GENERAL DESIGN AND SELECTION CONSIDERATIONS FOR INSTREAM STRUCTURES

This chapter is a draft version and the Aquatic Habitat Guideline program will be working to finalize it in the future

The term "structure" (in the context of these restoration guidelines) refers to any intentionally placed object in the stream or floodplain. Structures that come in contact with water obstruct streamflow and force it to run over, around, and/or under the structure. This redirection, concentration, or expansion of flow influences the form, structure, hydraulics, and consequently, the function of the stream. As a result, instream structures are prone to having unintended consequences; caution must be exercised when using this approach.

Placement of instream structures is commonly done as a means of improving instream habitat for fish. These structures are typically intended to serve as analogs to otherwise naturally-occurring features. Certain benefits associated with instream structures (such as cover, shelter from fast moving current, or creation of velocity gradients) are available to fish and wildlife immediately following their installation. However, other benefits (such as scour, deposition, or sorting of bed material) require one or more high flow events before they are realized. Instream structure installation can be successful. However, there is a tendency when using this approach to focus on the symptoms of habitat degradation rather than the cause[1], to act without full understanding of the needs of affected fish and wildlife communities[2], and to provide benefits for a specific target fish species, sometimes at the expense of other fish and wildlife[3]. As a result, benefits may be temporary without maintenance and repeat application, they may be limited in scope, or they may never be achieved if the treatment does not address the factors that limit ecosystem productivity and recovery. In addition, incorrectly designed or constructed structures are prone to failure and causing further ecosystem degradation (Beschta et al.[4], as cited by Roper et al.).

In a review of stream restoration techniques, Roni et al.[5] found that projects that involved installation of common instream structures had a moderate to high variability of success at meeting project goals and a low to high probability of success, depending upon the species studied and project design. Instream structures are most effective at restoring or rehabilitating ecosystems when they address the principal cause of ecosystem degradation or when they are used to provide immediate improvement of habitat condition in conjunction with other techniques that address the root cause of the problem but have a long delay before benefits will be realized. They can also be used to enhance habitat when the materials and processes necessary for the natural occurrence of desirable habitat features and conditions are absent and cannot be restored given current constraints.

Considering the risk of project failure and unintended consequences, structure installation and other instream restoration, rehabilitation, or enhancement work should never be conducted without adequate site, reach, and watershed assessment to determine the nature and extent of problems in the watershed, determine the nature and extent of the cause(s) of those problems, and to establish realistic restoration goals, objectives, and priorities (see Stream Habitat Restoration Guidelines Chapters 3, *Stream Habitat Assessment*, and Chapter 4, *Developing a Restoration Strategy)*.

Structures encompass a broad range of objects, consisting of differing materials, functions, longevity, and scale. In the interest of brevity, the structural techniques included in these guidelines are limited to those that are most commonly applied to habitat restoration, rehabilitation, enhancement, and creation projects and that have the potential to provide sustainable benefits to fish and wildlife when used appropriately. These structures include:

- Large wood and log jams
- Boulder clusters
- Porous weirs
- Drop structures

Considering the spectrum of possible structures that are not included in these guidelines, the purpose of this introduction is to provide general guidance on factors to consider when adding ANY structure to a stream.

1 PHYSICAL FUNCTION OF STRUCTURES

All structures placed in a channel have the potential to affect channel hydraulics, sediment scour and deposition patterns, and wood and sediment transport. The degree to which these effects achieve the desired results or place nearby habitat, infrastructure, property, and public safety at risk depends on a number of important variables that affect the way in which a structure functions in the stream. The following parameters should be considered in structure design.

- Channel constriction caused by the structure
- Location of the Structure Within the Channel Cross-section and Its Height Relative to the Depth of Flow
- Structure spacing
- Structure configuration and position in the channel
- Sediment supply and substrate composition
- Channel confinement
- Hydrology
- Time

The effects of these variables vary along a continuum, ranging from slight changes in the channel or floodplain, to huge, catastrophic channel aggradation, incision, or avulsion. Where a given project should be on this continuum depends on the project goals, which must be clearly identified from the outset. There are always potential unintended consequences of any structure placement. The designer should be aware of these consequences and realize that forces in streams act in ways that are beyond our control.

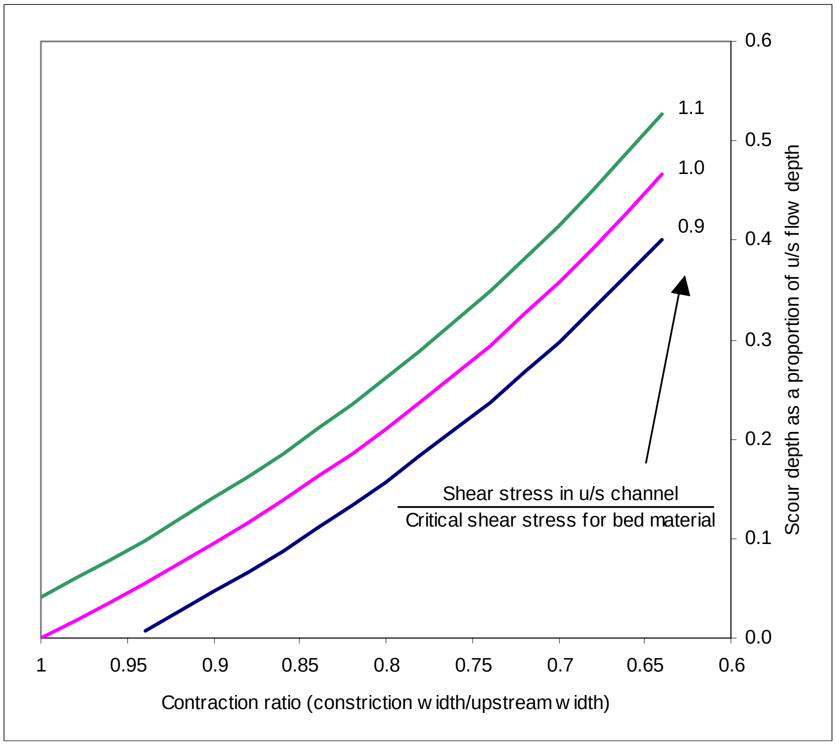
1.1 Channel constriction

Channel constriction is a fundamental parameter describing the scale of the structure relative to the channel. A given structure's effect on a channel is determined in part by how much of the cross-section it occupies. A structure that hugs the bank and blocks a very small percentage of flow in a gravel bed stream will have little effect on channel morphology in the short term. Placed so that it occupies one half or more of the bankfull channel cross-section, the structure has the potential to fundamentally change the channel during the first storm.

In channels with erodible beds and banks the response to significant channel constriction is scour in the vicinity of the structure, deposition of sorted bed material where the flow expands downstream of the constriction, and deposition of bed material upstream in backwatered sections of the channel. Scour results in an increase in cross-sectional area, relieving some of the constriction and decreasing the velocity of flow. The important point to make here is that, no matter how large the structure is or how much of the cross-sectional area it occupies, the deformable boundaries of the channel will adjust to accommodate it. The designer's purpose is to specify how much channel to affect.

The degree of scour created by a given constriction is a function of the bed material size and the available hydraulic stresses to move that substrate[6 7]. Even a minor constriction can cause scour in a sand-bed stream. But it takes a more significant constriction to cause scour in a cobble- or boulder-armored streambed. In an unpublished study, WDFW found that in three small streams (<8 feet) with slopes of 1.3 to 2.6 % and gravel beds, approximately 50% of the bankfull channel cross-section must be blocked by a structure to produce pools and sort gravel in a straight reach of channel. In larger streams [size of bed material???, slope???], Mike McHenry (Lower Elwah tribe, personal communication) has built many structures that occupy 25% of the channel width and significantly influenced morphology. Drury [8] installed structures on a larger river (average bankfull width 413 ft) [slope???, bed material???] that protruded out from the bank 7% of the channel width and produced 10 feet of scour. These structures were placed in the thalweg, a consideration covered below. Refer to the discussion of sediment supply and substrate composition, below, for further discussion.

The simplest approach to constriction scour functionally associates the depth of scour with the degree of constriction and ratio of upstream shear stress to the critical shear stress needed to scour the bed material. **Considerations for Instream Structures Figure 1** gives an example of the performance of this relationship. As the constriction ratio (width in the constriction divided by the width upstream) decreases, scour increases. As the shear stress ratio increases, so does the scour. The mathematical analysis of constriction scour shown here can be found in Raudkivi. This chart is for illustration purposes only and should not be used for design.



Considerations for Instream Structures Figure 1: Scour depth as a function of constriction, depth of flow, and shear stress. This figure was developed from Equation 9.15 on page 245 of A. J. Raudkivi, *Loose Boundary Hydraulics*

For information on how constriction relates to scour near groins (rock bank protection structures, an analog for habitat structures) see Klingeman et al.[9], Richardson and Davis[10] and Gill.

Constrictions also cause backwater effects upstream from the constriction. In the backwatered area, velocity is lowered and sediment tends to accumulate, a familiar phenomenon above undersized bridges and culverts. The upstream extent of backwater depends upon the scale of the constriction and the slope of the channel. Backwater effects extend much further on low-gradient streams than on high gradient streams. Effects will be localized for relatively small channel constrictions. But if the structure causes a significant reduction in channel cross-sectional area or a series of structures collectively increase the hydraulic roughness of the channel, backwater effects may be far reaching. Effects of large-scale backwatering can include increased flood levels and frequency of floodplain inundation, an adjustment of the elevation of streamside vegetation as lower-growing plants are drowned out, potential change in riparian species composition and distribution in response to changing inundation patterns and water table elevations, and reduced reach transport of sediment. Other effects associated with reduced sediment transport include channel aggradation and associated channel widening, bank erosion, increased channel meandering, decreased channel depth, and increased potential for avulsion where the main channel moves to the other side of the structure or to an entirely different location (refer to the *Fluvial Geomorphology* appendix for a discussion on channel avulsion).

Which, if any, backwatering effects are acceptable depends on the setting and the objectives of the project. For instance, encouraging large-scale sediment deposition may be desirable in an incised channel whose bed was scoured down to bedrock as a result of splash-damming or stream-cleaning activities so that it now lacks the structure necessary to retain bed material that is transported through the system. Installing a series of large wood complexes in such a setting can promote bed material retention, floodplain reconnection, and habitat diversity. On the other hand, implementing a similar project in close proximity to homes, businesses, or agricultural fields may be unacceptable. The risk to property, infrastructure, public safety, and the environment must be assessed for every project

Backwater effects associated with a constriction can be assessed using hydraulic analysis. General references include any book on open channel flow, such as Jobson and Froehlich[11] or Chanson[12]. Specific references for the blocking effects of wood in a stream include Young[13], who measured the backwater effect by placing increasing quantities of wood in a flume, and Gippel et al.[14], who developed a momentum equation specifically for wood loading in streams. Backwater effects of bridge constrictions have been thoroughly explored. See Matthai[15] for hydraulic effects in rivers. For smaller channels, Fiuzat and Skogerboe[16] developed constriction ratings. Computer modeling is widely used, employing such programs as HEC-RAS, available free from the USACE, to determine backwater effects in channels.

1.2 Location of the Structure Within the Channel Cross-section and Its Height Relative to the Depth of Flow

The proportion of flow blocked by the channel varies with the depth of flow. Low profile structures can redirect and block a relatively large percentage of base flow, but constrict a decreasing proportion of flow once the structure is overtopped. The effect of that structure on flow characteristics (resistance, velocity, shear, turbulence) will likewise change as the depth of flow increases over the submerged structure. In contrast, the constriction formed by a relatively high boulder cluster or log structure that breaks the surface during high flows could increase, decrease, or remain the same with increasing depth of flow, depending on the shape of the structure and the channel in cross-section. Breaking the surface in combination with significant constriction increases the likelihood of supercritical flow and associated hydraulic jump, producing high turbulence and scour. [Free surface resistance is one of the three components of flow resistance[17], which results in energy loss through turbulence and scour. Hubbard and Thorne[18] thoroughly examined the effects of boulders that break the surface and the associated hydraulic jump and drag, an effect that can easily be transferred to other structures that break the surface.]

In addition to having the potential to cause turbulence and scour, structures that protrude above the water surface increase flow resistance and are very effective at catching floating debris, carcasses and other material as they comb the water surface. Material that racks up on the structure increases the size of the constriction and the degree of backwater or hydraulic drop caused by the structure. Structures that protrude above the water surface are also less buoyant since a portion remains above the water surface.

Hubbard and Thorne discuss the relative submergence of boulders in a mountain stream. Gippel et al. comment on the effect of the relative depth of wood in the water column.

*Discuss effect and function of structures that are located in low flow channel vs. those above low flow but within bankfull channel vs. those suspended above channel vs. those outside the channel in the floodplain.

1.3 Spacing

The relative spacing of structures affects the hydraulic force imparted upon each individual structure within the sequence, the flow resistance through the reach, and the relative effect of each structure on the bed and banks. Morris[19] first discussed the spacing of elements in a channel and separated them into three classes; isolated-roughness flow, wake-interference flow, and skimming flow. He originally conceived these categories for flow in conduits, yet the concepts are useful on a larger scale. Placed very close together, structures appear hydraulically smooth at higher flows, producing little flow resistance and associated turbulence (this effect is dependent upon stage of flow relative to the height of the structures; at base flow, even in close proximity, structures will “appear” hydraulically rough, not smooth). As the spacing increases, wake eddies form between structures, which increase energy loss and flow resistance, but the next downstream structure is still too close for the wake to fully form. Finally, spacing increases to the point where one structure is independent of its upstream neighbor and creates maximum energy loss and flow resistance. Gippel et al. showed this with wood spacing, observing that when model cylinders were grouped less than 3 or 4 diameters apart skimming flow occurred, producing similar backwater elevation to a pair of closely spaced logs. Two cylinders spaced 2 diameters apart have a combined drag of less than one isolated cylinder. Maximum backwater occurs when groups of logs are spaced more than 5 diameters apart.

Similar spacing effects are shown in the study of groins (large roughness elements that project into the channel from the bank and extend above the high-flow water surface elevation[20]) that could be applied to any habitat structure that blocks flow. Groins are spaced to maximize bank protection with a minimum number of structures. This could be reinterpreted in the habitat context as maximizing hydraulic effect (roughness and channel diversity). Lagasse et al.[21] show that the expansion angle (the angle of the line that marks the expansion of flow off the tip of a structure that constricts the channel) is a function of the structure length as a percentage of channel width and of structure permeability. Impermeable structures have an expansion angle of about 17° for most lengths [range??—later it says the angle increases with length]. This means that such structures should be spaced roughly 3 times their effective length (perpendicular to the bank) in order to maximize their hydraulic effect. The expansion angle increases with permeability and length, meaning that closer spacing is necessary to achieve similar results. Lower profile barbs, which are submerged during high flows, are typically spaced 4 to 5 times their effective length[22].

The natural distribution of wood in small streams is somewhat random, having more to do with delivery than transport[23], whereas in larger streams wood is more associated with regular stream features[24]. This can be seen as a scale effect; as the size of the material diminishes with respect to the channel, structure spacing is determined by flow. In larger streams, structures should be spaced in conjunction with natural wood deposition sites to maximize their stability and mimic the effects of naturally deposited wood.

*Discuss combination effects of one structure on another (constriction, redirecting flow).—this relates to fact that one structure can focus/direct thalweg into the next structure

1.4 Structure configuration and position in the channel

*Discuss how orientation of structure relative to flow effects flow redirection and scour/deposition patterns (e.g., straight flat structure vs. a sloping structure; one that points upstream vs. downstream vs. perpendicular vs. parallel to flow)
*Located in thalweg vs. channel margin
*Located in pool vs. riffle (deep vs. shallow flow)

1.5 Sediment supply and substrate composition

*Will have a profound effect on structure performance (primarily scour and deposition).
*Aggrading vs. incising vs. equilibrium channel.
*Qualitative relationship between current shear stress and critical shear stress.

1.6 Channel confinement

*Discuss increased hydraulic forces and risk associated with placing structures in a channel with broad flood plain vs. one that is moderately entrenched vs. one that is severely confined.

1.7 Hydrology

*Free flowing streams vs. backwater due to beavers, vegetation, undersized bridges, etc
*Runoff vs. groundwater streams
*Urban flow regime vs. natural landscape.

1.8 Time

*****Time is extremely important when altering a stream.
*Are delayed effects (e.g., avulsion leads to u/s incision, then sediment pulse, passing of pulse, back to equilibrium conditions, may take many years).
*Maturation, number of restructuring flows may be necessary before effects of structure are fully realized (see Madej 2001[25]).
*Design life is caught up in the concept of disturbance. Structures installation can create disturbance. When they fail structures will also create disturbance. Where possible, disturbance should be considered a part of restoration design[26].

2 APPLICATION

The following table highlights the primary function of structures covered in this manual as they relate to restoration, enhancement or creation of stream habitat. Structures often provide numerous functions – only the primary function for typical applications is listed in this table. Most of the structure types listed herein can transcend their categorical listing and provide added habitat value beyond their primary function. This can be accomplished through site-specific and structure-specific design. Combinations of structures can be used to meet several different objectives at the same time.

Considerations for Instream Structures Table 1: Primary functions of instream structures in habitat applications.

Application	**Large Wood & Log Jams**	**Boulder clusters**	**Porous Weirs**	**Drop Structures**
Create bed and bank scour	X	X	X	X
Sort sediment	X	X	X	X
Create backwater	X	X	X	X
Stabilize or raise streambed	X		X	X
Alter stream grade	X		X	X
Provide cover, resting and high flow refuge	X	X	X	
Armor streambanks	X			
Improve wildlife habitat	X	X		
Redirect flow	X	X	X	X
Trap material	X	X		
Provide fish passage	X			X

Determination of when the application of structures to restoration efforts is appropriate will necessarily be dependent upon specific restoration objectives, site and watershed conditions, and an identified biological or morphological need.

3 DESIGN OF STRUCTURES

Design of structures in fluvial environments can involve considerable site-specific analysis, and as such it is impractical to establish common design routines that can be universally applied. While there are established analytical tools for estimating such design components as maximum scour depth and minimum size of material, and for conducting a hydraulic analysis, the specific tools applied for each of these design components will vary with site and channel conditions, risk, as well as the relative complexity of the project.

3.1 Common Design Criteria for Instream Structures

Design criteria are specific, *measurable* benchmarks developed to meet and clarify project objectives. They provide numeric allowable limits of project performance and tolerance. Common design criteria for instream structures are discussed below. Further discussion on developing and using design criteria is provided in Stream Habitat Restoration Guidelines Chapter 5, *Designing and Implementing Stream Habitat Restoration Techniques*.

Physical or Biological Response.

The first set of criteria for an instream project relate to the desired channel or biological response. For instance, if the intent of the project is to increase salmonid spawning utilization, then the criteria should relate to fish usage and structure design must create appropriate depositional patterns. If the intent is to create a forced pool-riffle morphology in a plane-bed channel, design criteria should specify a target pool/riffle ratio and minimum residual pool depth. While criteria are intended to be measurable, some projects may have criteria that are more qualitative. A qualitative design criterion might be to increase flow to a side channel to increase off channel habitat. A more complicated project associated with dam mitigation will require a specific flow in the side channel, e.g., 10 cfs during 1500 cfs main channel flow. Design criteria are further discussed in Stream Habitat Restoration Guidelines Chapter 5, *Designing and Implementing Stream Habitat Restoration Techniques*.

Design Discharge.

Design discharges are relevant to many aspects of structure design, including structure stability and desired habitat effects. The design discharge up to which a structure is expected to remain relatively stable will vary with the type of structure, the objectives of its installation, and the risk associated with its structural failure. For instance, drop structures installed to provide fish passage through an upstream culvert may need to withstand a 50- or 100-year flow without failure. A much lower design discharge could be applied to boulder clusters intended to increase habitat diversity and provide holding habitat for fish. But specific discharges may only be relevant when hydraulic analysis is required. Less stringent criteria may be appropriate in certain situations, such as the often-used bankfull flow (*e.g.* “roughly one quarter of the bankfull flow will be diverted into the side channel”).

Habitat created by structures may be critical at specific times of year or ranges of discharge. Therefore, it may be appropriate to establish design discharges that relate to specific fish and wildlife benefits, in addition to those that dictate structural failure. For instance, the limiting factor for fish may be cover during summer low flow or shelter during high flow events. Under these circumstances structures will need to be designed to function during this critical time, at a minimum, in order to optimize their effects. Timing and discharge requirements may be specific to the stream and target species and age class (e.g., fish passage requirements for adult chum salmon will differ from that for juvenile coho salmon).

Structures whose habitat value is realized after and during high flow events capable of redistributing sediment and wood should be designed to be effective at the dominant discharge. The *Hydrology* appendix provides discussion and guidance on how to determine dominant discharge.

Design Life.
The desired design life for a structure will vary with the application. Some structures may be temporary features intended to fill a function lost at this time in the watershed. In contrast, mitigation projects must last as long as the impacts for which it is intended to mitigate. Although a desirable goal of a project is to last long enough to realize the full maturation of its restoration benefits, including any delayed effects, the design life of an instream structure is virtually impossible to predict or account for. The longevity of a structure is influenced by some features that can be controlled (the structure design and the materials used to construct it) and others that are generally beyond our control (peak flows and channel or watershed disturbance). The design discharge for stability has an equal probability of being exceeded in every year, and therefore, the structure may fail at any time.

Deformability.
Structures can be designed and constructed to be relatively non-deformable, meaning that they persist as constructed indefinitely. Alternatively, they can be designed to eventually deform through undermining, entrainment of structural components, or degradation of components. Deformation generally occurs during high flow events that exceed the design flow, or as a result of channel incision or other changing watershed conditions. Deformation differs from design life and ultimate failure – deformation implies that the function of a structure may evolve or diminish over time through gradual mobility of materials rather than catastrophic and sudden failure.

Deformation of structures typically involves the gradual undermining of individual structural components (e.g., rocks or logs), or entrainment of a percentage of them during extreme flows. The downstream edge of a structure is most likely to deform, as scour below the structure may create holes into which part of the structure falls. In this manner, the function of a boulder weir may change from a drop structure to a low cascade and, eventually, to a short roughened channel as rocks roll and disperse before settling into the bed through natural scour and settling processes. In contrast, rigid structures (e.g., anchored log, plank, concrete, or sheet pile weirs) cannot adjust to changing flows, stream profile, cross-section, or planform.

Structures designed to deform over time should be comprised of natural materials; unnatural materials, such as rebar, wire rope, and concrete blocks should be avoided. Deformability may be achieved by sizing the material to withstand relatively low design flows, or by minimizing the amount of structure keyed into the channel bed or banks to prevent undermining and end runs, respectively. Designers should note that there is a high degree of uncertainty in the final form of a deformable structure once it deforms.

3.2 Design Factors to Consider

Some form of assessment of fish and wildlife communities, stream geomorphology, watershed processes, and channel and watershed history is necessary to evaluate the system conditions and the appropriateness of a site-specific structure project. This assessment will aid in estimating the project's likely effects on adjacent stream reaches and the system as a whole, as well as on nearby property and infrastructure. Without some level of understanding of the stream ecosystem and the factors that influence its condition, a structure project is not likely to fulfill its intended purpose and may have unintended consequences.

The amount of data collection and assessment required will be dictated by the project scope, availability of existing watershed assessment information, and by allowable risk and uncertainty. While it may seem prudent to collect an abundance of data, make sure that it is collected for a predefined purpose. This is especially the case for monitoring where data should be associated with specific goals. Assessment completed prior to adding a structure to a stream should be of a sufficient level so as to reveal the scale and cause of the problem in order to ensure the problem is correctly and fully addressed. At a minimum, the scale of assessment should be equal to or greater than the anticipated scale of the structures' effects. Refer to Stream Habitat Restoration Guidelines Chapter 3, *Stream Habitat Assessment*, for a detailed discussion of assessment. The following are minimum recommended assessment and analysis requirements for installing instream structures.

- *What is the objective of structure placement?* The type, configuration, and number of structures will vary with the objective.
- *Are structures the best alternative to meet those objectives?* Will structure placement treat only the symptom of the perceived problem or deficiency, or will it address its root cause? Are there other realistic alternatives that can provide a more long-term, far-reaching, and self-sustaining solution?
- *Have other complementary treatments been implemented that are necessary to maximize the effectiveness and longevity of benefits provided by instream structure placement?* For instance, if natural structures were dislocated, washed out, or otherwise prevented from functioning as a result of modifications to the channel, hydrologic regime or sediment supply, structure placement will be most effective when used in conjunction with other measures that restore the channel, hydrologic regime and sediment supply. If the project involves placing wood in the stream, have riparian restoration and management techniques been implemented to ensure a long-term source of wood is available to the stream that will replace the added wood as it decays or washes downstream?

- *Document baseline conditions of the project site.* Baseline conditions should be documented for the purpose of monitoring, liability in the event that there is damage or loss of property, to provide information needed in design, and to determine if conditions are appropriate for the structure under consideration. Analysis and documentation of baseline conditions typically includes the following.
  - A plan view sketch or, when necessary, a contour map. Use this to determine the structure's orientation to flow, its location in relation to the channel thalweg, and structure spacing.
  - General characteristics of bed material. What is the dominant substrate?
  - A channel profile can be used to determine channel gradient, structure spacing, resulting water surface and slope, head developed over the structure and other important details.
  - Cross-section survey at the structure site and a minimum of one channel-width upstream and downstream. Cross-sections should include the flood prone region, high water marks, top of bank, Ordinary High Water line, toe of bank, and at least three points within the active channel, including the thalweg. These cross-sections are easy to survey and provide the basis for determining important parameters such as structure constriction and height, and channel width and confinement. The depth of flow and, thus, shear stress on the bed and banks of the channel during high flow events increase with the degree of channel confinement. This increases the potential for boulder, wood, or other material transport and for bed and bank scour.
  - Condition of the banks. Are they relatively stable or actively eroding?
  - General assessment of the lateral and vertical stability of the channel and the overall stability of the watershed. Is the channel aggrading or incising in the vicinity of the site? If the channel is actively incising, has the cause of channel incision been identified and addressed? If not, the channel may continue to incise downstream and undermine or create a fish passage barrier at the lowermost structure.
  - Does the channel carry a relatively high bed or debris load? High gradient, high bedload channels can wear away structures placed in the stream (especially wood). Bed material and wood may become trapped on or upstream of the structure, potentially increasing its backwater effects and redirecting flow. Limiting the potential backwater effects of a structure may be desirable where wood accumulations could compromise the project or adjacent infrastructure.
  - Additional baseline data may be required for any monitoring planned at the site. The scope and nature of such an assessment depend upon monitoring objectives. Note that photo documentation of site, upstream, and downstream conditions is often valuable. Provide a brief written description of each photo.
- *Evaluate structure stability.* What is the necessary design life or design discharge of the structure? What kind and size of material will be necessary to meet those design criteria?

- *Material selection*. Structures are typically designed and constructed using either rock or large wood but may also be constructed using synthetic materials, such as concrete, sawn timber or steel. The selection of materials should be based primarily on its ability to meet restoration objectives and design criteria, which may include blending with natural material in the stream, project life, and deformability.
- *Evaluate access and materials availability.* Access to the site and availability of materials may influence structure design and construction as well as remediation or mitigation requirements. What access routes and staging areas are available? Will they limit the type of equipment, and therefore, the type and volume of material, that can be utilized? What impacts are likely to occur as a result of ingress and egress of equipment and materials? Will the cost or availability of materials limit the design? Refer to the *Construction Considerations* appendix for further discussion of access roads and implications to design, feasibility, and disturbance reclamation and mitigation.
- *Document the location and nature of instream and nearby infrastructure and utilities that may benefit or be harmed by the proposed structure.* This is best done in conjunction with developing good plan, profile and cross-section drawings of the site and reach. The presence of infrastructure will likely place limitations upon flow redirection, structure location and configuration, and the degree of allowable backwater.
- *Biological assessment*. Biological assessment of existing conditions within the project reach and associated riparian wildlife habitats is essential to develop appropriate design criteria and project solutions and to document baseline habitat use conditions. Biological assessment may include availability and distribution of spawning, rearing, high flow refuge, cover, and pool habitat as well as wetlands, riparian areas and associated uplands. Particular attention should be paid to priority habitats and species (http://wdfw.wa.gov/hab/phspage.htm) so that the project does not contribute to the loss of valuable wildlife habitat. Further information about and guidance on the value and application of biological assessment is provided in Stream Habitat Restoration Guidelines Chapter 3, *Stream Habitat Assessment*. The content and level of detail of a biological assessment will be dictated by the objectives of the project and the potential risks it poses to fish and wildlife. For example, a full spanning structure is legally required to provide fish passage over or through it and so will require a thorough assessment of species present. Additional information, such as an assessment of populations upstream and downstream of the project site and at a reference or control site may be necessary as a baseline assessment for subsequent monitoring of project success and impacts. The local state Area Habitat Biologist, Fish Biologist, and Wildlife Biologist should be consulted for additional information on local aquatic fauna
- *Will the placement adversely affect recreational navigation*? What measures can be taken to minimize public safety risks?
- *What are the potential impacts to upstream, downstream, and adjacent habitat, fish and wildlife, infrastructure (including utilities), and public safety during and following construction if the project succeeds, or if it fails structurally*? What is

the probability of those impacts occurring? What factors influence that risk (e.g., degree of channel confinement, slope, bedload, high flow events, material selection, structure configuration)? What can be done to minimize the risk? Is the risk acceptable?

- *Budget.* Cost is often a limiting factor in design and must be balanced with the level of acceptable risk. Lesser budgets may not allow for detailed design. In addition, cost may influence the number or size of the structures, the size or type of materials or equipment used to construct or place them, or the extent and scope of the project.

In relatively small, low energy streams where there is minimal risk to infrastructure, habitat, and public safety, elements of the design may be based on observing natural analogs at reference sites, rather conventional hydraulic or civil engineering analysis. For instance, the necessary size of material, structure configuration, and the anticipated depth of scour can be estimated by observing stable structures located in similar channel reaches operating under similar conditions. However, high risk projects, high cost projects, and projects conducted on larger streams (greater than 20’ wide), on steeper or more confined channels, and in close proximity to infrastructure may have additional data collection and assessment requirements. These could include, but are not limited to:

- *Hydrologic analysis*. Hydrologic analysis may be necessary to generate discharge values used in design and to evaluate potential impacts to the channel or nearby property. Common design discharges applied to design of structures include:
    - Low fish passage -flow
    - High fish passage flow
    - Dominant discharge
    - Maximum design discharge where structural integrity will be maintained. The design discharge will vary with the objectives of the project and risk associated with structural failure.
    - Flood discharge - 100-year discharge for determining impacts on regulatory flood flows

  A discussion of hydrologic statistics and their derivation is available in the *Hydrology* appendix.
- *Scour analysis*. Most structures create some degree of scour. The integrity of many structures depends, to some extent, on their depth of installation relative to the depth of scour. Critical flow conditions can occur at the crest of the structure with supercritical flow possibly occurring along the face of the structure at certain flows. These conditions create a hydraulic jump downstream of the structure that can cause bed or bank scour. The *Hydraulics* appendix defines varying types of scour under various site conditions, and how to estimate depth of scour. Data required for scour analysis depends on the type of scour evaluated. While scour can be evaluated empirically in some instances, analysis usually requires a minimum of three cross-sections (one at each structure plus upstream and downstream of the structure), a channel profile survey (extending upstream and downstream of the project for a distance of at least 200-ft above and below the first and last structure or 10 bankfull widths), and an evaluation of the bed substrate distribution. Substrate size should be estimated by sieve analysis, Wolman pebble count, (both of which are detailed in the

Sediment Transport appendix) or some other acceptable method. At a minimum, one representative substrate sample should be taken at each structure location. Significant changes in substrate composition along the project reach should be noted.

- *Sediment transport*. Sediment transport analysis may be necessary where large-scale backwatering effects are likely or where the project is intended to trap sediment or otherwise affect sediment transport (alter channel width, depth, or slope). Such effects are more likely to occur when a series of structures are installed. Local, individual structures will most likely affect scour and sorting without impacting general sediment transport characteristics through a reach. Sediment transport is a function of channel hydraulics (slope and depth in particular), sediment size, and volume of sediment supply. The evaluation of sediment transport is detailed in the *Sediment Transport* appendix.
- *Hydraulic analysis*. Hydraulic parameters for design include flow depth, velocity and bed shear. These parameters should be estimated for a range of flows for existing and post-project conditions. Common design discharges applied to design of structures are discussed above in *Hydrologic analysis*. These parameters will be used to size rock, wood, and other materials, and demonstrate fish passage conditions are met. Hydraulic design in a natural environment, using natural materials, necessarily involves a significant degree of uncertainty. Equations and methods presented in the *Hydraulics* appendix are useful in the analysis and design of instream structures. These tools should be employed with an understanding of the variability in natural stream systems and sound professional judgment.
- *Backwater analysis*. This effort will help identify potential flooding locations, both pre- and post-project. In some cases frequent floods or excessive flood elevations have to be avoided. In others, one of the main objectives will be to restore floodplain function and connectivity with the channel. A backwater analysis can help determine if the design will achieve that goal at the design discharge.

3.3 Expertise Required for Design

Certain analyses and design processes will require specialized expertise. For example, a project intended to affect sediment transport through a reach may require detailed analysis of flow durations, sediment supply, and the application of analytical methods typically only available to professionals with specialized training in engineering. The degree of expertise required to design and install instream structures will also be determined by the risk imparted to property, infrastructure, public safety and the environment due to both the presence and failure of the structure. For example, if a project has the potential to cause significant backwater that could compromise an upstream road via accelerated bank erosion and increased flooding, practitioners whose experience enables them to select and apply appropriate analytical methods to quantify and minimize the risk should conduct its design. Similarly, if failure of a drop structure has the potential to compromise the integrity of a high-pressure sewer line and cause significant damage to the ecosystem and public drinking water, that structure may be required to withstand all hydraulic forces up to a 100-year discharge. To ensure such integrity, its design should be conducted by someone experienced with modeling the forces associated with all flows up to the 100-year discharge and analyzing scour. They should also be familiar with the physical qualities of materials being used and their ability to withstand calculated forces.

On the other hand, less expertise is required to undertake small projects in areas where little is at risk if the structure fails to meet project objectives or if it fails structurally. Such designs could be effectively conducted using an analog approach (whereby a practitioner replicates features and structures found in nature[27]) by individuals familiar with stream processes, fish habitat requirements, and an appreciation for the unpredictability of the natural environment.

4 PERMITTING

Installation of structures necessarily involves in-channel work, streambed and bank excavation, and the placement of fill within the channel. Required permits and checklists may include, but are not limited to: State Environmental Policy Act (SEPA) and a Joint Aquatic Resource Permits Application (JARPA) (including a Hydraulic Project Approval and possibly a Shoreline Management Act Permit, Section 401 Certification, and a Section 404 Permit). A Clearing and Grading Permit, Washington Department of Natural Resources Use Authorization, and an Endangered Species Act Section 7 or 10 Consultation may also be required. Refer to the *Typical Permits Required for Work In and Around Water* appendix for more information regarding each of these permits and checklists, and other permits that may apply.

5 MONITORING

When designing instream structures, long-term monitoring and maintenance may be a pending issue. Monitoring conducted at the site depends on project objectives and the risks it imparts on property, public safety, infrastructure, fish passage, and the environment. Potential questions include: Did the structure stay in place? Does the structure provide unobstructed fish passage? Is infrastructure, property, public safety, or fish and wildlife compromised or at risk as a result of the structure? Is maintenance required? How has the habitat changed since the addition of the structure? Does the structure provide favorable fish and wildlife habitat (for what species, season, and age class)? Did the treatment affect overall fish and wildlife production in the system? Did the treatment prevent further erosion of the bank (if applicable)? The level and frequency of monitoring required will vary with monitoring objectives and project risk. Low risk projects may simply warrant annual site visits and a documentation of qualitative observations regarding patterns of scour and deposition, bank erosion, fish use, and structure stability. On the other hand, projects that pose a relatively high risk to infrastructure, property, public safety, or the environment may require frequent quantitative physical and biological surveys to be conducted. Such surveys may include taking photos, pre- and post-construction snorkeling of the site and a reference reach to document fish use, and detailed surveys of structure locations, channel cross-sections, and channel profiles to document changes over time. Annual monitoring would be required to insure unobstructed fish passage where it may be compromised by the presence of the structure. Refer to the *Monitoring Considerations* appendix for guidance on developing and implementing a monitoring plan.

6 MAINTENANCE AND MONITORING

Maintenance requirements for instream structures will be revealed through regular monitoring. It varies with the type of project. In general, maintenance will only be necessary if the structures do not meet project objectives or if unintended and unacceptable consequences have occurred. Maintenance or repair should be completed only after careful evaluation to determine the cause of project failure to avoid repeating the same mistake. Maintenance may include replacement, adjustment, or removal of the entire structure of elements of the structure, clearing of accumulated debris, or installation of additional structures. The legal requirement to provide fish passage necessitates that any necessary repairs to restore fish passage be identified and promptly addressed.

7 GLOSSARY

Structure - any object in a channel that protrudes from the bed or bank and creates an obstruction to flow within the channel

Stage – the elevation of the water surface in a channel relative to some arbitrary benchmark

Dominant discharge - the flow that produces the greatest morphologic effect over an extended period of time

Flow vectors – a quantity consisting of both magnitude and direction, which in the case of stream flow typically denotes velocity and direction in the horizontal plane

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