



**New Hampshire Stream Crossing Guidelines**

**May 2009**

This document was written to assist in the design, construction and permitting of stream crossings in New Hampshire. Many individuals from non-governmental organizations and state and federal agencies provided their expertise and thoughtful suggestions and comments in numerous meetings over nearly two years, and this document is the culmination of that work. Special thanks to Dr. Thomas Ballestero of the University of New Hampshire, who provided his time and civil engineering and geomorphic expertise, and to Matt Carpenter and Ben Nugent of New Hampshire Fish and Game Department, who did much of the work assembling the document. – John Magee, Fish Habitat Biologist, New Hampshire Fish and Game Department, September 2008.

Those who attended numerous workgroup meetings for nearly two years include representatives and members of: New Hampshire Timberland Owners Association, New Hampshire Wetlands Council, University of New Hampshire Technology Transfer Center, Rivers Management Advisory Committee, New Hampshire Rivers Council, Trout Unlimited, Antioch University, The Nature Conservancy, United States Army Corps of Engineers, United States Fish and Wildlife Service, United States Department of Agriculture Natural Resource Conservation Service, United States Department of Agriculture Forest Service, United States Geological Survey, New Hampshire Department of Transportation, New Hampshire Department of Environmental Services, New Hampshire Geologic Survey, New Hampshire Department of Resources and Economic Development, and New Hampshire Fish and Game Department. Additionally, many individuals interested in the topic such as private environmental consultants, municipal public works employees, and landowners attended the workgroup meetings.

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## **I. Background**

### **a) Introduction**

Habitat fragmentation by roads has typically been viewed as a terrestrial landscape issue (Forman and Alexander 1998). With aquatic habitats, the issue of fragmentation has been focused mainly on the impacts of dams, especially their effects on migratory fish (Jackson 2003). Until recently, the fragmentation of freshwater river and stream habitat by permanent stream crossings has gone largely unnoticed. New Hampshire's development history has resulted in over 4,572 dams (3,204 active; 143 breached; 958 in ruins; and 267 exempt from regulation) throughout the state (NHDES Dams Bureau dam database). While these dams have often had a negative impact on aquatic communities, very few new dams are now being built or planned, and there has been a trend toward dam removal. The number of stream crossings, however, is increasing as more people move to the state and the density of roads increases. The total number of stream crossings is estimated to be at least 17,000, which far exceeds the total number of dams. This growing network of stream crossings, if designed or replaced without consideration for river and stream ecology and geomorphology, has the potential to degrade aquatic habitats throughout New Hampshire.

Environmental impacts are not the only concern when it comes to designing permanent stream crossings. It may be financially impractical to construct crossings to accommodate relatively rare flooding events, such as greater than 100-year flows; however, taking into consideration geomorphic and ecological principles in stream crossing design may reduce future flood damage. More importantly, this approach will reduce the environmental damage that results from more frequent high flow events, like annual spring flood flows.

It has become apparent to biologists and hydrologists working in the Northeast and elsewhere that when stream crossing structures are not appropriately designed to allow for flow variability and natural sediment transport, aquatic organism passage is reduced and the occurrence of streambed and streambank erosion on the downstream side of the crossing and aggradation on the upstream side of the crossing are predictable consequences. The effects of an inappropriately designed crossing structure often extend well beyond the point where the structure and the stream intersect. To understand the potential impacts of an improperly designed stream crossing, one must first consider the geomorphic and ecological processes that are essential to a healthy river or stream ecosystem. Preserving these system processes, rather than focusing on the needs of individual "target" species or passing a certain volume of water, is the most effective way to address both the structural integrity of the road and the needs of all species present in a watershed. However, it must be stressed that stream crossings also have to be sized appropriately to achieve conveyance objectives, that is to pass a given flow of water and expected sediment, wood and ice during storm events) with desired hydraulics for both

public safety and aquatic organism passage. The geomorphic and ecological processes described below have the potential to be impacted by stream crossings.

The following guidelines for stream crossing construction and replacement are specifically intended to help minimize the impacts on streams and their associated riparian ecosystems and aquatic biota, and will likely minimize the potential for damage to the road and crossings themselves.

There has been a recent nationwide awakening to the need for states to reevaluate how stream crossing structures are installed and replaced. While states have developed different approaches for stream crossings, based on available science and resources, the intentions are the same. The writers of this document have chosen to use as a template the already established foundation of the stream crossing guidelines developed for Massachusetts (River and Stream Continuity Partnership 2006).

## **b) Connectivity**

Aquatic organisms move upstream and downstream throughout their life cycles. The survival of a population depends on access to spawning habitat, feeding areas, shelter, and the dispersal and colonization of available habitat by juveniles (Jackson 2003). These resources may be spread over a wide area in a watershed (Fausch et al. 2002), and therefore, a stream crossing can potentially block access to these areas. A healthy population also depends on unrestricted gene flow (Fahrig and Merriam 1985). Stream crossings may isolate populations, making them vulnerable to extirpation (Jackson 2003). In addition, many species of amphibians, reptiles, and mammals use riparian zones as travel corridors (Naiman et al. 1993), and the movement of these species may be impacted by certain crossings.

Stream crossing structures that are undersized relative to the natural width and depth of a stream, especially those crossings that do not have natural substrate within them, tend to have high velocities compared to what is typical elsewhere in the stream. Not only can these higher velocities reduce aquatic organism passage during periods of high flow, but also often create a scour pool immediately downstream. A scour pool can and often leads to the phenomenon called perching, in which the streambed is gradually eroded downstream of the crossing until the end of the culvert is well above the streambed, creating a waterfall at all but the highest flows. This condition limits fish from moving upstream through the culvert, especially as many fish species, and most other aquatic species, do not jump. Even with culverts that are not perched, shallow water within the structure can restrict aquatic organism passage at low flows.

## **c) Transport of Organic Material**

Wood and leaves form the basis of the food chain in headwater streams where primary production in the stream channel is limited by the lack of direct sunlight (Webster et al. 2001). Wood and plant matter that fall into the stream can be consumed by macroinvertebrates, many of which are preyed on by fish. Large trees and branches

that fall into rivers and streams become channel modifying features and add to the beneficial complexity of instream habitat. Instream wood has also been shown to increase the instream retention of nutrients, and thus reduce the nutrient load to waterbodies downstream (Warren et al, 2007). The downstream flow of wood, leaves, and other organic matter is a natural process on which stream organisms depend as a source of both food and shelter. Inappropriately sized crossings tend to restrict woody material movement, and oftentimes this important material is removed from the stream system during routine maintenance. The clogged structures become maintenance points and can lead to severe flooding and erosion hazards.

In a study in the northwest United States, wood blocked 39% of the culverts that failed during a series of large flow events ranging from less than 5-year to greater than 100-year recurrence intervals. Importantly, many crossing in the study failed during relatively frequent flow events such as those during 25-year recurrence interval flows. The authors also documented that relatively smaller storm events had a proportionally higher incidence of small wood-caused failures and that failed culverts often diverted the stream flow, which led to a cascade of crossing failures downstream (Furniss et al, 1998). They concluded,

“The behavior of sediment and debris at culvert inlets was crucial to stream-crossing performance. Crossings that presented the least change to channel cross-section, longitudinal profile, channel width, and alignment were most likely to pass sediment and debris...”.

Flanagan (2004) reported that 99% of the pieces of wood that were transported during flows with recurrence intervals of less than twelve years were shorter than or equal to the channel bed width, and recommended that stream crossings should maintain the channel’s natural cross section and planform.

Of particular interest is that the amount of wood in northeastern streams is predicted to increase in the near future as forests increase in age (Warren et al, 2007; Keeton et al, 2007).

#### **d) Transport of Inorganic Material**

The downstream movement of sediment is a natural process of erosion and deposition that dictates the physical characteristics of a river or stream and its floodplain. The physical nature, or geomorphology, of a river or stream has been shown to correlate with different types of fish communities (Sullivan et al. 2006), and impacts to the geomorphology of a stream has recently been linked to negative impacts on fish community diversity, productivity, and condition (Mazeika et al., 2006). In addition to a direct increase in sediment load from erodable soils around the structure, road-stream crossings that are geomorphically incompatible with a stream may either directly fail due to channel adjustment processes or alter the geomorphology of a river or stream by creating channel instability. This instability results in increased streambank and streambed erosion in some areas and excessive sediment deposition in others. This

process can occur relatively soon after the crossing is constructed or may take a number of years to occur.

The downstream movement of ice is another important process occurring in moving water ecosystems, as it scours and reshapes the streambed and riparian zone, creating new opportunities for aquatic organisms and riparian plants. Stream crossings can interfere with this process by blocking ice flow, and in some cases, creating dangerous impoundments.

#### **e) Natural Flow Regimes**

Riparian areas are essential to river and stream ecosystems (Naiman and Latterell 2005). Flooding during seasonal periods of increased rainfall or snow melt helps maintain flood plain and riparian plant communities by the process of water-transported seed dispersal and by preventing the encroachment of terrestrial plant species, which depend on drier soils (Merritt and Wohl 2002). Much of the organic matter essential to aquatic organisms becomes available when a river or stream floods its banks (Gregory et al. 1991). Aquatic species depend on the natural flow regime of a river to create habitats that are critical to their survival (Poff et al. 1997). Undercut banks and gravel deposits are important fish habitats that are created by natural variation in river flows.

Stream crossings can interfere with the natural flow regime by creating artificial flow constrictions. These constrictions may lead to cumulative effects including stream channel instability and disruptions to natural flow patterns and sediment transport. Unnatural channel migration or streambed erosion (degradation) can lead to floodplain abandonment or excessive sediment deposition, which can destroy both riparian and instream habitats. Pondered areas above undersized stream crossings may cause flooding and sediment deposition upstream. Altering the natural flow regime can change the structure and composition of streambank plant communities (Merritt and Wohl 2002).

Most of these environmental impacts are the result of stream crossings designed only to pass a designated flow without taking into account the geomorphology of the stream and the full range of natural flow variability (Richter et al., 1996). A crossing structure that is designed to be hydraulically and geomorphically transparent is one way to avoid environmental impacts and reduce the potential for crossing failure. In such a design, the stream crossing is nearly invisible to the ecosystem in that it creates no short- or long-term adverse consequences. A stream crossing structure, whether it is a bridge, open bottomed arch, or a pipe culvert, should be designed to be geomorphically compatible with the river or stream on which it is built. Geomorphic compatibility, in the context of a stream crossing, is a crossing structure designed to match, in size and shape, the geomorphic characteristics of the river or stream on which the crossing is to occur, while accounting for the natural range of geomorphic variability typical of the stream type and any anticipated changes in form that will occur as channel evolution takes place in the future. Geomorphic characteristics are determined by the landform characteristics of the valley in which a river or stream flows. Valley size, the slope of the valley walls,

and the geology or type of substrate of the valley will influence the physical nature of a stream channel. Dave Rosgen in his 1996 book, Applied River Morphology, has created a classification system for stream channel types based on measurable attributes of stream channel morphology.

From the perspective of stream crossing design, the important attributes to understand are the cross sectional channel dimensions, the width of the flood-prone area, the channel slope, and the sediment particle size distribution. With this information, along with an analysis of hydraulic capacity, one can design a stream crossing that will not alter the natural geomorphology of a stream. In general, a stream crossing structure that is geomorphically compatible with the stream will have a minimal effect on aquatic organism passage, the transport of sediment and organic materials, and the natural flow regime of a river or stream.

#### **f) Climate Change**

Although not an objective of this document, it is important for the reader to understand that many climate change models predict that large precipitation events are likely to increase in frequency (Pew Center on Global Climate Change, 2006). Due to the increased flow variability anticipated in the future, even greater span lengths in crossing designs are recommended to accommodate future hydrologic changes associated with global climate changes.

## **II. Existing Regulations**

Wetlands Rules – The Department of the Army, State of New Hampshire Programmatic General Permit (SPGP), issued by the Army Corps of Engineers, developed in cooperation with the New Hampshire Department of Environmental Services Wetlands Bureau:

This New Hampshire PGP minimizes duplication between New Hampshire's Regulatory Program governing work within coastal and inland waters and wetlands and the Corps Regulatory program. Subject to certain exclusions and conditions, the PGP eliminates the need to apply for separate approval from the Corps for most minor, non-controversial work in New Hampshire when that work is authorized by the New Hampshire Department of Environmental Services (DES) Wetlands Bureau. (NHSPGP effective June 28, 2007)

The objective of this guidance document is to assist permit applicants with their legal responsibility to comply with the existing SPGP, specifically General Condition 21, which states:

(a) All temporary and permanent crossings of waterbodies and wetlands 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) Aquatic Life Movements. 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.

Another permit application requirement is in ENV-Wt 302.03, which states:

“Env-Wt 302.03 Avoidance, Minimization, and Mitigation.

(a) The applicant shall submit a statement describing the impact of the proposed project design and provide evidence which demonstrates that, subject to (b) below:

- (1) Potential impacts have been avoided to the maximum extent practicable; and
- (2) Any unavoidable impacts have been minimized.”

Essentially, if the crossing does not interfere with the natural stream processes, it is very likely that the applicant will be able to comply with General Condition 21 of the SPGP and ENV-Wt 302.03.

### **III. Guidelines for New Stream Crossings**

One approach to setting design guidelines for stream crossings that will facilitate aquatic organism passage is to provide a general numerical standard that will work in most cases. The advantage of this approach is that it is relatively easy to communicate and apply. The disadvantage of a general standard approach is that it does not take into account the specific conditions, including stream stability, at the site of the proposed crossing. An analysis of hydraulic capacity is typically conducted for proposed stream crossing structures in New Hampshire. Designing a stream crossing structure with a geomorphic approach, which builds off of several aspects of standard hydraulic and hydrologic analyses, requires additional information about the dimensions of the river or stream. With an investment of additional survey work, one can design a stream crossing that is both hydraulically and geomorphically compatible with the dimensions of the stream or river on which it will be (re)built. A basic understanding of the geomorphic characteristics, in addition to the hydraulic capacity, of the site may be the difference between a crossing that blocks aquatic organism passage, and thus does not comply with the State Programmatic General Permit and also has a greater likelihood of failure in the future, and a crossing with minimal impact. The guidelines outlined below are intended to help anyone charged with building a stream crossing to include geomorphic principles in their design. They are organized into five sections:

General Considerations – Establishes the scope of this document and the general principles that must be observed when designing stream crossings that are based on geomorphic and ecological principles.

Data Collection – Introduces the information that must be gathered to design a geomorphically compatible stream crossing.

Applying the data – Provides examples of how to use the data collected to design a geomorphically compatible stream crossing along with special considerations for each Rosgen stream type.

Replacement Crossings – Outlines the special considerations for replacing existing crossing structures.

Construction – Lists the Best Management Practices for the construction phase of a stream crossing project.

## **a) General Considerations**

### **i. Application**

These guidelines are not intended for temporary crossings, such as skid roads and temporary logging roads. The UNH Cooperative Extension (UNHCE, 2005) and New Hampshire Department of Resources and Economic Development (Division of Forests and Lands, (NHDRED, DFL, 2001)) offers best management publications for forestry operations. These guidelines are also not intended for constructed drainage systems designed primarily for the conveyance of storm water or irrigation.

### **ii. Crossing Structure Site Selection**

Stream crossings should be avoided whenever possible. Land use planning that minimizes stream crossings will reduce both the environmental and financial costs of development. Aquatic systems need to be considered with any type of proposed construction project. If avoiding a stream, river, or wetland cannot be prevented, methods to minimize impacts to these aquatic systems need to be identified within the **initial** stages of project development and planning. The extent of potential flooding hazards, environmental impact, aquatic biota, hydraulic capacity, and stream and floodplain geomorphology need to be determined early on. Ideally, stream crossings should be constructed at the most stable stream locations in the absence of other social, cultural or other sensitive environmental resources. Evidence of such stability can be gleaned from historic information, for example, surveys, aerial imagery, vegetation, etc., which indicates that the vertical and horizontal position of the stream has changed very little. Where historical information is unavailable or unclear, an assessment of channel stability should be used to select the most appropriate crossing site.

### iii. Accounting for Variability

Rivers and streams develop geomorphologic variability associated with sediment load and discharge history as a result of natural conditions and land use practices. As streams move towards equilibrium, lateral bed shift, aggradation, and degradation can occur. The design of any structure must consider the channel type, longitudinal profile, and must account for likely variability of the stream or river for the life of the structure. David Rosgen, in his 1996 book entitled *Applied River Morphology*, provides a stream channel classification system, which identifies stream types based on morphological characteristics. This classification system can be a useful tool for predicting the behavior of the system, such as sediment transport and stability.

### iv. Structure Slope

Structures without bottoms are generally preferable. If an enclosed structure is constructed, the slope of the structure must be considered. In general, the placement of the structure should be at a slope similar to the gradient of the natural stream. Differences in slope between the crossing structure and the natural stream should be minimized to reduce changes in shear stress between the bottom of the structure and embedded bed material. A geomorphically designed structure should maintain water velocities at all seasonal flow variations and sediment carrying capacities consistent with the natural stream channel. The use of closed bottom structures for crossing streams with high gradients may require grade controls, for example constructed step pools, or baffles, to dissipate energy and maintain substrate within the structure.

### v. Structure Alignment

Lateral and vertical stream channel adjustment, sediment/woody material obstructions, and the overall site disturbance are necessary considerations when designing a stream crossing. The function of a crossing could be reduced if the structure is not designed to mimic the alignment of the natural channel. Outlets and inlets of crossing structures designed askew to the natural stream channel will potentially increase bank scour rates and lateral channel movement. Stream channel realignment should be considered only as a last option. Altering natural stream channels can lead to channel instability, changes to stream hydraulics, and the loss or degradation of aquatic habitat. Road development planning should always consider stream crossings and how to avoid or minimize them.

### vi. Bridges vs. Closed Bottom Structures

Bridges that span both the stream channel and floodplain generally have the least impact on fluvial ecosystems, but well designed culverts and open-bottom arches may also be appropriate. Site constraints may make the use of bridge spans impractical and in some cases, such as those areas with deep, soft substrate, well-designed culverts may

actually perform better than bridges (areas with deep soft substrate). However, in areas where site constraints do not limit the usefulness of these structures, bridges are preferred over culverts. It is important to maintain the bankfull channel width, flow rates, and substrates within the crossing structure consistent with the natural condition of the stream. If these characteristics are modified, even when a bridge is constructed, the natural sediment transport properties of the site will be changed. This will likely result in streambed aggradation and/or degradation and may increase structure maintenance costs. If the natural stream channel is altered by bridge construction or structure installation, the stream channel within the structure should be rebuilt to mimic the geomorphic processes of the natural stream channel.

Crossings should be designed to maintain river/stream continuity and facilitate passage for wildlife. The best designs for accomplishing this involve open bottom structures or bridges that not only span the river/stream channel, but also span one or both of the banks allowing dry passage for wildlife that move along the watercourse. Where the crossing involves high traffic volumes or physical barriers to wildlife movement, the crossing structure should be sized to pass most wildlife species (minimum height and openness requirements). To not obstruct the movement of wildlife species, especially aquatic wildlife, the crossing should be tied into the upstream and downstream banks, and instream bank-edge habitat should be maintained or constructed.

#### vii. Structure Width

The width of a stream crossing structure should be appropriate to provide for the adequate passage of water, sediment, aquatic biota, and organic matter at all flow levels. Because of the high variability of stream channel types in New Hampshire, it is recognized that a single standardized numeric value for the size of crossing structures based on any metric for all streams is unrealistic and may actually lead to long-term erosion or sedimentation problems at the crossings or obstruction of aquatic organism passage, consequences that this guidance document is intended to prevent. A stream crossing structure should be wide enough to accommodate the geomorphic characteristics of a stream without impacting the balance of sediment erosion and deposition that occurs naturally at the site. In all cases, to ensure aquatic organism passage for the long-term, it is critical to avoid channel constriction during typical bankfull flows, as these are the channel forming flows. A numeric standard that has been used to determine the appropriate width of the streambed inside the proposed structure is 1.2 times the bankfull width plus 2 feet (and also see other guidance documents in the “Examples of Other Agency Stream Crossing Guidelines” section at the end of this document, many of which also suggest that a minimum of 1.2 times bankfull width be used as a minimum). Barnard (2003) concluded that culverts that were built to this specification and included a stream simulation design within them (i.e., contained a designed and constructed streambed within the culvert), and had a culvert slope/channel slope ratio  $<1.25$ , did create similar fish passage conditions compared to the adjoining channel. The streams in this study were relatively small and steep, likely all Rosgen Type A and B channels, with bankfull channel widths ranging from 6.3 to 15 feet and channel slopes ranging from 2% to 17%, with most greater than 4%, and had been in place for only several years.

Therefore, although this information is useful, it should be used with an understanding of the limitations of the dataset and the conclusions drawn from the analysis. Simply applying this as a numeric standard for all crossings is not recommended given the amount of geomorphic variability in New Hampshire streams and rivers; however, this numeric value may be useful to those designing and constructing crossings and to those involved with reviewing applications for stream crossings.

Culverts **typically** should be no less than 6 feet and no more than 16 feet in diameter. Six feet is the minimum width needed to properly construct stream simulation; the inside of culverts smaller than this are too small to access and construct the streambed. For projects requiring a culvert 16 feet wide or greater, a bridge/span is likely more practical, but properly designed and constructed culverts may also be a solution in these cases. A stream with a 3 foot bankfull width requires, at a minimum, a culvert that is 6 feet wide at the streambed (3 feet times 1.2 plus 2 feet). A stream with a 12 foot bankfull width requires, at a minimum, a 16 foot wide culvert (12 feet times 1.2 plus 2 feet), or in other words, streams with a bankfull width less than 12 feet are culvertable while those 12 feet or wider typically should be a bridge/span.

#### viii. Embedding Structures

It is preferable for enclosed structures to be embedded, sloped, and aligned adequately to provide natural sediment transport, structure stability, and passage of water, organic matter and aquatic biota at all levels of flow. Stream stability, gradient, and flow magnitude highly influence the necessary levels of structure embedment. An appropriately embedded structure should have:

- Sufficient conveyance of water and sediment, with velocities suitable to maintain aquatic organism passage.
- Sufficient depth of material within the culvert to achieve stability of the culvert bed material comparable to that of the upstream and downstream channel.
- Sufficient depth of material to prevent dewatering and subsequent aquatic organism passage problems at any flow conditions.
- Sufficient embedment to account for long-term vertical channel adjustment anticipated for the adjacent streambed. In some cases site constraints may limit the degree to which a culvert can be embedded. In these cases, pipe culverts should not be used and pipe arches, open-bottom arches, or bridges should instead be constructed. The footing depths should be determined by the design engineer of record using scour analysis, geotechnical investigations, and/or other appropriate methods.
- Sufficient conditions to ensure adequate ecosystem connectivity and accessibility to both sides of the stream crossing (River and Stream Continuity Partnership 2006).

For general guidance, the following are often used to determine the minimum embedment depths for crossings:

- Greater than or equal to 2 feet for box culverts and other culverts with smooth internal walls.
- Greater than or equal to 1 foot for corrugated pipe arches.
- Greater than or equal to 1 foot and at least 25 percent for corrugated round pipe culverts.

#### ix. Natural Substrate Within the Structure

Careful attention must be paid to the composition of the substrate within the structure. The substrate within the structure should match that of the substrate in the natural stream channel (mobility, slope, stability, confinement) at the time of construction. If natural sediment transport is maintained, upstream particles are expected to replace materials lost within the crossing structure. If the amount of sediment moving into the structure is not equal to the amount of sediment moving out, then there will be problems with aggradation within or upstream of the structure or with scouring and/or bank erosion downstream of the structure. However, there may be some situations, such as in an enclosed bottom structure in a high gradient pool/cascade stream reach, in which it is specifically intended that natural substrates in the crossings are to remain stationary.

There may be specific situations in which some sort of armoring, that is using larger stone material than in the natural bed or on the banks, immediately along the face of culvert or bridge abutments may be necessary to resist scouring forces that are predicted to occur during a specific design flow. Those situations may be most common in streams with finer substrates like sand, silt, and mud, or locations with high levels of flow rate fluctuations. When possible, it is ecologically better to design a slightly wider structure so the armoring structures do not modify the channel width and flow velocity. This may also avoid damage to the structure and/or additional maintenance such as the removal of wood and sediment accumulated during large flow events. The stream channel dimensions (depth, bankfull width, and slope) in the crossing structure during all flow conditions should approximate those in the natural river/stream channel.

When armoring of the streambed is necessary, the armoring material should resist displacement during flood events and be designed to maintain appropriate channel characteristics through natural bed load transport. Sometimes, in order to ensure bed stability (not rigidity) at higher than bankfull flows, it may be necessary to use larger substrate within the structure than is generally found in the natural stream channel. In these cases, the substrate should, as closely as practicable, approximate the natural stream channel and fall within the range of variability seen in the natural channel upstream and downstream of the crossing.

The objective is to design the structure to maintain a streambed composition and form throughout the culvert similar to and continuous with the adjacent reaches. To do this, one should:

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

- Design sign 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.

#### x. Maintaining Depth at Low Flow in Enclosed Structures

In order to provide appropriate water depths and velocities at a variety of flows, and especially low flows, it is usually necessary to reconstruct the streambed within a closed bottom structure. Otherwise, the width of the structure needed to accommodate higher flows will create conditions that are too shallow at low flows. When constructing the streambed special attention should be paid to the sizing and arrangement of materials within the structure. If only large material is used, without smaller material filling the voids, there is a risk that flows could go subsurface within the structure, thereby creating a surface water disconnect (barrier) in the structure. Appendix E contains references for channel reconstruction methods. It should be noted that there are design and construction costs associated with rebuilding the streambed within a closed bottom structure; these costs should be considered relative to the cost of constructing an open bottom structure.

#### xi. Rare, Threatened, and Endangered Species

In some instances, following these guidelines for stream crossing structures may not be adequate to protect natural stream process and other sensitive environmental resources. In the event of an occurrence of a rare, threatened, or endangered species or exemplary natural community in the subject stream, based on state maintained databases, the protection of the species may require specific considerations that may be different than the guidelines presented here. These considerations are specific to each case, and therefore, generalizations regarding the protection of rare, threatened, or endangered species or exemplary natural communities cannot be made in this document.

#### xii. Openness Ratio

Openness ratio is the cross-sectional area of a structure opening, in square meter, divided by its crossing length in linear meters. For a box culvert, openness = (height x width)/ length. For crossing structures with multiple cells or barrels, openness ratio is calculated separately for each cell or barrel. At least one cell or barrel should meet the appropriate openness ratio standard. Embedded portions of culverts are not included in the calculation of cross-sectional area for determining openness ratio (*verbatim* from River and Stream Continuity Partnership, 2006).

At this time, documentation determining openness ratio requirements for aquatic wildlife is limited. However, for very small perennial streams with relatively small bankfull widths, a typical crossing length (upstream to downstream) may preclude aquatic organism passage because of the lack of light within the crossing, especially for those crossings that are very long under large road systems. In those cases, the very long crossing may be such a deterrent to some aquatic organisms that they attempt to cross the

road and may be subjected to vehicular mortality and collection. An openness ratio of 0.25 meters has been suggested in the Massachusetts Stream Crossing Guidelines as a minimum requirement for the passage of most aquatic species (River and Stream Continuity Partnership 2006).

In most cases, a geomorphically compatible stream crossing structure will allow for aquatic organism passage without the specific need to meet an openness ratio of 0.25 meters. In areas where the passage of semi-aquatic wildlife, such as turtles and amphibians, is a concern, it is recommended that an openness ratio of at least 0.25 meters be included in stream crossing design. Minimizing impacts to migration patterns will help maintain population viability and genetic diversity in populations that depend on the breeding success of wide ranging adults with delayed ages of sexual maturity (Marchand and Litvaitis 2004).

### xiii. Intermittent Streams

Headwater streams, including intermittent streams, support a significant proportion of the aquatic biodiversity in a watershed. Intermittent streams provide habitat (including rearing and spawning), migration corridors, and forage opportunities for several fish, insect, and wildlife species (Meyer et al 2007). The same geomorphic principles that apply to perennial streams are also exhibited in intermittent streams. To protect the values and functions of wetlands as well as public infrastructure appropriately-sized crossings on intermittent streams are necessary. Therefore, the design of crossings on intermittent streams should incorporate the same principles of stream crossing design used for perennial streams, designs that account for both hydrology and sediment transport characteristics. To avoid impacts to downstream areas, flow velocities and sediment transport within the structure should not be significantly different from the stream above and below the crossing. In most cases, this should be accomplished by spanning, at a minimum, 1.2 times the bankfull width plus 2 feet. In designs where a culvert is found to be appropriate, the structure should be embedded at an appropriate level where the downstream side of the structure remains at a consistent elevation relative to the natural streambed. The intent of embedding the culvert is to encourage the formation of a streambed within the structure; therefore the embedded portion of the culvert should not be included in the hydraulic analysis.

Determining bankfull width may, at times, be difficult on some intermittent streams, and in these cases best judgment should be used at each site to estimate the bankfull width of the channel. A solution that minimizes impacts throughout the intermittent stream without creating additional barriers to aquatic organism passage or impacting perennial streams or wetlands downstream of the intermittent stream needs to be identified. In most cases, this should be accomplished by spanning, at a minimum, 1.2 times plus 2 feet of the bankfull width of the channel. Culverts should be embedded and a streambed that is similar to the substrate above and below the crossing, should be rebuilt within the culvert using construction practices found in USDA Forest Service (2008b) or in some cases be allowed to reestablish naturally based upon favorable site specific conditions. If a specific intermittent stream is used directly by fish (e.g., an

intermittent stream that flows into a waterbody known to be used seasonally by spawning rainbow smelt [*Osmerus mordax*]) as in maps provided to the NHDES by NH Fish and Game Department, the crossing should also be additionally designed to not restrict fish passage at the flow levels expected during likely periods of movement.

## **b) Field Survey Data Collection**

Site-specific surveys should be conducted to determine the appropriate type, width, elevation, and length of the proposed crossing structure including the need for additional structures to convey floodwaters, especially where flood plains are present. Reference reach site selection, if needed, is critical for accurate data extrapolation and the overall success of stream crossing design. Observational data should also be collected to determine what would occur in the event that the crossing failed due to partial or complete blockage by sediment, wood, ice, or debris. This will help designers reduce the risk to additional flood damage should the crossing fail during a high flow event.

### **i. Reference Reach**

A sample area in proximity to the proposed crossing location needs to be highly representative of the physical dimensions of the stream channel. Impacted or degraded areas should be avoided during the selection phase of reference reaches. Ideally, information should be gathered from areas free to adjust with no excessive constriction/deposition. Harrelson et al. (1994) provides a detailed guide to choosing reference reach locations. The critical concepts that must be understood to design a geomorphically compatible stream crossing and analyze potential impacts to stream channel stability are described below.

### **ii. Hydraulic Capacity**

Typically, stream crossings are designed primarily to convey a chosen peak flow or precipitation event based on a specific predicted frequency of the event (e.g., 25 or 50 year flood). The magnitude of the chosen peak flow event is usually dependent on the road type, potential flood damage, and cost (Normann et al 2001). Predicted discharge rates (water depth and velocity) at bankfull stage flood events and other flood magnitudes also need to be considered in stream crossing design. The analysis of the hydraulic properties of a stream is necessary for both new and replacement stream crossing structures and is already traditionally conducted. Field data collection should consist of surveys to determine channel geometry, the channel width, depth, cross sectional area, longitudinal slope, and channel and floodplain roughness so that water velocity, shear stress, and discharge may be determined. It is beneficial to collect flow data during a variety of flow stages. A good reference for cross section surveys and other on site data collection can be found in Harrelson et al. (1994). Available regional curves, regression equations, FEMA flood studies or other reference flow data are useful tools to predict and/or compare measured bankfull flows and more infrequent, higher magnitude flows.

### iii. Rosgen Level II Stream Classification

In order to assess the stability and dimensions of a stream and its potential response to the installation or replacement of a crossing structure, including its effects on channel stability, the ability to convey sediment, and aquatic organism passage, the stream should be classified using the Rosgen Stream Classification system described in Rosgen (1996). A Level II classification uses measurable geomorphic variables, including entrenchment ratio and width to depth ratio, to place the stream into one of seven major stream types, Type A to Type G, each with more refined subcategories based on slope and substrate particle size. The characteristics of each stream type are important to consider during the design of a stream crossing structure. For example, F type streams, tend to be expanding laterally with eroding banks, which should be accounted for in the design of the crossing. The Rosgen Stream classification system provides the range of variability in geomorphic characteristics, the entrenchment ratio, width to depth ratio, and slope, which a stream crossing should be designed to accommodate. If a stream crossing is designed with dimensions that are outside of the natural range of variability for that stream type, the stream may become unstable and shift into a new stream channel type, which could in turn negatively affect the stream crossing structure and aquatic organism passage. Appendix A provides a summary of the range of descriptive statistics for each Rosgen stream type.

### iv. Bankfull Width

The identification of the bankfull dimensions within lotic systems is a useful tool to describe the overall flow capacity and evolution of the stream reach. The bankfull flow is commonly referred to as the channel forming flow. A good understanding of how to accurately determine bankfull dimensions is essential to the design of geomorphically compatible stream crossings. Several key analyses in this process are based on bankfull stage measurements. Incorrectly identifying the bankfull dimensions can lead to inappropriate assumptions about sediment transport and flooding magnitude, possibly resulting in a poorly functioning stream crossing. The bankfull stage is considered the stage at which water just begins to overflow onto the active floodplain (incipient point of flooding) and subsequent influences on the dimensions, patterns, and bed features of the river begin to occur (Leopold et al. 1964; Rosgen 1996). Stream geometry and sediment discharge (bedload transport) are strongly influenced by the frequency and scale of these bankfull discharges. On average, bankfull discharge events have a return period of approximately 1.5 years (Rosgen 1994). It should be noted however, that analyses of available recorded flow data at some gauge stations in New Hampshire has shown that bankfull flows can occur at shorter intervals (approximately 1.2 years). There are several useful guides to identify bankfull flow stage indicators (Harrelson et al 1994; Rosgen 1996; Vermont Agency of Natural Resources 2004; and USDA Forest Service 2005).

### v. Stream Entrenchment (Entrenchment Ratio)

The degree of confinement of a river, in relationship to its valley or flood plain, defines how flows are conveyed. Entrenched streams, which have low entrenchment

ratios, typically have minimal access to flood plains and tend to deepen in order to accommodate flood flows. Conversely, slightly entrenched streams, which have high entrenchment ratios, tend to accommodate the conveyance of increased water levels by expanding or spilling over into flood plains.

The entrenchment ratio is a field determinable metric that helps quantitatively define the entrenchment of a stream reach. The entrenchment ratio is defined as the ratio of the width of the flood-prone area to the surface width of the bankfull channel. The flood-prone area is considered the width at the elevation of twice the maximum depth at bankfull flow measured at a riffle or steep bed feature. The rate of confinement of a stream decreases as the entrenchment ratio increases. This can be an important metric especially in the design of flood plain culverts to convey floodwaters.

#### vi. Width/Depth Ratio (Bankfull Surface Width/Bankfull Mean Depth)

This parameter is used to illustrate the available energy and ability to move sediment at various flow levels within a stream reach. Reference site width/depth ratios are a good initial indicator of trends in the overall channel stability and can be used as a predictive tool for interpreting channel stability after channel disturbances, such as impacts from the installation of crossing structures. As width/depth ratios increase, hydraulic stress on the bed is reduced, yet higher stress along the banks may lead to increased erosion rates and therefore channel widening. A stream crossing design must consider not only the existing width/depth ratio of the channel, but any predicted changes that will occur in the future. A crossing on a stable stream reach that maintains the natural width/depth ratio of the stream over time will have the least impact on aquatic organism passage.

#### vii. Water Surface Slope

This parameter helps describe the rate of water surface elevation change in streams. Stream channel morphology, sediment loading, hydraulic, and biological characteristics are highly influenced by the water surface slope and resulting stream energy. Channel bed slope measurements are required in traditional hydraulic analyses. Water surface slope is required in the Level II Rosgen stream classification for stream type designation. Guides and documents previously listed provide accepted field methods to determine water surface slope.

#### viii. Bed Load Capacity Analysis

Sediment movement through structures at various flows should be consistent with that of the natural stream channel. Stream morphology and stability are highly influenced by its sediment regime. The sediment features of a stream channel can be expressed in a variety of methods. Measurements of sediment bedload, suspended sediment, as well as, sediment storage, size, and source all describe the physical parameters valuable in stream sediment analysis.

Bedload sediment movement, or potential movement, is considered to be the primary sediment metric for channel stability (Rosgen 1996). It is important to recognize that the natural stream has the capability to move and transport sediment at varying rates as a function of the flow. A geomorphically compatible stream crossing matches the competence, the ability to move a single particle, and capacity, the total volume or mass of sediment moving at any time, of the natural channel for a range of flows centered on the dominant (channel-forming) discharge. Crossings that alter sediment transport competence may instigate channel instability, especially on high bedload streams. When a crossing causes a decrease in the channel's ability to move its sediment load, channel aggradation can be expected. Conversely, degradation of the stream bed can be expected when a crossing causes the sediment transport competence to increase.

Bedload competence and capacity are calculated from sediment, geometric, hydrologic, and hydraulic data for the stream. The competence calculation is also referred to as incipient motion, and determines the particle size that moves during a specific flow. The measure for determining if a particle moves is the shear stress on the bed (units of force per unit area) – the bed shear stress ( $\tau_0$ ). Bed shear stress is estimated as the specific weight of water times the mean hydraulic depth times the water surface slope. The critical shear stress ( $\tau_c$ ) is the  $\tau_0$  that is just able to move a certain particle size. Critical shear stress is computed based on the size of the particles found on the bed or bars of the stream. The ratio of  $\tau_0$  to  $\tau_c$  provides an estimate as to whether a particular particle can be moved. When the ratio is equal to one, the particle is said to be at “incipient motion”. Common dimensionless measures of the critical shear stress are from Shields (see, for example, Simons and Sentürk, (1992); Leopold et al. (1964); or Rosgen (1994)). Methods of computing either the critical shear stress, the particle size at incipient motion, etc., may be found in Appendix B.

The particle size distribution of a stream is necessary to determine bed load capacity. When sampling sediment from the bed, it is important to sample below any “pavement” or partial armoring layer. For bed samples, they are typically taken at riffles, but not in the thalweg. Bar samples are superior to bed samples since the bar is truly representative of the sediments that move during channel-forming flows. Bars should be sampled in the lowest ½ elevation interval (full bar elevation is from the thalweg to the top of the bar) and on the downstream half of the feature. Both bed and bar samples may be pebble counts. Sieve analysis is preferable for smaller sediment sizes (e.g. smaller than cobble particles), although care must be taken to avoid washout of smaller particles when sampling below the water column. More samples and larger sample sizes will produce more accurate results. The sampling effort should be appropriate for the size of the project. Detailed guidelines for sampling particle size distributions are available in a publication by the U.S. Forest Service (Bunte and Abt 2001).

There are many formulas for predicting bedload sediment transport. Common formulas include Meyer-Peter, Müller; Einstein-Brown; Akers-White; Van Rijn; Yalin;

Larson; and Bagnold. When using one of these methods, it is important to understand that the designer is not comparing methods, but rather comparing the natural sediment transport capacity to that of the proposed stream crossing. To this end, the same formula should be used to estimate sediment transport in all cases when designing the stream crossing (before and after conditions). Details on the Meyer-Peter, Müller and Einstein-Brown methods may be found in Appendix B. Also see USDOT/FHWA (2001).

#### ix. Potential Catastrophic Failure Scenarios

As described in Section I.c., the amount of instream wood is expected to increase in northeastern streams as forests age in the region (Warren et al 2007), and studies of the mechanisms by which culverts have failed demonstrate that relatively small wood that is transported during relatively small high-flow events are often the causative agent for the blocking of the culvert. In light of recent flooding events in New Hampshire, applicants are urged to consider the potential of a catastrophic failure and the potential consequences of such an event.

Even well-designed crossing structures may be subject to failure in the event that they become overwhelmed by unforeseen circumstances such as the accumulation of sediment, wood, ice, or debris transported from upstream blocking the stream crossing structure. The site survey should capture sufficient topographic information to suggest what scenario(s) may occur in the event that the crossing experiences a catastrophic failure. The principal mechanisms of failure are stream capture, stream diversion, and washout. In the stream capture scenario, some or all of the flow travels along the road surface when the crossing becomes overwhelmed. This can occur if the road is sloped in either direction along the path of travel, or when the terrain is elevated on both sides of the roadway. In the stream diversion scenario, some or all of the flow travels parallel with the road, often in a drainage ditch, and may overwhelm down-gradient crossings or drainage pipes, or may be redirected to entirely different flow paths or properties. In the washout scenario, the fill or approaches are carried away by erosion when the crossing is overtopped, or by water piping through the fill. The impacts resulting from any of these scenarios can range from negligible to significant. Of these three scenarios, washouts have the greatest likelihood to result in catastrophic failure. This can occur if the crossing impounds water when it becomes blocked and begins to function like a dam and if the crossing were to fail, the result can be similar to a dam breach. For this reason, the site survey should capture sufficient information to estimate the potential upstream impoundment area and storage volume, and to describe the effect on downstream areas in the event of a catastrophic release of water.

#### c) **Data Analysis and Review**

To determine if a stream crossing is geomorphically compatible, the following information should be submitted for review.

- Rosgen geomorphic classification of the stream, which includes the bankfull width and depth measurements, entrenchment ratio, sinuosity, slope, and dominant particle size, at the location of the stream crossing. This should be the classification of the natural stream state, unaffected by any other stream crossings that may be in the vicinity. If the site of the proposed stream crossing is affected by another nearby structure or other impact, geomorphic data must be supplied that describes the natural system, unaffected by stream crossings. This may require data to be collected from further upstream or downstream, or from a reference reach.
- Demonstration that the stream crossing has accommodated the bankfull width, entrenchment ratio, bankfull width/bankfull depth ratio, and stream surface slope of the existing stream, within the natural ranges of variability for the stream type at the site of the stream crossing. To accommodate the entrenchment ratio, flood plain drainage structures may be utilized.
- Pre- and post-stream crossing bed load sediment transport calculations are to be submitted for flows from incipient motion to twice the maximum bankfull depth as measured at a riffle. This comparison should show that the stream crossing possesses similar bed load sediment transport characteristics as the pre-existing condition. For the pre-existing condition, if the stream is considered to be armored up to twice the maximum bankfull depth, this should be noted. Sediment transport calculation tools are provided in this document; however, if other tools (see “Examples of Other Agency Stream Crossing Guidelines” section at the end of this document) are proposed to be used during the design, the applicant should demonstrate that they are applicable to the site.
- Plan view drawing of the crossing demonstrating the crossing site is appropriate.
- Pre- and post-crossing water surface profiles for the bankfull flow event, 10-year and 100-year flow events.
- Narrative assessment of the long-term geomorphic consequences if the stream crossing is constructed.
- Methods or structures to be implemented to minimize any consequences identified in the previous bullet.

#### **d) Applying Geomorphic Characteristics to Structure Designs**

Once the data is collected at the site of the proposed stream crossing (or reference reach), the next step is to incorporate this information into the design of a geomorphically compatible stream crossing. An analysis of hydraulic capacity at the site provides a starting point for crossing design. This preliminary design employs a design flow (for example, 25-year flood) and then develops the necessary stream crossing open area that passes this flow while subscribing to relevant hydraulic constraints (for example, not overtopping the roadway, not flooding certain areas, etc.).

Determining the geomorphic dimensions of the structure begins with the Rosgen Level II stream classification. Each stream type falls within a range of variability for each geomorphic characteristic (See Rosgen Classification of Natural Rivers appendix A) with acceptable variability. For example, B3 type streams have entrenchment ratios

that fall between 1.4 and 2.2, width/depth ratios less than 12, and slopes between 0.02 ft/ft and 0.39 ft/ft. These ranges provide guidance on the size of the crossing structure necessary to accommodate a particular stream type without forcing that stream to adjust into a different channel type. The designer of a stream crossing has the freedom to work within these variables as long as an analysis of bedload transport capacity shows that the proposed structure has similar sediment transport capacity as that of the natural channel for the pre-described range of flows (incipient motion through twice the maximum bankfull depth. In other words, a structure that creates a new entrenchment ratio of 1.4 may be appropriate on a B3 type stream with an actual entrenchment ratio of 1.6 if the sediment transport capacity is unchanged. However, the larger the entrenchment ratio value, the more likely it will be that floodplain drainage devices or spanning a portion of the floodplain will be necessary.

To extend the B3 stream type example, a stream with a bankfull width of 16 feet and an entrenchment ratio of 1.6 would be accommodated by a stream crossing width of 1.4 times 16, or 22.4 feet, as long as sediment is neither aggrading in the structure, nor degrading downstream of the structure. If sediment transport is determined to be an issue at a structure width of 22.4 feet, then the structure could either be designed wider or a flood plain drainage device could be positioned at bankfull elevation in a way that alleviates the increased velocities in the main channel during high flows. Although it is preferable to span the flood-prone area to accommodate the entrenchment ratio, this approach may be cost prohibitive in some cases. Flood plain drainage structures allow for a more narrow structure width necessary to accommodate flows in the main channel without changing the bedload capacity of the stream. Maintaining the natural sediment transport capacity of a stream reach will ensure that flow velocities within the crossing structure will not present a barrier to aquatic organisms. While the Rosgen Level II classification provides general guidance on the range of variability in geomorphic characteristics that must be accommodated by the stream crossing design, it is the bedload capacity analysis that ensures that the crossing will not alter the natural flow regime specific to the site of the proposed structure.

An open bottom crossing structure that spans a stream a minimum of 1.2 times the bankfull width plus 2 feet should not impact the width/depth ratio or the slope of that stream. With a closed bottom crossing structure, the stream channel should be rebuilt, or allowed to reestablish, within the structure so that the width to depth ratio and the slope of the new channel falls within the range of variability for that stream type. This approach is often called stream simulation. Once again, an analysis of bed load capacity will act as a check to ensure that the new stream channel dimensions and slope are sufficient to maintain the existing sediment transport characteristics of that stream. The final product should have a height and width adequate to pass flows during infrequent storm events based on a hydraulic capacity analysis, allow for access to flood plains without significantly increasing flows in the main channel, maintain a channel slope and width/depth ratio that is within the natural range of variability for that stream type, and not substantially alter the existing sediment transport capacity of the natural stream reach.

When the geomorphic stream crossing design is completed, it should then be compared to the preliminary hydraulic design. If there is significant discrepancy between the two, the geomorphic design should be hydraulically studied (for example, with HEC-RAS) to ensure that it meets the hydraulic constraints. If it does not, the geomorphic designs need to be modified, within the range of geomorphic variables appropriate for that stream type, until both geomorphic and hydraulic constraints are met. For example, floodway drainage may be necessary (additional culverts in the flood plain) to meet the hydraulic constraints.

There are many excellent design resources on stream simulation, the most recent of which were published in 2008 (Bates and Kirn, 2008; USDA Forest Service 2008b). These documents contain detailed information on how to design stream crossings utilizing stream simulation tools, and applicants should consider using these tools in the design and construction of new and replacement crossings.

#### **e) Special Considerations by Channel Type**

The following section provides some general guidance on the stream crossing design issues that are typical of each Rosgen Level II stream type. Extremely variable factors such as adjacent land uses, local climatology, riparian buffer, and economic limitations all play a major role in each stream crossing project. It is unrealistic to briefly summarize these issues by stream type in this document, and therefore these variables need to be considered specifically at each potential site. There is no substitute for training and on the ground experience. A better understanding of the Rosgen Stream Classification system and the general principles of fluvial geomorphology among designers of stream crossing structures will result in stream crossings that greatly reduce the environmental impacts on New Hampshire's rivers and streams and comply with existing regulations.

When discussing stream channel stability and vertical adjustment, a time scale component needs to be considered. Some stream channels are evolving slowly and naturally on a geologic time scale. The rate of evolution should be identified to prevent "over engineered" structures with unintended ecological consequences. Natural changes in channel morphology may be happening at a rate that is too slow for concern on a human time scale. The channel evolution most impacting to stream crossing designs is that which is occurring rapidly. Stream types vary in their rate and pattern of channel evolution, as well as their vulnerability to disturbance. Whether it is a natural evolution or human induced impact, an unstable stream (e.g. see G type stream considerations) must be identified and appropriate efforts to stabilize the stream in the vicinity of the stream crossing may be necessary. Sediment transport, entrenchment ratios, bankfull width/ bankfull depth ratios, and stream slopes should still be maintained if stabilization techniques are utilized. Appendix D compares the sensitivity to disturbance, the erosion potential, and the typical sediment supply of Rosgen level II stream types. This can be a useful table, but it should not replace site-specific analyses.

i. Type A

Type A streams are high energy, entrenched streams with relatively steep slopes. In New Hampshire, they tend to occur in the more mountainous regions. These streams are very stable when the substrate is bedrock or boulders, but have high sediment loads and are very sensitive to disturbance in valleys with finer substrates. Due to the flashy nature of these streams, it is important to design a crossing with adequate height and cross sectional area to prevent over-topping during high flows. Because of the entrenched nature of A type streams, crossing structures designed at, or even slightly less than, bankfull width may be adequate as long as the sediment transport capacity of the stream is not altered. Caution should be used in the hydraulic analysis of this stream type since often the flow is critical and or supercritical.

ii. Type B

Type B streams display moderate sinuosity, slope, width/depth ratios, and entrenchment. This generally stable stream type commonly consists of riffles and rapids and occasional scour pools. Type B streams are often found in forested areas with flood plain vegetation moderately influencing channel stability. Streambank erosion is typically considered low and sensitivity to disturbance is often low to moderate. Fish habitat in this channel type is often attributed to scour pools developed by large woody material.

Stream crossings commonly occur over B and C type channels in New Hampshire because they tend to occur in valleys that are conducive to road building and development. From a stream crossing perspective, B type streams are a transition in design issues between A and C type streams. Approaches to crossing a B type stream vary with the size of the flood plain. At one end of the spectrum are B type streams with lower entrenchment ratios (1.4). The relatively narrow flood-prone area may be accommodated with a single opening. At the other end of the spectrum are the B type streams with entrenchment ratios of up to 2.1. These streams behave more like C type streams, with lower slopes and wider flood plains. The flood-prone area in relation to the bankfull width may be too wide for a single opening and should be either spanned or accommodated with flood plain drainage structures. In either case, an analysis of bedload capacity will ensure that the structure design will not impact sediment transport capacity through the stream reach.

iii. Type C

Type C channels have high entrenchment ratios and therefore commonly access well developed flood plains to accommodate high flow stages. Channels are typically sinuous with low slopes, less than 2%, and commonly consist of riffle/pool sequences. A

concern in designing stream crossing structures for this stream type is channel stability and lateral extension. Channel stability and lateral movement is highly dependent on the adjacent stability of the natural stream bank. If existing bank stability is impacted, this channel type can quickly become unstable. To compensate for possible channel instability and wider bankfull flows, larger crossing structures and/or flood plain drainage structures should be considered.

#### iv. Type D

Type D channels are braided stream channels with high width/depth ratios. They are characterized by multiple, laterally shifting stream channels separated by unvegetated, or sparsely vegetated, islands and bars. The constantly shifting stream channels in a D type stream present a problem for designing crossing structures. Although it is best to avoid building a road over a braided channel, a bridge or piered structure is the preferred option for crossing a D type stream. Attempting to position multiple culverts to accommodate each channel can result in higher than normal maintenance costs, as stream channels shift and culverts fill with sediment.

#### v. Type E

Type E channels are relatively stable, sinuous channels with very wide flood plains. The stream banks and flood plains are usually well vegetated, often with wetland plant species. Entrenchment ratios can be as high as 100 in broad, unconfined valleys. This high entrenchment ratio is difficult to accommodate with a single stream crossing structure. The least impacting approach to crossing an E type stream would be a bridge or piered structure that spans the flood-prone area. However, the costs associated with this approach may be prohibitive, and **thus it is recommended that crossings not be located on Type E channels.**

Two important considerations when designing a crossing of an E type stream are preserving the width/depth ratio of the stream channel and maintaining access to flood plains. Type E channels are stable, but vulnerable to disturbance, and can rapidly change into different channel types if stream channel dimensions are altered. It is highly recommended that crossings of Type E channels be at a minimum width of 1.2 times bankfull width plus 2 feet and that flood plain culverts at bankfull elevation be used to avoid constricting flood flows through the main channel. If the stream channel must be rebuilt within a structure, it is important to maintain the natural width/depth ratio to avoid destabilizing the stream.

#### vi. Type F

Type F stream channels are meandering, entrenched stream channels that are often in the process of widening and establishing a new flood plain. These channels have high bank erosion rates, which present a problem for crossing design. A crossing on an F type channel must account for the lateral movement of the stream banks. If a crossing over an F type channel cannot be avoided, some form of armoring and/or grade control

may be necessary to prevent bank erosion or sediment deposition that may threaten the crossing structure. Any modifications to the stream bank must be done with consideration for the effects of future channel adjustment that may impact or result from the project. A conservative approach to armoring will help minimize negative impacts to instream habitat and aquatic organism passage. Enhancing the streambank (riparian) buffer with woody vegetation in the vicinity of the stream crossing on an F channel is only recommended after the degree of channel incision has been reduced to less than 1.0.

#### vii. Type G

Type G channels are highly entrenched and are generally unstable both laterally and vertically. This channel type consists of streams that are deep and narrow with moderate sinuosity and slopes; often characterized by the term “gully”. The stream energy of G type streams expressed by a low width/depth ratio (less than 12) is an indication of high rates of sediment movement and bank erosion. Because of the high rates of down cutting experienced in most G type streams, an embedded culvert, or non-embedded culvert with a downstream grade control that helps back-up water into the culvert at low flows should be considered. A hard bottom culvert may be necessary to protect roads and stream banks within the structure from the inherent downcutting of type G streams. The instability or “disequilibrium” of this stream type may be a good illustration of impacts at both the stream and watershed levels.

### **IV. Guidelines for Stream Crossing Structure Replacement**

Numerous culverts and other crossing structures in New Hampshire currently act as a barrier to aquatic organism passage and sediment transport. It is important to assess the impact these structures have and what opportunities exist for mitigating those and future impacts. In the short term however, some barriers can be addressed by culvert retrofits: temporary modifications to improve aquatic organism passage short of replacement. However, crossing replacement programs and projects offer the best opportunity for restoring continuity and natural sediment transport, maintaining long-term protection of river and stream ecosystems, and providing adequate protection from damage during flood events.

Methods have been developed, and are continuing to be refined and adapted, for evaluating culverts and other crossing structures for their impacts on aquatic organism passage and other ecosystem processes. Along with these assessments there needs to be a process for prioritizing problem crossings for remediation. The process should take into account habitat quality in the river or stream and surrounding areas, upstream and downstream conditions, as well as the number of other crossings, discontinuities (channelized or piped sections), and barriers affecting the system. It is important to use a watershed-based approach to river and stream restoration in order to maximize positive outcomes and avoid unintended consequences. Although a watershed approach to stream crossing replacement is preferred, it is understood that limited funding forces most stream crossing structure replacement to occur as the need arises. However, this in no way

lessens the dramatic ecosystem impacts resulting from these culverts. Each individual stream crossing replacement should be evaluated as an opportunity to improve the overall connectivity of a watershed.

Stream crossing upgrades require careful planning and are not in all instances simply the replacement of a culvert with the same size or larger structure. Even as undersized crossings block the movement of organisms and material, over time rivers and streams adjust to the hydraulic and hydrologic changes caused by these structures, often leading to aggradation on the upstream side of the culvert and the increased potential of crossing failing due to this. Increasing the size of a crossing structure can destabilize the stream and cause head cutting, the progressive degradation of the stream channel, upstream of the crossing. There also may be downstream effects such as increased sedimentation. Crossing replacement can result in the loss or degradation of wetlands that formed upstream as a consequence of constricted flow. In heavily developed watersheds, undersized culverts may impede water to the point that storm flows are diminished in the watershed as a whole. Before replacing a culvert or other crossing structure with a larger structure, it is essential that the replacement be evaluated for its impacts on:

- Downstream flooding.
- Upstream flooding.
- upstream and downstream habitat (instream habitat, wetlands, riparian buffer, riparian areas).
- Potential for erosion and headcutting.
- Channel dimension, pattern, and profile in the vicinity of the structure.
- Sediment transport capacity.
- Stream vertical and lateral stability.

The replacement crossing will need to be carefully designed in order to maximize the benefits and minimize the potential for negative consequences resulting from the upgrade. In some instances, stream restoration may be needed in addition to culvert replacement in order to restore river/stream continuity and facilitate fish and wildlife passage. Culvert replacement may require attendant structures such as cross vanes, W weirs, and log vanes to ensure stream stability at that location. As with the design and construction of new crossings, the recent publication on stream simulation for stream crossings can be effectively utilized for the design and construction of replacement crossings (USDA Forest Service 2008b). Other tools specifically related to fish passage at culverts are available from a consortium of stakeholders (USDA Forest Service 2008a), from Maine (MEDOT 2004) and Vermont (Bates and Kirn 2008). These fish passage tools may provide fish passage for replacement culverts which are otherwise not impacting aquatic habitat or sediment and wood transport.

#### **a) General Considerations**

Replacement crossing structures should follow the design guidelines for new stream crossing structures (see Design Guidelines for New Stream Crossings section). With stream crossing replacements, the stream should be surveyed beyond the impact area of the existing crossing, upstream and/or downstream, to where the natural stream

channel exists. Upstream, the stream reach equal to or higher than the elevation of the top of the fill/road that covers the structure to be replaced should typically provide bankfull measurements that are outside the influence of the existing structure. In the case of high embankments, the headwater depth/elevation for the 25-year flood can be used. It must be demonstrated that the area surveyed for bankfull measurements is beyond any impact that may have been caused by the existing crossing. In addition, the existing stability of the stream within the proximity of the structure needs to be considered before any replacement/retrofitted structure is considered. Without identifying current stream stability a replacement structure may exaggerate sediment transport impacts limiting the function and lifespan of the replacement structure.

Replacement stream crossings should be designed to avoid or mitigate the following problems:

- Inlet drops
- Outlet drops
- Flow contraction that produces significant turbulence and increased velocities
- Tailwater armoring
- Tailwater scour pools
- Headwater pools
- Headwater flooding
- Physical barriers to aquatic organism passage
- Embankment failures/instabilities
- Channel entrenchment
- Channel sedimentation

As indicated by longitudinal profiles, scour analyses and other methods, structure design should include appropriate grade controls to ensure that the replacement will not destabilize the river/stream.

To the extent practicable stream restoration should be conducted, as needed, to restore river/stream continuity and eliminate barriers to aquatic organism movement.

The use of smooth bore materials or plastic pipes is not recommended unless they can be used and still allow the culvert to fall within the natural variability of the stream type and do not obstruct the movement of animals indigenous to the waterbody.

Slip-lined culvert replacement techniques are not recommended unless they can be used and still allow the culvert to fall within the natural variability of the stream type and do not obstruct the movement of animals indigenous to the waterbody. Situations in which slip liners are appropriate include:

- a. Drainage ditches not within the jurisdiction of the NHDES Wetlands Bureau.
- b. Locations where the entire length of the crossing is backwatered and analysis demonstrates that it will continue to be so after the slip-line installation (not including crossings backwatered by beaver activity).

- c. When the applicant has demonstrated through sound engineering that aquatic organism passage will not be precluded.

### **c) Field Survey Data Collection, Analysis and Review**

Many of the same parameters surveyed under the Guidelines for New Stream Crossings section are required under for replacement crossings. To determine if a replacement stream crossing is geomorphically compatible, the following information should be submitted for review.

- Description of the rationale for the stream crossing replacement.
- Rosgen stream classification upstream and downstream of the existing stream crossing. Rosgen geomorphic characteristics of the existing stream crossing.
- Detrimental geomorphic consequences that have occurred as a result of the existing stream crossing, if they exist.
- Bed load sediment transport capacity of the channel upstream of the existing stream crossing, (upstream of any 25-year flood backwater condition), from incipient motion through twice maximum bankfull depth. Bed load sediment transport capacity for the existing stream crossing for the same range of flows. In the case of multiple stream crossings, continue upstream until some semblance of the natural system, unaffected by stream crossings, is reached.
- Demonstration that the stream crossing has accommodated the bankfull width, entrenchment ratio, bankfull width to bankfull depth ratio, and stream surface slope of the existing stream, within the natural ranges of variability for the stream type at the site of the stream crossing. To accommodate the entrenchment ratio, flood plain drainage structures may be utilized.
- Pre- and post-stream crossing bed load sediment transport calculations are to be submitted for flows from incipient motion to twice the maximum bankfull depth. This comparison should show that the stream crossing possesses similar bed load sediment transport characteristics as the pre-existing condition. For the pre-existing condition, if the stream is considered to be armored up to twice the maximum bankfull depth, this should be noted. Sediment transport calculation tools are provided in this document; however, if other tools (see “Examples of Other Agency Stream Crossing Guidelines” section at the end of this document) are proposed to be used during the design, the applicant should demonstrate that they are applicable to the site.
- Plan view drawing of the crossing demonstrating the crossing site is appropriate
- Pre- and post-crossing water surface profiles for the bankfull flow event, the 10-year and 100-year flow events.
- Narrative assessment of the long-term geomorphic consequences if the stream crossing is constructed.
- Methods or structures to be implemented to minimize any consequences identified in the previous bullet.

## **V. Construction**

This section provides some recommendations that should help minimize impacts during stream crossing installation and replacement operations. Specific installation/replacement plans need to be developed for all projects due to the variety of site conditions. A well-developed plan should show how impacts would be minimized, how unexpected events may be mitigated, and how the project will be done as efficiently as possible.

Much of this section is derived from the Massachusetts River and Stream Crossing Standards (River and Stream Continuity Partnership 2006). Additionally, the U.S. Forest Service has recently published a comprehensive document on the design and construction of stream crossings (USDA Forest Service 2008b), and it is recommended that this document be considered as a source of information on construction practices for stream crossings.

#### **a) Road and Crossing Location**

Roads should be planned to avoid or minimize the number of road-stream crossings. Where crossings cannot be avoided they should be located in areas that will minimize impacts. Here are some guidelines:

- Avoid sensitive areas such as rare species occurrences and habitats and important habitat features (vertical sandy banks, underwater banks of fine silt or clay, deep pools, fish spawning habitat).
- Avoid unstable or high-hazard locations such as steep slopes, wet or unstable slopes, noncohesive soils, and bordering vegetated wetlands. Alluvial reaches are poor locations for road-stream crossings.
- Where possible locate crossings on straight channel segments (avoid meanders) and/or naturally entrenched locations.
- To the extent possible align crossings perpendicular to the stream channel and bankfull velocity vector; in addition give similar consideration to the floodplain flow.
- Crossings at bedrock outcrops, where the stream is cut into bedrock, are the most stable.

#### **b) Timing of Construction**

In general, the most favorable time for constructing road-stream crossings is during periods of low flow, generally July 1 to October 1. However, there may be occasions when a particular stream or river supports one or more rare species that would be particularly vulnerable to disturbances during low-flow conditions. Where rare species are a concern, contact the NHFGD or the New Hampshire Natural Heritage Bureau for information and advice on how to minimize impacts to those species.

#### **c) Duration of Construction**

Limiting the duration of instream work is the best way to avoid potential impacts.

- Have the new structure, equipment, and construction materials onsite and/or crane and delivery scheduled before the excavator bucket hits the stream.
- If possible, probe the footing or excavation areas to determine if ledge will need to be blasted - schedule the blaster accordingly.
- Adjust work schedules to minimize duration of vulnerability to inclement weather.

#### **d) In Stream Work**

- Whenever possible, all work should be conducted from the stream banks and heavy machinery should be kept out of the channel.
- In most cases, if appropriate sediment controls are applied, stream crossing replacement or installation can be done without stream diversion. The effects of sedimentation from an efficient and well planned installation/replacement project should be minimal when compared to the sediment transport during bankfull flows.
- Minimize the extent and duration of the hydrological disruption.
- Consider the use of bypass channels to maintain some river and stream continuity during construction.
- Use dams or cofferdams to prevent water logging of construction areas.
- Salvage aquatic organisms (fish, salamanders, crayfish, mussels) stranded.
- Segregate clean diversion water from sediment-laden runoff or seepage water, diversion water should re-enter the stream from an appropriate energy dissipation technology.
- Use anti-seep collars around diversion pipes, but in doing so, make due consideration of any nearby infrastructure that may be impacted by the water backed-up behind anti-seep collars.
- Use upstream sumps to collect groundwater and prevent it from entering the construction site.
- Collect construction drainage from groundwater, storms, and leaks and treat to remove sediment and floatable debris.
- Use downstream sediment control sumps to collect water that seeps out of the construction area.
- Use fish screens around the intakes of diversion pipes.
- Use appropriate energy dissipaters and erosion control at pipe outlets.

#### **Stormwater Management, Erosion and Sediment Control**

- Minimize bare ground.

- Minimize impacts to riparian vegetation. Native herbaceous and shrubby vegetation that must be disturbed should be salvaged and transplanted whenever possible.
- Prevent excavated material from running into water bodies and other sensitive areas.
- Stabilize exposed areas as soon as practicable, this includes stockpiles.
- Use appropriate sediment barriers such as silt fence, hay bales, mats, Coir logs for perimeter control.
- Manage and treat surface and groundwater encountered during excavation with the following:
  - Sediment basins
  - Fabric, biobag or hay bale corals
  - Irrigation sprinklers or drain pipes discharging into vegetated upland areas
  - Sand filters
  - Geotextile filter bags
- Turbidity of water 100-200 feet downstream of the site should not be visibly greater than turbidity upstream of the project site.
- Use best management practices for stormwater runoff. Minimize the amount of runoff flowing directly into the river or stream.

#### **f) Pollution Control**

- Wash equipment prior to bringing to the work area to remove leaked petroleum products and avoid introduction of invasive plants.
- When possible replace hydraulic oils with vegetable based oils in case a line is broken near the stream.
- To avoid leaks, repair equipment prior to construction.
- Be prepared to use petroleum absorbing “diapers” if necessary.
- Locate refueling areas and hazardous material containment areas away from streams and other sensitive areas.
- Establish appropriate areas for washing concrete mixers; prevent concrete wash water from entering rivers and streams.
- Take steps to prevent leakage of stockpiled materials into streams or other sensitive areas. Locate away from water bodies and other sensitive areas, provide sediment barriers and traps, and cover stockpiles during heavy rains.

#### **g) Construction of Stream Bed and Banks within Structures**

- Check construction surveys to ensure slopes and elevations meet design specifications.
- Use appropriately graded material, according to design specifications, that has been properly mixed before placement inside the structure.
- Avoid segregation of bed materials.
- Compact bed material.

- After the stream bed has been constructed wash bed material to ensure that fine materials fill gaps and voids.
- Construct an appropriate low-flow channel, thalweg and channel cross section.
- Carefully construct stream bed to ensure functionality and stability.
- Construct well-graded banks for roughness, passage by small wildlife, and instream bank-edge habitat.
- Tie constructed banks into upstream and downstream banks.

#### **h) Soil Stabilization and Re-vegetation**

- Surface should be rough to collect seeds and moisture.
- Implement seeding and planting plan that addresses both short term stabilization and long term restoration of riparian vegetation.
- Water vegetation to ensure adequate survival.
- Use seed, mulch, and/or erosion control fabrics on all slopes and other vulnerable areas.
- Jute netting and other erosion control materials that contain mesh near streams or rivers should be avoided (have been known to trap and kill fish and wildlife). If mesh materials are used, ensure mesh is biodegradable and properly placed and tacked down.
- Use native plants unless other non-invasive alternatives will yield significantly better results.
- Avoid mowing in the riparian zone to allow the natural succession of woody plants with deeper, more complex root structures.

#### **i) Monitoring**

- Ensure that BMPs are being implemented.
- Inspect for erosion after every precipitation event and at least twice per week. Inspections reports are to be documented.
- Evaluate structure stability.
- Inspect for evidence of stream instability.
- Inspect for presence of debris accumulations or other physical barriers at or within crossing structures.
- Ensure streambed continuity is maintained.
- Inspect for problems with infiltration in constructed stream beds (e.g., subsurface flows).
- Inspect for scouring of the streambed downstream or the aggradation of sediment upstream of the structure.
- Inspect revegetation health, success, and diversity. Cull invasive species.
- Inspect for mortalities of animals and plants.
- One cross section upstream and one downstream of the structure, surveyed before, immediately following, and for two successive years after construction.

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## **VII. Definitions**

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

**Bankfull Width:** (Refer to the description of bankfull width in Appendix A) Bankfull width is considered the stage at which water overflow into the active floodplain begins to occur (from WA). Stream geometry and sediment discharge (bedload transport) are strongly influenced by the frequency and scale of these discharges. On average, bankfull discharge events occur about every 1.5 years (.67 annual events) (from Rosgen 1994).

**Culvert:** As used in these Standards, culverts are round, elliptical or rectangular structures that are fully enclosed (contain a bottom) designed primarily for channeling water beneath a road, railroad or highway.

**Degradation (from WA):** 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.

**Deposition (from WA):** The settlement of material onto the channel-bed surface or floodplain.

**Embedded Culvert:** A culvert that is installed in such a way that the bottom of the structure is below the stream bed and there is substrate in the culvert.

**Flow Constriction:** When a culvert or other crossing structure is significantly smaller than the stream width the converging flow creates a condition called “flow contraction.” The increased velocities and turbulence associated with flow contraction can block fish and wildlife passage and scour bed material out of a crossing structure. Flow contraction also creates inlet drops.

**Inlet drop:** Where water level drops suddenly at an inlet, causing changes in water speed and turbulence. In addition to the higher velocities and turbulence, these jumps can be physical barriers to fish and other aquatic animals when they are swimming upstream and are unable to swim out of the culvert.

**Geomorphology (from WA):** The study of physical features associated with landscapes and their evolution. Includes factors such as; stream gradient, elevation, parent material, stream size, valley bottom width and others.

**Gradient (from WA):** 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.

**Incision:** the process of streambed degradation forming a deeper, narrower channel.

Outlet drop: An outlet drop occurs when water drops off or cascades down from the outlet, usually into a receiving pool.

Reach (or stream reach): A section of a stream having similar physical and biological characteristics.

Regional Hydraulic Geometry Reference Curve: a compilation of bankfull width and depth and watershed drainage area data stratified by channel type and sediment size to predict bankfull flow characteristics .

Riparian Area: land adjacent to waterbodies meshing aquatic, wetland, and terrestrial ecosystems.

River/Stream Continuity: Maintaining undisrupted the aquatic and benthic elements of river and stream ecosystems, generally through maintenance of appropriate substrates and hydraulic characteristics (water depths, turbulence, velocities, and flow patterns).

Scour pool: A pool created downstream from high flows exiting the culvert. The pool is typically wider than the stream channel and banks are typically eroded. Some plunge pools may have been specifically designed to dissipate flow energy at the culvert outlet and control downstream erosion.

Streambed: the composition of substrates within the stream channel not in suspension.

Structure Armoring (From WA): A surface streambed layer of coarse grained sediments that are rarely transported. This layer protects the underlying sediments from erosion and transport, while creating enough roughness to prevent channel down-cutting.

Supercritical flow: conditions in which the flow velocity is larger than the wave velocity.  
[http://en.wikipedia.org/wiki/Supercritical\\_flow](http://en.wikipedia.org/wiki/Supercritical_flow)



## Appendix B – Sediment Competence (Incipient Motion) Calculations

### Glossary

- $d_{BKF}$  = Bankfull flow depth (L)  
 $D$  = Particle size (L)  
 $D_c$  = Critical particle size at incipient motion (L)  
 $R_h$  = Hydraulic Radius (L) {commonly approximated by the mean depth}  
 $S_o$  = Slope of stream bed (riffle to riffle) at bankfull or for the flow under investigation (-)  
 $\gamma$  = Specific weight of water (F/L<sup>3</sup>)  
 $\tau_c$  = Critical shear stress at incipient motion (F/L<sup>2</sup>)  
 $\tau_o$  = Shear stress on the stream bed (F/L<sup>2</sup>)

### Sediment Competence Formulas

#### Shields Curve fitted by equations (Shulits and Hill)

$D$  = particle size in feet and  $\tau_c$  is critical bed shear stress in psf.

$0.0003 < D < 0.0009$	$\tau_c = 0.0215 D^{0.25}$
$0.0009 < D < 0.0018$	$\tau_c = 0.315 D^{0.633}$
$0.0018 < D < 0.022$	$\tau_c = 16.8 D^{1.262}$
$D > 0.022$	$\tau_c = 6.18 D$

#### Shields (coarse particles larger than 10 mm, where $\tau_{*c} = 0.047$ to $0.06$ )

$$D_c = (12.9 - 10.1) R_h S_f \quad \left\{ \sim \gamma d_{BKF} S_o \right\} \quad \text{Eq. 1}$$

#### Using Colorado data as a modified Shields estimate of incipient motion

$$\tau_o = \gamma R_h S_f \quad \left\{ \sim \gamma d_{BKF} S_o \right\}$$

$$D = 152.02 \tau_c^{0.7355} \quad D \text{ in mm and } \tau_c \text{ in psf} \quad \text{Eq. 2}$$

### Effect of large particle protrusion height versus particle embedded into the layer

$\hat{D}$  = particle size from the bar or sublayer sample

D = particle size from the riffle count

When  $3 < D_{50} / \hat{D}_{50} < 7$

$$\tau_{*c} = 0.0834 \left( \frac{D_{50}}{\hat{D}_{50}} \right)^{-0.872} \quad \text{Eq. 3}$$

When  $1.3 < \hat{D}_{100} / D_{50} < 3$

$$\tau_{*c} = 0.0384 \left( \frac{\hat{D}_{100}}{D_{50}} \right)^{-0.887} \quad \text{Eq. 4}$$

#### For either of the protrusion height cases:

Mean bankfull depth necessary to move the largest bar/subpavement particle at the bankfull water slope

$$\frac{1}{d_{BKF}} = \frac{1.65 \tau_{*c} \hat{D}_{100}}{S_o} \quad \text{Eq. 5}$$

Necessary slope to move the largest bar/subpavement particle at the identified bankfull mean depth

$$S = \frac{1.65 \tau_{*c} \hat{D}_{100}}{d_{BKF}} \quad \text{Eq. 6}$$

## Appendix C – Sediment Capacity (Bed Load Sediment Transport or Sediment Discharge)

### Glossary

$Q_s$  = Volumetric sediment transport for the entire stream cross section ( $L^3/T$ )  
 $q_s = Q_s/W_{BKF}$  = volumetric sediment discharge per unit width of cross section  
 ( $L^2/T = L^3/T/L$ )

$G_s$  = Weight sediment flux (F/T)

$$= \gamma_s Q_s$$

$g_s$  = Weight sediment flux per unit width of stream (F/T/L)

$$= \gamma_s q_s = G_s / W_{BKF}$$

$q_s^*$  = Dimensionless sediment bed load flux

=

$$\frac{q_s}{\sqrt{(s-1)gD^3}}$$

$s$  = Sediment specific gravity (-)

$D$  = particle size (L)

$G$  = acceleration due to gravity

$\tau^*$  = Dimensionless bed shear stress

$$= \frac{\tau_0}{(s-1)\gamma D} = \frac{R_h S_f}{(s-1)D}$$

$D^*$  = Dimensionless sediment particle size

=

$$D \left[ \frac{(s-1)g}{\nu^2} \right]^{1/3}$$

$\nu$  = Kinematic viscosity of water ( $L^2/T$ )

### Meyer-Peter, Müller

$$q_s^* = 8(\tau^* - \tau_c^*)^{3/2} \quad (\text{they assumed } \tau_c^* = 0.047) \quad \text{Eq. 1}$$

### Einstein-Brown

$$q_s^* = \begin{cases} \frac{Ke^{(-0.391/\tau^*)}}{0.465} & \text{for } \tau^* < 0.182 & \text{Eq. 2a} \\ 40K\tau^{*3} & \text{for } \tau^* \geq 0.182 & \text{Eq. 2b} \end{cases}$$

where:

$$K = \sqrt{\frac{2}{3} + \frac{36}{D^{*3}}} - \sqrt{\frac{36}{D^{*3}}}$$

## Appendix D. Management Interpretations by Stream Type (Rosgen 1994, 1996)

Stream Type	Sensitivity to Disturbance <sup>a</sup>	Recovery Potential <sup>b</sup>	Sediment Supply <sup>c</sup>	Streambank Erosion Potential	Vegetation Controlling Influence <sup>d</sup>
A1	very low	excellent	very low	very low	negligible
A2	very low	excellent	very low	very low	negligible
A3	very high	very poor	very high	very high	negligible
A4	extreme	very poor	very high	very high	negligible
A5	extreme	very poor	very high	very high	negligible
A6	high	poor	high	high	negligible
B1	very low	excellent	very low	very low	negligible
B2	very low	excellent	very low	very low	negligible
B3	low	excellent	low	low	moderate
B4	moderate	excellent	moderate	low	moderate
B5	moderate	excellent	moderate	moderate	moderate
B6	moderate	excellent	moderate	low	moderate
C1	low	very good	very low	low	moderate
C2	low	very good	low	low	moderate
C3	moderate	good	moderate	moderate	very high
C4	very high	good	high	very high	very high
C5	very high	fair	very high	very high	very high
C6	very high	good	high	high	very high
D3	very high	poor	very high	very high	moderate
D4	very high	poor	very high	very high	moderate
D5	very high	poor	very high	very high	moderate
D6	high	poor	high	high	moderate
DA4	moderate	good	very low	low	very high
DA5	moderate	good	low	low	very high
DA6	moderate	good	very low	very low	very high
E3	high	good	low	moderate	very high
E4	very high	good	moderate	high	very high
E5	very high	good	moderate	high	very high
E6	very high	good	low	moderate	very high
F1	low	fair	low	moderate	low
F2	low	fair	moderate	moderate	low
F3	moderate	poor	very high	very high	moderate
F4	extreme	poor	very high	very high	moderate
F5	very high	poor	very high	very high	moderate
F6	very high	fair	high	very high	moderate
G1	low	good	low	low	low
G2	moderate	fair	moderate	moderate	low
G3	very high	poor	very high	very high	high
G4	extreme	very poor	very high	very high	high
G5	extreme	very poor	very high	very high	high
G6	very high	poor	high	high	high

a Includes increases in streamflow magnitude and timing and/or sediment increases.

b Assumes natural recovery once cause of instability is corrected.

c Includes suspended and bedload from channel derived sources and/or from stream adjacent slopes.

d Vegetation that influences width/depth ratio-stability.

This table comes from <http://www.epa.gov/warsss/seds/source/type.htm>

## **Appendix E - Links/Resources**

### **Constructing a Representative Stream Channel Within a Closed Bottom Structure**

Bates, K., B. Barnard, B. Heiner, J. P. Klavas, P. D. Powers. 2003. Design of Road Culverts for Fish Passage. Washington Department of Fish and Wildlife.

Available at: [http://wdfw.wa.gov/hab/engineer/cm/culvert\\_manual\\_final.pdf](http://wdfw.wa.gov/hab/engineer/cm/culvert_manual_final.pdf)

Bates, K.K. and R. Kirn. 2008. Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organisms in Vermont. Final Draft. February 2008. 127 pp.

Johansen, D. K. 2003. Design and Construction of Aquatic Organism Passage at Road Stream Crossings: Construction Challenges and Case Studies of Stream Simulation Structures for Aquatic Organism Passage. 53-72, CD-ROM Conference Proceedings, International Conference of Ecology and Transportation. Lake Placid, New York

### **Field Protocols for Surveys and Bankfull Width Determination**

Harrelson, C.C., Rawlins, C.L. and Potyondy, J.P. (1994) Stream Channel Reference Sites: An Illustrated Guide to Field Techniques. USDA Forest Service General Technical Report RM-245.

Available at: [http://www.fs.fed.us/rm/pubs\\_rm/rm\\_gtr245.pdf](http://www.fs.fed.us/rm/pubs_rm/rm_gtr245.pdf)

Rosgen, D.L. (1996) Applied river morphology: 2nd Edition, Wildland Hydrology, Pagosa Springs, Colorado, 388 p.

U.S. Department of Agriculture, Forest Service (2005) Guide to identification of bankfull stage in the northeastern United States: Rocky Mountain Research Station, Stream Systems Technology Center, General Technical Report RMRS-GTR-133-CD, 4 CDs.

Vermont Department of Environmental Conservation. Water Quality Division. 2005. Vermont Stream Geomorphic Assessment Protocols. Available at:

[http://www.anr.state.vt.us/dec/waterq/rivers/htm/rv\\_geoassesspro.htm](http://www.anr.state.vt.us/dec/waterq/rivers/htm/rv_geoassesspro.htm)

### **Best Management Practices for Stream Crossing Structure Installation and Replacement**

Gubernick, B., Clarkin, K., and Furniss, M. (2003) Design and Construction of Aquatic Organism Passage at Road-Stream Crossings: Site Assessment and Geomorphic Considerations in Stream Simulation Culvert Design. 30-41, CD-ROM Conference Proceedings, International Conference of Ecology and Transportation. Lake Placid, New York

Gubernick, B., and Bates, K. K. (2003) Design and Construction of Aquatic Organism Passage at Road-Stream Crossings: Designing Culverts for Aquatic Organism Passage: Stream Simulation Design. 42-53, CD-ROM Conference Proceedings, International Conference of Ecology and Transportation. Lake Placid, New York

## **General Stream Classification, Sediment Transport Tutorials, and Discussions**

United States Environmental Protection Agency. 2006. Watershed Assessment of River Stability & Sediment Supply (WARSSS) Version 1.0. Available at: <http://www.epa.gov/warsss/>

United States Fish and Wildlife Service. Planning, Design and Construction of Fish Friendly Stream Crossings. Available at:

<http://www.fws.gov/midwest/Fisheries/StreamCrossings/index.htm>

Note: this website also contains several additional reference links.

Richter, B. D., J. V. Baumgartner, J. Powell, and D. P. Braun, 1996. A Method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology* 10(4):1163-1174.

Rosgen, D., L. Silvey, and D. Frantila, 2006. Watershed Assessment of River Stability and Sediment Supply (WARSSS), Wildland Hydrology, Fort Collins, CO.

## **Examples of Other Agency Stream Crossing Guidelines**

Alberta Environment. 2001. Guides to the Code of Practice for Watercourse Crossings, Including Guidelines for Complying with the Code of Practice. 29pp. Available at:

<http://www3.gov.ab.ca/env/water/Legislation/CoP/WatercourseGuide.pdf>

Bates, K.K. and R. Kirn. 2008. Guidelines for the Design of Stream/Road Crossings for Passage of Aquatic Organisms in Vermont. 127 pp.

Etowah Habitat Conservation Plan Technical Committee. 2006. Stream Crossing and Culvert Design Policy. Athens, GA. Available:

[http://www.etowahhcp.org/research/documents/road\\_crossings\\_tech\\_rpt\\_2006\\_08\\_18.pdf](http://www.etowahhcp.org/research/documents/road_crossings_tech_rpt_2006_08_18.pdf).

Accessed: March 2007.

Maine Department of Transportation. 2004. Fish Passage Policy and Design Guide. Second Edition. 87pp. Available at: <http://www.maine.gov/mdot-stage/environmental-office-homepage/documents/FISH%20PASSAGE%20POLICY%20AND%20DESIGN%20GUIDE%202nd%20Ed%202004.pdf>

River and Stream Continuity Partnership. 2006. Massachusetts River and Stream Crossing Standards: Technical Guidelines. University of Massachusetts, Amherst, MA. 9 pp. Available at: [http://www.umass.edu/nrec/pdf\\_files/guidelines\\_river\\_stream\\_crossings.pdf](http://www.umass.edu/nrec/pdf_files/guidelines_river_stream_crossings.pdf)