CULVERT DESIGN GUIDELINES FOR ECOLOGICAL FUNCTION

U.S. Fish and Wildlife Service
Alaska Fish Passage Program

The information provided below describe the basic culvert design guidelines preferred by the U.S. Fish and Wildlife Service (USFWS) Alaska Fish Passage Program when a culvert has been chosen as the stream crossing structure in a fish bearing stream. Whenever possible, the USFWS supports minimizing the degradation of the ecological continuity of stream corridors and wetlands by choosing transportation routes that avoid the stream crossing altogether or by using bridges that span across the floodplain. The Alaska Fish Passage Program, is a voluntary, non-regulatory initiative in the USFWS to provide funding and technical assistance to reconnect aquatic habitats. These guidelines are a modified version of the USDA Forest Service guidelines for Aquatic Organism Passage, or Stream Simulation method.

Users Note: The ability of a structure to pass fish, water, sediment and debris is highly dependent on local hydrology, species, life stage, geomorphic setting and other site-specific considerations. The guidelines herein provided, while based on national, state and local experience and studies, are not universally applicable and should not replace site-specific recommendations, limitations or protocols. The guidelines are not intended as an alternative to active consultation with USFWS and application of these guidelines in the absence of consultation does not imply approval by USFWS or other agencies. This document will be updated on a periodic basis to address new research, comments or questions. A summary of these guidelines and a comparison to other stream simulation guidelines is available in Appendix E. Please submit comments or questions to heather_hanson@fws.gov or william_rice@fws.gov.

(All terms in bold italics in the following paragraphs are defined starting on page 5 in the "Description of Terms" section. Refer to commentary in Appendix D for further information at sections referenced A0, A1, A2, etc.)

Ecological Functioning

- All stream crossings in alluvial systems should be designed using an approach that mimics the natural stream characteristics to the greatest extent possible. The USFWS Alaska Fish Passage Program has adopted a ***geomorphic analog method*** which follows the United States Forest Service stream simulation approach (A0) with the modifications outlined in this document (USFS, 2008). An example design procedure for stable, alluvial channels is available upon request. In order to apply the geomorphic analog method, a stream first need to be classified using its geomorphic characteristics. We have chosen the Rosgen stream classification method as it provides a rigorous, repeatable and widely accepted classification method based on stream channel, flood plain and substrate characteristics. The geomorphic analog approach is recommended for stable Rosgen type A, B, C or E channels. Bridges should be used for Rosgen type D channels if the flow is actively moving between braids. Refer to Rosgen, 1996 for an in depth explanation of Rosgen channel types.

- Culvert crossings in systems that are actively degrading such as Rosgen F or G channels, should be avoided (Rosgen, 1996). If they cannot be avoided, these channels must be stabilized at least on a reach-length basis to prevent headcut or excessive lateral movement prior to the construction of a new crossing structure.
- Culverts used in stream crossings should be designed, constructed, and maintained so as to provide for ***ecological functioning*** of the stream, including connectivity of wetlands and riparian areas adjacent to stream channels to allow for the unrestricted movement of water, all species of fish and wildlife, nutrients, sediment, and woody debris, to the greatest extent possible. A longer span structure such as a bridge that spans the entire flood plain is the ideal solution for providing ecological functioning. (See figure 1, page 9). If a bridge is not feasible, floodplain culverts can also be considered to reduce the alteration of wetland hydrology upstream and downstream of the crossing. .
- Crossing structures should be designed to accommodate at least the ***100-year flood flow*** (USFS, 2008). (A13)
- The width of the primary crossing structure should not be less than 1.0 times the ***bankfull width*** of the channel (USFS, 2008).(A1).
- Crossing structures should be placed within/over the pre-development natural channel alignment when possible. Road alignment should be as close to perpendicular to the channel as possible. The crossing location should also be chosen to cross at a straight riffle feature. The stream may need to be realigned at existing roads; however, avoid cutting off meander bends. Avoid placing crossing structures at pools or stream bends, including immediately downstream of meander bends. (A2)

Culvert Size, Slope, and Substrate

- Culvert substrate material within/under the crossing structure should remain ***dynamically stable*** at all flood discharges up to and including a ***50-year flood flow***. (FHWA, 2010).(A3) For culverted crossings without an adequate upstream sediment supply, the substrate material within the crossing should be designed to resist the predicted critical shear forces up to the 100-year flood. For culverts in sand bed channels sediment retention sills may be used if necessary. For culverts with slopes 6% or greater, steps and cascade features should be sized and keyed in so not to move up to the 100 year flow event, but if necessary sills can be used to keep footer rock in place (USFS, 2008).
- Culvert slope should be within 25% of the ***bankfull slope*** of the selected reference reach. For example, if a reference reach is 1.0% slope, the minimum design slope of the stream simulation culvert would be 0.75% and the maximum design slope would be 1.25% (USFS, 2008)
- Culverts should have a minimum diameter of five feet (5') (FHWA, 2010)(A4). This minimum diameter applies for small streams with a bankfull width of five feet or less. For larger streams, a longer span structure (bridge or culvert) should be used that meets the requirements of these guidelines. A bridge should also be considered for all stream widths in order to provide better floodplain connectivity.

- ***Streambanks*** are recommended inside of culverts where feasible to protect the culvert from abrasion, provide resting areas for fish, and provide for small mammal crossing. If streambanks are constructed through a crossing, the streambanks should be constructed of rock substrate designed to be stable at the 100-year flood (USFS, 2008). The streambank width should be a minimum of 1.5 times the maximum sieve size of the streambed material (D100). The crossing width should be increased to allow for the channel width plus the streambanks; however the crossing width should not exceed 1.4 times the bankfull width. Streambanks are not recommended for areas with permafrost or severe freeze-thaw issues, for areas with large amounts of sheet flow or ice flows, or in the intertidal zone. (A5) For streams with entrenched channels, the designer should err on the side of caution to ensure the stability of banks constructed inside culverts or use a bankfull width culvert (A6).
- Round culvert pipes should have a minimum invert burial depth (measured from the thalweg) of forty percent (40%) of the culvert diameter into the substrate; box culverts and pipe arch culverts, should have a minimum invert burial depth of twenty percent (20%) of the culvert's rise into the substrate, unless vertical adjustment potential (VAP) analysis shows less fill is acceptable See Chapter 5, USFS, 2008 for an explanation of the VAP analysis process. Bottomless culverts with footers need to have sufficient burial depth and armor material to protect the footings from potential scour over the life of the structure. In areas where permafrost is very close to the surface, a hybrid of the stream simulation and hydraulic method may be considered to reduce the culvert embed and prevent thaw of the permafrost (A7).
- Substrate material within/under the crossing structure should incorporate a continuous ***low flow channel*** that simulates the reference reach to allow for adequate fish passage during minimum flows. A "V" shaped thalweg is recommended for channels with the potential for very low flow regimes to prevent aggradation and maximize fish passage during drought conditions.
- The gradation of the substrate material within a culvert should be designed to be a dense, well graded mixture with adequate fines to ensure that the majority of the stream flows on the surface and the minimum water depth is maintained (FHWA, 2010). The Fuller-Thompson equation should be used to ensure a minimum void content. In addition, the combined gradation should have a minimum of 5% passing the #10 sieve (2 mm). (USFS, 2008).
- The D100 of the substrate should not exceed the bankfull width divided by 4 (USFS, 2008).
- If substrate ***retention sills*** must be used (for example, sand bed systems or on slopes >6%), they should have a maximum weir height of one half (0.5) of the culvert invert burial depth (i.e. 20% of diameter for round pipes and 10% of rise for pipe arches) (USFS, 2008). Substrate retention sills should be spaced so that the maximum drop between weirs is four inches (4"). Sills should not be used without substrate(A8)
- Culvert pipes and arches should be corrugated; smooth wall metal pipes should not be used. (A9)
- Beaver barriers, trash racks or debris interceptors should not be used because of the potential to block adult salmon without robust and regular maintenance. Bollards at least one bankfull width upstream of the culvert may be used if needed to trap debris or move beaver dam building upstream. However, we have found that these are not usually needed because using a HW/D ratio of 0.8 allows for debris passage. In addition, beavers are not attracted as long

as there is no increase in velocity and sound over the natural stream conditions.

Use of Reference Reach in Design

- A ***Reference Reach*** is defined in the Description of Terms with basic selection parameters found under the definition of the ***geomorphic analog method.*** Data gathered should include at a minimum:channel ***bankfull width***, ***bankfull cross-sectional area***, reach gradient based on water surface slope (see "***Slope Ratio***" in Description of Terms section) substrate grain size key pieces, stream type, bankfull average depth, ***flood prone width***, stream order, and watershed area (USFS 2008). The reference reach bankfull dimensions should be determined in the field by surveying a detailed cross section at the upper 1/3 of a representative riffle.
- Under normal flow conditions, the channel in the crossing structure should not substantially differ from the reference reach condition in regards to the channel width at bankfull, bankfull cross-sectional area, gradient, stream type, and bankfull average depth (USFS, 2008).

Special Conditions:

- Relic channel or slough: (***synthetic width method*** *(A10)*) Should field geomorphic data show an existing stream in a relic channel (i.e. old glacial outwash) or slough, with no defining bankfull features, a synthetic width may be estimated for culvert sizing by utilizing a calculated 2-year flood event with an average cross-sectional velocity of less than 4 fps and ideally similar to adjacent water velocities and water depth, unless there is additional supporting data or other agency criteria to design otherwise. The recommended maximum velocity of 4 fps was chosen based on the observation by Leopold (1994) that "For rivers of moderate size (2 to 100 square miles of drainage area), the flow at bankfull stage will ordinarily have a mean velocity on the order of 4 feet per second" (p. 33). Note that this method or velocity may not be applicable for all cases and the velocity would ideally be less, particularly in stream gradients of 1% or less.
- Wetland complexes:
  1. If possible, avoid crossing wetlands to minimize the ecological impacts on these important ecosystems. If they must be crossed, the ideal crossing in a wetland complex is a backwatered crossing that emulates the low velocity and water depth of the surrounding wetland environment, yet meets flood standards on its own or with additional floodplain culverts. To develop initial widths for such a crossing, the following situational methods could be applied:
     - Method A: The designer may use a reference reach upstream or downstream in a single thread portion of the creek to size the proposed crossing. Recommendations for choosing a reference reach may be found under ***geomorphic analog method*** in the Description of Terms section below.
     - Method B: If no reference reach is available on the same stream or if the crossing slope needs to be steeper than any reference reach due to constraints such as road height or maintaining upstream water levels, crossing stream types should be selected using an appropriate geomorphic analog primarily based on slope (see figure 5) in conjunction with the ***synthetic width method*** to develop the crossing structure dimensions.
  2. For both Method A and Method B, floodplain culverts should be provided as conditions permit to allow for wetland continuity across the floodplain area and to minimize flow

constriction at flood levels (USFS, 2008). Floodplain culverts should be placed in the floodplain outside of the primary channel and at a higher elevation to insure a minimum depth will be maintained in the primary crossing structure for fish passage at low flows.

- In low gradient (less than 0.5%) stream environments at relic channels, sloughs or wetland complexes, backwatering with similar depth as the adjacent area is the preferred method for providing fish passage combined with the synthetic width method to develop a culvert size where potential for aggradation is low.
- Tidally influenced culverts:
    1. Fish passage criteria for tidally-influenced culverts should be satisfied 90 percent of the time. (A11) Tidally-influenced streams may sometimes be impassable due to insufficient depth at low flow and low tide. If the tidal area immediately downstream of a culvert is impassable for fish at low tide under natural conditions, the 90 percent passage criterion would apply only to the time during which fish can swim to the culvert.

Habitat Conservation Measures

- Reduce the project footprint to the maximum extent and locate associated activities in already disturbed areas or lower functioning/quality habitat, where possible
- Avoid removing vegetation during the bird nesting season, when possible.
- Reconstruct the disturbed channel upstream and downstream of the project to mimic the reference reach. Fill in scour holes to emulate the channel width of the reference reach and remove excess sediment in the channel deposited as a result of undersized culverts and previous crossing failures. Except for the reconstruction of scour holes, banks with healthy native plants should be left intact if possible.
- Plan to transplant vegetative mat with native plants that reflect typical riparian area species for the stream location along all disturbed streambanks (3’-4’ width is typical). At least 9”, including topsoil and underlying soil layer, should be harvested for transplanting. If available mat has thinner soils, spread imported topsoil under the vegetative mat, prior to transplanting.
- Plant native riparian species that mimic the reference reach in disturbed riparian areas not covered by vegetative mat.
- Use appropriate bioengineering techniques such as root wads or toe wood to protect reconstructed banks until vegetation is established.
- Consider strategically placing root wads, large logs, or boulders in the riparian area after seeding, to provide topographical relief and micro-climates, and to increase the variety of plant species difficult to establish by seed (e.g., increase habitat complexity).
- Use weed free gravel, weed free topsoil, and weed free erosion control materials (compost wattles or coconut fiber roll instead of straw wattles). Wash all equipment prior to mobilization to the site. Use native weed-free seed (preferably locally collected), specific to

the habitat type, applied at specified rates, and cover the seed to specified depth. Consider using a tackifier, mulch, or other bonding agents to keep seed in place.

- Plastic degradable netting is not recommended for use in erosion control for any aspect of the proposed project. Prior to degradation, the netting can entangle wildlife, including amphibians, birds, and small mammals.
- If using foam sheets for permafrost insulation, use closed-cell foam rather than styrofoam insulation. Styrofoam pellets degrade water quality and break into tiny pieces creating an ingestion hazard for fish, mammals, and birds.

DESCRIPTION OF TERMS

100-Year Flood Flow: The stream discharge that has a reoccurrence interval of 100 years, or a 1 in 100 chance of occurring in a given year; also known as the 100-year recurrence interval event. If the crossing structure is not designed to accommodate the 100-year flow, a route must be established to safely convey flows exceeding the design flow without causing damage to property, endangering human life or public health, or causing significant environmental damage. In cases of crossings within high entrenchment ratio environments (flood prone width/bankfull width >2) then floodplain overflow culverts may be beneficial to floodplain connectivity and can be used to pass the 100-year flood, but minimum width requirements for the primary culvert still apply.

50-Year Flood Flow: The stream discharge that has a reoccurrence interval of 50 years, or a 1 in 50 chance of occurring in a given year

Bankfull: For non-entrenched stream types (C, D, DA and E), bankfull is the height on the streambanks where water flow fills the channel and begins to spread out onto the floodplain. (See Figure 3). For entrenched stream types(A, B, F and G), other indicators are required to identify the bankfull elevation such as the highest active depositional feature, slope breaks, change in particle size distribution, small benches, staining of rock, lichens, and certain riparian vegetation species (Rosgen, 1996). (See figure 4). Use multiple indicators wherever possible to determine a common bankfull stage elevation. Where possible, calibrate field-determined bankfull stage elevation and corresponding bankfull channel dimensions to known recurrence interval discharges at gage stations. Bankfull features are typically wider than the ***ordinary high water mark***. Correctly identifying the bankfull channel dimensions is critical to the success of the geomorphic analog method. The design professional should pursue training in this area and use hydrologic data to verify bankfull dimensions are reasonable.

Bankfull width: The surface width of the stream measured at bankfull. (See figure 2 for an example of bankfull width on a small stream).

Bankfull cross sectional area: The sum of products of unit width and depth at the bankfull stage elevation in a riffle cross section.

Bankfull discharge: A frequently occurring peak flow whose stage represents the incipient point of flooding. The bankfull discharge is expressed as the momentary maximum of instantaneous peak flows rather than the mean daily discharge. It is often associated with a return period of 1-2 years, with an average of 1.5 years (Rosgen, 1996). (Note: return intervals for bankfull of up to 5 years have been found for some streams in the continental United States. Stream gaging is recommended if the designer desires confidence in the bankfull discharge return interval).

Bankfull slope: The average slope through the bankfull indicators recorded at multiple locations along the longitudinal profile. The bankfull slope of a given reach should match the water surface slope measured between stable grade control features. See "Slope Ratio" term for more information on measuring the slope of a reference reach.

Dynamically Stable: Dynamic stability means that channel dimensions, slope and planform do not change radically even though they adjust to changing inputs of water, sediment and debris. (FHWA, 2010). Dynamically stable channel features will fluctuate around a mean value but will stay within the predicted VAP lines. Streambanks are not expected to move horizontally more than a few inches in the typical 50 to 100 year design life of a crossing structure..

D100 particle size: This corresponds to the largest particle size in a given material gradation. In other words, 100 percent of the particles in the material are smaller than the D100 size.

D84 particle size: This corresponds to the size of the particle in a material gradation such that 84% of the particles in the material are smaller than the D84 size.

Ecological Functioning: A crossing is considered to be ecologically functioning if it allows for conveyance of water, sediment, debris, marine derived nutrients, and passage of fish and other organisms in the channel, floodplain and riparian area floodplain both upstream and downstream during flows ranging from low flows during dry periods up to a 100-year flood flow. Sediment transport should remain in equilibrium throughout the range of flows so that no significant aggradation or degradation will result. In embedded culverts there is always some sediment movement into and out of the culvert if upstream sources exist. However, vertical adjustment of the channel beyond the upper and lower VAP lines should be designed to occur at the 50-year design flow or higher for locations with upstream sediment sources and 100-year or higher at locations without sediment sources such as lake outlets. Also, constructed banks should be designed for stability up to the 100-year flood flow.

Entrenchment Ratio: The vertical containment of a river, obtained by dividing the flood-prone width by the bankfull width at a reference riffle (Rosgen, 1996).

Flood-prone Area and Width: Per Rosgen stream type methodology, the flood prone area and width is the area adjacent to the watercourse constructed by the watercourse in the present climate and inundated during periods of high flow. The flood-prone width is the width of the floodplain at an elevation two times (2X) the maximum bankfull depth (Rosgen, 1996).

Geomorphic Analog Method: A geomorphic analog means that the crossing is designed using reference data from a representative section (reference reach) of the specific water body being crossed. The geomorphic analog method is a crossing design technique that attempts to replicate the natural stream channel conditions found upstream and downstream of the crossing. Sediment transport, flood and debris conveyance, and fish passage function much as they do in the natural channel if designed correctly. The geomorphic analog uses bankfull channel dimensions to size the crossing structure and channel. If there are no suitable reference reaches on the specific body of water being crossed, a reference reach may be chosen from another water body with similar geomorphic and hydrologic characteristics. In these cases, we recommend following the criteria outlined in the River Morphology and Applications workshop by Wildland Hydrology for selecting a reference reach:

- The reference reach bankfull width should be at least one half, but not more than two times the water body being crossed
- The reference reach bankfull discharge should be at least one half and no more than one and one half times the bankfull discharge of the water body being crossed

- The stream order of the reference reach should be within one stream order of the water body being crossed
- The reference reach should be within 25% of the crossing gradient as noted in the guidelines above.

The crossing design channel width, area and other features should be scaled to the reference reach using ratios to the bankfull dimensions.

Hydraulic Methods: A culvert designed with the hydraulic method is designed to maintain flow velocities to be less than the swimming abilities for the weakest swimming fish at the high fish passage flow predicted with hydrologic modeling. Due to the limitations of hydrologic modeling accuracy and the limited data on fish swimming abilities, the hydraulic method should be avoided if possible. (A12)

Low Flow Channel: A low flow channel is a narrower channel constructed within the bankfull channel intended to provide fish passage at minimum flows. The low flow channel should mimic the reference reach where possible. A "V" shaped thalweg within the low flow channel is recommended for streams that have periods of very low flow. If the low flow channel dimensions are not discernable from the reference reach, the low flow channel should have a cross section sectional area of 15-30% of the bankfull cross sectional area and a minimum depth of four inches (4") for small streams up to twelve inches (12") for larger streams. The low flow channel should be defined by rock features that will resist critical shear forces up to the 100-year flood. (See figure 2 for an example of a low flow channel on a small stream).

Ordinary High Water Mark (OHWM): OHWM is a legal, non-geomorphic term defined by Alaska statute §41.17.950 (15) which states the "ordinary high water mark means the mark along the bank or shore up to which the presence and action of tidal or non-tidal water are so common and usual, and so long continued in all ordinary years, as to leave a natural line impressed on the bank or shore and indicated by erosion, shelving, changes in soil characteristics, destruction of terrestrial vegetation, or other distinctive physical characteristics" (Alaska Legal Resource Center, 2008). Reference http://www.adfg.alaska.gov/index.cfm?adfg=uselicense.faqs#howdoiknow for more information on identifying the OWHM. Also, see figure 2 for an example of the OHWM on a small stream.

Reference Reach: A portion of a stream that represents a stable channel (dimension, pattern, profile) within the geomorphic context that exists in that segment and can represent a natural or a stable, modified condition (USFS, 2008). A reference reach should be a minimum 20 times the reference bankfull width and no less than 200 feet in length for creeks less than 10 feet in bankfull width. A reference reach should also include a minimum of 4 stable grade control features. See the definition for the geomorphic analog method for further reference reach selection recommendations.

Retention Sills: Metal or wood plates welded or bolted into a culvert with a height of no more than one half of the embedment depth. Retention sills are intended to hold substrate in place in culverts greater than 6% slope. Retention sills do not protrude into the flow (USFS, 2008).

Slope ratio: The ratio of the culvert bed slope to the upstream reach or reference reach channel slope. The slope of the reference reach should be calculated using the water surface elevations between stable grade control features at the top and bottom of the reach assuming the reach slope is consistent In order to verify grade control features are accurately identified and stable, at least three grade control features should be included along the longitudinal profile. For stable streams without obvious grade control features use of the average water surface slope is acceptable. Unstable streams should not be used for a reference reach.

Streambanks: The streambanks correspond to the bankfull elevation of a natural channel. Streambanks inside a culvert may be simulated with large rock designed to be stable up to the 100-year flood flow.

Substrate Grain Size: A particle size distribution based on a particle count taken in the reference reach of at least 100 particles. This is also commonly referred to as a "pebble count." Refer to Bunte and Abt (2001) for recommended sampling methods.

Synthetic Width Method: A method of calculating culvert width dimensions when the current flow regime does not coincide with the geomorphic bankfull indicators such as in a relic channel or slough or no defining bankfull features exist.

Vertical Adjustment Potential: The elevations between which the streambed might vary over the service life of the structure. Refer to USFS, 2008, chapter 5 for a thorough explanation of the factors that should be considered when determining the vertical adjustment potential (VAP).

Figure 1: Range of crossing ecological objectives and examples of corresponding design approaches (USFS, 2008).

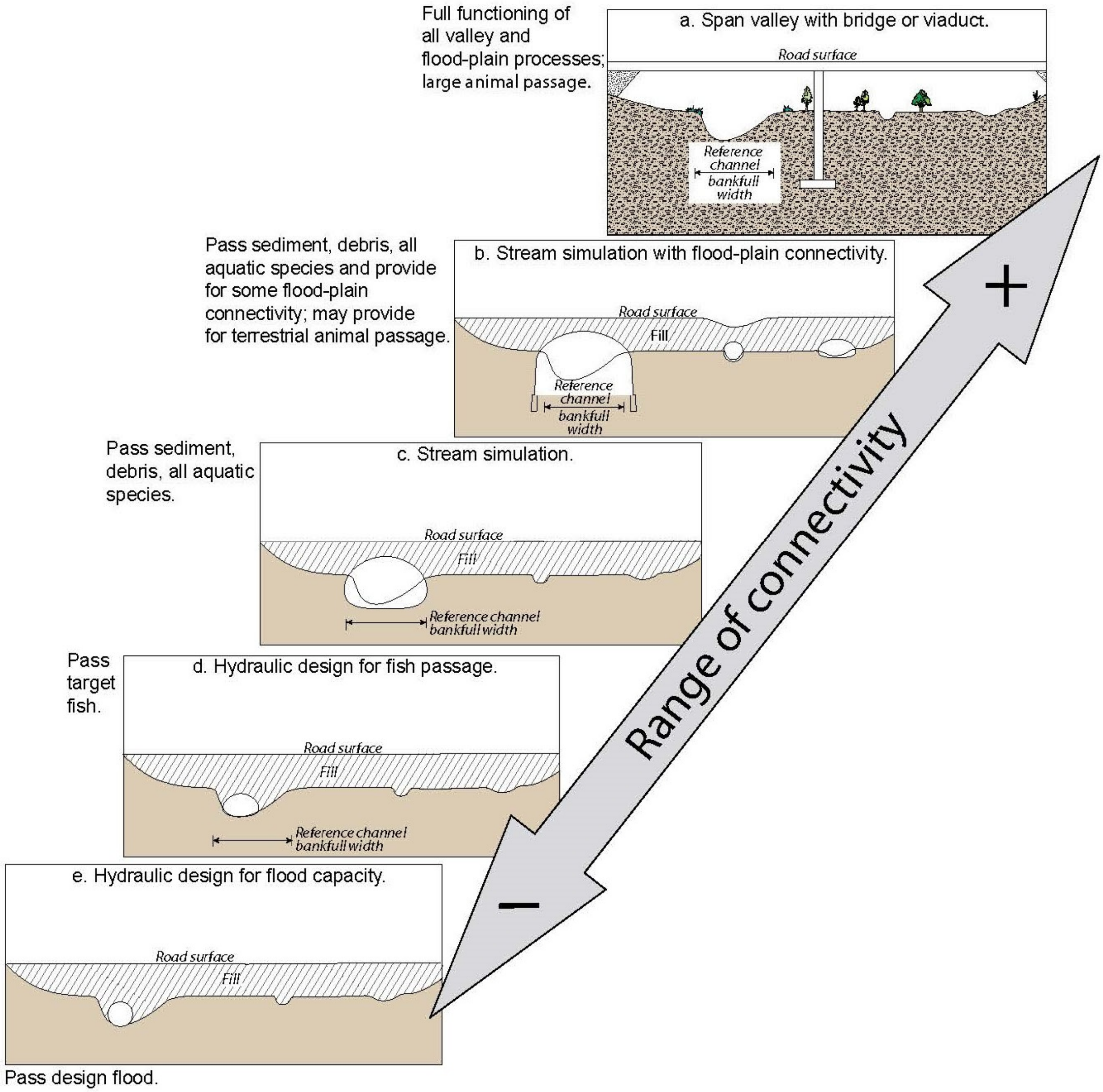


Figure 2: Bankfull width, OHWM and a low flow channel on an E3b stream type

Figure 3. Typical channel features for a non-entrenched channel (Rosgen, 1996).

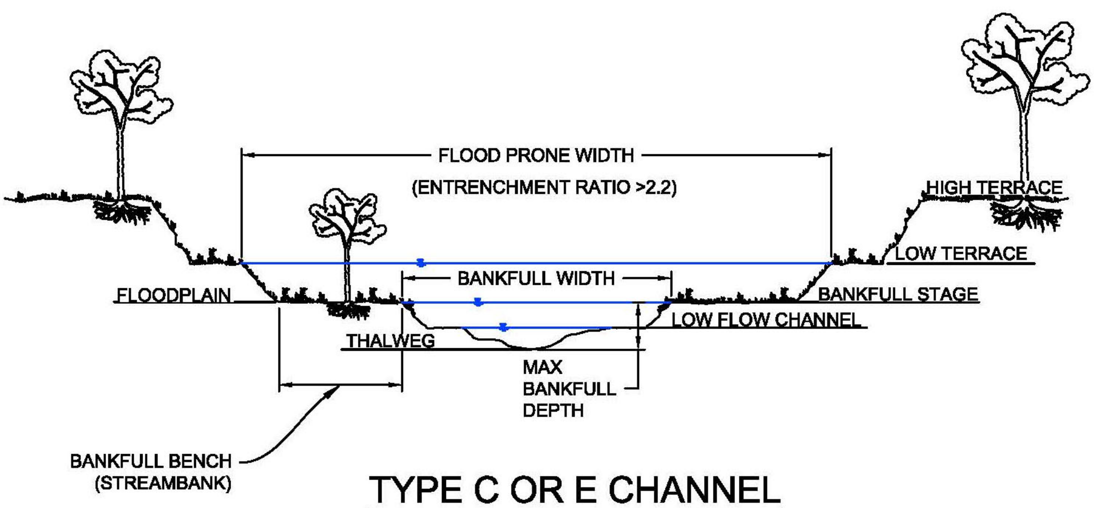


Figure 4. Typical channel features for an entrenched channel (Rosgen, 1996).

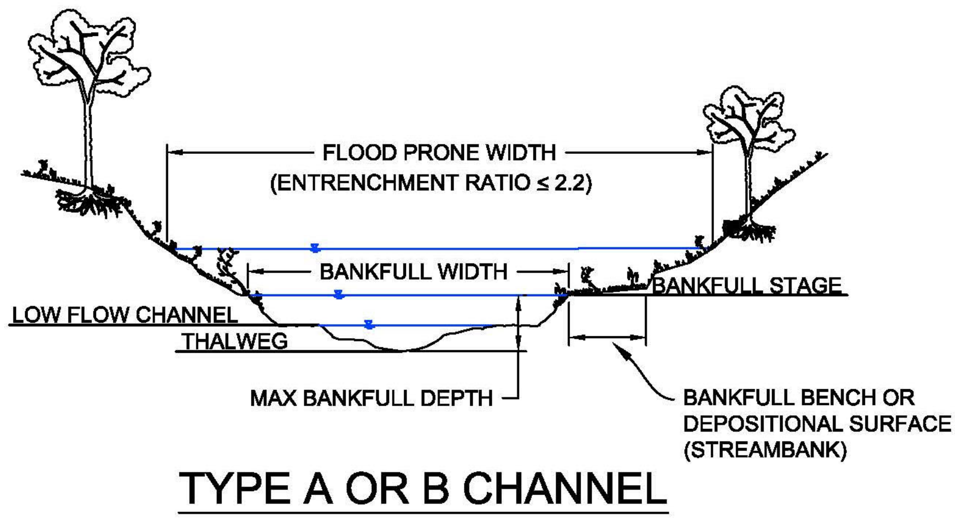
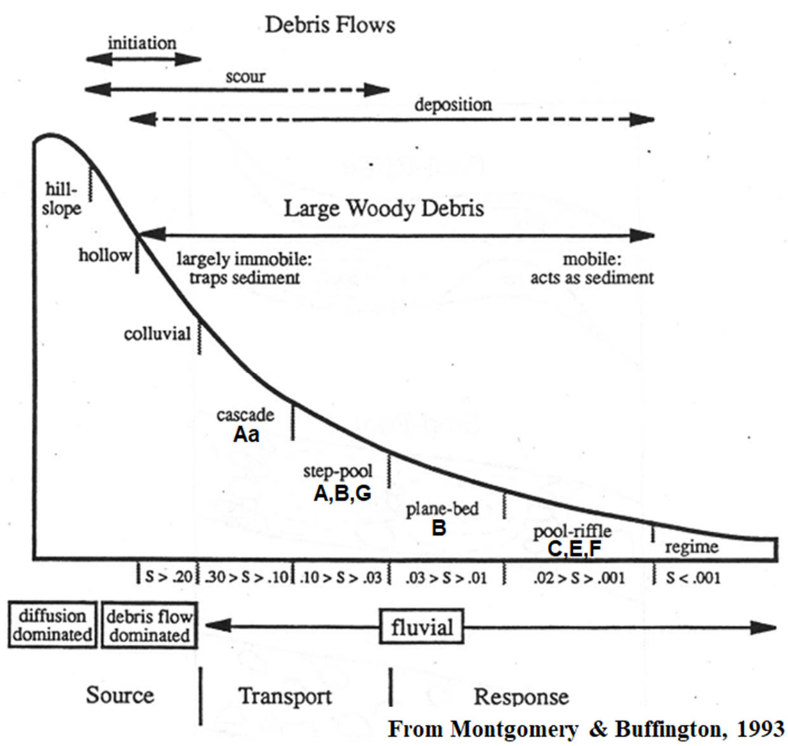


Figure 5. Geomorphic processes and stream types relative to channel slope (Montgomery and Buffington, 1993).



APPENDIX A

EXAMPLE CULVERT DESIGN PROCEDURE FOR ECOLOGICAL FUNCTION

U.S. Fish and Wildlife Service
Alaska Fish Passage Program

This step by step guide is intended as a companion to the "Fish Passage Design Guidelines." The following list sequentially describes a procedure used by the USFWS Alaska Fish Passage program for Fish Passage Culvert Design in alluvial channels. It is not intended to preclude other design approaches. Whatever design approach is chosen, we do not recommend omitting any of the steps outlined in this section. We recommend consultation with the local Alaska Department of Fish and Game habitat permitting office early in the design process.

1. Complete a hydrology report. If site is un-gaged try multiple flood frequency estimation methods (USGS equations, Manning's Equation, TR-55, etc.).
2. Complete survey at the crossing site including channel cross sections and a detailed longitudinal profile at least 20 times the bankfull width both upstream and downstream of the crossing and channel cross sections, more if there is any indications of instability or other information needs like headcut potential, debris jams, etc. The longitudinal profile should contain at least 4 stable grade control features outside of the area of influence of the existing road crossing. If there is a slope break at the road, then 6 stable grade control features are recommended (3 upstream and 3 downstream). Locate cross sections in channel features needed for design information. A minimum of three cross sections is suggested with at least two located in the upper third of a riffle or at a step feature. Use channel survey data and site observations to determine the channel type and valley type using the Rosgen classification system (Rosgen, 1996).
3. Determine the design approach and the location of the reference reach for the given channel type and site geomorphology. The length of the reference reach survey should be at least 20 times the bankfull width and at least 200 feet for streams 10 feet bankfull width or less. The reference reach should contain at least 4 stable grade control features.
4. Perform pebble count at the reference reach and upload survey data and pebble count data to, CAD or aspreadsheet as appropriate for analyzing the data. Refer to Bunte and Abt (2001) for recommended pebble count sampling methods.
5. Plot long profile and cross sections and determine bankfull width (Wbkf) of the reference cross section (typically a representative riffle).
6. Determine valley slope from CAD, GIS, or field measurements.

7. Determine reference reach slope from long pro - use the water surface head of riffle to head of riffle. Compare with bankfull slope and adjust bankfull calls if necessary. (Bankfull slope should match water surface slope. If it doesn't this may indicate the bankfull calls made in the field were incorrect or that channel evolution is occurring). Make sure Wbkf of reference cross section makes sense with the other bankfull calls along the profile. (Use CAD or other graphical program for this task).
8. Determine new culvert alignment, slope, vertical adjustment potential (VAP) lines, tie in points to the existing stream bed and draw this in on the long pro. See U.S. Forest Service (USFS, 2008) Stream Simulation Manual, chapter 6, for considerations in choosing tie in points and VAP lines. Also, see Figure 1 in Appendix B for further VAP line guidance from the USFS. Make sure new culvert design slope is within 25% of reference reach slope. Expect there may be sediment deposition upstream and/or downstream at the culvert that may need to be removed. Check actual length of culvert in CAD based on tie in points to existing thalweg, embedment depth, minimum cover depth, road width and embankment slope.
9. Fill out reference reach stream classification page– "River Stability Field Guide" WS2-3 (See Figure 2, Appendix B) (Rosgen, 2008). See Figures 10-13 in Appendix B for guidance on the Rosgen channel classification system (Rosgen, 2007).
10. Determine bankfull discharge and velocity for the reference cross section based on reference cross section, bankfull slope, and Manning's or other open channel equations. (The tailwater channel calculator Manning's n should be estimated from D84 of riffle pebble count, stream type, tables, etc. and compare results of different methods. ("River Stability Field Guide" WS2-2, Figure 3, Appendix B) (Rosgen, 2008). Check that average bankfull velocity is between 2.5 to 5 fps for fish streams. Check that bankfull discharge is relatively close to the 1-2 year storm predicted by hydrology or gage.
11. Create model of the existing crossing in HY8 so the existing flood capacity can be compared with the new crossing design capacity. (Note: Other hydraulic analysis software such as HEC-RAS or other culvert design software may be used in lieu of HY8 throughout the design).
12. Model new culvert in HY8. Design flow should be Q100. Check the bankfull flow as well to see if the elevation is as expected. Create tail water cross section with bankfull channel, floodplain, and low flow channel. (See Fish Passage Culvert Design Guidelines for guidance on low flow channel dimensions and step 22 for guidance on floodplain width). Model the channel cross section inside the culvert by choosing an appropriate average embedment depth that accounts for the area blocked by fill. Or use a user generated culvert cross section to model the bankfull channel and low flow channel shape directly. Choose a culvert that passes Q100 with HW/D =0.8 or with enough headroom to pass the expected debris during a floodCulvert should either be bankfull width or if streambanks are necessary or desired a minimum bankfull width + 3xD100. Designer should assume D100 and check it in next step (iterate as needed). Banks are desirable for fish passage and small mammals if feasible. Mammal crossing is more important on higher volume roads. We recommend culvert width be less than or equal to 1.4x Wbkf for culverts less than 12 feet or 1.2xWbkf for culverts greater than 12 feet or aggradation may result. USFS (2008) recommends not increasing the designed channel width to more than 1.25XWbkf. Desired bank widths are 2-3 feet per side unless you are using class 3 (D100=30")

or larger rip rap to construct the banks. Slope bankfull surfaces towards the thalweg at min 5% slope both inside and outside of the culvert.

13. Size coarse material using Corps of Engineers equation for rip rap design found in FHWA "River Engineering for Highway Encroachments", page 6.25 to 6.30 (Richardson, Simons and Lagasse 2001). FWS has developed the "Streambed Material Sizing Analyzer.xlsx" spreadsheet to use this method (See Figure 4, Appendix B for example). Input the design flood velocity in culvert (use average velocity at a given cross section) and model flow height to determine the D30 size of the coarse material required for stability. Use HY8 water surface profile to find where the max average velocity is; which may be inlet or outlet. Determine coarse and fine aggregate gradation using Fuller Thompson equation as a target (compare in the Streambed Material Sizing Analyzer spreadsheet). The spreadsheet is set up to use the AKDOT rip rap sizes or to use a custom coarse aggregate gradation. Note, AKDOT rip rap gradations are very uniform and will need to be mixed (i.e. 33% Type I + 33% Type II + 34% Fine Aggregate) in order to achieve a well graded combined gradation. For a copy of the spreadsheet send an e-mail to heather_hanson@fws.gov. Note: The FHWA HEC No. 23 circular titled "Bridge Scour and Stream Instability Countermeasures: Experience, Selection and Design Guidance" provides alternative methods for rip rap design.
14. Determine if there is adequate upstream sediment supply to move through the culvert. You will not have adequate sediment if the culvert is at a lake outlet, you have a wetland upstream, or a stream with a silty substrate. If there is adequate sediment supply design the culvert substrate for Q50. If sediment supply is not adequate, design culvert substrate for Q100. Check design substrate size against the upstream reach wide pebble count (Q50) and key pieces count (Q100). If the pebble counts are showing larger material than the sizes calculated, your hydrologic estimate may be low. However, in a relic channel you may have a larger pebble count in the system than would be mobilized by the current flow regime. (Note: the USFS stream simulation method relies on sediment moving through the culvert to replenish scoured sections inside the culvert. In contrast, the U.S. Fish and Wildlife Service modified approach is to have a minimum stability for the coarse sediment in the culvert corresponding to the Q50 flow recognizing that mobility will only occur for the fine fraction of the sediment or at flows higher than Q50. See the U.S. Forest Service Stream Simulation Design Manual, Appendix E for further discussion of the USFS approach) (USFS, 2008).
15. Design immobile key pieces and stream bank material inside the culvert for Q100. Use either rock clusters or rock bands to define the low flow channel and design for Q100. Check Q100 size against key pieces count data. See Figures 5-7 in Appendix B for rock clusters size, spacing and design guidance.
16. Check embed of culvert is 1.5xD100 (USFS, 2008) and allows for potential scour (lower VAP, Figure 1, Appendix B). Typical embedment depths range from 25-40% of culvert height. Also check culvert width is adequate to construct banks of 1.5xD100 per side if using banks. Will likely need to iterate to find a solution.
17. Check culvert capacity for potential aggradation- upper VAP. This would be head of riffle to head of riffle and this could reduce capacity if there is a concave slope change. If there's potential for debris flows use bankfull elevation for upper VAP instead of head of riffle.

Situational awareness is key in determining the potential for debris flow. Look for landslides, old failing banks and talk to locals about the history debris flows at the crossing.

18. Consider floodplain relief culverts where entrenchment ratio is greater than 2.0 and / or obvious side channels exist. (See Figure 8-9 in Appendix B and USFS (2008), chapter 5 for guidance). Floodplain relief allows water on the floodplain to drain more quickly during flows greater than bankfull and helps to prevent aggradation of the floodplain that is common in large flood events. Floodplain relief culverts should be placed with their flow line at bankfull elevation at a minimum. (Rock stable to the Q100 may be used to infill the culvert and set the elevation of the flow line). They should not be placed at the same elevation as the thalweg of the main culvert to eliminate chance of capturing creek. Allow enough space between culverts to construct stable banks for the main culvert and not reduce the competence of the main culvert fill compaction. Use a higher Manning's n for the floodplain relief culvert in HY8 assuming brush and grass will grow on the floodplain (Reference Arcement and Schneider (1989) for guidance on Manning's n for floodplains).
19. Transfer design to CAD. Double check alignment, slope and tail water cross section for final culvert design and iterate if necessary.
20. Continue culvert substrate upstream and downstream of inlet and outlet for approximately 50% of Wbkf. Design substrate in constructed channel outside of culvert for Q50 or pebble count, depending on scour mitigation as flow transitions from culvert to natural channel and floodplain. If streambanks are designed in the culvert, extend rock banks outside of culvert a minimum of 2 times the D100 rock size to transition to natural or bioengineered banks, depending on length of channel disturbance.
21. Design stream banks to withstand predicted velocities using appropriate bioengineering techniques. (See Fischenich (2001) for design guidance and ADF&G's Streambank Revegetation and Protection guide (Walter, Hughes, Moore and Inoue, 2005) for details commonly used in Alaska). In the long run, mature vegetation is expected to protect the banks from erosion after the temporary measure such as root wads and toe wood deteriorate. Therefore it is important to plant and maintain vegetation until it is well established along the reconstructed banks. Vegetation should mimic stable banks in undisturbed areas of the stream.
22. Construct cross section for reconstruction of disturbed stream upstream and downstream of the culvert. The cross section should include the low flow channel, bankfull channel and bankfull bench dimensions as well as bioengineering details. See Table 1 for bankfull bench width recommendations and Figures 2 and 3 for an illustration of typical channel, floodplain and terrace features for different types of channels. Also look at floodplain width in the reference reach for guidance. If the contractor is able to disturb less streambank than anticipated we will typically preserve undisturbed stable streambanks if possible.

Table 1. Recommended bankfull bench widths as a function of percent of bankfull channel width from Wildland Hydrology 2017 Level IV River Restoration and Natural Channel Design Workshop.

Bankfull Bench Width Recommendations	
Bankfull Channel Width (ft)	Recommended Bankfull Bench Width (% of Channel Width)
<20 ft	75%
20-50 ft	50%
>50 ft	25%

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APPENDIX B

Slides, Forms, and Examples

FIGURE 1: LOWER VAP LINE RECOMMENDATIONS FOR VARIOUS CHANNEL TYPES

Newbury Creek, longitudinal profile assessment

12) Delineate the lower vertical adjustment potential (scour) line.

- Choose deepest pool along channel not influenced by the undersized culvert.
- Adjust line to reflect scour/fill processes that occur during floods. Recommended criteria:
  - o 1.00 x Pool Max Depth (PMD): Step-pool channels, S > 5%, boulder-cobble boundaries.
  - o 1.25 x PMD: Step-pool channels with S < 5%, cobble-gravel boundaries.
  - o 1.50 x PMD: Steep riffles with ribs, cobble-gravel boundaries.
  - o 1.75 x PMD: Riffles, gravel-cobble boundaries.
  - o 2.00 x PMD: Rffles, sand-fine gravel boundaries.
  - o No adjustment for bedrock.

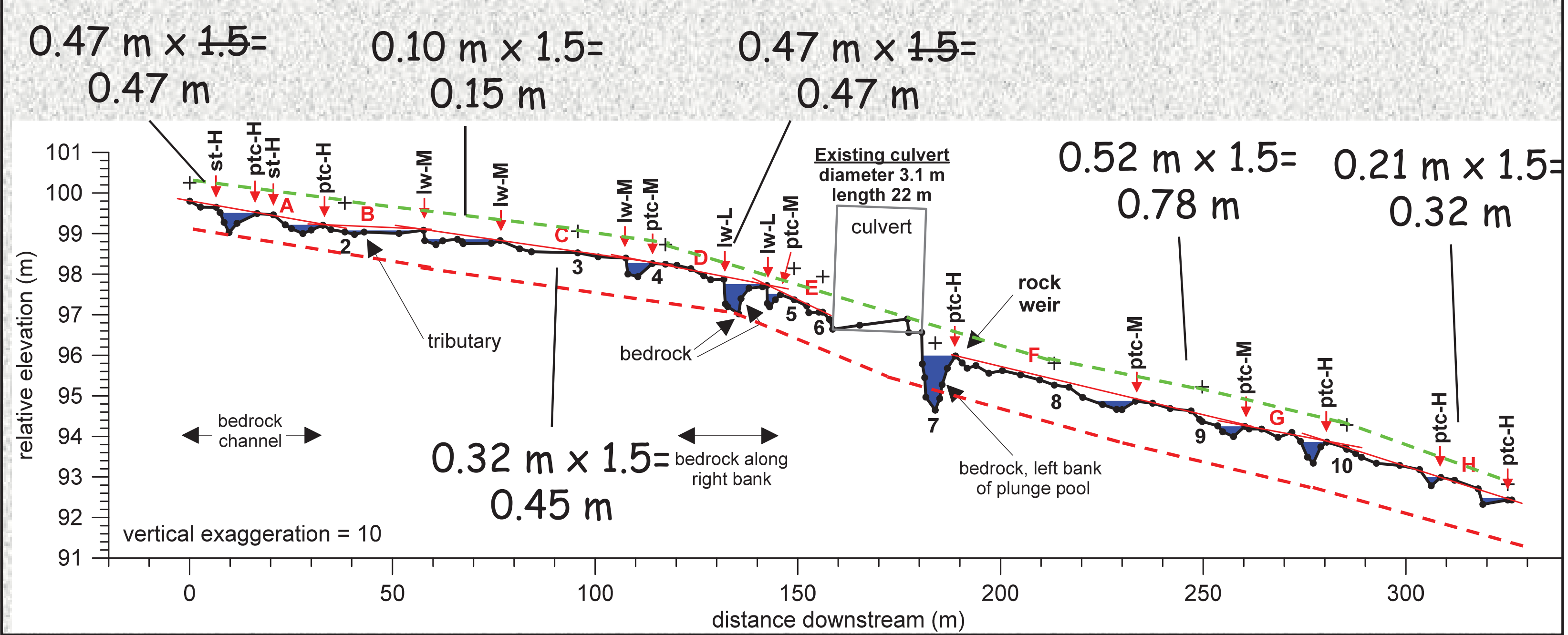


FIGURE 2: STREAM CLASSIFICATION WORKSHEET

Worksheet 2-3. Field form for *Level II* stream classification.

Stream:		
Basin:	Drainage Area: acres	mi^2
Location:		
Twp.&Rge:	Sec.&Qtr.:	
Cross-Section Monuments (Lat./Long.):		Date:
Observers:		Landscape Type:

Bankfull Width (W_{bkf}) The surface width of the stream at bankfull stage elevation, in a riffle section.		ft
Bankfull Mean Depth (d_{bkf}) Mean depth of the stream channel cross-section, at bankfull stage elevation, in a riffle section ($d_{bkf} = A_{bkf} / W_{bkf}$).		ft
Bankfull Cross-Sectional Area (A_{bkf}) Area of the stream channel cross-section, at bankfull stage elevation, in a riffle section.		ft^2
Width/Depth Ratio (W_{bkf} / d_{bkf}) *Bankfull Width* divided by *Bankfull Mean Depth*, in a riffle section.		ft/ft
Bankfull Maximum Depth (d_{max}) Maximum depth of the bankfull channel cross-section, or distance between the bankfull stage and Thalweg elevations, in a riffle section.		ft
Flood-Prone Area Width (W_{fpa}) Width of the channel at an elevation that is twice the *Bankfull Maximum Depth*, measured perpendicular to the fall line of the valley in a riffle section.		ft
Entrenchment Ratio (ER) The *Flood-Prone Area Width* divided by *Bankfull Width* (W_{fpa} / W_{bkf}), in a riffle section.		ft/ft
Channel Materials (Particle Size Index D_{50}) The D_{50} particle size index represents the median or dominant diameter of channel materials, as sampled proportionately from the channel surface between the bankfull stage and Thalweg elevations.		mm
Average Water Surface Slope (S) The elevation difference of water surface measurements over the stream length between two similar bed features (e.g., start of riffle to start of last riffle) for several riffle–pool or step–pool sequences, representing channel gradient.		ft/ft
Channel Sinuosity (k) An index of channel pattern determined from stream length divided by valley length (SL / VL), or from valley slope divided by average water surface slope (S_{val} / S).		ft/ft

Stream Type

See Classification Key (Figure 2-35)

FIGURE 3: BANKFULL DISCHARGE WORKSHEET

Worksheet 2-2. Computations of bankfull mean velocity and bankfull discharge using various methods.

Bankfull VELOCITY & DISCHARGE Estimates

Stream:		Location:	
Date:	Stream Type:	Landscape Type:	
Observers:		HUC:	__ __ __ __ __ __ __ __ __ __ __

INPUT VARIABLES			OUTPUT VARIABLES		
Bankfull Riffle Cross-Sectional Area		A_{bkf} (ft^2)	Bankfull Riffle Mean Depth		d_{bkf} (ft)
Bankfull Riffle Width		W_{bkf} (ft)	Wetted Perimeter $\approx (2 * d_{bkf}) + W_{bkf}$		W_p (ft)
D_{84} Particle Size at Riffle		D_{84} (mm)	D_{84} Particle Size in Feet D_{84} (mm) / 304.8		D_{84} (ft)
Bankfull Slope		S_{bkf} (ft / ft)	Hydraulic Radius A_{bkf} / W_p		R (ft)
Gravitational Acceleration	32.2	g (ft / sec^2)	Relative Roughness R (ft) / D_{84} (ft)		R / D_{84} (ft / ft)
Drainage Area		DA (mi^2)	Shear Velocity $u^* = (gRS)^{1/2}$		u* (ft / sec)

ESTIMATION METHODS	Bankfull VELOCITY		Bankfull DISCHARGE	
1. Friction Factor / Relative Roughness $\bar{u} = [\,2.83 + 5.66 * \text{Log}\,\{ R / D_{84} \}\,]\, u^*$		ft / sec		cfs
2. Roughness Coefficient: a) Manning's *n* from Friction Factor/Relative Roughness (Figs. 2-29, 2-30) $\bar{u} = 1.49 * R^{2/3} * S^{1/2} / n$ **n =**		ft / sec		cfs
2. Roughness Coefficient: b) Manning's *n* from Stream Type (Fig. 2-31) $\bar{u} = 1.49 * R^{2/3} * S^{1/2} / n$ **n =**		ft / sec		cfs
2. Roughness Coefficient: c) Manning's *n* from Jarrett (USGS): $\bar{u} = 1.49 * R^{2/3} * S^{1/2} / n$; $n = 0.39 * S^{0.38} * R^{-0.16}$ **n =** **Note:** This equation is applicable to **steep, step/pool, high boundary roughness, cobble- and boulder-dominated stream systems**; i.e., for Stream Types A1, A2, A3, B1, B2, B3, C2 & E3		ft / sec		cfs
3. Other Methods (Hey, Darcy-Weisbach, Chezy C, etc.)		ft / sec		cfs
3. Other Methods (Hey, Darcy-Weisbach, Chezy C, etc.)		ft / sec		cfs
4. Continuity Equations: a) USGS Gage Data $\bar{u} = Q / A$ **Return Period for Bankfull Q** **Q =** ____ **year**		ft / sec		cfs
4. Continuity Equations: b) Regional Curves $\bar{u} = Q / A$		ft / sec		cfs

Protrusion Height Options for the D_{84} Term in the Relative Roughness Relation (R/D_{84}) – Estimation Method 1

Option 1.	For **sand-bed** channels: Measure 100 **"protrusion heights"** of sand dunes from the downstream side of feature to the top of feature. Substitute the D_{84} sand dune protrusion height in ft for the D_{84} term in method 1.
Option 2.	For **boulder-dominated** channels: Measure 100 **"protrusion heights"** of boulders on the sides from the bed elevation to the top of the rock on that side. Substitute the D_{84} boulder protrusion height in ft for the D_{84} term in method 1.
Option 3.	For **bedrock-dominated** channels: Measure 100 **"protrusion heights"** of rock separations, steps, joints or uplifted surfaces above channel bed elevation. Substitute the D_{84} bedrock protrusion height in ft for the D_{84} term in method 1.
Option 4.	For **log-influenced** channels: Measure **"protrustion heights"** proportionate to channel width of log diameters or the height of the log on upstream side if embedded. Substitute the D_{84} protrusion height in ft for the D_{84} term in method 1.

FIGURE 4: SAMPLE STREAMBED MATERIAL SIZING

New Stream Channel Design (Culvert, Rock Ramp)

Using Corps of Engineers Equations - FHWA Circular on Development in the River System - Page 6.25.
FHWA NHI 01-004; River Engineering for Highway Encroachments, 2001
http://www.fhwa.dot.gov/engineering/hydraulics/library_arc.cfm?pub_number=8&id=20

YELLOW ARE INPUTS		
Safety Factor	**1.5**	
Stability Coefficient for Incipient Failure	0.3	(0.36 round rock, 0.3 angular rock)
Vertical Velocity Distribution Coeff	1.00	(1.0 for straight channels)
Blanket Thickness Coeff	1	(1xD100 or 1.5 or D50 max, whichever is greater)
Local depth of flow	2.5	ft for 100 year event
Unit Weight of water	62.4	lb/ft^3 assumed
Unit weight of rock	165	lb/ft^3 assumed
Local depth-average velocity	9.8	ft/s from 100-year event avg. velocity in pipe
Side Slope correction factor	1	
Gravitational Acceleration	32.2	ft/s^2
D85/D15	3.8	(1.7-5.2)
D50/D30	2	

Note: This method is based on the minimum D30 size

Riprap Design Method - Selecting Proper Gradation, Page 131.
Design Hydrology and Sedimentology for Small Catchments, Haan, Barfield and Hayes, 1981.

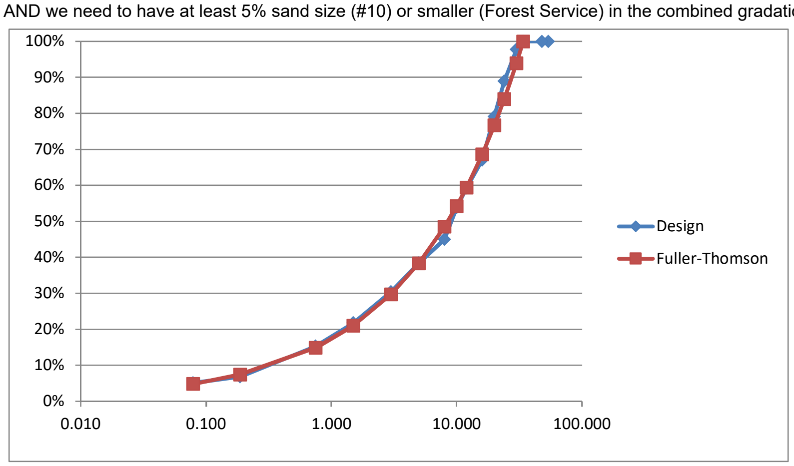
D15	0.5	ft	7.0	inches	
D30	0.8	ft	10.0	inches	
D50	1.2	ft	15.0	inches	Coarse
D85	2.0	ft	24.0	inches	
D100	2.4	ft	29.0	inches	

Using D50 size, used FHWA circular for Rip Rap design to spec out D100, D85 and D15.
D100 = 2.0D50

Fuller-Thompson Estimating for Maximum Density:	D100 (inches)	34	input designed D100 from table below	
Method Adapted from US Forest Service Stream Simulation Guidelines	D30	10.0	Stability (D30)	OK
	D30 Req'd	10.0		

YELLOW ARE INPUTS		COARSE MATERIAL					FINES
		Custom	Type IV Rip Rap	Type III Rip	Type II Rip R	Type I Rip Rap	FA
	relative %	0	0	0.22	0.2200	0.2200	0.3400
Size (inches)	Sieve Size	% Passing	% Passing	% Passing	% Passing	% Passing	% Passing
54	54"	0.00	1.00	1.00	1.00	1.00	1.00
48	48"	0.00	0.90	1.00	1.00	1.00	1.00
34	34"	0.00	0.50	1.00	1.00	1.00	1.00
30	30"	0.00	0.35	0.90	1.00	1.00	1.00
24	24"	0.00	0.25	0.50	1.00	1.00	1.00
20	20"	0.00	0.15	0.15	0.90	1.00	1.00
16	16"	0.00	0.00	0.00	0.50	1.00	1.00
12	12"	0.00	0.00	0.00	0.15	1.00	1.00
10	10"	0.00	0.00	0.00	0.00	0.90	1.00
8	8"	0.00	0.00	0.00	0.00	0.50	1.000
5	5"	0.00	0.00	0.00	0.00	0.20	1.000
3	3"	0.00	0.00	0.00	0.00	0.10	0.830
1.5	1.5"	0.00	0.00	0.00	0.00	0.00	0.640
0.75	.75"	0.00	0.00	0.00	0.00	0.00	0.450
0.187	#4	0.00	0.00	0.00	0.00	0.00	0.200
0.0787	#10 Sand	0.00	0.00	0.00	0.00	0.00	0.150

Gradation values should be within +/-5% of this gradation (Rice)
AND we need to have at least 5% sand size (#10) or smaller (Forest Service) in the combined gradation



DATA for Graph & Fuller-Thomson Eqn

Size (in)	Combined % pa	F-T equation
54.000	100%	126%
48.000	100%	119%
34.000	100%	100%
30.000	98%	94%
24.000	89%	84%
20.000	79%	77%
16.000	67%	69%
12.000	59%	59%
10.000	54%	54%
8.000	45%	49%
5.000	38%	38%
3.000	30%	30%
1.500	22%	21%
0.750	15%	15%
0.187	7%	7%
0.079	5%	5%

FIGURE 5: ROCK CLUSTERS

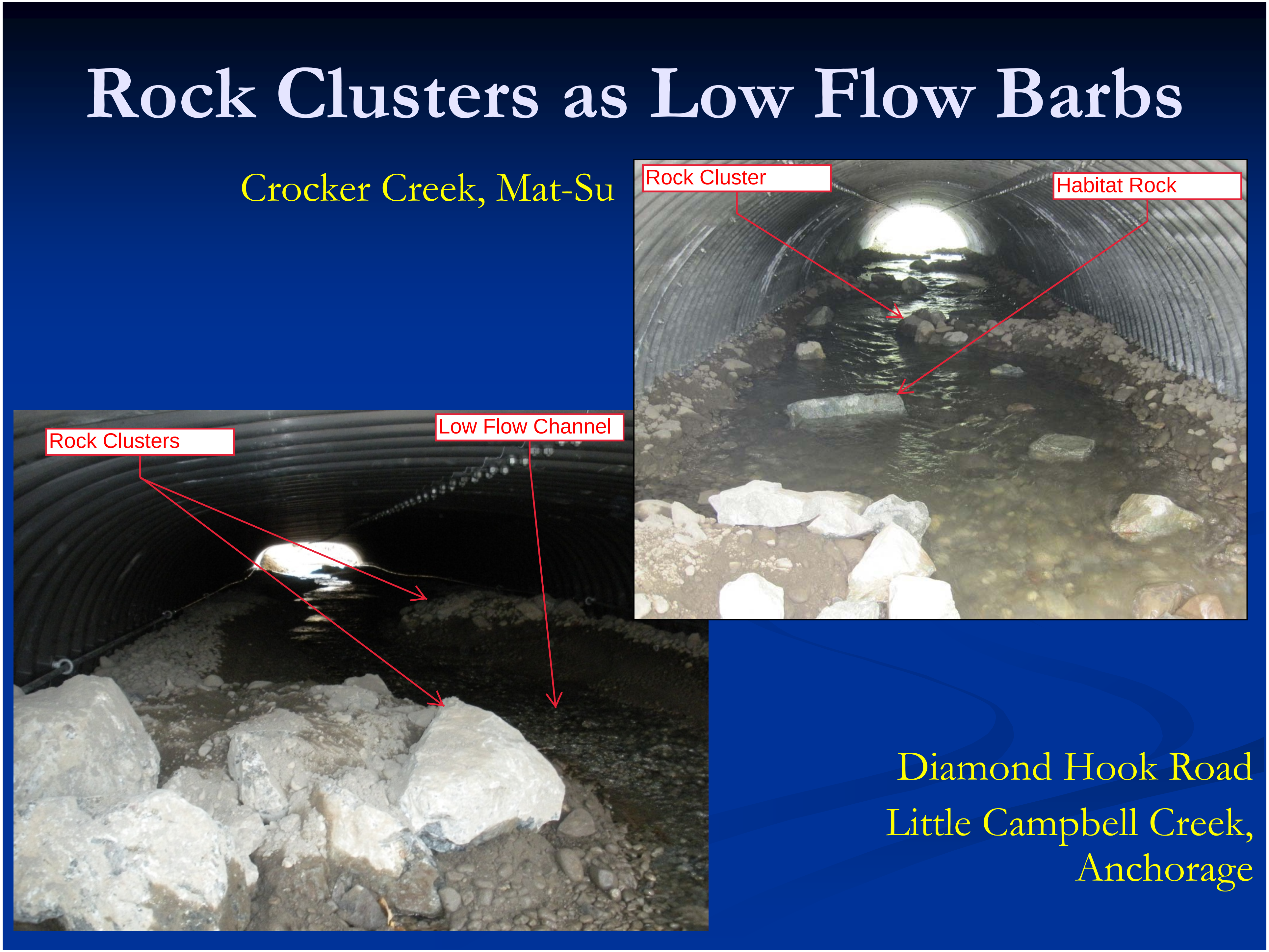


FIGURE 6: ROCK CLUSTER SPACING GUIDANCE

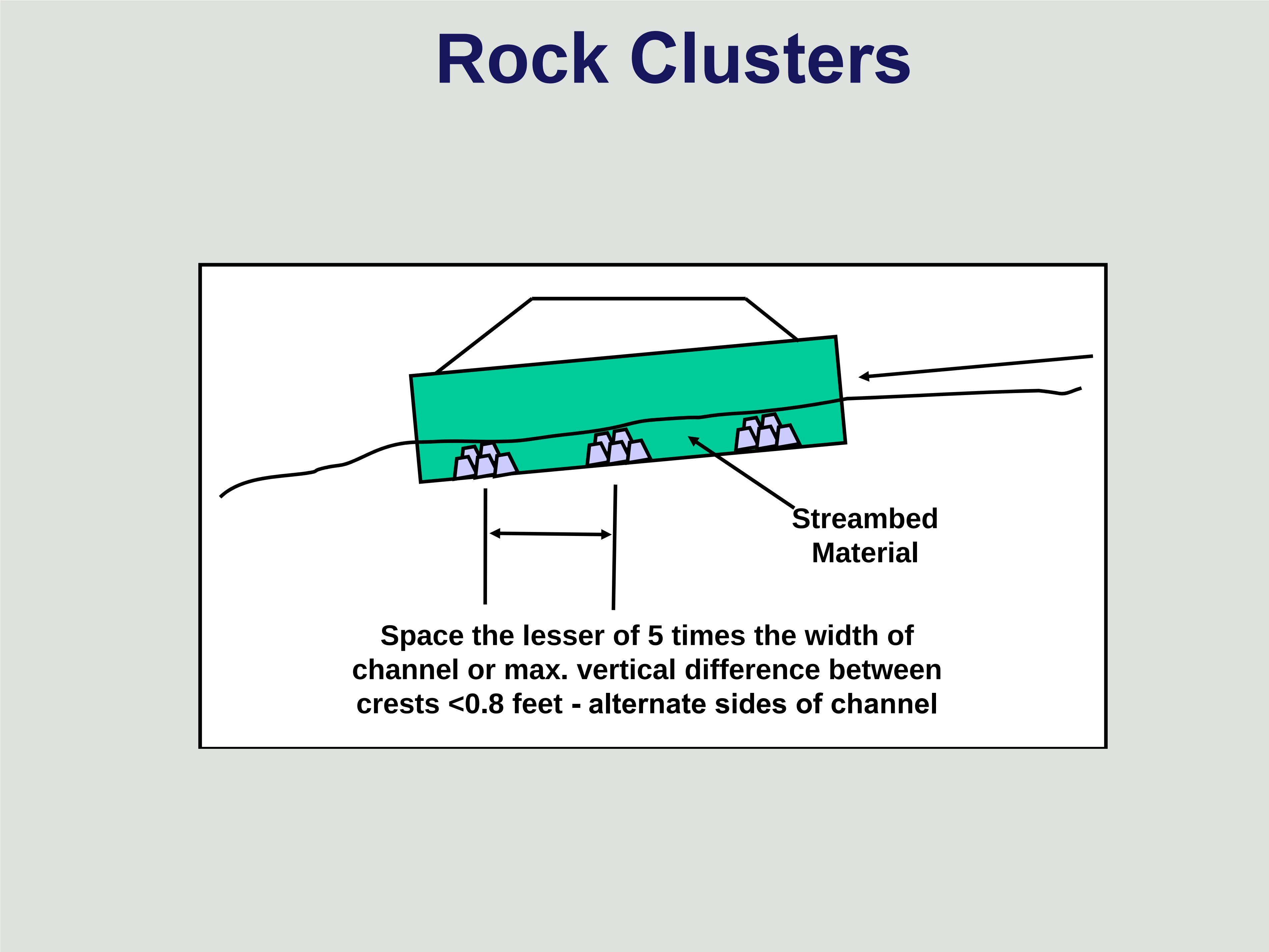


FIGURE 7: ROCK CLUSTER EXAMPLE - BANKFULL WIDTH CULVERT

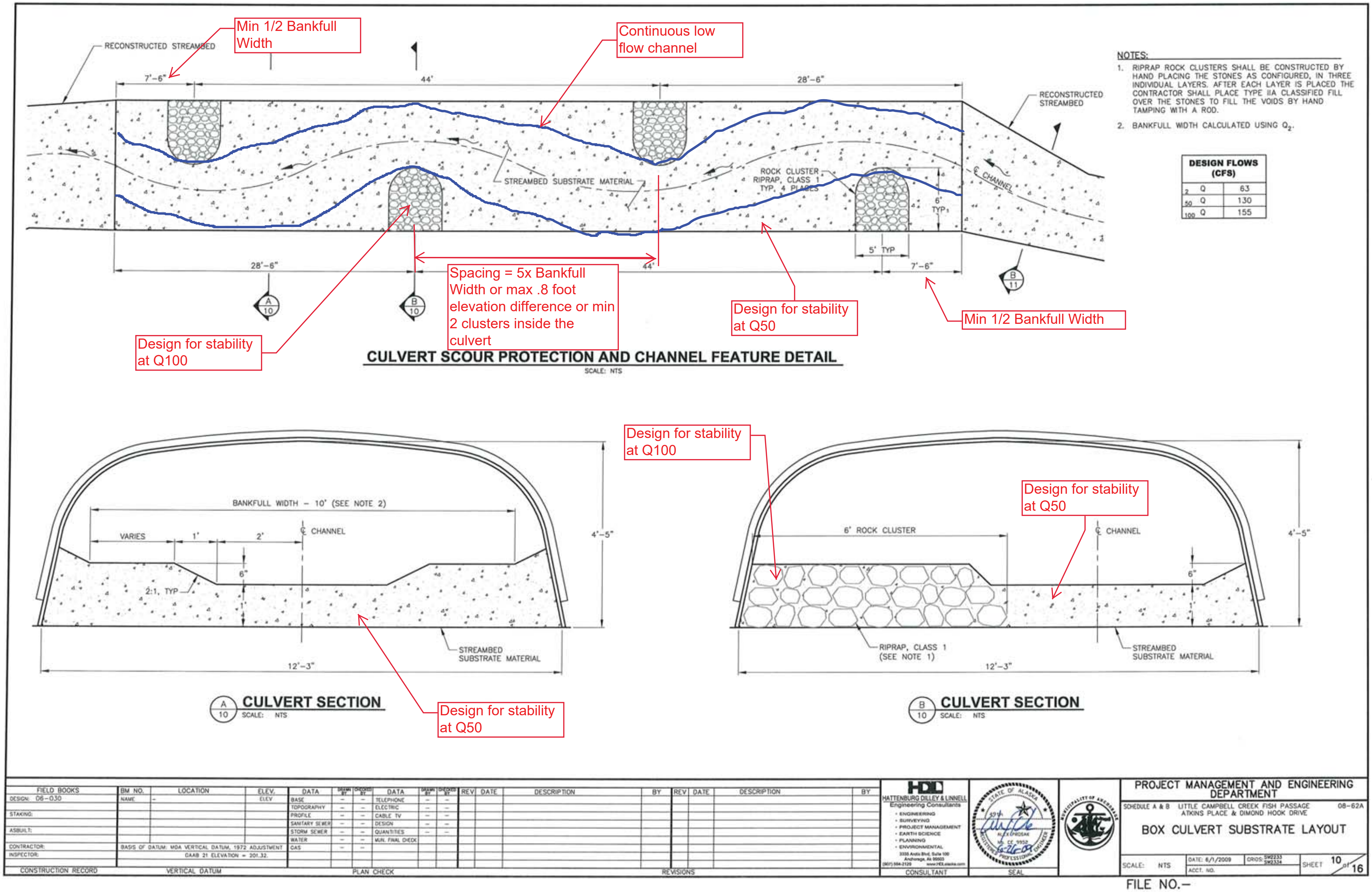


FIGURE 8: FLOODPLAIN CULVERTS

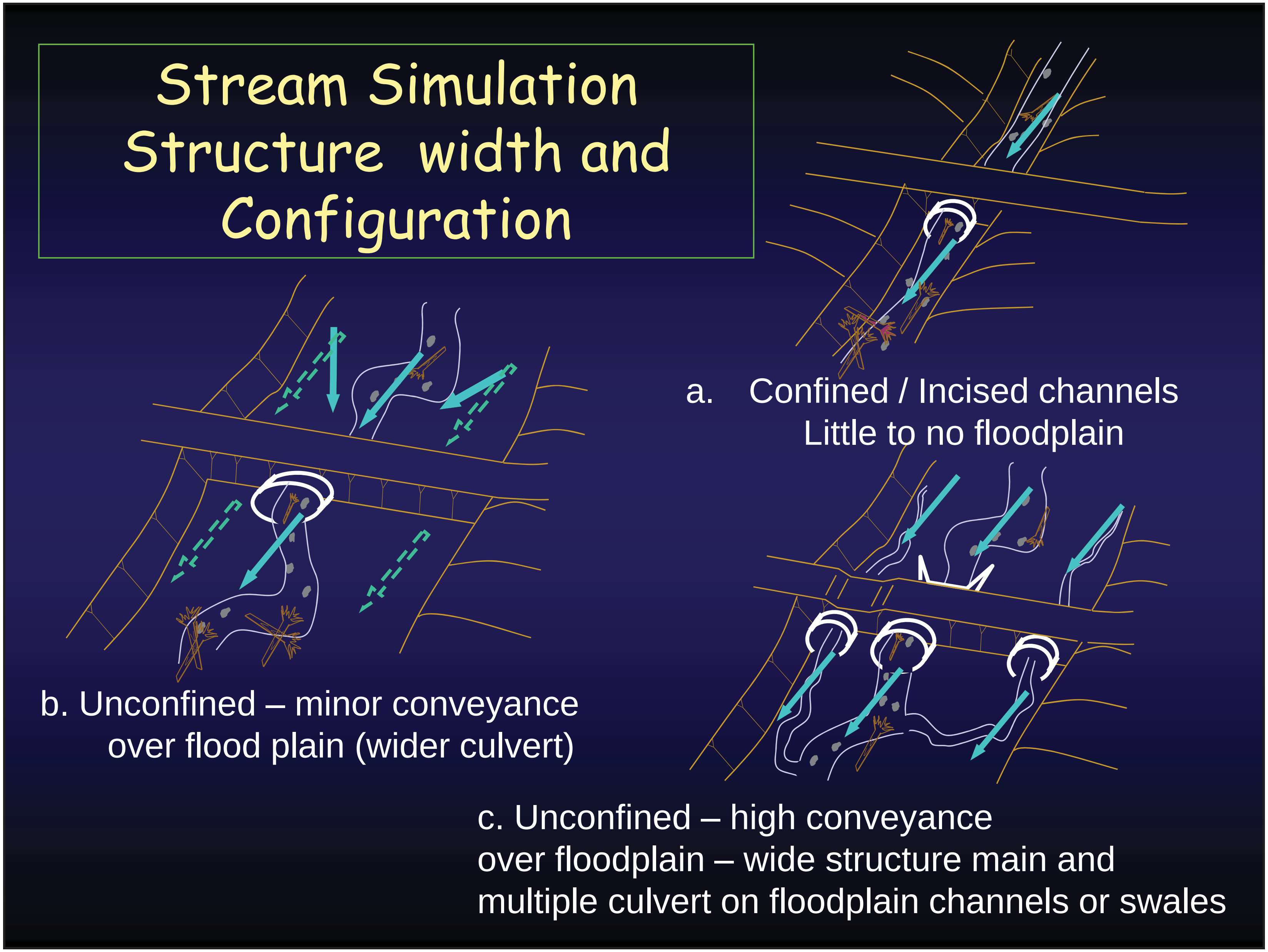


FIGURE 9: FLOODPLAIN CULVERT GUIDANCE

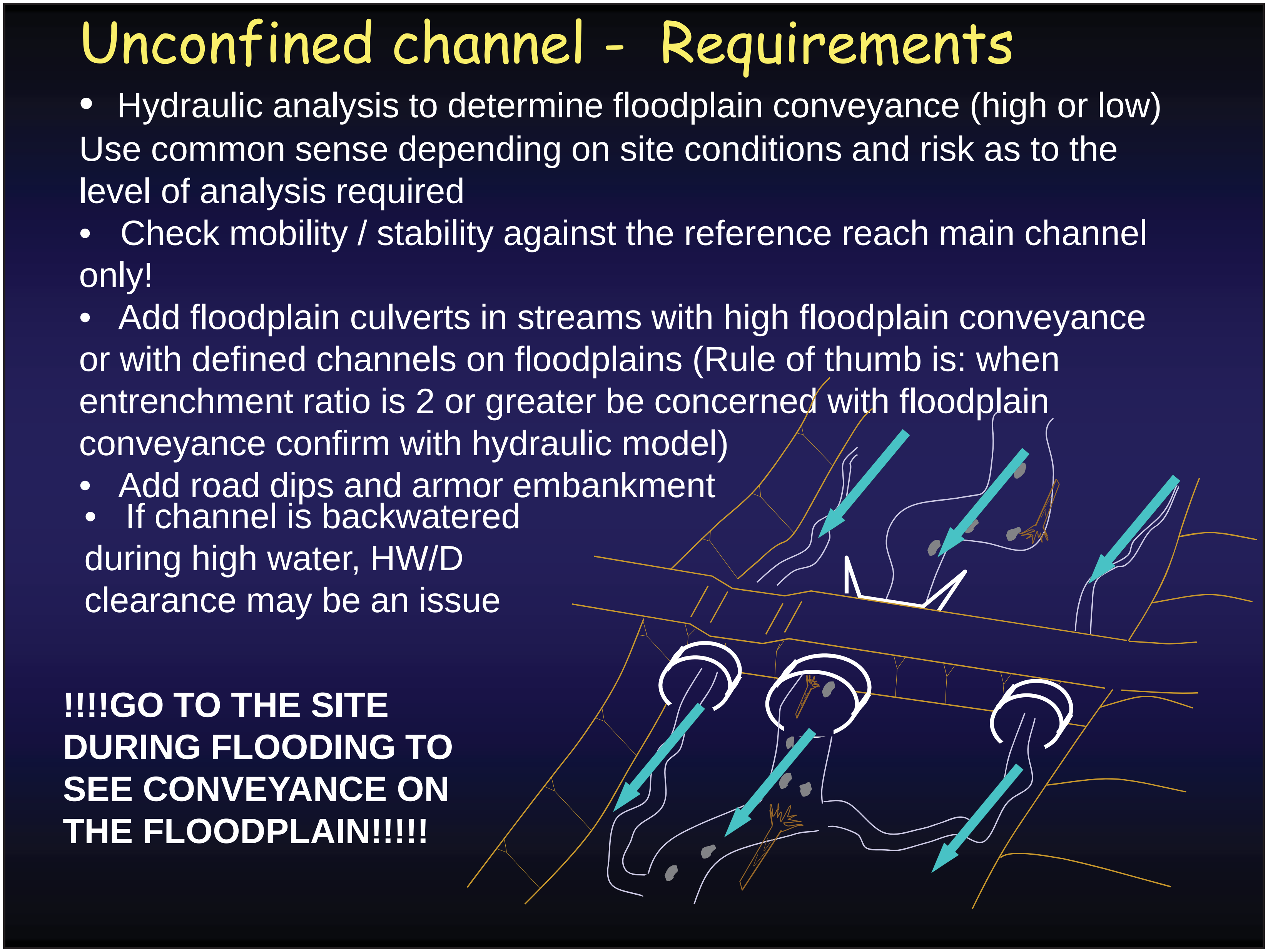


FIGURE 10: ROSGEN STREAM TYPES

Figure 11–2 Broad-level stream classification delineation showing longitudinal, cross-sectional, and plan views of major stream types

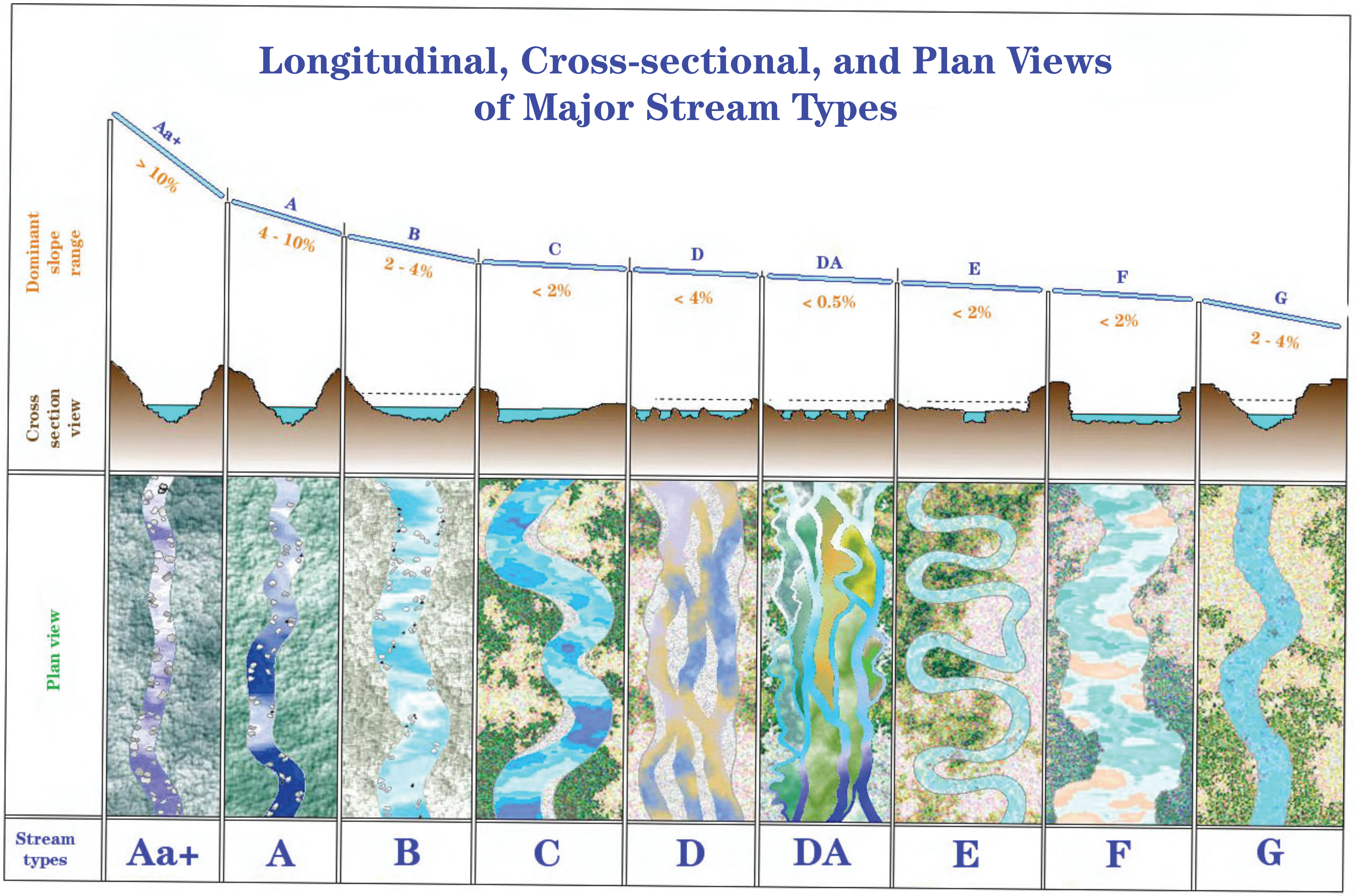
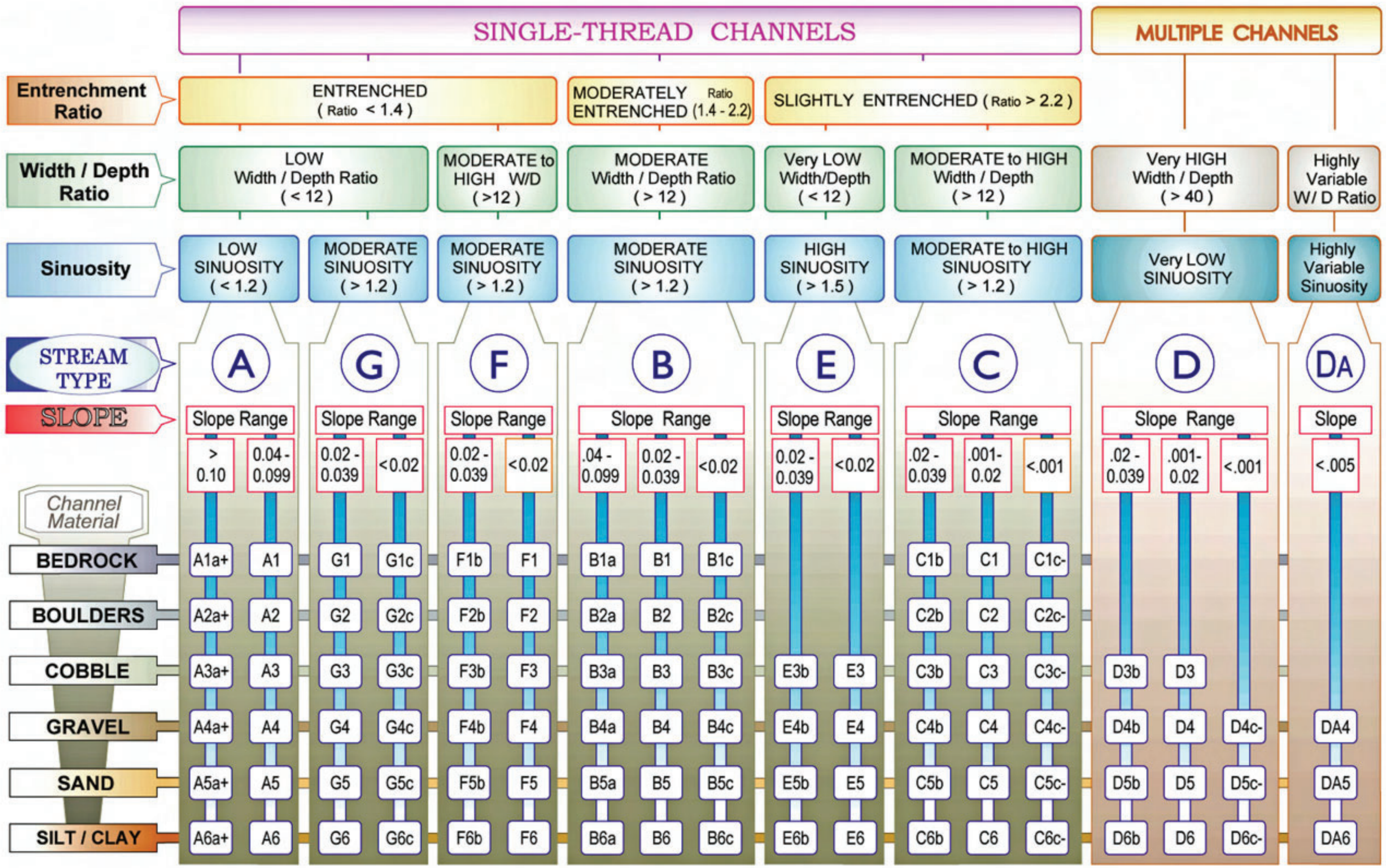


FIGURE 11: ROSGEN CLASSIFICATION KEY

Figure 11–3 Classification key for natural rivers



KEY to the ROSGEN CLASSIFICATION of NATURAL RIVERS. As a function of the *"continuum of physical variables"* within stream reaches, values of ***Entrenchment*** and ***Sinuosity*** ratios can vary by +/- 0.2 units; while values for ***Width / Depth*** ratios can vary by +/- 2.0 units.

FIGURE 12: DESCRIPTIONS OF ROSGEN STREAMS TYPES

Table 11–2 General stream type descriptions and delineative criteria for broad-level classification (level 1)

Stream type	General description	Entrench-ment ratio	W/d ratio	Sinuosity	Slope	Landform/ soils/features
Aa+	Very steep, deeply entrenched, debris transport, torrent streams	<1.4	<12	1.0 to 1.1	>.10	Very high relief. Erosional, bedrock, or depositional features; debris flow potential. Deeply entrenched streams. Vertical steps with deep scour pools; waterfalls
A	Steep, entrenched, cascading, step-pool streams. High energy/ debris transport associated with depositional soils. Very stable if bedrock or boulder-dominated channel	<1.4	<12	1.0 to 1.2	.04 to .10	High relief. Erosional or depositional and bedrock forms. Entrenched and confined streams with cascading reaches. Frequently spaced, deep pools in associated step-pool bed morphology
B	Moderately entrenched, moderate gradient, riffle dominated channel with infrequently spaced pools. Very stable plan and profile. Stable banks	1.4 to 2.2	>12	>1.2	.02 to .039	Moderate relief, colluvial deposition and/or structural. Moderate entrenchment and width-to-depth ratio. Narrow, gently sloping valleys. Rapids predominate with scour pools
C	Low gradient, meandering, point bar, riffle/pool, alluvial channels with broad, well-defined flood plains	>2.2	>12	>1.2	<.02	Broad valleys with terraces, in association with flood plains, alluvial soils. Slightly entrenched with well-defined meandering channels. Riffle/ pool bed morphology
D	Braided channel with long-itudinal and transverse bars. Very wide channel with eroding banks	n/a	>40	n/a	<.04	Broad valleys with alluvium, steeper fans. Glacial debris and depositional features. Active lateral adjustment with abundance of sediment supply. Convergence/divergence bed features, aggradational processes, high bed load and bank erosion
DA	Anastomizing (multiple channels) narrow and deep with extensive, well-vegetated flood plains and associated wetlands. Very gentle relief with highly variable sinuosities and width-to-depth ratios. Very stable streambanks	>2.2	Highly variable	Highly variable	<.005	Broad, low-gradient valleys with fine alluvium and/or lacustrine soils. Anastomized (multiple channel) geologic control creating fine deposition with well-vegetated bars that are laterally stable with broad wetland flood plains. Very low bed-load, high wash load sediment
E	Low gradient, meandering riffle/pool stream with low width-to-depth ratio and little deposition. Very efficient and stable. High meander width ratio	>2.2	<12	>1.5	<.02	Broad valley/meadows. Alluvial materials with flood plains. Highly sinuous with stable, well-vegetated banks. Riffle/pool morphology with very low width-to-depth ratios
F	Entrenched meandering riffle/pool channel on low gradients with high width-to-depth ratio	<1.4	>12	>1.2	<.02	Entrenched in highly weathered material. Gentle gradients with a high width-to-depth ratio. Meandering, laterally unstable with high bank erosion rates. Riffle/pool morphology
G	Entrenched gully step-pool and low width-to-depth ratio on moderate gradients	<1.4	<12	>1.2	.02 to .039	Gullies, step-pool morphology with moderate slopes and low width-to-depth ratio. Narrow valleys, or deeply incised in alluvial or colluvial materials (fans or deltas). Unstable, with grade control problems and high bank erosion rates

FIGURE 13: REFERENCE REACH DATA SUMMARY FORM

Table 11–3 Reference reach summary data form

River Reach Summary Data

Channel dimension

Mean riffle depth (d_{bkf})		ft	Riffle width (W_{bkf})		ft	Riffle area (A_{bkf})		ft^2
Mean pool depth (d_{bkfp})		ft	Pool width (W_{bkfp})		ft	Pool area (A_{bkfp})		ft^2
Mean pool depth/mean riffle depth		d_{bkfp}/(d_{bkf})	Pool width/riffle width		W_{bkfp}/W_{bkf}	Pool area/riffle area		A_{bkfp}/A_{bkf}
Max riffle depth (d_{mbkf})		ft	Max pool depth (d_{mbkfp})		ft	Max riffle depth/mean riffle depth		
Max pool depth/mean riffle depth						Point bar slope		
Streamflow: estimated mean velocity at bankfull stage (u_{bkf})					ft/s	Estimation method		
Streamflow: estimated discharge at bankfull stage (Q_{bkf})					ft^3/s	Drainage area		mi^2

Channel pattern

Geometry	Mean	Min.	Max.		Dimensionless geometry ratios	Mean	Min.	Max.
Meander length (Lm)				ft	Meander length ratio (Lm/W_{bkf})			
Radius of curvature (Rc)				ft	Radius of curvature/riffle width (Rc/W_{bkf})			
Belt width (W_{blt})				ft	Meander width ratio (W_{blt}/W_{bkf})			
Individual pool length				ft	Pool length/riffle width			
Pool to pool spacing				ft	Pool to pool spacing/riffle width			

Channel profile

Valley slope (VS)		ft/ft	Average water surface slope (S)		ft/ft	Sinuosity (VS/S)	
Stream length (SL)		ft	Valley length (VL)		ft	Sinuosity (SL/VL)	
Low bank height (LBH)	start	ft	Max riffle depth	start	ft	Bank height ratio (LBH/max riffle depth)	start
	end	ft		end	ft		end

Facet slopes	Mean	Min.	Max.		Dimensionless geometry ratios	Mean	Min.	Max.
Riffle slope (S_{rif})				ft/ft	Riffle slope/average water surface slope (S_{rif}/S)			
Run slope (S_{run})				ft/ft	Run slope/average water surface slope (S_{run}/S)			
Pool slope (S_p)				ft/ft	Pool slope/average water surface slope (S_p/S)			
Glide slope (S_g)				ft/ft	Glide slope/average water surface slope (S_g/S)			

Feature midpoint[a/]	Mean	Min.	Max.		Dimensionless geometry ratios	Mean	Min.	Max.
Riffle depth (d_{rif})				ft	Riffle depth/mean riffle depth (d_{rif}/d_{bkf})			
Run depth (d_{run})				ft	Run depth/mean riffle depth (d_{run}/d_{bkf})			
Pool depth (d_p)				ft	Pool depth/mean riffle depth (d_p/d_{bkf})			
Glide depth (d_g)				ft	Glide depth/mean riffle depth (d_g/d_{bkf})			

Channel materials

Geometry		Reach[b/]	Riffle[c/]	Bar		Reach[b/]	Riffle[c/]	Bar	
% Silt/clay					D_{16}				mm
% Sand					D_{35}				mm
% Gravel					D_{50}				mm
% Cobble					D_{84}				mm
% Boulder					D_{95}				mm
% Bedrock					D_{100}				mm

a/ Minimum, maximum, mean depths are the average midpoint values except pools which are taken at deepest part of pool
b/ Composite sample of riffles and pools within the designated reach
c/ Active bed of a riffle

APPENDIX C

Culvert Construction
Inspection Checklist

December 9, 2019

APPENDIX C

U.S. Fish and Wildlife Service
Alaska Fish Passage Program
Culvert Replacement
Project Inspection Checklist

Pre-construction:

- ☐ Verify environmental permitting is current (e.g. USACE Section 404, DNR water use, ADFG habitat).
- ☐ Verify all necessary ROW and easements have been obtained
- ☐ Notify local residents and businesses of construction activity and closures
- ☐ Check that utility locates have been done
- ☐ Check that utilities have been relocated by 3rd parties as necessary
- ☐ Verify the stream profile has not experienced significant grade changes compared to the design profile.
- ☐ Inventory owner supplied materials and sign over to contractor
- ☐ Check that survey monuments are located and a plan to relocate disturbed monuments is made
- ☐ Review diversion and dewatering plan with contractor and ADFG.
- ☐ Ensure contractor has adequate pump capacity, discharge hose, correct fuel types for pumps, extra suction hose gaskets, and backup stream diversion materials. If pumping stream flows around the construction site, use screened intake for water withdrawals to avoid suction entrapment and entrainment injury to small and juvenile fish present in the area of the withdrawal.
- ☐ Confirm that the fish resource permit has been obtained and review plan for relocating fish with ADFG
- ☐ Confirm that contractor has obtained traffic control permit if required
- ☐ Review erosion and pollution control plan; ensure SWPPP permit obtained from ADEC if > 1 acre.
- ☐ Plastic degradable netting is not allowed for use in erosion control for any aspect of the project. Prior to degradation, the netting can entangle wildlife, including amphibians, birds, and small mammals.
- ☐ Isolate wetlands from construction-generated sediment and pollutants by maintaining a minimum 200-foot setback from waterways when storing hazardous or toxic material or refueling. Confirm that containment and cleanup materials are on site prior to starting work.
- ☐ Review the revegetation plan. Confirm source of vegetative mat. Vegetative cover should be capable of stabilizing the soil against erosion. In addition to topsoil and seed, consider transplanting willows, alder and/or spruce in the riparian area behind the vegetative mat. If rip-rap was used, backfill with finer sediments, cover with topsoil, and seed with native seed.
- ☐ Confirm and review aggregate material sources and gradations

- ☐ Use weed free gravel, weed free topsoil, and weed free erosion control materials (compost wattles or coconut fiber roll instead of straw wattles). Wash all equipment prior to mobilization to the site. Use native weed-free seed (preferably locally collected), specific to the habitat type, applied at specified rates, and cover the seed to specified depth. Use a tackifier, mulch, or other bonding agents to keep seed in place.
- ☐ Count number of trees to be removed or already removed if a replacement ratio is specified
- ☐ Review area of disturbance required for construction. Reduce the project footprint to the maximum extent and locate associated activities in already disturbed areas or lower functioning/quality habitat, where possible.

During construction and prior to re-watering culvert:

- ☐ Confirm culvert alignment has been staked out according to drawings and meets project objectives; notify engineer if adjustment are needed
- ☐ Check grade elevation and slope of excavation prior to setting the culvert
- ☐ Check top (or invert) of culvert placed at correct elevation and correct slope per drawings prior to filling with substrate
- ☐ Prior to placement in culvert, inspect streambed infill materials at quarry or stockpile; check against design gradation, ensure enough fines are present to seal streambed during wash-in procedure
- ☐ Check stream material is sufficiently sealed and water pools on surface prior to re-diverting the creek back into the culvert
- ☐ Check that substrate has been sprayed down and discharge is clean and clear
- ☐ Walk thru culvert and check substrate is firm (similar to the natural streambed)
- ☐ Discuss plan to remove diversion
- ☐ Discuss revegetation plan and revise where necessary; save undisturbed banks if possible
- ☐ Check channel thalweg and bank elevations at culvert inlet and outlet
- ☐ Check channel tie in location and elevation upstream and downstream
- ☐ For culverts with streambanks constructed inside of the culvert, check that the banks are extended outside of the culvert 2xD100 minimum and tied into natural banks.
- ☐ Check channel planform matches drawings
- ☐ Check bankfull channel width and depth matches drawings
- ☐ Check low flow channel width and depth matches drawings
- ☐ Check channel dimensions upstream and downstream from culvert
- ☐ Check rootwads or toewood constructed per plans or revise as necessary to adapt to site conditions. Check elevation of rootwads – centerline of bole at OHW or top of bole at bankfull

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During construction after re-watering culvert:

- ☐ Check embed depth of willow cuttings (min 2/3 in dirt) and trim as needed
- ☐ Check live vegmat placed as noted on drawings
- ☐ Check disturbed areas without vegmat have topsoil that has been track walked and seeded
- ☐ Check revegetation matches plans and discuss required watering going forward
- ☐ Check volume of flow in culvert matches flow upstream (not losing water in the substrate)
- ☐ Check rip rap collar placed as noted on plans.
- ☐ Check rip rap in the collar has been filled with fines.
- ☐ Verify compaction methods are adequate and meet specs during backfill of the road prism.
- ☐ Check minimum cover provided over culvert
- ☐ Check roadway width and surface material
- ☐ Check roadway grade
- ☐ Check for correct installation of post-construction erosion and sediment controls.
- ☐ Re-contour slopes to blend with surrounding topography and use waterbars or contour furrowing (by track walking or manual raking- see ADOT&PF spec section 618) on steeper slopes.
- ☐ Strategically place root wads, large logs, or boulders in the riparian area after seeding, to provide topographical relief and micro-climates, and to increase the variety of plant species difficult to establish by seed (e.g., increase habitat complexity).

APPENDIX D

Commentary

Culvert Design Guidelines – U.S. Fish and Wildlife Service

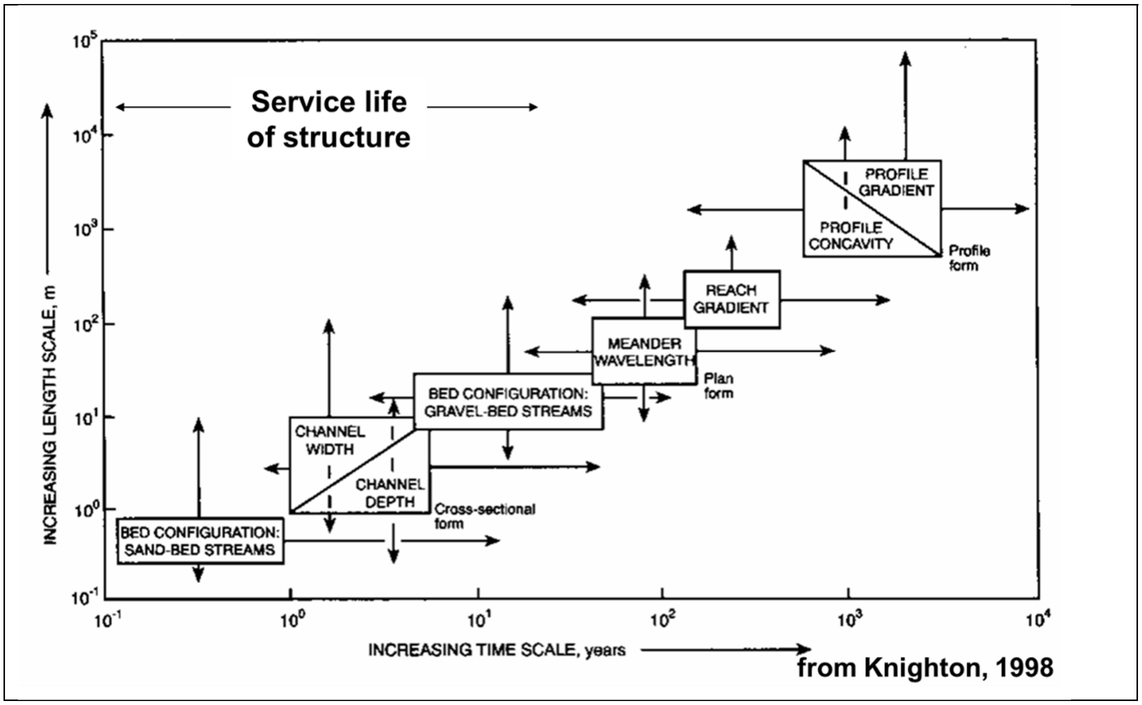
Commentary

This commentary describes the background of main non-referenced portions of the guidelines. Much of the non-referenced sections are based on the experiences over the years of U.S. Fish and Wildlife Service in implementing on the ground projects across the State, visual monitoring over time as well as discussions with ADOT&PF and other infrastructure owners' experiences and modes of practice.

- A0 - *The USFWS Alaska Fish Passage Program has adopted a geomorphic analog method which follows the United States Forest Service stream simulation approach…* The term "stream simulation" has been used over the years to describe different methods to design a "nature like" channel at a road stream crossing when it should only be used in reference to the USFS guidance. In order to avoid confusion, we have chosen the term "geomorphic analog" to more precisely describe the methodology adopted in this guidance. This geomorphic analog method has much of the same approach as stream simulation but differs in terms of defining more parameters for various project settings, defining dynamic stability and culvert widths.

- A1 – *The width of the primary crossing structure should not be less than 1.0 times the bankfull width of the channel*. Flows up to the bankfull stage have been shown to be responsible for forming and maintaining channel features and transporting the majority of sediment in alluvial systems. By maintaining the hydraulic geometry of the channel up to the bankfull flow we can maintain sediment transport equilibrium between the crossing and the natural channel. US Forest Service (USFS) guidelines for stream simulation are based on emulating the geomorphic condition of the bankfull channel. Studies in the Pacific Northwest have also shown road/stream crossing channels that are at least bankfull width carry the propensity of debris down a channel. The goal of this guidance is to provide a crossing that will pass aquatic organisms, water AND debris to the extent reasonable and possible.

- A2 - *Crossing structures should be placed within/over the pre-development natural channel alignment when possible. Road alignment for new roads should be as close to perpendicular to the channel as possible.* For the stable creeks that these guidelines are recommended for, lateral movement typically occurs on the order of hundreds of years (Knighton, 1998), therefore it is reasonable to assume that the minimum amount of movement risk is associated with the current natural channel alignment. Additionally, putting a road crossing over as straight a section of the stream as is present generally represents the most stable lateral movement portion of the stream. If possible, we would recommend not locating a crossing immediately downstream of a meander bend as they are more likely to migrate downstream and may impact the road prism when roads persist for 50 years or more. If realignment of the stream is required, we recommend mimicking the meander geometry of the reference reach and keeping the slope within 25% of the reference reach.



A3 - *Culvert Size, Slope and Substrate - Culvert substrate material within/under the crossing structure should remain dynamically stable at all flood discharges up to and including a 50-year flood flow.* ADOT&PF design standards require a 50 year flow for culvert design at primary and secondary highways. Conversations with hydraulic engineers at ADOT&PF say they use the 50-year as the design flood as a minimum most of the time, even in remote areas, as it provides for the more cost effective design in the long run. FHWA methodology has established design for dynamic stability of the culvert substrate at the design flood as a standard of good engineering practice. We maintain that in embedded culverts there is always some sediment movement into and out of the culvert if upstream sources exist but significant movement between upper and lower VAP lines be designed to occur at the 50-year design flow or higher for locations with upstream sediment sources and 100-year or higher at locations without sediment sources such as lake outlets. Exceptions can exist, for instance "D" type stream with multiple channels on alluvial fans, where a stream simulation approach to streambed design may be more appropriate.

A4 - *Culverts should have a minimum diameter of five feet (5').* This minimum was developed both by USFWS experience in constructability at the smaller culvert diameters and in conversations with the USFS as to their minimums for constructability on the Tongass – which is five feet diameter. The FHWA publication, Culvert Design for Aquatic Organism Passage (HEC 26) recommends 6 feet as the minimum diameter in order to allow sufficient space to construct and maintain the stream channel inside the culvert.

A5 - *Streambanks are not recommended for areas with permafrost or severe freeze-thaw issues, for areas with large amounts of sheet flow or ice flows, or in the intertidal zone.* Incorporation of streambanks inside of culverts is typically recommended when feasible. However, their design and stability over time is both more involved and riskier in terms of correct estimations of flood flows and shear stresses. Streambanks should not be used if the rock size needed for streambank stability results in an overall crossing width of greater than 1.4 times the bankfull width as the risk of aggradation is much higher for the wider crossing if the streambanks fail. For permafrost and freeze-thaw, aufeis areas, the risk of exacerbation of these icing areas and potential risk and maintenance of the road should streambanks fail is significantly higher than other locations so they are not recommended to reduce risk. In the intertidal zones, these are transitional areas so the benefits of streambanks is less apparent for fish passage and the risk of sedimentation in some intertidal settings by lowering the velocities through the culvert with streambank evacuation can be high. Again, these are generalities to conservatively accommodate all situations in Alaska and there may be project locations where streambanks can be installed at lower risk than what is being accommodated here.

A6 - *Due to the higher energy environment of entrenched channels, the designer should err on the side of caution to ensure the stability of banks constructed inside culverts or use a bankfull width culvert.* Channels in entrenched environments should have streambanks designed with higher factor of safety concurrent with the associated risk of higher energy environments and error in correctly predicting the design flood events. For an entrenchment ratio less than 1.4, streambanks are not recommended inside the culvert. For entrenchment ratios between 1.4 and 2.2, a higher safety factor may be appropriate. Banks inside culverts are generally more stable for streams with entrenchment ratios greater than 2.2 as long as sufficient flood plain culverts are provided and/or the culvert is wide enough to keep the shear stresses on the banks inside the culvert low.

A7 - *In areas where permafrost is very close to the surface a hybrid of the stream simulation and hydraulic method may be considered to reduce the culvert embed and prevent thaw of the permafrost.* This guideline is based on discussions with Fairbanks ADOT&PF and ADFG in what is the current practice based on their experiments in applying the ADOT&PF/ADFG MOA and geomorphic culvert design in Arctic conditions.

A8 - *Substrate retention sills should be spaced so that the maximum drop between weirs is four inches (4"). Sills should not be used without substrate.* A 4" drop is maximum perch for juvenile salmon passage per historic discussions with ADFG so in case there is complete evacuation of sand from the culvert, fish passage is technically possible until the next flood event. USFWS experience is that sills can be 1) used in step-pool or cascade environments to help hold steps in place and 2) in sand bed systems to capture sand on the receding limb of flood events for a streambed. While USFS Guidance indicates that sills should be placed below the lower VAP line, we maintain that step-pool or cascade environments sills should be based on where the stability is needed and for a sand bedded channel, it will depend on the longitudinal surveys and minimizing headcut potential upstream. Refer to Chapter 5 of the USFS publication "Stream Simulation: An Ecological Approach to Providing Fish Passage for Aquatic Organisms at Road-Stream Crossings (2008)" for a thorough explanation of VAP lines.

A9 - *Culvert pipes and arches should be corrugated; smooth wall culverts should not be used.* This guideline is based on the need for culverts to have some frictional surface to assist in keep substrate within them as well as have some corrugations for small fish passage along the edges in cases where no streambanks are incorporated. Conversations with hydraulic engineers and fish passage professionals over the years indicate that smooth bore pipes readily evacuate sediment adversely compared to corrugated pipes. Modeling experiences by FWS, ADOT&PF and others also indicate that fish passable velocities are much harder to meet without some frictional corrugations, particularly at slopes greater than 1%.

A10 - *Synthetic Width Method*. The synthetic width method was developed by USFWS fish passage engineers William Rice and Heather Hanson as a design method for culvert sizing in extensive wetland environments with very low entrenchment. In many cases in these environments the bankfull width is very ill-defined, road fill height is to be minimized and velocity and substrate regime can be created to facilitate fish passage without the need to span the entire length of the wetland complex. USFWS notes this is still considered a work in progress. A description of the synthetic width method can be found under Special Conditions in the guidelines.

A11 - *Fish passage criteria for tidally-influenced culverts should be satisfied 90 percent of the time.* This is the same criteria in place in the Anchorage design standards for fish passage and is based on criteria reviewed from Puget Sound and compared to tidal movements in Upper Cook Inlet.

A12 - *Due to the limitations of hydrologic modeling accuracy and the limited data on fish swimming abilities, the hydraulic method should be avoided if possible*. Overall, there are very limited situations where the hydraulic method can meet the 1 ft/sec criteria for juvenile salmon and other weak swimming fish for high fish passage flow events. Hydrology estimates and fish swimming speeds provide the basis for the success of the hydraulic design method. Yet, there are significant errors associated both with the estimation of hydrology and fish swimming speeds. We do not believe a culvert can be designed with conservative assumptions that resolve the very large margins of error common for hydrologic predictions, especially when there is no gage data on which to base these predictions. Another problems with the Hydraulic Design method is that it is species dependent so not all fish or other aquatic organisms may be able to pass the culvert even if you are confident of your flow predictions and fish swimming abilities. The biggest concern with the Hydraulic Design method is it does not require maintenance of the geomorphic form of the channel. Mimicking the geomorphic form of the natural channel is the best way to maintain sediment transport in equilibrium because it helps to maintain the hydraulic geometry and thus the shear stresses experienced by the stream substrate at varying flow levels. Providing for sediment transport equilibrium is important both to the health of the ecosystem and the long term maintenance and viability of a culvert as a fish passage structure.

A13 - *Crossing structures should be designed to accommodate at least the 100-year flood flow.* Designing for Q100 is a choice we have made for projects funded by USFWS to maximize success over the long term considering the wide margin of error in hydrologic predictions. Although the 100 year flood flow only has a 1% probability of occurring in any given year, for any 50-year period, there is a 40% chance that the 100-year flood will occur and a 64% chance that the 50-year flood will occur. Given the rather high likelihood of exceeding the design flow during the culvert lifetime, the designer should carefully consider the consequences of potential failures during flood events. Ultimately, selection of the design flood is up to the road owner and project funders to determine their risk tolerance. The designer should also adhere to any applicable design standards that require higher flood flows than recommended in these guidelines.

APPENDIX E

Guidelines Summary and Comparison Table

Summary and Comparison of USFWS, USFS, and NOAA Culvert Design Guidance			
Guidance Topic	**USFWS - Geomorphic Analogy Method - 2019**	**USFS - Stream Simulation Method - 2008**	**NOAA - Streambed simulation design method (Northwest Region) 2011**
Culvert width	1.0-1.4 x bankfull width	Min 1.0 x bankfull width + 1.0xD100 banks, no max width.	Min 1.3 x bankfull width unless stream is fully entrenched (Rosgen A or B stream type)
Culvert conveyance - Design Flood	100-year flood	Design flood - per designer or agency	No guidance or criteria
HW/D ratio at design flood	0.8 or as needed to pass debris at 100 year flood	0.8 at design flood	Min 6 feet clearance between culvert bed and ceiling
Substrate stability (for crossings with upstream sediment supply)	50-year flood	Mimic stability of reference reach. (ie - D84 in culvert moves at same flow as D84 in reference reach). May increase particle sizes to a max of 25% larger than reference reach to account for flow constriction and increase bankfull channel width to 25% wider to reduce shear stresses in the culvert. If similar stability/mobility to upstream sediment supply is not possible, use a hybrid design method.	Must demonstrate ability to maintain substrate over life of culvert using stability analysis - reference Washington Dept. of Fish and Wildlife Fish Passage Culvert Design Criteria (WDFW), 2003
Substrate stability (for crossings without upstream sediment supply)	100-year flood	Stream simulation method does not apply.	Must demonstrate ability to maintain substrate over life of culvert using stability analysis - reference WDFW 2003
Bank stability (inside culverts)	100-year flood	Design flood	No guidance or criteria
Forcing features for low flow channel stability (Inside culverts)	100-year flood	Design flood	No guidance or criteria
Culvert Slope	Within 25% of reference reach	Within 25% of reference reach	Approximate average slope of adjacent stream or reference reach; max slope 6%
Low flow channel	Yes, mimic reference reach	Yes, mimic reference reach	Yes, mimic reference reach
Channel hydraulic geometry	Mimic reference reach geometry	Mimic reference reach geometry	Mimic velocities in reference reach, refers to hydraulic design method

Summary and Comparison of USFWS, USFS, and NOAA Culvert Design Guidance

Guidance Topic	USFWS - Geomorphic Analogy Method - 2019	USFS - Stream Simulation Method - 2008	NOAA - Streambed simulation design method (Northwest Region) 2011
Tidal Culvert	Passable 90% of the time	No guidance; mentioned as a special condition	Passage required for entire range of tidal fluctuation
Culvert Batteries (multiple culverts installed at the same elevation)	Do not use	No specific prohibition on culvert batteries. However, min bankfull width culvert is recommended.	No guidance or criteria
Flood plain culverts (culverts have flow only when water reaches the bankfull or floodplain elevation)	Recommended	Recommended	Connectivity of flood plain systems is recommended by increasing the width of primary culvert.
Embedment depth	Round - 40%; Arch & Box - 20%; or use a VAP analysis	VAP analysis to determine required embedment	30% min, 50% max, min 3'
Trash racks	Not recommended, bollards upstream are OK	Not recommended	Prohibited except if installed above bankfull elevation
Substrate retention sills	Only for >6% slope or sand bed streams, 4" max drop between sills, height limited to 50% of	Only for >6% slope, should not project above the lower VAP line.	No guidance or criteria
Smooth wall metal pipes	Do not use	Not recommended	No guidance or criteria
Check of culvert velocity versus fish swimming ability	Not required	Not required	Not required
Max culvert length	No guidance	No guidance	150 feet
Fish resting zones	Streambed roughness creates fish resting zones	Key features to mimic reference reach create fish resting zones	Larger materials provides fish resting areas
Hydraulic Design Method	Not recommended	Not recommended	Allowed for streams with less than 1% slope
Revegetation	Bioengineering and revegetation with native riparian species recommended	Bioengineering and revegetation with native riparian species recommended	Re-vegetation with native riparian species recommended. No dicussion of bioengineering techniques.