APPENDIX A: GLOSSARY

aggradation: The geologic process by which a streambed is raised in elevation by the deposition of additional material transported from upstream (opposite of **degradation**).

armor: A surface streambed layer of course grained sediments that are rarely transported. This layer protects the underlying sediments from erosion and transport, while creating enough roughness to prevent channel down-cutting.

backwater: Stream water, obstructed by some downstream hydraulic control, is slowed or stopped from flowing at its normal, open-channel flow condition.

baffle: Pieces of wood, concrete or metal that are mounted in a series on the floor and/or wall of a culvert to increase boundary roughness, thereby reducing the average water velocity and increasing water depth within the culvert.

bankfull width: The bankfull channel is defined as the stage when water just begins to overflow into the active floodplain. In streams where there is no floodplain it is the width of a stream or river at the dominant channel forming flow with a recurrence interval in the 1 to 2 year range. Bankfull is fully defined in ***Appendix C.***

bed: The land below the ordinary high water lines of the waters of the state of Washington. This definition does not include irrigation ditches, canals, storm water run-off devices or artificial watercourses, except where they exist in a natural watercourse that has been altered by man.

bedload: The part of sediment transport that is not in suspension, consisting of coarse material moving on or near the channel bed surface.

bed roughness: The unevenness of streambed material (i.e. gravel, cobbles) that contributes resistance to stream flow. The degree of roughness is commonly expressed using Manning's roughness coefficient (see ***Equation 2*** in ***Chapter 6: Hydraulic Design Option***).

cascade: A relatively steep channel unit composed of a series of small steps or very rough boulder chute. A cascade can be natural or man-made (often the basis for a roughened channel).

channel-bed width: For the purpose of culvert design, the channel-bed width is defined as the width of the bankfull channel, although bankfull may not be well defined in some channels. For those stream which are non alluvial or do not have floodplains, the channel width must be determined using features that do not depend on a floodplain. Refer to ***Appendix C***, for details and information on how to measure channel-bed width.

clast: An individual particle in the channel bed.

countersink: Countersink means to place below the level of the surface; in reference to culvert design, to countersink is to set the elevation of the culvert invert below the level of the streambed.

debris: Material distributed along and within a channel or its floodplain either by natural processes or human influences. Generally wood; whole trees, logs, root wads, branches, sticks, and leaves.

degradation: The removal of streambed materials caused by the erosional force of water flow that results in a lowering of the bed elevation throughout a reach (Opposite of **aggradation**).

deposition: The settlement of material onto the channel-bed surface or floodplain.

dewater: To remove water from an area, usually done before construction of an in-stream project.

fishway: A system specifically designed for passage of fish over, around or through an obstruction. Such systems include hydraulic-control devices, special attraction devices, collection and transportation channels, fish ladders, a series of weirs designed for fish passage, culvert retrofit systems.

floodplain utilization ratio (FUR): The floodplain utilization ratio is the flood-prone width divided by the bankfull width. (The Floodplain Utilization Ratio is referred to as the "entrenchment ratio" in several publications). As a rule-of-thumb, flood-prone width is defined as the water surface width at a height above the bed of twice the bankfull depth.

fork length: The length of a fish measured from the most anterior part of the head to the deepest point of the notch in the tail fin.

freshet: A rapid, temporary rise in stream flow caused by snow melt or rain.

geomorphology: The study of physical features associated with landscapes and their evolution.

grade stabilization or **grade control**: Stabilization of the streambed surface elevation to protect against degradation or to increase stream gradient in excess of the prevailing gradient.

gradient: The slope of a stream-channel bed or water surface, expressed as a percentage of the drop in elevation divided by the distance in which the drop is measured.

headcut: The erosion of the channel bed, progressing in an upstream direction, creating an incised channel. Generally recognized as a vertical drop or waterfalls, or an abnormally over-steepened channel segments.

incised channel: A stream channel that has lowered in gradient be degrading its bed. Generally the bed is well below the historic flood plain, often deep and narrow, and containing all or most of the flood flow within its banks. Incision is a transitional state.

mitigation: Actions taken to avoid or compensate for the impacts to habitat resulting from man's activities (WAC 220-110-050).

OHW Mark: Ordinary high water mark.

ordinary high water mark: The legal definition of ordinary high water mark per WAC 220-110-020(31) is:

> "Ordinary high water line means the mark on the shores of all waters that will be found by examining the bed and banks and ascertaining where the presence and action of waters are so common and usual and so long continued in ordinary years, as to mark upon the soil or vegetation a character distinct from that of the abutting upland: Provided, That in any area where the ordinary high water line cannot be found the ordinary high water line adjoining saltwater shall be the line of mean higher high water and the ordinary high water line adjoining freshwater shall be the elevation of the mean annual flood."

perched: A culvert whose outlet is elevated above the downstream channel water surface.

reach: A section of a stream having similar physical and biological characteristics.

regrade: The channel's process of stabilization usually caused by new or extreme conditions. Generally, regrade occurs when a grade control is added or removed: a *perched* culvert is removed and the upstream channel lowers as a result. See *headcut* and *degradation*.

riffle: A reach of stream in which the water flow is rapid and usually more shallow that the reaches above and below. Natural streams often consist of a succession of pools and riffles.

riparian area: The area adjacent to flowing water (e.g., rivers, perennial or intermittent streams, seeps, or springs) that contains elements of both aquatic and terrestrial ecosystems, which mutually influence each other.

riprap: Large, durable materials (usually fractured or quarried rocks) used to protect a stream bank, bridge abutment or lake shore from erosion; also refers to the materials used for this purpose.

rise: The maximum, vertical, open dimension of a culvert; equal to the diameter in a round culvert and the height in a rectangular culvert.

scour: The process of removing material from the bed or banks of a channel through the erosive action of flowing water.

shear strength: The characteristic of soil, rock and root structure that resists the sliding force of flowing water.

shear stress: A measure of the erosive force acting on and parallel to the flow of water. It is expressed as force per unit area (lb/ft^2, N/m^2). In a channel, shear stress is created by water flowing parallel to the boundaries of the channel; bank shear is a combined function of the flow magnitude and duration, as well as the shape of the bend and channel cross section.

slope: Vertical change with respect to horizontal distance within the channel (see gradient).

slope ratio: The ratio of the proposed culvert bed slope to the upstream water-surface slope.

substrate: Mineral and organic material that forms the bed of a stream.

tailout: The downstream end of a pool where the bed surface gradually rises and the water depth increases. It may vary in length, but usually occurs immediately upstream of a riffle.

thalweg: The longitudinal line of deepest water within a stream.

toe: The base area of a streambank where it meets the streambed.

weir: A channel-spanning structure that raises the water surface upstream and forces flow to drop at a specific location.

Water Resource Inventory Area (WRIA): Areas or boundaries created around major watersheds within the State of Washington for administration and planning purposes. These boundaries were jointly agreed upon in 1970 by Washington's natural resource agencies (departments of Ecology, Natural Resources and Fish and Wildlife). They were formalized under WAC 173-500-040 and authorized under the Water Resources Act of 1971, RCW 90.54.

waters of the state or state waters: Includes lakes, rivers, ponds, streams, inland waters, underground water, salt waters, estuaries, tidal flats, beaches and lands adjoining the sea coast of the state, sewers, and all other surface waters and watercourses within the jurisdiction of the State of Washington.

wetlands: (WAC 173-201A-020) means areas that are inundated or saturated by surface water or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, bogs, and similar areas. Wetlands do not include those artificial wetlands intentionally created from non-wetland sites, including, but not limited to, irrigation and drainage ditches, grass-lined swales, canals, detention facilities, wastewater treatment facilities, farm ponds, and landscape amenities, or those wetlands created after July 1, 1990, that were unintentionally created as a result of the construction of a road, street, or highway. Wetlands may include those artificial wetlands intentionally created from nonwetland areas to mitigate the conversion of wetlands. (Water bodies not included in the definition of wetlands as well as those mentioned in the definition are still waters of the state.)

width ratio: The ratio of the proposed culvert-bed width to the upstream channel bankfull width.

Appendix B: Washington Culvert Regulations

RCW 77.57.030

Fishways required in dams, obstructions — penalties, remedies for failure.

(1) subject to subsection (3) of this section, a dam or other obstruction across or in a stream shall be provided with a durable and efficient fishway approved by the director. Plans and specifications shall be provided to the department prior to the director's approval. The fishway shall be maintained in an effective condition and continuously supplied with sufficient water to freely pass fish.

(2)(a) if a person fails to construct and maintain a fishway or to remove the dam or obstruction in a manner satisfactory to the director, then within thirty days after written notice to comply has been served upon the owner, his or her agent, or the person in charge, the director may construct a fishway or remove the dam or obstruction. Expenses incurred by the department constitute the value of a lien upon the dam and upon the personal property of the person owning the dam. Notice of the lien shall be filed and recorded in the office of the county auditor of the county in which the dam or obstruction is situated. The lien may be foreclosed in an action brought in the name of the state.

(b) if, within thirty days after notice to construct a fishway or remove a dam or obstruction, the owner, his or her agent, or the person in charge fails to do so, the dam or obstruction is a public nuisance and the director may take possession of the dam or obstruction and destroy it. No liability shall attach for the destruction.

(3) for the purposes of this section, "other obstruction" does not include tide gates, flood gates, and associated man-made agricultural drainage facilities that were originally installed as part of an agricultural drainage system on or before may 20, 2003, or the repair, replacement, or improvement of such tide gates or flood gates.

[2005 c 146 § 903; 2003 c 391 § 1; 1998 c 190 § 86; 1983 1st ex.s. c 46 § 72; 1955 c 12 § 75.20.060. Prior: 1949 c 112 § 47; Rem. Supp. 1949 § 5780-321. Formerly RCW 77.55.060, 75.20.060.]

WAC 220-110-070 WATER CROSSING STRUCTURES.

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. Pier placement waterward of the ordinary high water line shall be avoided, where practicable. Other structures which may be approved, in descending order of preference, include: Temporary culverts, bottomless arch culverts, arch culverts, and round culverts. Corrugated metal culverts are generally preferred over smooth surfaced culverts. Culvert baffles and downstream control weirs are discouraged except to correct fish passage problems at existing structures.

An HPA is required for construction or structural work associated with any bridge structure waterward of or across the ordinary high water line of state waters. An HPA is also required for bridge painting and other maintenance where there is potential for wastage of paint, sandblasting material, sediments, or bridge parts into the water, or where the work, including equipment operation, occurs waterward of the ordinary high water line. Exemptions/5-year permits will be considered if an applicant submits a plan to adhere to practices that meet or exceed the provisions otherwise required by the department.

Water crossing structure projects shall incorporate mitigation measures as necessary to achieve no-net-loss of productive capacity of fish and shellfish habitat. The following technical provisions shall apply to water crossing structures:

(1) Bridge construction.

(a) Excavation for and placement of the foundation and superstructure shall be outside the ordinary high water line unless the construction site is separated from waters of the state by use of an approved dike, cofferdam, or similar structure.

(b) The bridge structure or stringers shall be placed in a manner to minimize damage to the bed.

(c) Alteration or disturbance of bank or bank vegetation shall be limited to that necessary to construct the project. All disturbed areas shall be protected from erosion, within seven calendar days of completion of the project, using vegetation or other means. The banks shall be revegetated within one year with native or other approved woody species. Vegetative cuttings shall be planted at a maximum interval of three feet (on center), and maintained as necessary for three years to ensure eighty percent survival. Where proposed, planting densities and maintenance requirements for rooted stock will be determined on a site-specific basis. The requirement to plant woody vegetation may be waived for areas where the potential for natural revegetation is adequate, or where other engineering or safety factors preclude them.

(d) Removal of existing or temporary structures shall be accomplished so that the structure and associated material does not enter the watercourse.

(e) The bridge shall be constructed, according to the approved design, to pass the 100-year peak flow with consideration of debris likely to be encountered. Exception shall be granted if applicant provides hydrologic or other information that supports alternative design criteria.

(f) Wastewater from project activities and water removed from within the work area shall be routed to an area landward of the ordinary high water line to allow removal of fine sediment and other contaminants prior to being discharged to state waters.

(g) Structures containing concrete shall be sufficiently cured prior to contact with water to avoid leaching.

(h) Abutments, piers, piling, sills, approach fills, etc., shall not constrict the flow so as to cause any appreciable increase (not to exceed .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 watercourse.

(i) Riprap materials used for structure protection shall be angular rock and the placement shall be installed according to an approved design to withstand the 100-year peak flow.

(2) Temporary culvert installation.

The allowable placement of temporary culverts and time limitations shall be determined by the department, based on the specific fish resources of concern at the proposed location of the culvert.

(a) Where fish passage is a concern, temporary culverts shall be installed according to an approved design to provide adequate fish passage. In these cases, the temporary culvert installation shall meet the fish passage design criteria in Table 1 in subsection (3) of this section.

(b) Where culverts are left in place during the period of September 30 to June 15, the culvert shall be designed to maintain structural integrity to the 100-year peak flow with consideration of the debris loading likely to be encountered.

(c) Where culverts are left in place during the period June 16 to September 30, the culvert shall be designed to maintain structural integrity at a peak flow expected to occur once in 100 years during the season of installation.

(d) Disturbance of the bed and banks shall be limited to that necessary to place the culvert and any required channel modification associated with it. Affected bed and bank areas outside the culvert shall be restored to preproject condition following installation of the culvert.

(e) The culvert shall be installed in the dry, or in isolation from stream flow by the installation of a bypass flume or culvert, or by pumping the stream flow around the work area. Exception may be granted if siltation or turbidity is reduced by installing the culvert in the flowing stream. The bypass reach shall be limited to the minimum distance necessary to complete the project. Fish stranded in the bypass reach shall be safely removed to the flowing stream.

(f) Wastewater, from project activities and dewatering, shall be routed to an area outside the ordinary high water line to allow removal of fine sediment and other contaminants prior to being discharged to state waters.

(g) Imported fill which will remain in the stream after culvert removal shall consist of clean rounded gravel ranging in size from one-quarter to three inches in diameter. The use of angular rock may be approved from June 16 to September 30, where rounded rock is unavailable. Angular rock shall be removed from the watercourse and the site restored to preproject conditions upon removal of the temporary culvert.

(h) The culvert and fill shall be removed, and the disturbed bed and bank areas shall be reshaped to preproject configuration. All disturbed areas shall be protected from erosion, within seven days of completion of the project, using vegetation or other means. The banks shall be revegetated within one year with native or other approved woody species. Vegetative cuttings shall be planted at a maximum interval of three feet (on center), and maintained as necessary for three years to ensure eighty percent survival. Where proposed, planting densities and maintenance requirements for rooted stock will be determined on a site-specific basis. The requirement to plant woody vegetation may be waived for areas where the potential for natural revegetation is adequate, or where other engineering or safety factors need to be considered.

(i) The temporary culvert shall be removed and the approaches shall be blocked to vehicular traffic prior to the expiration of the HPA.

(j) Temporary culverts may not be left in place for more than two years from the date of issuance of the HPA.

(3) Permanent culvert installation.

(a) In fish bearing waters or waters upstream of a fish passage barrier (which can reasonably be expected to be corrected, and if corrected, fish presence would be reestablished), culverts shall be designed and installed so as not to impede fish passage. Culverts shall only be approved for installation in spawning areas where full replacement of impacted habitat is provided by the applicant.

(b) To facilitate fish passage, culverts shall be designed to the following standards:

(i) Culverts may be approved for placement in small streams if placed on a flat gradient with the bottom of the culvert placed below the level of the streambed a minimum of twenty percent of the culvert diameter for round culverts, or twenty percent of the vertical rise for elliptical culverts (this depth consideration does not apply within bottomless culverts). Footings of bottomless culverts shall be buried sufficiently deep so they will not become exposed by scour within the culvert. The twenty percent placement below the streambed shall be measured at the culvert outlet. The culvert width at the bed, or footing width, shall be equal to or greater than the average width of the bed of the stream.

(ii) Where culvert placement is not feasible as described in (b)(i) of this subsection, the culvert design shall include the elements in (b)(ii)(A) through (E) of this subsection:

(A) Water depth at any location within culverts as installed and without a natural bed shall not be less than that identified in Table 1. The low flow design, to be used to determine the minimum depth of flow in the culvert, is the two-year seven-day low flow discharge for the subject basin or ninety-five percent exceedance flow for migration months of the fish species of concern. Where flow information is unavailable for the drainage in which the project will be conducted, calibrated flows from comparable gauged drainages may be used, or the depth may be determined using the installed no-flow condition.

(B) The high flow design discharge, used to determine maximum velocity in the culvert (see Table 1), is the flow that is not exceeded more than ten percent of the time during the months of adult fish migration. The two-year peak flood flow may be used where stream flow data are unavailable.

(C) The hydraulic drop is the abrupt drop in water surface measured at any point within or at the outlet of a culvert. The maximum hydraulic drop criteria must be satisfied at all flows between the low and high flow design criteria.

(D) The bottom of the culvert shall be placed below the natural channel grade a minimum of twenty percent of the culvert diameter for round culverts, or twenty percent of the vertical rise for elliptical culverts (this depth consideration does not apply within bottomless culverts). The downstream bed elevation, used for hydraulic calculations and culvert placement in relation to bed elevation, shall be taken at a point downstream at least four times the average width of the stream (this point need not exceed twenty-five feet from the downstream end of the culvert). The culvert capacity for flood design flow shall be determined by using the remaining capacity of the culvert.

Table 1
Fish Passage Design Criteria for Culvert Installation

Criteria	Trout > 6 in. (150mm)	Adult Pink Salmon	Adult Chinook, Coho, Sockeye, Steelhead
1. Velocity, Maximum (fps)			
Culvert Length (ft)			
a. 10 – 60	4.0	5.0	6.0
b. 60 – 100	4.0	4.0	5.0
c. 100 – 200	3.0	3.0	4.0
d. > 20 0	2.0	2.0	3.0
2. Flow Depth Minimum (ft)	0.8	0.8	1.0
3. Hydraulic Drop, Maximum (ft)	0.8	0.8	1.0

(E) Appropriate statistical or hydraulic methods must be applied for the determination of flows in (b)(ii)(A) and (B) of this subsection. These design flow criteria may be modified for specific proposals as necessary to address unusual fish passage requirements, where other approved methods of empirical analysis are provided, or where the fish passage provisions of other special facilities are approved by the department.

(F) Culvert design shall include consideration of flood capacity for current conditions and future changes likely to be encountered within the stream channel, and debris and bedload passage.

(c) Culverts shall be installed according to an approved design to maintain structural integrity to the 100-year peak flow with consideration of the debris loading likely to be encountered. Exception may be granted if the applicant provides justification for a different level or a design that routes that flow past the culvert without jeopardizing the culvert or associated fill.

(d) Disturbance of the bed and banks shall be limited to that necessary to place the culvert and any required channel modification associated with it. Affected bed and bank areas outside the culvert and associated fill shall be restored to preproject configuration following installation of the culvert, and the banks shall be revegetated within one year with native or other approved woody species. Vegetative cuttings shall be planted at a maximum interval of three feet (on center), and maintained as necessary for three years to ensure eighty percent survival. Where proposed, planting densities and maintenance requirements for rooted stock will be determined on a site-specific basis. The requirement to plant woody vegetation may be waived for areas where the potential for natural revegetation is adequate, or where other engineering or safety factors preclude them.

(e) Fill associated with the culvert installation shall be protected from erosion to the 100-year peak flow.

(f) Culverts shall be designed and installed to avoid inlet scouring and shall be designed in a manner to prevent erosion of streambanks downstream of the project.

(g) Where fish passage criteria are required, the culvert facility shall be maintained by the owner(s), such that fish passage design criteria in Table 1 are not exceeded. If the structure becomes a hindrance to fish passage, the owner shall be responsible for obtaining a HPA and providing prompt repair.

(h) The culvert shall be installed in the dry or in isolation from the stream flow by the installation of a bypass flume or culvert, or by pumping the stream flow around the work area. Exception may be granted if siltation or turbidity is reduced by installing the culvert in the flowing stream. The bypass reach shall be limited to the minimum distance necessary to complete the project. Fish stranded in the bypass reach shall be safely removed to the flowing stream.

(i) Wastewater, from project activities and dewatering, shall be routed to an area outside the ordinary high water line to allow removal of fine sediment and other contaminants prior to being discharged to state waters.

[Statutory Authority: RCW 75.08.080. 94-23-058 (Order 94-160), § 220-110-070, filed 11/14/94, effective 12/15/94. Statutory Authority: RCW 75.20.100 and 75.08.080. 83-09-019 (Order 83-25), § 220-110-070, filed 4/13/83.]

APPENDIX C: MEASURING CHANNEL WIDTH

SUMMARY

- Bankfull width is the preferred measurement for designing water crossings.
- Bankfull width is commonly defined as the width at incipient flood, but it is more practically defined for Washington tributaries as the width between channel indicators.
- Bankfull width is best determined in the field but can be confirmed with a regional regression using watershed characteristics. A regression equation is supplied for western Washington gravel-bedded steams.
- A method for measuring bankfull width is given along with a series of example photographs.

INTRODUCTION

At least three definitions commonly used to describe channel width:

- Active channel width
- Ordinary high water width
- Bankfull width

In Washington, the actual, measured, channel width may not vary significantly among these definitions. The language used to describe them is similar and we would expect them to be about the same in some circumstances. But in many cases they are different and this appendix was written to help the water crossing designer measure channel width correctly.

These definitions were developed for, and apply primarily to, alluvial channels – those formed by the action of flowing water. There is a group of non-alluvial channels (backwatered, bedrock, underfit, channelized, colluvial or debris-controlled channels) that have a “channel width,” although this may or may not be useful for the design of crossing structures since that width does not respond to the frequency or magnitude of channel-defining flows.

The term “active channel” is a geomorphic expression describing a stream’s recent discharges, those that have been “actively” working on the channel in the last few years. Beyond the boundaries of the active channel, stream features are typically permanent and vegetated (Hedman and Kastner 1977). The upper limit of the active channel is defined by a break in the relatively steep bank slope of the active channel to a more gently sloping surface beyond the edge. This normally corresponds to the lower limit of perennial vegetation. Features inside the active channel are partially if not totally sculpted by the normal process of water and sediment discharge (Hedman and Osterkamp 1982).

The term, “ordinary high water line” is defined in several places in state law (*e.g.* WAC 220-110-020) as:

> “the mark on the shores of all waters that will be found by examining the bed and banks and ascertaining where the presence and action of waters are so common and usual and so long

> continued in ordinary years, as to mark upon the soil or vegetation a character distinct from that of the abutting upland; Provided, That in any area where the ordinary high water line cannot be found the ordinary high water line adjoining saltwater shall be the line of mean higher high water and the ordinary high water line adjoining freshwater shall be the elevation of the mean annual flood."

The distance between ordinary high water (OHW) marks on the bank is considered the ordinary high water width. Since OHW is the term used in the WAC 220-110-070 water crossings provisions, it has been applied to these designs in the past. We now understand that OHW varies considerably depending on the channel size and type, and that for the purposes of bridge and culvert design, bankfull width is a more appropriate design parameter. A thorough and well-researched discussion of OHW can be found in the Dept. of Ecology's *DETERMINING THE ORDINARY HIGH WATER MARK ON STREAMS IN WASHINGTON STATE* (Olson and Stockdale 2008). This document also clearly defines the difference between OHW and bankfull.

BANKFULL WIDTH

The "bankfull channel" is defined as the stage when water just begins to overflow into the active floodplain. In order for this definition to apply a floodplain or a bench is required – features often not found along many Washington tributary streams (Pleus, Schuett-Hames et al. 1998). Incised channels, for instance, do not have bank heights that relate to "bankfull" discharges and may never be overtopped(Williams 1978). The U.S. forest service manual, *STREAM CHANNEL REFERENCE SITES* (Harrelson, Rawlins et al. 1994), use features to determine channel width that do not depend on a floodplain; features that are similar to those used in the description of active channel and ordinary high water:

- A change in vegetation (especially the lower limit of perennial species);
- A change in slope or topographic breaks along the bank;
- A change in the particle size of bank material, such as the boundary coarse cobble or gravel with fine-grained sand or silt;
- Undercuts in the bank, which usually reach interior elevation slightly below the bankfull stage;
- The height of depositional features, especially the top of the point bar, which defines the lowest possible level for bankfull stage; and/or
- Stain lines or the lower extent of lichens on boulders.

Using a combination of indicators at a variety of locations improves the estimation of the channel width, since stream anomalies may mask or accentuate a given mark on the bank. As an example, perennial vegetation may grow lower on the bank during the dry period, not only lowering that indicator but forcing the channel into a more constricted width in that reach. In an adjacent reach the upper-story canopy may be denser, limiting understory growth on the stream banks negating the effect.

For culverts, the designer should use these indicators to determine channel width, unless there are legitimate reasons not to use them. One such case is alluvial channels in lower-gradient reaches with a true floodplain. These channels have more traditionally defined bankfull width indicators (Rosgen 1994) and should be used instead. The floodplain is the relatively flat area adjoining the channel, and the bankfull width is the horizontal distance from the break between channel and floodplain on one side of the channel to the other side of the channel. Floodplains may be discontinuous, or may occur on only one side, so measurements must be taken at appropriate locations. The indicators listed above also apply to alluvial channels and provide additional indicators for identifying bankfull width in alluvial channels (Dunne and Leopold 1978; Pleus, Schuett-Hames et al. 1998).

For bridges on larger rivers, floodplains are often present and bankfull width is easy to measure. This also means that the relative importance of bankfull is diminished because a greater proportion of the total flow is on the floodplain. The *floodplain utilization ratio*, explained in detail in ***Chapter 4***, describes the relative importance of the floodplain in bridge and culvert design.

Even if we can carefully describe and determine channel width indicators, measuring channel width is not easy. The next section discusses some watershed methods. The final section describes how to measure channel width.

Watershed Characteristics

There is a fundamental connection between watershed characteristics and channel width. This can be estimated for a given region by using s regression correlating the watershed area, rainfall and channel width.

Over the years WDFW has measured channel width as well as the average annual precipitation and watershed area for a large number of steams. Fifty-three high gradient (>2%), coarse bedded (bed material gravel and coarser) streams in western Washington were used to develop a regression relationship. The analysis was done using log values. The following equation is the result of that multivariate regression:

$W_{ch} = 0.95*WA^{0.45}AAP^{0.61}$ **Equations C.1**

Where

W_{ch} = width of the bankfull channel in feet

WA = watershed area in square miles

AAP = average annual precipitation in inches per year.

The standard error associated with this equation is 16%. The graph below, ***Figure C-1*** shows the relationship between the measured channel width and the calculated channel width, blue diamonds. Also shown are the measured and calculated channel widths for an independent data set from the stream simulation culvert effectiveness study (Barnard, Yokers et al. 2011), red Xs.

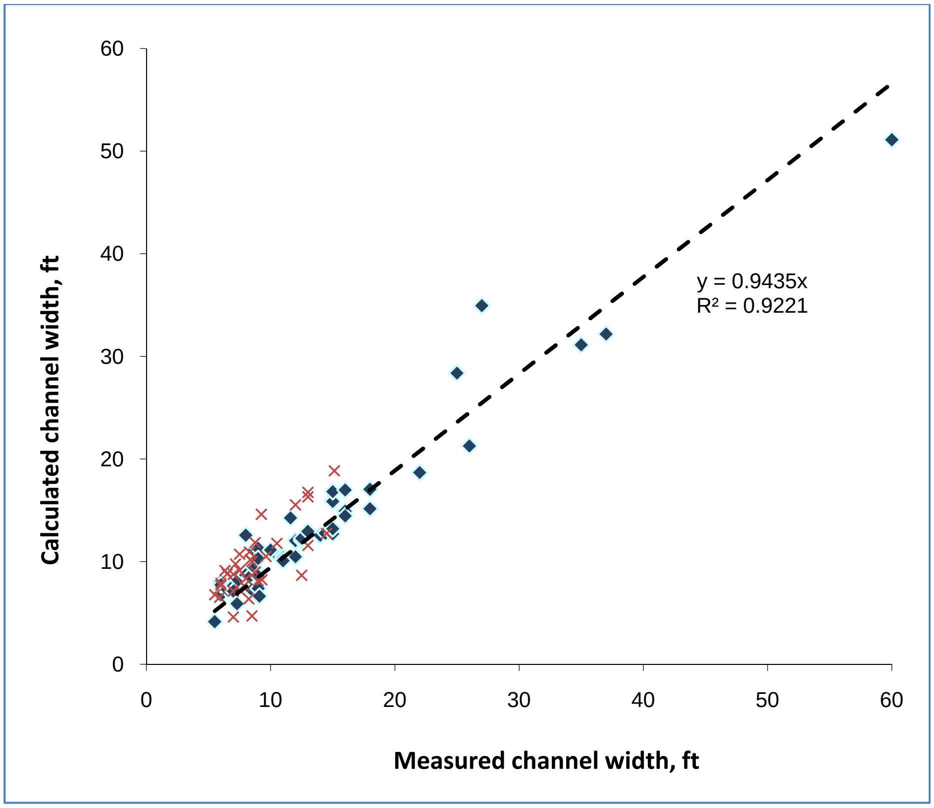


Figure C.1: Measured channel width of selected sites compared to calculated channel width. Blue diamonds are the regression data and red Xs an independent data set.

This equation has proven to be accurate and useful. While it is no substitute for actual measurements, it does help to point out what is a reasonable measurement and what is not. This regression can also be used when there is no easily-measured channel width in the reach containing the crossing.

Once channel cross sections have been measured, it is possible to use modeled flows to determine channel width. This is not an invitation to use a given flood flow to design a culvert or a bridge, but as a way to help better define the bankfull with in a natural cross section. This may seem an academic distinction, but it is not: many factors influence the development of channel shape and these cannot be assumed or simulated in a theoretical cross section. As part of the stream simulation culvert effectiveness study (Barnard, Yokers et al. 2011), bankfull width was measured and the width of the water surface at the 2-year recurrence interval flood (as calculated from USGS regression equations) was calculated. ***Figure C-2*** shows the relationship between these two widths. While there is a fair amount of scatter, there is a general trend. The 2-year flood width can be both greater or less than the measured bankfull width, but a linear regression shows that it is about 15% wider.

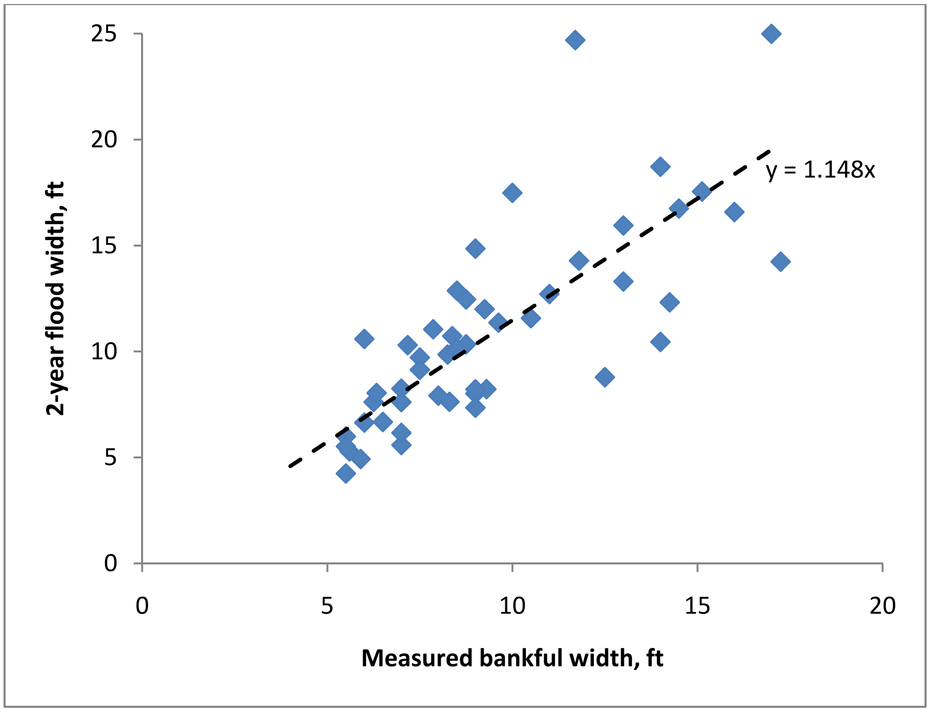


Figure C.2: Measured bankfull width compared to the estimated width based on a 2-year flood.

This data tells us that in these high gradient coarse-bedded streams the width of the bankfull channel is similar, though slightly smaller than the top with of a 2-year flood. This is in keeping with the WAC 220-110-020 provision that "ordinary high water line adjoining freshwater shall be the elevation of the mean annual flood," which is about the 2.3-year flood.

Measuring Bankfull Width

Theoretically, the average of a large enough number of random width measurements will yield an average stream width. This may be true in alluvial streams where the bed and banks are freely modified by stream flow and have developed over many years in the absence of various forcing factors and unmodified by man. Very few tributaries in Washington are like this and we need to be careful where we measure or we will get an inaccurate bankfull width.

In a natural Washington setting with abundant wood there are many things that make a steam wider, but few that make it narrower. Examples of factors that increase width include; full or partial spanning logs embedded into the bed; full spanning log jams; gravel bars or sediment wedges; increased roughness from vegetation; backwater above a constriction of any sort. So, an average of evenly spaced widths will tend to be wider than the alluvial bankfull width. One must measure a bankfull width outside the influence of these factors that tend to increase the channel width. These are described below.

Undersized culverts and bridges, because of the heavy inlet and outlet energy losses, tend to widen the channel. One should obviously be well outside their influence. Severely undersized culverts under big fills on low gradient streams can influence the channel for a surprisingly long distance upstream with deposits that fill and scour quite frequently.

In developed or urbanized streams, many things tend to decrease the channel width, such as bank protection measures and channelization.

Some of the concerns are specifically addressed in guidelines from the USFS reference channel guide (Harrelson, Rawlins et al. 1994):

- Where the channel has been realigned or modified by construction activity or in reaches lined with riprap, channel width will not be indicative of natural conditions. Usually these cross sections will be substantially narrower.
- Avoid reaches with cemented sediments, hard clay or bedrock.
- Large pools downstream of culverts or confined steep sections will be wider than channel width.
- Braided sections will indicate a wider width than single-thread reaches on the same stream (although, if the culvert is located in a naturally braided section, culvert sizing should reflect conditions).
- Avoid unusually shaped cross sections and sharp bends.
- Areas of active bank cutting, degradation or deposition may indicate that width is in the process of changing, in which case, conservative culvert sizing is recommended.
- Areas with natural or man-made log sills or channel-modifying logjams will affect width. These can be very common in forested, western Washington streams. Width measurements should be taken between such structures, but be sure to avoid backwater effects.
- Side channels, especially those that go undetected and act only at high flow, narrow the measured channel width.
- Active and remnant beaver dams obscure flow-generated channel processes.
- Dense vegetation and small woody debris in the channel increase the channel width and fragment the flow.
- Know the recent flood or drought history of the area to avoid misleading indicators.

Incised channels pose some problems when trying to determine bankfull width. Channel incision is a transitional state where the stream tries to seek equilibrium by reducing slope. Where in the time span of this transitional state one measures width influences the result; the channel starts out narrow, but as it reaches its final elevation, it widens and develops floodplain. In addition, the type of soils the channel is cutting into will also influence the result. Incised channels in cohesive materials may have a measured width only a fraction of what it would be if it was connected to a floodplain. On the other hand, streams incised into granular soils – Rosgen's type F8 (Rosgen 1996)– may be wider than the equivalent type C. One must carefully study the channel and refer to experts in this area to correctly measure bankfull width. It is not recommended that culvert sizes be reduced for streams that have been narrowed by incision, except with appropriate site analysis, since it is rarely clear what the appropriate measured width should be.

Examples of Bankfull Width Measurements

Examples of some typical tributary stream bankfull widths and additional data are shown on the following pages. Yellow line on photos shows the approximate bankfull width.

Figure C.3

Site ID	1
Stream name	Summit
Channel width, ft	6
Reach slope, ft/ft	0.028
Floodplain utilizatin ratio	1.9
Stream type	Plane Bed
% cut banks	0
% soft bank	100
% hard bank	0
D50, ft	0.03
D84, ft	0.05
D100, ft	0.1
Watershed area, sq mi	5.32
AAP, in/yr	22
Q2, cfs	21
Q100	100
Level 3 Ecoregion	North Cascades

Small high elevation headwater stream. Scoured roots and sloped floodplain clearly indicate bankfull channel.

Figure C.4

Site ID	2
Stream name	Chilliwist
Channel width, ft	4
Reach slope, ft/ft	0.005
Floodplain utilization ratio	10.2
Stream type	Wetland
% cut banks	0
% soft bank	100
% hard bank	0
D50, ft	0.02
D84, ft	0.02
D100, ft	3
Watershed area, sq mi	3.1
AAP, in/yr	20
Q2, cfs	11
Q100	57
Level 3 Ecoregion	North Cascades

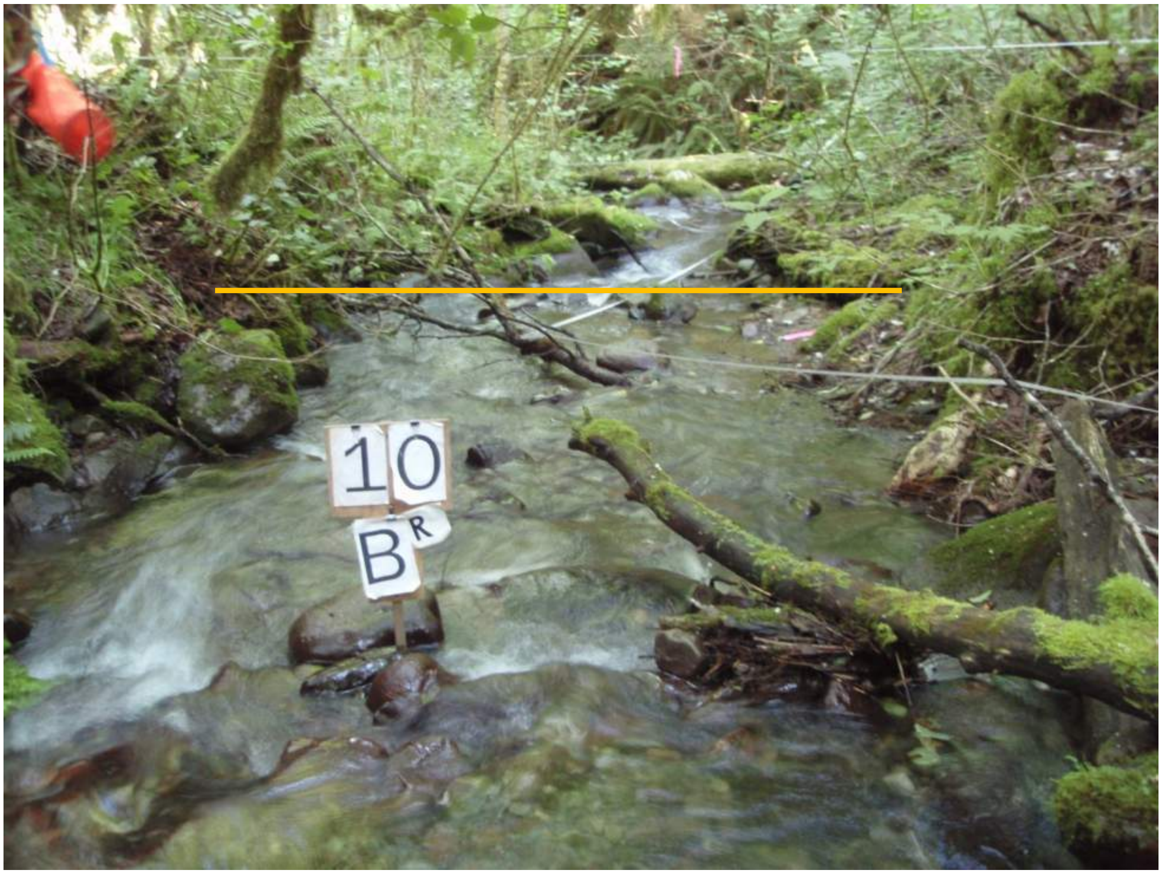
Wetland channel with a high FUR. Well defined channel controlled by vegetation. Culvert span should be increased beyond recommendations in **Chapters 2** and **3** to compensate for wide floodplain.

Figure C.5

Site ID	4
Stream name	Cecile Ck
Channel width, ft	17
Reach slope, ft/ft	0.060
Floodplain utilization ratio	1.6
Stream type	Cascade
% cut banks	0
% soft bank	0
% hard bank	100
D50, ft	0.64
D84, ft	1.27
D100, ft	3.7
Watershed area, sq mi	17.2
AAP, in/yr	24
Q2, cfs	68
Q100, cfs	298
	North Cascades

This steep, coarse-beded stream is largely non-alluvial. Bankfull indicator is the upper edge of coarse sediment. Annual vegetation grows down into the bankfull channel but does not define it.

Figure C.6



Site ID	10
Stream name	X-Nooksack
Channel width, ft	9
Reach slope, ft/ft	0.076
Floodplain utilization ratio	1.5
Stream type	Step - Pool
% cut banks	5
% soft bank	90
% hard bank	10
D50, ft	0.31
D84, ft	0.79
D100, ft	2.3
Watershed area, sq mi	1.4
AAP, in/yr	67
Q2, cfs	69
Q100	211
Level 3 Ecoregion	North Cascades

Very similar but smaller version the previous channel, ID 4. This channel is in the moist western region and the previous one in the arid east.

Figure C.7

Site ID	18
Stream name	x SF Willapa
Channel width, ft	8
Reach slope, ft/ft	0.018
Floodplain utilization ratio	11.9
Stream type	Wetland
% cut banks	95
% soft bank	100
% hard bank	0
D50, ft	0.06
D84, ft	0.1
D100, ft	0.2
Watershed area, sq mi	0.34
AAP, in/yr	118
Q2, cfs	48
Q100	109
Level 3 Ecoregion	Coast Range

Broad wetland floodplain with well-defined bankfull channel. High floodplain roughness reduces overbank flow and the need for a larger culvert in this instance.

Figure C.8

Site ID	19
Stream name	Trib to mill ck
Channel width, ft	9
Reach slope, ft/ft	0.026
Floodplain utilization ratio	2.0
Stream type	Bedrock
% cut banks	80
% soft bank	100
% hard bank	0
D50, ft	0
D84, ft	0
D100, ft	0.2
Watershed area, sq mi	0.74
AAP, in/yr	76
Q2, cfs	52
Q100, cfs	144
Level 3 Ecoregion	Coast Range

Figure C.9

Site ID	20
Stream name	Midway Ck.
Channel width, ft	10
Reach slope, ft/ft	0.051
Floodplain utilization ratio	1.4
Stream type	Step - Pool
% cut banks	10
% soft bank	85
% hard bank	15
D50, ft	0.24
D84, ft	0.59
D100, ft	2
Watershed area, sq mi	0.52
AAP, in/yr	81
Q2, cfs	41
Q100, cfs	115
Level 3 Ecoregion	Coast Range

Figure C.10

Site ID	22
Stream name	x S.F. Ahtanum
Channel width, ft	14
Reach slope, ft/ft	0.055
Floodplain utilization ratio	1.4
Stream type	Cascade
% cut banks	35
% soft bank	35
% hard bank	65
D50, ft	0.43
D84, ft	0.94
D100, ft	1.8
Watershed area, sq mi	5.5
AAP, in/yr	41
Q2, cfs	59
Q100, cfs	264
Level 3 Ecoregion	Eastern Cascades Slopes and Foothills

Figure C.11

Site ID	24
Stream name	Nasty Ck
Channel width, ft	12
Reach slope, ft/ft	0.035
Floodplain utilization ratio	1.5
Stream type	Step - Pool
% cut banks	0
% soft bank	Na
% hard bank	Na
D50, ft	0.25
D84, ft	0.55
D100, ft	1.1
Watershed area, sq mi	8.3
AAP, in/yr	32
Q2, cfs	82
Q100, cfs	362
Level 3 Ecoregion	Eastern Cascades Slopes and Foothills

Figure C.12

Site ID	27
Stream name	Paw Print
Channel width, ft	8
Reach slope, ft/ft	0.069
Floodplain utilization ratio	1.2
Stream type	Step - Pool
% cut banks	25
% soft bank	75
% hard bank	25
D50, ft	0.33
D84, ft	0.9
D100, ft	2.5
Watershed area, sq mi	0.25
AAP, in/yr	95
Q2, cfs	26
Q100, cfs	84
Level 3 Ecoregion	Cascades

Figure C.13

Site ID	28
Stream name	Green Gold/Wildcat
Channel width, ft	6
Reach slope, ft/ft	0.036
Floodplain utilization ratio	2.1
Stream type	Pool - Riffle
% cut banks	25
% soft bank	75
% hard bank	25
D50, ft	0.09
D84, ft	0.21
D100, ft	1.12
Watershed area, sq mi	0.27
AAP, in/yr	64
Q2, cfs	15
Q100, cfs	48
Level 3 Ecoregion	Puget Lowland

Figure C.14

Site ID	31
Stream name	Taylor Ck
Channel width, ft	14
Reach slope, ft/ft	0.049
Floodplain utilization ratio	1.7
Stream type	Cascade
% cut banks	35
% soft bank	65
% hard bank	35
D50, ft	0.11
D84, ft	0.35
D100, ft	3.5
Watershed area, sq mi	Na
AAP, in/yr	Na
Q2, cfs	22
Q100, cfs	64
Level 3 Ecoregion	Puget Lowland

Figure C.15

Site ID	33
Stream name	Xtrib Puget Sound
Channel width, ft	9
Reach slope, ft/ft	0.017
Floodplain utilization ratio	1.7
Stream type	Pool - Riffle
% cut banks	20
% soft bank	80
% hard bank	20
D50, ft	0.13
D84, ft	0.25
D100, ft	0.6
Watershed area, sq mi	1.17
AAP, in/yr	30
Q2, cfs	18
Q100, cfs	49
Level 3 Ecoregion	Puget Lowland

Figure C.16

Site ID	39
Stream name	Bear Ck
Channel width, ft	16
Reach slope, ft/ft	0.009
Floodplain utilization ratio	1.2
Stream type	Pool - Riffle
% cut banks	5
% soft bank	95
% hard bank	5
D50, ft	0.18
D84, ft	0.37
D100, ft	0.9
Watershed area, sq mi	2.4
AAP, in/yr	54
Q2, cfs	80
Q100, cfs	237
Level 3 Ecoregion	Coast Range

Figure C.17

Site ID	44
Stream name	Newberry Ck
Channel width, ft	17
Reach slope, ft/ft	0.012
Floodplain utilization ratio	1.6
Stream type	Plane Bed
% cut banks	5
% soft bank	90
% hard bank	10
D50, ft	0.16
D84, ft	0.38
D100, ft	2.9
Watershed area, sq mi	1.22
AAP, in/yr	130
Q2, cfs	176
Q100, cfs	401
Level 3 Ecoregion	Coast Range

Figure C.18: Newberry Ck stage hydrograph superimposed over a surveyed cross section. This is the same cross section shown in Figure C.18. Newberry Ck is located in the coastal rain forest with an annual average precipitation of 130 inches. 2007 was a year with several large rain events, which are shown as peaks in the hydrograph, one of which was larger than the bankfull discharge. The important interpretation of this figure is that creeks generally run less than the bankfull stage and surpass it for only short periods of time, usually only a matter of a few hours every one or two years.

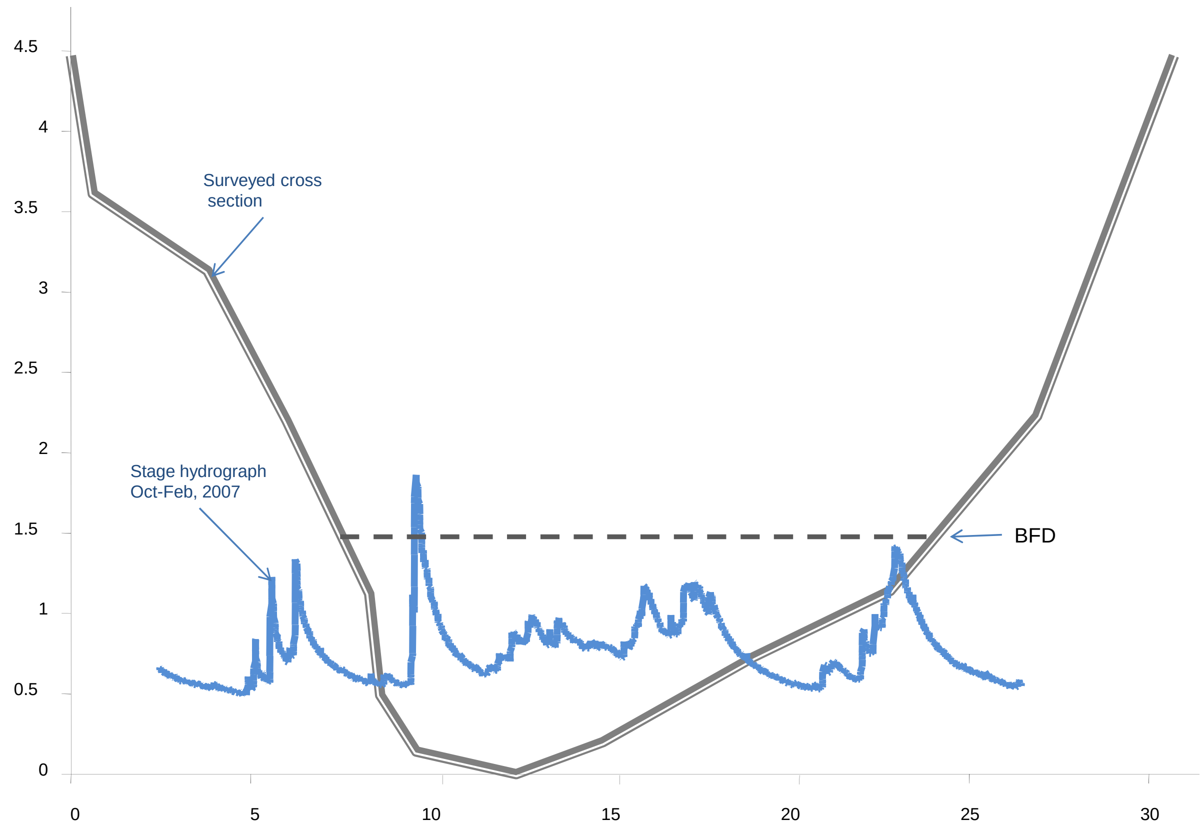


Figure C.19

Site ID	47
Stream name	SF Dogfish Ck
Channel width, ft	6
Reach slope, ft/ft	0.056
Floodplain utilization ratio	1.7
Stream type	Pool - Riffle
% cut banks	55
% soft bank	Na
% hard bank	Na
D50, ft	0.12
D84, ft	0.27
D100, ft	0.8
Watershed area, sq mi	0.4
AAP, in/yr	42
Q2, cfs	11
Q100, cfs	34
Level 3 Ecoregion	Puget Lowland

APPENDIX D: TIDALLY INFLUENCED CROSSINGS

Figure D.1: US 101 crossing of the Hama Hama River delta (Washington Dept. of Ecology photo).

SUMMARY

- Tidally influenced crossings require a different approach to design than those in non-tidal areas.
- Requirements at these crossings are complicated by the fact fish passage it is largely defined by upstream passage in freshwater streams, although tidally influenced crossings clearly have an effect on fishlife that must be avoided or mitigated.
- The design of estuarine openings in road embankments and dikes can be approached through an alternative analysis using a hierarchy of benefits.
    - A conceptual model of openings is used to define important components in a restoration scheme for two shoreforms commonly crossed by roadways in the nearshore
        - Barrier beaches
        - Deltas
    - The benefits of increasing crossing size are then analyzed for different alternatives.
    - The benefits of changing the crossing location in the estuary are examined.
    - An assessment process is described with three levels
        - Level 1, a qualitative assessment of tidal effects

- Level 2, a more sophisticated engineering approach
- Level 3, quantitative assessment with computer modeling

- A case study is used to show how the hierarchy of benefits works.

INTRODUCTION

The design of water crossings in tidally influenced areas is particularly complex. The degree to which the opening constricts or regulates tidal flow affects fish passage and natural processes in many ways. ***Figure D.1*** shows US 101 crossing the Hama Hama River delta on Hood Canal and how it truncates the delta and estuarine processes. Tidal bridge scour and longshore transport have been covered in the literature, but the effects of bridges and culverts on estuarine functions have not. This appendix is divided into two general sections; the concept of fish passage in a tidally influenced crossing (particularly culverts and tide gates) and the effects of the crossing on estuarine processes (mostly estuarine geomorphology). The second section on geomorphology can be extended to the sizing of dike breaches for restoration projects.

FISH PASSAGE

The law concerning fish passage at manmade barriers, RCW 77.57.030, is clear that a way to efficiently pass fish is required. *How efficiently* is not so clear and WAC 220-110-070 is the only technical guide we have for fish passage and habitat protection at crossings. The rule largely concerns the upstream migration of adult salmonids in riverine environments, a very different situation than tidally influenced crossings, both in terms of hydraulics and fish requirements and behavior. WAC 220-110-070 tells us to prefer bridges that do not constrict flow. This was covered in ***Chapter 4*** for riverine bridges and is discussed below (**Hierarchy of Benefits**) for tidal ones. Then the WAC says we should design culverts using the natural channel as our guide (***Chapter 2: No-Slope Culvert Design*** and by extension to higher gradient streams, ***Chapter 3: Stream Simulation Culvert Design***) or to create hydraulic conditions inside the culvert that do not exceed criteria more than 10% of the time during the migration season (***Chapter 6: Hydraulic Culvert Design***). The basis of this allowable exceedance, "90% passage," is rooted in several concerns.

Upstream migrating anadromous salmonids have a limited life span in fresh water. Any delay can reduce their spawning success and the extent to which they can populate a watershed. In addition, it was believed that while fish do migrate on low discharge floods, they hold in refuge areas during high flows. This has been shown to be false in *Improving stream crossings for fish passage* (Lang, Love et al. 2004)which found adult coho migrating at 2% exceedance flows. The issue of timing is less critical for adult fish in the estuary than it is for upstream migrating adults in fresh water. Whether the 90% passage criteria should be applied to tidal crossings is open to question. Some biologists believe that temporary blockages are not important, that timing is not critical for upstream moving adult salmonids from the estuary to fresh water. Groot and Margolis (Groot and Margolis 1991) state that coho mill about in the vicinity of a creek mouth for weeks or even months. Most salmon have the leisure to wait for freshets or appropriate temperatures. Where the culvert is backwatered by the flood tide, upstream passage is likely at some time during the tidal cycle and fish wait to move up. There is the possibility that the stimulus for migration coincides with unfavorable passage conditions. For example, the culvert is small enough that flood flow maintains a constant, high velocity outflow even with tidal backwater.

As discussed extensively throughout this guideline, the passage of salmonid adults is only one aspect of fish migration and this is abundantly clear in the estuarine setting. Many other species of fish and life stages are present year round in the estuary and move freely in response to tidal conditions, predator /prey relationships, and other behavior and environmental factors. Crossings that limit the movement of these fish and their prey affect the whole food web (Clancy, Logan et al. 2009). Design strategies that optimize the passage of adult salmonids will clearly be inadequate to address the passage of "fish" at tidally influenced crossings.

The previous edition of this guideline, *FISH PASSAGE AT ROAD CULVERTS* (Bates, Barnard et al. 2003), stated that conditions inside the culvert must meet the hydraulic design criteria, but where replacement of the culvert is not possible, alternatives might be acceptable. An example is given that specifies a maximum time period that the criteria can be exceeded (maximum of 4 continuous hours at any time during the fish passage season). This example is not supported by WAC and is not necessarily recommended for all cases, or any particular case. In the same section, *FISH PASSAGE AT ROAD CULVERTS* described 90% tidal exceedance elevations for four marine locations. Culverts were said to be passable at tides above this level 90% of the time. This observation only shows that access to the culvert and backwatering above the invert occurs frequently, but passage is not assured since it is dependent on stream flow, culvert size, approach channel conditions, fish species and timing. Hydraulic conditions are evaluated using both stream flow and stored tidal prism.

If the culvert is small with respect to the tidal range, then it is only periodically available to small fish travelling along the nearshore in the top layer of the water column at certain tide elevations. If the outlet of the culvert is located significantly below MLLW, then juvenile fish are unlikely to find the opening since they tend to migrate in the top layer of water. Conversely, if a culvert has been installed at a high elevation, it is only available or backwatered at the top of the tidal frame. Increasing the culvert rise is one way to increase access, but replacing the culvert with an open channel is preferred. Small size will also affect tidal inundation, tidal channel development, salinity mixing, and other estuarine functions.

ESTUARINE OPENING GEOMORPHOLOGY - HIERARCHY OF BENEFITS

(with Jeremy Lowe, Phillip Williams, Bob Battalio and Sara Townsend, ESA PWA)

INTRODUCTION

A hierarchy of benefits will likely accrue to the natural processes, structure, and function of an ecosystem for variously located and sized openings in crossings of tidal and tidally influenced fluvial channels. There is a dearth of information regarding the ecological impacts of constructing bridges or culverts across tidally influenced areas in the scientific literature. While hydrological and hydraulic impacts, such as amount and extent of anticipated scouring and longshore transport of sediment, are carefully considered during crossing design, impacts to overall geomorphology and ecological function are not. This may be because many decisions establishing culvert or bridge crossing design practice were made prior to 1969, before the passage of federal and state statutes that require inclusion of environmental impacts. Almost all tidal channel crossings were, and sometimes still are, designed to simply optimize hydraulic conveyance for drainage or design floods at least cost. The loss of connectivity that occurs when dikes are constructed across wetlands and floodplains is well documented (see C***hapter 4***). Embanked bridge crossings can generate similar environmental impacts because they too may restrict the flow of animals, water, sediment, organic plant material and detritus (again, see ***Chapter 4***). Today, however, there is an opportunity to assess and rectify the impacts of existing structures through restoration and the design of new structures. The question that will need to be addressed is: what are the tradeoffs between enhanced ecologic benefits and restoration costs for breaches or bridges larger than those required for hydraulic conveyance and simple fish passage?

The hierarchy of benefits represents a new approach to crossing design by expanding its view from the minimum opening size that the hydraulics requires to one that considers how location and size of openings will impact the morphology and ecology of the ecosystem. Crossing designers can use this approach to determine the crossing width which has the maximum benefit for the lowest incremental cost.

Conceptual Models Of Openings

The Puget Sound Nearshore Ecosystem Restoration Program (PSNERP) has described 21 management measures that that can be used to develop and evaluate Puget Sound nearshore restoration alternatives at individual sites. One of these, Management Measure 3 (MM3)(Clancy, Logan et al. 2009), describes in detail the need for and expected outcomes of dike removal or modification. Dike or levee removal restores processes such as the reintroduction of historically present hydraulic forces and sediment transport that can induce structural changes in the tidal channel network and recolinization of tidal marsh vegetation. The functional responses to these changes are the valued good and services like increased numbers of fish and wildlife, including salmon and waterfowl. This model connects our planning and design decisions to those things that we would like to, or are required by law to protect and preserve.

Similarly, Management Measure 9 (MM9) describes the need for and expected outcomes of hydraulic modification. MM9 has expected outcomes comparable to MM3 and its conceptual model expresses how the restoration action (replace tide gate with open breach) will likely restore processes and create structural changes to improve salmon production and enhance other nearshore functions. These two management measures (dike removal or modification and hydraulic modification without full levee/dike removal) will result in different types of openings across a tidally influenced area, such as a marsh or delta. However, both measures offer potential to improve degraded conditions caused by a more constricted opening.

The impacts of opening width location and size need to be considered not only on tidal and fluvial hydrology, but also on the geomorphic and ecologic processes of the broader tidally influenced area. This adds an additional dimension to the conceptual model described above because the rate at which ecosystem process restoration goals can be achieved will be impacted by these characteristics.

IMPACTS OF CROSSING SIZE ON BARRIER ESTUARIES

Barrier estuaries are fronted by a continuous ridge of sand deposited above high tide. They form across embayments or places along the shoreline that lead to the accumulation of sediment. Ecologic functioning of a number of barrier estuaries in the Puget Sound is constrained by road crossings. Typically, a road embankment has been constructed that follows the alignment of the natural barrier beach ***Figure D.2***. The connection to tidal waters is often restricted to a single culvert or constricted bridge crossing, and sometimes a tide gate. In addition, the inlet is often fixed in location and high tide storm surge flows across the barrier beach are prevented by the embankment acting as a dike. This reduces general flow over the marsh surface toward the bay front and eliminates wave action within the estuary.

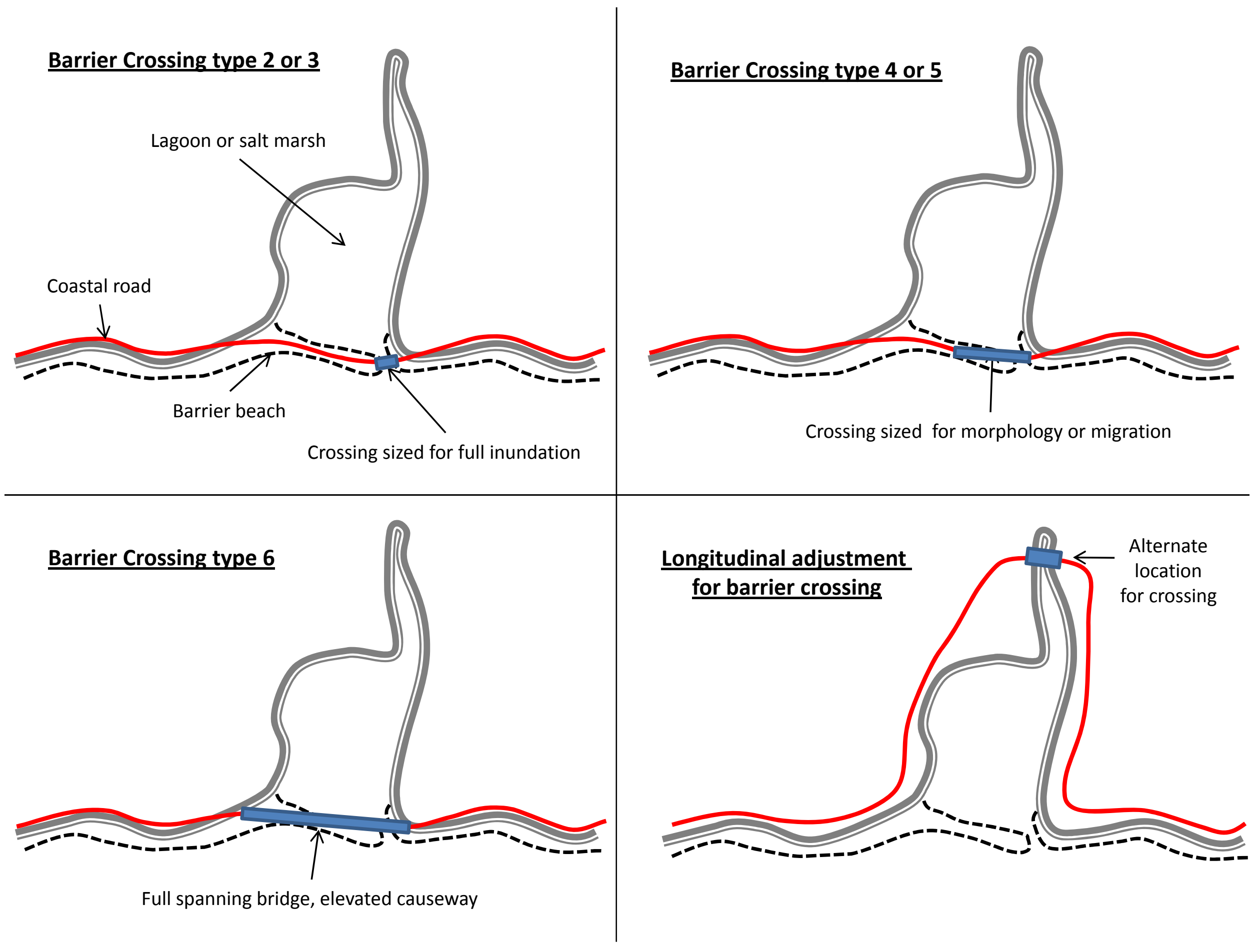


Figure D.22: A barrier beach shore form and several types of crossings discussed in the text.

The potential impacts of crossings on barrier estuaries are listed in ***Table 1*** in terms of hydraulic and sedimentary processes and geomorphic and water quality impacts. The size of the inlet is often limited by the crossing structure, which may partially or completely block the flow of water and mute the tide. This has implications for the location of head of tide and tidal prism volume. Small openings in the roadway or dike may partially or completely block detritus, large woody debris, and organic plant material from entering and exiting the estuary. Intertidal habitats landward of the causeway may aggrade at a higher rate than areas outside due to the capture of sediment conveyed by floods from a contributing watershed, or degrade when isolated from deposition of estuarine sediments brought in by long shore drift or on flood tides, making these marshes more susceptible to the effects of sea level rise and geologic subsidence.

Further, these impacts do not occur in isolation. For example, within a barrier estuary, alteration of the tidal signal has multiple hydrodynamic and geomorphic impacts including the lowering of high tide elevations, the raising of low tide elevations, the raising of mean tide elevations, reducing the tidal frame, reducing the tidal prism in the marsh and reducing the tidal excursion. The structural and functional responses include isolation of marsh plains and conversion to fresher water habitats, a reduction in area of intertidal mudflat and sandflat habitat, siltation of tidal channels, an elevated water table affecting marsh to forest transition, a limited fluctuating water table affecting plant growth, atrophy of the channel system due to sedimentation and reduced channel connectivity, and passive transport of organisms into the estuary through baroclinic circulation.

The combination of embankment and reduced inlet size reduce both the area of habitat and habitat connectivity, which in turn impacts all aspects of ecosystem function including distribution and abundance of species, community dynamics, productivity, and invasive species.

In restoring the ecosystem functions of these estuaries, the main tool is to reduce the hydraulic constriction due to the crossing and thereby increase habitat connectivity. The size of the opening will determine the type and amount of ecosystem processes that are impacted. Emulating historic natural conditions by recreating the largest possible opening size will eliminate these impacts, while an artificially constricted opening size will likely produce all of them. Intermediately sized openings will have impacts between these two endpoints.

BENEFITS OF INCREASING BRIDGE CROSSING SIZE

To illustrate the degree to which ecological benefits increase as opening size increases, we have carried out an assessment of five general categories of crossings as described below (see ***Figure D.2***). These five crossing types are evaluated within the four constraints to processes in a qualitative way in ***Table 1*** and discussed below. These quantities represent the proportional decrease in a given stressor or constraint. The numbers in ***Table 1*** are not intended to be fixed quantities, but can be adjusted to suit a given situation. Overall, a valid assumption is that constraints to hydraulic and water quality processes are relatively easy to remove; that constraints to sedimentary processes are more difficult to remove; and geomorphic process are the most difficult to restore. The goal of this analysis is to use the relative sum of benefits, shown in the last row, combined with the relative costs to evaluate each alternative. That alternative which meets the project goals and does so with the lowest incremental cost is preferred. This process is further described in the case study at the end of this appendix.

The 5 alternative crossings are described below and shown in ***Figure D.2***, then quantitatively evaluated in ***Table D.1.***

1. <u>Tide Gate:</u> The tide gate alternative assumes a raised embankment or dike along the barrier beach. These manmade structures completely eliminate tidal inundation and the movement of sediment and organisms within the estuary, but allow marsh drainage. Tide gates profoundly affect all natural processes. Many social and economic values are supported by tide gates, however their use often conflicts with ecological restoration, which is the foundation of many other social values such as wildlife viewing, hunting, fishing, and other outdoor activities.

2. Culvert or Small Bridge: This alternative also assumes an embankment or dike has been constructed. Tidal flow is restricted to a single culvert or narrow bridge crossing sized to drain the area landward of the barrier. The tidal regime will be strongly muted. All flows over the barrier beach will be blocked by the embankment.

3. Expanded Inlet Size: This alternative assumes an expanded inlet size with large culverts or a bridge crossing to allow regular tidal inundation of the area landward of the barrier. The inlet crossing is designed to be the minimum size to allow the full average diurnal tidal range within the estuary, based on the hydraulic geometry for tidal channels. However, tidal velocities will be greater than naturally occurring at the inlet requiring armoring to prevent scour and lateral migration. In addition, storm surge tides will still be constricted. All flows over the barrier beach will be blocked by the embankment.

4. Expanded Inlet Size to allow for a Naturally Adjusting Channel Inlet to Form: This alternative would require a clear span bridge designed wide enough to allow a natural convex sided inlet channel that can adjust to storm surge tides. All flows over the barrier beach are blocked by the embankment.

5. Expanded Inlet Crossing to allow for Lateral Migration of the Inlet Channel: This alternative assumes a bridge would be sized not only for the appropriate inlet channel morphology, but also for historic lateral migration width. Laterally meandering inlets have a tendency to 'reset' the estuarine drainage system and marsh habitats through bank erosion and migrating flood tide shoals, and this process would be accommodated by this approach. All flows over the barrier beach are blocked by the embankment.

6. Complete Removal of Tidal Barriers: This would include a bridge crossing to allow inlet channel migration and replacement of the embankment with an elevated causeway on pilings. The former road embankment would be graded down to natural beach crest elevations to allow for storm surge inundation and transport of large woody debris (LWD) into the estuary. The input of LWD creates habitat structure for all trophic levels from algae to invertebrates to fishes and wildlife; it allows for various species to seek shelter, find food, spawn, roost or nest. LWD also impacts sediment movement, potentially creating beach berms. More recently, LWD has been cited in facilitating tidal marsh succession acts by providing a nursery habitat for salt-intolerant species (Maser and Sedell).

It should be noted that while this spectrum of design approaches addresses potential restoration options at a typical barrier beach estuary, the general approach could be similar if applied to other estuary types (i.e. riverine estuaries). However, special attention should be paid to any differences in estuary form or function which could affect the restoration approach. Specifically, river deltas are considered below.

Table D.1: A quantitative assessment of the impacts of various barrier beach crossings on nearshore ecosystem processes.

			Crossing type	1	2	2	4	5	6
			Process Impacts	Tide gate	Culvert or small bridge	Culvert sized to allow inundation of marsh plain	Bridge sized to inlet channel morphology	Bridge sized for migration width	Full-span bridge
	Process	**Structural Impact**	**Functional Response**						
Hydraulic/ Hydrodynamic Process Impacts	Alteration of tidal stage characteristics	Lowering of high tide elevations - isolates marsh plains and causes conversion to fresher habitats	Reduce marsh productivity and loss of aquatic habitat area	0	0.2	0.7	0.7	0.7	0.7
		Raising low tide elevations – reduces area area of intertidal mudflat/sandflat habitat	Reduction of benthic productivity and low interitdal habitat						
		Raising mean tide elevations – affecting marsh-to-forest transition	Change in productivity, species composition and organic export						
		Reduction in tidal frame	Water table fluctuation limited affecting plant growth						
		Reduction in tidal prism in marsh	Channel system atrophies through sedimentation; reduced channel connectivity						

		Reduced tidal excursion	Passive advective transport of organisms in and out of estuary diminished						
	Alteration of salinity distribution	Vertical salinity stratification degraded through mixing	Reduction of passive transport of organisms into estuary through baroclinic circulation	0	0	0.1	0.1	0.15	0.15
		Salinity mixing zone length truncated- 'squeezing'and reduction of brackish zone habitats	Salinity changes, reduced qualityof rearing habitat						
	Elimination of storm surge overwash across beach	Transport of large woody debris into marsh	Habitat heterogeneity reduced	0	0	0	0.1	0.15	0.15
		Mobilization of detritus due to storm surge wave action eliminated	Export of nutrients to estuary reduced						
			Category total	**0**	**0.2**	**0.8**	**0.9**	**1**	**1**
Sedimentary process impacts	Alluvial sedimentation altered by backwater affects	Fine sediment accumulates on marsh plain, shift to upland habitats	Reduce marsh productivity	0	0.1	0.2	0.3	0.5	0.5
		Coarse sediment accumulates in tidal channels	Loss of blind channel habitat						

	Estuarine sedimentation limited by reduction in tidal flows	Reduced tidal prism reduces sediment delivery to marsh plain, causes lowering relative to tidal frame	Reduced productivity of marsh vegetation	0	0.2	0.3	0.4	0.5	0.5
		Increased turbidity in tidal channels due to loss of marsh plain sediment sink	Adverse affect on benthic organisms and eelgrass						
			Category total	**0**	**0.3**	**0.5**	**0.7**	**1**	**1**
Geomorphic Impacts	Alteration of entrance channel morphology from broad shallow to narrow	Increased tidal velocity through entrance creates scour holes	Increased fish mortality	0	0	0.1	0.2	0.3	0.33
		Channel location fixed instead of lateral migration affecting ebb and flood shoal extent	Reduced production of benthic organisms						
		Fixed channel location may lead to permanent closure of confined marsh by longshore drift	Eliminates exchange of water, sediment, nutrients and organisms						
	Atrophied tidal drainage system	Tidal channels shallower	Degraded estuarine habitat	0	0	0	0.1	0.1	0.33
		Dendritic tidal channel system becomes disconnected	Estuarine habitat degraded						

	Marsh plain elevations changed	Lowered marsh plain	Reduced marsh productivity	0	0	0.1	0.1	0.2	0.33
		Areas raised by alluvial sedimentation	Change to freshwater or upland species						
			Category total	**0**	**0**	**0.2**	**0.4**	**0.6**	**1.00**
Water Quality Impacts	Increased residence time	Reduction in tidal exchange	Algal blooms in marsh channels, anoxic in poorly drained holes	0	0.3	0.4	0.5	0.5	0.5
		Reduction in tidal excursion	Export of water column productivity to larger estuary limited						
	Accumulation of toxics	Reduced tidal scouring allows accumulation of polluted sediments from watershed	Toxic effects on organisms	0	0.3	0.4	0.5	0.5	0.5
		Reduced residence time means concentration of dissolved pollutants in water column is higher	Toxic effects on organisms						
			Category total	**0**	**0.6**	**0.8**	**1**	**1**	**1**
			Sum of ecological benefits	**0**	**1.1**	**2.3**	**3**	**3.6**	**4.00**
			Relative sum of benefits	**0%**	**28%**	**58%**	**75%**	**90%**	**100%**

Impacts Of Crossing Size And Location On River Deltas

River Deltas are dynamic geomorphic landscapes, with river distributary channels that evolve and migrate in response to major floods. They sustain a gradient of wetland habitat types from forested floodplains to forested tidal wetland to tidal marsh and mudflat. Roadways, railway corridors, flood protection levee system traverse river deltas at many locations in Puget Sound and other estuaries in Washington State. An example is shown in ***Figure D.1***. Typically these have been constructed with little consideration of ecological impact on embankments on flat intertidal areas across the delta front and have concentrated river flows at a single bridge or culvert crossing location. Fixing the river channel in this way can significantly impact the geomorphic processes mentioned above and reduce the area of active delta. Typically, upstream of the crossing the river is restrained from avulsing into different distributary channels, resulting in a reduced variety of habitat types. Further, because of increased sediment deposition upstream of the crossing the floodplain and former intertidal habitats aggrade due to increased sediment deposition. Downstream, constricted river delta estuary openings may partially or completely block the flow of sediment that sustains estuarine habitats. Channelizing the outflow of riverine sediments and flows along a single alignment forces delta progradation, causes changes in channel form, changes salinity distribution, in addition to other impacts to natural estuarine systems.

For instance, the size and location of bridge crossings within the estuary are factors that determine the size, quality and connectivity of habitat. Altering the size and location of a new estuary opening can add new habitat, connect existing habitats, and increase habitat capacity. Restored tidal or distributary channels will help to increase all three of these criteria, which can enhance the distribution and composition of various fish and wildlife species such as salmonids by allowing greater expression of varying life history strategies. Additionally, degraded energy and material flow patterns can be restored and result in increased viability for many estuary dependent species.

Benefits of Increasing River Delta Estuary Opening Size

To illustrate how ecologic benefits of river delta habits could be restored with increasing the size of bridge or culvert crossings we have conducted a first cut qualitative assessment of the four alternatives described below (see ***Figure D.4***) and quantified in ***Table D.2***:

1. <u>Bridge or Culvert Sized for Hydraulic Capacity</u>: This alternative assumes the roadway has been constructed on an elevated embankment that prevents tidal and river flows, and the crossing itself has been sized to the typical design flood. Channel avulsions and distributary channel formation are restricted to the area downstream of the crossing. Elsewhere downstream of the embankment, tidal marshes are not replenished by sedimentation and relict distributary channels silt in. Upstream, pre-existing intertidal wetlands convert to floodplains and the river channel is prevented from migrating or avulsing with river training structures that simplify habitat structure within the river channel.

2. <u>Two or more Crossings that Emphasize Distributary Channels</u>: The existing bridge crossing is duplicated at location(s) where there is evidence of major distributary channel which has been blocked off by the embankment. This would encourage a channel avulsion upstream and permit the main river to switch its course between two crossings, doubling the size of

the active delta. An alternative to the two bridge option at a similar cost level for smaller delta situations would be to increase the size of a single crossing to account for marsh connectivity. This would be a common scenario for creek systems with watershed areas less than several square miles and impounded intertidal areas less than 100 acres or so.

3. Two or more Crossings sized for Channel Migration and Marsh Connectivity: This alternative assumes bridge spans are widened to allow for historic rates of lateral channel migration. Laterally meandering channels 'reset' the fluvial system through bank erosion and subsequent deposition on point bars across floodplains and estuary deltas. This introduces sediment and organic inputs such as LWD into channels from riparian zones , and promotes the exchange of nutrient-rich soils into the fluvial system. The erosion of banks, and subsequent deposition, results in a dynamic system with a mosaic of habitat types.

4. Bridges and Causeway spanning entire Estuary Delta: This alternative would allow for restoring complete tidal exchange across the delta front. Ideally, this restoration approach would include removal of upstream river embankments, and thereby restore fluvial processes acting across the delta.

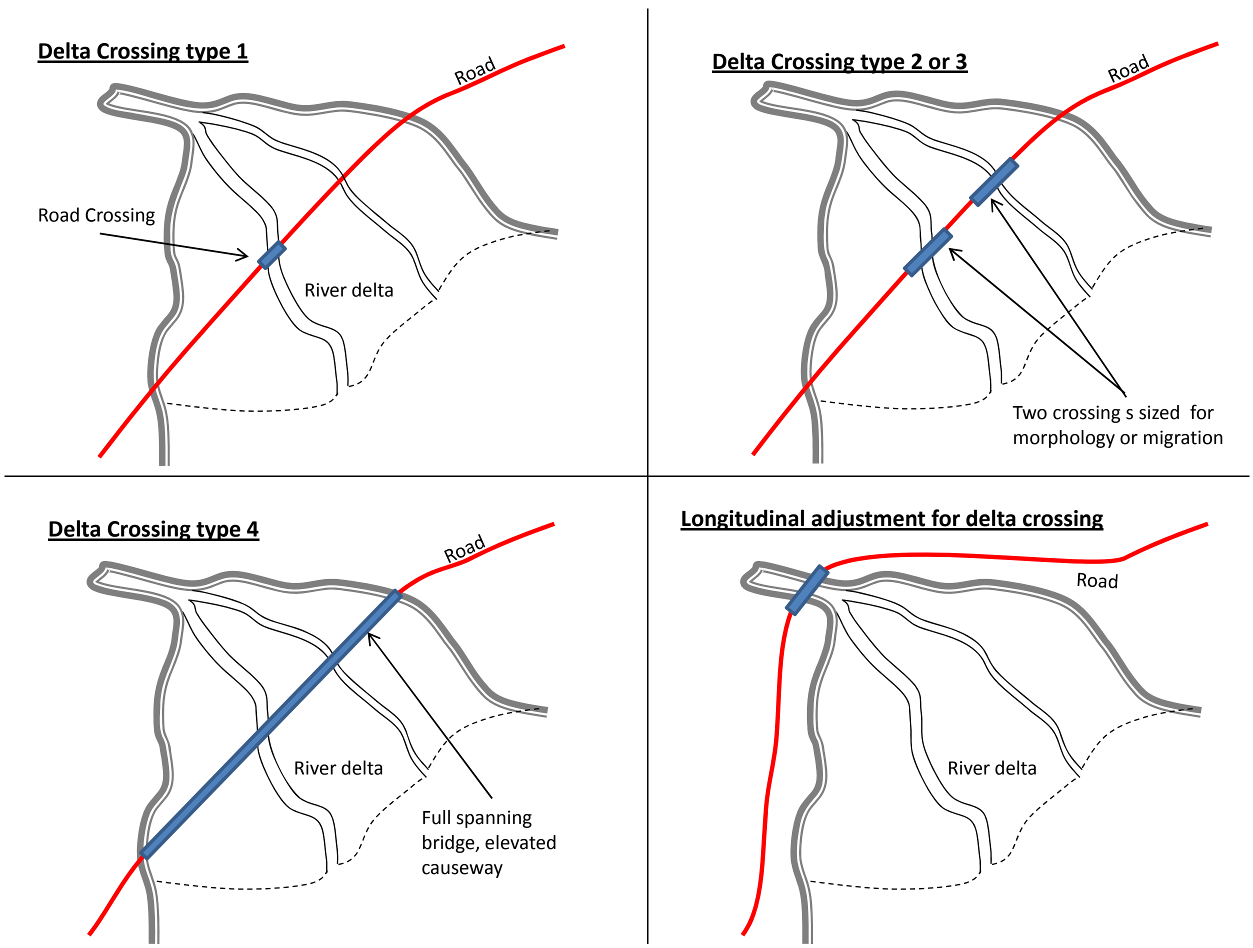


Figure D.3: Delta crossings and the types of crossings described in the text.

Table D.2: A quantitative assessment of the impacts of various delta crossings on nearshore ecosystem processes.

			Crossing Types	1	2	3	4
				Bridge or Culvert Sized for Hydraulic Capacity	Two or more Crossings that Emphasize Distributary Channels	Two or more Crossings sized for Channel Migration and Marsh Connectivity	Bridges and Causeway spanning entire Estuary Delta
	Process	Structural Impact	Functional Response				
HYDRAULIC/ HYDRODYNAMIC PROCESS IMPACTS	Alteration of fluvial flows	Concentration of flood flows at one discharge point raises flood stages upstream	Shift from marshplain to floodplain ecologic processes	0.1	0.2	0.4	0.5
		Elimination floodplain flows to saltwater which increases main channel discharge, scouring and flood velocities in main channel.	Countermeasures reduce habitat quality and sediment delivery to marsh plain				
	Alteration of estuarine salinity distribution	Extension of single channel into deeper waters creates abrupt fresh to salt water mixing zone	Adverse impacts on anadramous migration and nearshore shallow water migrating fish.	0	0.2	0.4	0.5
		Elimination of distributary channels alters spatial distribution of mixing zones across delta front.	Reduction in aerial extent of brackish zone and organisms dependant on it				
			Category total	**0.1**	**0.4**	**0.8**	**1**

SEDIMENTARY PROCESS IMPACTS	Alluvial sedimentation	Increased sedimentation on marshplain/floodplain upstream	Conversion from tidal marsh to floodplain habitats and eventually upland.	0.1	0.2	0.3	0.4
		Reduced sediment delivery and erosion where distributary channels have been blocked. Reduction in intertidal elevation with sea level change					
		Coarse sedimentation concentrated at mouth of single channel, instead of being distributed along multiple channels across delta front	Loss of habitat heterogeneity				
	Estuarine sedimentation	Estuarine mudflats not replenished during flood events –fine alluvial sediments lost to deep water	Loss of intertidal mudflat/sandflat habitat	0	0.2	0.3	0.4
		Reduced flood tide suspended sediment concentrations reduce marshplain sedimentation rates	Loss of productivity and area of marshplain habitat				
	Large wood accumulation	More export of large woody debris	Reduction in complexity of channel habitat	0.1	0.2	0.2	0.2
			Category total	**0.2**	**0.6**	**0.8**	**1**
GEOMORPHIC IMPACTS	Spatial reduction of active delta	Reduction in area	Loss of benefits of large scale ecologic processes	0	0.05	0.1	0.2
		Simplification of deltaic system	Reduction in heterogeneity of habitats, loss of alternate migratory routes				
		Disruption of natural gradient of wetland habits from floodplain to mudflat	Loss of connectivity of habitats, fragmentation of habitats				
		Delinking of river channel from marshes	Adverse affect on migrating fish				

	Main river channel changes	Deeper river channel	Simplification of fish habitat	0	0.05	0.1	0.2
		Channel location fixed	Reduction in habitat complexity derived from meandering processes				
		Extension of delta lobe to deeper water reducing channel slope, increasing in-channel sediment deposition	Loss of watershed derived nutrients to estuarine system				
	Distributary channel changes	Remnant distributary channel atrophies	Loss of channel edge habitat and migration routes	0	0.05	0.1	0.2
	Marshplain system changes	Marshplain erosion	Loss of marsh area, conversion to mud/sand flat	0	0.05	0.1	0.2
		Marshplain lowering	Reduction of productivity				
	Mudflat changes	Mudflat lowering	Loss of mudflat habitat	0	0.05	0.1	0.2
			Category total	**0**	**0.25**	**0.5**	**1**
			Sum of ecological benefits	**0.3**	**1.25**	**2.1**	**3**
			Relative sum of benefits	**10%**	**42%**	**70%**	**100%**

BENEFITS OF CHANGING BRIDGE CROSSING LOCATION

Impairments to ecological functions not only result from an inappropriately sized opening, but also by its location within an estuary. The location of the crossing within an estuary influences tidal inundation, sediment penetration, lateral channel movement, and the development of distrbutary channels (***Figure D.4***).

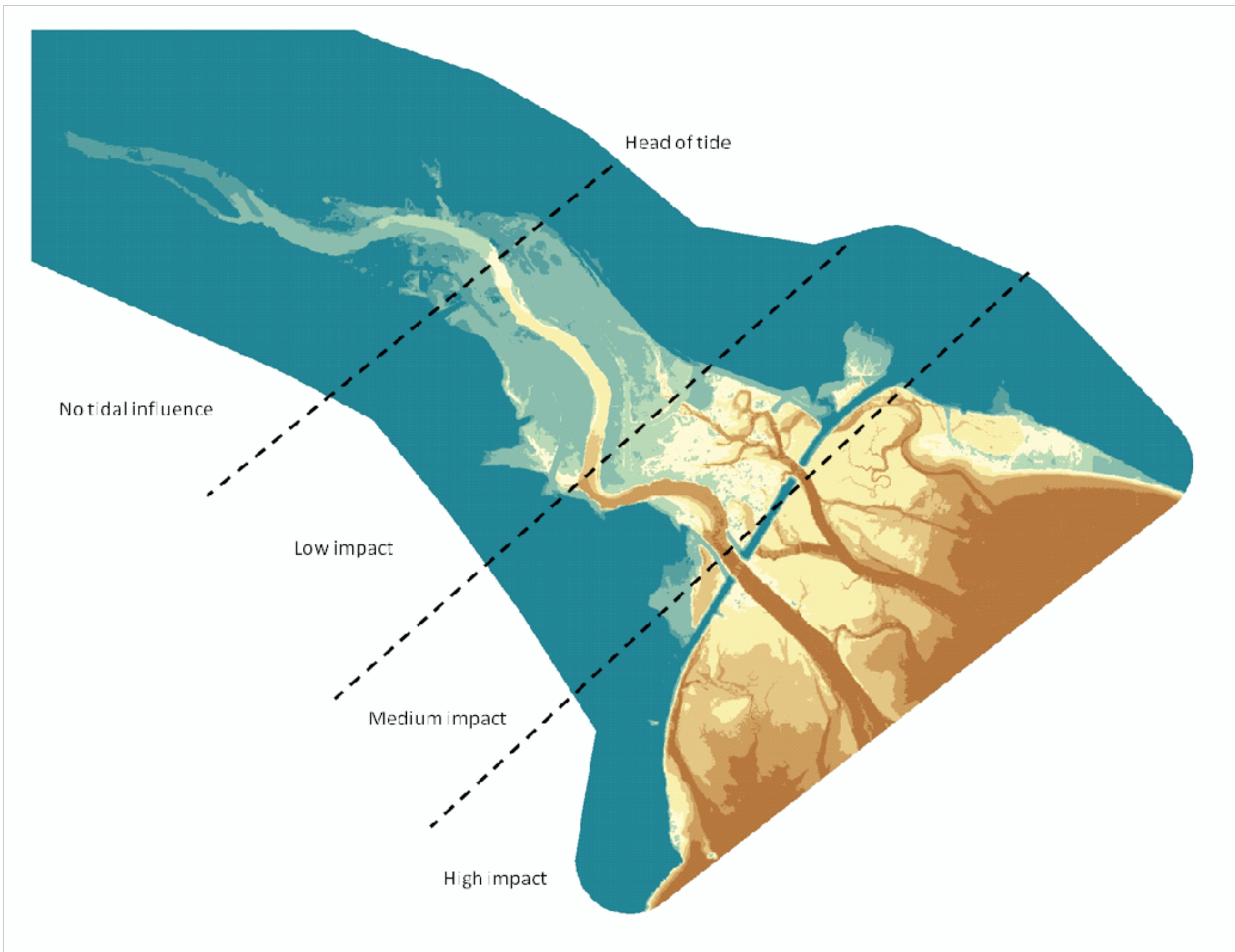


Figure D.4: False color Lidar image of the lower Dosewallips River: brown colors indicate tidal influence, green colors indicate supratidal elevations.

A qualitative assessment of tidal effects can be accomplished by expanding upon an approach published in *HYDRAULIC ENGINEERING CIRCULAR 18* (Richardson and Davis 2001) that is used to evaluate hydrological processes at crossings. This is in large part a measure of the distance from the head of tide to the crossing location. As this distance increases, the volume of tidal prism and discharge through the crossing associated with each tidal cycle increases. Discharge drives the transport of fluvial and marine sediment in the estuary and scour at crossings. The distance from head of tide is also a measure of the crossing's effect on estuarine processes. Estuarine development (fill, dikes, and land use) modifies the level of impact.

Qualitative categories of impact include (see ***Figure D.4***):

1. Low impact– the crossing is located near head of tide where tidal inundation occurs within the main channel banks, or where the tidally inundated marsh area is small.

2. Medium impact – this category encompasses most of the cases where the road embankment is built in the middle of the delta.

3. High impact– the crossing is located at the marine edge of a marsh, or encloses a large area principally below mean high water. These are cases where tidal volume is large and that significant inundated areas are funneled through a single opening, cutting off flow into distributary channels and over the marsh edge.

ASSESSMENT

As a way to approach this difficult design challenge, we suggest an approach similar to the one outlined in *HYDRAULIC ENGINEERING CIRCULAR 18* (Richardson and Davis 2001), but expanded to include an assessment of the crossings effects on geomorphological and biological processes. *HYDRAULIC ENGINEERING CIRCULAR 18* uses three levels of analysis for tidal bridges, which are outlined here.

LEVEL 1 analysis is a qualitative assessment of tidal effects. This is, in large part, a measure of the distance from the head of tide to the crossing location. As this distance increases, the volume of tidal prism increases and, in turn, the discharge associated with each tidal cycle increases. Discharge drives the transport of riverine and marine sediment in the estuary and scour at bridges. The distance from head of tide is also a measure of the bridge's effect on estuarine processes. Estuarine development (fill, dikes, land use) typically increases the level of impact.

Many estuaries in Washington State are completely converted to agriculture or urban development and crossings can do little more than follow the outlines of land use set out a century ago. The crossings must provide fish passage by creating stream-like conditions and should not decrease the productive capacity of the stream, but options for considering restoration beyond these baseline conditions are constrained by these developments. Examples of such a scenarios in Puget Sound include diked farm lands on the Skagit and Stilliguamish deltas; urbanized lower river reaches such as the Duwamish in Seattle, or Goldsborough Creek near Shelton Washington.

This situation is analogous to that discussed in ***Bridge Design, Chapter 4***, where bridge span may be determined by flood control dikes or other flood plain development. One must be cautious in allowing these external factors to determine crossing design, since habitat restoration is currently a strong force in our society and future plans to remove dikes or wetland fill should not be precluded by decisions made now about bridge or culvert span. During project scoping the owner should consult local planning organizations and documents for future restoration projects or initiatives. These included Shoreline Master Plans, Watershed Plans, Critical Areas Ordinances, fisheries enhancement groups, Dept. of Fish and Wildlife area habitat biologist and watershed steward.

Several categories of impact are proposed:

- Low – the crossing is located near to head of tide or backwater from receiving river where tidal or seasonal backwater inundation occurs within the main channel banks, or where the tidally inundated marsh area is less than 0.5 acres. Low tidal impact crossings such as this will require only **level 1** analysis and would proceed normally through the sizing steps outlined previously in this document for riverine crossings.

- Medium – this category encompasses most of the cases where the road was built in the middle of the estuary or across an inlet to a lagoon.

- High – the crossing is located at the outer edge of a marsh, or encloses a large area principally below MHW. These are cases where tidal volume is large and significant flows are funneled through a single opening, cutting off flow into distributary channels and flow over the marsh edge.

LEVEL 2 analysis requires engineering, biological and geomorphological assessment of the effects of the crossing on the estuary or tidal inlet. Level 2 analysis can be performed by qualified professionals.

In order to focus the investigation at this level of analysis, bear in mind the following observations:

1. Single openings channelize the flow of riverine sediment out along a single alignment, forcing delta progradation, main channel incision, floodplain disconnection, and associated impacts to natural systems. These impacts include the conversion of drowned river valley and lagoon estuary types into deltaic, changing the character of the habitat and impacting species dependent upon it.

2. Single openings also starve adjacent marsh and other wetland surfaces which depend on sediment deposition to contribute to estuary function, counteract the effects of sea level rise and, when present, counteract geologic subsidence.

3. Roads and other transportation corridors act as dikes, reducing general flow over marsh surfaces toward the bay front and eliminating wave action. Estuary areas landward of such embankments aggrade at a higher rate than areas seaward of the embankment when exposed to sediment laden flood waters, and degrade when isolated from these sediments.

LEVEL 3 analysis uses sophisticated computer models, physical modeling, or other scientific studies to give a deeper understanding of the problem than Level 2 analysis. Level 3 analysis should be done by experts in the field.

Design of tidally, or seasonally high river stage, influenced crossings should consider the following features:

1. Restore full tidal and high-flow backwater inundation to all areas which supported intertidal floodplain habitats.

2. Ring or setback dikes may be required to protect low elevation development.

3. Allow for the rejuvenation of remnant tidal drainage features. Additional crossings may be required and should be located to take full advantage of any opportunities to reestablish connections between an existing remnant channel network within the site and the truncated higher order channel on the natural marsh.

4. Maximize opportunities for creating single, large, complex tidal drainage systems within the marsh rather than multiple smaller systems. Ideally, marsh watershed areas should be large enough to sustain high-order, subtidal channel habitat within the marsh.

Ensure compatibility with public and maintenance access requirements/needs.

WASHINGTON HARBOR: CASE STUDY OF ALTERNATIVES ANALYSIS IN A PUGET SOUND ESTUARY

Washington Harbor is located at the north end of Sequim Bay along the Strait of Juan de Fuca, ***Figure D.5***. The current crossing limits tidal inundation, wave energy, and the movement of organisms, sediment and wood. A crossing replacement has been proposed and the alternatives analyzed by Cardno ENTRIX and ESA, Inc. This case study draws extensively on their sophisticated analysis.

Figure D.5: vicinity map for Washington Harbor.

The northern end of Washington Harbor is currently separated from the rest of the lagoon, and Sequim Bay, by a 1,400 foot causeway that contains a pipeline from the City of Sequim Wastewater Treatment Plant to its outfall in the Strait of Juan de Fuca.

Three alternative crossings were considered by Cardno ENTRIX and ESA and are shown in ***Figure D.6***. A fourth was proposed in the PSNERP SRS CD which removed the entire causeway and lowered the sewer pipeline beneath the surface, ***Figure D.7***. (This fourth alternative also removed the dikes at the north end of this lobe of Washington Harbor and the shoreline armoring and fill extending onto the beach north of Gibson Spit for a full restoration of natural process in this area, but these features are included in this case study.) The fourth alternative was not pursued by Cardno ENTRIX and ESA because of expense and the fact that it eliminated access to private lands and the outfall. It is included in this analysis to provide a "full restoration" alternative to gage the relative ecological benefits of the other alternatives – full restoration represents 100% of the natural process benefits, the current condition 0% restoration, and the other three alternatives somewhere in between, based on the hierarchy of benefits.

Figure D.6: Three alternatives for Washington Harbor, Cardo ENTRIX.

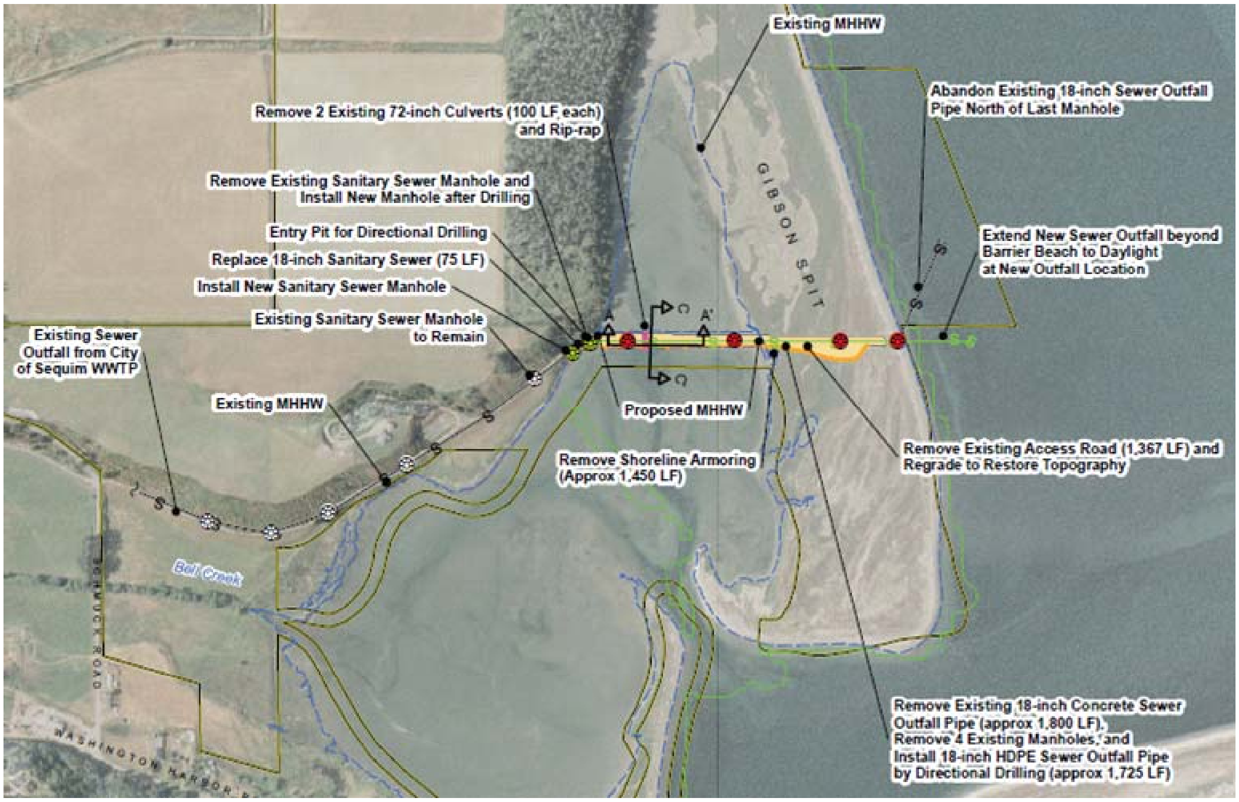


Figure D.7: Alternative 4, complete restoration of the Washington Harbor barrier inlet. Plan from PSNERP Conceptual Design Report, 2010, Anchor QEA Washington Harbor lead designer.

The ecological benefits are evaluated in a similar manner to the **Hierarchy of Benefits** section above, but using more simplified categories more suitable to the Cardno ENTRIX analysis. Cardno ENTRIX did not quantify these benefits, but in order to use the method proposed here, some way to value them is necessary. The exact numerical value could be established through a systematic quantification of these processes, although for this case study they are assigned a value as one might rate something as "high/medium/low."

As we have seen in the hydraulic analysis of many nearshore restoration projects, achieving full tidal inundation is relatively easy – the rapid rise and fall of the flood and ebb water surface builds up head at an obstruction driving prodigious discharges through relatively narrow openings. With this in mind, we can say that the 76 ft bridge is unlikely to cause tidal asymmetry. Similarly, the increase in total Washington Harbor tidal prism and the overall exchange rate will be largely restored with the 76 ft bridge. The 76 ft bridge will affect circulation patterns, salinity gradient and other subtle effects, but these will disappear as the opening is enlarged, as is shown.

Habitat connectivity is a catchall category that includes fish passage and the passive and active movement of aquatic organisms. These organisms enter and leave the estuary by various pathways; some in the tidal channels, some over the marsh edge. Simply providing passage in the main channel, as is the case with the 76 ft bridge, does not create the same level of connectivity as a opening which spans the various habitat types. Many organisms migrate along the nearshore in shallow water. A small opening at the main channel would eliminate this pathway along the shore.

Habitat connectivity is more difficult to achieve and this is show in the slow increase in benefit in this category as the opening size increases.

As Cardno ENTRIX points out, wave energy is the main driver for sediment suspension and transport in the estuary. Waves are all but eliminated by a narrow opening and only small benefit comes from a 76 ft bridge. Similarly, the movement of wood is precluded by the long road fill across the estuary with only a small hole in it. These categories improve substantially with wider openings.

Table D.3: A quantitative evaluation of restoration alternatives for Washington Harbor.

		0 Existing culverts	A 76 ft bridge	B 535 ft bridge	C 760 ft bridge	D Full restoration
Tidal inundation	**WA Harbor tidal prism**	0	0.9	1	1	1
	Internal tidal range					
	Exchange rate					
Habitat connectivity		0	0.5	0.7	0.9	1
Transport of sediment		0	0.2	0.8	0.9	1
Transport of wood		0	0.2	0.8	0.9	1
	Sum of ecological benefits	0	1.8	3.3	3.7	4.0
	Relative sum of benefits	0%	45%	83%	93%	100%

The relative sum of benefits shows that **Alternative A** achieves only 45% of the full restoration benefits. **Alternatives B** and **C** achieve the majority of possible benefits.

Choosing between these alternatives can be approached by evaluating their costs as in **Table D.3**. Here the "benefit costs" – the infrastructure costs in millions of dollars is divided by the relative benefits – give a monetary value to the benefits. This measure shows a steady increase in the cost of the benefits. On the other hand, the "incremental costs and benefits" – the change in benefits for a given change in costs between alternatives – is substantial for the first alternative but decreases to a minimum at **Alt C**.

Table D.4: Comparative benefit costs and incremental costs for Washignton restoration alternatives.

		Infrastructure cost	Relative benefits	Benefit costs	Incremental costs and benefits
0	Existing culverts	$0	0.00	0.0	
A	78 ft bridge	$0.67	0.45	1.5	0.67
B	562 ft bridge	$1.60	0.83	1.9	0.41
C	762 ft bridge	$2.20	0.93	2.4	0.17
D	Full restoration	$2.50	1.00	2.5	0.23

Using this table to make decisions requires more information and a clear statement of goals. We already know that **Alt D** is unacceptable, but we do not know the budget constraints for restoration at Washington Harbor. The goal might be to maximize the restoration of natural processes, which would cause us to look more carefully at Alts B and C. If the goal is to maximize the incremental costs and benefits, then Alt A is clearly the best. Alt B achieves most of the ecological benefits for a low cost and a moderate incremental value.

This sort of systematic evaluation can help to explain how we decide between various sizes of water crossings in tidally influenced areas in a systematic way.

APPENDIX E: FEMA POLICY ON FISH ENHANCEMENT STRUCTURES

[The following is taken from the National Flood Insurance Program Floodplain Management Guidebook, produced by U. S. Dept. of Homeland Security - Federal Emergency Management Agency – Region 10, 5th Edition, March 2009, Bothell, WA]

The balance required between anadromous fish and the human environment is unique to the Northwest. Maintaining that balance often makes implementing regulations a challenge. Sometimes the local, State and Federal regulations contradict each other. This is the case with fish enhancement structures.

FEMA's regulations require communities to prohibit encroachments in regulated floodways unless provided with a no-rise analysis. The current listing and proposed listing of certain anadromous fish species as Threatened or Endangered requires the restoration of their habitat to ensure their survivability. Restoring that habitat often entails encroaching in the floodway. A strict interpretation of this standard could require a relatively expensive analysis that might exceed the cost of the enhancement project.

FEMA recognizes this. While we believe the best course of action is to preserve the floodway encroachment standard as it exists, an informed judgment regarding fish enhancement structures can be made as to exceptions for which is less than the maximum hydraulic analyses are required. The community official often does not have the qualifications to make an informed judgment regarding the impacts of these structures on flood hazards. Therefore, FEMA will allow the community to defer to the "judgment" of a qualified professional regarding such impacts. Such qualified hydraulic or hydrology professionals would include staff of Rural Conservation and Development and the Natural Resource Conservation Service. It would also include similarly qualified staff of fisheries, natural resource, or water resources agencies.

The qualified professional should, as a minimum, provide a feasibility analysis and certification that the project was designed to keep any rise in 100-year flood levels as close to zero as practically possible and that no structures would be impacted by a potential rise. Additionally, routine maintenance of any project would be necessary to sustain conveyance over time and the community should commit to a long-temm maintenance program in their acceptance of the project. FEMA also recommends a condition be placed on the projects emphasizing the dynamics of a river and, if the community deems necessary, further analysis be required.

We believe this is preferable to trying to specify in the ordinance language all the different types of "development" that need not comply with the "no rise" standard. Typically, any rise caused would require some offsetting action such as compensatory storage, channel alteration, or removal of existing encroachment. One of these alternatives would be appropriate to compensate for any rise and still preserve the integrity of the floodplain standards.

FEMA Region 10 feels this policy is in keeping with the concept of wise floodplain management which means enjoying the benefits of floodplain lands and waters while still minimizing the loss of life and damage from flooding and at the same time preserving and restoring the natural resources of floodplains as much as possible. If you have any questions regarding this policy, please contact the Mitigation Division at (425) 487-4737.

APPENDIX F: ROAD IMPOUNDED WETLANDS

Figure F.1: Road impounded wetland.

SUMMARY

- Road impounded wetlands are wetlands created or altered by undersized or elevated culverts and impermeable road fills.
- Fish passage laws combined with the requirement for no net loss of wetlands create a paradox that can be solved with an evaluation of the benefits from various alternatives.
- There are three types of wetland-generating crossing and their characteristics point toward particular solutions.
- The evaluation process has several steps
    - Small, low quality wetlands with no species of concern can be drained to restore fish passage in a free-flowing stream
    - Larger more valuable wetlands should go through a more thorough evaluation process.
    - RIW functions and values are paired with stream functions and values in the evaluation process.
- Design alternatives are listed.
- Roads act as dams that interfere with stream continuity.

- RIWs that impound wetlands less than about 0.2% of the area of the watershed are not likely to significantly affect the downstream flood peak flow and can be opened up without causing unexpected flooding downstream. On the other hand, RIWs with an area greater than 0.4% of the watershed may reduce peak flow by 50%. Draining these larger wetlands increases the likelihood of flooding downstream.

INTRODUCTION

Road impounded wetlands are the result of undersized or perched culverts in combination with impermeable road fills that create wetland conditions in the upstream impoundment, ***Figure F.1***. Often these same culverts block fish and wildlife passage up and down the stream course and interrupt natural channel processes. State law requires that road owners provide fish passage at road crossings (see ***Appendix B***). There are basically two alternatives to address this situation. One, lower and enlarge the culvert to create passage and encourage the continuity of stream processes (e.g., sediment and debris transport). This alternative removes the control that created the wetland and causes it to return to a stream.

The other alternative is to construct hydraulic control using artificial structures that provide fish passage and maintain either all or part of the wetland. This can be expensive, not always possible, and often not in keeping with naturally sustainable stream processes.

In spite of state law requiring fish passage in streams affected by road crossings, state and federal policies also call for a no net loss of wetland functions, values and acreage. This document is intended to help biologists, landowners and designers evaluate road crossings with wetlands impounded above them so that they may intelligently and legally choose between the two alternatives discussed above. This guidance was completed in cooperation with various concerned groups, including state and federal regulatory agencies and a number of prominent forest land owners. The focus here is overall ecological health and compliance with Washington State regulations, although one must pay careful attention to other relevant laws, including the Clean Water Act sec. 404, Shoreline Management Act, local Shoreline Management Programs, and local critical areas ordinances.

GUIDING PRINCIPLES

In order to focus our analysis, several guiding principles were developed for planning and designing crossings where wetlands have formed upstream of road fills:

1. As a basic principle, pre-disturbance processes should be restored. Through examination of the hydrologic and biological systems, the form and function of the watercourse that approaches the unaltered condition should be identified and restored.
2. At the same time, we should strive for no net loss of habitat, function, and acreage of wetlands where possible, and strive for an overall increase in the quantity and quality of wetlands when the opportunity arises.
3. High value wetlands that are important features in the local or regional ecosystem should be preserved.

4. Wetlands that can serve an ecological function that has been lost or significantly diminished elsewhere in the system should be preserved.
5. For each instance where a road fill and the associated culvert has created or increased a wetland, the wetland's fate is a negotiated decision between the landowner, area habitat biologist and any other agency with jurisdiction.

The paradox of the first two principles is what drives the analysis of road impounded wetlands (RIWs). This is intentional. Each principle alone would result in either removing or maintaining every wetland that occurs above a road fill. No considered decisions or negotiations would be possible.

Truly "natural" processes may be long gone in a watershed and impossible to restore. "Naturally sustainable" conditions should be an alternative in those cases. Significant RIWs warrant the attention of a wetland specialist and geomorphologist in the evaluation and decision-making process. These evaluations and decisions should be documented. The remainder of the document outlines considerations and procedures for this evaluation.

ROAD IMPOUNDED WETLAND SCENARIOS

Three types of wetland-generating crossings have been observed in the field and serve to simplify our approach to solving the situation.

1. ***Independent***: The wetland is generated by a structure that may once have been associated with the crossing but is now independent of it. Two instances are immediately obvious: a beaver dam that appears above the culvert, ***Figure F.2***, or a debris flow that terminated at the road fill. The actual drop occurs upstream of the culvert and would maintain the wetland regardless of the hydraulic control offered by the crossing structure

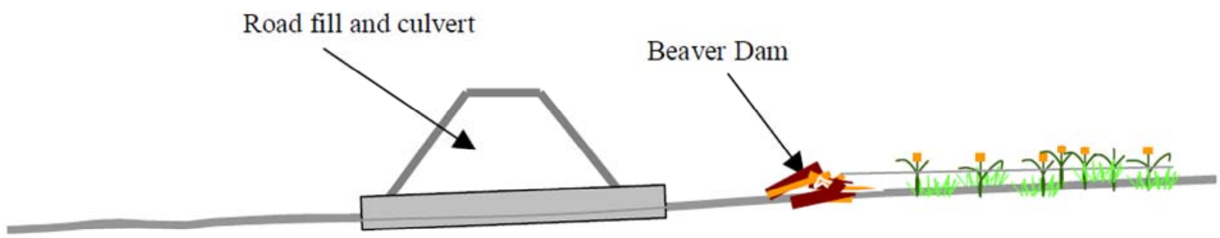


Figure F.2: Independent type RIW.

2. ***Continuous***: The road fill was originally placed over an existing wetland or low gradient stream reach, ***Figure F.3***. The hydraulic control created by the culvert and road fill increase the water surface elevation above the original condition. This may result in a change in character of the wetland from downstream to upstream of the road, such as from marsh to open water habitat. Alternatively, it may change a low gradient, free-flowing stream into a backwatered wetland. In any case, the change in character is not dramatic, and the overall drop in water surface elevation through the road fill is not great (on the order of

1 or 2 feet). Wrapped up in this scenario is the tendency to form wetland habitat in the given reach because of soil type, ground water elevation and valley slope. The road impounded wetland is less an anomaly in the continuous scenario and more easily maintained in a variety of culvert and bridge design options.

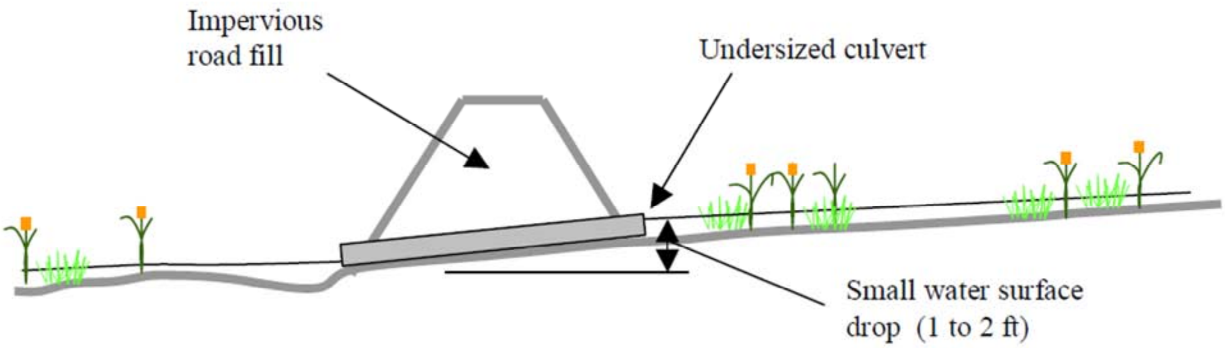


Figure F.3: Continuous type RIW.

3. Distinct: The road fill creates a totally different type of upstream habitat, distinct from the rest of the reach. Wetlands that appear above undersized or elevated culverts on high gradient streams are of a clearly different habitat type and interfere with the continuity of stream processes. The drop in water surface is generally large -- greater than 2 feet and reaching 15 or 20 feet in some cases. See ***Figure F.4***.

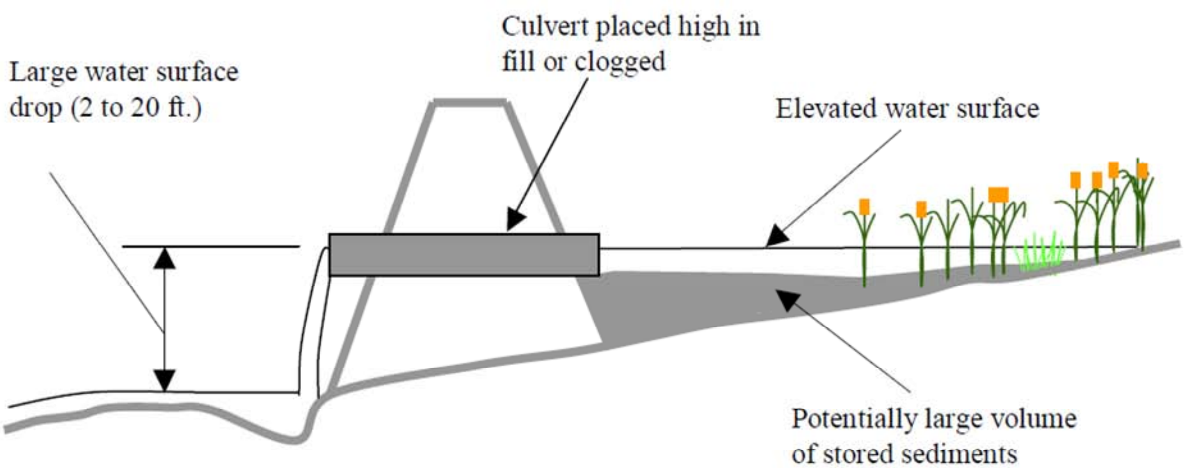


Figure F.4: Distinct type RIW.

These three types of RIWs lead to different approaches to making decisions about the fate of the wetland and the type of crossing structure and hydraulic control. In the case of the independent type, the crossing itself has little to do with the wetland (although it should be constructed to accommodate the movement of the debris when it fails) and removing it might not change wetland conditions.

Continuous type wetlands may be easily maintained with simple hydraulic controls, provided that the functions and values found in the created wetland are consistent with overall stream health. It should be noted that such control creates a sediment and debris trap that will change the trajectory of the RIW. Consideration should also be given to the role of disturbance regime in healthy, productive habitat when permanent structures are proposed. Mitigation may be necessary in cases where loss in productivity is clearly identifiable (see Mitigation at the end of this chapter).

Distinct RIWs are much more difficult to address. To maintain them would require complex and expensive fish passage structures that interfere with stream continuity, including non-target fish passage and the movement of sediment and debris. On the other hand, the habitat may be so unique that heroic efforts to preserve it are justified. The accumulated sediment upstream may have a harmful and prolonged impact on the downstream habitat if the control is removed.

The role of beavers in all three of these types cannot be overemphasized. In some regions beavers are present at every road crossing, tirelessly creating wetlands. When beavers are included in the solution to a road impounded wetland problem, the final design may be very different than if they were absent. By relying on the activity of beavers, we can lower and enlarge a culvert and, without adding artificial grade control, still count on wetland formation. This may not be immediate, but likely in the long run.

SEDIMENT CONCERNS

Road fills and undersized culverts decrease the capacity of the upstream reach to transport sediment and debris. This material then accumulates in the backwatered area and may even extend further upstream. If the culvert is lowered and/or increased in size a potentially large volume of stored sediments will be released as a channel cuts down through it and widens out into an equilibrium configuration. This is the same sequence of events associated with channel incision.

The volume of material liberated from this process may be large and have lasting effects on the downstream channel habitat. Sediment may also be transported at low flow and adversely affect organisms that need clear water conditions, rather than just at storm flow when all streams have a high level of sediment transport. The sediment above these culverts may have to be removed during construction of the new crossing to prevent downstream impacts.

EVALUATION PROCESS

Road impounded wetlands may be placed in two categories. Some clearly serve important functions, while others provide marginal functions. In order to simplify the evaluation process, it is reasonable to have two levels of analysis, one for each of these categories. The first establishes a threshold of concern, and the second weighs important stream and wetland functions. Examples of important wetland functions might be habitat for special species or maintenance of base flow conditions in the downstream channel. WDFW Priority Habitat and Species maps, the WDFW Wildlife Heritage Database, DNR Natural Heritage Program, and the Washington State Wetlands Rating System (Ecology) are important references in this and subsequent sections.

THRESHOLD OF CONCERN

The following criteria will help to distinguish between important RIWs that require careful analysis from those that can be easily evaluated on site.

1. If high quality wetlands are abundant nearby in the watershed, the RIW may best be restored to a pre-disturbance condition, especially if stream processes have been impaired and affect overall stream health. Expert opinion should be employed at this stage in the evaluation. (Wetlands should be rated using the Ecology Eastern or Western WA method).
2. If special species are at stake in the road-impounded wetland, it should have a full evaluation. Special species are indicators of management concerns in a given wetland, and their presence in the RIW elevates its status. The following are species of concern to the agency and/or WDFW staff with species expertise:
    a. Western and Woodhouse's toads (Bufo boreas and B. woodhousei)
    b. Oregon spotted frog (Rana pretiosa) (require large area wetland)
    c. Columbia spotted frog (Rana luteiventris) (do not require large area wetland)
    d. Cascade frog (Rana cascadae)
    e. Olympic mudminnows (Novumbra hubbsi)
    f. Cavity-nesting ducks (wood duck [Aix sponsa], Barrow's goldeneye [Bucephala islandica], common goldeneye [Bucephala clangula], bufflehead [Bucephala albeola], hooded merganser [Lophodytes cucullatus])
3. Overall stream health may be improved by returning low quality RIWs to freeflowing streams. Indicators of low quality include:
    a. Low plant diversity. Low quality RIWs has limited plant diversity and often an unequal abundance among the species present.
    b. Presence of exotic species. Species such as bullfrogs, warm water fish, purple loosestrife and reed canary grass may dominate, thereby suppressing native species and diversity.
    c. A completely closed tree canopy. The lack of insolation retards wetland development and limits RIW quality. There are ancillary benefits to water quality in lower stream temperature.

FULL EVALUATION

The following outlines a process to evaluate the wetland functions and values at a given site and determine their contribution to overall stream health. The ecological issues are then weighed against the physical constraints of the road crossing and the desires of the landowner. Ultimately, one must document and justify a decision on a given course of action at an RIW site. Some action will require a permit.

The in-depth evaluation process begins by examining the stream system at the appropriate scale (watershed, subbasin, stream). Scale can be determined by any number of criteria. For instance, an RIW that is home to a sensitive species should be examined at a larger scale to determine if it is unique habitat, if it is the only habitat available in the watershed, or if it is widely available and already colonized by the sensitive species.

1. Determine the extent of alteration of "natural" processes at the site. How far has the system departed from unaltered conditions, and what can we now expect from it in terms of habitat and health? Important parameters include:
    a. Stream and valley gradient and the channel type, particularly whether the natural channel has a flood plain. Steep valley gradients with confined channels are unlikely to have fostered riverine wetlands, while lowgradient, unconfined channels are more likely to have riverine wetlands that could be maintained with simple hydraulic control.
    b. Base flow conditions and the RIW's role in their maintenance. If a stream has chronic low flow problems, removing a RIW will likely exacerbate them. If, on the other hand, the stream has good summer flow, then draining a small RIW will have little effect.
    c. Presence of existing wetlands or the tendency to form wetlands in the reach.
    d. Size and elevation of culvert relative to the stream and the water surface drop through road fill. The profile of the stream through the culvert determines the RIW scenario (outlined above) and the range of practicalsolutions.
    e. Time since impoundment. The alteration of the stream channel and the development of the wetland are both time-dependent. Short time frames lead to simpler solutions with less impact. Old RIWs have had a chance to develop complex, well-entrenched structure that may be difficult to revert back to free-flowing stream.
    f. Volume and composition of sediment wedge, especially in the area that would potentially be regraded to form a natural channel with a flood plain. Large upstream deposits make restoration costly, either in their permitting and removal or the impacts to downstream habitat and water quality.
    g. Beaver activity -- past, current and expected. Beavers build wetlands, and their presence may simplify restoration efforts.
    h. Wetland type and seral stage. The type and age of a wetland must be known to determine what is being maintained or lost and to determine the trajectory of any design option. (Hruby 2004)
2. List stream and wetland functions present, lost, and/or gained in maintaining the RIW (including the fish passage structure and artificial grade control) as well as in restoring historical processes. Below is a general list of paired functions for evaluation purposes(Hruby 2011). Note that these functions will vary with wetland and stream channel type under consideration.

RIW Functions and Values	Stream Functions and Values
Wetland temperature regime	Stream temperature regime
Water quality improvement	Pollutant transport downstream
Nutrient storage and transformation	Nutrient leakage
Sediment storage	Sediment transport
Large woody debris storage	Large woody debris transport
Stillwater fish, amphibian and reptile habitat (species and life stage)	Flowing water fish, amphibian and reptile habitat (species and life stage)
Wetland plant habitat	Riparian plant habitat
Wetland invertebrate habitat	Stream invertebrate habitat
Flood storage (size dependant)	Flood wave transported
Waterfowl habitat	Fish habitat
Groundwater recharge	Hyporheic flow
Base flow storage	No base flow storage
Anaerobic soil conditions	Aerobic soil conditions in riparian
Fine soil texture and associated habitat	Coarse soil texture and associated habitat

Assess wetlands to determine proposed losses in function and area associated with the RIW in question and prioritize wetland value within the watershed. The object of this exercise is to get a sense of how important this RIW is in the immediate landscape and the relative importance of the functions it provides. This information is necessary to determine if the third and fourth guiding principles apply or not. A suggested reference is the Wetland Rating System(Hruby 2004; Hruby 2004) . The level of detail here may range from expert opinion to a thorough watershed-scale inventory and assessment. Large blocks of land with multiple crossings involving impounded wetlands would lead to extensive inventories. Small landowners with only one crossing might employ the expert opinion method. There is no specific percentage of total wetlands in a watershed removed through the replacement of culverts that is considered critical for ecological integrity. The purpose of this step is to provide a watershed context, and no target value is implied.

The RIW can then be evaluated using the guiding principles:

Weigh the wetland functions and values determined in the steps above. If overall stream health and the greatest benefit to watershed lies with maintaining the RIW, then preliminary designs should seek to maintain it. If the greatest benefits lie with a return to natural stream processes, then design and permitting should proceed in that direction.

Examine the design alternatives available given the site restraints and intended use.

Take into consideration the social and economic impacts of each design alternative.

Negotiate a design alternative and mitigation (if required) that maintains or improves the overall stream health of the watercourse and that meets the needs of the landowner.

DESIGN ALTERNATIVES

These are some alternatives that should be considered at each site. This is not a complete list, so new and creative designs are encouraged.

Status Quo: do not modify the crossing at this time.

Regrade: remove hydraulic control, drain RIW and return to a free-flowing stream, with possible mitigation requirments.

Streambed controls: step up channel to maintain existing RIW water surface elevation.

Fishway: construct a formal facility to pass fish upstream and maintain RIW.

Roughened channel: increase downstream channel slope to maintain RIW.

Bypass channel: lengthen channel reach on a different alignment to maintain RIW.

The last 5 alternatives are explored in a more detailed way in ***Chapter 7: Channel Profile Adjustment.***

FISH-RELATED RIW CONSIDERATIONS

Draining a road-impounded wetland is not likely to significantly affect fish in the former wetland because these fish were present before the road fill and culvert were installed and they survived under those natural conditions. Abundance and survival strategies may change as competition and predation are reintroduced with fish passage and a return to natural processes, but the population should survive.

There could be exceptions to this if species of concern are involved. A notable example is mudminnows, which cannot survive in the free-flowing stream environment. How mudminnows came to be present in an RIW may be lost in a complex stream history. Their unique habitat should not be lost by the removal of a road-associated hydraulic control.

Providing fish passage into an RIW that is to be maintained as a wetland is not likely to significantly affect resident populations. Once again, abundance and survival strategies

may change as competition and predation are reintroduced with fish passage and a return to natural processes, but the population should survive.

Again, there may be exceptions to this if species of concern are involved. Examples might include pure strains of westslope cutthroat or red band trout in specific Eastern Washington geographic regions that could be impacted by interbreeding with hatchery strains and competition. However, these examples are more likely to occur by opening up passage to upstream flowing reaches rather than road impounded wetlands. If providing natural connectivity (and restoring natural stream processes) poses a potential risk to a species of concern, fishery managers should develop alternatives to the use of permanent man-made barriers.

It is worthwhile to electroshock road impounded wetlands in order to give an indication of fish species present. However, because of the complex cover, sediment, and deeper areas of water, electroshocking does not provide a very high sampling efficiency and should not be used to rule out presence of other species that are not detected. Minnow traps may also provide some indication of species present.

Sampling the downstream plunge pool also gives an indication of what species could be present in the RIW, but their presence does not necessarily mean that they will utilize the upstream reach once fish passage is restored.

The number and kinds of fish species potentially utilizing the RIW will depend on various factors such as summer low flows, summer maximum temperatures, etc. The RIW may or may not provide good summer rearing habitat, but it may provide important

winter habitat. Therefore, summer conditions without passage may preclude the existence of resident populations; however, with passage, certain species may utilize the habitat when seasons and conditions are favorable.

One of the more difficult issues relating to this issue is: Should it be our priority to restore natural stream processes and accept whatever species adaptations occur as a result of restoration to those natural processes? This might even mean significant changes in some populations. Or should we try to take charge of those natural processes so that we can try to control the outcome (e.g., isolate species of concern, mitigate for lost wetlands in other places, etc.)?

Roads as Dams

In many ways the roads that create RIWs are similar to dams and we can follow the lead of research on the impacts of such structures. Generally, road impounded wetlands are on small, low order streams either in headwaters or direct tributaries to larger rivers. Large river issues (such as flood pulse effects on flood plains or islands) don't necessarily apply. Some of the important areas of concern are:

Size ratio of particulate **organic matter**. Transport of larger debris (consider leaf-sized pieces as opposed to small particles) blocked by the road and/or culvert may change invertebrate feeding groups, particularly downstream.

The effects of impoundment on the **sediment quantity and size distribution** behind the impoundment and in the downstream reach. Effects of sediment deposition could be significant in the remaining length of the tributary.

Effects on the maximum and daily range of stream **temperature**. Effects may be less important in forested situations but more important in open water systems with minimal ground water input.

Effects on **discharge patterns**. Moderated flow fluctuations and a muted flood wave that reduces sediment and debris transport may be issues.

Regulation of the headwaters will suppress the **biotic diversity** in the receiving stream, primarily because of the disruption of detrital transport and the spiraling of nutrients and organic matter.

Nutrient levels will increase downstream of headwater impoundments, but decrease downstream of middle-order stream impoundments.

RIWs as Reservoirs

The existence of a road impounded reservoir indicates some level of hydraulic control on stream flow. The degree to which the road fill and culvert influence important stream functions is difficult to determine without detailed analysis and modeling. This section of the guidance looks at a method to help decide when analysis is necessary. RIWs act as detention basins that reduce and delay flood peaks. This may be a benefit to downstream property owners, but it is at the detriment to the natural channel. The following is a short list of stream functions affected by RIWs:

- Reduction in habitat-forming processes such as channel scour and pool formation.
- Limited wood and gravel recruitment because of reduced erosion.
- Reduced extent and/or frequency of flood plain inundation.

Basic principles indicate that the combination of a steep-sided or urbanized watershed (with a short time-to-peak flow) with a large RIW area and a small outlet structure (culvert) leads to a significantly reduced and delayed flood peak. Conversely, a low gradient landscape with a high percentage of wetlands with a small RIW area and a large outlet structure may lead to no change in outlet discharge.

In order to determine when to expect significant effects, we modeled various watershed sizes and RIW areas and computed the effect on the downstream discharge peak flow. A number of assumptions were made in order to simplify the analysis. The watersheds were on the west side of the Cascades (USGS region 2), but not in coastal areas. A 25- year recurrence interval storm was chosen since it is relatively common and likely to scour the channel. The RIW reservoir was modeled as a straight-sided cylinder, which is not at all like a natural valley that gets wider as it gets deeper. The outlet of the reservoir was assumed to be a weir that is as wide as a channel that would be expected in the watershed area modeled. Rainfall was assumed to be 50 inches a year. The chart below shows the results of 21 independent simulations.

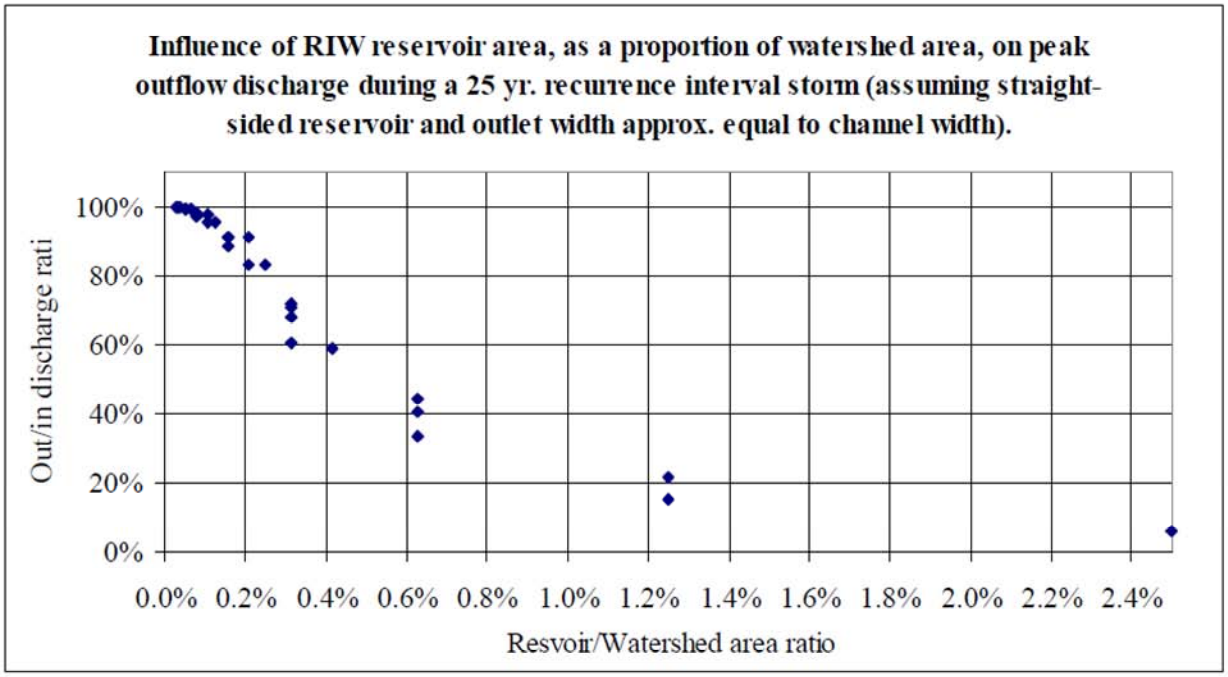


Figure F.5: A chart that relates the proportion of the watershed area impounded by the road and culvert, with the ratio of flow into the culvert/wetland system divided by the flow out. This chart was developed using simplified assumptions concerning reservoir routing.

The general observation is that RIWs that impound wetlands less than about 0.2% of the area of the watershed are not likely to significantly affect the downstream flood peak flow in USGS region 2. As seen from the graph, out flow peak discharge is about 90% or more of the inflow. 0.2% of a one square mile watershed is about 1¼ acre. On the other hand, RIWs with an area greater than 0.4% of the watershed may reduce peak flow by 50%.

This analysis does not address low flow. As mentioned above, wetlands recharge groundwater and store water during wet periods, releasing it during dry periods. Clearly, some RIWs influence the low flow characteristics of their streams. Unfortunately, the factors involved are subtle, complex and poorly understood and cannot be evaluated without extensive, site-specific information.

MITIGATION

In cases where RIWs can be shown to contribute values and functions found in natural wetlands, impacts caused by any actions arrived at through this guidance should follow a mitigation sequence. Actions are listed in the order of preference:

1. Avoid the impact altogether by not taking a certain action or parts of an action.
2. Minimize impacts by limiting the degree or magnitude of the action and its implementation, by using appropriate technology, or by taking affirmative steps to avoid or reduce impacts.
3. Rectify the impact by repairing, rehabilitating, or restoring the affected environment.
4. Reduce or eliminate the impact over time by preservation and maintenance operations.
5. Compensate for the impact by replacing, enhancing, or providing substitute resources or environments.
6. Monitor the required compensation and take remedial or corrective measures when necessary.

APPENDIX G: DESIGN FLOWS FOR FISH PASSAGE AND HIGH FLOW

INTRODUCTION

This first portion of this chapter is an adaptation of Appendix C in *ROAD CROSSINGS FOR FISH PASSAGE* (WDFW 2003) by P. D. Powers and C. S. Saunders. In 2003 the hydraulic design method (see ***Chapter 6)*** played a greater role in fish passage than it does today, as discussed in more detail in the in the ***Introduction***. As a result, there was greater emphasis on a method to determine the fish passage design flow, the primary design parameter, for a wide range of projects. Since then the emphasis has shifted to a more geomorphological approach for culvert design. Those few projects that still require hydraulic design should be based on flows developed through a more robust process than regional regression methods like the one described here. The error inherent in regional regressions is large enough, and the design requirements of the hydraulic method stringent enough, that the success of a project based solely on this method may be severely limited.

Fish passage projects based on the hydraulic method (***Chapter 6***) should be designed using stream gauge recordings at the project site. Much can be gained from even a single year of data when it is compared to locally gauged streams. Two or more years can result in quite accurate estimates. A statistically accurate 10% exceedance flow is much easier to achieve than, say, an estimate of the recurrence interval of annual peak flow. Finally, stream gauging equipment has become relatively inexpensive, reliable, and easy to install.

The original Powers and Sunders report provided guidance on estimating the fish passage design flow by calculating regional regression equations for ungauged catchments. The basis of these design flows can be found in WAC 220-110-070(3)b(ii)B, which says that the flow used to determine the maximum velocity in the culvert is the flow that is not exceeded more than ten percent of the time during the months of adult fish migration. As a simple and conservative alternative, the 2-year peak flow can be used (Sumioka, Kresch et al. 1998). The two-year peak flow is often much higher (by 200 to 300 percent) than the 10-percent exceedance flow, so there may be some economy gained in gauging streamflow. For gauged catchments, the 10-percent exceedance flow for any month can be determined easily by developing a flow-duration curve(Wiessman, Lewis et al. 1989)

CALCULATING THE FISH PASSAGE DESIGN FLOW FOR WESTERN WASHINGTON

This report uses the U.S. Geological Survey regions and basin parameters (Sumioka, Kresch et al. 1998)to develop regression equations for the 10-percent exceedance flow for the months of January and May. These months were selected to represent the high fish-passage design flow (Q_{FP}) for two periods when upstream passage has been observed (Cederholm and Scarlett 1981; Peterson 1982). January represents the month of highest flow, when adult salmonids are passing upstream, and May represents the most critical month for upstream passage of juvenile salmonids. Other months are also important, but January and May represent the two extreme combinations for design considerations. Equations were developed for three regions of western Washington (***Figure G.1***). Fish passage design flows for Eastern Washington can be calculated using a separate document (Rowland, Hotchkiss et al. 2002).

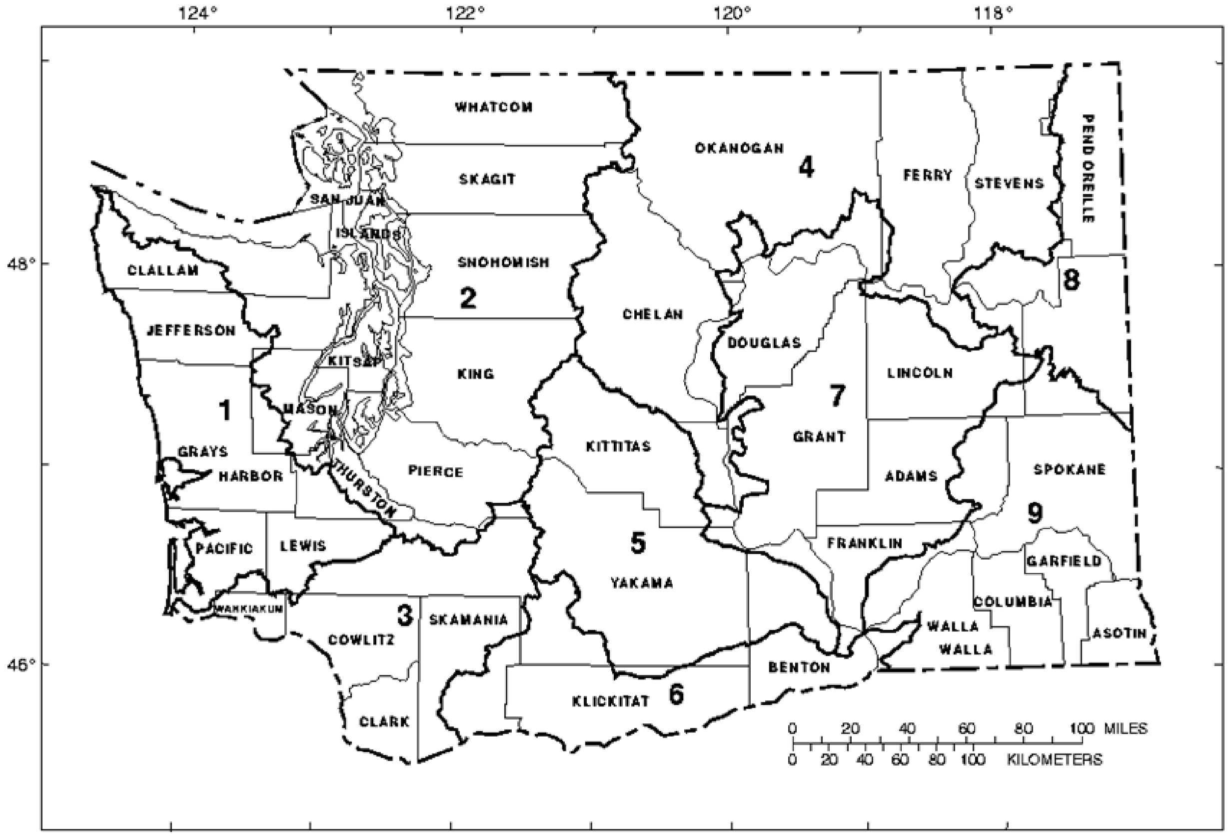


Figure G.1: Flood frequency regression regions in Washington State.(Sumioka, Kresch et al. 1998)

DESCRIPTION OF REGIONS

The state of Washington was divided into subsections based on their drainage-flow characteristics. These regions were derived from a number of relevant sources and are the same as those regularly employed by the U.S. Water Resources Council and the U.S. Geological Survey.

The Coastal Lowland Region (Region 1) includes parts of Clallam, Jefferson, Mason, Thurston, Pacific, Lewis and all of Grays Harbor counties. Streams in Region 1 drain directly into the Pacific Ocean.

The Puget Sound Region (Region 2) includes sections of Clallam, Jefferson, Mason, Thurston and Pierce counties, and all of King, Snohomish, Whatcom and Skagit counties. Streams in Region 2 drain into the Puget Sound.

The Lower Columbia Region (Region 3) includes all of Wahkiakum, Cowlitz and Clark counties, and sections of Skamania, Pacific and Lewis counties. In this region, rivers flow from westward and southward from the crest of the Cascade Mountains and drain into the Columbia River.

METHODOLOGY

To create a usable model for estimating fish-passage design flows, a data-selection process was necessary. The selected parameters required that the drainage areas under consideration be less than 50 square miles, with at least five years of January and May data compiled by the U.S. Geological Survey, and all selected data reported was required to be characterized as fair, good or excellent. Sites where the measured data were reported to be poor or had large periods of estimation during the months of interest were excluded from the analysis. Certain sites were also rejected because of major upstream diversions, lakes or reservoirs acting as stream controls. Data were compiled using US West Hydrodata® CD-ROM, 1997, for USGS Daily Values, as well as Open File Reports 84-144-A, 84-144-B, 84-145-A and 84-145-B. Most mean annual precipitation and precipitation intensity were gathered from the Open File Reports; however, when figures were not available in the Open File Reports, values were determined by locating the latitudinal and longitudinal coordinates of the gauge stations. The 10-percent exceedance flow values were calculated using the Hydrodata® software via the Weibul formula:

$$P = M/(N+1)$$

where N is the number of values and M is the ascendant number in the pool of values.

REGRESSION ANALYSIS

A least-squares, multiple-regression analysis was run on a logarithmic transformation of the data. Drainage area and mean annual precipitation (precipitation intensity for Region 1) were the independent values. The independent variables used were those specified in the 1996 U.S. Geological Survey report.

Reasonable correlations were found within the western Washington regions. Correlation improved upon further division of the individual regions. Separate analyses were run for the high passage flows during the January and May migration periods for each region/subregion defined. Percent standard error (Tasker 1978) was derived from the formula:

$$SE_{percent} = 100(e^{\text{mean squared}} - 1)$$

where the units of the mean are natural log units. A table used for this formula allowed for simple derivation of standard error in percent from logarithmic units (Tasker 1978).

It's important to remember the nonsymmetrical nature of the log-normal distribution. The higher the calculated design flow, the greater the probability that the upper design flow will fall higher than one standard error above the regression line and less than one standard error below the regression line. It is, however, correct to assume an equal probability within one standard error above or below the regression line when the calculated flow and the standard error are expressed in logarithmic (base 10) units. However, the imprecise nature of accurately predicting high-passage design flows would more often than not influence the user to add the standard error, making the probability distribution somewhat unimportant.

RESULTS

Table G.1 is a summary of the regression equations that were developed. The original Powers and Saunders analysis included lowland (elevation <1000 ft) and highland (elevation > 1000 ft) stations in Regions 2 and 3. Through the use of these equations during the intervening years some doubt about the accuracy of the highland and urban coefficients has arisen. Sort of recalculating the regression equations, the prudent course of action at this point is to remove the highland and urban coefficients. It is recommend that designers using these regressions use the lowland versions, ***Table G.1***, as preliminary estimates and use gauging or other more rigorous methods to refine their design flows.

Table G.1: Regional regression equations for fish passage design flows in Washington. Qfp = fish-passage design flow; A = drainage area, square miles; I = two-year, 24-hour precipitation, in inches; P = mean annual precipitation, in inches.

		Equation	Constant a	Coefficients b	c	SE (%)
REGION 1	January	$Qfp= aA^bI^c$	6.99	0.95	1.01	25.7
	May	$Qfp= aA^bI^c$	2.25	0.85	0.95	30.6
REGION 2						
Lowland Streams < 1000 feet Elevation	January	$Qfp= aA^bP^c$	0.125	0.93	1.15	48.6
	May	$Qfp= aA^bP^c$	0.001	1.09	2.07	75
REGION 3						
Lowland Streams < 1000 feet Elevation	January	$Qfp= aA^bP^c$	0.666	0.95	0.82	38.1
	May	$Qfp= aA^bP^c$	0.014	0.87	1.42	38.1

Computation of a fish-passage design flow at an ungauged site is made as follows:

1. From the map showing hydrologic regions ***Figure G.1***, select the region in which the site is located.
2. From ***Table G.1*** select the appropriate equation from the region and select the appropriate month.
3. Using a U.S. Geological Survey topographic map, or other map, measure the drainage area above the site.
4. From a map of mean annual precipitation, for instance (Sumioka, Kresch et al. 1998), select the precipitation for the watershed in question.
5. Substitute the values determined from Step 3 and 4 into the equation from Step 2 and solve for the fish-passage design flow.
6. Apply the percent standard error as appropriate. In most cases, the standard error is added to the result because the high end of the passage flow is desired.

Example

Lake Creek Tributary (Lake Cavanaugh Road)

From Table 1: Region 2, January

A = 1.82 sq mi

P = 80 in/yr

$Qfp = 0.125(A)^{0.93}(P)^{1.15}$

$Qfp = 0.125(1.82)^{0.93}(80)^{1.15}$

Qfp = 34 cfs, Standard Error is 48.6%

Answer: Qfp = 18 to 50 cfs

LIMITATIONS AND COMMENTS

The equations presented in this study can be used within certain limitations to predict fish-passage design flows for western Washington. The relationships were determined from gauging-station data for natural-flow streams and should not be applied where artificial conditions have altered stream hydrology. These equations are not a substitute for hydrologic synthesis within a region, where flows are actually measured to develop a correlation to gauged data. Extrapolations beyond the limits of the basic data used in each region are not advised. Relationships can be used with the most confidence in lowland areas, where runoff is dominated by rainfall, and with the least confidence in highland or desert areas with little rainfall. Many urbanized streams in Puget Sound have been modeled using continuous simulation models. Watershed basin plans may be available from local governments with data that should be used to generate flow-duration curves for a specific stream location.

DETERMINING DESIGN FLOOD FLOW

The design of hydraulic structures is based on calculated risk using an agreed-upon recurrence interval. WAC 220-110-070 states that the 100-year peak flow will be used for the design of bridges and culverts (an argument can be made for the use of larger or smaller recurrence interval design flows depending on project goals, safety regulations and cost). The magnitude of this event can be calculated in 4 ways, stated in order of order of preference:

1. Gauge data for a period of at least 10 years. The accuracy of the prediction increases with the length of record. The table below gives the relative error (max_predicted_flood – population/population) for several confidence intervals (IACWD 1982; McCuen and Galloway 2010)

	Relative error in the 100-year flood for a given C.I.		
Years of record	**80%**	**90%**	**95%**
10	0.61	1.0	1.5
25	0.42	0.6	0.8
50	0.33	0.45	0.6
100	0.25	0.36	0.4

   For low risk projects (risk to both habitat and infrastructure) a lower confidence interval (C.I.) can be used and a correspondingly low relative error. For a low risk project with 10 years of record, one might cautiously add 60% to a predicted flood flow. On the other hand, a high risk project might need to double the estimate to compensate for potential events not included in the record. Further risk analysis will be necessary to understand the implications of structure life span and other relevant factors.
2. Continuous flow simulation model which has been calibrated to existing conditions. Errors in estimating rainfall, model setup, calibration, and other uncertainties should be quantified and a safety factor reflecting the risk and confidence interval applied to the estimate.
3. Local regression model to a closely matched gauged stream(s) with at least 10 years of flow data. As with method (1), the error of prediction is dependent on years of station record and a safety factor should be applied. Local regressions are covered in numerous publications (Dunne and Leopold 1978; Haan, Barfield et al. 1994), although a simplified method is given in (Sumioka, Kresch et al. 1998)
4. Regional regression model to which one standard error has been applied to the estimate to compensate for the inherent uncertainty (Sumioka, Kresch et al. 1998)

Local knowledge of flood events, or measured high water marks, should be used to verify model results.

APPENDIX H: WATER CROSSING HABITAT IMPACTS

The following list of impacts and compensatory measures is provided as a guide to designers. This list is not a comprehensive analysis of mitigation. For a complete discussion of mitigation issues and policy see ***WDFW Compensatory Mitigation Guidance*** (in development as of July, 2011). The intention here is to show how good design and construction practice compensates for most impacts and that, conversely, conflicting design goals or compromises made to reduce cost will require mitigation. The list is set up with the impact in bold type and the design features that compensate for these impacts bulleted below.

CONSTRUCTION IMPACTS

Fish kill

- properly designed up- and downstream blocknets
- blocknet maintenance plan
- fish removal by qualified personnel
- pump screen for dewatering pumps or bypass pumps

Water quality

- properly designed and maintained diversion
- containment and treatment of construction water
- contingency plan for pump diversions; if the diversion pump fails or runs out of fuel there should be a plan to remedy the situation
- isolate concrete, paint, adhesives until cured

Disruption of riparian and uplands

- restore adjacent natural contours
- clean up and revegetate storage and access points
- revegetate fill slopes with native vegetation

Foreign materials

- remove old abutments and other remnants from the previous crossing structure

GEOMORPHIC IMPACTS

Disruption of stream profile

- channel regrade plan to restore equilibrium
- properly designed up- and downstream transitions

Crossing skew

- realign crossing to reduce skew

- realign stream to reduce skew
- use large wood to redirect flow or reduce the effect of skew on the road fill or the crossing structure

Exposure of bedrock or hardpan

- place large wood to store sediment (must be dug in or ballasted with sediment)

Transport of sediment and debris

- proper crossing design using stream simulation or a properly designed bridge
- maintenance and contingency plan for other designs
- sediment or wood supplementation plan for downstream reach

Channel simplification

- proper crossing design using stream simulation or a bridge

Disruption of meander migration

- size crossing to accommodate meander migration expected to be encountered within the life span of the structure
- add large wood jams to alter flow patterns

RIPARIAN IMPACTS

Permanent removal of riparian vegetation

- enhance remaining riparian vegetation, if degraded, by eliminating invasive species and revegetating with appropriate native species
- restore off-site area with native vegetation
- restore natural wood loading in a specified reach

Filling of riparian wetland

- steepen fill slope to reduce impact
- remove unnecessary fill
- enhance remaining riparian vegetation if degraded
- remove invasive species from specified area and replant with native vegetation
- provide off-site compensation

BIOLOGICAL IMPACTS

Spawning habitat loss

- proper crossing bed design and material specification
- gravel-poor streams: supplement gravel
- gravel-rich streams: supplement large wood to natural levels

Rearing habitat loss

- place large wood structures to form pools
- create off-channel habitat
- enhance remaining riparian vegetation if degraded

Placement of non-native materials, such as quarry rock, concrete, sheet pile, etc.

- substitute biotechnical techniques for riprap
- move non-native materials from frequently inundated areas to outside OHW
- cover non-native materials with soil and revegetate
- increase structure span to reduce need for riprap
- reduce fill slope to increase stability and vegetation success

Ecological connectivity

- proper crossing design using stream simulation or a properly designed bridge
- long term impacts cannot be mitigated in kind

Fish passage

- proper crossing design using an accepted fish passage method such as those represented in this document
- barriers to some species cannot be mitigated in kind unless habitat can be created or access to equivalent areas restored.

APPENDIX I: REFERENCES

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