FISH PASSAGE
DESIGN GUIDELINES

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

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 longer span structures that do not impact the floodplain. 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. 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 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. Please submit comments or questions to heather_hanson@fws.gov or william_rice@fws.gov.

Hydrologic Functioning

- All stream crossing structures 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 the United States Forest Service stream simulation approach with the modifications outlined in this document (USFS, 2008). An example design procedure for stable, alluvial channels is also attached as Appendix A. The stream simulation approach is recommended for stable channels, Rosgen type A, B, C or E channels (Rosgen, 1996). Bridges should be used for type D channels if the flow is actively moving between braids. For crossings of relic channels, sloughs, or wetland complexes, design modifications are described below under "Special Conditions."
- 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 should be designed, constructed, and maintained so as to provide for *hydrologic*

functioning of the water body they are crossing, including connectivity of wetlands and riparian areas adjacent to stream channels, 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 hydrologic functioning. (See figure 1). 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. (See Appendix C for information on the importance of the riparian area for stream health).

- Crossing structures should be designed to accommodate at least the *100-year flood flow*.
- The width of the primary crossing structure should not be less than 1.0 times the bankfull width of the channel.
- 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.

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*. 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.
- *Culvert slope* should be within 25% of the natural stream 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 .75% and the maximum design slope would be 1.25%.
- Culverts should have a minimum diameter of five feet (5'). 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 small streams 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. 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. Streambanks are not recommended for areas with permafrost or severe freeze-thaw issues, in wetland complexes, for areas with large amounts of sheet flow or ice flows, or in the intertidal zone. For type A or B 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.
- Round culvert pipes should have a *minimum invert burial depth* of forty percent (40%) of the culvert diameter into the substrate and arch culvert pipes (i.e., "squash" pipes), should have a minimum invert burial depth of twenty percent (20%) of the culvert's rise into the substrate, <u>unless</u> vertical adjustment potential (VAP) analysis shows less fill is acceptable. 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.
- 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.
- 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. The Fuller-Thompson equation should be used to ensure a minimum void content (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 arch pipes). Substrate retention sills should be spaced so that the maximum drop between weirs is four inches (4”). Sills should not be used without substrate.
- Culvert pipes and arches should be corrugated; smooth wall culverts should not be used.
- Beaver barriers, trash racks or debris interceptors should not be used because of the potential to block adult salmon without robust and regular maintenance.

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 *Stream Simulation Design*. Data gathered should include at a minimum: channel width at bankfull, bankfull cross-sectional area, gradient, substrate grain size key pieces, stream type, bankfull average depth, flood prone width, stream order, and watershed area. 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.

Special Conditions:
- In low (less than 0.5%) to zero sloped 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 (defined below) to develop a culvert size.
- Relic channel or slough: (*Synthetic Width Method*) 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 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, crossing of wetlands are best avoided. 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 *Stream Simulation Design* 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. If possible, the designed crossing should have a slope of 1% or less to maximize success in these environments and minimize beaver issues.
  2. For both Method A and Method B, flood plain culverts should be provided as conditions permit to allow for wetland continuity across the flood plain area and to minimize flow constriction at flood levels. Flood plain culverts should be placed in the flood plain 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.
- Tidally influenced culverts:
  1. Fish passage criteria for tidally-influenced culverts should be satisfied 90 percent of the time. 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.

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. 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 flood plain. (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.*

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).

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.

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: 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 flood plain at an elevation two times (2X) the maximum bankfull depth (Rosgen, 1996).

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.

Hydrologic Functioning: A crossing is considered to be hydrologically functioning for fish passage if it allows for hydraulic conveyance, debris conveyance and fish passage in the channel and flood plain 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 aggradation or degradation will result.

Low Flow Channel: A low flow channel is intended to provide fish passage at minimum flows. The low flow channel should mimic the reference reach where possible. 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. 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. See the definition for Stream Simulation Design for further reference reach selection recommendations.

Retention Sills: Metal or wood plates welded 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 should not protrude into the flow.

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 from head of reference reach riffle at the top of the reach to head of riffle at the bottom of the reach assuming the reach slope is consistent.

Stream Simulation Design: Stream simulation means that the crossing is designed using reference data from a representative section (reference reach) of the specific water body being crossed. Stream simulation 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. Stream simulation 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. 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.

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. 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 coincided with the geomorphic bankfull indicators such as in a relic channel or slough or no defining bankfull features exist (See *bankfull* definition).

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

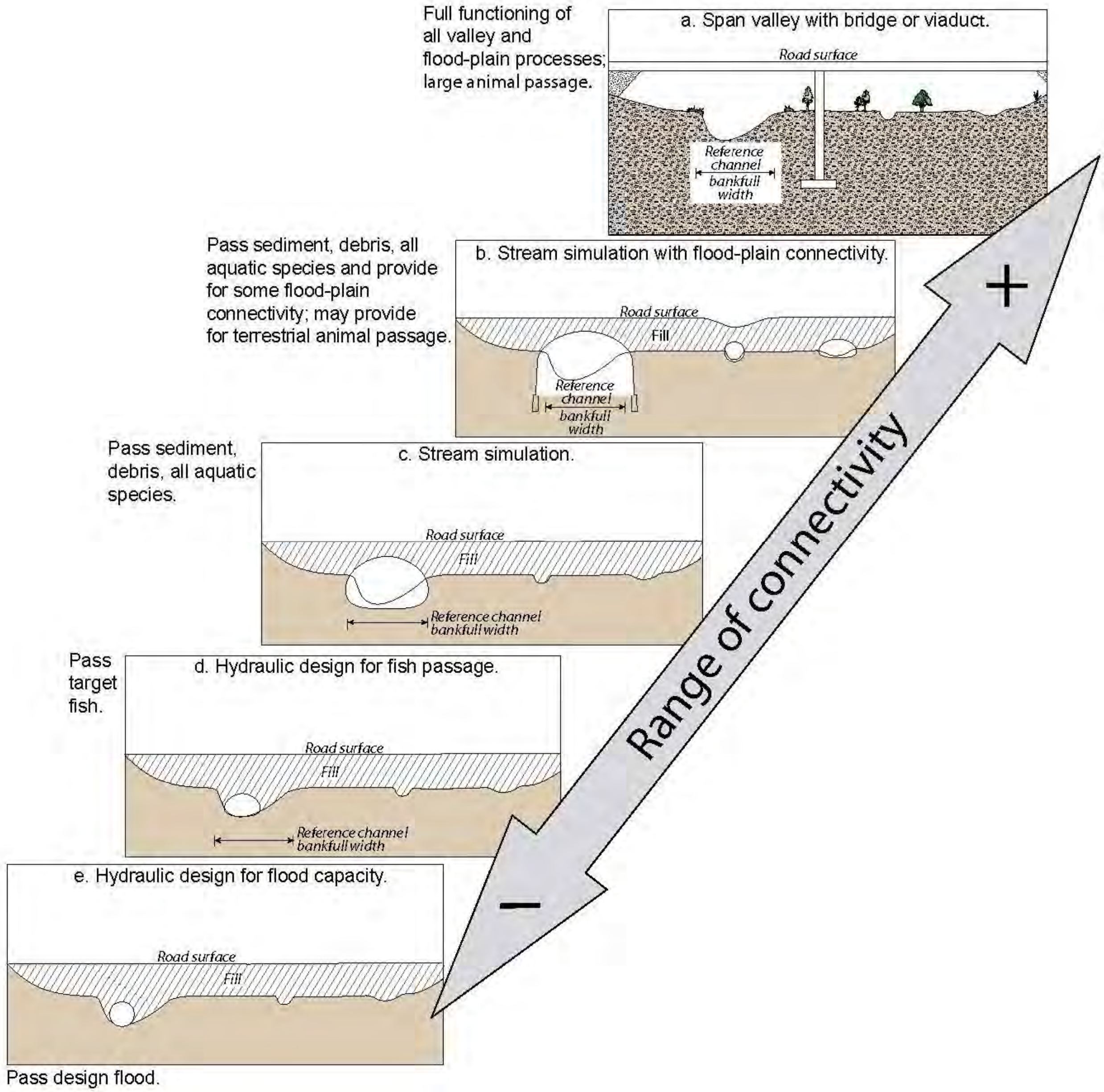


Figure 2: Bankfull width, OHWM and a low flow channel on an E3b stream type

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

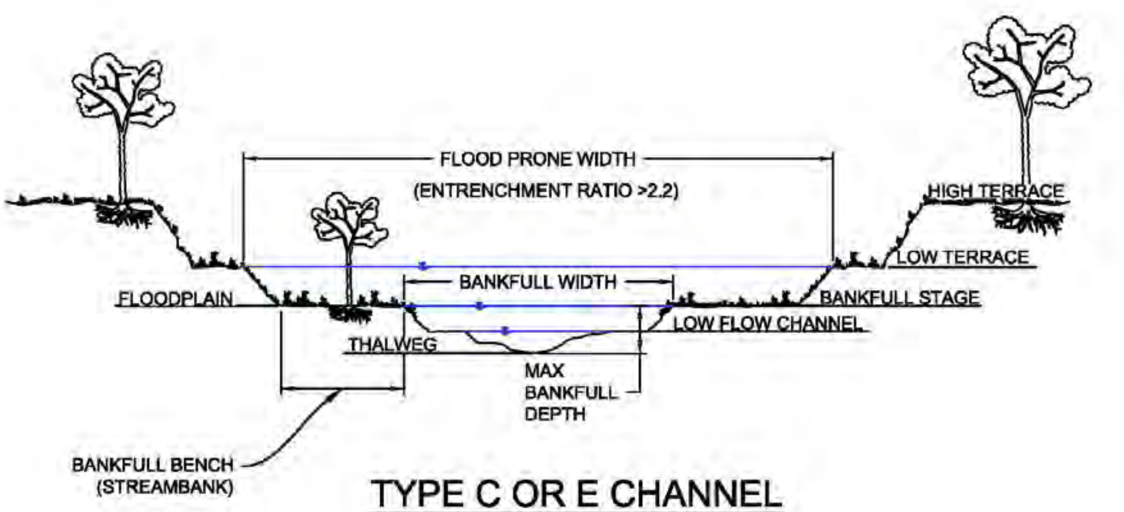


Figure 4. Typical channel features for an entrenched channel (Rosgen, 1996).

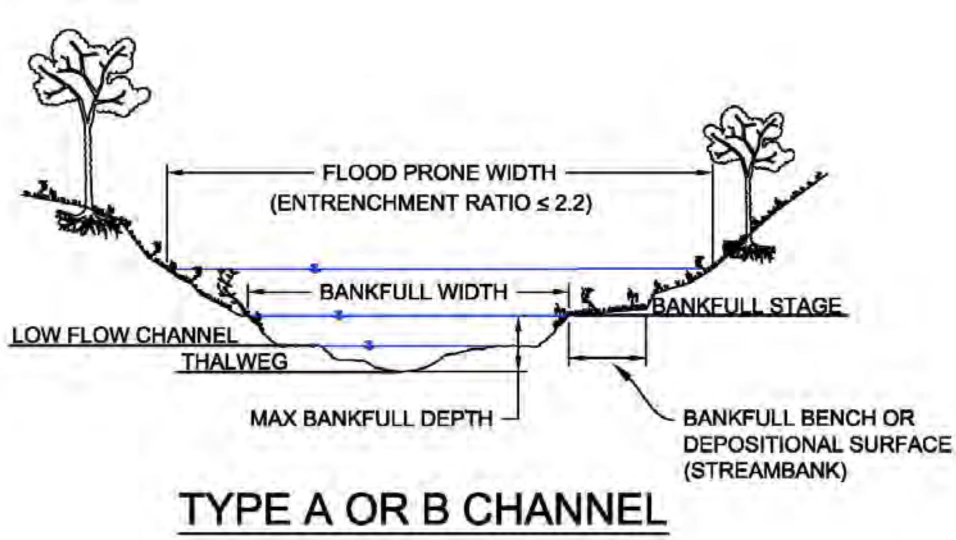
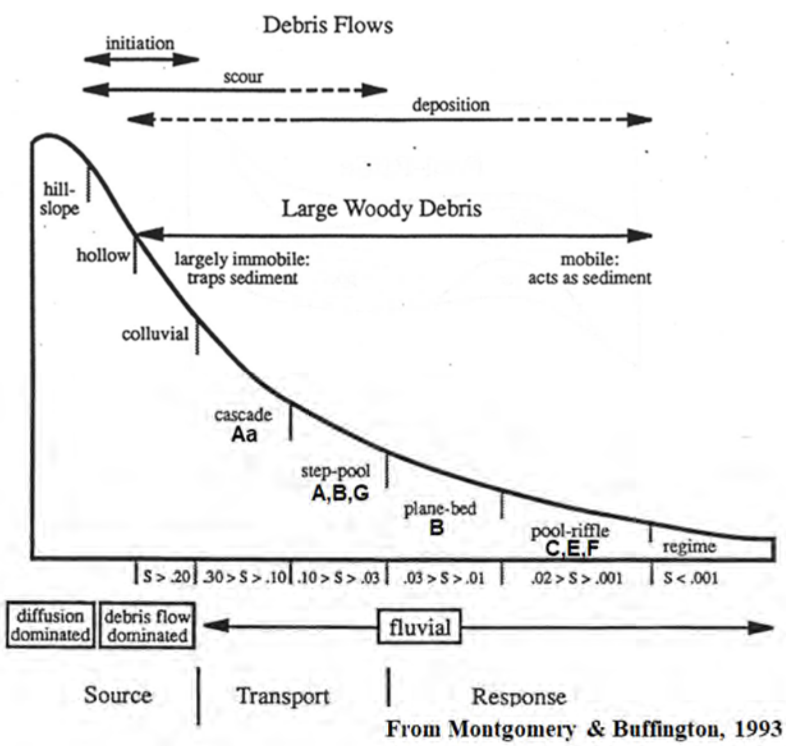


Figure 5. Geomorphic processes and stream types relative to channel slope (Montgomery and Buffington, 1993).



APPENDIX A

EXAMPLE DESIGN PROCEDURE FOR FISH PASSAGE CULVERTS

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 but it is not intended to preclude other design approaches. 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. 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.
4. Perform pebble count at the reference reach and upload survey data and pebble count data to Rivermorph, CAD, or excel spreadsheet. 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 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 Rivermorph or CAD 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 in Rivermorph, CAD or Excel. 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 in Rivermorph or by hand – "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 in Rivermorph or using a simple cross section program (WinXS Pro is free online) based on reference cross section, bankfull slope, and Manning's or other open channel equations. 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 Culvert Master 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 and high fish flows 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 flood plain 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. Culvert should either be bankfull width or if streambanks are necessary or desired a minimum bankfull width + 4xD100. Designer should assume D100 and check it in next step (iterate as needed). Banks are desirable for fish Passage and small mammals if feasible. We typically don't recommend a culvert wider than 1.4x Wbkf for culverts less than 12 feet or 1.2xWbkf for culverts greater than 12 feet or aggradation may result. 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.
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 2xD100 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 2xD100 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.
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). Flood plain 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).
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 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

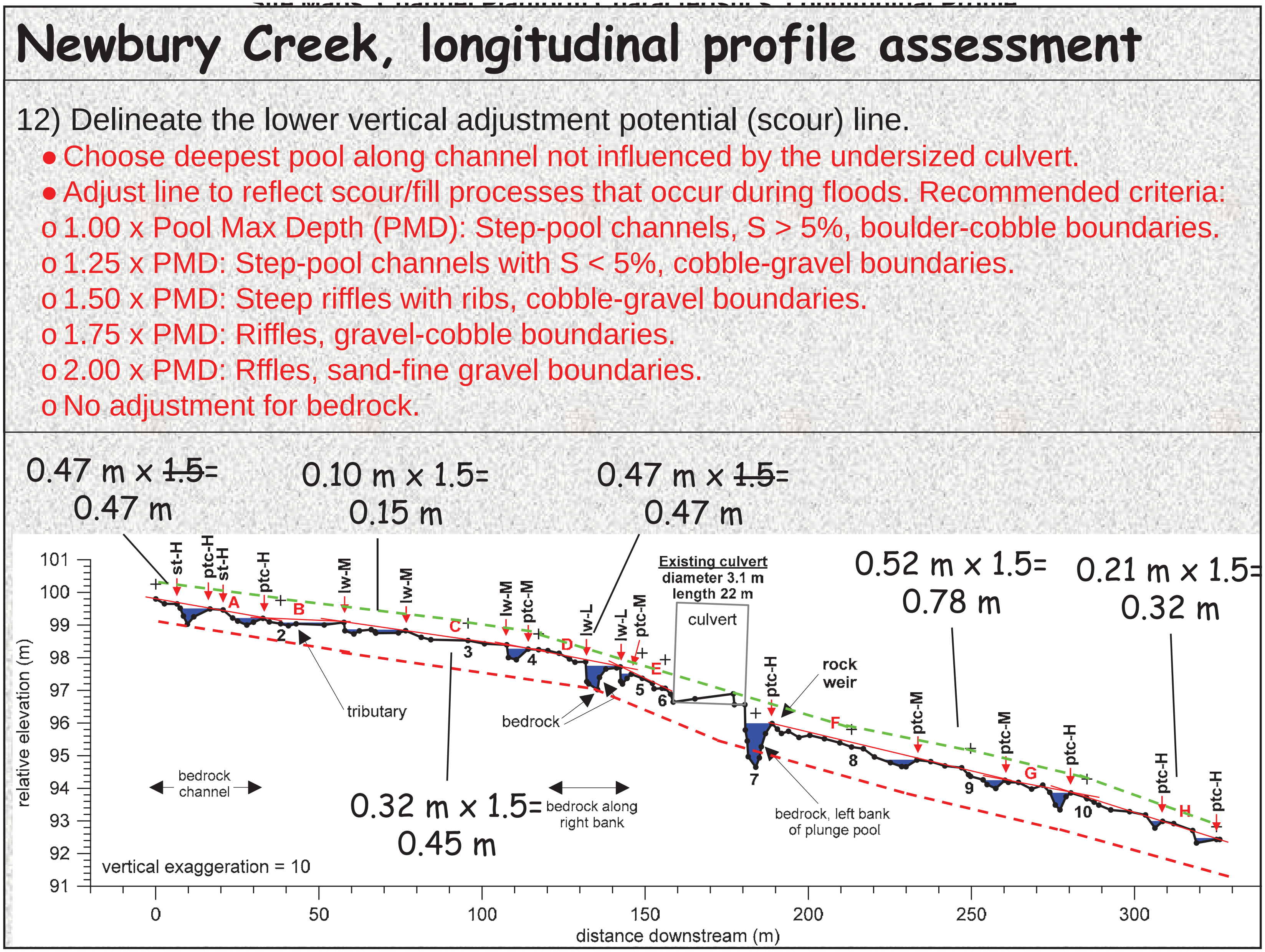


FIGURE 2: STREAM CLASSIFICATION WORKSHEET

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	

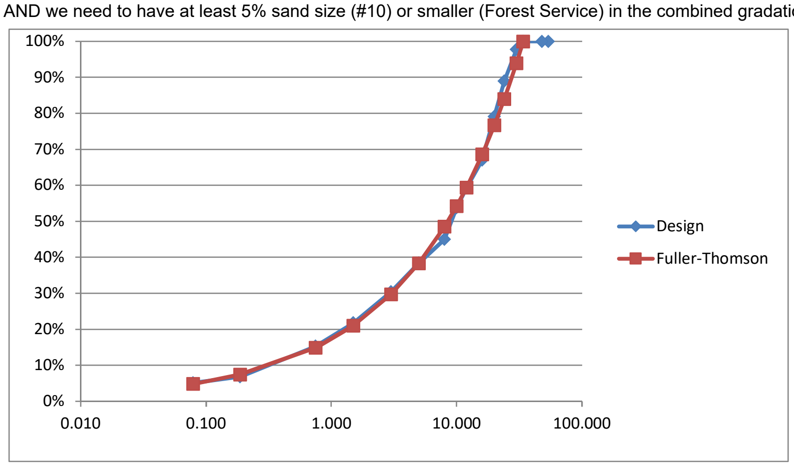
Using D50 size, used FHWA circular for Rip Rap design to spec out D100, D85 and D15.
D100 = 2.0D50

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

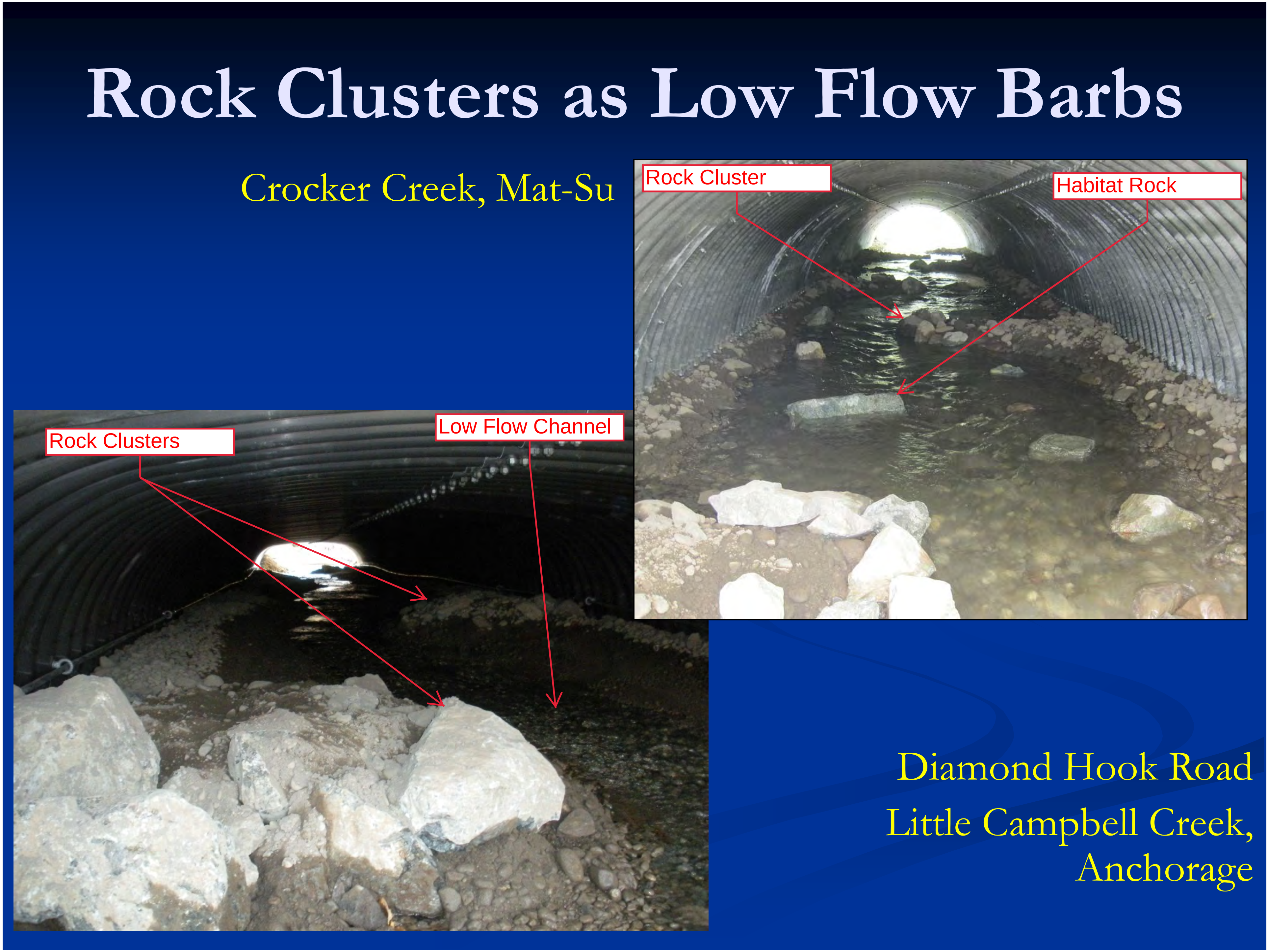


FIGURE 6: ROCK CLUSTER SPACING GUIDANCE

Rock Clusters

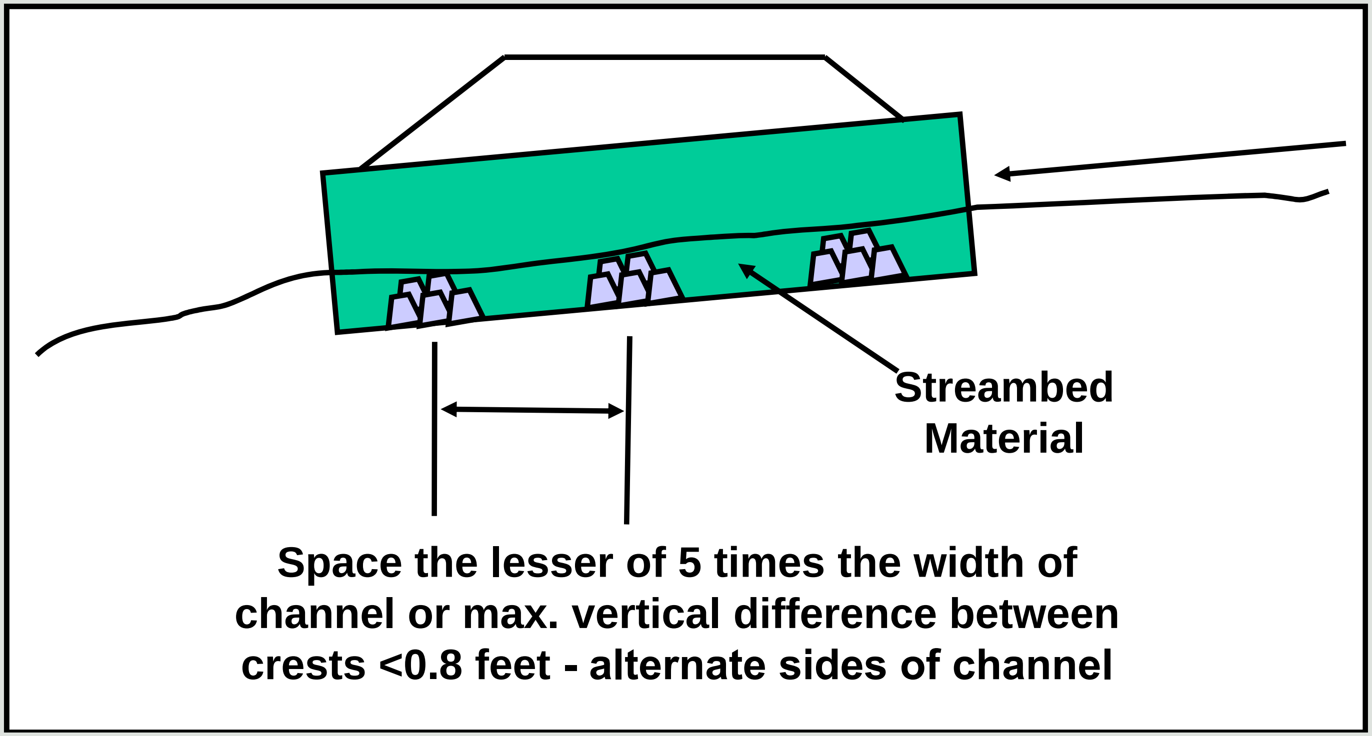


FIGURE 7: ROCK CLUSTER EXAMPLE - BANKFULL WIDTH CULVERT

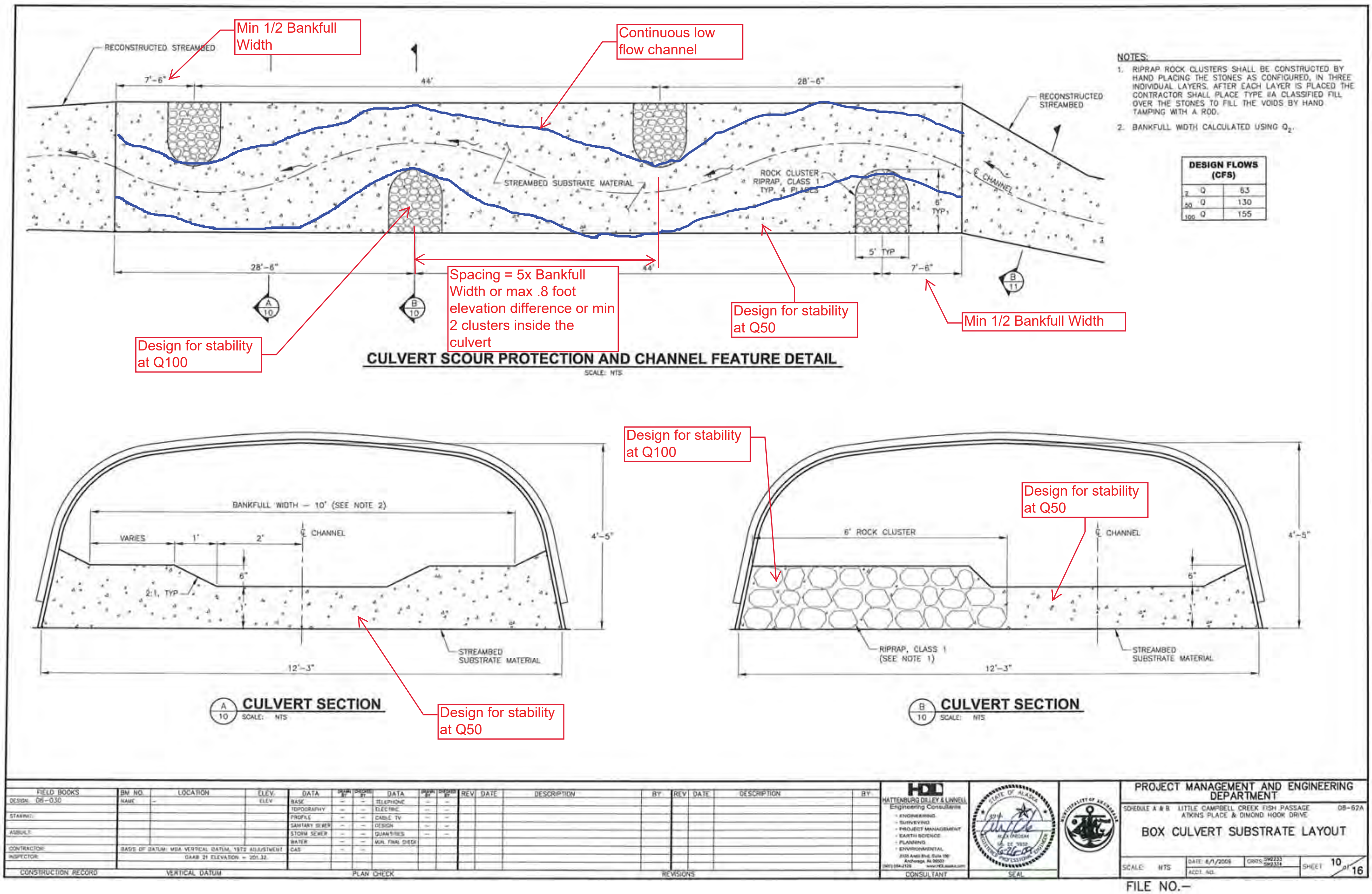


FIGURE 8: FLOODPLAIN CULVERTS

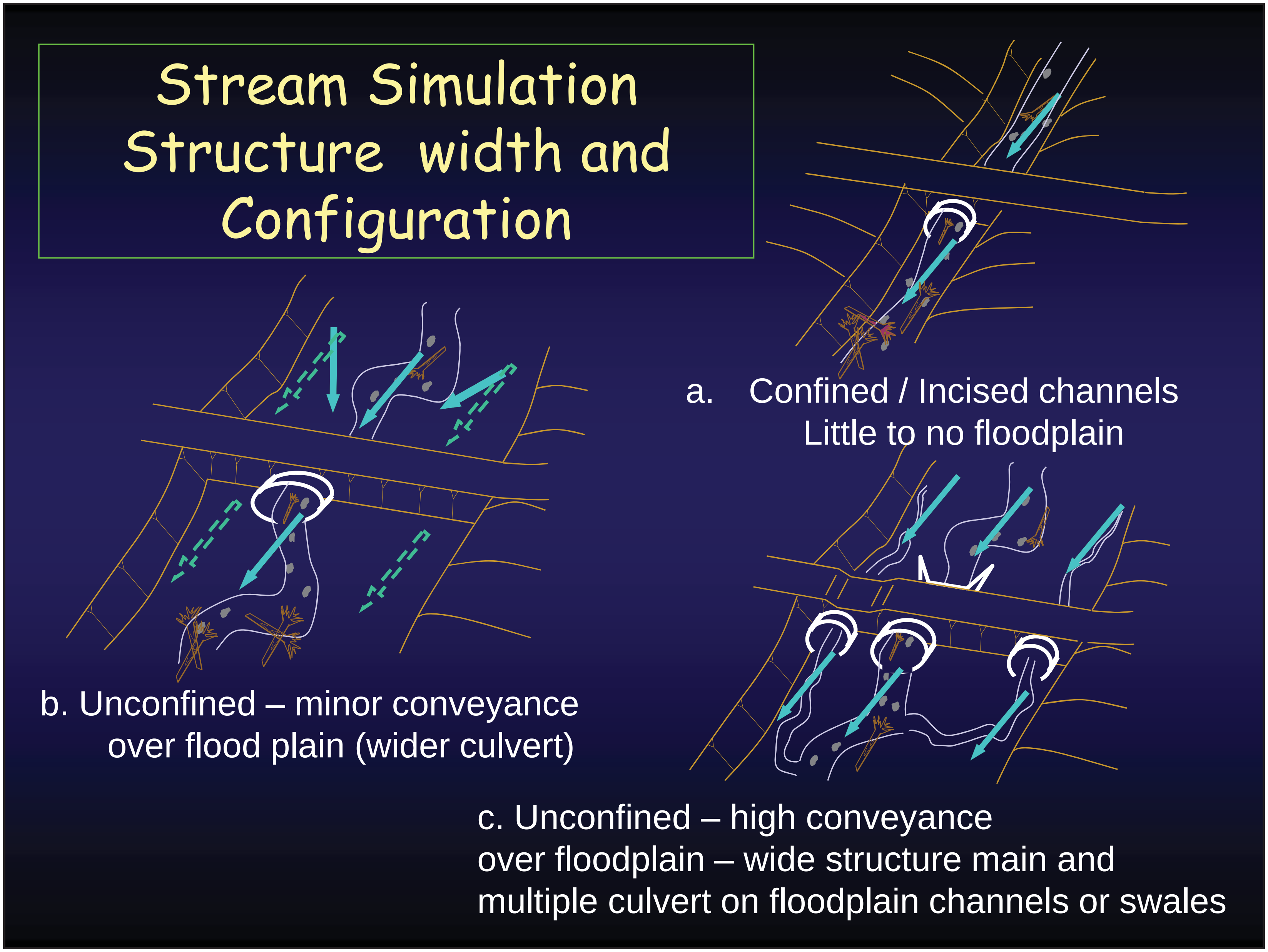


FIGURE 9: FLOODPLAIN CULVERT GUIDANCE

Unconfined channel - Requirements

- Hydraulic analysis to determine floodplain conveyance (high or low) Use common sense depending on site conditions and risk as to the level of analysis required
- Check mobility / stability against the reference reach main channel only!
- Add floodplain culverts in streams with high floodplain conveyance or with defined channels on floodplains (Rule of thumb is: when entrenchment ratio is 2 or greater be concerned with floodplain conveyance confirm with hydraulic model)
- Add road dips and armor embankment
- If channel is backwatered during high water, HW/D clearance may be an issue

!!!!GO TO THE SITE DURING FLOODING TO SEE CONVEYANCE ON THE FLOODPLAIN!!!!!

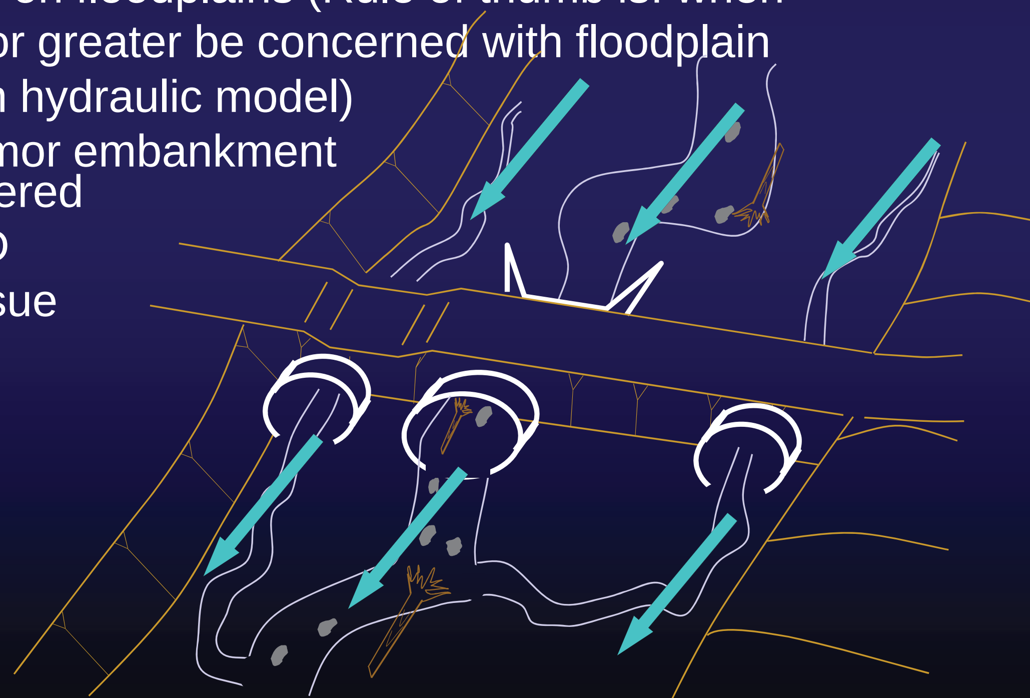


FIGURE 10: ROSGEN STREAM TYPES

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

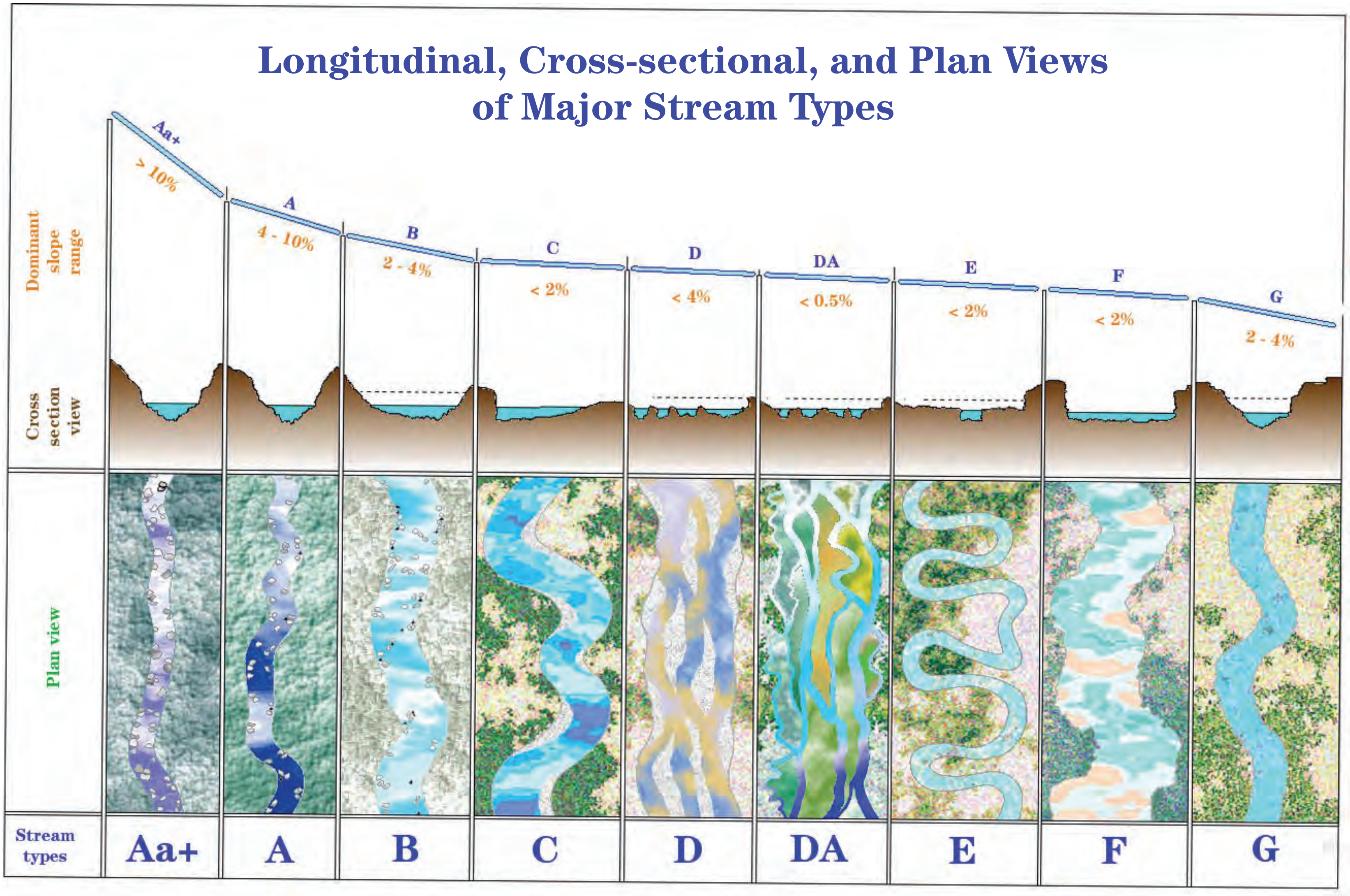
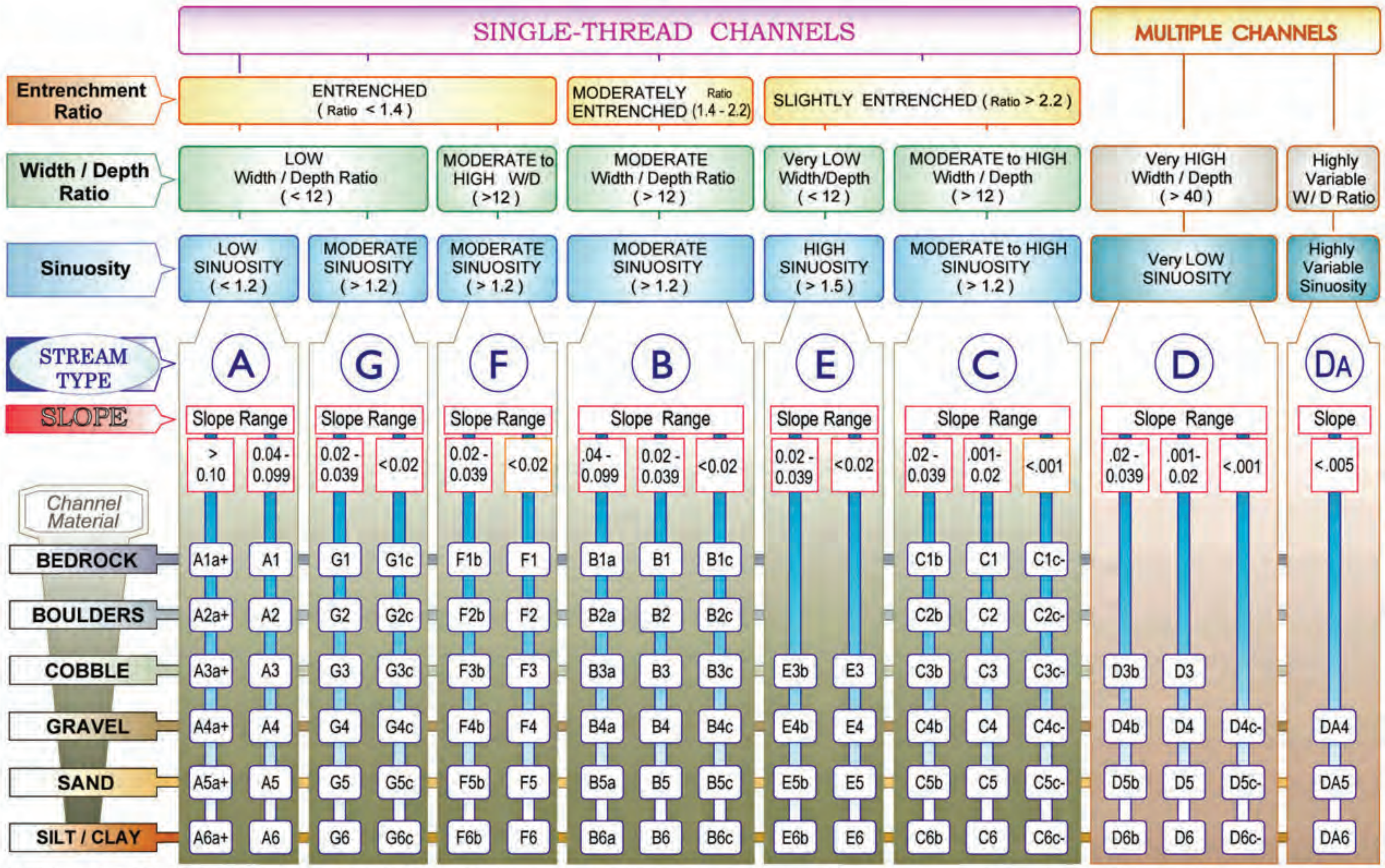


FIGURE 11: ROSGEN CLASSIFICATION KEY

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 / end	ft / ft	Max riffle depth	start / end	ft / ft	Bank height ratio (LBH/max riffle depth)	start / 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

Riparian Connectivity and Stream Health

APPENDIX C

U.S. Fish & Wildlife Service

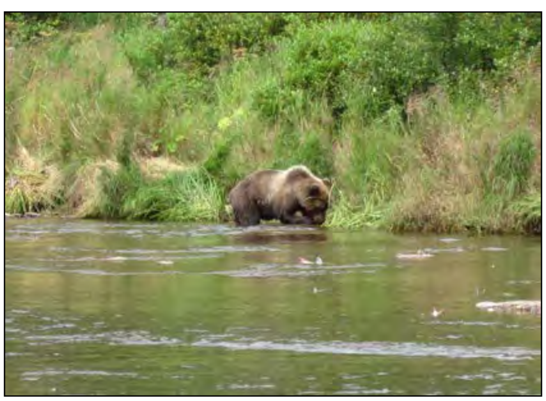
RIPARIAN CONNECTIVITY AND STREAM HEALTH

It is the USFWS mission to work with others to conserve, protect and enhance fish, wildlife, and plants and their habitats for the continuing benefit of the American people. The Service strives to maintain riparian connectivity and the Service's Conservation Planning Assistance (CPA) Branch works with project sponsors to identify project alternatives that avoid and minimize impacts to aquatic and riparian habitats.

Fish Creek's healthy riparian habitat supports five species of Pacific salmon as well as other anadromous and resident species. Photo: USFWS

Beyond Fish Passage: A healthy and productive stream provides a variety of habitats for fish and other aquatic life, as well as riparian habitat and movement corridors for terrestrial wildlife. The connectivity of habitats within a watershed sustains fish and wildlife populations.

Moose cow and calf using riparian corridor. Photo: USFWS



Brown bear using riparian corridor, Southwest Alaska Photo: USFWS

The four types of stream connectivity:

Longitudinal Connectivity is the linear connectivity between the upstream and downstream sections of a river. Structures within the floodplain or that cross the stream (e.g., roads) can interrupt longitudinal connectivity.

Vertical Connectivity consists of the interaction between surface and groundwater and includes flow through the hyporheic zone (mixing zone between surface and groundwater) and up- and down-welling through the stream bed.

Lateral Connectivity refers to the connectivity of the stream with its floodplain. Floodplain width may be narrow at a stream's headwaters and wider in downstream reaches due to more active channel meanders and larger floods. Channel incision due to channel straightening or increased discharge disconnects the channel from its floodplain, resulting in increased flood damage and the loss of floodplain habitats.

Temporal Connectivity refers to the physical, chemical, and biological interactions over time, during multi-year, annual and seasonal timeframes. Alterations to a stream's flow can isolate portions of the channel or associated habitats (e.g., side channels, oxbows), severing temporal connectivity.

Stream-floodplain-riparian corridor Donlin Creek area. Photo: USFWS

Riparian Connectivity, the key to stream health: Aquatic and riparian habitats are established and maintained by riparian and floodplain processes such as the transport of sediment and bed material, the conveyance of debris and flood flows, and the assimilation of nutrient inputs from the watershed. Nutrient inputs include marine derived nutrients from anadromous fish such as salmon, eulachon and some lamprey species. Full functioning of these riparian and floodplain processes requires connectivity from a stream's headwaters to its mouth.

Fluvial debris and sediment transport, McNeil River State Game Refuge. Photo: ADFG

Bridge and Culvert Designs: Stream crossing design criteria should focus on protecting stream health by maintaining riparian and floodplain processes. The USFWS supports use of design criteria for stream crossings that maintain normative physical processes within the stream-floodplain-riparian corridor by: **1)** promoting natural sediment transport patterns, **2)** providing unaltered fluvial debris movement, and **3)** maintaining or restoring functional continuity and connectivity of the stream-floodplain-riparian corridor.

Spawning sockeye pair, (Onchorynchus nerka) Southwest Alaska Photo:USFWS

Avoidance and Minimization: All crossings should consist of a bridge or culvert that spans the floodplain, provides for long-term dynamic channel stability, retains existing spawning habitats, maintains food (benthic invertebrate) production, and minimizes risk of failure. All crossing designs should be based on site-specific information such as: estimates of peak discharge, flow velocities and patterns; channel stability; sediment and bed load transport; flooding regime (50-year to 100-year flood frequency and magnitude); cross-section profiles of channel morphology and water surface elevations.

Avoiding a fragmented landscape: Riparian connectivity should be considered when planning or evaluating projects that could affect a stream's channel, floodplain, or riparian corridor. Land use activities that don't maintain riparian connectivity have the potential to fragment and alter habitats beyond their capacity to function ecologically.

Pacific lamprey (Lampetra tridentata), Rainbow Lake, Mat-Su Borough. Photo: EPA

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