of pool-riffle beds with D_{100} of medium gravel (> 16mm) or larger. The basic design process applies to these channels. [Note: The 16mm cutoff point is only a matter of practicality related to specifying a bed mix of graded fine material.]

The bed material is a well-graded mix that approximates the reference reach particle-size distribution. It must include enough fines to seal the bed. Most commonly, the simulation bed mix is specified based on the pebble count from the reference reach. Bunte et al (2001) describe pebble count methods. A sieved bulk sample can also be used if desired.

For the pebble count technique, the D_{95}, D_{84}, and D_{50} of the reference reach bed are used directly as the corresponding grain sizes of the bed mix. In using the surface pebble count to design the simulation bed material, we are directly simulating the surface of the reference channel bed. This means that, if the bed is armored, the large particle sizes will be over represented in the rest of the mix. 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.

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.

The smaller grain sizes in the subarmor are very important as they affect bed permeability and stability. A porous bed can allow substantial flow to move through it; the entire streamflow may go subsurface. The simulation bed mix must have enough fine materials 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 streamflow 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.

Since pebble counts on the armor layer show very low content of fines (< 2mm) compared to the subarmor, the smaller grain sizes for the simulated mix are calculated from the reference channel D_{50} using a standard relationship. One method of sizing the smaller material is to use the equation developed by Fuller and Thompson (1907), which defines dense sediment mixtures commonly used by the aggregate industry.

The Fuller-Thompson equation is:

$$P = \left(\frac{d}{D_{100}} \right)^n$$

Equation 6-1

Where d *is any particle size of interest,* P *is the percentage of the mixture smaller than* d, D_{100} *is the largest size material in the mix, and* n *is a parameter that determines how fine or coarse the resulting mix will be. An* n *value of 0.5 produces a maximum density mix when particles are round.*

The Fuller-Thompson equation can be rearranged to find any particle size relative to D_{50}. The equations for D_{16} and D_5 are:

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

Equation 6-2

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

Equation 6-3

To develop the design particle-size distribution curve, we suggest using n values between 0.45 and 0.70, a standard range for high-density mixes. Select an n value that results in 5–10 percent sand and finer materials, which are needed to reduce permeability and to help lock the larger pieces together. If the D_5 resulting from the Fuller-Thompson equation is larger than 2mm (for n = 0.45, this occurs when D_{50} is larger than 330mm or 13 inches), adjust the mixture such that fines comprise 5 percent. If you have a good field estimate of reference reach subarmor fines that is much higher than 5-10%, you may want to adjust the mixture to approximate the field value.

The entire bed material mixture is defined by the gradation curve as shown in Figure 6-2. The lower half of the design mix particle size distribution curve can be anywhere between the two Fuller-Thompson distributions with *n* values of 0.45 and 0.70. In this case, selecting an n value of 0.45 produces a mix with approximately 10% finer than 2mm, which is close to the actual fines content in the subsurface.

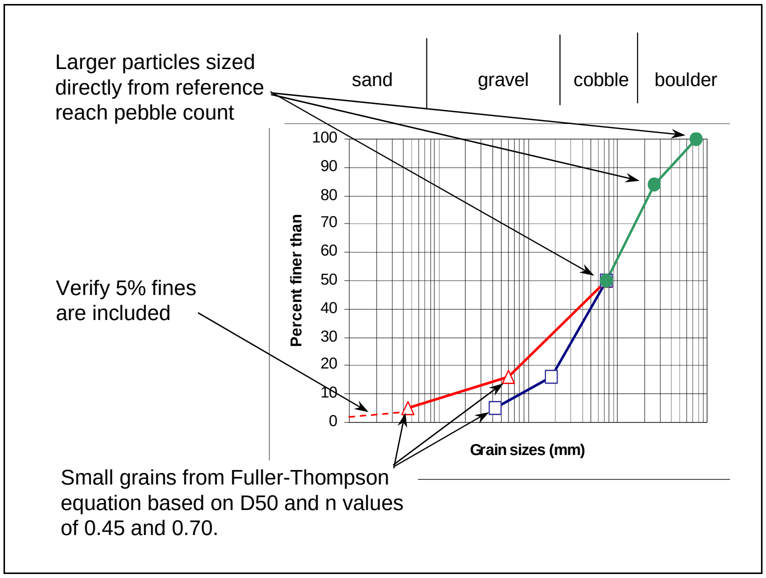

Figure 6-2. Stream simulation bed gradation.

This procedure develops an acceptable distribution curve of particle sizes. Later, you may modify the distribution to deal with various risk factors; for example, you might increase the sizes somewhat if the simulation needs to be slightly steeper than the reference reach (see Section 6.3.8, Bed mobility and stability analysis). The gradation will then have to be converted into a contract specification. It is important that the bed mix be as well graded as the reference reach. There should not be a gap in sizes between any classes of material in the mix; a dense, stable bed requires all sizes. Ideally, each class of bed material that makes up the mix is well graded, so all sizes within the category are represented. This is especially important for the smaller size fractions in a mixture of large material.

It is probably not critical to spend a large effort to replicate the particle size distribution exactly. It is, however, *very* important to

- Replicate the large bed material that provides bed structure and buttresses the finer material and
- Provide enough fines to limit bed permeability and to bind the bed together.

Including fines in the bed mix commonly arouses justifiable concerns about water quality and habitat impacts immediately after construction. Without special care, fine sediment in a freshly constructed bed will wash downstream in low or moderate streamflows that would not normally move the material. This can be mitigated by jetting the fine material down into the bed with high pressure jets and/or placing a veneer of washed gravel over the surface.

Bed material rock must be durable and it should be at least as angular as in the reference channel. If it is less angular it may be significantly more mobile than intended. It makes sense to try to find the bed material locally, because it will more likely resemble the natural bed material.

6.3.3.2 Channel cross-section

The width of the stream simulation channel is the bankfull width of the reference reach. It might be greater if the culvert constricts the floodplain flow. This width is not necessarily the *culvert* width; The shape and dimensions of the culvert structure itself are described in Section 10.1 Culvert shape, style, and material.

The channel bankfull width is the distance between channel bankfull elevations, which is the elevation at which flow first floods over the bank into the floodplain. Depending on the environment and channel type, this point may or may not be obvious. Guidance for identifying bankfull elevation is provided by Harrelson et al (1993), USDA Forest Service (2005), and VANR (2003). If there is no discernable bankfull elevation, the *ordinary high water mark* can be substituted for it.

In simple situations, bedform shapes (riffles and pools) are not constructed, but some temporary bed features are needed to set the stage for channel margins to develop. In the simplest case, a V-shaped low-flow channel with a width of about ten feet is 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. Channels that are more complex are described in following sections.

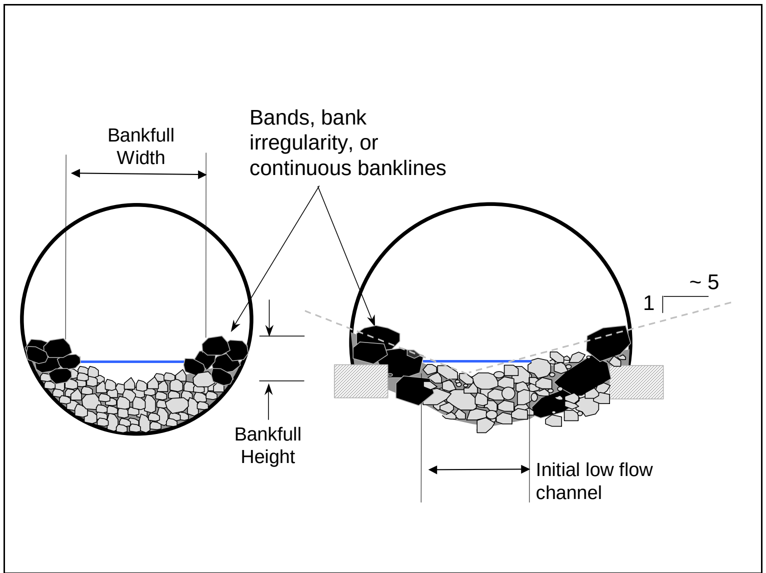

Figure 6-3. Stream simulation cross-section.

Even riffle-pool channels are generally more complex than this. Based on the complexity of the reference reach any of several structures might be added to the stream simulation bed. Each structure type has a different specific objective:

- Features constructed on the margins simulate the reference channel banklines and edge diversity.

- o Rock bands shape the initial cross-section in dune-ripple and pool-riffle channels if no bankline is constructed.
- o Key features are structures that simulate specific features, such as bankline rootwads, of the reference channel.

Each of these structures is described below.

6.3.3.3 Banklines and margins

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.

Bars may form in a crossing structure — perhaps just on one side or through part of its length — and they may provide some of the benefits of a bankline. However, without root structure, cohesive soils, or the ability to scour into parent bed material, true banklines will not form naturally inside the structure. Banklines and specific channel margin features should be also included when they are needed for hydraulic roughness, habitat diversity, or to prevent channel trenching along culvert walls and protect footings from scour. Use the reference reach bankline diversity (including frequency and size of wood or rock protrusions) as a guide to design the bankline/margin. Where wood is an important feature on the channel banks, simulate its functions of roughness and edge diversity using rock sized to be immobile.

The intent is to create a permanent bankline, so material large enough to be stable during the high design flood is required. The size of rocks that appear to be immobile in the reference reach may also be a clue to sizing bankline rocks. As a starting point, bank material might be up to twice the size of D_{100} in the reference reach. If D_{100} is 3 inches or less, 6-inch-minus quarry spalls might be used. Later in the design process the size of the bank rock and other key pieces will be verified with a stability analysis.

A minimum-width bankline is a line of large rock placed along each wall. For additional roughness and diversity, make the line of rocks discontinuous or add clusters of rock to simulate bankline irregularities of the reference reach banks. Appropriate structure width is necessary to create a stable bankline without constricting the bankfull channel. Fill over and behind the bank rock with bed material so it will wash into place between the rocks and help to stabilize them.

If a floodplain bench is included in the culvert, construct it similar to a bankline, with the entire surface being stable rock. The top of a floodplain bench should slope in at about 1:10, so it will be less likely to have pockets that could trap fish.

6.3.3.4 Rock bands and clusters

Rock bands are temporary rock diaphragms or clusters placed at intervals through the culvert to provide some diversity as the channel evolves. If a bankline is not constructed in a channel with a mobile bed, rock bands should at least be included.

When there is no disruption of flow over mobile bed material, a very flat bed will develop resulting in very shallow flow from wall to wall. Alternatively, a narrow trench is often scoured in mobile bed material along smooth culvert walls where there is no flow disruption. The purpose of rock bands is to prevent either of these problems. They obstruct any tendency to scour along the culvert wall, and help create the bed diversity that exists in natural channels (from flow deflecting off bankline irregularities like woody debris or root wads).

Bands are diaphragms of rock that extend across the entire cross-section of the bed and are lower in the middle to encourage the thalweg toward the center of the channel. Clusters of rock at the walls of the culvert can provide the same function.

Bands and clusters can provide initial support for the cross-section shape. They also supply material for high flows to rework into natural features such as riffles. Bands only help create an initial cross-section shape and provide diversity: they are not intended to control channel grade.

Bands and clusters are not permanent rigid structures; high flows will rearrange them. They are generally mobile at flows that mobilize bed structures in the reference reach and might consist of rocks the size of D100 in the reference reach or slightly larger. Where D100 is smaller than coarse gravel (16mm), use coarse gravel. The high points of clusters and bands at the culvert walls should rise above the elevation of the bed profile.

Because the rock bands are not persistent, their spacing is not critical. Nonetheless, it makes sense to locate the bands to resemble the spacing of the riffle crests in the reference channel, unless doing so would create a vertical difference between crests larger than ½ foot. A larger vertical drop could cause the band to become a temporary drop structure.

6.3.3.5 Key features

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 remnants of glacial action. 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, and they block part of the channel cross-section. These features often play a significant role in the reference reach. When they do, they are key features, and their functions should be simulated. Functions can include buttressing the bed material and controlling grade, providing diverse hydraulic conditions usable by aquatic species for cover and resting areas, and providing hydraulic roughness.

In current practice, we directly simulate key feature roughness by imitating the size and distribution of individual elements using large rock. Key features such as embedded logs often span the entire channel and should be simulated that way. The step height should not exceed the dimension of D_{100}; a series of steps might be necessary to achieve the full height of the key feature. 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.

An alternative method of simulating reference reach roughness might be to measure the total frontal area of all roughness elements in the reference channel and reproduce it in the simulation using boulders. Ferro (1999) describes a method of quantifying the roughness created by various arrangements and concentrations of boulders placed on a gravel streambed.

To size the key-feature rocks, mimic the size of immobile rocks in the reference channel, and/or do a stability analysis (Section 6.3.8, Bed mobility and stability analysis). Rocks locked together in clusters are more stable than individual rocks and can be somewhat smaller. Angular rock is more stable than round rock. Key-feature rocks are mixed into the bed rather than bearing on the culvert floor.

Since key features are considered immobile in the stream simulation design, rock sizes can be over-designed to reduce the risk of failure. Careful construction is essential, especially in steeper (>6%) channels where dissipation of energy by key features is critical to channel pattern, form, and stability. If possible, consult with experienced stream simulation practitioners about steep simulations.

6.3.4 Special considerations for other channel types

Section 6.3.3, Streambed design, is a discussion of pool-riffle and plane bed channels. The same procedures apply to other channel types with some special considerations that are described in this section. See Table 6-1 for a summary of channel types and design strategies for various bed materials.

6.3.4.1 Dune-ripple channels

Although dune-ripple channels are usually low gradient sand-bed channels, for design purposes we include channels with mobile fine- and medium-gravel beds because of the similarity of the bed material design. This section generally applies to channels in which D_{100} is medium gravel (16mm) or smaller and is mobile at flows below bankfull.

The key to design in this category is the fine-grained bed and its mobility. Because the bed mobilizes and mixes during frequent moderate flows, the bedforms form more readily. For this reason, there is no need to build structure into the simulated channel, except for rock bands that are useful initially to help maintain the initial channel cross section shape.

In these channels, designing a bed mix in the process described in Section 6.3.3, Streambed design would result in a specification with classes very close in absolute size, which would be impractical for a contractor to supply. Several alternative strategies can be used.

Culverts in low-gradient channels are nearly flat. If the space within the culvert is entirely *backwatered* by the downstream channel, the design team may choose to allow it to fill with bed material naturally. Banklines and/or rock bands can be built as described previously. Consider volume of material required to fill the culvert bed and the effects of a headcut if it is not controlled. The upstream bed might be temporarily held in place so the culvert bed fills with bedload rather than material scoured in a headcut.

Clean sand or pit-run material might be used. It is important to use material that is similar to and not larger than the natural channel so the same initial mobility is achieved.

In new installations, the native bed material might be used if it is available from the excavation for the crossing and matches the size distribution of the reference reach bed. Fine-grained beds are typically not armored or are only weakly armored, so there is no great risk in mixing and replacing excavated bed material. The bed material may be used by itself or to supplement imported material in order to make up the required channel fill volume.

In sand channels, pebble counts are impractical. A visual estimation of particle sizes is usually adequate. It is also feasible to sieve bulk samples of these finer materials. Sample sizes are smaller and the problems associated with a layered (armored) bed do not arise. In this case, use the particle size distribution from the sieve analysis directly to create the bed material specification.

In some fine-grained channels, small pieces of debris scattered and buried partially in the bed may control slope. Consider whether that function should be replicated in the designed channel.

6.3.4.2 Step-pool channels

Steps form when the largest particles in the bed congregate and support each other to form a structure that is more resistant to movement than the individual pieces. Usually boulders form the step framework, which supports smaller cobbles and gravels. In nature, step-pool bedforms can take several decades to form (Madej 2001), depending on when channel-organizing flows occur and what key features are present. Bed-organizing flows are generally higher than bankfull; depending on the size of the boulders, steps may not reform at flows less than the 30-

year or higher flow (Grant et al 1990). For these reasons, we cannot rely on bankfull flows to form step-pool features naturally, as we do with most pool-riffle channels. Rather, since they are critical for energy dissipation and channel stability, steps must be constructed.

Except for the steps themselves, the step-pool channel bed is designed from a pebble count of the reference channel (see basic design process). Frequent high flows will scour and replenish the material between steps as bedload moves through the system. Pools will form naturally, and generally are not constructed.

Steps should be designed to match natural channel. They should be within the range of composition, spacing, and structure as those in natural channel. They should be constructed with the expectation that individual rocks will adjust their position and location during high flows to lock together. See Figure 6-4. Use rocks of at least the same size and angularity as the step-forming rocks in the reference reach, so that step height is as similar as possible. Space the steps the same as in the reference channel; step-pools in natural channels are typically spaced one to four channel widths apart and are closer in steeper channels. Until the larger particles congregate and support each other, they are vulnerable to being scoured out of the culvert, so it is wise to be conservative. Rock stability will be checked later in the design process, see Section 6.3.8, Bed mobility and stability analysis.

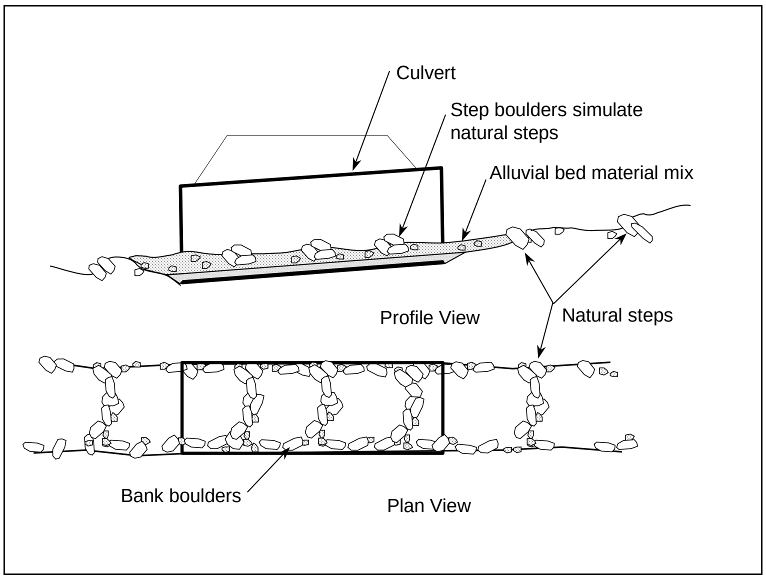

Figure 6-4. Schematic of step-pool stream simulation.

In channels with very large, stable step-forming boulders, steps may not move except in very high flows. Even in a culvert as wide as bankfull, these very high flows will be confined and shear stresses will be higher than in the natural open channel. It is not likely that steps would reform inside the culvert if the constructed ones were washed out. For this reason, steps made of large rock are designed to be immobile. Rock angularity and/or size can be increased a moderate amount for added stability. Smaller bedload will still move across the steps and be retained by them, as in the reference reach.

6.3.4.3 Cascade channels

Cascade channels are steep and the largest bed particles are large relative to normal flow depths (Montgomery and Buffington 1993). Energy is dissipated by water flowing over or around individual rocks. Smaller sediments move over or around the larger rocks at flows somewhat larger than bankfull. Rocks that are key to bed structure and stability, however, are immobile up to very high flows (> 50-year). 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 failed, the bare culvert would be unlikely to recover naturally. On a simulation this steep, it is wise to conduct a hydraulic stability analysis to ensure the largest bed-forming particles (e.g., D_{84}) are stable in the design flood (e.g., Q_{100}).

6.3.4.4 Bedrock channels

If a culvert is being replaced and the adjacent channel is primarily bedrock, investigate the channel and footing locations to determine bedrock location, elevation and suitability for a foundation.

If the bed at the site of a new crossing is sound bedrock, and bedrock is continuous throughout the site, stream simulation may consist of placing an open-bottom arch culvert over the bedrock. Depending on the shape of the rock surface, the entire footing might be anchored to it with a stem wall extending up to the bottom of the prefabricated culvert. The height of the footing and stem wall accommodate any variation in the bedrock surface. Exposed bedrock is often tilted; so, when contained by a culvert, a deep, smooth channel forms along one wall at low flow. Consider adding boulders for roughness in such a case. Special construction procedures, such as embedding, anchoring, or clustering, may be required to keep large boulders from rolling or sliding out of a bedrock channel.

Frequently, bedrock is exposed in the bed while the stream banks are composed of other material. The banks may have large roughness elements such as wood, and single or clustered boulders. These may be important key features for retaining sediment and debris that provide diverse habitats and migration pathways in the channels. Channel margins and/or banklines may therefore be important to achieving the objective of the project.

Bedrock channels sometimes exist where a bed of alluvial material has scoured, leaving the bedrock exposed. This often occurs where woody debris has been removed or where a debris flow has scoured the channel to bedrock. If the bedrock does not show typical erosional features such as fluting, longitudinal grooves, or potholes, this could be an indication that an alluvial veneer has recently washed away. In these cases, consider placing debris and/or immobile key feature rocks to help develop a natural alluvial bed and/or to stabilize a constructed bed.

6.3.4.5 Channels with cohesive bed material

A channel with cohesive bed or banks cannot be constructed inside a pipe. The best stream simulation alternative is probably to span such a channel completely using a bridge or arch. For new installations in cohesive bed channels, avoid disturbing the bed and keep bottomless culvert footings outside of the active channel so they will not induce scour. Any excavated or disturbed bed material should be replaced with material intended to be permanent.

6.3.5 Crossing structure shape, dimensions, and elevation

Now, for the first time in the design process, we consider the crossing structure itself. Up to this point, we have defined the probable range of stream profiles at the site, and the size, shape, materials and arrangement of the stream simulation channel using a geomorphic design method. Now we design the structure by fitting it around the designed channel. It could be a culvert of various shapes. In this part of the design process, the culvert elevation and dimensions are also determined.

Several iterations may be required to select the final structure dimensions if the bed stability calculations (see Section 6.3.8, Bed mobility and stability analysis) indicate the initial structure size is too small.

The design should also meet or exceed other applicable local, state, or federal standards for hydraulic capacity, headwater depth, and other design parameters.

6.3.6 Culvert width

Several factors go into determining the size and elevation of the culvert, including:

- The bankfull width of the channel, and any banklines and overbank surfaces
- The range of possible bed profiles, scour depth
- Maximum sizes of alluvium and colluvium
- Results of the checks on bed stability and flow capacity

The structure must satisfy all these conditions simultaneously.

The goal of stream simulation is that the simulated channel be self-sustaining and free to adjust similarly to the natural channel. For the simulation bed characteristics to be self-sustaining, the culvert must simulate the hydraulics of the natural channel at sediment-transporting flows, especially those flows that create and rearrange major bed structures. Constricting the channel at that flow will change the character of the bed; it may wash out, lose its structure, and/or become coarser. For this reason 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.

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

The first estimate of culvert width is simply the width needed to span the channel designed previously. If the design includes banks, the culvert must be wide enough to span the bankfull bed plus the size of bank rock on both banks. If banklines are included,, add two to four times the diameter of the largest mobile material in the bed to the bankfull width as an initial estimate. This is only a first estimate subject to change based on the stability analysis. As noted earlier, where the reference reach has a rough and highly irregular bankline, the simulated banks may be laterally deeper and may require more structure width.

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, overbank flow will be forced from the floodplain into the constriction of the culvert. The real issue is conveyance. If the conveyance of the floodplain is significant (perhaps 20% or more of flow in floodplain), the stream simulation channel will have significantly different flood hydrology.

Section 6.3.8, Bed mobility and stability analysis, discusses risks associated with flow concentration in active floodplains and some possible solutions. Your best option is to minimize the risk by placing additional culverts or drains that permit floodplain flow through the road fill. However, you may also need to provide additional culvert width to allow an overbank flow surface within the culvert.

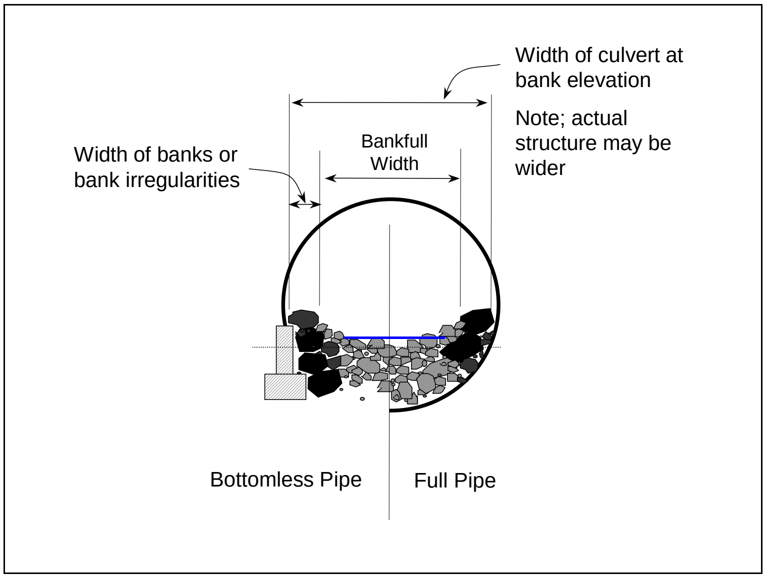

Figure 6-5. Stream simulation culvert width.

In choosing culvert width, consider how the largest key feature rocks (or alluvial rock clusters) in the simulated bed will interact with rock and wood pieces moving during high flows. A natural channel can usually scour around a large boulder or debris accumulation. In a culvert, however, a large individual boulder can create a constriction, or form a bridge with other large particles, creating a culvert-wide drop structure or debris jam, possibly limiting aquatic species passage. A good rule of thumb is that bed width inside the culvert should be at least four times the intermediate diameter of the largest particles in the simulated bed.

Incising channels may look narrow early in their development but will widen with age as they recover from disturbance. Stream simulation culverts should be sized to anticipate the expected evolution of the natural channel near the crossing. If a channel is unnaturally wide due to disturbance and you expect it to narrow in the future, size the culvert for current channel with the expectation that recovery will occur inside the culvert as in the adjacent reaches.

The final culvert width must also accommodate the high design flood capacity and potentially accommodate the road alignment or natural lateral migration of the channel.

6.3.7 Culvert invert elevation and height

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

1. The low profile of the vertical adjustment range (VAR) (Section, 3.4-Project profile design);
2. The depth of scour pools within that profile (Section, 6.3.1-Stream Simulation Site Assessment Needs); and
3. A thickness of the bed below for the bed material to be well-integrated and able to structure itself.

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.

This analysis might have to be re-done if later steps in the design cause a change to the bed material size.

Bottomless arches are typically built on stemwalls that are part of the footing. The elevation and design of the footing is determined by the structural design of the foundation and the projected bed scour depth. A rule of thumb recommendation is to bury the top of the footing 2 feet below the lowest expected channel profile. A thorough analysis is typically necessary (Federal Highway Administration, 2001). Where the consequences of failure are large, use a larger culvert or a deeper footing.

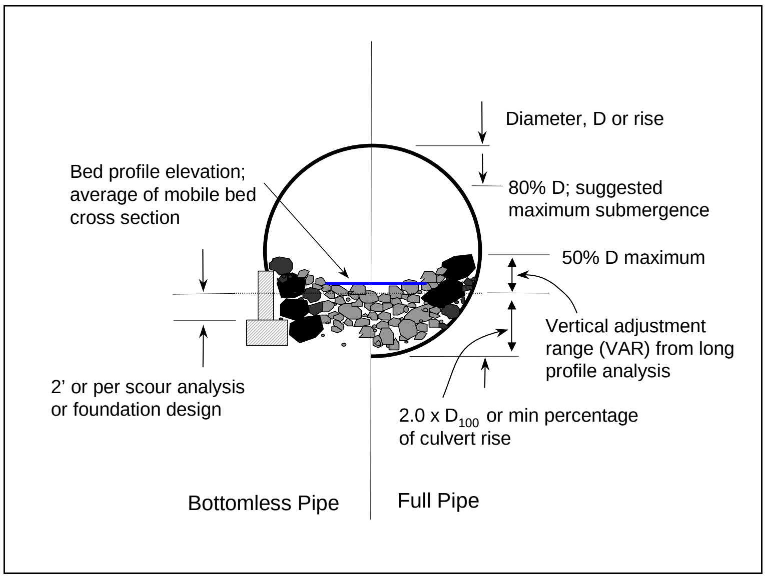

Figure 6-6. Stream simulation culvert embedment.

A second goal that affects culvert elevation is to maintain flood and debris capacity when the bed is at its high adjustment range. This will determine the culvert height. The high bed design flow is the flow at which the bed including any permanent features within it (key features, banklines, step structures) is likely to 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 should not exceed 80% submergence during the high bed design flow.

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.

6.3.8 Bed mobility and stability analysis

In a stream simulation design, bed mobility and/or bed stability might be important. Either or both might be used in any specific project.

Mobile streambeds are designed for “equal mobility” of the simulation and the reference reach streambed. When the bed mobility of the stream simulation bed is equal to the mobility of the reference reach, the bed shape, distribution of bed material, and bedforms are assumed similar and the goal of stream simulation is achieved. This analysis is useful where the simulation differs somewhat from the reference reach (e.g., steeper or floodplain flow is confined into a culvert).

Bed *stability* means key bed pieces stay in place during the high bed design flow. Stability analyses are used to check that the rock sizes of key features are stable.

Which analysis to use depends on the mobility of the streambed and the frequency of bed-forming flows relative to the life of the project. Material that moves in common floods is mobile. Typically sand-bedded and pool-riffle channels are mobile. See the characteristics of mobile and immobile channels in Section 3.2, Pre-Design Site Assessment,

Material that doesn’t likely move at flows that occur less than once in 20 years within a structure that is expected to last 50 years should designed to be stable in the bed design flow. The project cannot wait for it to create or restore those bedforms if they are scoured out.

Bed-forming flows vary from below bankfull in a low-gradient fine-grained channel, to bankfull flow in many gravel-bed streams, to as much as a 50-year flood in a steep, boulder step-pool channel. Normally, all stream simulations except step-pool, cascade and bedrock reaches would be designed for equal mobility.

When evaluating the risk of a bed failure consider what headcut might occur if the bed fails. See Section 3.4.5, Headcut issues.

6.3.8.1 Bed mobility analysis

The bed mobility analysis compares the flow at which specific-sized particles in the reference reach are entrained to the comparable flow in the culvert. If the simulated channel closely mimics the reference reach, the entrainment flows should be the same for all flows until the culvert significantly constricts flow width. If there are differences between the simulation and the reference reach, the designer can use the results of the analysis to adjust the simulation to achieve equal mobility. The analysis is done in mobile streambeds or for the material that is mobile in step-pool channels.

When is a mobility analysis necessary? Two key factors that determine whether a mobility analysis is necessary are bed mobility and risk of failure.

Low-gradient, fine-grained channels where the bed is fully mobile during frequent high flows are more self-healing than higher energy streams and may not need to be analyzed. For example, in dune-ripple channels, where sand-sized sediment is in transport at most flows, it is not necessary to do a mobility analysis. In straightforward projects on stable, moderately entrenched pool-riffle streams where the culvert bed closely replicates a reference reach just upstream, we can assume similar bed mobility and stability during the bed-forming (near bankfull) flow.

Steep pool-riffle, plane-bed, and moderate-gradient, cobble and small-boulder step-pool channels most often require a mobility analysis; they are in the range between being very mobile and immobile. They may be fully mobile at frequent flows (5- to 10-year recurrence interval), but infrequent enough that a partial bed failure may not heal itself within a reasonable timeframe. In these channels, it is worthwhile evaluating whether the same sizes are entrained in the structure and the reference reach over a range of flows from bankfull to the high design flow.

Every project entails some level of risk of failure. Table 6-2 is modified from USDA – Forest Service (in press). It lists risk factors associated with culvert and stream simulation failures and some design and construction strategies to mitigate the risk. Details are described elsewhere in this guideline and are further described in USDA – Forest Service (in press). Strategies in the table marked with "*" might be identified and quantified in a mobility analysis.

Table 6-2 Culvert risk factors and strategies

Risk Factor	Design / Construction Strategy
All culverts – Risks of structural failure *	
Debris blockage, debris flows	Limit headwater depth during high design flow to conservative level to avoid pressurization
	Ensure efficient transition at inlet to facilitate debris and sediment passage
	Harden fill; design for overtopping and cleanout; plan for possible streambed maintenance after overtopping; prevent stream diversion
	Provide inlet protection to reduce risk of scour during large flood events
Stream diversion	Sag vertical curve to prevent diversion; harden fill to allow overtopping instead
	Provide armored roadway dip, ditch dams, redirect road ditches to safe area
Stream simulation culverts – Risks of bedform, bed failure	
Culvert steeper than reference reach	Minimize slope increase; modify/restore downstream and/or upstream channel
	Increase bed material size * **
	Increase width of stream simulation channel, wider culvert to reduce shear stress * **
	If simulation is step-pool channel, install *bed retention sills* to reduce possibility of loss of key pieces
	Provide access for maintenance and repair
Floodplain constriction	Widen culvert to include “floodplain” inside of culvert*
	Increase size of bed material * **
	Add floodplain relief culverts, road overflow dips *
	Place layer of large rock armor under stream simulation bed
Lack of initial bed consolidation	Compact bed layers during construction
	Wash fines in between and around larger material to embed and stabilize it
	Hand-place key bed features for stability
	Construct thicker streambed (to elevation higher than VAR) to allow some initial consolidation
Downstream channel instability	Ensure vertical adjustment range is accurate
	Ensure simulated bed is deep enough and the culvert large enough to accommodate the range of potential profiles
	Provide grade controls downstream of outlet
	Use full-bottom pipe or deepen foundation of open-bottom structure; place layer of large rock under simulation bed to reduce probability of structural failure
Pressurized pipe	Increase culvert size to limit headwater depth during high design flow to 80% of culvert rise

Risk Factor	Design / Construction Strategy
	Provide wider culvert with “floodplain, add floodplain relief culverts, road dip overflow *
Long culvert	Add headwalls to shorten culvert
	Add safety factor to stability analysis to compensate for possible compounding design flaws *
* Design options that can be designed with bed stability/mobility analysis. Analysis may indicate a need for bed material larger than reference reach, a wider culvert, floodplain culverts, or dips, etc. ** Strategies that are effective within limits as described in the text. *** Note that bed failure in bottomless culvert may lead to structural failure.	

What particle sizes are analyzed? Generally, the analysis is done on the bed material that characterizes structure, stability, and roughness of the bed. For pool-riffle and plane-bed channels, D_{84} is the recommended grain size to analyze. D_{84} is recommended because when it is mobile, most if not all of the bed is mobile. Additionally D_{84} is a good indicator of bed roughness and of the larger particle sizes that affect bed form.

In step-pool channels, the fine material between the steps (sands, gravels, etc.) moves over the steps at near bankfull flows (Adenlof and Wohl 1994; Blizzard and Wohl 1998). The reference reach comparison would apply to D_{84} of that material, although normally there would be no need to do the analysis.

What flows are analyzed? In a simple analysis, you don't need to analyze a pre-determined flow based on return frequency. To verify equal mobility between the reference reach and the stream simulation reach we want D_{84} to be mobile at the same flow in both channels. Find the flow that mobilizes D_{84} in the reference reach and then find the stream simulation design that causes D_{84} move there at that flow.

There is tremendous uncertainty in determining specific recurrence interval flows in most watersheds. The process of comparing the simulation to the reference reach reduces the need for highly accurate estimates. We don’t need to know exactly at what flow bed material is actually entrained, as long as we know that it will behave the same in both channels.

Specific higher flows might also be analyzed. If the culvert causes a significant constriction of flow off a floodplain at flows higher than the bed mobility flow described above, it should be analyzed. The analysis might lead to wider culvert with “floodplain” area and/or additional culverts within the floodplain for flood relief.

6.3.8.2 Bed stability analysis

Key features (steps, banklines, colluvium) in the natural channel may move infrequently. Steps in a steep step-pool channel may move once in 30 to 80 years Grant et al (1990) though more frequently in some cases. Colluvium and key buried wood pieces may never move in the lifetime of the structure. These features are simulated in the stream simulation and a bed stability analysis is applied to design them to be permanent during a high design flow.

A bed stability design flow is selected for the analysis. Typically, it’s a 100-year flood but could be less if the risk is low and/or there is a means of repairing a failed bed.

6.3.8.3 Mobility/Stability analysis models

Mobility and stability are evaluated using equations that estimate what flow moves (entrains) a certain size particle. Though there are no precise models for particle entrainment in steep channels, the following equations are the best available for our purposes here:

- Unit discharge equation (Bathurst, 1987)

  This model estimates the critical unit discharge (flow per unit channel width, cfs/ft) at which a certain particle size will begin to move in a steep, rough channel.

  The equation by Bathurst is consistent with natural streambed material that is expected to move at this flow intensity and is recommended for the design of the mobile bed in stream simulation culverts.

  This model can also be used to size immobile bed material though it should be the lower limit of particle sizes in that case.

- Critical shear stress method

  Critical shear stress is an often-used method to estimate the initial movement of particles. This equation applies to channels with low-to-moderate gradients (less than about 2.0%) where water depth is large compared to the size of the bed material. The method is therefore limited for application with stream simulation.

- Riprap sizing equations

  U.S. Army Corps of Engineers (1994) describes a modified shear stress approach to riprap design. The manual clearly states that this method should not be applied to channels over 2%. Maynord (1994) modified this method for slopes up to 20%.

  These equations were originally developed for designing riprap bank protection and rock chutes such as spillways. They are useful in stream simulation for the design of banklines and key features, which are designed to be immobile during the high design flow. They are also useful for sizing material in a roughened channel.

Like all hydraulic and hydrologic models, these are approximations and simplifications of the real world. The Bathurst and modified Shield's equations apply best in purely alluvial settings; the stabilizing effects of key features, such as embedded debris or colluvium, are not included. All the equations are based on empirical field and laboratory studies with data sets of limited size and variability and they should be applied within those limits. If it is not evident which equation is more appropriate, use more than one and compare the results. Understanding why the results differ can be important to a good design. USDA – Forest Service (in press) describes in some depth the background, criteria for application, and limitations of these models and has examples of their application to stream simulation designs.

Do not allow the models to drive the design. Rather, they are tools to be applied with geomorphic and engineering expertise. Visualize how the channel will look and function as it adjusts over time. Use the models to test the sensitivity of the bed and to help predict bed mobility in different channel/structure configurations. Test sensitivity by varying design values in the models to see if they greatly affect the results. There is less risk of error when changes to the results are small.

Always check the results of the equations against your understanding of how the channel will function. For example, if the simulation is steeper than the reference reach, the model will indicate that the structural rocks mobilize at lower flows. To offset this, you might consider making the cross-section wider, increasing the calculated entrainment flow to match the reference reach. Question whether the simulated channel is likely to retain what may be an artificial shape over time. Larger bed material might be a better solution in this case.

Also consider how the models compare to the existing channel. Do the model results make sense compared to material that appears stable (or not) in the reference reach?

To ensure safety and remain within the range of natural variability, we suggest increasing bed material sizes and/or channel width no more than about 25 percent unless you have a clear understanding of the implications of a greater change. If these minor alterations in bed material size or culvert width are not enough to match bed mobility with the reference reach, review the risk factors in Table 6-2. Consider selecting a new project profile. Stream simulation may not be feasible at the site.

7. Hydraulic Design

7.1 Definition of Hydraulic Design Option

Hydraulic design has been used for decades as the primary design method for fish passage at road crossings. Due to the inherent uncertainties of the hydraulic, hydrologic and biological assumptions required in this design, it should generally be avoided for new installations requiring AOP. This design option will be most often appropriate for retrofit applications for sound structures with passage deficiencies or for new installations where other designs are not feasible.

Premise of hydraulic design

A structure designed with appropriate hydraulic conditions will allow target species to swim through it within a specific range of design flows.

The Hydraulic design option is a design process that matches the hydraulic characteristics of a culvert at a specific range of flows with the swimming abilities of a target species and age class of fish. The hydraulics of the culvert might be controlled by the culvert slope, width, and roughness.

This method targets distinct species of fish, therefore it does not account for biological requirements of non-target species. There can be significant errors associated with estimation of hydrology and fish swimming speeds that are mitigated by making conservative assumptions in the design process.

Hydrologic data, high and low fish passage design flows and hydraulic characteristics (depth, velocity, turbulence) are required for this option. Information on the timing of movement, swimming ability, and behavior of the target fish is required.

The resulting culvert size is often narrower than the channel bankfull width.

It should be understood, that in retrofit applications where improvements to passage through an existing structure is desired, full attainment of biological criteria might not be possible. In these cases, project success might be limited to improvements in passage for only a portion of a fish population or aquatic community.

7.2 Hydraulic Application

For best results, the hydraulic design criteria can generally be achieved in the following situations:

- New, replacement and retrofit culvert installations where physical limitations make other design options (low-slope, stream simulation, bridges) not feasible.
- Low to moderate culvert slopes (less than about 1.0%) without baffles or other added roughness.
- Moderate to steep culvert slopes (up to about 3.5%) with baffles retrofitted. *Fishways* can be constructed at steeper slopes but cannot typically be retrofit into culverts.
- Where swimming ability and behavior of target species of fish are known.
- Where complete ecological connectivity is not required.

These are general descriptions of applications. Hydraulic designs must satisfy specific hydraulic design criteria. The method might be applied in more extreme conditions than described above but with reduced results.

Many species of fish and other organisms migrate through the stream corridor. This design method targets distinct species of fish and therefore does not account for ecosystem requirements of non-target species. We know little about the movement patterns and swimming and movement abilities of many species. These issues are compounded by the uncertainties of hydrologic and hydraulic parameters that must be applied for this concept to be applied.

Maximum average velocity and turbulence are basic design criteria in the hydraulic option. The roughnesses of the culvert material, installed baffles, or of the bed material if the pipe is sized appropriately and embedded, create resistance to flow and reduce the velocity.

The hydraulic option may not address the ecological and habitat issues at road crossings discussed in the ecological considerations section of this guide. Depending on the criteria and assumptions made in the hydraulic design, changes caused by the crossing can transform the crossing into a barrier to many species.

The hydraulic method is used as a primary design concept in many locations. It is often used to design retrofits or temporary retrofit installations until more suitable designs can be constructed. Roughened channel design is discussed in this guide as a means of steepening a channel within or near a road crossing. The distinction between roughened channels and stream simulation as defined in this guide is that roughened channels are designed using the velocity, length, and turbulence parameters of the hydraulic culvert design method; stream simulation is designed by geomorphic and bed characteristic parameters.

7.3 Hydraulic Design Process

The hydraulic design follows the pre-design described in Section 3, Culvert Pre-Design.

The process for a hydraulic design is reversed from the typical engineering orientation of culvert design for flood flows. Think like a fish. Start in the channel below the culvert and proceed in the upstream direction through the culvert; the direction of fish passage. Culverts designed for fish passage normally result in outlet control conditions at all fish passage flows. An inlet control analysis must then be done to verify adequate culvert capacity for the high structural flow. In many situations the fish passage criteria controls the culvert design; flood passage criteria are normally less stringent.

Proper culvert design simultaneously considers the hydraulic effects of culvert size, slope, material and elevation to create depths, velocities and a hydraulic profile suitable for fish swimming abilities. There are consequences to every assumption; adequate information allows you to optimize the design. Inadequate information, which is often the case with this method, requires conservative estimates and assumptions. The following steps make up the hydraulic design:

1. General and hydraulic design site assessments, Sections 3.2, Pre-Design Site Assessment, and 7.3.1, Hydraulic Design Site Assessment Needs.
2. Pre-design. See Section 3, Culvert Pre-Design.
3. Culvert length. Find the culvert length based on geometry of the road fill.
4. Biological design. Determine target species, sizes and swimming capabilities of fish requiring passage. Species and size of fish determine velocity criteria. Actual allowable maximum velocity depends on species and length of culvert.

5. Hydrology. Determine the range of fish passage design flows at which the fish passage criteria must be satisfied.
6. Culvert elevation. Set the culvert elevation and verify the backwater elevations throughout the range of low to high flows are at least as high as the water surface in the culvert.
7. Velocity, depth, and turbulence. Find the size, shape, roughness and slope of culvert to satisfy velocity criteria assuming open channel flow and no bed material. Verify that the flow is sub-critical throughout the range of fish passage flows.
8. Final Design. See Section 10, Final Design.

Several iterations of some of these steps may be required to achieve the optimum design. The following sections further describe all of the design steps.

7.3.1 Hydraulic Design Site Assessment Needs

The site assessment for the hydraulic method is described in Section 3.2, Pre-Design Site Assessment. Since the hydraulic design is normally used for retrofits, some of the data described in that section may not be necessary. It is assumed here that a project profile was determined in the pre-design phase also. The only remaining site assessment need is to develop the high and low fish passage design flows. They are described in Section 7.3.4, Hydrology.

7.3.2 Length of Culvert

The hydraulic design process is based on the maximum water velocity for target fish species to be able to negotiate the length of the culvert; the longer the culvert, the lower the maximum allowable velocity. The culvert length includes aprons unless they are countersunk below the invert of the culvert. Adding headwalls to each end of the culvert, narrowing or lowering the road, and/or steepening the fill embankments, can minimize the culvert length.

The length of the replacement culvert might be different than the existing pipe; the length might be affected by its elevation and size.

7.3.3 Biological Design

Since the hydraulic design is based on the swimming ability and behavior of one or more target species, those species and their migration timing, sizes, and swimming capabilities and behaviors must be determined. Species and size of fish, together with culvert length, determine design velocity criteria.

The following fish species found in Vermont are most likely to be impacted by culverts.

- Brook trout *
- Rainbow trout
- Brown trout
- Atlantic salmon: land-locked & sea-run *
- Rainbow smelt

- American eel *
- White sucker
- Longnose sucker
- Northern brook lamprey *
- Silver lamprey *
- American brook lamprey *
- Sea lamprey * (Connecticut River)
- Minnows, shiners, etc. (15 +/- species *)

* = Identified as species of greatest conservation need in the Vermont's Wildlife Action Plan (Vermont Fish and Wildlife Department, 2005)

Despite extensive research on these fish species, uncertainties in the hydraulic, hydrologic and biological requirements for successful fish passage persist. Most studies have been limited to laboratory studies, which cannot mimic the range of natural conditions encountered or account for effects of fish behavior. To address these uncertainties, the design values provided here are conservative.

The hydraulic design method targets hydraulic conditions through the culvert that accommodate the swimming ability and timing of target species and sizes of fish. Fish passage design is based on the weakest species or size of fish requiring passage and is intended to accommodate the weakest individuals within that group. What species are potentially present? When are they present? VDFW District Fisheries Biologists will determine aquatic organism passage needs on a case-by-case basis. See Section 3.1, Aquatic Resource Objectives.

Upstream movement of fish other than adult trout and salmon must also be considered. Rainbow smelt, sucker species, as well as other fish species use tributaries of lakes and ponds for spawning. The upstream movement of juvenile salmonids and other fish species is also important for dispersal and recolonization of vacant habitats. These fish are generally smaller and weaker than adult trout and salmon and therefore require lower velocities and turbulence for passage. It is therefore often not practical to design for passage of weak swimming species directly by the hydraulic design option. Instead, either the Low-slope method or the Stream Simulation method may be more appropriate.

The hydraulic conditions described for the default design will generally result in bed material accumulating and a natural roughened channel through the culvert that juvenile fish can successfully use for passage. An exception to the presumption of a stable bed formation for juvenile fish passage might occur in situations where a pipe becomes deeply submerged and pressurized during an extreme flood event and bed material is therefore scoured from it. Until new bed material is recruited into the culvert, there may be a barrier to weaker swimming fish.

7.3.3.1 Timing of Movement

The hydraulic design criteria must be satisfied a certain portion of the time during the migration season for the target species and age class. Since the timing of movement varies among species and watersheds, knowledge of the specific movement timings is necessary for development of hydrology. Different species or age classes at a site may migrate at different times of the year; therefore multiple hydrologic analyses may be needed to determine the controlling hydraulic requirements.

An overview of aquatic organism movement and migration is presented in Section 2.1, Passage of Fish and other Aquatic Organisms . Table 7-1 provides general information of spawning and general movements for selected fish species in Vermont. A VDFW fisheries biologist should confirm these timing guidelines or provide site-specific information if available.

Table 7-1. Expected periods of movement for selected fish species in Vermont. Solid represents spawning movements, shaded represents general (e.g. foraging, refugia) movements).

Species	Lifestage	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Brook trout	All									
Rainbow trout	All									
Brown trout	All									
Atlantic salmon	Adult									
	Juvenile									
Rainbow smelt	Adult									
American eel	Juvenile “Yellow” eel									
White sucker	Adult									
Other resident fishes	All									

Since hydraulic characteristics are design criteria for this method, the flows at which they are achieved must be defined. Determine the range of passage design flows at which the fish passage criteria must be satisfied. The hydraulic criteria in Section 7.3.5, Hydraulic Criteria; Velocity, Jump Height, Depth, and Turbulence, are not achieved at all flows. They should be achieved throughout a range of flows from the low to the high fish passage design flows. Compliance with criteria at flows beyond this range is not essential for several reasons. Extreme flows are less frequent; design for extreme flows is difficult and costly; design for extreme flows may compromise the design for more frequent flows; and fish are less likely to naturally move during extreme flows.

7.3.4 Hydrology

Many streams in Vermont have characteristic prolonged high flows in the spring (March-May) as snow melts and then again brief high flows in the Fall-winter (October-December) due to rainfall events. These high flow events coincide with the general migration timing described above and therefore highlight the need to accommodate fish passage during high flows.

The focus of this section is on fish passage design flows. Other structural and stability design flows might be necessary. See Section 10, Final Design.

7.3.4.1 High fish passage design flow

For the purpose of defining high passage flow requirements, there are two periods of concern for fish on spawning migrations in Vermont: spring and fall.. Spring spawners include rainbow smelt, various suckers, and rainbow trout. Common fall spawners include brook trout, brown trout, and Atlantic and landlocked salmon. While exceptions may occur, other Vermont species that spawn in the spring (walleye, bass, pike, etc) or fall (lake trout) are usually associated with larger streams, which would generally not accommodate culverts.

High passage flow criteria were developed for spring and fall spawning periods using a subset of USGS gauge station average daily flow data with the following criteria:

- minimum of 10 years of continuous data
- <50mi2 drainage area
- Vermont & western New Hampshire streams
- minimally regulated or unregulated streams.

This analysis used “average daily flow statistics” and therefore does not reflect actual peak streamflows. Methods, specific locations, and summary statistics of the 20 stream gauges selected are provided in Appendix B – Vermont High Passage Design Flow.

Spring Spawning - High Passage Flow criteria

Most spring spawning movements of Vermont fishes in streams occur in the months of April and May. Vermont streamflow statistics indicate April receives higher flow during this period; therefore, this month was selected to define the high passage flow for spring spawning movements.

Fish do not move under all flow conditions, and therefore peak runoff events would not provide an appropriate standard for fish passage design. However, spawning is a physically and physiologically stressful time for fish, leaving them vulnerable to predation and disease. The longer fish are delayed during these migrations, the less likely successful spawning and subsequent recruitment of young will occur.

This premise led to the development of hydrologic criteria based upon both duration (number of continuous days average daily flows will be exceeded) and exceedance (probability that specific flows will be exceeded) statistics. Due to the effect of snowmelt on spring flows, peak flows tend to be of longer duration than at other times of the year. Based upon evaluations of various flow criteria on annual hydrographs of Vermont streams, a spring high passage flow recommendation is described as the flow that has a **20% probability of being exceeded for 2 consecutive days in April.**

For sites on ungauged streams, the April 2-day 20% exceedance flow can be estimated with the following model (Appendix B – Vermont High Passage Design Flow:

$$\text{April } Q_{2\text{-}20} = A_{Basin} \times (-41.15 + 0.000038 \times \text{Northing} + 1.248 \times P)$$

Where:

- April $Q_{2\text{-}20}$ is the flow (in cubic feet per second) that has a 20% probability of being exceeded for 2 consecutive days in April.
- A_{Basin} is the area of the basin above the project in square miles.
- Northing is the distance north in Vermont State Plane Coordinates (VSPC) and can be found in *Flow Frequency Characteristics of Vermont Streams* (Olson, 2002).
- P is mean annual precipitation in inches.

The derivation of this model and stepwise instruction for its application is described in Appendix B – Vermont High Passage Design Flow. If available, site-specific flow data should be used to determine the seasonal high passage flow for a given stream.

The basin characteristics can be derived through the USGS Vermont Streamstats interactive map at http://water.usgs.gov/osw/streamstats/Vermont.html.

Fall Spawning - High Passage Flow criteria

A similar approach was taken to develop fall spawning high passage flow criteria, with November flows providing the higher flows during the fall spawning period. Based upon review of various flow criteria on annual hydrographs of Vermont streams, a spring high passage flow recommendation is described as the flow that has a **20% probability of being exceeded for 2 consecutive days in November.**

For ungauged streams, the November 2-day 20% exceedance flow (csm) can be estimated with the following model (Appendix B – Vermont High Passage Design Flow:

$$\textbf{Nov } Q_{2\text{-}20} = A_{Basin} \times (-13.709 + 0.4555 \times P + 3.0855 \times \log N (1 + A_{Lakes}))$$

Where:

- November $Q_{2\text{-}20}$ is the flow (in cubic feet per second) that has a 20% probability of being exceeded for 2 consecutive days in November.
- A_{Basin} is the area of the basin above the project in square miles.
- P is mean annual precipitation in inches.
- A_{Lakes} is the portion of the watershed area in lakes and ponds.

The derivation of this model and stepwise instruction for its application is described in Appendix B – Vermont High Passage Design Flow. If available, site-specific flow data should be used to determine the seasonal high passage flow for a given stream.

The basin characteristics can be derived through the USGS Vermont Streamstats interactive map at http://water.usgs.gov/osw/streamstats/Vermont.html.

Non Spawning Migration Flow

We assume that a design for passage of a particular species and lifestage during the migration periods will, by default, satisfy general passage needs that are shown in Table 7-1. It is assumed that if the design provides for passage at migration flows and meets the jump height and low flow depth criteria, passage at intermediate flows will likely be accommodated. The design will not necessarily meet the general needs for passage of all species and life stages.

7.3.4.2 Low Fish Passage Design Flow

The low design flow for fish passage is used to determine the minimum depth of water within the culvert. For this purpose, the two-year, seven-day low flow (7Q2) is used.

Passage criteria must be met for all flows from the low fish passage design flow up to the high fish passage design flow. More than one fish passage design flow may have to considered, if different life stages or species require passage at different times of the year. It is not known which fish passage design flow will control the design until the hydrology is analyzed and the culvert hydraulics are designed to accommodate these life stages.

The depth requirement is a moot issue in culverts designed with natural beds. Culverts designed by the hydraulic option for species with low swimming speeds (less than about 2 fps) will generally accrete bed material in which a thalweg will develop. Exceptions to this are when there is not sufficient natural recruitment of bed material or when a culvert is pressurized during an extreme flood event. If a culvert is pressurized and if bed material isn't immediately replenished, the bare bed condition may persist for some time as a depth barrier. Another exception is culverts with baffles in which turbulence might prevent accumulation of bed material.

To calculate 7Q2, a general relationship of the low flow to the basin area, 0.139 cfs per square mile, can be used. This relationship was determined from a subset of Vermont stream gages and is shown in Table 1 of Appendix B – Vermont High Passage Design Flow.

7.3.5 Hydraulic Criteria; Velocity, Jump Height, Depth, and Turbulence

The hydraulic conditions allowable depend on the target species and length of culvert. The criteria for velocity and jump height are intended to provide passage conditions for the weakest and smallest individuals of each species. The minimum depth in the structure should, however, accommodate the largest fish expected.

These criteria should be applied where fish passage is required and the hydraulic design method is appropriate.

- **Maximum cross-section-averaged water velocities** at the high fish passage design flow are shown in Table 6-1 for a variety of Vermont species.
- **Maximum outlet drops** for several Vermont fish species are shown in Table 7-3**.** While the avoidance of an outlet perch should be the goal of all designs, it is recognized that retrofit applications may not be able to always eliminate the drop.
- **Minimum water depth** in the culvert at the low fish passage design flow is shown in Table 7-4 for several Vermont species.

Fall and spring spawners are defined in Section 7.3.3.1, Timing of Movement.

Table 7-2. Maximum velocity criteria for several Vermont fish species.

Species/Lifestage	Maximum Velocity (fps)				Reference
	Culverts <40’	Culverts 40-100’	Culverts 100-200’	Culverts >200’	
Brook trout –adult (>6”)	2.6	2.4	2.2	1.9	Peake et. al. 1997
Brook trout –juvenile	1.0	0.8	0.7	0.7	
Brown trout – adult (>8”)	4.5	4.3	4.1	4.1	Peake et. al. 1997
Brown trout – juvenile	1.7	1.7	1.7	1.7	
Rainbow trout – adult (>8”)	4.3	3.6	3.4	3.2	Belford and Gould 1989, NA:Peake et. al. 1997 (BNT)
Rainbow trout – juvenile	1.7	1.7	1.7	1.7	
Steelhead trout – adult (>10”)	6.0	5.0	4.0	3.0	NA: use WDFW Steelhead
Steelhead trout – juvenile	1.7	1.7	1.7	1.7	NA:Peake et. al. 1997 (BNT)
Atlantic salmon – adult	6.0	5.0	4.0	3.0	NA: use WDFW Steelhead
Atlantic salmon – juvenile	2.1	2.0	1.9	1.8	Peake et. al. 1997
Rainbow smelt	NA				NA
Longnose and White sucker – adult (10”+)	1.3				Jones et. al. 1974
Smallmouth bass-adult (>10”)	3.0				Peake 2004
Minnows (Cyprinids) Darters (Percids) Sculpin (Cottids)	1.0				Warren and Pardew 1998 Jones et. al. 1974

NA = information not available

Table 7-3. Maximum outlet drop criteria for retrofit applications for passage of several Vermont fish species.

Species/Lifestage	Maximum Outlet Drop (inches)*	Reference
Brook, brown, rainbow trout - adult	8	Kondratieff and Myrick 2006 Coffman 2005
Brook, brown, rainbow trout – juveniles;	4	Coffman 2005
Steelhead trout – adult	12	WDFW
Atlantic salmon – adult	12	NA: use WDFW steelhead criteria
Atlantic salmon – juvenile	4	NA: use trout juvenile criteria
Rainbow smelt	NA	
Longnose and White Sucker	NA	
Smallmouth bass	NA	
Darters (Percids) Sculpin (Cottids)	0	Coffman 2005

* Outlet drop is the vertical dimension from normal water level in the culvert to water level downstream.

* Pool Depth/Outlet Drop ratio > 1.25 (Stuart 1962)

NA = information not available

Table 7-4. Body depth/total length ratios and low flow depth recommendations for several Vermont fish species.

Species	Body Depth/Total Length ratio	Target Length (inches)	Target Low Flow Depth (1.5 x maximum body depth in inches)	Reference
Brook trout – juvenile Brook trout – adult	0.28	3-5 6-10	2.1 4.2	Scott and Crossman 1973
Brown trout – juvenile Brown trout – adult	0.24	3-5 6-21	1.8 7.5	Scott and Crossman 1973
Rainbow trout – juvenile Rainbow trout – adult	0.22	3-5 6-18	1.7 6.0	http://stream.fs.fed.us/fishxing/
Steelhead trout – juvenile Steelhead trout – adult	0.22	3-8 14-26	3.3 8.6	NA: use rainbow trout
Atlantic salmon – juvenile Atlantic salmon – adult (anadromous) Atlantic salmon – adult (landlocked)	0.22	3-8 14-30 24-36	3.3 9.9 11.9	Scott and Crossman 1973
White sucker	0.20	3-14	4.2	Scott and Crossman 1973
Longnose sucker	0.18	3-10	2.7	Scott and Crossman 1973
Smallmouth bass	0.28	3-18	7.6	Scott and Crossman 1973

Species	Body Depth/Total Length ratio	Target Length (inches)	Target Low Flow Depth (1.5 x maximum body depth in inches)	Reference
Minnows (Cyprinids) Darters (Percids) Sculpin (Cottids)	0.16-0.26	3-5	2	Scott and Crossman 1973
Fallfish	0.21	3-12	3.8	Scott and Crossman 1973

To achieve the hydraulic criteria listed in these above, the designer of a new culvert can modify the roughness, slope, and/or size of the culvert and bed within it. The designer of a retrofit culvert normally has no control over the culvert slope or size. Culvert baffles or other roughness devices can be installed to modify roughness.

This design method does not account for the lower velocities in the boundary layer that fish might use to move through a culvert. Boundary layer velocities are difficult to predict with different culvert materials and bed configurations, turbulence can become a barrier, and continuity of a boundary layer through a culvert is not ensured.

A simple hydraulic design option uses the average velocity and maximum depth in the cross-section. Depth and velocity are derived from a calculation of open channel flow conditions (e.g. Manning's equation) or from a chart of culvert hydraulic characteristics. This assumes there is no backwater influence. Backwater influence means the flow depth is increased due to deep water downstream; depth within the pipe is greater than what would be predicted by normal open channel flow. A backwater analysis is needed if the downstream channel is raised to backwater the culvert to control depth and/or velocity.

Depending on culvert size, velocity, and bedload characteristics a streambed may or may not develop and be persistent within the culvert. Bed material might deposit and a thalweg might form in a culvert designed by the hydraulic option for species with low swimming speeds. This occurs when the velocity is low enough in the culvert during flows at which bedload is mobile that it accumulates in the culvert. Exceptions to this are when there is not sufficient natural recruitment of bed material or when a culvert is pressurized during an extreme flood event. If it is pressurized and if bed material isn't immediately replenished, the bare bed condition may persist for some time as a depth and/or velocity barrier.

Because of these uncertainties, the hydraulic analysis for fish passage is normally done with the assumption that there is no streambed in the culvert unless a permanent bed is constructed as a roughened channel. On the other hand, for the flood capacity analysis, it should be assumed that there is a bed in the culvert. See Section

10.2 Hydraulic Capacity.

Alternatively, the culvert can be designed with mobile bed material in place though the analysis of this design introduces other uncertainties. If the upstream channel has a mobile bed, the flow at which bed material is entrained in the upstream channel can be compared to the comparable flow in the culvert. To be successful the culvert has to be close to or larger than the natural bankfull channel. This essentially becomes a stream simulation design.

It is often difficult to achieve both the depth and velocity criteria in a culvert. A larger culvert will reduce the velocity at the high design flow but will cause the depth to be too shallow at the low design flow. This can be resolved by using a roughened channel or by countersinking the culvert low enough that depth is created by the backwater from downstream through the culvert.

The flow will typically be sub-critical for all flows at least up to the fish passage design flow. An exception to this is in a roughened steep channel with mixed-flow hydraulics.

Computer backwater programs such as FishXing, HEC-RAS™, HY8, or CULVERT MASTER™ and others can help refine the design. The minimum amount of information needed for these programs varies with the program and complexity of the project. They are all limited in some way; either roughness is a constant, no bed material can be included in the floor, the bed has to be flat, or hydraulics within the culvert are not shown. A backwater analysis allows the designer to optimize the design by using the lower velocities created by the backwatered condition. A backwater model that shows conditions within the culvert should be used to evaluate passage at a culvert that is not backwatered.

7.3.5.1 Culvert and Bed Slope

In a new installation, the culvert should normally be placed on the grade of the project profile defined in Section 3.4, Project profile design. The culvert might be installed at a lesser slope to increase the water depth and reduce the velocity. If that is done, the project profile must be re-evaluated to be sure the culvert elevation will be effective for any profile within the vertical adjustment range. The culvert rise (vertical dimension) still has to accommodate the flood capacity analysis. See Section

10.2 Hydraulic Capacity. The effect may be to cause transient or permanent bed deposition within the culvert as described above. Passage is improved in that case by the roughness and diversity of the natural bed.

The designer has no control of the culvert slope in a retrofit design.

7.3.5.2 Culvert and Bed Roughness

Roughness also controls velocity. Roughness is provided by the culvert walls and bed and might be modified with a roughened channel, and/or baffles within the pipe.

Increased roughness is not necessarily a solution to passage of aquatic species however. Theoretically, the roughness can always be increased to reduce any velocity to a value suitable for fish passage. The approach is not realistic though because roughness converts velocity to turbulence and the combination of turbulence intensity and scale can be a barrier to passage. Roughness can merely convert a velocity barrier to a turbulence barrier, especially for small and weak-swimming fish.

The type of roughness used can greatly affect passage success. Diverse hydraulic conditions, as in a natural channel, can provide a number of passage corridors and opportunities and therefore turbulence will have less effect on passage.

Turbulence can be quantified by the energy that is dissipated in a unit volume of water, referred to as the energy dissipation factor (EDF). Bates et al (2003) suggest limitations of EDF in baffled and roughened culverts based on passage of adult salmon. Those limits are listed below. There is no data on the subject and there are no EDF limits suggested for other species or life stages.

The EDF is calculated by Equation 7-1 in fishways, culverts, and other channels.

$$EDF = \frac{\gamma Q h}{Vol_e}$$

Equation 7-1

In the equation γ (Gamma) is the unit weight of water (62.4 lb/cubic foot), Q is the flow (cubic feet per second), h is the sum of the potential and kinetic head entering the space (feet), and Vol_e is the effective volume in which energy is dissipated (cubic feet). Metric units can be used just so they are consistent. This equation can be directly applied to pool and weir fishways where the volume is the volume of the fishway pool and h is the head differential entering the pool.

For open channels and culverts this equation can be simplified to:

$$EDF = \gamma V S$$

Equation 7-2

V is the velocity (feet per second) and S is the hydraulic slope (feet per feet).

7.3.5.2.1 Roughened Channel

A roughened channel is a continuous and immobile channel constructed of a well-graded mix of rock and sediment. The hydraulic design method for fish passage is used to combine channel dimensions, slope, and bed material to create depths, velocities, turbulence, and a hydraulic profile suitable for target species to pass. The channel is rough and/or wide enough that energy is dissipated in turbulence consistently through the reach.

The design principles described here can be used for channels inside and outside of culverts. If built within a culvert it is normally built within a new installation. The use of roughened channels inside of culverts is therefore an exceptional case since the hydraulic design is normally appropriate only if other methods are not physically feasible. An example of such a case providing passage through a replacement culvert into a road-impounded wetland that will be preserved. Neither the low-slope or stream simulation design methods will apply so the hydraulic option with a roughened channel may be the most preferred solution.

Roughened channels are similar to natural cascade reaches. They can be designed to have banklines, shallow water margins, and other diversity to provide diverse opportunities for passage of aquatic species. A “hybrid” design uses a channel shape that is similar to the channel type that would naturally occur at the required project slope though it may not occur in the project stream.

The similarity can only be approximate since the roughened channel is a rigid, non-alluvial design. The bed material is not intended to evolve as a natural channel or a stream simulation design. It is a fixed semi-rigid structure. Individual rocks are expected to adjust position but the larger grain sizes are not expected to scour out of the reach. Bed stability is therefore essential. Smaller sediments moving across the top of the larger material and depositing temporarily will probably enrich the streambed.

Examples of hybrid-type designs in open channels can be found in Castro (2003), describing artificial step-pool and cascade reaches.

If a roughened channel is located downstream of a fixed structure, such as a culvert, it should be designed carefully. Any degradation to the channel will result in the culvert countersink or velocity criteria being exceeded. The roughened channel is most applicable upstream of culverts to control channel headcutting. The stream simulation option gives a much more conservative design for fish passage than roughened channels and should be investigated before roughened channels.

The following steps are a suggested design procedure for a roughened channel. These steps are iterative; several trials may have to be calculated to determine a final acceptable design. This procedure is adopted from Bates et al (2003); refer to that document for more details on each of the steps.

1. Assume a culvert width. A bed width equal to the natural channel width is a reasonable starting assumption.
2. Size the bed material on the basis of unit discharge for an appropriate bed stability design flow such as the 100-year event (Q100)

   Use the bed stability models described in Section 6.3.8.3, Mobility/Stability analysis models, and further described by Bates et al (2003).

   Bed stability considerations rather than fish passage velocities usually dominate the design of the bed material composition so the bed stability analysis should be performed before verifying the fish passage velocity.
3. Verify the largest bed particle size is less than one quarter the culvert bed width.

If the largest bed material is large relative to the width of the culvert bed, there are few passage options and the rocks are more likely to bridge from wall-to-wall and create a drop structure within the culvert. If the largest rocks are too large, increase the culvert width to decrease the unit discharge and, in turn, the relative and absolute particle size.

4. Create a bed material gradation to control porosity.

   In order for low flows to remain on the surface of the culvert bed and not infiltrate through a course, permeable substrate, bed porosity must be controlled in two ways. First, the design should be well graded to include fine material for an initial mix that is impermeable. This can be achieved by designing the smaller fractions of the bed material based on the D84 (and/or D100) needed for stability and roughness and on the Fuller-Thompson relationship described in Section 6.3.3.1, Stream simulation bed material.

   Second, the bed material should be checked to verify it would continue to trap bed material that is naturally recruited from the channel upstream. Smaller grains that control the porosity in the roughened channel may be washed out of the bed over time. If material transported into the roughened channel is too small to be trapped in the voids of the bed, the bed will become porous. To create an effective filter that will trap bed material, the U.S. Army Corps of Engineers (1941) method for designing filter blankets can be used. Essentially, to filter sands and gravels, D16 of the filter (roughened channel bed) must be less than five times the D84 of the source (natural bedload).

5. Verify the average velocity and energy dissipation factor (EDF) criteria

   The hydraulic fish passage design is used for the fish passage design. Velocity should at least meet criteria in Table 7-2. at the high fish passage design flow on the basis of culvert width and the bed D_{84} from gradation in previous steps. If the velocity or EDF exceed the criteria, increase the culvert span.

   Velocity and depth are commonly calculated using models that include Darcy-Weisbach friction factor or the Manning coefficient. Values of these parameters for steep channels should be based on bed characteristics rather than textbook estimates. Bathurst (1982, 1985), Ferro (1999), and Paggliara and Chiavaccini (2006) present models for calculation of channel roughness in steep channels based on bed material size.

   Minimum depth requirements in a roughened channel can be relaxed since the depth calculation is not precise and the diversity of the bed provides multiple passage pathways.

   The EDF in a roughened channel can be relatively high because the diversity in a roughened channel provides many diverse hydraulic conditions and migration pathways. Bates et al (2003) recommends as mentioned previously there is little data on the subject and there are no EDF limits suggested for species or life stages other than adult salmon. Bates et al (2003) suggest a maximum EDF of 7.0 in roughened channels for passage of adult salmon.

   No depth of flow criterion needs to be applied as long as the diversity of the bed is comparable to the size of the target species being designed for. A suggested target is that the largest particles in the bed be at least as large as the length of the target species fish.

6. Check culvert capacity for extreme flood events.

   This step is not detailed here but is required as it is for any new culvert or retrofit culvert design that affects the culvert capacity.

7.3.5.2.2 Baffles

Baffles are a feature added to a culvert to increase the hydraulic roughness of the culvert and thereby reduce the average velocity. A series of baffles works together as roughness elements rather than as individual hydraulic control structures. The flow over a series of baffles at high flow is a streaming pattern. To create streaming flow the baffles have to be relatively close together and short compared to the depth of flow. At low flow, baffles usually perform as weirs, which requires a different analysis than baffles.

Baffles within the culvert are not a desired solution and are not typically used in the design of new or replacement culverts. There are several inherent problems with them. Little is known about the effectiveness of baffles to provide fish passage conditions, especially for juvenile and weak-swimming fish. Baffles may block these fish by turbulence. The allowable turbulence (EDF) in a baffled culvert is much more limited than in a roughened channel because there is much less diversity in hydraulic conditions and migration pathways are very limited.

Many culverts currently being addressed for fish passage were originally designed only for hydraulic capacity. Adding baffles reduces hydraulic capacity. The tendency of baffles to catch woody debris exacerbates the culvert capacity problem and creates an added possibility of a fish barrier as well as culvert plugging and road fill failure.

If a culvert has a slope less than about 2.0%, bedload transported into it will likely deposit between the baffles and reduce the hydraulic effect and efficacy of the baffles. A minimum energy dissipation factor (EDF) can be used to assess the susceptibility to deposition. Though not thoroughly tested Bates (2003) recommends a minimum EDF of 3.0 for gravel-bed streams. It can be argued that the deposition of bed material then provides hydraulic characteristics for fish passage. There is very little certainty in that argument though.

The added roughness of baffles raises the hydraulic profile through the culvert and is therefore more difficult to match to the profile of the downstream channel.

Styles, designs, and a design process for baffles are described further in Appendix C – Baffles for Hydraulic Designs and by Bates et al (2003). The design process assumes that baffles are being installed only in existing culverts as a retrofit measure.

7.3.5.3 Culvert Elevation and Channel backwater

In the hydraulic method, the culvert elevation is set to satisfy two criteria.

1. Countersink the culvert into the streambed so the floor of the culvert is below the bed profile by a distance of at least 20% of the rise (height) of the culvert and a minimum of one foot.
2. Set the culvert so the normal water level within the culvert at the high fish passage design flow is at or below the backwater elevation in the downstream channel at that flow.

In a retrofit design, the culvert elevation isn't changed but the downstream channel might be modified to increase the backwater of the culvert and thereby reduce the velocity through it.

Whether it is a new installation or a retrofit of an existing culvert the culvert is countersunk into the channel profile of the low vertical adjustment range defined in Section 3.4, Project profile design.

Verify that the normal depth water surface (no *drawdown*) is at or above the water surface in the downstream channel (tailwater) at the high fish passage design flow. If the water level in the culvert is higher, the outlet condition might be a velocity and/or drop barrier. This should be checked at both the profiles of the low and high ends of the vertical adjustment range. The downstream water surface profile can be determined by either observations of the water surface at flow events near the fish passage design flow, or by calculation of the water surface profile in a uniform flow condition.

To satisfy these criteria the culvert may have to be lowered or enlarged or the downstream channel may have to be modified. The downstream backwater may have to be raised and steepened to an appropriate elevation. Grade control structures are described in Section 9, Profile Control. Several iterations of calculations and designs may be required to establish the culvert slope and roughness to satisfy both of these criteria.

An exception to these criteria might be necessary for a culvert retrofit project. In that case, a drop is allowed at the outlet as defined in Table 7-3. The drop is defined as the distance between the normal depth water level in the culvert and the downstream backwater at the high fish passage design flow.

7.3.6 Summary of Hydraulic Design Steps

The following list summarizes the steps described above for a fish passage design by the hydraulic method to achieve elevation, velocity, depth, and turbulence criteria. Several iterations of some of the steps might be necessary.

1. Complete the biological and hydrologic portions of the hydraulic design. Determine the target species, timing, swimming abilities, low fish passage design flow (Q_{LP}), and high fish passage design flow (Q_{HP}) hydrology. This analysis might have to be done for several target species.
2. Calculate the average cross-section velocity at the high fish passage design flow and compare with the design criterion.
3. If the velocity is high, add roughness and/or backwater depth and recalculate. If baffles have to be used, refer to the steps described in Section C-3.4, Summary of Baffle Hydraulic Calculations.
4. A velocity greater than the target criteria may have to be accepted if additional roughness causes other criteria (turbulence) to be exceeded and additional backwater depth is not feasible. The final design in that case should be a balance to optimize both criteria even if targets are exceeded. Whether this is an acceptable design depends on how well it satisfies the project objectives.
5. Calculate the energy dissipation factor at the high fish passage design flow and compare with the turbulence design criterion.
6. If the turbulence is high, add more backwater depth and/or balance it with the velocity criterion.
7. Calculate the water depth at the low fish passage design flow and compare with the depth design criterion.
8. If the depth is low, add roughness, baffle height, and/or backwater depth and recalculate.
9. Set the culvert and/or backwater elevation to comply with the countersink criterion and verify the normal water level in the culvert is no higher than the channel backwater.

These steps are modified if baffles are included in the design. See Appendix C – Baffles for Hydraulic Designs.

The design should also meet or exceed other applicable local, state, or federal standards for hydraulic capacity, headwater depth, and other design parameters.

8. Alternative Designs

The design approaches described in this guideline are the result of advances in stream crossing design technology from focused research and evaluation over the past decade. Recognizing that techniques used in designing stream crossings for aquatic organism passage are rapidly evolving, the evaluation of alternative design methods will be a necessary component to further our understanding of this complex issue. However, it must also be recognized that Vermont has hundreds of examples of projects previously “designed” for fish and aquatic organism passage that have not fulfilled their project objectives, and which will remain passage barriers for decades until their replacement or retrofit.

It is critical that stream crossing designs for aquatic organism passage incorporate the principles, concepts, and considerations presented in this guideline document to be considered as acceptable alternatives. Follow-up evaluations on the biological, fluvial and structural performance of these crossings will be important to make further meaningful advances in our ability to design structures which successfully pass aquatic organisms while minimizing project costs.

To meet the objective of aquatic organism passage, the following performance standards should be met:

- Design the structure to maintain a streambed composition and form throughout the culvert similar to and continuous with the adjacent reaches. To do this,
    - Design and install streambed material and bedforms if not adequately supplied and developed naturally,
    - Design profile and alignment through structure similar to those of adjacent stream reaches,
    - Design culvert elevation to remain embedded for the life of the structure and in consideration of future channel conditions.
- Maintain velocities, turbulence, and depths within the structure similar to those found in adjacent stream reaches across a range of desired flows.

9. Profile Control

Profile control structures are artificial structures that control the channel elevation in a *forced profile*. They are used outside of the culvert as one possible remedy to a large elevation drop across the crossing as in Figure 3-8.

The need and general scale of profile controls are defined in Section 3.4, Project profile design.

The general information given here is not adequate for a complete design. U.S. Department of Agriculture Natural Resource Conservation Service (2001), Rosgen (1996), and Saldi-Caromile et al (2004) provide detailed descriptions, design considerations and limitations.

Specific structures may or may not be compatible with the premise of stream simulation depending on how well they mimic structures found in the natural channel. Artificial profile control structures are sometimes part of the compromise made to maintain a grade through a site that is steeper than natural. Biological monitoring may be necessary to determine the suitability of these constructed features with respect to passage of specific aquatic organisms.

The more rigid a control structure is and the more uniform in cross-section and hydraulic characteristics, the less certain that passage is provided for aquatic organisms. If sills are used, select a design that best preserves natural channel shape and diversity. Boulder and log weirs can be designed to imitate natural steps, and are appropriate for stream simulation in step-pool channels and channels with forcing features such as colluvium and debris. In other channel types, the degree to which they permit passage of aquatic organisms will vary. The key is to design any control structure for maximum variety of passage opportunities.

Do not place any drop structure near the culvert inlet. If the energy dissipated below the structure scours the culvert bed, any streambed within the culvert can be affected and potentially washed out of the culvert. Leave enough space for a pool and its tailout to form downstream of the structure without affecting the culvert inlet. Likewise, profile controls should not be located near the outlet. If the culvert is sized and channel is built as stream simulation, a control structure should not be closer to the culvert than one channel width, and further if the crossing constricts the floodplain. If the culvert and bed are not stream simulation, keep the first downstream structure far enough away so there is room for a scour pool and energy dissipation at the outlet. A rule of thumb is to keep it at least twenty-five feet away. Use any existing scour pool as a guide and consider additional energy that will be concentrated at the outlet due to retrofit modifications.

Be aware that profile controls have the risk of a “domino” failure. A failure of one structure or the downstream channel can propagate upstream, undermine the next control, and cause additional weir failures. If a culvert upstream depends on the elevation established by the controls, it can also be at risk of failure. All profile control options have this risk but it is greatest with boulder weirs.

9.1 Channel rehabilitation

USDA-Forest Service (in press) describes channel rehabilitation as the re-establishment of structure, grade, and function of the stream with the goal of achieving a self-sustaining channel that can be stable over the long term. It is the most elegant and durable way to correct a large elevation drop caused by channel incision, rather than forcing the culvert into an artificially oversteepened profile. Rehabilitation might include realigning the channel to restore the meander pattern and channel length. Alternatively, the downcut bed could be built back up to a profile and elevation that provides access to the culvert.

Channel rehabilitation should be considered as an option in any project associated with an incised channel. The opportunity for channel rehabilitation should be recognized in the pre-design phase, see Section 3.4.2, Scale of the project.

A project that includes restoration of an incised channel can extend a long distance downstream, and may be the most expensive option available. Its benefit is that it may have habitat restoration values that go far beyond passage of aquatic organisms; for example, such a project can restore in-stream, riparian and floodplain habitats, and channel-floodplain interactions. Side-channels previously blocked by the existing culvert or roadfill can be reconnected. It can also reverse bank erosion, and is likely to be more self-sustaining than other options.

If channel degradation has been caused by a change in the watershed's flow regime, perhaps due to land use changes, it may not be possible to rehabilitate the channel to historic, predisturbance conditions. Instead, design the channel for the current and future hydrologic regime. There are a number of valuable design references for channel rehabilitation. See FISRWG (1998) for an introduction to the process of channel rehabilitation. See also Douglas et al (2003), and Saldi-Caromile et al (2003) among others.

9.2 Boulder Weirs

Low boulder weirs have been built for many years as retrofits to backwater perched culverts and low dams and to control channel grades. Though many of those structures have deteriorated and disappeared over time, they can be durable and effective if designed and constructed well. Their success depends to a large degree on the size and quality of material used, the care and skill of the equipment operator, supervision, and equipment used to place the rocks.

The diversity of boulders in a weir create a number of possible passage routes over them. They have a discrete drop that a fish must swim through.

To create a long-lasting structure, rock should be durable and shaped so that individual rocks can be keyed together. Specific rocks should be individually selected to fit together; somewhat angular boulders and rectangular are much more stable than round ones. Boulders are commonly sized based on experience and by observation of the channel; there are no analytical tools specifically for this purpose. A common rule of thumb is to use rock twice the size of the largest mobile particles in the channel. Designers can also use references for riprap bank protection in turbulent flow, such as the U.S. Army Corps of Engineers (1994) or U.S. Dept. of Transportation (1989). The USDA Natural Resources Conservation Service (2001) suggests that D_{50} of the weir rock be equal to what is calculated as stable riprap, and that D_{100} be twice that size. Scour depth is also a factor. For a one-foot drop, rocks should be founded on footer rocks, which should be embedded about 2.5 feet in gravel and 3.5 feet in sand beds.

Carefully place individual rocks with equipment that allows the rock to be rotated for precise alignment and fitting. In plan view, the weir is shaped like an arch or a "V" pointing upstream so rocks support each other. First, place footer rocks below the elevation of the final grade to support the header rocks. Then place header rocks against the footer boulders and slightly upstream of them so that they are supported against them. Fit them against each other continuing the arch shape, so that each boulder bears against its downstream neighbor and ideally two footer rocks below it. The force of the streamflow and bedload is then transferred through the weir to the footer rocks and banks.

In cross-section, the weir crest should slope down toward the middle and should approximate the cross-section of the stream. Key end boulders into the banks to bankfull elevation. Place well-graded seal material with some fines on the upstream side of the control to limit permeability and leakage through the structure. Bed material that accumulates on the upstream face of the weir provides much of the structural integrity and sealing of boulder weirs. If there is no continued recruitment of sediment to maintain the weirs, they will become more porous, allowing them to leak and become vulnerable to failure. See Saldi-Caromile et al (2004) for a more complete description of rock weirs and other drop structures.

Upstream of a culvert, the V can be offset to one side of the channel, if necessary, to improve culvert inlet alignment at bankfull flow.

Boulder weirs carry the risk of “domino” failure. If one weir in a series fails, the risk of other failures increases as the added head differential increases the plunging flow, scour, and hydrostatic forces on the next weir upstream.

9.3 Roughened Channel

Roughened channels are described in Section 7.3.5.2.1, Roughened Channel as a roughness feature inside of culverts. The principles described there apply to roughened channels outside of culverts as well as a profile control feature.

9.4 Chutes

A chute is a short steep reach constructed within a low gradient channel that mimics similar forms in natural channels. Like a roughened channel, it is designed to be semi-rigid and permanent. Its similarity to a natural mobile feature is therefore limited.

They are a combination of a boulder weir and a roughened channel. Think of a chute as a pair of boulder weirs more or less a channel width apart with a roughened channel between them. They are constructed of natural cobble and gravel and the downstream face typically slopes 5% to 10%. They are constructed in a series spaced so energy is dissipated in the pools between the chutes and the overall channel slopes up to about 2.5% and possibly higher in smaller streams.

The weirs support and define each short roughened channel. They are constructed with a cross-section V-configuration to concentrate low flow and to provide a diversity of hydraulic conditions at all flows. The flow along the margin is shallow at all flows contained within the V and provides a low-energy passage corridor. The plan view shape is concave with the opening pointing downstream so flows are concentrated towards the center of the channel creating diverse hydraulic conditions.

A benefit of chutes compared to roughened channels is that much of the energy is dissipated in the scour hole below each chute rather than just by the roughness of the chute itself. The individual chutes are roughness elements of a much larger scale than individual boulders. They are also valuable because upstream and downstream migrants only have to negotiate a short reach instead of along continuous slope.

9.5 Rigid Weirs

Rigid Weirs are fixed non-deformable structures used to control the channel profile precisely. They can be built out 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 other steepened channel options, thus minimizing the project footprint. They can also be built to function well even at very low flow.

Uniform rigid weirs often have negative impacts on aquatic habitats of some species. They tend to create channel structure that is trapezoidal and uniform in cross section. Full channel-spanning horizontal structures lack the variety of passageways found in rock structures though they may simulate embedded wood structures in a natural situation.

Like rock structures, they must be designed and constructed correctly to prevent failure. Poorly designed structures commonly fail by scouring either under or around the end of the structure. Rigid structures are more likely to become barriers to fish passage when downstream scour occurs than are flexible structures.

Log sills can be built into the streambed to span the entire channel and create a series of small drops to raise the downstream water surface up to the elevation of a culvert. They are a low-cost and durable means of fish passage for streams with moderate gradients and channel toe widths of less than about 30 feet. They are typically used downstream of a culvert, but may also be used upstream. There are a variety of designs; single logs, multiple stacked logs, straight weirs, angled weirs, V-weirs, and K-dams.

Simple, straight, double-log sills are the most secure and the easiest to construct. These require the least overall channel length and are the least costly of the styles. They can be placed to a maximum grade of 5 percent.

Styles that dip toward the middle of the channel or angle downstream tend to create more channel complexity and diversity. They are more complicated to build and may have to be built on a lower gradient. Because of the recommended maximum slope for a series of log sills, it is difficult to steepen a channel with a natural slope already greater than about 3 percent.

An advantage of precast concrete or steel sheet-pile weirs is that they can be manufactured precisely, resulting in a good seal, with a varied cross-section similar to the natural channel, and a crest shape that is specifically designed for fish passage. They can be designed to include diversity by building variability into the weir crest.

Installations can be custom-designed to fit the needs of the site; for example, a single pre-cast concrete unit could include a weir, a stilling basin, and wing walls. Steel-pile weirs can be solid sheet-piles or H-piles with wood or pre-cast concrete lagging between them.

Concrete highway median barriers and “ecology blocks” are not recommend; they commonly fail when used as weirs unless they are anchored for stability, modified to provide a sharp crest and a deep plunge pool, and are sealed permanently to prevent leakage.

10. Final Design

Final design is the completion of the design to make it ready for contracting and construction. It includes structural and dimensional details of the structure, road fill, and channel modifications. The high flow capacity must be checked. Final design and specifications documents are prepared and project controls are established. Final design may also include project sequencing, care of the site and stream, and other special provisions.

Most final design elements are the same for any culvert design. Elements described here are only those that affect the design for passage of aquatic organisms.

10.1 Culvert shape, style, and material

Culvert size, elevation and alignment issues have been defined in previous design phases. Other key design parameters in the final design are culvert shape, style, material, and thickness. These design elements are more related to site conditions, constructability, designer preference and cost. Considerations include

- Commercial availability,
- Structure longevity,
- Road elevation,
- Streambed and culvert constructability,
- Construction time, sequencing, and allowable 'in-water' work period,
- Soil bearing capacity,
- Site access, and
- Flood capacity.

Since these are not usually directly related to passage of fish or other aquatic organisms, no more detail is provided here. Further guidance for selecting the shape, style, and culvert material is provided by USDA-Forest Service (in press).

10.2 Hydraulic Capacity

Regardless of the design option used, the high flow capacity of the culvert must be checked to ensure stability of the culvert and road fill during extreme flow events.

Road fill stability, road overtopping, allowable headwater depth, the likelihood of debris plugging the culvert, backwater effects, or a combination of these factors might determine the high flow capacity. In assessing for stability, consider that in forested environments culvert failures caused by debris plugging are often more frequent than failures due solely to flow capacity.

Probability of failure can be minimized by a variety or combination of ways; adequate flood and debris capacity and culvert height, design for overtopping or routing excess flow past the culvert without jeopardizing the culvert or associated fill, or preventing diversions. Design practices can help; minimize and account for uncertainties in hydrologic and hydraulic models with better site-specific data or better models.

Design for risk of failure. Once you've designed the installation to not fail, consider what the consequences would be if or when it does fail. Minimize the consequences of failure even if the probability is low.

Design the high flow capacity for the situation in which the streambed is at its highest adjustment profile (see Section 3.4.1, Channel vertical adjustment range) simultaneously with the high structural design flood.

The design of a culvert should consider future peak flows as land uses change. Usually the size and shape of the culvert, as developed by the design processes described in this manual, will be adequate to pass most debris and bed material. A culvert designed by the hydraulic design method may not have adequate size for debris passage so an alternative design may be more appropriate.

The standard practice for analysis for flow capacity is to analyze the backwater created by the culvert and limit it to some elevation relative to the culvert inlet. Models for this analysis are mentioned in Section 7.3.5, Hydraulic Criteria; Velocity, Jump Height, Depth, and Turbulence. Roughness calculations for stream simulation and roughened channels are found in the references mentioned in Section 6.3.8.3, Mobility/Stability analysis models, and roughness calculations for baffles are described in Appendix C – Baffles for Hydraulic Designs.

As described in Section 6.3.8, Bed mobility and stability analysis, a stream simulation culvert should not become pressurized during the high bed stability design flow.

The design should also meet or exceed other applicable local, state, or federal standards for hydraulic capacity, headwater depth, and other design parameters. Other standards might include VTrans Hydraulics Manual, project environmental documents, VTrans Structures Manual, and AASHTO Specifications for Highway Bridges. For example, the VTrans Hydraulics Manual requires culverts to have flood capacities that vary from a 25-year flood to a 100-year flood by road class. These criteria may be more or less than what would be prudent for protection of passage facilities and habitat.

10.3 Design Documentation

Documentation is important for any design to preserve the design process for future reference. Good documentation should summarize methods, assumptions, data sources, calculations, and conclusions.

Good documentation will help reviewers and managers to understand the project and design process for the purposes of permitting, prioritizing, and funding. Not all details are needed for every project; depending on the site and design, some sections may not be applicable.

A checklist for the documentation of design for passage of aquatic organisms is included in Appendix D. The items listed there will provide full documentation of the site and project data, design process, calculations, and assumptions. The checklist is arranged in a logical order from assessment to design.

Designers are encouraged to work with the checklists or similar tools.

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Appendix A - Glossary

Aggradation: The geologic process by which a streambed is raised in elevation by the deposition of additional material transported from upstream (opposite of degradation).

Backwater: Stream water, obstructed by some downstream hydraulic control, is slowed or stopped from flowing at its normal, open-channel flow condition.

Baffle: Structures mounted in a series on the floor and/or wall of a culvert to increase boundary roughness, thereby reducing the average water velocity and increasing water depth within the culvert.

Bankfull height and width: The bankfull channel is defined as the water level (stage) when water just begins to overflow into the active floodplain. Bankfull height is the vertical distance from the thalweg to the bankfull elevation. Determining bankfull width requires the presence of a floodplain or a bench. In cases where these features are absent, bankfull channel is determined using features that do not depend on a floodplain, such as those used in the description of ordinary high water.

Bed: The land below the ordinary high water lines of the waters of the state of Vermont. This definition does not include irrigation ditches, canals, storm water devices or artificial watercourses, except where they exist in a natural watercourse that has been altered by man.

Bedload: The part of sediment transport that is not in suspension, consisting of coarse material moving on or near the channel bed surface.

Bed retention sill: Structure placed in the bottom of a culvert to trap and hold the bed material inside the pipe.

Bed roughness: The unevenness of streambed material (i.e. gravel, cobbles) that contributes resistance to stream flow. The degree of roughness is commonly expressed using Manning's roughness coefficient.

Cascade: A series of small, vertical drops within a channel. They can be natural or man-made.

Debris: Material distributed along and within a channel or its floodplain either by natural processes or human influences. This includes gravel, cobble, rubble and boulder-sized sediments, as well as trees and other organic accumulation scattered about by either natural processes or human influences.

Degradation: The removal of streambed materials caused by the erosional force of water flow that results in a lowering of the bed elevation throughout a reach (opposite of *aggradation.*)

Deposition: The settlement of material onto the channel-bed surface or floodplain.

Dewater: To remove water from an area.

Dxxx: The size of a particle of which xxx percent (e.g. 84%) of the particles of a mix are smaller. For example 84% of the particles in a specific mix have median dimensions smaller than D84. The median dimension of a particle is commonly used for this analysis.

Energy dissipation factor (EDF): The power dissipated per unit volume of flow in channels and fishway pools as a criterion for maximum allowable turbulence.

Entrenchment: The ratio of the channel bankfull width to the valley *floodprone* width.

FIshway: A system specifically designed for passage of fish over, around or through an obstruction. Such systems include hydraulic-control devices, special attraction devices, entrances, collection and transportation channels, fish ladders, exits, and operation and maintenance standards.

Floodprone width: The width of the valley at an elevation twice the bankfull height.

Forced profile: A constructed channel profile that is controlled artificially.

Gradient: The slope of a stream-channel bed or water surface, expressed as a percentage of the drop in elevation divided by the distance in which the drop is measured.

Headcut: Erosion and lowering of the channel bed, progressing in an upstream direction, creating an incised channel. Generally recognized as small, vertical drops or waterfalls, or abnormally over-steepened channel segments. See *nick point*.

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

Nick point: A steep inflection in a channel profile created by erosion and lowering of the downstream channel but where the upstream channel is resistant to erosion or has not yet been incised. A nick point can be permanent or temporary. See *headcut*.

Ordinary high water (OHW): The line on the shore in non-tidal areas established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding area.

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

Reach: A section of a stream having similar physical and biological characteristics.

Rehabilitate (habitat or channel): Return of a degraded stream ecosystem to a close approximation of its remaining natural potential. *(Shields et al, 2003)*

Restore (habitat or channel): Return existing habitats to a known past state or to an approximation of the natural condition by repairing degradation, by removing introduced species or by reinstatement. (*Australia Department of Environment and Heritage, 2003*)

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

Rise: The maximum, vertical, open dimension of a culvert; equal to the diameter in a round culvert and the height in a rectangular culvert.

Scour: The process of removing material from the bed or banks of a channel through the erosive action of flowing water.

Shear stress: A measure of the erosive force acting on and parallel to the flow of water. It is expressed as force per unit area (lb/ft2). In a channel, shear stress is created by water flowing parallel to the boundaries of the channel; bank shear is a combined function of the flow magnitude and duration, as well as the shape of the bend and channel cross section.

Slope: Vertical change with respect to horizontal distance within the channel (*see gradient*).

Substrate: Mineral and organic material that forms the bed of a stream.

Thalweg: The longitudinal line connecting the deepest points in a stream.

Vertical adjustment range (VAR): The range of channel profiles the channel might experience during the life of the new project. The initial VAR is established with the assumption that no culvert or other artificial control is present. If that VAR is not acceptable, a forced profile will be necessary to change the VAR.

Weir: A small dam that causes water to back up behind it, with plunging flow over it. Weirs are often notched to concentrate low-flow water conditions.

Appendix B – Vermont High Fish Passage Design Flows

The hydraulic design option (Section 7; Hydraulic Design) requires the determination of high fish passage design flows to use in conjunction with biological criteria (swim speeds, jump heights, etc.) to design stream crossing structures capable of passing target species/lifestages at critical times. The intent of the hydraulic design is that the selected biological criteria will be satisfied at all flows between the low and high design flows. This appendix describes derivation of models to estimate high fish passage design flows in Vermont.

The primary periods of concern for spawning movements of fish in Vermont is during the spring and fall, more specifically April/May and October/November (Table 7-1). For these periods, April and November represent the higher flows for spring and fall periods, respectively. While fish movements also occur at other times of the year, the April and November periods reflect the highest flow conditions when critical spawning fish movements can be anticipated for a given species. Depending on which species are expected at a site, either or both of the spring and fall design flows might be applicable.

Methods

The high fish passage flow models were derived from historical flow data. Monthly flow statistics from a subset of USGS gauge stations in Vermont and western New Hampshire were selected for analysis based upon the following criteria:

- watershed size <50 mi^2
- minimum period of record $\geq$ 10 years
- unregulated or minimally regulated waters

This selection resulted in a total of 20 gauge sites, including two from western New Hampshire (Table 1). Drainage area of these streams ranged from 2.09 to 44.3 mi^2.

Annual, monthly or spawning period exceedance flows (e.g. 2%, 5%, 10%) are often used to define high passage design flows for fish passage (Powers and Saunders 2002). The use of multiple-day exceedance flows provides the additional benefit of developing criteria that account for both the frequency of flows at which passage is desired and the maximum duration of flows when fish will be delayed during spawning movements. Fish on spawning migrations will often continue to attempt to access structures under impassable conditions, expending critical energy reserves during a physiologically stressful period. Delays may increase the likelihood of stress, leaving fish vulnerable to injury, predation and disease and may ultimately reduce spawning success (Lang et. al. 2004).

A review of various flow thresholds against annual hydrographs of several Vermont streams revealed that the 2-day 20% high exceedance flows for both April and November, when used as design flow, appears to provide for unrestricted fish passage for the majority of fish spawning periods in most years, while generally avoiding significant periods of delay. Annual flows vary widely, and it should be recognized that flows greater than these design flows may disrupt spawning movements of fish in some years. Figures 1 and 2 show annual hydrographs for two Vermont streams where these design flows are exceeded for several days in the spring and fall, respectively. Additional protection for spawning movements can be applied by using more conservative flow criteria when warranted.

Regression Analysis:

To calculate high passage flow criteria for structures on ungauged streams, a linear statistical model using readily available measures as independent variables was developed. Least squares stepwise multiple regression analysis was conducted to determine the best predictors of the 2-day 20% exceedance flows for April and November (cubic feet/second/ mi^2 drainage area; csm) from among a variety of physical watershed descriptors. The following parameters were determined to explain the greatest amount of variability in 2-day 20% exceedance flows for April and November, without exhibiting excessive autocorrelation (maximum Spearman R = 0.43):

- Portion of basin that is a lake or pond (Nov. only)
- Northing (Y coordinate of the basin centroid in map coordinates) (Vermont State Plane Coordinates; VSPC) (April only)
- Mean annual precipitation in inches (April and Nov.)

Results

The April model was highly significant (R^2 adj = 0.7, $F_{2,17}$ = 22.7, p<0.0001, RMSE = 3.84 csm), and takes the form:

$$\textbf{April } Q_{2\text{-}20} = A_{Basin} \times (-41.15 + 0.000038 \times \text{Northing} + 1.248 \times P)$$

Where:

- April $Q_{2\text{-}20}$ is the flow (in cubic feet per second) that has a 20% probability of being exceeded for 2 consecutive days in April.
- A_{Basin} is the area of the basin above the project in square miles.
- Northing is the distance north in Vermont State Plane Coordinates (VSPC).
- P is mean annual precipitation in inches.

The November model was also highly significant (R^2 adj = 0.60, $F_{2,17}$ = 13.04, p=0.0004, RMSE = 2.52 csm), and takes the form:

$$\textbf{Nov } Q_{2\text{-}20} = A_{Basin} \times (-13.709 + 0.4555 \times P + 3.0855 \times \text{logN}(1 + A_{Lakes}))$$

Where:

- November $Q_{2\text{-}20}$ is the flow (in cubic feet per second) that has a 20% probability of being exceeded for 2 consecutive days in November.
- A_{Basin} is the area of the basin above the project in square miles.
- P is mean annual precipitation in inches.
- A_{Lakes} is the portion of the watershed area in lakes and ponds.

Application

A VDFW Fisheries Biologist will determine the target species and appropriate spawning period. Steps to calculate high passage design flows for stream crossing structures in Vermont streams are provided for each spawning period:

Spring Spawning High Passage Design Flow Calculation

1. Use the *Basin Characteristics* feature of the USGS Vermont Streamstats interactive map http://water.usgs.gov/osw/streamstats/Vermont.html to define:

   a. the drainage area above the proposed stream crossing structure (square miles)

   b. a northing reading for the structure location (Y-coordinate of centroid)

   c. mean annual precipitation for the watershed (inches)

2. Use values determined from Steps 1 a, b and c, in the April model to determine the April 2-day 20% exceedance flow. This is the Spring Spawning High Passage Design Flow.

Example:

Bull Run Brook, Bull Run Road, Northfield

Target Species: Rainbow trout (spring spawner)

1. Drainage area = 7.8 mi^2
2. Northing = 174859
3. Mean annual precipitation = 43 inches
4. April $Q_{2\text{-}20} = A_{Basin}$ x (-41.15 + 0.000038 x VSPC Northing + 1.248 x P)
   April $Q_{2\text{-}20}$ =7.8 mi^2 x (-41.15 + 0.000038 x 174859 + 1.248 x 43)
   April $Q_{2\text{-}20}$ = 149 cfs

Fall Spawning High Passage Design Flow Calculation:

1. Use the *Basin Characteristics* feature of the USGS Vermont Streamstats interactive map http://water.usgs.gov/osw/streamstats/Vermont.html to define:

   a. the drainage area above the proposed stream crossing structure (square miles)

   b. the percent of basin area that is lakes and ponds (0.000-100.000)

   c. mean annual precipitation for the watershed (inches)

2. Use values determined from Steps 1 a, b and c, in the November model to determine the November 2-day 20% exceedance flow. This is the Fall Spawning High Passage Design Flow.

Example:

Woodward Brook, Carrie Howe Road, Roxbury

Target Species: Brook trout, (fall spawner)

1. Drainage area = 1.57 mi^2
2. Portion of basin area that is lake or pond = 0.0123 (1.23% of basin area)
3. Mean annual precipitation = 44.4 inches
4. Nov $Q_{2-20} = A_{Basin} \times (-13.709 + 0.4555 \times P + 3.0855 \times \ln(1+ A_{Lakes}))$
   Nov $Q_{2-20} = 1.57 \times (-13.709 + 0.4555 \times 44.4 + 3.0855 \times \ln(1+0.0123))$
   Nov Q_{2-20} = 10.3 cfs

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Table 1. Summary statistics from subset of USGS gauge stations (recreated from Olson, 2002, and USGS unpublished analysis). Abbreviations: 2-yr rec = 2 year recurrence flow; 7Q2 = 7-day low flow, 2 year recurrence; cfs = cubic feet /second;

csm = cubic feet /second/square mile of drainage area.

River	USGS #	Record	Drainage area	% lake or pond	% above 1200'	Northing (VSPC)	mean annual precip (inches)	2-yr rec (cfs)	2-yr rec (csm)	April 2day-H (20%) csm	Nov 2day-H (20%) csm	7Q2 (csm)
Kirby	01134800	63-74	8.13	0.361	74.0	220716	41.8	225	27.68	19.0	5.2	0.088
Pope Brook	01135150	91-04	3.27	0.038	98.7	220797	44.0	146	44.65	21.9	6.5	0.347
E. Orange Branch	01139800	58-2004	8.79	0.162	100.0	177164	41.7	245	27.87	14.5	4.9	0.178
S. Branch Waits	01140000	40-51	43.80	0.172	69.3	169051	39.8	961	21.94	12.5	4.8	0.143
Mink (NH)	01141800	63-98	4.88	0.289	90.6	133909	40.8	216	44.26	18.7	6.0	0.036
Ayers	01142500	40-75,77-04	30.50	0.199	65.0	167034	40.6	703	23.05	16.1	4.7	0.153
Kent	01150800	64-74	3.26	0.490	100.0	128291	55.0	117	35.89	23.6	11.8	0.286
Ottauquechee	01150900	85-04	23.30	0.841	97.8	128834	52.6	944	40.52	33.8	12.0	0.272
Sacketts	01155200	63-74	10.02	0.486	22.4	57835	43.3	140	13.97	15.7	4.1	0.176
Flood	01155300	63-74	9.28	0.403	100.0	83942	51.2	217	23.38	26.2	10.0	0.084
Otter Brook (NH)	01158500	24-58	41.90	2.120	89.1	57814	43.9	1150	27.45	17.8	7.9	0.108
Beaver	01167800	63-77	6.36	0.520	100.0	39854	53.0	360	56.60	30.4	18.9	0.082
Mettawee trib	04280300	63-74	2.09	0.018	48.9	93099	45.8	34	16.46	12.3	5.8	0.058
Lewis Creek trib	04282700	63-74	5.34	0.189	70.5	194167	45.1	118	22.10	22.3	4.8	0.064
Laplatte	04282795	90-04	44.30	1.100	1.8	204271	36.3	1040	23.48	11.4	9.4	0.045
Sunny	04287300	64-74	2.38	0.000	31.1	198551	39.8	73	30.63	20.4	4.7	0.026
Green River	04291000	15-20,23-32	15.90	6.860	97.6	239564	45.5	429	26.98	26.5	13.0	0.293
Stony Brook	04292100	63-74	4.24	0.644	82.4	246254	48.5	212	50.00	33.1	7.8	0.225
Stone Bridge Brook	04292700	63-74,90-00	8.41	0.478	0.0	245095	36.9	168	19.98	11.3	5.7	0.103
Brownington	04296200	63-74	2.21	0.000	98.2	257480	44.4	35	15.66	23.3	8.8	0.010
Mean (<50 mi2)			***13.92***	***0.77***	***71.87***		***44.50***	***376.65***	***29.63***	***20.53***	***7.84***	***0.139***
SD			**14.57**	**1.51**	**33.59**		**5.27**	**365.86**	**11.93**	**6.95**	**3.79**	**0.100**

Figure 1. Annual hydrograph of average daily flows and selected flow parameters for Ayers Brook, 1994 (source: USGS)

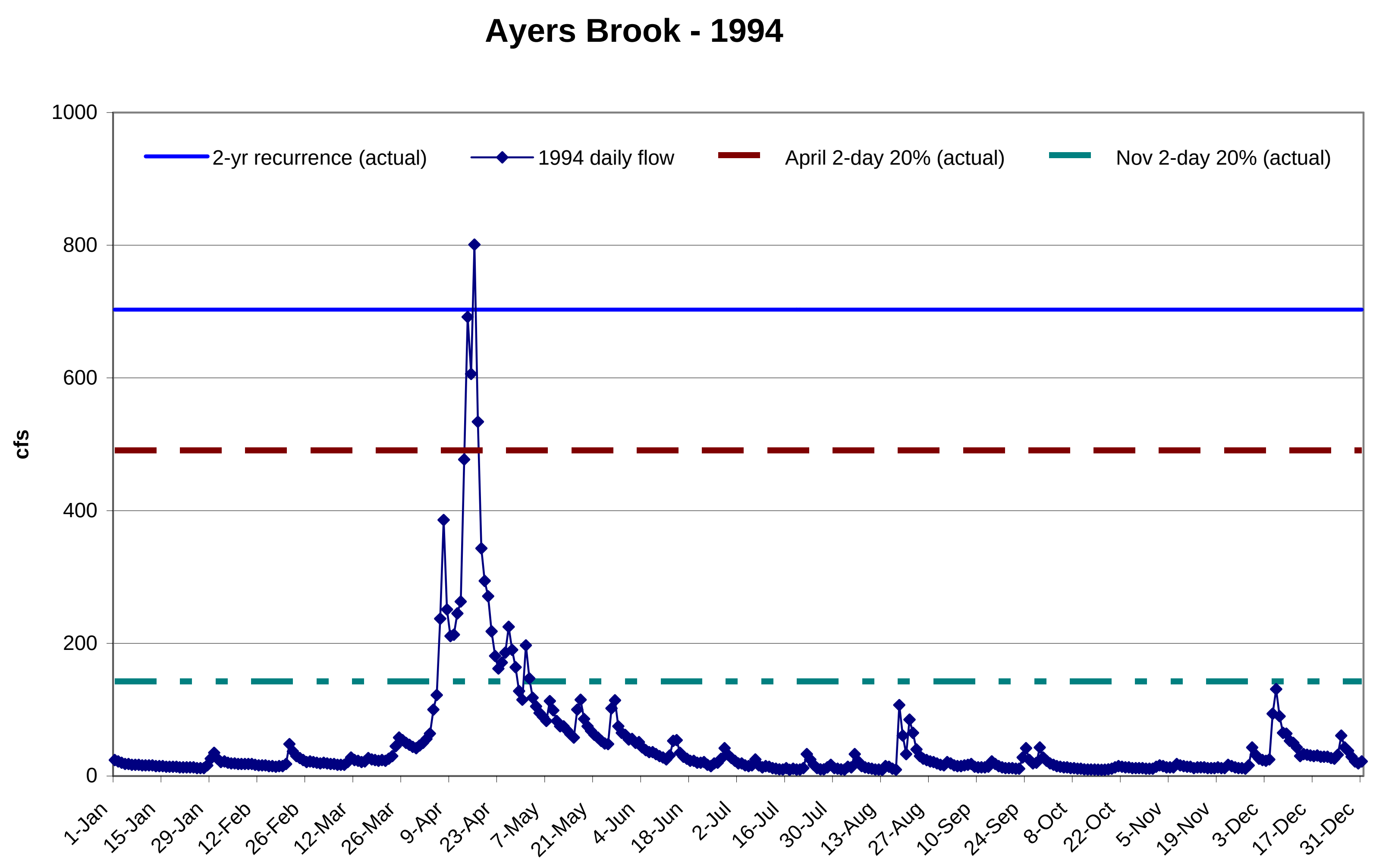
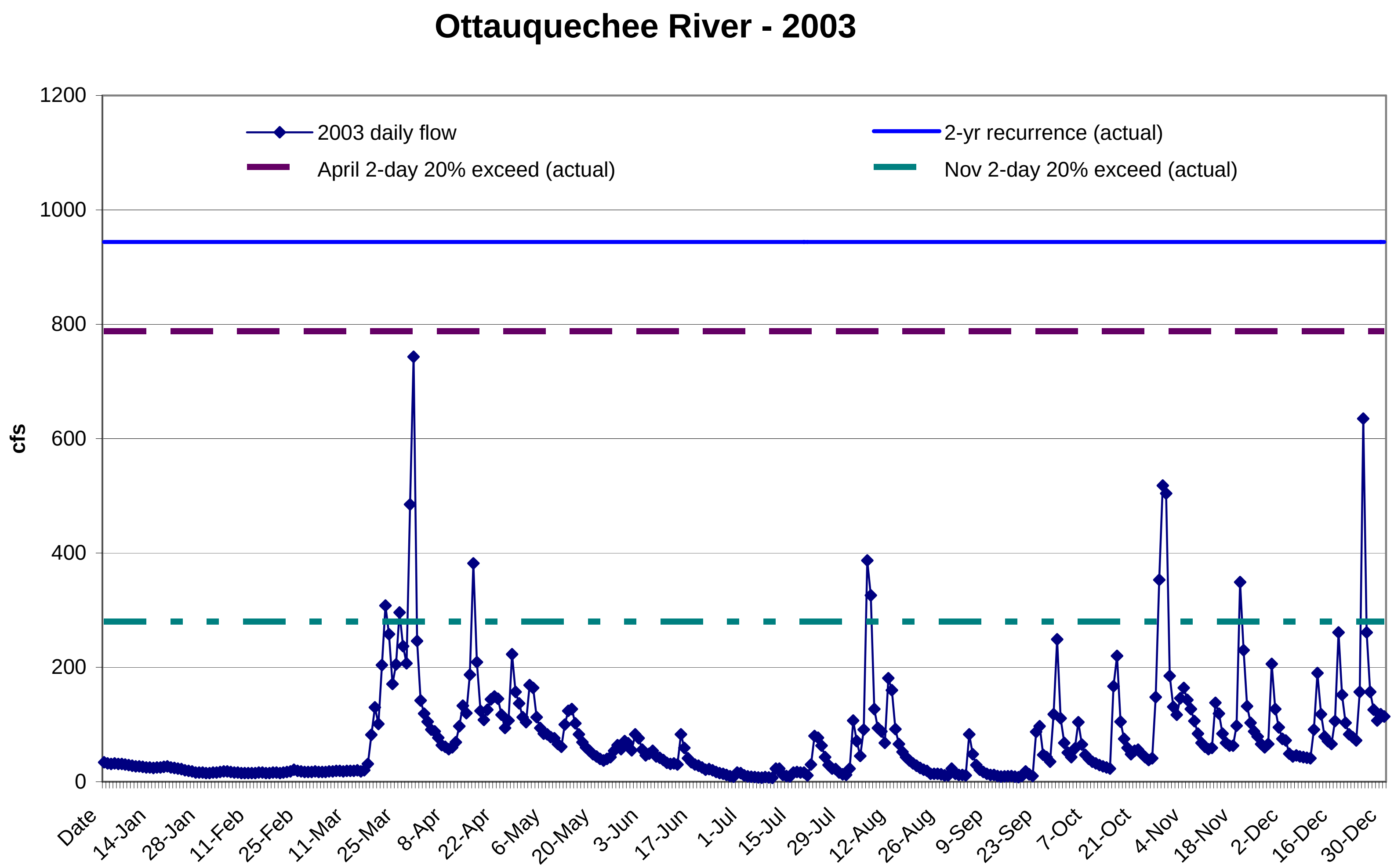


Figure 2. Annual hydrograph of average daily flows and selected flow parameters for the Ottauqueechee River, 2003 (source: USGS)



Appendix C – Baffles for Hydraulic Designs

This appendix describes styles and design of baffles for the hydraulic design method.

Baffles are a series of features added to a culvert that work together to increase the hydraulic roughness of the culvert and thereby reduce the average velocity. The flow over a series of baffles at high flow is a streaming pattern. To create streaming flow the baffles have to be relatively close together and short compared to the depth of flow.

Weirs on the other hand are discreet hydraulic elements. The flow plunges over each weir and the energy of each drop is dissipated in the pools between weirs. This is a very different concept than baffles acting as roughness. Typical baffles act as weirs at low flows and transition to roughness elements at higher flows. When designed as weirs, *fishway* design criteria should be applied. Those criteria are not discussed here but are discussed by Bates (2000).

As described in Section 7.3.5.2.2, Baffles, baffles within the culvert are not a desired solution and are not typically used in the design of new or replacement culverts. Little is known about the effectiveness of baffles to provide fish passage conditions, especially for juvenile and weak-swimming fish.

Many culverts currently being addressed for fish passage were originally designed only for hydraulic capacity. Adding baffles reduces hydraulic capacity. The tendency of baffles to catch woody debris exacerbates the culvert capacity problem and creates an added possibility of a fish barrier as well as culvert plugging and road fill failure.

It is often not possible to satisfy desired design criteria with baffles. Criteria of maximum velocity, maximum turbulence, sediment deposition, and culvert capacity often conflict with each other. Project objectives may have to be balanced to improve fish passage even though criteria are not entirely satisfied. The designer should recognize these conflicts and balance them for the most prudent and safe design.

C-1 Baffle Design

Baffles are steel, concrete, or wood panels placed vertically and attached to the floor and/or walls of a culvert. They typically are 6-18 inches high depending on culvert slope, desired velocity reduction, allowable turbulence, and culvert capacity. They can be bolted, wedged, or welded in place.

The hydraulic design of baffles for fish passage is a balance between making a culvert too smooth (excess velocity) and too rough (excess turbulence and/or bedload deposition).

Culverts with baffles are generally limited to slopes less than or equal to about 3.5% (Bates, 2003). At higher slopes, the flow does not transition to streaming flow and is very turbulent. Stream simulation or fishway weir designs are utilized for steeper slopes.

A design process is described below. The results for different criteria often conflict with one another in which case there may not be a valid baffle design. Objectives of the project might not be satisfied by a hydraulic design solution.

There are no precise hydraulic models for many baffle designs because experiments have been performed only on a few baffle designs. An analysis of baffles requires considerable engineering judgment; a person with expertise and or experience in hydraulic engineering should generally develop designs.

Starting with the biological design criteria for the hydraulic design the design of baffles follows the summary of steps described in Section 7, Hydraulic Design. As addition detail to those steps the baffle style, dimension, spacing, and installation details have to be determined. There is no direct solution; any of these steps might be iterative.

C-2 Baffle Styles

Three basic styles of baffle are suggested; two for round culverts and one for box culverts. They are shown in Equation C- 1. They are all designed with the alignment of notches continuously along one wall or in the center rather than alternating back and forth. This allows less resistance to high flows and an uninterrupted line of fish passage along one or both sides. This is particularly important for weak fish, which would be forced to cross the high velocity zone at every baffle in an alternating baffle design. Two details of angled baffles are shown for box culverts; the continuously sloped baffle is generally used for juvenile passage situations and in culverts six feet wide and less. The intent is to have enough of a slope to the baffle so the upper corner of the baffle is exposed or only barely submerged at the high fish passage design flow.

Corner baffles are placed on only one side of culvert perpendicular to flow in small culverts or on both sides for larger culverts. They are intended to provide wall roughness with minimum potential for blockage by debris.

The notched baffle is similar but for a wider culvert. It is two corner baffles with a sill between them to maintain a depth of water at low flow.

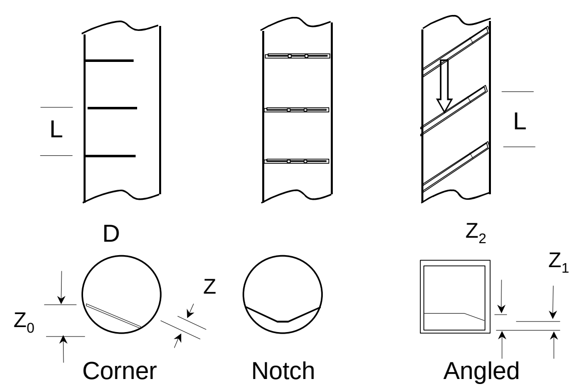


Figure C- 1. Baffle styles.

Baffles installed in the area of the culvert inlet contraction may significantly reduce the culvert capacity when it is in inlet control condition during large floods. The upstream baffle should be placed at least one culvert diameter downstream of the inlet and should be high enough to ensure subcritical flow at the inlet at the high design flow. A modification to the culvert such as a mitered end or wingwalls may also be required to improve its hydraulic efficiency.

C-3 Target Velocity

The culvert hydraulics (velocity, and flood capacity) can be estimated using empirical equations. Rajaratnam and Katopodis (1990), and Rajaratnam et al (1989) studied various combinations of baffle geometries, heights, spacings, slope and flow in models of circular culverts. Shoemaker (1956) studied weir baffles in square box culverts. These models can be used for both the fish passage velocity and culvert capacity analyses.

Rajaratnam and Katopodis developed hydraulic equations for all the styles they tested. Those equations are rearranged to solve for water depths and simplified here to the form of Equation C- 1.

$$Q = C\left(Y_0 / D\right)^a \sqrt{g S_0 D^5}$$

Equation C- 1

Where C and a are the coefficient and exponent that depend on the baffle configuration and were determined experimentally. Q is the discharge, Y_0 is the depth of water, g is the gravitational acceleration, and S_o is the non-dimensional slope of the culvert. The equation is dimensionless as long as all units are consistent.

The dimensions and their respective coefficients and exponents for Equation C- 1 are shown in Table C-1. The first column shows the labels of experimental baffles provided by the authors; data for those without labels have been extrapolated. The dimensions in the next two columns show the differences in styles; Z_0 is the average height of the baffle as shown in Figure C- 2, L is the spacing between baffles and D is the diameter of the culvert. The limits shown in the table are the limits of experimental data or valid correlation for the coefficients and exponents.

The weir baffles studied by Rajaratnam and Katopodis were actually horizontal weirs rather than sloping baffles as shown in Figure C- 2. This is the best information available for predicting the roughness of baffles like those recommended in the manual and must be used with sound judgment. Box culverts were not included in this study. The models presented below for culvert capacity with baffles can be used for fish passage analysis in box culverts.

Table C- 1. Baffle hydraulics

	z_o	L	C	.a	Limits
WB-1	0.15D	0.6D	5.4	2.43	0.25 $y_0/D < 0.8$
WB-2	0.15D	1.2D	6.6	2.62	0.35 $y_0/D < 0.8$
	0.15D	2.4D	8.5	3.0	
WB-3	0.10D	0.6D	8.6	2.53	0.35 $y_0/D < 0.8$
WB-4	0.10D	1.2D	9.0	2.36	0.20 $y_0/D < 0.8$
	0.10D	2.4D	9.6	2.5	

To calculate the velocity, rearrange Equation C- 1 to solve for depth of water and divide it by the cross section flow area between the baffles. The rearranged equation is

$$Y_o = D\left[\frac{Q}{C\sqrt{gS_oD^5}}\right]^{1/a}$$

Equation C- 2

By simple geometry and trigonometry the area of flow is

$$A = \frac{R^2}{2}\left(\theta - \sin\theta\right)$$

Equation C- 3

A is the flow area in the cross section, R is the radius of the culvert, and θ is the angle of the circular sector that includes the flow area. For this form of the equation θ is in radians and is derived by the following equation:

$$\theta = 2\cos^{-1}\left(\frac{R - Y_o}{R}\right)$$

Equation C- 4

Again, θ is in radians. The geometry is shown in Figure C- 2.

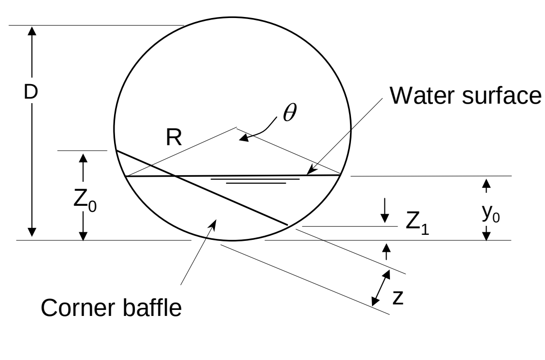


Figure C- 2. Baffle geometry nomenclature.

C-3.1 Turbulence

In order to maintain a desired velocity, energy is dissipated in turbulence. Excess turbulence is a barrier to fish passage. The importance of turbulence in fish passage design is described in Section 7.3.5.2, Culvert and Bed Roughness.

Typical baffles act as weirs at low flows with water plunging over each weir and the energy dissipated in the pools between them. As flow increases the flow transitions from plunging flow to streaming flow and the baffles act together as a roughness element. Turbulence is evaluated for each of these conditions as well as turbulence required to scour bed material. Too little turbulence at bedload transport flows will cause the bedload to deposit in the culvert and reduce the effect of the baffles.

C-3.1.1 Baffle Turbulence

There is little research data available to determine the appropriate maximum EDF for fish passage. Bates (2003) recommended a maximum energy dissipation factor (EDF) of 5.0 foot-pounds per cubic foot per second (ft-lb/ft^3/sec) for passage of adult salmon at flows up to the high fish passage design flow. This recommendation is based on observations and recorded passage of fish through a number of baffled culverts through a range of flows. Additional data is needed for other species. The allowable EDF would be lower for weaker or smaller fish but specific design recommendations are not available. A higher EDF is appropriate for situations with more diverse conditions than a series of simple baffles.

For open channels and culverts EDF can be calculated by:

$$EDF = \gamma VS$$

Equation C- 5

Where: γ is the unit weight of water (62.4 lb/ft^3), V is the average velocity (feet per second) in the cross section, and S is the hydraulic slope (feet / feet).

For more background on turbulence and this equation, see the discussion of EDF in Section 7.3.5.2, Culvert and Bed Roughness.

C-3.1.2 Bed Material Scour Turbulence

The value of EDF should be greater than 3.0 ft-lb/ft^3/sec in a baffled culvert during high flows at which bed material is moving. Lacking additional bed transport information, a bankfull flow would be an appropriate flow to use. Lower turbulence causes sediment deposition and/or debris accumulations that either make the baffles ineffective or create a direct fish passage barrier.

C-3.1.3 Weir Turbulence

For the range of flows in which the flow plunges, *fishway* design criteria should be applied. For a fishway pool, the volume between baffles, the energy dissipation factor (EDF) is calculated using Equation 7-1. The maximum EDF value commonly used for adult salmon is 4.0 ft-lb/sec/ft^3 and for adult trout 3.0 ft-lb/sec/ft^3. Values are not known for other species. An unlimited pool length cannot be used in the calculation since fish have to swim through the entire pool length and turbulence will be concentrated at the upstream end. For adult fish no more than six feet, or the spacing between baffles if it is less, should be used to calculate the effective volume.

The flow transitions from plunging (fishway weir) flow at low flow to streaming (baffle roughness) flow at high flow. Rajaratnam et al (1988) described the flow at which the transition occurs as

This work assumes the weirs have level crests, which is not the case for corner or notch baffles described here. An average weir height might be used for the analysis.

Bates (2000) discusses additional fishway criteria, which normally don't apply to culverts.

C-3.2 Water Depth

The criterion for minimum water depth should be applied as the depth of water over the floor of a culvert. When baffles are used it can also be used as a guide as a minimum depth over the baffles which at low flow they will act as weirs. It is analyzed at the low fish passage design flow.

There is also a depth consideration at high flows. An intent of the design of baffles is that at the high fish passage design flow the water level is just at the top corner of the baffle as is shown in Figure C- 2. That theoretically maintains a low-turbulence passage corridor along the edge of the culvert with the shallow baffle overflow.

C-3.3 Hydraulic Capacity

The point of installing baffles is to increase the roughness, which will usually decrease the high flow capacity of the culvert. See Section 9.2, Hydraulic Capacity.

The equations derived from Equation C- 1 that were used to calculate the velocities for fish passage can also be used to analyze the effect of the baffles on culvert capacity. Equation C- 1 is based on hydraulic studies that only considered relative depths up to 80% of the culvert diameter however.

The culvert capacity can be calculated by applying a roughness coefficient derived from Equation C- 1 in a standard culvert backwater analysis. The steps are listed in Section C-3.4, Summary of Baffle Hydraulic Calculations.

An alternative analysis is described by Bates et al (2003). Shoemaker (1956) studied the effect of weir baffles on the hydraulic capacity of square box culverts. Shoemaker used the Darcy-Weisbach friction as a hypothetical model to calculate culvert capacities directly.

Friction factors for short baffle spacings should be used cautiously. As would be expected, as the baffle spacing approaches zero, the baffle roughness actually decreases and the effective cross sectional area of the culvert becomes the area of the culvert remaining above the baffles. Shoemaker, in his calculation of velocity head, used the gross culvert area.

If the calculated capacity with baffles is not sufficient, the spacing and/or height of the baffles should be modified. The baffles just near the culvert inlet might be modified for additional capacity. These changes obviously affect the success of passage of fish.

The design should also meet or exceed other applicable local, state, or federal standards for hydraulic capacity, headwater depth, and other design parameters.

C-3.4 Summary of Baffle Hydraulic Calculations

The baffle design process in application is often not linear. A number of criteria and tests are to be complied with simultaneously but can often not all be achieved. The following steps summarized from the discussion above and are easiest calculated on a spreadsheet to test sensitivities and optimize the design. These steps assume the decision has already been made to design baffles. To do a good hydraulic and flood capacity analysis you should be familiar with the source and limits of the models, understand the implications of full-pipe flow, and differentiate between inlet and outlet control.

1. Complete the initial hydraulic design as described in Steps 1 and 2 in Section 7.3.6, Summary of Hydraulic Design Steps. This task is no different than other hydraulic designs.
2. If the hydraulic criteria are not satisfied by other means, begin the baffle design. Select an initial baffle geometry; culvert diameter (D) and slope (S_o), calculate baffle height (Z in Figure C- 2), baffle spacing (L) and the vertical drop between baffles (h).
3. Calculate the water depth at the high passage design flows (Q_{HP}). Assume the flow is streaming across the baffles and the baffles are functioning as large roughness elements. With this assumption, Equation C- 1 can be applied for determining water depths and velocity.
    a. Verify the design geometry is within the range of data in Table C- 1 and select appropriate values for "a" and "C" from the table directly or by interpolation. Check to see that you are using the equation within its limits.
    b. Calculate the water depth (Y_o) for the selected baffle arrangements using Equation C- 1 at the Q_{HP} flows.
4. Modify the height of the baffle so the top corner is near the water surface at the high passage design flow. Several iterations might be necessary.
5. Calculate the baffle hydraulics at the high passage design flows (Q_{HP}). Assume the flow is streaming across the baffles and the baffles are functioning as large roughness elements. With this assumption, Equation C- 1 can be applied for determining water depths and velocity.
    a. Repeat steps 3a and 3b with the modified baffle geometry.
    b. Calculate the wetted area (A) and average velocity for each Q_{HP} using the geometric relationships in Equation C- 3, Equation C- 4, and Figure C- 1. The wetted area is the area between the baffles.
    c. Calculate the average cross-sectional velocity using the area and Q_{HP}
    d. Calculate the Energy Dissipation Factor (EDF) using Equation C- 5.
    e. Compare the calculated water velocities to the velocity and EDF criteria for each design fish. If the velocities or turbulence are high return to step 2 and try another baffle geometry with tighter baffle spacing and/or taller baffles.

       It may not be possible to satisfy the velocity and turbulence criteria as well as the baffle height guidance simultaneously. 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. The final design in that case should be a balance to optimize hydraulic criteria and the baffle height even if targets are exceeded. Whether this is an acceptable design depends on how well it satisfies the project objectives...
6. Calculate turbulence at a flow that the natural bed upstream is mobilized and compare it with the minimum turbulence criterion to ensure that bed material is scoured from between the baffles. An acceptable level of turbulence is usually generated if the drop at each baffle is 0.2 foot or more.
7. Verify the minimum water depth criterion is satisfied at the Q_{LP} flow.
    a. Assume the flow is plunging over the baffles and the baffles are functioning as weirs at low passage design flows.

b. Use a sharp crested weir equation (Vee-weir with submergence) to calculate the depth of flow over the baffles at Q_{LP}.

c. Calculate the minimum water depth (Y_{min}) between each baffle and compare it to the depth criterion for each design fish. If there is insufficient depth at Q_{LP}, modify the low point of the baffle (Z_1 in Figure C- 2) to increase the depth at the next baffle upstream and recalculate from Step 5.

   If this fails to increase depth sufficiently, return to step 2 and select a baffle arrangement with smaller baffle spacing and/or taller baffles.

8. Review the water level at the high passage design flow and make sure it matches the elevation of the backwater from downstream. See Section 7.3.5.3, Culvert Elevation and Channel Backwater.

   Assuming this is a retrofit design, the culvert elevation and slope can't be changed so if the water surfaces don't match, the roughness will have to be modified or the downstream channel elevation changed.

9. Verify the flood capacity is adequate.

   a. Select a structural design flow and acceptable headwater depth. See Section 9.2, Hydraulic Capacity.

   b. Calculate the flow at which the relative depth is 80% (Y_o is 80% of D) using Equation C- 1.

   c. Calculate the roughness coefficient based on that condition using Manning's Equation.

   d. Run a standard culvert backwater analysis using the roughness coefficient and the high structural design flow.

   e. Compare the headwater created to the acceptable headwater depth.

C-3.5 Baffle Installation

Baffles in concrete culverts can be made of wood timbers, steel plate or precast concrete. Bent steel plates work well with one leg bolted to the floor and pointing downstream.

Expansion ring anchors work well for installing baffles in existing round pipes. They can be installed without diverting flow from the work area. The rings are expanded out against the entire pipe circumference. Threaded rods are rolled to the shape of the culvert interior and are attached to an anchor plate. The rod and anchor plate are attached to the culvert by expanding the rod into the recess of a corrugation. This is done by tightening a nut on one end of the rod against a sleeve attached to the other end of the rod. Once the rod and anchor plate are secured, the baffle is bolted to the anchor plate. This system also works in smooth culverts. A set of shear bolts must first be anchored to the culvert wall; the expansion ring is then installed against the upstream side of the shear bolts.

Generally, 3/16" steel is adequate for baffles though 1/4" plate can be used as a conservative design for long baffle life especially in areas with corrosive water or high bed load movement. Gussets should be added to stiffen and strengthen baffles when the baffles are greater than nine inches deep.

Appendix D - Culvert Design Data Forms

Design data forms are provided to summarize the design process of a culvert using any of the three design methods described in this guideline.

Not all sections will apply to any culvert; so chose the sections relevant to your 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. Data is summarized to show design milestones, assumptions, and conclusions. This isn't necessarily all of the data required for a design. This isn't necessarily all of the data required for a complete design.

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)		
ID Team members		
Date		

Brief description of project ______________________________

____

____

Project type (new, retrofit, replacement) ______________________________

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 ______________________________

____

2 - BASIS OF 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 _________

Show proposed project profile on a long profile plot.

Channel elevations at ends of proposed culvert:

	Downstream end	Upstream end
At low potential profile		
At high potential profile		
At proposed constructed profile		

Reference Reach

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 ____________________

Reference reach channel types (e.g.; 75% pool-riffle, 25% plane bed)

____

____

Key bed features, function, and spacing (debris, steps, bends, etc)

____

____

____

____

Bed mobilitiy and how it was determined

____

____

Key bank features and frequency

____

____

____

Project ______________________________

Project ID ______________
Date ______________

3 - BASIS OF DESIGN

Reference reach cross sections

Cross section labels			
Locations			
Bankfull width			
Bankfull depth			
Floodprone width			
Depth to high water mark			

Reference reach slope Average ______________ Range ______________

Reference reach bed material

	Particle size (inches or mm)	How was particle size determined?
D95		
D84		
D50		
D16		
D5		
Fines		

Reference reach key features

	Size (inches or mm)	Function	Spacing	dh	Permanence, mobility, condition
Debris and live wood					
Colluvium					
Bedrock					
Steps, clusters					

Function: Profile control, Roughness, Confinement, Bank stability

Project ________________________________ Project ID _______________
Date _______________

4 - DESIGN

Mobility / stability analysis

Design flows

Design Flows	Return period (years)	Flow (cfs)	How was flow estimated?
Floodplain contraction			
Stability of key features			
Flood capacity			
Headwater depth			

Stream simulation bed material

	Particle size (inches or mm)	How was particle size determined? (what model, observations)
D95		
D84		
D50		
D16		
D5		

Additional features if included in the design

	Particle size (inches or mm)	Frequency, spacing	How identified, designed
Bands			
Banklines			
Key features			

5 - DESIGN

High flow hydraulics

Event	Flow (cfs)	Tailwater elevation	Rough-ness (n)	Water surface elevation upstream	HW depth (HW/culvert rise)
Q2					
Q25					
Q100					

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 ______________________________

____

Other special considerations, recommendations ______________________________

____

____

____

____

Vermont Fish Passage Design Data Checklist
Hydraulic and Low-Slope Designs

This is a summary for design and review of a road / stream crossing using the Hydraulic or Low-Slope design methods for fish passage at culverts. Data is summarized to show design milestones, assumptions, and conclusions. This isn't necessarily all of the data required for a complete design. All parts of the data data sheet are normally needed for a Hydraulic Design. Those marked with "(LS)" are normally needed for a Low-Slope Design.

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 (LS)

Project name and ID		
Stream		
Road, location		
Lat / Long (d/m/s)		
ID Team members		
Date		

Brief description of project ______________________

____

____

Project type (new, retrofit, replacement) ______________________

Design method: (hydraulic or low-slope) ______________________

Does this design satisfy design method criteria? If not, 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

Target Species

Species	Age class (Juv, Adult)	Fish length (in)	Movement seasons (months)	Hydraulic criteria		
				Swim speed (fps)	Swim mode	Min depth (ft)

Describe data sources ______________________________

____

Hydrology

Watershed characteristics (LS)

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.) (LS)

____

____

Peak design flows (LS)	Derived flow (cfs)	Standard error (%)	Design flow (cfs)
2 - yr event			
25 - yr event			
100 - yr event			

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. (LS)

____

____

Project ________________________________ Project ID _______________

Date _______________

3 - DESIGN

Channel (LS)

	Downstream	Upstream
Average slope	%	%
Average bankfull width	ft	ft
Bed Elevation - low potential profile		
Bed Elevation - high potential profile		
Description of channel		
Channel roughness (n)		
Bed Elevation - project profile		
Elevation of downstream control		

How is profile controlled? ____

____

Culvert Description (LS)

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	Rough-ness (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 (LS)

Event	Flow (cfs)	Tailwater elevation	Rough-ness (n)	Water surface elevation upstream	Headwater (HW/culvert rise)
Q2					
Q25					
Q100					

Describe methods and sources of data high flow hydraulic calculations. ____________________

____

____

Road and Alignment (LS)

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 ____________________

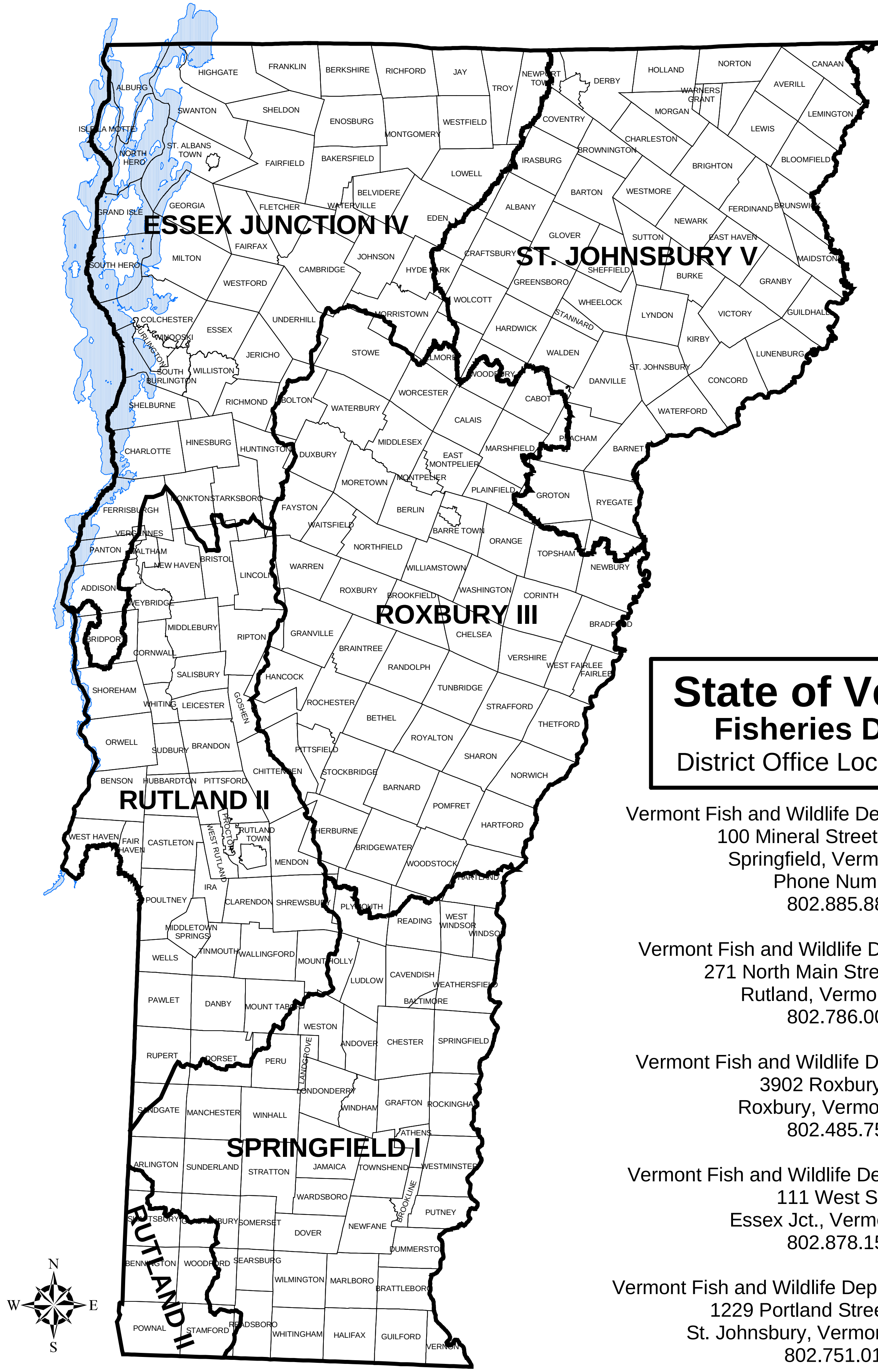
____

Appendix E - Instream Construction Periods

Seasonal instream construction dates are to be followed to protect fish spawning activities. Exceptions may be allowed on a case-by-case basis as determined by VDFW District Fisheries Biologists. In general, exceptions may be permitted where the work area can be isolated from the stream or where there is no possibility of discharge of sediments or contaminants from the construction area into the water body. The following list details when construction is allowed in streams inhabited by the species listed:

- Rainbow and Steelhead Trout: spring runs July 1-Mar. 31, fall runs July 1-Sept. 30
- Brook Trout, Brown Trout, Atlantic and Landlocked Salmon: June 1-October 1
- Largemouth and Smallmouth Bass: July 1-May 14
- Walleye: June 1-March 31
- Northern Pike: May 16-March 14
- Other Species: case by case basis for known spawning areas (e.g., lake sturgeon, rainbow smelt, white sucker)

VDFW District Fish Biologists should be contacted early during the planning of projects. Use the following map to identify the appropriate office to contact.



State of Vermont
Fisheries Districts
District Office Location/Region

Vermont Fish and Wildlife Department - Springfield
100 Mineral Street, Suite 302,
Springfield, Vermont 05156
Phone Numbers:
802.885.8855

Vermont Fish and Wildlife Department - Rutland
271 North Main Street, Suite 215
Rutland, Vermont 05701
802.786.0040

Vermont Fish and Wildlife Department - Roxbury
3902 Roxbury Road
Roxbury, Vermont 05669
802.485.7566

Vermont Fish and Wildlife Department - Essex Jct.
111 West Street
Essex Jct., Vermont 05452
802.878.1564

Vermont Fish and Wildlife Department - St. Johnsbury
1229 Portland Street, Suite 201
St. Johnsbury, Vermont 05819-2099
802.751.0100

Appendix F – Existing Regulations and Recommended Practices

Regulations:

The importance of aquatic organism passage is recognized in several state and federal regulations and programs. This section is a summary of regulations related to stream crossing structures in Vermont.

VDFW District Fish Biologists should be contacted early during the planning of projects. Use the map in Appendix E – Instream Construction Periods to identify the appropriate office to contact.

For current information on Stream Alteration Permit from the Vermont Department of Environmental Conservation (DEC), including specific regulations, permit applications, and Stream Alteration Engineer contacts see:

http://www.anr.state.vt.us/dec/waterq/permits/htm/pm_streamalt.htm

U.S. Army Corps of Engineers, Vermont General Permit

(Applicable Structures: All)

General Condition #21. Waterway/Wetland Work and Crossings

(a) All temporary and permanent crossings of waterbodies shall be suitably culverted, bridged, or otherwise designed to withstand and to prevent the restriction of high flows, to maintain existing low flows, and to not obstruct the movement of aquatic life indigenous to the waterbody beyond the actual duration of construction.

(b) No activity may substantially disrupt the necessary life-cycle movements of those species of aquatic life indigenous to the waterbody, including those species that normally migrate through the area, unless the activity's primary purpose is to impound water.

(c) To meet the objective of aquatic organism passage in (a) and (b) above, all temporary and permanent crossings of rivers, streams, brooks, etc. (hereon referred to as "streams") shall meet the following performance standards in order to qualify for Category 1 (refer to Additional References on Page 18): VT GP 13 December 2007.

i. Design the structure to maintain a streambed composition and form throughout the culvert similar to and continuous with the adjacent reaches. To do this:

   a. Design and install streambed material and bedforms if not adequately supplied and developed naturally,

   b. Design profile and alignment through structure similar to those of adjacent stream reaches,

   c. Design culvert elevation to remain embedded for the life of the structure and in consideration of future channel conditions.

ii. Maintain velocities, turbulence and depths within the structure similar to those found in adjacent stream reaches across a range of desired flows.

V.S.A. Title 10: Conservation and Development

Chapter 111. Fish

(Applicable Structures: All)

§ 4607. Obstructing streams

(a) A person shall not unless authorized by the commissioner, prevent the passing of fish in a stream or the outlet or inlet of a natural or artificial pond on a public stream, by means of a rack, screen, weir or other obstruction, and shall comply with the terms of the notice provided in subsection (b) of this section.

(b) The commissioner may order such an obstruction removed by the person erecting the same or by the owner of the land on which it is located, by serving on such person or owner a written notice requiring the removal of such obstruction within ten days after service thereof. When such person fails to remove any such obstruction within the time required in such notice, the commissioner may remove the same and recover the expense thereof in a civil action on this section. (Added 1961, No. 119, § 1, eff. May 9, 1961.)

Vermont Water Quality Standards

(Applicable Structures: All)

Section 1-03. Anti-Degradation Policy"All waters shall be managed in accordance with these rules to protect, maintain, and improve water quality. Existing uses of waters and the level of water quality necessary to protect those existing uses shall be maintained and protected regardless of the water's classification."

V.S.A. Title 10: Conservation and Development

Chapter 41: Regulation Of Stream Flow

http://www.anr.state.vt.us/dec/waterq/permits/htm/pm_streamcrossing.htm

(Applicable Structures: For drainage areas 10mi^2 and greater)

§ 1023. Investigation, permit

(a) Upon receipt of an application, the secretary shall cause an investigation of the proposed change to be made. Prior to making a decision, a written report shall be made by the secretary concerning the effect of the proposed change on the watercourse. The permit shall be granted, subject to such conditions determined to be warranted, if it appears that the change:

(1) will not adversely affect the public safety by increasing flood hazards,

and

(2) will not significantly damage fish life or wildlife,

(3) will not significantly damage the rights of riparian owners, and

(4) in case of any waters designated by the board as outstanding resource waters, will not adversely affect the values sought to be protected by designation.

Vermont 401 Water Quality Certification of U.S. Army Corps of Engineers, Vermont General Permit

(Applicable Structures: For drainage areas greater than 1mi²)

Section 401(a)(1) of the Clean Water Act requires applicants to obtain a water quality certification or waiver from the Vermont Agency of Natural Resources, DEC, Water Quality Division. For activities in wetlands and waterways listed in Category A of Appendix A, Definition of Categories of this general permit, the Vermont DEC has granted WQC subject to obtaining the State permits and approvals listed above, when applicable, with the exception of stream crossing structures over streams greater than 1mi² watershed size at the location of the crossing. In such cases an individual 401 Certification or waiver must be obtained. The State has conditioned this certification so it is valid only for those activities that fully comply with all terms and conditions of this general permit.

V.S.A. Title 10: Conservation and Development

Chapter 151. State and Land Use Development Plans (Act 250)

(Applicable Structures: Projects under Act 250 jurisdiction)

Act 250 Criteria that may address stream-crossing proposals:

(D) Floodways. A permit will be granted whenever it is demonstrated by the applicant that, in addition to all other applicable criteria:

(i) the development or subdivision of lands within a floodway will not restrict or divert the flow of flood waters, and endanger the health, safety and welfare of the public or of riparian owners during flooding; and

(ii) the development or subdivision of lands within a floodway fringe will not significantly increase the peak discharge of the river or stream within or downstream from the area of development and endanger the health, safety, or welfare of the public or riparian owners during flooding.

(E) Streams. A permit will be granted whenever it is demonstrated by the applicant that, in addition to all other applicable criteria, the development or subdivision of lands on or adjacent to the banks of a stream will, whenever feasible, maintain the natural condition of the stream, and will not endanger the health, safety, or welfare of the public or of adjoining landowners.

(F) Shorelines. A permit will be granted whenever it is demonstrated by the applicant that, in addition to all other criteria, the development or subdivision of shorelines must of necessity be located on a shoreline in order to fulfill the purpose of the development or subdivision, and the development or subdivision will, insofar as possible and reasonable in light of its purpose:

(i) retain the shoreline and the waters in their natural condition,

(ii) allow continued access to the waters and the recreational opportunities provided by the waters,

(iii) retain or provide vegetation which will screen the development or subdivision from the waters, and

(iv) stabilize the bank from erosion, as necessary, with vegetation cover.

8 (A) Necessary wildlife habitat and endangered species. A permit will not be granted if it is demonstrated by any party opposing the applicant that a development or subdivision will destroy or significantly imperil necessary wildlife habitat or any endangered species, and

(i) the economic, social, cultural, recreational, or other benefit to the public from the development or subdivision will not outweigh the economic, environmental, or recreational loss to the public from the destruction or imperilment of the habitat or species, or

(ii) all feasible and reasonable means of preventing or lessening the destruction, diminution, or imperilment of the habitat or species have not been or will not continue to be applied, or

(iii) a reasonably acceptable alternative site is owned or controlled by the applicant which would allow the development or subdivision to fulfill its intended purpose.

9 (K) Development affecting public investments. A permit will be granted for the development or subdivision of lands adjacent to governmental and public utility facilities, services, and lands, including, but not limited to, highways, airports, waste disposal facilities, office and maintenance buildings, fire and police stations, universities, schools, hospitals, prisons, jails, electric generating and transmission facilities, oil and gas pipe lines, parks, hiking trails and forest and game lands, when it is demonstrated that, in addition to all other applicable criteria, the development or subdivision will not unnecessarily or unreasonably endanger the public or quasi-public investment in the facility, service, or lands, or materially jeopardize or interfere with the function, efficiency, or safety of, or the public's use or enjoyment of or access to the facility, service, or lands.

Recommended Practices:

Natural Resources Conservation Service - Conservation Practice Standards

Fish Passage Code 396

(Applicable Structures: Projects designed or funded through NRCS)

CRITERIA

Planning and Evaluation

Evaluate sites for variations in stage and discharge, tidal influence, hydraulics, geomorphic impacts, sediment transport and continuity, and organic debris movement. Design passage features to account for the known range of variation resulting from this evaluation.

Minimize any foreseeable channel plan or profile shifts resulting from the modification or removal of a passage barrier.

Plan and locate passage for compatibility with local site conditions and stream geomorphology, to the extent possible.

Avoid locating fishway entrances and exits in areas that will obstruct function, increase harassment or predation, or result in excessive operation and maintenance requirements.

Design Requirements

Design passage to accommodate present and reasonably anticipated changes in watershed conditions.

Design passage structures according to known swimming and leaping capabilities of target species or a similar species with comparable swimming abilities. Utilize hydraulic computations to document how designs satisfy the physiological requirements of target organisms.

Design and evaluate passage structures for hydraulic performance and structural integrity at the bankfull and 25-year peak flow events (at a minimum).

Design passage features to minimize or avoid energy deficits, physical stress, and harm to migratory organisms.

Design passage features to minimize or avoid excessive delays during migration periods.

Provide adequate attraction flow into a passage facility across the full range of discharge during which target species will move.

Use trashracks on culverts only if required or necessary. Ensure that trashracks are self-cleaning and/or easily maintained.

Select construction materials and methods that are non-toxic, minimize adverse consequences to aquatic organisms, and are resistant to degradation.

CONSIDERATIONS

Develop or adopt a quantitative method to identify and evaluate passage barriers (see References). Information derived from this method can assist planning and budgeting activities.

Consider removing a passage barrier before installing or retrofitting a new facility or structure. Complete or partial barrier removal usually provides better passage conditions, and is more economical than designing, constructing, operating, and maintaining many passage structures.

Culverts or bottomless arches that incorporate natural streambed substrates throughout their length are preferred over other culvert configurations for passage purposes. Natural streambeds provide numerous passage and habitat benefits to many life stage requirements for fish and other aquatic organisms compared to man-made surfaces.

Design and locate features to improve or provide passage for as many different aquatic species and age classes as possible.

Replacing or removing an existing instream structure may trigger channel adjustments (e.g., aggradation and/or degradation) upstream and/or downstream of the work site. Install grade controls or other slope modifications to mitigate adverse physical or ecological consequences (see Channel Stabilization – Code 584 and Grade Stabilization Structure – Code 410).

Analyze any potentially negative interactions, including hybridization, disease, competition, or predation, between target and aquatic nuisance species when passage is provided above a barrier. If serious consequences are likely, take steps to minimize adverse effects.

Where possible, consider the habitat requirements of other aquatic or terrestrial species that may be affected by a passage project. Some passage facilities may improve survival for terrestrial vertebrates by providing safe migration routes under roadways.

Consider the amount of habitat upstream and downstream of a barrier to evaluate into project feasibility, cost effectiveness, and/or potential for connecting fragmented habitats. Using a watershed approach whenever possible provides a framework for project planning.