Bridge Design for Fish Passage and Habitat Protection

Habitat Engineering Technical Assistance
Washington Dept. of Fish and Wildlife

Guiding principles of bridge design

We understand that bridges are a unique engineering and emvironmental challenge that goes far beyond the difficulties presented by most transportation projects. Thus, we recognize the need to make decisions at an early point in the process, before the scope of the project is developed.

A holistic approach will be key to integrating all issues in a successful project. Those issues include, but are not limited to, those related to shorelines, land use, environment, safety, and flooding.

WAC 220-110-070 states that “In fish bearing waters, bridges are preferred as water crossing structures by the department in order to ensure free and unimpeded fish passage for adult and juvenile fishes and preserve spawning and rearing habitat.” These benefits can only be realized if the bridge is properly designed and constructed. This guidance is intended to assist the designer in constructing bridges that prevent impacts to fish and wildlife habitat and mitigate for unavoidable ones.

Properly designed bridges provide these benefits to the productive capacity of the stream. Values and functions to be preserved in the design and construction process are:

1. Preserve or restore natural stream processes
2. Prevent bed scour and coarsening of the substrate
3. Prevent backwater during storm events that leads to the deposition of sediment and increased lateral movement.
4. Allow the free movement of debris which reduces maintenance and distributes wood throughout the river.
5. Reduce the risk from catastrophic flood (bridge failure affects habitat both when it occurs and in the various construction activities that lead up to its replacement)
6. Allow channel migration and profile evolution, reducing maintenance, increasing lifespan and leading to more complex and productive habitat.
7. Provide for the down-valley flow water across the flood plain, reducing flood height, providing flood refugia, and increasing side channel development and other riparian functions.

As explained in ~~Design of Road Crossings for Fish Passage[1]~~ elsewhere in this guideline, culverts can provide a very high level of stream connectivity, similar to that provided by a bridge in the applicable size range. But when the design process leads away from a culvert as a viable crossing structure, a bridge should be considered. This is particularly the case where; the bankfull width is greater than 15 feet, the structure clear span exceeds 20 feet, or when the movement of debris is ~~large and~~ frequent (debris is woody material transported by the channel and, in this case, in high enough volume that a culvert is unable to accommodate it). The 20 foot span threshold provides a clear line between bridge and culvert, requiring the designer to bear the burden of proof that the chosen alternative maintains ~~normal~~ stream processes, protects habitat and provides fish passage when they design~~s~~ a culvert beyond this recommended range. Road geometry may also influence the decision to use a culvert for safety or traffic flow reasons. This threshold is similar to Federal and State guidelines distinguishing bridge from culvert.

While general considerations regarding the use of bridges at crossings are discussed in this guideline, their structural design is not addressed. An experienced bridge design engineer is required for such an undertaking.

For the purpose of this guideline, a bridge is any crossing that has separate structural elements for the span, its abutments and foundation. Unencumbered by the dimensional limitations of culverts, a bridge can be large enough that the structure does not significantly affect the flood hydraulic profile or specific stream processes. Piers and abutments can be supported on piles or deeply buried spread footings so that there is very little risk of failure. In some agencies, 3-sided and other bottomless structures may be treated as bridges, but for this document, they are culverts.

Like culverts, however, bridge designs must also comply with regulations; in this case, regulations addressing water crossings and the creation of new channels (WAC 220-110-070 and 220-110-080). The initial stages of bridge design must begin with considerations for habitat impact. Properly designed bridges can have many benefits in terms of habitat preservation and restoration; however, mitigation measures may still be necessary to compensate for impacts from construction, bank armoring or other habitat losses caused by the presence of the bridge.

The channel created or restored near and beneath the bridge must have a gradient, width, floodplain and general configuration similar to the existing natural channel upstream or downstream of the crossing. Where possible, habitat components normally present in these channels should also be included.

For replacement bridges, the existing approach fill, piers, abutments and foundations have not become a part of the stream; they are part of the original bridge structure. If these components can be shown to affect the productive capacity of fish and shellfish habitat, they ~~must~~ should be removed with the old bridge, or modified to mitigate their effects. This does not apply to fills that provide local access to adjacent properties when there is no alternative, or abutments that are built into existing levees.

Geomorphic setting

Bridge design for fish passage and habitat protection ~~must~~should be based on prevailing reach conditions. Every major new or replacement bridge should be preceded by a reach analysis to understand the stream context and to design better bridges. The general approach to reach analysis is described in WDFW's Integrated Streambank Protection Guidelines[2] and Stream Habitat Restoration Guidelines[3], although there are areas of interest specific to bridge design that will be covered here.

The Aquatic Habitat Guidelines guiding principles for project planning and implementation suggests that a holistic approach is preferred and that compensatory mitigation ~~must~~should offset immediate and future impacts. Reach analysis is the only way to integrate all the processes and impacts of a proposed bridge.

Reach analysis is an evolving field. WDFW is open to different approaches providing they provide insight into the impacts of the proposed project on fish passage and habitat. It can be approached from a variety of angles depending on the type of project and the expertise of the analysis team.

The concept of reach analysis is scalable to the size and complexity of the project and can be phased to match the applicant's project development process. This means that a private forest landowner completely spanning a small entrenched stream may choose to use professional expertise and limited survey information to describe the geomorphic setting and habitat impacts of their proposed bridge. On the other hand, a major ~~WSDOT~~ crossing of large lowland river will require a sophisticated reach analysis, although this may be phased to match to their scoping and design process. Levels of reach analysis are discussed below.

It is not our intent to make reach analysis a costly add-on to an already expensive ~~design and construction~~ project. We need to know the impacts of the project to the productive capacity of the stream. But it is also benefits the bridge owner by leading to a design that works with the dynamic nature of the stream to minimize maintenance and extend the life of the structure. We all benefit when we avoid, for instance, significant upstream bank erosion that may cost many hundreds of thousands of dollars to repair (often repeatedly), threaten stream-side infrastructure, and significantly impact fish life.

The table below shows the recommended level of analysis for bridge design based on readily measured attributes.

Level	Analysis recommended	Width of channel	Entrenchment ratio	Stream type	Bridge performance	Meander migration rate
1	Limited assessment	<15	<3	Transport	Excellent	Low
2	Qualitative assessment	<15	<3	Transport	Good	Low
3	Reach assessment	>15	>3	Response	Fair	Medium
4	Reach analysis	>50	>5	Response	Poor	High
5	Corridor analysis	>100	>10	Response	Failure	High

The attributes are the width of channel, which is the width of the bankfull channel; entrenchment ratio is defined below, as the ratio of the flood prone width and the bankfull channel; stream type is the Montgomery-Buffington[4] channel type where *transport* is the morphologically resilient supply limited reaches and *response* is the transport limited reaches where channels adjust frequently to changes in sediment supply; bridge performance[BB1] describes the history of the bridge and and its effect on the channel (scour, adjacent bank erosion, frequency of maintenance, failure of the bridge structure, etc.); and meander migration rate, describing the rate of lateral or translational channel migration.

The simplest case for the use of this table is where all the attributes indicate the same level of assessment. For instance, a small, entrenched, non-meandering channel in a transport reach where the bridge has had no scour problems and no significant affect on the channel, one would conclude that only a simple site assessment is required. More difficult to interpret are the cases where the attributes a mixed. A full reach analysis is probably necessary for a large, unentrenched meandering stream even though it has had an excellent repair history.

The level of assessment is described below.

1. **Limited assessment** is the lowest level and would be used where the bridge performance has been excellent and all parties involved agree that the replacement of the bridge with a similar structure would not adversely impact the stream.
2. A **qualitative assessment** relies on the technical expertise of the design team but considers the bridge in a reach context. Projects area low risk and easily understood. All the reach characteristics listed below are considered, but typical measurements limited to those done with a tape and clinometer. A limited hydraulic report may be required.
3. **Reach assessment** requires limited survey work to do rudimentary analysis. Cross sections are surveyed and aerial photograph analysis performed. A hydraulic report is required.
4. **Reach analysis** uses a variety of resources to answer difficult and important questions about channel behavior and predicts complex outcomes. A full site survey, longitudinal profile, and enough cross sections to characterize the channel are necessary. A full hydraulic report and one dimensional modeling is typical
5. **Corridore analysis** is a full blown river analysis with numerical modeling and a sophisticated geomorphological study.

The important reach characteristics to be examined for bridge design are:

- ~~Meander~~ Channel migration; ~~and reach-scale~~ lateral, translational and vertical movement
- Known sediment supply and transport
- Poterntial debris loading
- ~~Stream-wise~~Longitudinal profile, with particular attention to slope, discontinuities, regrade potential, possible nick points
- Average bankfull width
- Flood prone width

- Flood plain utilization, particularly the down-valley movement of water over the flood plain
- Sufficient survey information to conduct hydraulic analysis, when necessary

These characteristics are examined to the extent required by the level of assessment and briefly described below.

Initially, the bridge reach should extend 20 channel widths upstream to 20 channel widths downstream. In the case of a 15 foot channel the reach would be 600 ft long. The reach for a 200 ft river would be 1.5 miles. It is not suggested here that this entire length be examined with equal intensity. The area within a few channel widths should be carefully surveyed and examined for the design and hydraulic analysis. A thalweg profile should extend sufficiently far to establish slope, channel continuity, and determine the effects of regrade. Meander migration, and the associated lateral movement at the bridge site, can only be examined by looking at the entire reach, usually by examining a historical sequence of aerial photographs. Shortening the reach to less than 40 channel widths should only be done when it is clear that the major stream processes are exclusively confined to a lesser length. Longer lengths may also be required to answer important questions for large and dynamic rivers.

Knowledge of sediment supply and transport is important for bridge design. A channel in equilibrium is one which the majority of the sediment supplied to the reach is transported through; it is neither aggrading or degrading. Small vertical changes in bed elevation are common and expected, say in the range of 1 or 2 feet, depending on channel size, and are not necessarily signs of disequalibrium. True disequilibrium, on the other hand, is a chronic condition where channel elevation changes many feet and requires special consideration. Disequilibrium is a transitional state that may take decades to resolve and it is difficult to determine the final elevation of the channel, or its lateral location, without careful analysis. Usually, techniques to control the elevation of a channel will fail under disequilibrium conditions.

Often, when a replacement bridge is designed, it replaces an undersized bridge or culvert. The upstream channel is likely to have aggraded and will scour down to an equilibrium slope. This temporary disequilibrium may be difficult to predict and may result in a complex response. This is discussed briefly below and covered more completely in Design of Road Culverts for Fish Passage **Chapter 7 – Channel Profile**.

Disturbance, such as debris flows, fires, and atypical flash floods, have a powerful effect on channel morphology and evolution. Disturbance of this sort is not usually captured by Log-Pearson annual peak flood analysis. Designing to a 100 year flood does not ensure all stream functions are accounted for. One cannot assume that woody debris, sediments and all fish at all life stages will pass unencumbered with a design that only evaluates a 100 year flow. It is, none the less, a standard and supported by the watercrossings WAC. By using the **Bridge Span** recommendations outlined below the design is informed by channel geometry that has been determined by long term trends in the watershed where the bridge is located. This adds a margin of safety for both the structure and habitat in the immediate vicinity of the bridge.

Crossings that are subject to ~~repeated and frequent~~ debris flows need special consideration. Some regions are well known as landslide-prone and this knowledge simplifies the selection of an alternative. Alternatives in such a situations include properly designed fords, temporary bridges, bridges with high clearance and moving the road to where its crossing is less problematic (out of the expected path or away from the response reach), among other alternatives. Bridge clearance is covered below. Other areas that have not been analyzed for mass wasting hazard, or have been stable for the period of record, create some uncertainty in design. Debris flows, when they occur, are completely unexpected. We can only design with caution in such cases, recognizing the location of the crossing in the valley profile, the landscape slope, road density, and soils. ~~Alternatives in such a situation include properly designed fords, temporary bridges, bridges with high clearance and moving the road to where its crossing is less problematic. Other alternatives will be considered as well.~~

Channel confinement is particularly important for the design of bridges, as discussed in the next section. Confinement is often quantified by the entrenchment ratio, which is the flood-prone width divided by the bankfull width (bankfull width is determined using the method described in Appendix ##). It expresses the relationship between the channel and the extent of overbank flow. Flood-prone width has been defined as the distance between points on the bank at the elevation of twice the maximum bankfull depth[5]. (Maximum bankfull depth is the difference in elevation between the lowest point in the channel cross section and the bankfull water surface.) The discharge which corresponds to the stage at twice the bankfull depth is roughly between a 50 and 100 year recurrence interval flood stage. The benefit of using flood prone width is that it is determined by actual channel measurement rather than referring to regional regressions or hydraulic modeling, both of which have significant error. Flood prone describes the area that is active during significant flood events, those events that determine channel morphology are most affected by bridge geometry. Flood prone width is shown in **Figure 1** below for two different entrenchment ratios.

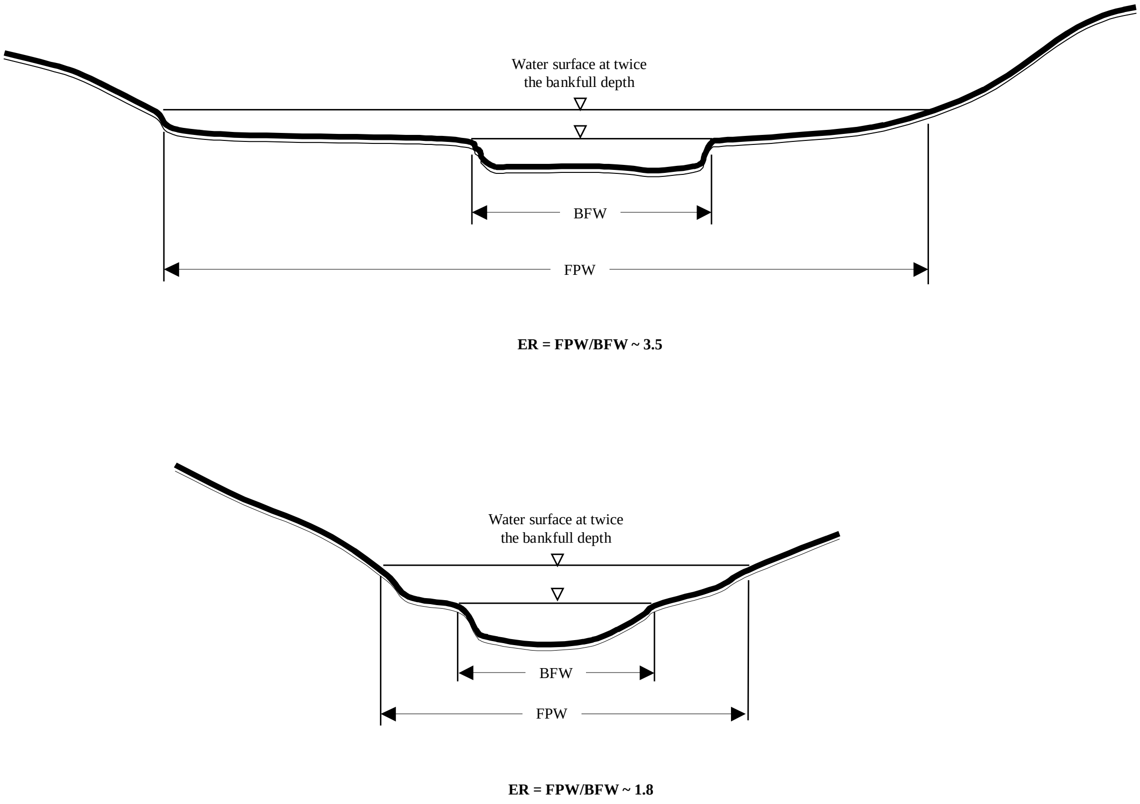


Figure 1 Flood prone width for a slightly entrenched and a moderately entrenched channel.

A more comprehensive and accurate method to determine the flood prone width would be to map the floodplain in the reach, defined in part by the cross sectional geometry as shown here, but also by sedimentation, breaks in grade, and vegetation. Once would also consider periods of incision or aggradation and their long term effects on the channel and its flood plain. .

~~Most of the year, bridges are passive structures that simply span a river channel only partially occupied by flow. During the few percent of the time, when the river is in flood, the channel and flood plain are deep in swiftly moving water. Depending on how the bridge is designed, the bridge becomes more or less interactive with floodwaters; either constricting the flow, causing backwater and channel wide scour, or not constricting the channel, and having little effect on natural processes. In order to minimize the effect of bridges on fish and wildlife habitat, the latter situation is preferred and is the basis of the sizing methods described in the next sections.~~

Bridge span

In order to fit in with natural stream processes (flooding, transport of debris and sediment, fish passage, riparian health), bridges should be designed using channel properties. The reach analysis described above supplies the data and analysis required to design the bridge with varying levels of risk and complexity. ~~Constricted channels shorten bridge life, require more maintenance, interfere with the transport of materials and have many unintended effects on the channel and adjacent properties.~~ Bridge span is determined in process that evaluates the bridge in its context, which varies from a rural, natural valley, to highly developed, urban settings. The steps in this process are listed here and discussed in detail in the following paragraphs.

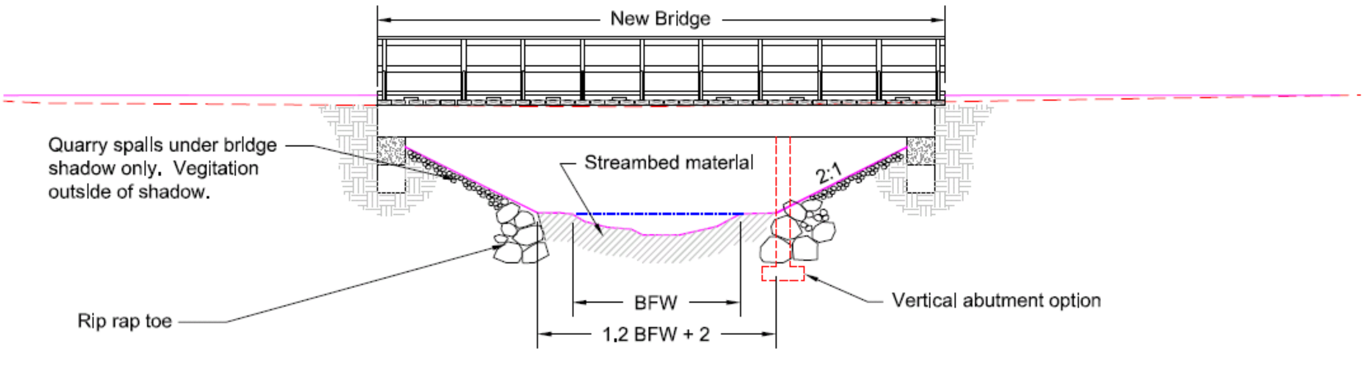
1. Brige condition and history
2. Channel size
3. Flood prone width
4. Channel migration
5. Flood plain utilization
6. Flood plain management
7. Infrastructure
8. Approach road elevation
9. Bridges in tidally influenced areas

Brige condition and history

Bridges replaced because the structure has deteriorated, but have an excellent performance rating, may require little change in design to protect natural processes and can, therefore, exit this process here. On the other hand, bridges replaced because they failed from scour or flanking, require frequent maintenance, or have significant environmental impacts should proceed with this design process.

Channel size

Bridges over moderately entrenched channels less than 15 ft in width ~~In the case of smaller,~~ that are ~~moderately entrenched streams,~~ ~~(generally, bankfull width <15 ft and entrenchment ratio <3)~~ should use the bankfull channel ~~should be~~ as the design parameter. The stream-simulation width criteria [BB2](see Design of Road Culverts for Fish Passage **Chapter ~~6~~## - Stream-Simulation Design Option**) may be used to determine channel width under the bridge. The performance of stream simulation culverts has been excellent and it is a widely accepted design method. This sizing method may



ROAD PROFILE

lead to bridge that provide a wider water surface width at elevated flows than a similarly designed culvert, but the consistency in design approach and variety of structure types (for instance, vertical abutments) covered by the method makes the use of one criteria preferable. Piers, vertical abutments, flow-through abutment slopes, and all bank protection materials should be placed outside this width, as shown on **Figure 2**.

Figure 2: An example of a bridge on a small stream.

The use of rock slope protection in the bridge shadow, shown in **Figure 2,** could be larger than quarry spalls if the slope or hydraulic conditions warrant it or they are necessary for slope stability.

Flood prone width

For larger streams, where floodplain provides significant flow relief and habitat, flood-prone width should be the initial design parameter. Ideally, the entire flood-prone width would be spanned by a single span bridge, ~~or in carefully controlled circumstances,~~ but multiple spans are acceptable to decrease structure depth and to create a more economical design. Practically, some encroachment may be acceptable and can have minimal effect on habitat~~,~~ continuity or morphology.

~~The allowable encroachment is quantified and codified in WAC 220-110-070(h), as discussed in the next section. From an ideal, geomorphic point of view, the portion of the flood prone width that must be spanned to limit undesirable channel effects depends, in part, on site specific conditions.~~

- ~~Big rivers with significant flood plain flow with net down-valley movement, and valley wide channel migration, should be spanned to their full flood prone width.~~
- ~~Rivers with restricted channel migration and well-established side channels may be spanned with one main bridge and ancillary bridges at the side channels. In large flood plains, extreme floods commonly flow across the approach roadway. This should be considered a part of the bridge design, significantly reducing the required span. The net effect of these structures on the backwater rise should be less than 0.2 ft.~~
- ~~Rivers with limited access to their flood plain and little net down-valley flow should span 1.3 to 2 times the bankfull width. Flood plain flow during the 100 year flood event must be less than 10% of total flow to qualify for this approach.~~
- ~~In the case of fully entrenched channels, where the 100 year flood stays within the banks, the bridge may simply span from top-of-bank to top-of-bank.~~

~~The general case for larger rivers is shown in **Figure 3.**~~

Channel migration

Next in the in bridge design sequence is the need to accommodate channel migration. The width required for these processes is not necessarily contained within the flood prone width and the structure must in some cases be wider than flood prone. The channel migration zone would be determined in the higher levels of reach analysis and is described in Dept. of Ecology's A Framework for Delineating Channel Migration Zones[6]

Flood plain utilization

Some flood plains are not active in the net down valley movement of water, debris and sediment. Flood plains in this case act more like storage areas. Encroachment into areas like this does not have a significant effect on the hydraulics and morphology of the river. Encroachment may impact riparian wetlands or change the inundation frequency, affecting some habitats. These secondary effects should be considered when proposing a bridge where the fill intrude into flooded areas. Bridges that will encroach into the flood prone width should demonstrate that stream processes and fish habitat will not be impacted. Considering the permanent nature of such impacts, mitigation should not be considered an alternative and avoidance the recommended option.

Flood plain management

The bridge must fit in with the current and expected flood plain management regulations in the county where it is located and the flood control infrastructure protecting development in the flood pain. The regulations include the Shoreline Management Act and the Shoreline Master Programs which permit modification and use provisions intended to protect ecological functions and processes while allowing development; Growth Management Act and the Critical Areas Ordinances. Levees often determine the 100 year floodplain and the laws that govern them. Bridges need to only span these levees, unless there is reason to believe that changes in local flood plain planning would set back the levees.

Flood plain development can have a strong influence on bridge design. This includes flood control levees, stream parallel roads that contain flood flow, and adjacent structures. These artificial constraints force the river into an unnatural morphology and it is often not possible to use a sizing criteria designed to allow natural process to take place, and which are based on expected channel geometry. This is probably the most common difficulty in developed areas. A few scenarios are discussed here, although others may occur and must be evaluated using the principles developed in this document.

a. Levees occur on both sides of the stream protect a completely developed flood plain. Houses and businesses are dependent on the levees for flood protection and there is no reasonable expectation that they will ever be moved or eliminated. In this case the bridge need only span from levee top to levee top. On-site mitigation opportunities in this scenario are limited, although this should not preclude mitigation where impacts are unavoidable.
b. If the levees unnecessarily constrain the stream creating chronic scour requiring repeated bank protection measures, and an overall decrease in habitat quality, levee setback should be considered by the owners and local government, and the bridge designed to span the expected increased width. The bridge owner is not required to do anything to the adjacent property, only not to preclude levee setback.
c. If only one side of the stream has a levee with infrastructure dependant on it, but the other side has a bench within the flood prone area, then the bridge should span the main channel and the bench.
d. If a comprehensive flood management plan identifies a leveed area as a flood hazard or an avulsion hazard and such a plan recommends the

removal or setback of the levees, the bridge should be designed to span to those setbacks.

e. If a restoration plan recommends the removal or setback of levees, the bridge design should not prevent those actions.

Infrastructure

Infrastructure considerations include road intersections, houses, and businesses which should be moved or modified in order to properly design the bridge, yet are not owned or controlled by the bridge owner. Early in the design process, projects that could impact adjacent property owners should meet with regulatory agencies and neighbors to discuss design alternatives. Stakeholders can then choose an alternative that minimize impacts to both habitat and the public. In the end, if adjacent neighbors are not cooperative, compromises must be made.

Occationally there are undersized road or railroad crossings that are near the bridge site. Theoretically, the new crossing should be designed as if these undersized structures were not there at all, but significant expansion or contraction of flood flows could endanger the adjacent structure, among other possible scenarios. If the current undersized bridge creates a flow “shadow” or otherwise supports the neighboring bridge, the design of the new structure should consider the increased risk it causes.

Approach road elevation

In broad flood plains, the approach road is often at flood plain elevation, forcing the bridge structure either down into the channel or high above on large approach fills that occupy the flood plain. This is particularly a problem for long bridges with a deep section. Raising the bridge to move it higher in the stream cross section requires increased approach fill (increased costs) and potential impacts to riparian, wetland and other sensitive habitats (requiring other permits and causing other impacts), or fill placed off right of way (out of jurisdiction). The choice between forcing a deep bridge section into the banfull channel or raising the whole structure above the channel on approach fills can be expanded to include other alternatives such as, multiple spans with piers landward of OHW to decrease cost and section depth (preferred), or multiple spans with piers within OHW (not preferred, but may be acceptable). These ancillary issues make the design of each bridge a negotiated settlement between the various parties involved (WDFW, DOT, Counties, adjacent landowners, Federal regulatory agencies, etc.) to optimize benefits and costs on all levels. This process would begin by listing the costs, functions and values associated with the various design alternatives and then determining the one which preserves the greatest functions and values for the lowest cost.

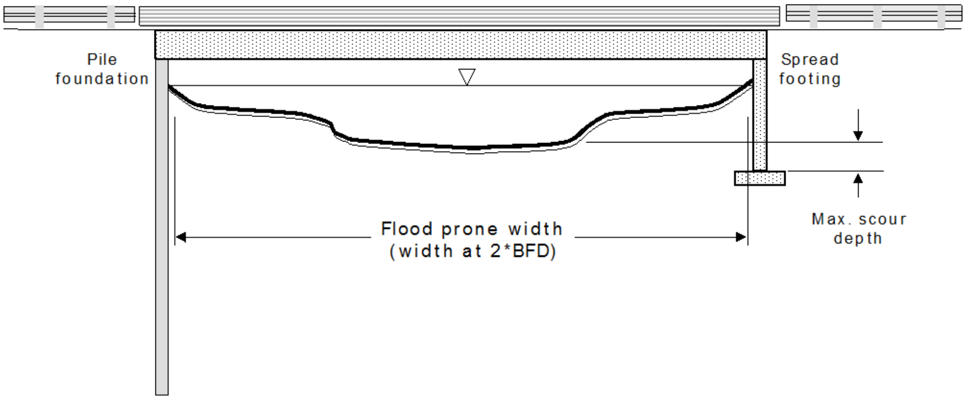


Figure 3: An example of a bridge that spans the flood prone width on a larger river.

Many of the situations described above may force the designer to size a bridge that deleteriously affect stream processes and impact habitat. The bridge designer should minimize these impacts in cooperation with regulatory agencies and adjacent property owners.

Bridge-span calculations should begin with the required width and proceed to embankment slope and abutment allowances to arrive at the correct clear span dimension. The side slopes up to the abutments should be placed at an angle that leads to natural stability. Large riprap retaining walls that encroach on the channel should be avoided.

Hydraulic Requirements of WAC 220-110-070(h)

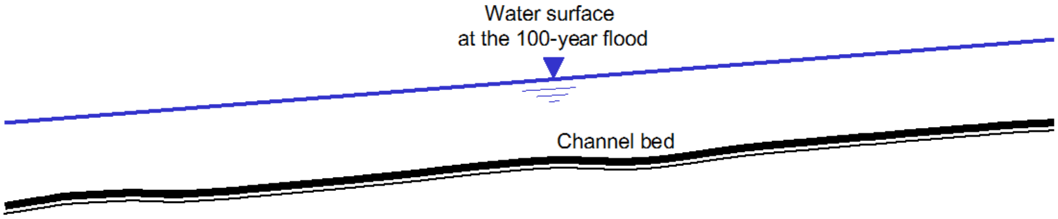
WAC 220-110-070(h) states that

> "abutments, piers, piling, sills, approach fills, etc., shall not constrict the flow so as to cause any appreciable increase (not to exceed 0.2 feet) in backwater elevation (calculated at the 100- year flood) or channel wide scour and shall be aligned to cause the least effect on the hydraulics of the water course."

The purpose of these criteria is to limit the effect of the bridge on the channel, especially in channels with a high entrenchment ratio or significant gravel bedload. The sizing criteria suggested in the **Bridge Span** section above seeks to address these effects in a more direct way that does not require modeling and is more likely to "achieve no-net-loss of productive capacity of fish and shellfish habitat." If the designer decides not to follow the recommendations in the **Bridge Span** section and seeks only to satisfy WAC 220-

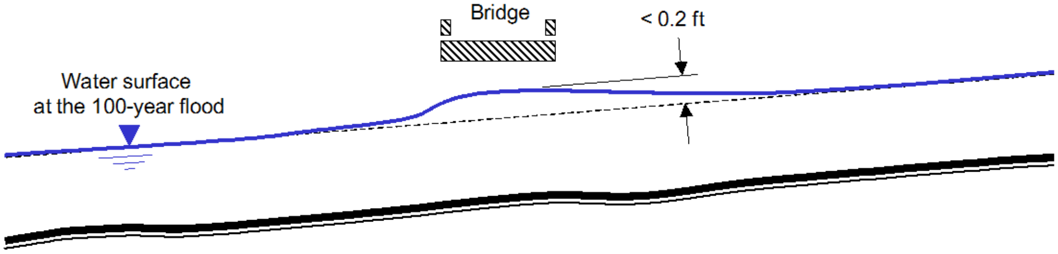
110-070(h), a backwater analysis ~~must~~should be performed. Hydraulic modeling has been performed on a number of generalized cases and results indicate that the 0.2 foot backwater rise criteria can only be met with bridge spans similar to the recommendations above.

The implication of WAC 220-110-070(h) is that the items stated, “abutments, piers, piling, sills, approach fills, etc.,” are those parts of the bridge that modify the prevailing channel conditions so as to cause a backwater or channel-wide scour. The 0.2 ft backwater rise uses as a baseline the normal flow in the natural stream reach. (Existing streamside ~~dike~~levees that are employed solely to channel high flows through the old bridge should be considered an integral part of the existing bridge structure and the baseline hydraulic model should not include them.) The bridge and its supporting structure are then added to the model and the change in water surface elevation as a result of this addition is measured. The backwater analysis is **not** performed with the existing bridge cross section in place and then measured against the proposed bridge. This is shown in the **Figure 4** below.



Longitudinal profile without existing bridge structure

Without existing “abutments, piers, piling, sills, approach fills, etc.”



Longitudinal profile with proposed bridge structure

With proposed “abutments, piers, piling, sills, approach fills, etc.”

Figure 4: Illustration of the 0.2 backwater rise criteria.

The length of reach required to perform this analysis is dependant on site conditions and ~~must be determined by a qualified modeler~~the requirements and assumptions of the model. The location of surveyed cross sections at the bridge is prescribed by the model.

At least 2 cross sections up and downstream of the bridge are also required to establish normal flow. The scale of the spacing should be based upon the spacing of channel units for the channel type. For instance, a large pool-riffle stream has channel units spaced roughly 5-7 channel width apart. Smaller, steeper channels will have channel units spaced more closely, on the order of 1-4 channel widths. As a general guide, the cross section should be located 2-7 channel widths from the bridge. The locations of cross sections are shown in **Figure 5** below.

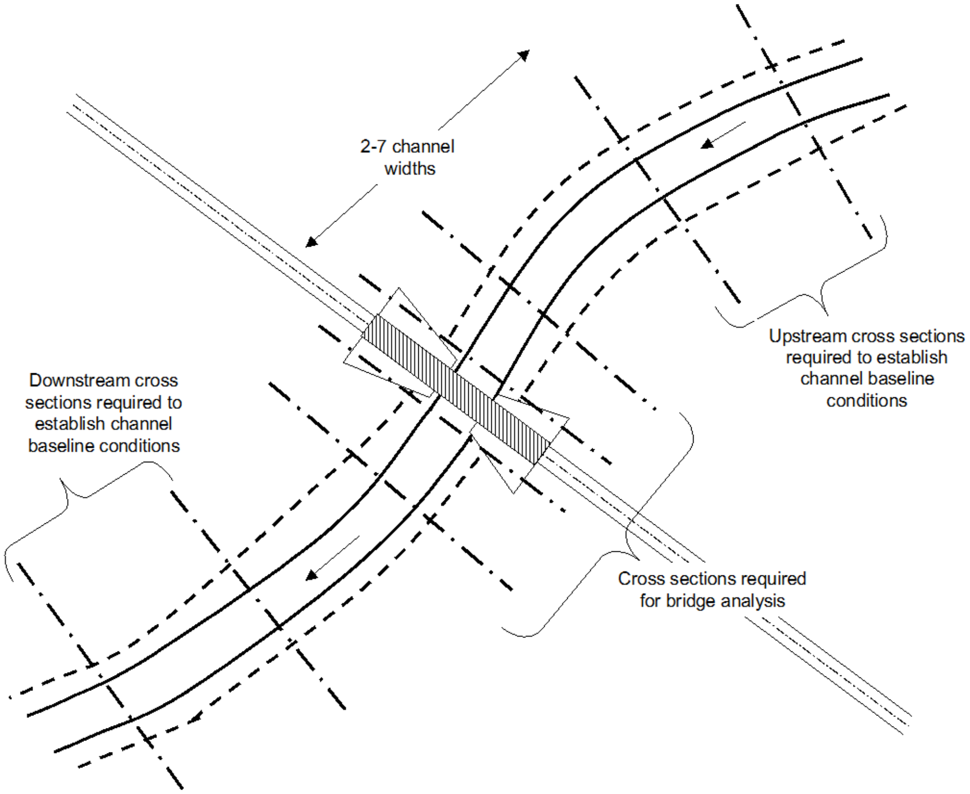


Figure 5: A suggested arrangement of channel cross sections to determine bridge backwater effects.

Various models are available to do backwater analysis. The most common one-dimensional model is HEC RAS, created by US Army Corps of Engineers in Vicksburg. This model is commonly used to model bridge scour and general river analysis. Other generally accepted one-dimensional models may be used. Two-dimensional models are becoming more and more common and would provide a much greater degree of accuracy, provided they are properly designed and calibrated. On the other end of the sophistication scale is hand calculation of backwater using an energy equation for normal flow with kinetic energy correction factors and an appropriately chosen coefficient of discharge. All of these methods are acceptable, providing the assumptions of the model are well understood and followed, and the calculations performed~~ carefully by a qualified modeler~~.

~~Treatment of complex sites~~

~~Many factors are at play in the final selection of a bridge span. We have discussed the preferred approach with the greatest likelihood of protecting and enhancing fish habitat. We have also discussed the maximum encroachment allowed by WAC. Yet there are still a whole host of factors that complicate the design process at the site specific level. Below are a number of example situations and recommended approaches to bridge design.~~

~~Existing dikes and stream-parallel adjacent roads and railroads.~~ ~~These artificial constraints force the river into an unnatural morphology and it is often not possible to use a sizing criteria designed to allow natural process to take place, and which are based on expected channel geometry. This is probably the most common difficulty in developed areas. Scenarios:~~

~~a. Dikes occur on both sides of the stream protect a completely developed flood plain. Houses and businesses are dependent on the dikes for flood protection and there is no reasonable expectation that they will ever be moved or eliminated. In this case the bridge need only span from dike top to dike top. On-site mitigation opportunities in this scenario are limited, although this should not preclude mitigation where impacts are unavoidable.~~

~~b. If the dikes unnecessarily constrain the stream creating chronic scour requiring repeated bank protection measures, and an overall decrease in habitat quality, dike setback should be considered and the bridge designed to span that increased width. The bridge owner is not required to do anything to the adjacent property, only not to preclude dike setback.~~

~~c. If only one side of the stream is diked with infrastructure dependant on it, but the other side has a bench within the flood prone area, then the bridge should span the main channel and the bench.~~

~~d. If a comprehensive flood management plan identifies a diked area as a flood hazard or an avulsion hazard and such a plan recommends the removal or setback of the dikes, the bridge should be designed to span to those setbacks.~~

~~e.~~f. ~~If a restoration plan recommends the removal or setback of dikes, the bridge design should not prevent those actions.~~

~~Nearby road or railroad crossings that are undersized.~~ ~~Theoretically, the new crossing should be designed as if these undersized structures were not there at all, but significant expansion or contraction of flood flows could endanger the adjacent structure, among other possible scenarios. If the current undersized bridge creates flow "shadow" or otherwise supports the neighboring bridge, the design of the new structure must consider the increased risk it causes.~~

~~Road at flood plain elevation forcing the bridge structure either down into the channel or high above on large approach fills that occupy the flood plain.~~ ~~This is~~

~~particularly a problem for long bridges with a deep section. Alternatives include, multiple spans with piers landward of OHW to decrease cost and section depth (preferred), or multiple spans with piers within OHW (not preferred). Raising the bridge to move it higher in the stream cross section requires increased approach fill (increased costs) and potential impacts to riparian, wetland and other sensitive habitats (requiring other permits and causing other impacts), or fill placed off right of way (out of jurisdiction). These ancillary issues make the design of each bridge a negotiated settlement between the various parties involved (WDFW, DOT, Counties, adjacent landowners, Federal regulatory agencies, etc.) to optimize benefits and costs on all levels. This process would begin by listing the costs, functions and values associated with the various design alternatives and then determining the one which preserves the greatest functions and values for the lowest cost.~~

~~**Infrastructure close to the crossing site**, such as intersections, houses, businesses, and the like, which must be moved or modified in order to properly design the bridge, yet are not owned or controlled by the bridge owner. Early in the design process, projects that may place a burden on adjacent property owners should meet with regulatory agencies and neighbors to discuss design alternatives. Stakeholders can then choose an alternative that minimize impacts to both habitat and the public.~~

~~Any one of the situations described above may force the designer to size a bridge less than optimally and impact habitat. The bridge design should modified to minimize these impacts.~~

Bridge support and protection measures

~~Bridges are best supported on deep pilings located outside the required channel or flood prone width.~~ The designer should give careful consideration to the type and location of the foundations. The method chosen should have the least impacts to habitat and be the easiest to construct. Foundations that don’t require rip rap scour protection are preferred. Bank protection should be minimal, using rip rap only in the bridge shadow and where necessary at the toe of embankments, as shown in **Figures 2 and 3**. Vegetation or biotechnical techniques should be used elsewhere.

Bridges supported on spread footings should have the base of these footings well below scour depth, for the current bed elevation and for the expected elevation after ongoing incision, or locate them at a distance laterally outside the expected range of channel migration. Protecting spread footings with massive rock bank protection that encroaches into the required width is unacceptable.

Mid-channel piers are not recommended. In some instances they are unavoidable, in which case they ~~must~~should be designed to minimize the build up of debris and other effects on channel processes. Scour at these piers ~~must~~should be addressed at the design phase; pilings and pile caps ~~must~~should be set well below expected scour depth so that rip rap protection is not required later on.

Bridge clearance

General guidance for bridge clearance is that the bottom of the superstructure should be 3 feet above the 100 year flood water surface. This is a widely used criteria and allows for uncertainty predicting water surface and the presence of floating debris that may hang up on the bridge. This criterion ~~must~~should be used with caution since the size of the river influences the size of the debris carried. Major rivers will need greater clearance and smaller rivers less.

In the case of channels prone to debris flows, a vented ford is a preferred alternative. The height of debris flows in the response reach may have no relation to expected flood depths: providing 3 feet of clearance above the 100 year flood is meaningless when the debris flow is 25 ft hight.

Channel modifications

Much of the preceding discussion has considered the design of the bridge itself. ~~Both~~ When an old structure is removed and a new one placed the channel plan and profile are often modified ~~by the bridge design~~. The old bridge may have had an effect on the channel or rock placed in the channel to support it. New bridges should address this legacy and ~~These modifications must~~ be constructed in such a way to avoid impacts to habitat and mitigate when impacts occur.

Old bridges in degrading streams are propped up by modifying the channel to reduce scour. Weirs and lining the channel with rock are common remediation. Significant repercussions result from fixing the stream in place and these methods should only be used on a temporary basis. When a new bridge is proposed, all the rock used to build these instream remdiation structures should be removed and the natural channel materials replaced.

When an undersized bridge or culvert is removed and replaced with a properly designed bridge, some upstream channel instability is likely. This can be due to stored sediment above the culvert and/or channel incision below the culvert. The result is excessive drop through the area of the crossing. The designer should carefully consider the channel headcut and regrade factors (see the discussion addressing channel regrade in Chapter ##~~7~~, Channel Profile Adjustment).

~~In certain circumstances some sort of grade control, temporary or permanent, may be necessary to ensure channel and habitat integrity. In other cases, no control is preferred for the long term recovery of the equilibrium channel profile. A typical culvert replacement profile is shown in **Figure 6** below.~~

~~**Figure 6: A channel profile illustrating the some possible channel adjustments after an undersized structure is removed.**~~

General design considerations

When a bridge is properly sized there is little need for massive bank and abutment protection. The new structure is not expected to increase velocity at flood flow or otherwise increase erosion. With this in mind the designer should minimize heavy rock and use geotechnical approaches to slope stabilization. **Figure 7** below shows a plan view of a site that reflects this approach with rip rap toe protection, rip rap abutment protection in the shadow of the bridge where vegetation based techniques would not work for lack of sunlight, and geotechnical slope stabilization on the rest of the embankment.

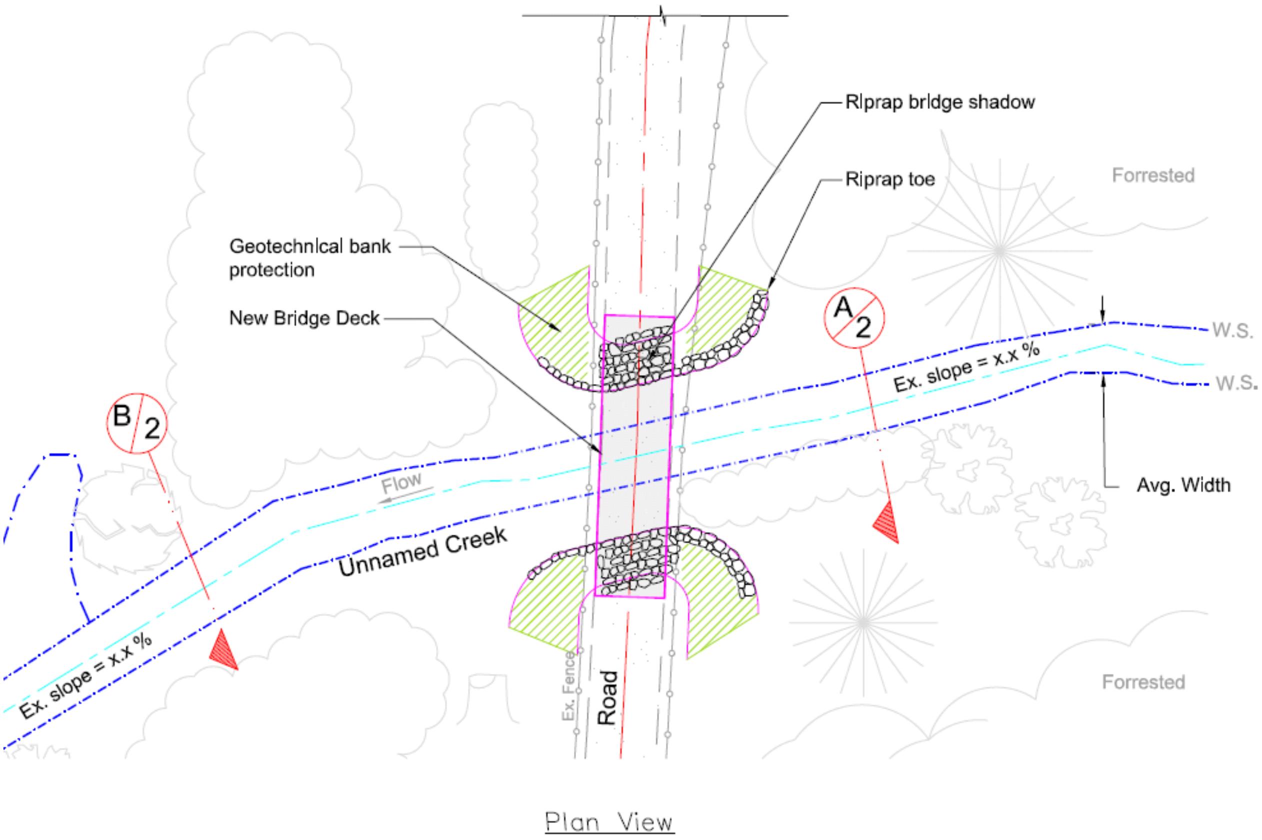


Figure 7: A plan view of a bridge showing reinforcements to the road embankment.

When a new bridge is installed all the components of the old bridge ~~must~~should be removed from the stream channel and flood plain. A common practice is to leave old abutments in the channel. This is harmful and unnecessary. Even when cut off at the bed line, footings are inevitably exposed, causing scour and racking up debris. Old footings ~~must~~should be removed~~.~~ unless it can be shown that there ae overarching safety, engineering, or ecological reasons for not doing so, or that these footings are part of an existing levee system.

Avoid designing bridges in the bottom of a sag curve. Instead allow wheel track generated sediment to be routed across the bridge into sediment traps or away from the stream. <<from DNR, rework the wording>>

Construction practices

All major bridge construction work must be isolated from flowing water. Proper bypass, containment and fish removal practices must be followed. Contaminated water should be pumped out and filtered or disposed without impacting downstream habitat.

Impacts and Mitigation

~~Below are well-recognized impacts from undersized bridges.~~

1. ~~Undersized bridges increase average velocity leading to bed scour, coarsening the substrate and reducing bridge life.~~
2. ~~Undersized bridges backwater the upstream channel, leading to the deposition of materials and increased lateral movement. Such deposits are an attractive nuisance since they are readily spawned but frequently washed out. Lateral movement affects upstream property and often leads to bank protection that further impacts habitat.~~
3. ~~Undersized bridges interfere with the free movement of debris which puts bridge span and abutments at risk and limits the distribution of wood throughout the river.~~
4. ~~Undersized bridges are at greater risk from catastrophic flood. Bridge failure affects habitat both when it occurs and in the various construction activities that lead up to its replacement.~~
5. ~~Undersized bridges constrain lateral movement and the expression of meander migration more severely than do properly sized bridges. Downstream-migrating meanders upstream of such bridges are arrested at the narrow bridge opening, and tend to progressively compress against the adjacent road approaches, causing bank erosion and creating the need for bank hardening. Changes in flow alignment through the bridge caused by meander migration also tend to cause downstream bank erosion~~
6. ~~Undersized bridges limit the down-valley flow water across the flood plain, concentrating flow in the main channel, eliminating flood refugia, and limiting side channel development and other riparian functions.~~

All of these impacts occur over the life of the structure, which could be many decades. Mitigation would, therefore, need to take place on a similar time frame. Following the sizing criteria suggested above will avoid these impacts.

Miscellaneous considerations

Sediment delivery from ~~gravel~~ unpaved roads deteriorates stream water quality. The proper design of the road approach and bridge can eliminate such delivery. The designer is directed to the references and standards offered by the forest industry, the U.S. Forest Service and Washington Dept. of Natural Resources. The following is offered as general guidance. The bridge should be elevated above common flood flow and curbs installed to prevent fine sediment from running off the deck. Avoid designing bridges in the bottom of a sag curve. Proper ditch design and frequent cross drains help prevent direct delivery of runoff to the channel. All ditchwater should be treated before it enters the stream.

Various maintenance issues should be addressed in the design, permitting and long term care of the crossing. Remember to apply for an HPA to do any work that affects fish and fish habitat.

Under long span bridges in alluvial channels bars may form. These should not be assumed to limit flow capacity since they are composed of mobile bedload and should not be removed. Occasionally they become heavily vegetated with perennial plants, such as willow, and become hardened to erosion. These vegetated bars, when they occur in the adjacent channel, are important for the quality and complexity of the habitat for fish and wildlife. Therefore, to preserve the productive capacity of the stream, the bridge owner ~~must~~should carefully assess the affects of the bar on flow capacity and balance them against the requirement to preserve habitat.

When bioengineering is used to reinforce the road fill outside the bridge shadow, maintenance will be required to insure its success. Watering during the initial dry season and the replacement of dead or poorly performing planys may be ~~required~~necessary to insure plant survival. In addition, the height of vegetation may impact traffic and may have to be thinned.

Various federal and local permits may have requirements not covered here, such as encroachments.

~~[1] **Design of Road Crossings for Fish Passage,** 2003, WDFW. http://www.wdfw.wa.gov/hab/engineer/cm/culvert_manual_final.pdf~~

[2] **Integrated Streambank Protection Guidelines**, 2003, WDFW http://www.wdfw.wa.gov/hab/ahg/ispgdoc.htm

[3] **Stream Habitat Restoration Guidelines**, 2004, WDFW http://wdfw.wa.gov/hab/ahg/shrg/index.htm

[4] Montgomery, D. R. and J. M. Buffington (1998). Channel Processes, Classification and Response. River Ecology and Management. N. a. Bilby. New York, Springer**:** 705.

[5] Rosgen, D. Applied River Morphology. Pagosa Springs, CO: Wildland Hydrology; 1996.

[6] Abby, T., C Rapp, A Framework for Delineating Channel Migration Zones. Washington State Department of Ecology Final Draft Publication #03-06-027, November 2003