FISH PASSAGE DESIGN AT ROAD CULVERTS

A design manual for fish passage at road crossings

Washington Department of Fish and Wildlife
Habitat and Lands Program
Environmental Engineering Division

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Updates and Feedback

This version of 'Fish Passage Design at Road Culverts' is a work in progress; we welcome comments and ideas for improvement. Updates will be available on the web through the Washington Department of Fish and Wildlife web page; www.wa.gov/wdfw/habitat.htm. If you have comments or ideas for the manual, they can be emailed to ees@dfw.wa.gov or by regular mail to:

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FISH PASSAGE DESIGN AT ROAD CULVERTS

INTRODUCTION

This manual is for the design of permanent new, retrofit, or replacement road crossing culverts that will not block the migration of salmonids. The manual is intended for use by designers of culverts including private landowners and engineers. The level of expertise necessary to use this manual varies depending on site conditions and the design option selected. For all but the no-slope design option (described below), it is assumed that the designer has a basic background of hydraulic engineering, hydrology, and soils/structural engineering to accomplish an appropriate design.

Formal fishways may be required at some culvert sites to provide passage. The design of fishways is beyond the scope of this manual though there is a brief description of some basic design concepts included here. A fish passage engineer should be consulted for additional assistance for the design of fishways.

The organization of the manual follows the logical steps expected in a prudent culvert design. A data form is provided in **Appendix F** describing the data needed for the design and for those evaluating the design. For explanations and definitions of terms describing the channel, hydrology and data requirements see the Explanation of Data also in **Appendix F**. Several case studies showing various culvert design options are described in **Appendix G**.

The manual is based on the premise that a culvert is the desired road crossing option at a site. That does not mean that for fish traffic, fish passage or other ecological functions, a culvert is the actually best solution or even permitted. Though this manual focuses on fish passage, there are other habitat and ecological considerations that are factors in the siting and design of road crossing structures. Those considerations are outlined in the section **Other Passage and Habitat Considerations.**

This manual does not provide guidance about the inventory of culverts or the prioritization of culvert barrier remedies. That information is included in *Fish Passage Barrier Assessment and Prioritization Manual*, 1998 by WDFW.

WAC 220-110-070; Fish Passage at Road Crossings

This manual describes the design of new or retrofit culverts to aid culvert owners and designers be in compliance with Washington Department of Fish and Wildlife (WDFW) fish passage criteria as defined by WAC 220-110-070 (WAC: Washington Administrative Code -

included as **Appendix B**).

The information contained within this manual is the most current guidance for construction and retrofit of culverts for fish passage in Washington State. Recommendations in this publication vary somewhat from WAC 220-110-070 but do not conflict with it. This publication is intended to clarify that WAC, and provide up-to-date guidance and application of the WAC across a broader range of fish passage projects including steeper culverts. These guidelines can be applied as provided for in WAC 220-110-032 “Modification of technical provisions”. Information gathered, concepts and guidance developed for this draft publication will be incorporated into any future review and update of WAC 220-110-070.

CULVERT BARRIERS

The parameters provided in WAC 220-110-070 are the technical definition of a fish passage barrier as well as the basis for fish passage design. Some level of barrier is assumed to be present when the criteria are not achieved. The WAC is included in this manual as **Appendix B.**

Complete barriers block the use of the upper watershed, often the most productive spawning habitat in the watershed considering channel size and substrate. Access to upper portions of the watershed is important; fry produced there then have access to the entire downstream watershed for rearing. **Temporal barriers** block migration some of the time and result in loss of production by the delay they cause (anadromous salmonids survive a limited amount of time in fresh water and a delay can cause limited distribution or mortality). **Partial barriers** block smaller or weaker fish of a population and limit the genetic diversity that is essential for a robust population. Fish passage criteria accommodate weaker individuals of target species including, in some cases, juvenile fish.

There are five common conditions at culverts that create migration barriers:

- excess drop at culvert outlet;
- high velocity within culvert barrel;
- inadequate depth within culvert barrel;
- turbulence within the culvert;
- debris accumulation at culvert inlet.

Fish passage barriers at road culverts are created by several conditions. Culverts are usually uniform and efficient to optimize water passage; they often do not have the roughness and variability of stream channels and therefore do not dissipate energy as readily. The concentration and dissipation of energy in the form of increased velocity, turbulence or downstream channel scour are the most prevalent blockages at culverts.

Culverts are a rigid boundary set into a dynamic stream environment. As the natural stream channel changes, especially with changes in hydrology due to land use changes, culverts often are not able to accommodate those changes and barriers are created.

Barriers at culverts are the result of improper design or installation, or subsequent changes to the channel. They are very often the result of degrading channels that leave the culvert perched above the downstream channel. Changes in hydrology due to urbanization are a primary reason for degrading channels. Barriers are also caused by scour pool development at the culvert outlet. The scour pool may be good habitat in itself but it moves the backwater control of the downstream channel further downstream and therefore to a lower elevation creating a drop at the outlet. The presence of large scour pools and/or upstream mid-channel bars are often an indicator that a velocity barrier exists within the culvert at high flows.

Fish passage barriers are often created by a lack of maintenance. The maintenance done at a culvert for the purpose of high flow capacity is often different than what is required for fish passage. Debris plugging slots in baffles for example may not affect the flow capacity of a culvert but may be critical to fish passage. More than a cursory inspection of the culvert inlet may be necessary for an adequate fish passage maintenance inspection. Adult fish typically migrate during the high flow seasons and in response to freshets. Timely inspections and maintenance during inclement weather are therefore necessary.

Many fish passage barriers that occur at high stream flows are not apparent during low and normal stream flows. Culverts must be analyzed at both the low and high fish passage design flows. Definition and selection of design flows are discussed in this manual. A summary of an example analysis of fish passage through a culvert is included in the manual in **Appendix H**.

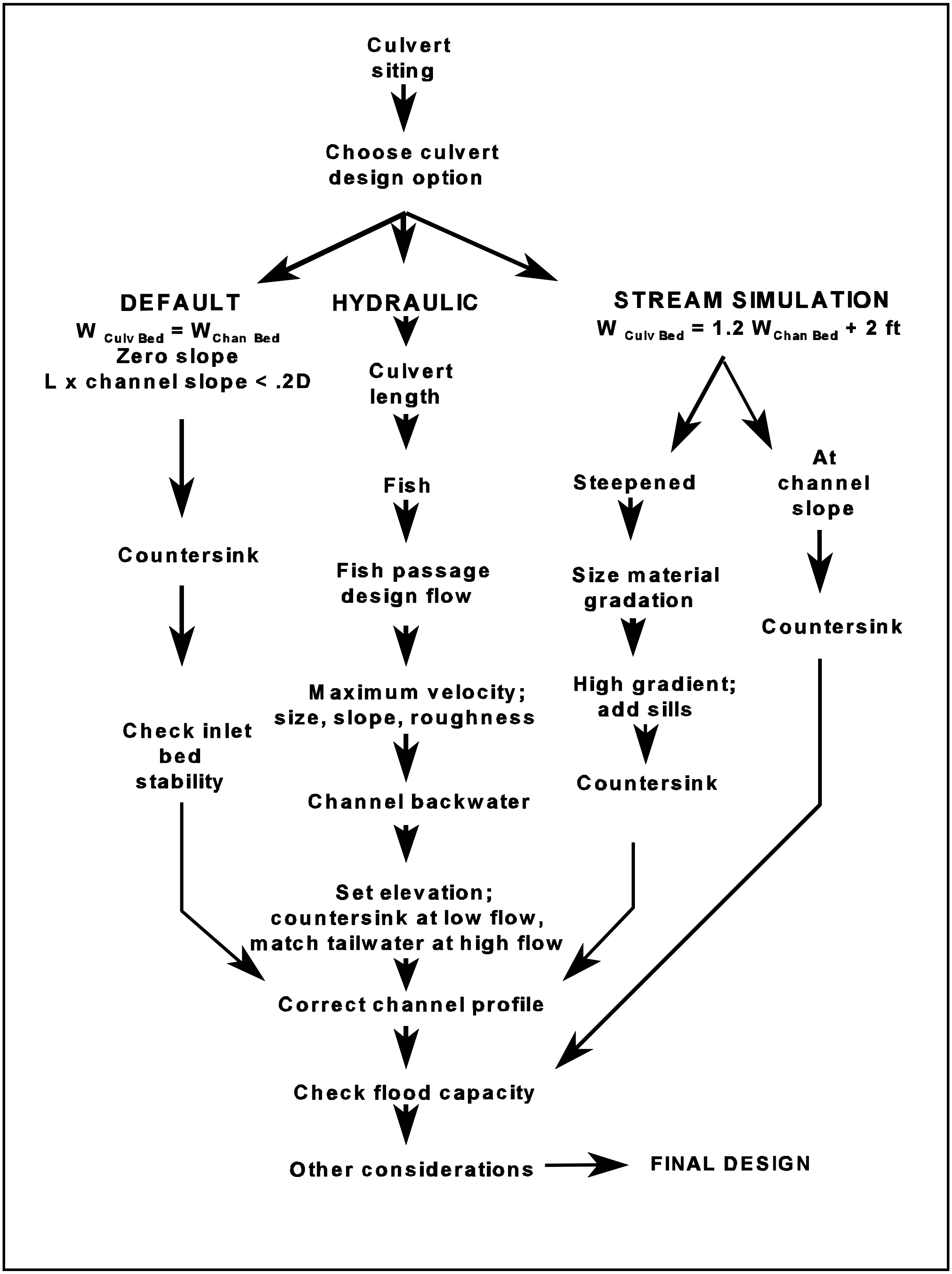

Figure 1 Culvert Design Process For Fish Passage.

CULVERT DESIGN PROCESS

Many culverts in Washington State have been designed or retrofitted to provide fish passage. This experience together with research on fish swimming capabilities has led to several straightforward design procedures outlined in this manual. A summary of the procedures described in the manual are shown in **Figure 1** which is a general flow chart of the culvert design process explained in the text of the manual.

This manual provides specific guidance to satisfy state regulations and to cover situations that exceed those defined by regulations. Culverts cannot be designed for all situations to provide adequate fish passage. If the criteria provided here can not be achieved in a design, other road crossing means should be considered such as a temporary culvert, rerouting the road to eliminate the stream crossing, or a bridge. Recent experience in Western Washington has been that to achieve these fish passage criteria, about 20% of barrier remedies require a culvert replacement. Some of these have been accomplished by boring new culverts through high road fills. Likewise, about 5% require replacement of the culvert with a bridge or abandonment of the road.

The criteria provided here are not absolute. Some of these guidelines will not apply in every situation; designs can be approved if adequate justification is provided for variance of criteria and processes defined here.

Fish passage may be provided by various combinations of culvert slope, size, elevation, roughness, formal structures, and allowing the upstream channel to regrade to a steeper gradient. Fish passage work can usually be limited to 100 feet or less of the channel length outside the culvert at low gradient sites; steeper sites may extend further or require formal fishways or culvert removal. The determination of adequate fish passage at a culvert is based on criteria described in the Washington Administrative Code (WAC 220-110-070). The WAC describes two different approaches for permanent culverts. In this publication the two options are called the no-slope option and the hydraulic design option. The **no-slope option** requires few if any calculations but results in very conservative culvert sizes. The hydraulic design option requires hydrologic and open channel hydraulic calculations but usually allows smaller culverts than the no-slope option. The **hydraulic design option** is based on velocity, depth and maximum turbulence requirements for a target species and age class. A third option is also acceptable; it is the **stream simulation** option in which an artificial stream channel is constructed inside the culvert and therefore passage is provided for any fish that would be migrating through the reach.

When juvenile passage is required at a site, the design criteria of the hydraulic option will usually be difficult to achieve. The no-slope and stream simulation design options, on the other hand, are assumed to be satisfactory for adult and juvenile passage and are therefore applied more where juvenile passage is required. Application of the no-slope option is somewhat limited to relatively short culverts in low gradient sites.

CULVERT SITING

Success of fish passage and the cumulative habitat loss caused by culverts depend in part on culvert siting and minimizing the number of road crossings. Both siting of specific culverts and the land use planning that creates the need for the culvert are important.

Specific culvert siting

Siting of specific culverts should be done to optimize the skew of a culvert relative to the upstream and downstream channels and length of the culvert. A culvert at an extreme skew (greater than about 30° to the channel) will affect the success of fish passage by increasing inlet contraction and turbulence at high flows. That increased contraction will also make the culvert less efficient for flood capacity and sediment transport. In-channel deposition and bank scour often occur upstream of culverts with excess skew. When the culvert is skewed relative to the downstream channel and the culvert outlet is not directed at the channel alignment, there is an increased risk of bank erosion.

The purpose of increasing culvert skew is usually to reduce the length of the culvert. On the other hand, an increased culvert length creates additional difficulty in providing fish passage and increases direct habitat and channel loss.

Consider potential natural migration of the channel when siting a culvert. The installation of a culvert fixes a section of the channel rigidly in place. If it were naturally unstable and/or migrating across a floodplain, the rigidity of the culvert may exacerbate the instability or make a tendency of gradual migration to be more pronounced and chaotic. This issue is also discussed in the section **Other Passage and Habitat Considerations.**

Land use planning

Many new stream crossings can be avoided (or at least the numbers can be reduced) through proper planning. Regardless of our best fish passage designs each stream crossing now has the potential to become a fish passage obstacle. The way local jurisdictions prepare and implement land use plans and critical areas ordinances has a direct influence on fish passage based on the distribution of land uses and the transportation systems necessary to support them. For example if a county fails to allocate any forest or agricultural land, applying instead a very dense pattern of urban and suburban or rural residential land uses, one can expect a variety of stream crossings to be forthcoming. This would not be the case if less dense and intense land uses such as forestry or agriculture, coupled with compact urban growth areas and a mixture of large rural parcels is applied.

In addition to the number of road crossings, changes in hydrology and riparian areas due to dense urbanization also affect fish passage. These changes cause channel incision and channel simplification that often leave culverts perched and barriers to fish migration. Other likely impacts are sediment and temperature impacts. With these changes, the remaining habitat is left upstream of the urbanized areas; the barriers thus become more and more critical to fish production.

There are also channel maintenance impacts due to poor road crossing and culvert siting other than fish passage. They are further described in the section **Other Passage and Habitat Considerations.**

NO-SLOPE DESIGN OPTION

Fish passage can be expected if the culvert is sufficiently large and installed flat, allowing the natural movement of bedload to form a stable bed inside the culvert. The no-slope option is defined by a culvert with:

- Width equal to or greater than the average streambed width at the elevation the culvert intersects the streambed,
- Flat gradient,
- Downstream invert countersunk below the channel bed by a minimum of 20% of the culvert diameter or rise;
- Consideration of upstream headcut,
- Adequate flood capacity.

Generally, the **no-slope design option** might be applied in the following situations:

- New and replacement culvert installations,
- Simple installations; low to moderate natural channel gradient or culvert length,
- Passage required for all species,
- No special design expertise or survey information required.

The no-slope option can only be applied to culvert replacements and new culvert installations. Although no flows or velocities are calculated, the fact that velocities are sufficiently low to allow a bed to deposit in the culvert is accepted as evidence that a broad range of fish species and sizes will be able to move through the culvert. In some cases channel morphological features such as gravel bars and a thalweg form inside the culvert. Culverts installed using the no-slope option are typically somewhat larger than culverts designed using the hydraulic option. Combining the requirements of countersinking the outlet and the culvert width for a circular culvert, the diameter must be at least 1.25 times the channel bed width. The primary advantage of this option to the culvert owner is the avoidance of additional surveying and engineering costs required for other options.

Information needed for the no-slope option are:

- the average natural channel bed width,
- the natural channel slope,
- the elevation of the natural channel bed at the culvert outlet,
- an evaluation of potential headcut impacts as the upstream channel regrades.

The first three of these parameters are described, together with standards for their measurement, in **Appendix F**. The channel bed width, as defined by the WAC, is the lateral dimension between ordinary high water marks. The local channel slope, width and elevation will be affected by any existing culvert if the culvert is either perched or undersized. In addition to the information described above, a surveyed profile of the channel will be required where it has been affected by the existing culvert. The profile is used to predict the natural channel slope and elevation at the culvert site by interpolating from unaffected conditions upstream and downstream. The downstream channel profile may have to be steepened in situations where it has been scoured due to an undersized culvert. That steepened channel may become buried eventually as the channel aggrades over it.

The channel bed width, as defined by the WAC, is the dimension across the channel between ordinary high water marks. The glossary in **Appendix A** has a definition of ordinary high

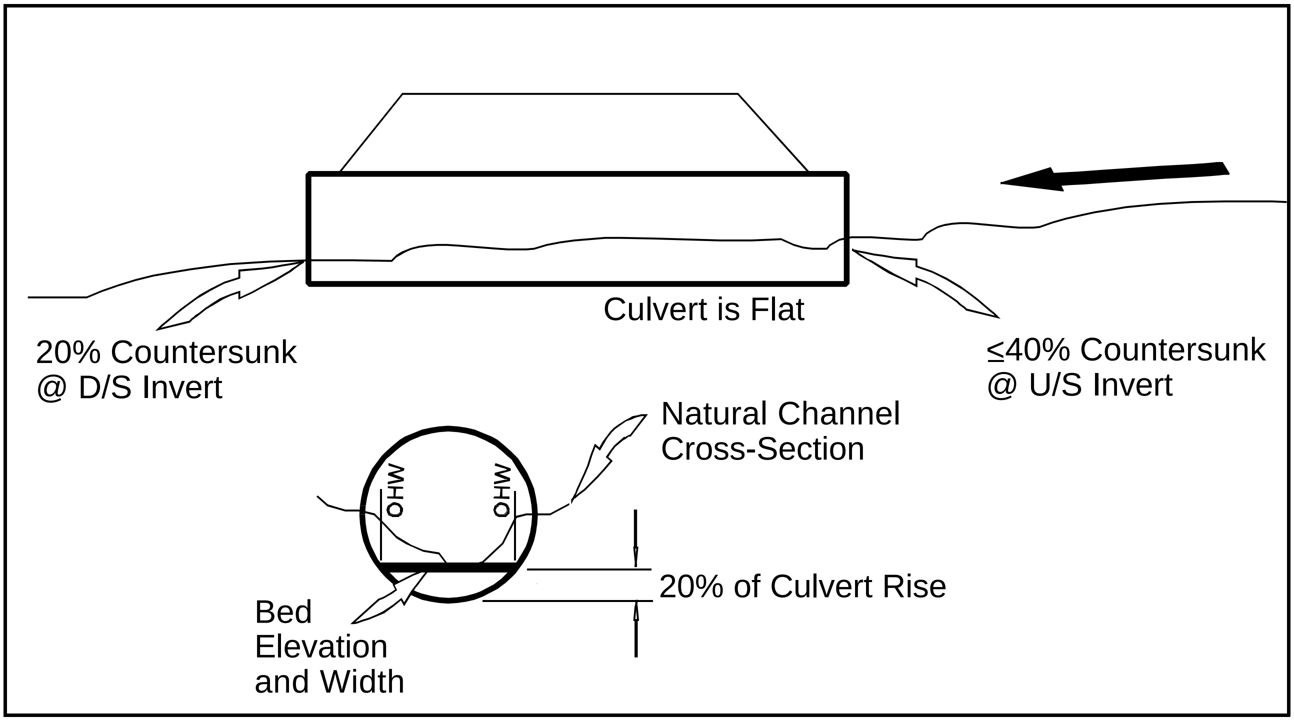

Figure 2 Culvert No-slope Design Option

water marks. For design purposes, use the average of at least three typical widths both upstream and downstream of the culvert. Measure widths that describe normal conditions at straight channel sections between bends and outside the influence of any culvert or other artificial or unique channel constrictions.

Assuming the culvert is large enough to not create a constriction, a sloping channel will develop inside the culvert even though the culvert itself is placed flat. The result of this is the upstream end of the culvert will have a higher bed and less cross section open area than the downstream end. Longer culverts in steeper channels under this option will result in less open area at the upstream end. This situation leads to the limitation of the no-slope design option to shorter culverts at low gradient sites. A reasonable upper limit of this option would be to use this option at sites where the product of the channel slope (ft/ft) and the culvert length (ft) does not exceed 20% of the culvert diameter or rise.

This limitation can be overcome by more thoroughly understanding and accounting for implications of constricting the upstream end of the culvert with the accreted bed or by installing a larger culvert.

Channel profile, flood capacity, other considerations

The design of a new culvert should provide mitigation for future design flows as land uses change. Additional considerations in the no-slope design option are similar to other options described here. Issues of channel profile, flood capacity and other considerations are described in the sections **Channel Profile, High Flow Capacity, and Other Passage and Habitat Considerations.**

HYDRAULIC DESIGN OPTION

The second option provided in the WAC **(Appendix B**) requires culvert be designed based on swimming abilities of a target fish species and age class. The hydraulic design option can be applied to retrofits of existing culverts as well as to the design of new culverts. Hydraulic open channel flow and hydrologic computations together with specific site data are required for this option.

Generally, the **hydraulic design option** might be applied in the following situations:

- New, replacement and retrofit culvert installations,
- Low to moderate culvert slope without baffles,
- Moderate (up to 3.5%) culvert slope with baffles (only as retrofit),
- Target species identified for passage,
- Engineering design expertise, hydrology, and survey information required.

The hydraulic design option has been the traditional engineering method for designing fish passage. It is not necessarily the preferred method however. The method has limitations of culvert slopes; other design methods might provide less costly but more reliable designs in steep channels. The hydraulic method targets distinct species of fish and therefore does not account for ecosystem requirements of non-target species. There are significant errors associated with estimation of hydrology and fish swimming speeds that are resolved by making conservative assumptions in the design process.

The fish passage design process for hydraulic design is reversed from the typical engineering orientation of culvert design for flood flows. Think like a fish. Start in the channel below the culvert and proceed in the upstream direction through the culvert; the direction of fish passage. Culverts designed for fish passage normally result in outlet control conditions at all fish passage flows. The usual inlet control analysis must then be done to verify adequate culvert capacity for the high structural flow. Fish passage criteria will usually control culvert design; flood passage criteria are normally less stringent.

Proper culvert design must simultaneously consider the hydraulic effects of culvert size, slope, material and elevation to create depths, velocities and a hydraulic profile suitable for fish swimming abilities. It must be understood that there are consequences to every assumption; adequate information allows you to optimize the design. The following sequence of steps is suggested for the hydraulic culvert design for fish passage:

1. **Length of culvert.** Find the culvert length based on geometry of the road fill.
2. **Fish passage requirements.** Determine target species, sizes and swimming capabilities of fish requiring passage. Species and size of fish determine velocity criteria. Actual allowable maximum velocity depends on species and

length of culvert.

3. **Hydrology.** Determine the fish passage design flows at which the fish passage criteria must be satisfied.
4. **Velocity and depth** Find size, shape, roughness and slope of culvert to satisfy velocity criteria assuming open channel flow. Verify that the flow is subcritical throughout the range of fish passage flows.
5. **Channel backwater depth.** Determine the backwater elevation at the culvert outlet for low and high fish passage design flow conditions.
6. **Culvert elevation** Set the culvert elevation so the low and high flow channel backwater elevations are at least as high as the water surface in the culvert.
7. **Flood flow capacity.** Verify that flood flow capacity of the culvert is adequate.
8. **Channel profile.** If necessary the upstream and/or downstream channel profiles may have to be adjusted to match the culvert elevation.

Several iterations of Steps 4 - 8 may be required to achieve the optimum design. Steps 1, 8, and 9 are common to all culvert design options. The following sections further describe all of the design steps.

Length of culvert

The hydraulic design process is based on the maximum water velocity for target fish species to be able to negotiate the length of the culvert; the longer the culvert, the lower the maximum allowable velocity. Determine the overall length of the culvert. Include aprons in the length unless they are countersunk below the invert of the culvert. The length can be minimized by adding headwalls to each end of the culvert, by narrowing the road, or by steepening the fill embankments.

Fish passage requirements

Species and size of fish

The hydraulic design method creates hydraulic conditions through the culvert that accommodate the swimming ability and timing of target species and sizes of fish. Fish passage design is based on the weakest species or size of fish requiring passage and is intended to accommodate the weakest individuals within that group. What species are potentially present? When are they present? This information should be obtained from the WDFW Area Habitat Biologist or Regional Fish Biologist.

The requirement of design for passage of adult trout as small as 6" fork length (150 mm) is a requirement in most areas of Washington State. It is assumed to be a requirement at each site unless it can be shown that, either by distribution of species or habitat it is not justified.

Upstream migration of juvenile salmonids (50 to 120 mm salmon and steelhead) is also important at many sites depending on species present and habitat distribution within the basin or reach. These fish are small and weak and therefore require a very low passage velocity and at a low level of turbulence. It is therefore not generally practical to design for juvenile passage directly by the hydraulic design option. Juvenile passage may not be necessary in every situation; the biological need should be clearly stipulated by appropriate qualified biological staff before a design is attempted specifically for juvenile fish.

It is the intent that a culvert specifically designed by the hydraulic design option for 6 inch trout will also provide passage for juvenile salmonids. If the hydraulic characteristics for adult trout passage are achieved during peak flows, adequate juvenile passage is provided at appropriate lesser flows. The trout passage hydraulic conditions will result in bed material deposition and a natural roughened channel through the culvert that juvenile fish can successfully use for passage. It is believed that juvenile fish can tolerate some delay and, because of their normal migration timing, will be subjected to less severe hydraulic conditions than adult migrants. An exception to the presumption of stable bed formation for juvenile fish passage might occur in situations where a pipe becomes deeply submerged and pressurized during an extreme flood event and bed material is therefore scoured from it. Until new bed material is recruited into the culvert, there may be a barrier to weaker swimming fish.

The use of adult trout as a conservative default condition may not apply to fishway design since passage through the fishway does not depend on the accretion of a natural bed and design issues of flow control and energy dissipation are unique in design of fishways. The design of fishways is not included in this manual though there is a brief overview of the subject in the section on **Fishways.**

Much of this manual is based on passage of salmonid fishes. Additionally there are tremendous ecological benefits to providing connectivity between upstream and downstream reaches for other biota and physical processes. In addition to salmon and steelhead, there are at least fifteen species of migrating fish in Washington State for which there is little or no information regarding migration timing, migration motivation or swimming ability. Ecological

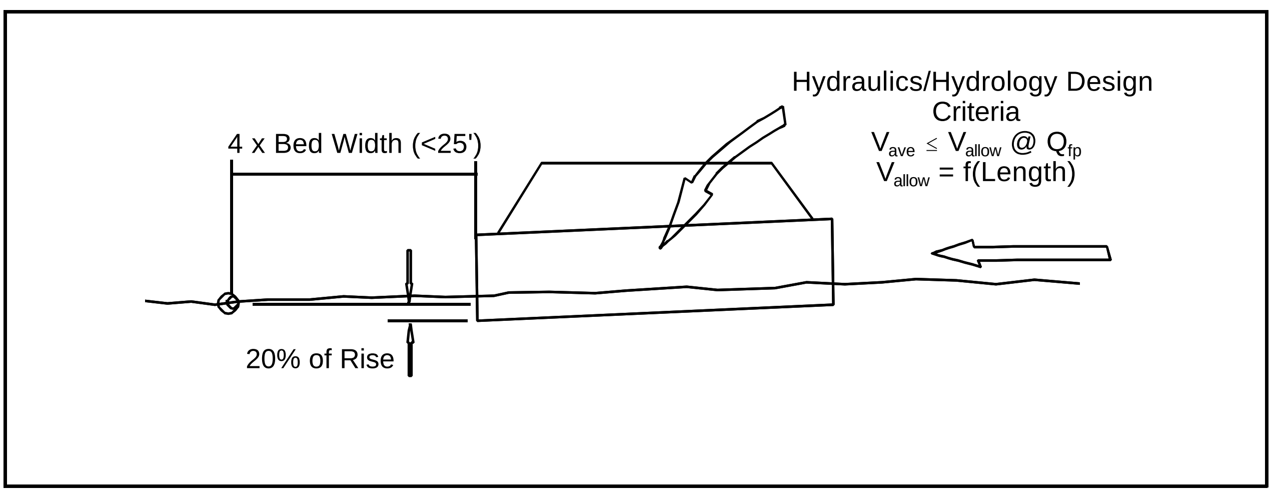

Figure 2. Culvert Hydraulic Design Option

health of both upstream and downstream reaches depends on connectivity of physical processes such as sediment and debris transport, channel patterns and cycles and patterns of disturbance and recovery. Stationary culverts at a fixed elevation may not be able to communicate these processes and may therefore affect overall ecosystem health. Many of these values are not likely provided by using the hydraulic design option. They are more likely achieved by using the stream simulation option or certainly by using options other than culverts such as full spanning bridges and road abandonment or relocation.

Species and size of fish determine velocity criteria

The actual allowable velocity and depth of flow for adult fish depend on the target species and length of culvert and are shown in **Table 1** adapted from WAC 220-110-070. These criteria are intended to provide passage conditions for the weakest and smallest individuals of each species.

As described above, the passage of juvenile fish is provided by these criteria when the design actually targets adult trout. If the design does not target adult trout, juvenile salmonid passage cannot normally be designed by the hydraulic option. It is unusual that juvenile fish passage can be provided by controlling the velocity to a prescribed maximum by installing artificial roughness. The low velocities and level of turbulence required for passage of juvenile

Table 1. Fish Passage Design Criteria for Culvert Installations

	Adult Trout >6 in. (150 mm)	Adult Pink, Chum Salmon	Adult Chinook, Coho, Sockeye, Steelhead
Culvert Length	Maximum velocity (fps)		
10 - 60 feet	4.0	5.0	6.0
60 - 100 feet	4.0	4.0	5.0
100 - 200 feet	3.0	3.0	4.0
Greater than 200 feet	2.0	2.0	3.0
	Minimum water depth (ft)		
	0.8	0.8	1.0
	Maximum hydraulic drop in fishway (ft)		
	0.8	0.8	1.0

fish are so low, they are impractical to achieve in design. Based on evaluation of juvenile passage through culverts by Powers (1997), the recommended design velocities for fry and fingerlings are 1.1 and 1.3 fps respectively. Fry are spring migrating juveniles generally less than 60 mm in length fork; fingerlings are fall migrating fish generally greater than 60 mm in fork length. Allowable velocities for these fish depend on the type of corrugation of the pipe; refer to Powers (1997) for details. These velocities are average cross section velocities and would apply to any length of culvert; Powers observed that the fish were swimming in a prolonged swimming mode. That is to say they could continue at that rate for and extended period time. These velocities might be achieved at some low gradient sites with large culverts or spring fed streams with low peak flows.

Increasing the roughness with features like baffles can create a low enough average velocity but the turbulence created to do that becomes a barrier to juvenile fish at moderate slopes. If juvenile passage is desired, it is recommended that a natural channel be built within the culvert. The complexity and diversity of natural channels are better suited to providing fish passage opportunities for small fish. The natural channel design is the recommended option and is described in the section on **Stream Simulation Option.**

The hydraulic design option uses the average velocity in the cross section of the flow and assumes normal open channel flow throughout the culvert. This is a conservative design because it does not account for a backwater condition that will increase the depth, and thus somewhat reduce the velocity. In reality, flow is seldom at normal depth throughout a culvert, particularly in a culvert that is on a relatively flat slope. Backwater profile programs can be used to further refine the design. Keep in mind however that errors from hydrologic calculations may far outweigh differences between velocity calculation models. This design method also does not account for the boundary layer velocities that fish will use in moving through a culvert. Boundary layer velocities cannot be used because they are difficult to predict, turbulence can become a barrier, and continuity of a boundary layer through a culvert is difficult to create.

Migration Timing

The hydraulic design criteria must be satisfied 90% of the time during the migration season for the target species and age class. Since migration timings vary among species and watersheds, knowledge of the specific migration timings is necessary for development of hydrology. Different species or age classes at a site may migrate at different times of the year; multiple hydrologic analyses may be needed to determine the controlling hydraulic requirements. Generally adult salmon and steelhead migrations occur during the fall and winter months. Juvenile salmon migrations occur in the spring as fry and in the fall as fingerlings.

Hydrology

The hydraulic option design criteria described above under Fish Passage Requirements must be satisfied 90% of the time during the passage season for the target species. The 10% exceedance flow for each target species is then the fish passage design flow. There may be more than one fish passage design flow if different life stages or species require passage at different times of the year. Until the hydrology is analyzed and the culvert hydraulics designed to accommodate these life stages, it is not known which fish passage design flow will control the design.

In tidally controlled situations, independent analyses of tidal influence and streamflows is necessary. For the tidal data, the hydraulic criteria should be complied with at least six daylight hours on 90% of the days during the migration season. This criteria may apply to culverts and tide gates.

High fish passage design flow

These criteria require a hydrologic analysis to determine the fish passage design flow. There are four levels of hydraulic analysis that are acceptable for a range of fish passage designs. The scale and importance of the project and availability of data will dictate which level is applied to a specific project. They are, in order of preference:

1. Stream gauging;
2. Continuous simulation model;
3. Local regression model;
4. Regional regression model.

Another option is to use data obtained from one of the above methods to calibrate a basin to basin correlation between recorded flows in a nearby system and spot flows measured in the stream system where design flows are needed. Extreme care should be used when creating this correlation as the probability of induced errors increases.

Interpretation of historic stream gauging data for a specific stream is the most preferred type of analysis but adequate data for specific sites are rare. With a few flow data points, however, a regional flow model can easily be verified and calibrated. Calibration data should be within 25% of the fish passage design flow to be valid. Continuous flow simulation models are acceptable though not normally justified solely for a fish passage design. Single event models are generally not acceptable since the fish passage design flow is based on a flow recurrence frequency rather than a peak flow.

An acceptable regional regression model for Washington State is the Powers-Saunders model (Powers and Saunders, 1994) which is included here as **Appendix C**. It can not be used in other regions nor for sites that do not fit within the range of watershed sizes and climate parameters used in the regression analysis.

The Powers-Saunders model was built by a multiple regression analyses on streamflow data from 188 Washington streams with drainage basins from less than 1.0 to about 50 square miles and with minimum gauging records of 5 years. Regression models for predicting fish passage design flow (10% exceedance flow) were developed for three hydrologic provinces in Western Washington for winter and spring months. Two regions have models for highland streams (gauge elevation above 1000 feet) and second models for lowland sites. No valid correlation was found for Eastern Washington.

The models are in the form of **Equation 1**:

$$Q_{HP} = aA^{b}P^{c}I^{d}$$ **Equation 1**

The parameters are defined as:

Q_{HP}	High fish passage design flow
A	Basin area in square miles;
P	Mean annual precipitation at the gauging station in inches;
I	Rainfall intensity; 2-year, 24-hour precipitation;
a	Regression constant;
b,c,d	Regression exponents for basin area, precipitation and rainfall intensity. Mean annual precipitation and rainfall intensity were not statistically significant in all cases so exponents for some regions are zero.

The standard statistical errors for the regression formulae vary from about 26% to 75%. Sound judgement must be used in applying standard error to the predicted fish passage design flow for a specific site. It is recommended that, as a default, at least one standard deviation be added to the estimated flow from **Equation 1** unless a lower value can be justified by current and future watershed conditions.

This produces a conservative estimate in most cases. Consideration should be given to specific hydrology of the basin, target species for fish passage and future watershed conditions. Lower values would be justified in streams that have a slow response to rainfall events such as spring fed streams and basin with a lot of storage available. Higher estimates should be applied to steeper and urbanized or urbanizing watersheds. Will land use and basin hydrology change during the life of the project? Will the maximum and minimum flows change? A complete description of the model, regression constants and the statistics of the basins for each region are provided as **Appendix C**.

Whatever model is used, future watershed conditions should be considered when choosing the fish passage design flow. Continuous flow simulation models and calibrated regional models most likely provide the best estimate of future conditions.

Structural design of the culvert will depend on an analysis of flows higher than the high passage design flow and are discussed briefly in the section on **High Flow Capacity.**

Low fish passage design flow

The low fish passage design flow is used to determine the minimum water depth at any time. The low flow used is the two-year, seven-day low flow as described in WAC 220-110-070. A simpler option is to use the zero-flow condition as described below.

The depth requirement is a moot issue in culverts designed with natural beds. Culverts designed by the hydraulic option for trout as the default condition as described in the section on **Hydraulic Design Option** will generally accrete bed material in which a thalweg develops and the depth requirement is also moot. An exception to this is when a culvert becomes pressurized during an extreme flood event, the bed in the culvert scours out. If bed material doesn't immediately recruit, the bare bed condition may persist for some time.

Velocity and depth

To keep the average cross section velocity at or below the velocity criteria select the appropriate combination of culvert size, material (roughness) and slope. Several types of hydraulic analyses are acceptable; they vary in their complexity, resulting factor of safety, and cost for the final design. Stage-discharge relationships can be developed by simple calculations or complex water surface profiles. The most simple analysis is the calculation of depth and velocity assuming uniform flow; that is, with no backwater influence. This is the depth and velocity generally derived from a calculation of Manning's formula or from a chart of culvert hydraulic characteristics. Calculate the depth and velocity; the depth will be matched to the hydraulic profile of the downstream channel as described later.

Computer backwater programs such as HEC-RAS™, HY8™, or CULVERT MASTER™ and others can assist in the design process. The minimum amount of information needed for these programs varies with the program and complexity of the project. A backwater analysis allows the designer to optimize the design by using the lower velocities created by the backwatered condition. Without a backwater calculation, the culvert velocities are less accurate but more conservative. Estimation of culvert and channel roughness are described in data explanation in **Appendix F**.

A good rule of thumb for fish passage is to keep the flow sub-critical for all flows up through the fish passage design flow. This usually keeps the velocity low enough to satisfy the criteria and eliminates turbulence that would have been caused by a hydraulic jump inside the culvert.

Baffles

Baffles are a feature added to a culvert that act in concert to increase the hydraulic roughness of the culvert and therefore reduce the average cross section velocity. Baffles work together as a roughness element rather than as individual hydraulic control structures such as weirs. The flow over a series of baffles at high flow is a streaming pattern rather than, for weirs, a plunging pattern. To create streaming flow the baffles have to be relatively close together and short compared to the flow depth. The quantitative design of baffle hydraulics includes the size and spacing and is described in **Appendix D**.

Typical baffles act as weirs at low flows and transition to roughness elements as the flow increases. Baffles have often inappropriately been designed as weirs. Weirs are discreet hydraulic elements and the energy is dissipated in the pools between them; this is a very different concept than a series of baffles that act together as roughness. When designed as weirs, the fishway pool volume criteria, in the section on **Fishways** of this manual must be complied with.

Baffles within the culvert are not a desired solution to meeting velocity criteria and are not appropriate for new culvert installations. There are several inherent problems with them. Many culverts currently being addressed for fish passage were designed only for hydraulic capacity. Adding baffles reduces hydraulic capacity and often becomes a limit to flood capacity. The tendency of baffles to catch woody debris exacerbates the culvert capacity problem and creates an added possibility of a fish barrier as well as culvert plugging and road fill failure. Because of the requirement for maintenance access, baffles should not be installed in culverts with less than five feet of headroom.

The need for frequent inspection and maintenance of baffled culverts is widely recognized, but few maintenance programs establish the protocol or budget for adequate maintenance. Passage for many salmonid species is most critical during freshets in the winter months. This is the same time as the greatest risk of floods and the greatest presence of debris. Maintenance is usually impossible during high flow fish passage seasons so passage is lost for at least part of a season when they fail or plug. Since the baffles and the potential barriers are out of site, they often go unaddressed. Finally, The added roughness raises the hydraulic profile through the culvert and is therefore more difficult to match to the profile of the downstream channel.

Baffles may block juvenile passage by creating large scale turbulence relative to the size of the fish (Powers et.al., 1996). They are therefore not recommended as a solution when juvenile passage is required. With appropriate hydraulic design and site conditions, juvenile passage might be provided by weirs that become baffles at higher discharges.

Though the hydraulics of baffles have been studied, there has been no thorough evaluation of adult or juvenile fish passage through baffled culverts at design flows.

Baffle Styles

Where baffles are unavoidable, three basic styles of baffle are suggested; two for round culverts and one for box culverts as shown in **Figure 4**. They are all designed with a continuous alignment of notches along one wall rather than alternating back and forth. This allows less resistance to high flows and an uninterrupted line of fish passage along one or both sides. This is particularly important for weak fish which would be forced to cross the high velocity zone at every baffle in an alternating baffle design. Two details of angled baffles are shown for box culverts; the continuously sloped baffle is generally used for juvenile passage situations and in culverts six feet wide and less.

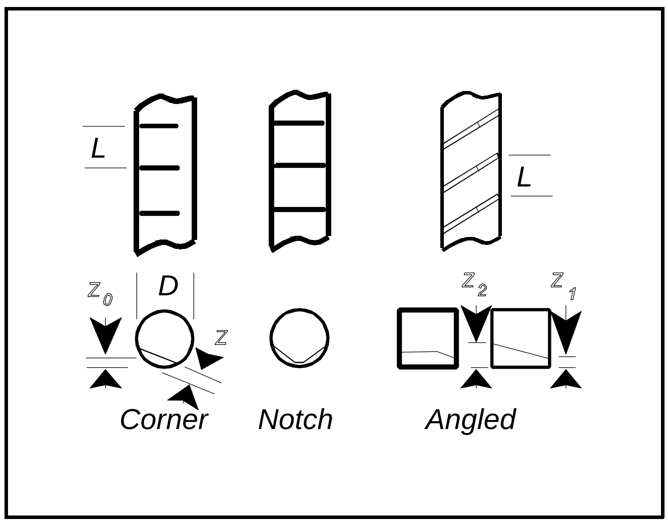

Figure 4 Recommended styles of baffles for round and box culverts.

Baffled culverts are generally limited to slopes less than or equal to 3.5% slope. This is based on direct observation of existing baffle systems; improved baffle systems may change this limit. Steeper slopes require either a stream simulation or fishway weir designs. Some basic concepts of fishway design are discussed briefly in the section on **Fishways**.

The notch baffle is especially useful in large culverts. The central segment of the baffle can be up to several feet high or it can be eliminated in which case there are two independent corner baffles. Corner baffles generally apply to culverts with slopes in the range of 1.0 to 2.5%. They are intended to provide wall roughness with minimum potential for blockage by debris. The notch baffle can be applied to culverts with slopes of 2.5 to 3.5% and have been installed successfully at greater slopes but are designed as fishway weirs at slopes over 3.5%.

Baffles installed in the area of the culvert inlet contraction may significantly reduce the culvert capacity when it is in inlet control condition. The upstream baffle should be placed at least one culvert diameter downstream of the inlet and should be high enough to ensure subcritical flow at the inlet at the high design flow. A modification to the culvert such as a mitered end or wingwalls may also be required to improve its hydraulic efficiency.

Roughened Channel

Roughened channels a graded mix of rock and sediment built into a culvert to create enough roughness and diversity to achieve fish passage. The roughness controls the velocity and the diversity provides migration paths and resting areas for a variety of fish sizes through local higher velocity and turbulence areas.

The same design principles can be used for the design of channels outside of culverts, though it should be done very cautiously where they are located downstream of a fixed structure, such as a culvert, and any degrading of the channel will result in the culvert countersink or velocity criteria to be exceeded. The roughened channel is acceptable upstream of culverts to control channel headcutting as described in the section on **Channel Profile**. The stream simulation option gives a much more conservative design for fish passage than roughened channels and should be investigated before roughened channels.

Installations of this technique inside of culverts have had mixed results with regards to fish passage and stability. Because of this, **culverts designed as roughened channels are viewed as experimental at this time.** Being experimental, several conditions should be applied to culverts designed by this process. A contingency plan and a commitment to upgrade the facility if it fails in function or structure should be provided. A study plan that includes specific experimental objectives that will further the development or acceptance of the concept should be developed. There should be commitment to a monitoring plan including reporting and peer critique of findings. At the conclusion of the study, the facility would either be accepted as adequate by WDFW or be considered an unresolved passage barrier.

A history of monitoring experimental installations will be required before the technique is accepted as a standard method and specific design details are provided. In the meantime, details of current design principles are provided in **Appendix E**. Changes in the recommendations given are likely as new observations and data becomes available.

Roughened channels are designed to control velocity within the culvert utilizing large scale roughness. Ideally, channels are roughened to the point where the potential energy available at the upstream end is dissipated in turbulence through the pipe and that no excess kinetic energy of flow is present at the downstream end. It should be recognized that these culverts will have greater flow per unit width than the adjacent upstream channel and therefore higher bed stress, turbulence and velocity. As a result, roughened channel culverts have higher sediment transport rates than the natural stream and tend to become scoured and non-alluvial. This situation is less likely where roughened channels are built without the confinement of culvert walls.

The most important aspects to consider in the design of roughened channels are;

- Average velocity at flows up to the fish passage design flow,
- Bed stability during the 100 year recurrence interval flow event,
- Turbulence,
- Bed porosity.

Maximum average velocity is a basic criteria of the hydraulic option. The bed materials inside the culvert create the fish passage structure. Their stability is fundamental for the permanence of that structure. The effect of turbulence on fish passage can be approximated by limiting the energy dissipation factor (EDF, see Appendix C, page iv). In order for low flows to remain on the surface of the culvert bed and not percolate through a course, permeable substrate, bed porosity must be minimized. A section is devoted to each of these considerations in **Appendix E**.

Channel backwater

The downstream invert elevation of the culvert is set by matching the water surface profile at the culvert outlet to the backwater elevation of the downstream channel. The downstream water surface profile can be determined by either observations of the water surface at flow events near the fish passage design flow, or by calculation of the water surface profile in a uniform flow condition. Several iterations of calculations and designs may be required to establish the culvert slope and roughness and match the profile to the downstream channel backwater.

The downstream backwater may also be created by raising and steepening the channel to an appropriate elevation. Structures for that purpose are described in the section **Channel Profile.**

Water surface observations

Direct observations of water surface elevations, tied to recorded stream flows, provide the most reliable backwater elevation. A flow at least within 25% of the high fish passage design flow should be included in a set of at least three observations to produce a reliable stage discharge curve. The stage discharge curve can then be extrapolated to get the water surface elevations for any fish passage design flow. If the stage discharge curve is extrapolated, verify that the backwater elevation for the fish passage design flow is not actually controlled by the bankfull capacity of the channel. Water surface observations only apply to new installations or where the downstream channel elevation and water surface profile will not be affected by the project. Otherwise, a calculated backwater elevation is required.

Calculated backwater

A second option is to calculate the water surface downstream of the culvert using an open channel flow calculation such as Manning’s equation. It should be calibrated with at least one high flow water surface observation. It is less preferable to use an estimated Manning’s roughness coefficient (n) for the open channel flow calculation. Selection of an appropriate value for Manning's n is very significant to the accuracy of the computed water surface profiles. The value is highly variable and depends on a number of factors including: surface roughness; vegetation; channel irregularities; channel alignment; scour and deposition; obstructions; size and shape of the channel; stage and discharge; and suspended material and bedload. These variables are combined into a single composite roughness coefficient by methods such as described by Chow (1959).

In situations where the project will affect the downstream channel, either directly as part of the design or indirectly as the channel evolves to fit the project, use the new channel slope, roughness and cross section for the backwater calculation. The stage calibration should be in a reach similar to the eventual cross section at the culvert outlet; use an unaffected reach upstream or downstream of the culvert but away from its influence.

Culvert elevation

The culvert invert elevation is set relative to the elevation of the high and low flow fish passage design water surface profiles. Match the elevation of the water surface of the culvert to that of the downstream channel; both at the high fish passage design flow. This is a conservative estimate of the water surface profile. A backwater profile analysis can be used to optimize the culvert design by taking advantage of the lower velocities created by the backwater to achieve the required maximum velocity shown in **Table 1.**

The local channel slope, width and elevation will be affected by any existing culvert if the culvert is either perched or undersized. A surveyed profile of the channel will be required where it has been affected by the existing culvert. The profile is used to predict the channel slope and elevation at the culvert site by interpolating from unaffected conditions upstream and downstream.

The low flow backwater must also be checked. As required by the WAC criteria, the bottom of the culvert shall be placed below the natural channel thalweg elevation a minimum of twenty percent of the culvert diameter (or twenty percent of the vertical rise for other shapes). The downstream bed elevation, used for culvert placement is taken at a point downstream at least four times the average width of the stream but not necessarily more than twenty-five feet from the culvert. Thalweg elevations may be higher further than that from the culvert; they are appropriate to use. For explanations and definitions of terms such as channel width, see the Explanation of Data in **Appendix F**. This criteria is intended to reduce the risks of the bed scouring from within the culvert and the risk of a future passage barrier caused by the downstream channel degrading.

If channel degrading is expected in the future, whether caused by natural process or by changes in watershed characteristics, the elevation of the culvert must be set to accommodate expected changes within the life of the structure. Review the condition of other culvert outlets and channels in the watershed to see if their is a history of channel degrading that must be accounted for in the design of new culverts.

Channel profile, flood capacity, other considerations

The design of a new culvert should provide mitigation for future design flows as land uses change. Additional considerations in the hydraulic design option are similar to the two other options described here. Issues of channel profile, flood capacity and other considerations are described in the sections **Channel Profile, High Flow Capacity, and Other Passage and Habitat Considerations.**

STREAM SIMULATION OPTION

Stream simulation is a design process to create natural stream processes within a culvert. Sediment transport, fish passage, flood and debris conveyance within the culvert are intended to function as they would in a natural channel. As a result, the criteria of the hydraulic design option (velocity and depth) do not apply. Passage for species for which criteria have not been set is improved, if not assured.

Culverts designed for stream simulation are sized substantially wider than the channel width and the bed inside the culvert is sloped at a similar or greater gradient than the adjacent stream reach. These culverts are filled with boulder/cobble mix that resists erosion and is unlikely to change grade unless specifically designed to do so. This fill material is placed to mimic a stream channel and allowed to adjust in minor ways to changing conditions.

Stream simulation design culverts are usually the preferred alternative for steep channels and long culverts.

Generally, the **stream simulation design option** might be applied in the following situations:

- New and replacement culvert installations,
- Complex installations; moderate to high natural channel gradient and culvert length,
- Passage required for all species,
- Ecological connectivity required,
- Engineering design expertise, hydrology, and survey information required,
- Minimum culvert width 6 feet,
- Culvert slope does not greatly exceed slope of natural channel,
- Narrow stream valleys.

Design Process

A preliminary design process has been developed for steam simulation culverts. Since so few of these culverts have been designed in an intentional way, this process will need to be revised as experience with them broadens. Since there is little experience with this technique, some risk is involved in culverts designed for stream simulation. This guidance should be used conservatively and contains the best of our knowledge to this date.

<u>Suitability of the site</u>

The primary factors that determine the suitability of a site for stream simulation culverts are the channel bed width and the natural reach gradient. The channel width should be less than 20 feet. Bridge crossings should be considered for wider channels. Reach slopes of 6 percent and less are within the limits of this design process. We expect that higher gradients will become common in the future.

Where the culvert grade will be steeper than the adjacent stream reaches, special consideration will have to be given to the design. This will tend to increase the overall cost and complexity of the project.

Stream simulation culverts may be designed with upstream and/or downstream channel profile changes, just as any other culvert style. If the reach gradient is greater than the maximum culvert gradient then there will have to be some profile adjustment, such as grade controls, to make up the difference.

The culvert itself will be installed either flat or at a grade. This depends on length and bed slope. Obviously longer pipes will require some slope to maintain waterway area at the inlet. Culvert slope should be minimized to decrease shear stress between the culvert bottom and the bed material.

It is important to assess the channel’s susceptibility to vertical changes. If the channel downstream is actively degrading then the stream simulation culvert, as any other style, must be protected with a downstream bed control that anticipates the degradation. Conversely, if the reach is susceptible to aggradation then the culvert must be sized to allow for additional material.

<u>Assessment of the adjacent stream reach</u>
The characteristics of the adjacent stream reach determine the size, slope and degree of embedment of the pipe. New culverts will generally be installed at the natural channel gradient. Replacement culverts, in situations where the downstream channel has degraded, will be installed at a steeper gradient than the adjacent channel. Where the stream simulation culvert will be placed at the same gradient as the channel, the composition and pattern of the adjacent channel (outside the influence of structures) will suggest what the bed in the culvert should look like. The exception is channels that are dominated by large pieces of wood. Stream simulation culverts using wood as roughness or to form steps are not recommended at this point and for reaches that are dominated by wood an alternative paradigm should be found. While stream simulation culverts are probably the best culvert alternative for streams with high debris potential, there is still the risk that wood will form a jam inside the pipe and back up flow. Bridges are much better than culverts for transporting debris.

<u>Culvert type and size</u>
The exact type of culvert used for Stream simulation is largely a matter of preference. All types of CMP’s and concrete boxes have been used. Bottomless structures have been successful and have the advantage that the channel can be built from above before the culvert is set in place. In general round CMP’s are preferred to pipe arches for several reasons. A round pipe of a diameter similar to a given pipe arch span will have greater depth of fill for the same bed and crown elevations, allowing more vertical bed change before the pipe bottom is exposed. These two pipes will cost roughly the same. Assembly and installation of the round pipe is easier than the corresponding pipe arch.

The minimum width of the bed in the culvert ($W_{culvert\ bed}$) should be determined by the formula,

$$W_{culvert\ bed} = 1.2W_{ch} + 2 \quad \text{(in feet)}$$

where W_{ch} is the width of the channel bed. This channel bed is as was defined for the no slope option and as described in the glossary in **Appendix A.** The result, $W_{culvert\ bed}$, is rounded up to the next available pipe size. In cases where the channel bed width is poorly defined or indeterminate, the width should correspond to approximately the 2-year recurrence interval flood.

There are a number of reasons for this relationship, and some exceptions. It is generally accepted that natural channels need width over and above their active channel to function normally. The degree to which the culvert sides must extend beyond this width is a matter of debate. If the designer can demonstrate that a culvert needs to be wider or narrower than provided by the above equation, then that width may be acceptable. Some concerns that must be addressed before deviating from the equation are mentioned here.

Contraction at the inlet is potentially a serious source of bed scour. This scour would occur at a higher recurrence interval flood and could alter the characteristics of the stream simulation bed and adjacent channel. These effects have to be assessed in order to recommend a smaller pipe. A worst case scenario would involve a low gradient, wide alluvial channel upstream of the culvert. The channel width may contain only a fraction of the total flow during a 10-year storm. Inlet contraction in this case would be severe and it may be advisable to size the culvert wider than the width given by the equation above. Inlet modifications may reduce turbulence-induced scour but contraction velocities can remain high.

In a confined valley channel where the stream width does not change substantially with stage, the culvert need not be any wider than the channel. Obviously the culvert must be sized to safely pass flood flows. There is a lower limit to this, as mentioned below, where the culvert is just too small to construct a channel in. That limit is dependant on length, but 6 feet wide is a minimum for shorter culverts. As a word of caution, incised channels may look narrow early in their development but will with widen with age (Schumm, *et. al.*, 1984). Stream simulation culverts should be sized to anticipate this future widening.

By adding the constant of 2 feet to the equation, we avoid very small culverts that would result from just a 20 percent increase in small streams. These small culverts could not achieve stream simulation. They would have a severely restricted waterway area when deeply counter sunk and may be easily plugged by debris, which is something that larger stream simulation culverts are less prone to.

A motivating factor for developing stream simulation culverts is juvenile fish passage. These fish use stream margins where low velocity and small levels of turbulence occur. The above equation allows for 20% of the channel width plus 2 feet to be reserved for margins. In effect, the stream simulation culvert has “banks” inside at approximately the fish passage design flow.

Some vertical and plan form variation can take place in a stream simulation culvert that is wider than the channel width. This is to say that there will be some “meander” and/or “step-pool” formation inside. In the existing stream simulation installations low flow channels meander within the length of the pipe.

Wildlife passage under roads maybe created with large stream simulation culverts. In one stream simulation culvert (W. F. Stossel Cr., Tolt watershed) grass grows on the margin a short distance into the pipe. Coho also spawn in this culvert.

Bed inside culvert

Typically the bed inside the stream simulation culvert is filled 30 to 50 percent of the culvert rise. The reason for so much material is to raise the channel to the widest part of the pipe (for CMPs), to create a deep, monolithic bed structure and to allow for significant bed adjustments without encountering the culvert bottom.

Stream simulation culverts are more easily adapted to higher gradient reaches. Natural channels with 3-10 percent gradients are generally sediment limited. They require a supply of sediment to keep from being scoured to all but the coarsest fraction having no alluvial characteristics at all. The simplest case for stream simulation culverts is where the slope of the bed in the culvert matches the slope of the adjacent reach. In this case there will be little discontinuity in sediment transport characteristics. The bed load transported through the upstream reach will continuously supply the bed in the culvert with materials for form adjustments and rebuilding in case of catastrophic floods.

The more challenging case is where the slope in the culvert is substantially greater than the upstream reach. Coarser bed material is not recruited and over time the bed is winnowed out. Under these circumstances special attention should be paid to the sizing and arrangement of materials in the culvert. A step-pool morphology is recommended for slopes over 3 percent. This type of channel insures that stream energy is dissipated in pool turbulence creating better fish passage and more stable channels.

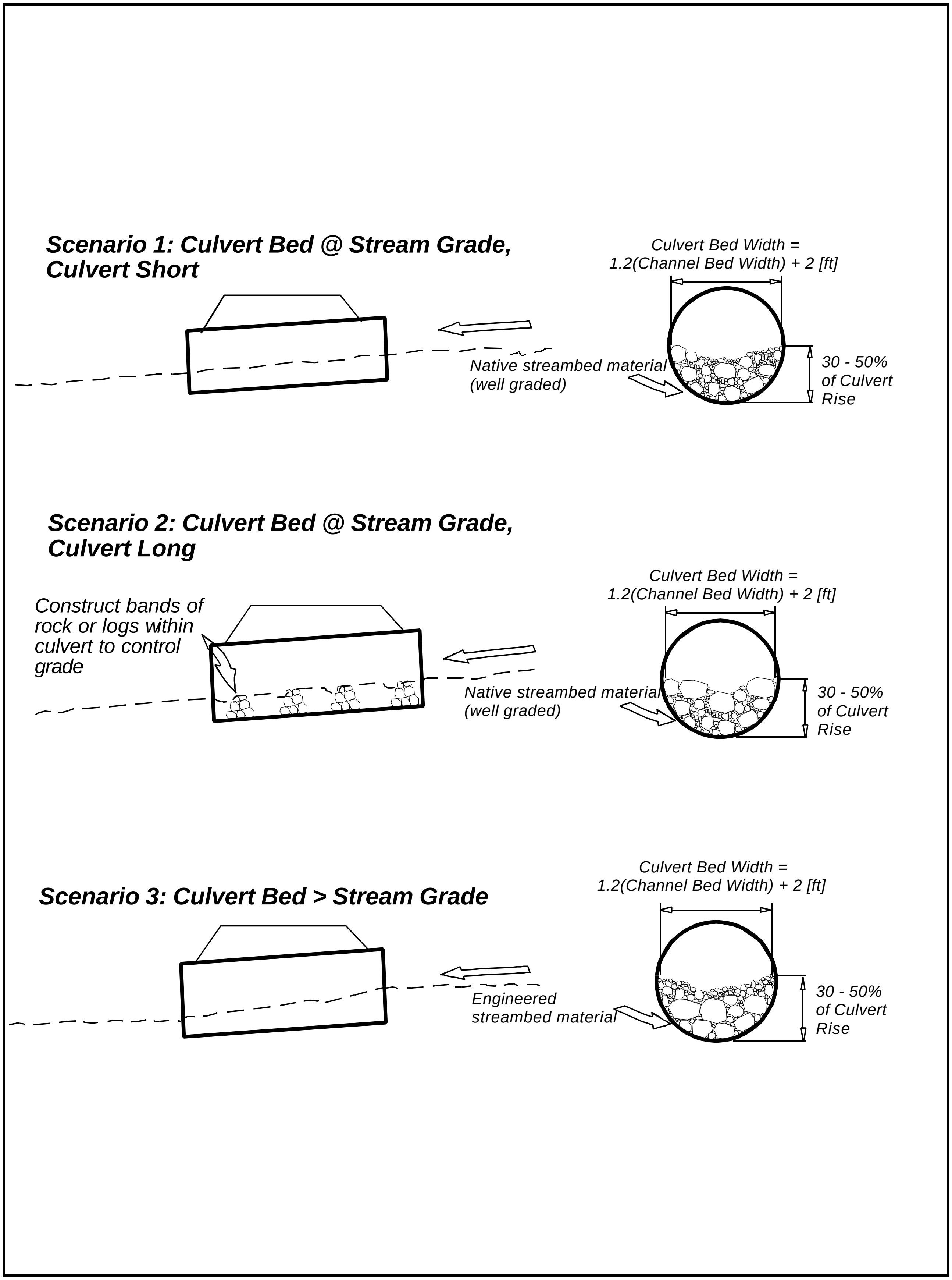

Figure 5. Stream simulation design scenarios

There are three general stream simulation scenarios; they are depicted schematically in **Figure 5**.

1. Culvert bed is at adjacent stream gradient and the culvert is short, less then about 60 feet. Native or engineered bed material is used throughout the fill. No bed control structures are needed. The bed form could be determined by flows or built in; at a minimum, a meandering low flow channel should be defined.

2. Culvert bed is at adjacent stream gradient and the culvert is long, greater than 60 feet. Predominantly native material with bands of rock to control grade. The bed of the culvert must be more specifically designed.

3. Culvert is steeper than adjacent gradient or adjacent channel is debris dominated. An engineered material should be used as fill. Some analysis (as described below) must be done to determine what the appropriate gradation should be.

The selection and gradation of channel fill material must address bed stability at high flows and must be evenly graded to prevent significant subsurface flow. Where the bed is placed at the gradient of the adjacent channel, native size and gradation may be used as a guide to the fill mix. This is done with the understanding that conditions inside the culvert may be more severe than those in the natural channel.

There are established approaches to the stability problem for low gradient gravel bed streams using a critical shear stress analysis. It has been suggested that this method is inappropriate where slopes exceed one percent and relative roughness is high (particle size is greater than 1/10 the water depth) (Olsen 1990, Bathurst et al, 1987). Clearly conditions in stream simulation culverts are outside the range for shear stress analysis. Several other approaches are available, three of which are outlined here.

1. Reference reach. Maximum particle size can be found in reference reaches and/or as a function of flow depth. In situations where the hydraulic conditions and natural bedload movement inside the culvert are the same as those in the upstream reach, the native sediment gradation can be duplicated in the culvert fill without modification. Where the hydraulic conditions are more severe and transport capacity is greater, the native sediments will have to be modified by some factor of safety to insure that the bed is stable. This factor of safety will be a function of contraction ratio, headwater to culvert rise ratio and slope ratio. When there is a significant contraction of flow at the culvert entrance or a high headwater to rise, the culvert bed will experience greater scour and should, therefore, contain larger sediment sizes. Likewise, when the culvert bed is at a significantly greater slope than the upstream channel, the bed material must be heavier to resist flow acceleration and the lack of bedload to replenish scoured materials.

2. Paleohydraulic analysis. Costa (1983) developed a relationship between maximum particle size and flood depth. This work was done to determine the discharge of flash

floods, but it may be useful to design stream channels. He used four different approaches to determine the incipient motion of the largest particles and averaged their results.

3. Rip rap sizing techniques for channel linings.

4. Critical Unit discharge. Bathurst (1987) found unit discharge to be a better indicator of incipient motion for higher gradient streams. His equation can be used to determine incipient motion of any given particle size. Two empirical coefficients must be determined for this relationship to be reliable and a thorough understanding of the concepts are required.

These sediment sizing methods above should use the 100-year recurrence interval peak flow as the design discharge. A stream simulation culvert fails as a fish passage structure at the point where the largest sediment fraction becomes mobile.

Knowing the size of the largest material, D_{max}, or any other characteristic size, the rest of the channel bed mixture is graded down to fines in such a way that permeability is at a minimum. A suggested method is to use a maximum density distribution such as the Fuller-Thompson curve. This equation gives the percent finer, F, of a given particle size, D_i, in relation to the maximum particle size.

$$F = 100(D_i/D_{max})^N$$

The exponent N adjusts for the coarseness of the gradation. N = 0.7 is considered coarse and may be appropriate for this application. The gradation given by this equation should be considered starting point for the mixture. It can be refined as the designer considers available materials. The result is the raw material for the stream bed and should reflect the composition of a natural channel.

Generally, rounded material is used in stream simulation culverts. If one portion of the gradation is not available in rounded material, fractured rock is acceptable. In many areas gravel and cobble is available but boulder sized rock must be reduced from bedrock. In the interest of creating designs and specifications that are practical and economical, gradations should not be too restrictive. As long as all the broad ranges of size are represented, a good bed material can result. For instance, a select pit run can be combined with cobble and large fractured rock, delivered in truck load units and mixed on site with an excavator or front end loader. This material is then loaded into the pipe with a small "Bobcat" style front end loader, conveyor belt, rail mounted cart or pushed into the culvert with a log manipulated by an excavator.

In order to achieve stream simulation fill materials must be arranged to mimic channel conditions. Avoid grid patterns or flat, paved beds of the largest rocks. A low flow channel and secondary high flow bench on either side should be created in the culvert. Natural channels with 3 to 8 percent slope tend naturally to be step-pool in pattern with the steps spaced 1-4 channel widths apart. Do not exceed 1 foot of drop between successive steps. It should be remembered that the same material comprises the whole depth of fill. No stratification is recommended. The formation of steps may involve laying bands of heavier material but these should go from the top to the bottom of the fill.

As the bed settles and adjusts to the shear stress of storm flows, some shifting of bed material should be anticipated. If compacting the bed material proves impossible because the culvert is too small, the upstream end of the pipe should be overfilled with bed material to compensate for settling.

It is recommended that all stream simulation culverts have a grade control placed a minimum of 20 feet downstream of the outlet. This grade control should backwater the outlet of the culvert.

Bed retention sills

Bed retention sills are steel or concrete walls placed in the bottom of stream simulation culverts to hold the bed material inside the pipe. Sills are not a desirable option and the use of them does not really encourage stream simulation. They should be considered an option of last resort. Culverts placed on a significantly greater slope than the adjacent channel or those that may experience large inlet contraction scour are candidates for bed retention sills. The need for these sills reflects our lack of experience in sizing and placing stream simulation bed materials under extreme conditions and are, in that light, a safety factor. In part, a bed stability analysis, like those mentioned above, should be done to determine the need for these structures. Bed retention sills are used in roughened channel culverts which are described in the hydraulic option.

Concrete 4-sided boxes set at a steep slope may need concrete retention structures since concrete is relatively smooth and may not hold bed material as well as corrugated pipes. Shifting may result.

The crest of bed retention sills should be V-shaped with a 1:10 slope. They should be placed 20 percent of the culvert diameter below the stream bed as constructed in the culvert. The maximum drop between sills should be 0.8 feet so that each backwaters the next from below in case the bed material scours out.

CHANNEL PROFILE

Satisfying the countersink and velocity or no slope criteria for a culvert often requires steepening the downstream and/or upstream channel gradients. This can be done by installing grade control structures or a steeper roughened channel, excavation of bed material, allowing the channel to regrade without controls or a combination of these approaches.

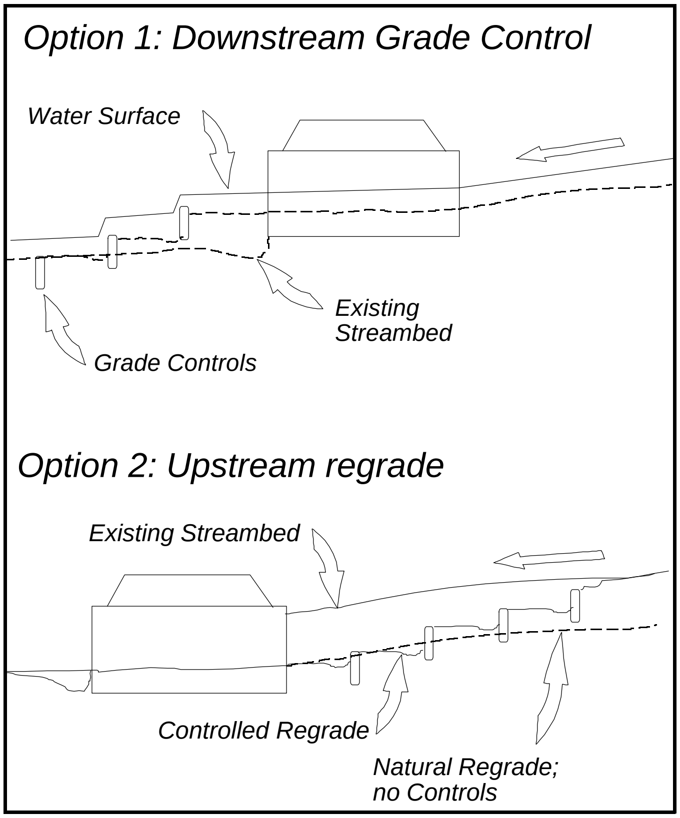

Figure 6. Channel steepening options

No single solution is the best answer for all situations. Often choices among these options will be influenced by issues other than fish passage such as property lines, habitat considerations, risk to infrastructure or flood or erosion issues. These factors are described in this section.

The retrofit of an existing culvert will usually require downstream controls. Other situations which lead to the use of downstream controls include the protection of an upstream wetland or other upstream habitat features or floodplain function, protection of structures or buried utilities, and the feasibility of a deep excavation for a culvert installation.

A culvert can provide a valuable function as a nick point that prevents a downstream channel degrade from progressing further upstream. Placing downstream controls and maintaining the culvert elevation as a nick point is, in some cases, valuable for upstream habitat protection. Any grade control structures must, of course, anticipate for future degraded channel conditions. A simple way to accommodate continuing degrading is to bury additional control structures into the bed downstream of the visible project. Those controls would become exposed and effective only as the downstream channel degraded.

If the downstream side is chosen, control structures should be long lasting and stable at the designed elevation. This is required because the culvert is a long term feature (25 to 50 yr life) with a fixed elevation. Any loss or lowering of the downstream controls could result in another barrier at the culvert or structural risk to the culvert.

The upstream channel grade may be adjusted to fit a new or replacement culvert with an upstream invert lower than the existing streambed. Control structures upstream may either have rigid elevations or they may be expected to gradually adjust over time. This will depend on the factors described in the next paragraphs. All or part of the upstream regrade may in some cases be allowed to occur uncontrolled.

The addition of channel regrade structures or channel modifications to increase the channel slope extends the length of channel affected by the culvert installation. Habitat impacts, as discussed in the section on **Other Passage and Habitat Considerations**, may have to also be mitigated in the modified channel reach and may affect the design of the steepened reach.

Channel headcut and regrade factors

A channel degrades when its bed scours and lowers over time either by natural process, exacerbated by watershed changes and/or lowering or removal of a control point in the channel. Channel headcut is the process of the upstream channel being lowered locally by scour in response to a replacement culvert being larger and/or set at a lower elevation. The headcut itself is a steep section of channel the erodes and, in that process, migrates upstream eventually lowering the entire channel for some distance. The same situation occurs if an undersized culvert is replaced with a larger one since the flood hydraulic profile is lowered by the reduction of the culvert constriction. Habitat impacts of channel degradation can be extensive and prolonged. They can be managed by reconstruction of the upstream channel either into a natural grade or steepened with hydraulic controls.

A reach degrades when there is a net lowering of the bed elevation. During the initial stages of degradation, a channel will becomes deeper and narrower, the relative height of the banks increases and the banks steepened. Loss of floodplain connection and concentration of flows within the channel exacerbate the degrading process. Reinforcement of root structure is decreased. Banks fail and the channel then widens over a period of time erosion until the channel reestablishes its natural slope, floodplain, and bankfull width and depth at the lower elevation. This process is shown graphically in **Figure 7**.

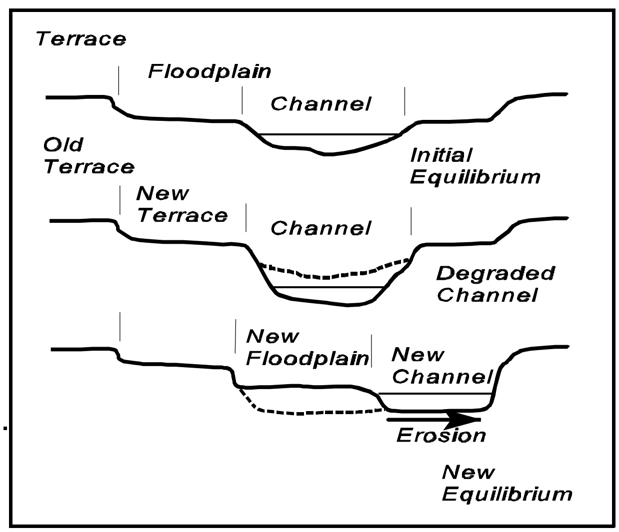

Figure 7. Evolution of Degrading Channel

A variety of habitat impacts may occur during the degrading process. The most obvious is the erosion of the bed and habitat associated with it. The remaining bed is narrow, confined, and usually consists of a steep run with little diversity because the channel has no floodplain for relief from high flows. Bed and bank erosion introduce additional sediment. A degrading channel may lower the ground water table to below the root zone dewatering the bank and adjacent wetlands or side channels and affecting the survival of vegetation. This in turn may trigger secondary causes of erosion such as reduced vegetative structure.

Channels that are most vulnerable to habitat impacts of a degrading channel are those that have functional floodplains, habitat diversity, and/or adjacent side channels or wetlands and channels with banks that are already oversteepened and on the verge of failure.

The following aspects should be part of the consideration of a channel regrade. Detail information on some of these issues may be required if the expected degrade is greater than about a foot.

- Extent of regrade
- Condition of upstream channel and banks
- Habitat impacts to upstream channel from incision
- Habitat impacts to downstream channel from sediment release
- Incision history of downstream channel and the value of culvert as nick point
- Decrease in culvert and channel capacity due to initial slug of bed material
- Risk to upstream utilities and structures
- Potential for fish passage barriers created within the degraded channel
- Access.

<u>Extent of regrade</u>
The extent of regrade depends on the upstream bed slope and composition, sediment supply to and through the reach and the presence of debris in the channel. The length of regrade in may be less in cobble bedded streams than in shallow gradient sand bedded streams. Sandy beds often regrade uniformly without increasing slope until they hit the next nick point of debris or larger bed material.

A channel rich in bed material transport will be affected less and heal more rapidly than channels with limited bed material transport. Structures and utilities must be identified in the upstream bed that might be exposed or affected by the degrade. Culverts should be designed to transport sediment at the same rate as the adjacent channel.

The upstream channel slope and bed composition influence sediment supply to maintain the bed inside a culvert and is especially important in culverts that are dependent on the recruitment of that material.

<u>Condition of upstream channel and banks</u>
Two extremes of upstream bed condition are an incised channel and an aggraded channel created by the backwater of an undersized culvert. The incised channel and banks will be further affected by a channel degrade as described above. Any floodplain function will be further reduced and instream habitat will be subjected to increased velocities and less diversity. Banks will become less stable by the degrading channel undermining them. An aggraded channel on the other hand can be stabilized and returned to its natural condition by allowing some degrade through it.

Habitat impacts to upstream channel from incision

The channel of a degrading stream is narrow, confined, and usually consists of a steep run with little diversity or stability because the channel has no floodplain for relief from high flows. Eventually the channel may evolve back into its initial configuration but there may be substantial bank erosion and habitat instability in the meantime.

Habitat impacts to downstream channel from sediment release

Habitat impacts to downstream channel and habitats from sediment release
Aquatic habitats downstream will also be at risk from the increased sediment released. In addition to the volume of material, it will be released at moderate flows until the upstream channel and banks have stabilized.

Incision history of downstream channel and the value of culvert as nick point

Channel degrading can be a natural process or it can be caused or accelerated by watershed land use practices. A culvert can provide a valuable function as a nick point that prevents a downstream degrade from progressing further upstream; lowering the culvert will likely allow the degrading process to continue upstream. Compare channel conditions upstream and downstream. If the downstream channel is degraded (narrow, incised, over steepened bank, without floodplain function) and the upstream channel is the opposite, consider maintaining the culvert elevation as a nick point while designing it for fish passage.

Decrease in culvert and channel capacity due to initial slug of bed material

Allowing an uncontrolled headcut upstream of a culvert may result in a slug of material mobilized during a single flow event. As this material moves through the culvert and the downstream channel it can reduce the flood capacity of both. Less degrade should be allowed where the culvert has significant but even a short term risk of plugging by a mixture of a slug of bed material and debris. Similar limitations should be considered where structures downstream are at risk from a loss of channel capacity or where banks are at risk of erosion. Without further technical analysis of degrade implications and culvert flood capacity, a culvert inlet should be depressed no more than 40% of its rise or diameter. Relevant factors to consider include design flow probabilities, bank height, culvert dimensions, substrate material, and allowable headwater depth.

Proximity of upstream utilities and structures

If a regrade is allowed to continue upstream it can jeopardize structures in the channel or on the banks. Be aware of buried utilities under the channel and the risk of increased bank erosion on structures on or near the channel banks.

Potential for fish passage barriers created within the degraded channel

The last headcut consideration is the potential for fish passage barriers to be created within the degraded channel. Buried logs and compacted till or clay sills are commonly exposed by channel headcuts. As the channel headcuts to these features, they become the new nick point and fish passage barrier. Adding to the difficulty, these problems may occur where they are not visible from the project site and they may occur on other properties making them more difficult to deal with.

Access

Table 2. Comparison of channel profile designs

Tools	Advantages	Disadvantages	Limitations
Log Sills	Downstream bed elevation control.	Limited to < 3% gradient streams.	Minimum spacing of 15 feet.
Baffles	Increases hydraulic roughness.	Turbulence, hydraulic profile raised, debris problems. No small fish passage.	Slope less than or equal to 3.5%.
Plank Sills	Hand labor.	Less durability.	Limited to < 5% gradient streams, small streams.
Roughened Channel	Natural appearance, flexible, can provide passage for all fish.	Technical expertise required, not technical fish passage analysis required.	Limited to < 3% gradient streams, moderate streams.
Boulder Controls	Flexible, allowing channel to regrade slowly.	Not recommended downstream of culverts.	Maximum drop of 9 inches.
Fishway	Can provides passage for all fish.	Expensive. Technical expertise and site specific, flow regime data required. Debris and bedload problems.	Narrow range of operating flow.

Impacts to the channel, riparian structure, or infrastructure of equipment access for either upstream or downstream channel construction should be considered in the selection and extent of upstream and downstream components.

Channel profile structures

Following are descriptions of several grade control designs. These techniques, with a few exceptions, can be used to control grade either upstream or downstream of a culvert. When used downstream of a culvert, they are intended to backwater the culvert and stabilize a steepened channel reach. When used upstream of a culvert they are intended to stabilize a steepened reach to prevent a headcut and channel degradation. Each technique has advantages and disadvantages as summarized in **Table 2**.

Log sills

Log sills can be built into the stream bed to span the entire channel width. They are a low cost and durable means of fish passage for streams with natural gradients of less than about 3% and channel toe widths of less than about 30 feet. The log sills described here are intended for fish passage. Similar designs are used with objectives of enhancing rearing or spawning habitat or stabilizing certain channel erosion problems. Those designs may be different than described for fish passage and are not discussed here.

Log sills have been used in many situations to create a series of drop structures to raise the downstream water surface and backwater a culvert. They are typically used downstream of a culvert, but may also be used upstream. A variety of designs have been employed including single logs, multiple logs, straight weirs, angled weirs, V-weirs and K-dams. Simple straight, double-log sills described here are the most secure, require the least overall channel length and the least costly of the styles.

Channel slope

To accommodate fish passage, and create a stable structure without downstream impacts leads to a maximum gradient for a series of sills. A design limit of 5% gradient is used for streams with typical rainfall dominated hydrology. Steeper slopes may not dissipate energy adequately and are therefore not stable and/or create downstream impacts. Log sills are intended to support the streambed which protects and seals the log weirs. A closer spacing (higher slope) causes the scour pool of each log to extend to the next sill downstream and therefore does not allow the accumulation of bed material necessary to protect the upstream face of the sill. The exception is for small spring-fed streams that don't experience extreme high flows.

The WAC limits hydraulic drop at any point in the culvert to 0.8 or 1.0 feet depending on the species present. Logs are typically installed in a series with a spacing about equal to the channel width and a minimum spacing of 15 feet. A 20-ft spacing and 1-ft drop (or 15-ft spacing and 9 inch drop) yields the suggested maximum slope of 5%.

Because of the recommended maximum slope of a series of log sills it is difficult to steepen a channel with an initial natural slope greater than about 3% with this style of log sill. Control structures in small, spring-fed streams may exceed the 5% gradient criteria.

Design Details

A pair of logs, each with a minimum diameter of one foot are placed into the bed; it is recommended that the sum of the diameters at any point along the structure is at least 2.5 feet. The pool below each sill will scour to a depth greater than two feet below the downstream control elevation. A good rule of thumb to control deflection of the top log is to use a log with a diameter 1/25th of the log length.

Double logs are used to prevent the scour pool from undermining the structure. The ends are buried into trenches excavated into the streambanks a minimum of five feet. The logs are normally douglas fir due to availability, straightness and longevity. Their longevity is enhanced by being installed level so they are permanently submerged and resist decay.

Log controls built in accordance with WDFW standard details as early as 1984 are still in good condition (as of 1999).

The bottom log is offset upstream on a line about 45° from vertical to allow the scour to undercut the upper log. The top log is strapped to precast concrete blocks buried below each end of the sill and sized adequate to anchor the logs. Careful anchorage or ballasting of the logs is a critical to their stability. The design described here depends entirely on the ballast blocks. Rock placed on the ends of the structure is for closure of the installation trench and protection of the backfill but is not necessary directly for anchorage.

A seal is attached to the upstream face of the top log, buried 2 feet and extended upstream at least 6 feet. Geotextile fabric is used with a tensile strength of at least 600 pounds and a burst strength of at least 1200 pounds. Geotextile fabric has good longevity, availability and flexibility for ease of construction. It is easier to install than impermeable material which billows in the current during installation. The fabric must be extended into the trenches to completely seal the structure.

Riprap mixed with soil is packed over the ends of the logs within the trenches and on the banks extending to six feet downstream of the sills. The riprap is bank protection not ballast. A pool is excavated two feet deep by six feet long in the channel downstream of each log sill in anticipation of a scour pool that will develop there. If a pool is not initially constructed, there is a risk that the first high flow will stream over the sills, energy will not be adequately dissipated and the downstream channel will be damaged. The bank rock must extend to the floor of the pool. In installations where bed material does not pass into and through the fishway, the floor of the pool should also be lined with riprap rock.

By observation, the maximum fish passage design flow is limited to about 9.5 cfs per foot of length of the log sill. The maximum safe high design flow has not been quantified. The highest known flow safely experienced by a series of log sill structures is 15 cfs per foot of length. The weir coefficient for a log weir submerged to 50% of its depth is about 2.7 based on field measurements. Heiner (1991) found a weir coefficient of about 3.8 for full scale unsubmerged smooth (PVC pipe) weirs in a laboratory.

Sills should be located in straight sections and at the entrance and exits of channel bends; they should not be installed in bends. There is a risk that if a lower sill of a series fails, those above it will be undermined and also fail in a chain reaction. If a number of bed sills are placed in a series, deeper sills should be placed at intervals, say, every fifth sill. The deeper sills should be designed as independent dams assuming the downstream controls do not maintain a backwater. Their purpose is to prevent the chain reaction and the failure of the entire series.

When used for fish passage, sills within a series should be constructed with equal lengths for uniform hydraulic conditions at high flows. Energy is often not dissipated over log controls during peak floods. The downstream channel is therefore scoured and lowered in the vicinity of the logs. To prevent a barrier from occurring below the downstream sill, an additional downstream sill should be constructed at or below the channel grade.

A notch is cut in the crest of the sill after it is installed. The shape and size of the notch depends on the species requiring passage and the low flow expected at the time of passage. The notch generally slopes down to form a plume that fish can swim through rather than be required to leap through a free nappe. Be careful to not make the notch so large that at low flow the top of the log is dewatered.

Single or multiple log sills can be cabled into bedrock channels using 9/16" galvanized steel cable and C-10 HIT Hilti dowelling cement (Espinosa and Lee, 1991).

Plank controls

Plank weirs can be substituted for logs in very small channels where flows are small and hand labor is available. Rough cut milled timbers are placed across the bed of a channel to form sills similar to the log sills described above. They are intended to be constructed by hand in small or spring source streams with regular flow. They are installed with a maximum drop between pools of 8 inches. When installed in steady spring source streams, a series of plank sills can be installed at a slope up to 7%. Plank sills have an application limited to channel toe widths of about 10 feet. The maximum standard timber length available is 16 feet; each end is imbedded three feet into the bank.

Untreated fir timbers are used in perennial streams where the wood will be always be submerged. Cedar is used in ephemeral streams. The planks are trenched into the bed of the channel and anchored with U-bolts to steel pipes driven into the streambed. They are tilted about 20° downstream so the nappe spills free of the sill for better juvenile fish access. The ends are buried in the channel banks; the excavated trenches are filled with light riprap rock mixed with soil.

Plank sills are especially useful for providing upstream juvenile salmon passage. They are well suited for streams with sandy beds. A benefit of plank sills is they can be constructed entirely by hand. Plank sills have been constructed in wide channels using zig-zag and spider weir designs. They are primarily intended for juvenile fish passage.

Roughened channel

A roughened channels is a graded mix of rock and sediment built to create enough roughness and diversity to steepen the channel and provide fish passage. The roughness controls the velocity and the diversity provides migration paths and resting areas for a variety of fish sizes through local higher velocity and turbulence areas.

Principles of roughened channels that are described in **Appendix E** can be used to design open channels outside of culverts. The design should be very conservative for steepening channels downstream of culverts or other fixed structures where any degrading of the channel will result in the culvert countersink or velocity criteria to be exceeded. The culvert should be countersunk deeper than normally required with the expectation of some degrading of the backwater control. The roughened channel is acceptable upstream of culverts to control channel headcutting.

Boulder controls

Low sills built out of boulders have been built for many years; most of them have deteriorated and disappeared over time. They are therefore not generally a desirable bed control option where a precise control elevation has to be preserved for the life of a culvert. They may have an application where the culvert upstream will be replaced within a few years. Future improvements in design and construction of the concept may eventually allow their use below culverts.

A common acceptable application is to control channel regrade upstream of a culvert that has been enlarged and/or lowered. Since the rock controls tend to fall apart over time, they gradually change from a drop structure to a low cascade, and eventually to a short roughened channel. Gradual channel regrade processes may be less impacting than a sudden change, especially in terms of sediment release.

Boulder controls used to temporarily control regrade are built as arch structures with the arch pointing upstream. Each boulder is securely placed against the boulder next to it and the downstream boulders are imbedded into the bankline. In cross section the crest of the weir slopes toward the middle and approximates the cross section of the stream.

Additional work is needed to improve the design of boulder controls intended as permanent structures. Sizing, shape, and placement of the boulders are essential to the longevity of the structure. A minimum of two rows of rock form the weir; one row creates the crest over which the flow drops, the other row is below and slightly in front of the crest and prevents scour beneath the top row. Boulders used for weir and foundation rocks should be sized on the basis of the stream design discharge and slope. Small, lower gradient streams should use a minimum of 2 foot mean dimension rock. Larger high gradient streams would require rock as large as 4 to 6 feet mean dimension.

Boulders are best placed with equipment that allows the rock to be rotated (a “wrist”) to allow precise fitting. Careful attention must be paid to how the weir boulders are fit into the foundation boulders to insure that they are stable and gaps are reduced to a minimum. Ideally each boulder should bear against its downstream neighbor and the thrust of streamflow and bedload is transferred through the weir to the bank. Push in a downstream direction on each boulder as it is placed to see that it will not tip under load .

Concrete or sheet pile weirs

Precast concrete weirs is an option for rigid controls. One style is a series of concrete beams stacked to the required height and bolted together. Another design includes a weir, stilling basin, and wing walls in a single precast unit.

An advantage to concrete weirs is their self-ballasting feature. Concrete highway median barriers and “ecology blocks” are not acceptable as fish passage weirs unless they are anchored for stability, modified to provide a sharp crest and a deep plunge pool and permanently sealed to prevent leakage. Potential disadvantages are aesthetics and the equipment and excavation required to place heavy precast units.

HIGH FLOW CAPACITY

Flood capacity

Regardless of the design option used, the high flow capacity of the culvert must be checked to ensure stability during extreme flow events. The high fish passage design flow rather than the flood capacity usually controls the culvert design. The high flow capacity must be analyzed to confirm this for each culvert design. WAC 220-110-070 specifies that "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." This can be done by providing adequate flood and debris capacity, designing a spillway for overtopping, or routing excess flow past the culvert without jeopardizing the culvert or associated fill.

The high flow capacity may be determined by road fill stability, road overtopping, allowable headwater depth or the likelihood of debris plugging the culvert. Selection of additional high flow capacity parameters depends on requirements of the culvert owner and are not discussed further here.

FISHWAYS

Fishways are formal structures that optimize fish passage conditions for maximum vertical gain over a given distance. Fishways applied at culverts are typically pool and weir style; a series of pools separated by weirs that control the elevation differential between pools. A fishway might be designed in parallel with the stream so fish moving upstream leave the stream and enter the fishway, move through the fishway, and then re-enter the stream or culvert. They might also be designed as in-stream fishway so the fishway weirs span the channel and the entire stream flow goes through the fishway. Log sills described on Page37 are a form of pool and weir fishway.

The primary limitation of pool and weir fishway is the narrow range of stream flow through which they operate effectively. The upper limit of operation is the flow at which their is not sufficient volume in the pools to dissipate the energy entering them and therefore there is too much turbulence to provide successful fish passage. They are also vulnerable to debris and/or sediment plugging and therefore require substantial maintenance effort. These factors lead to of limited application in association with culverts and the need for specific fishway engineering expertise for their successful design. Refer to Bates (1992) or Bell (1991) for further information on the design of formal fishways.

This discussion of fishways is limited to some general concepts that govern the size and location of a fishway. Designers should consult with a fish passage engineer for specific design details. The following general criteria are adapted from the Washington Department of fish and Wildlife fish passage policy (POL-M5001). Only the criteria that are not covered elsewhere in this manual are included here. Criteria not included relate to target species and the fish passage design flow which are part of the hydraulic design option described in this manual.

Fishway siting

A fishway shall be located so the entrance is near the furthest point upstream that is accessible to fish. Hydraulic and layout design of the fishway must be so attraction and entry to the fishway are optimized. Turbulence below the barrier must be considered when siting the fishway entrance. The fishway shall be located to minimize instream maintenance necessary to provide a continuous water supply and fish access to the fishway.

Hydraulic design

The hydraulic design shall optimize passage for the weakest fish expected to encounter a barrier. Fishways may either consist of a steep channel designed with appropriate velocities and turbulence limits or a series of distinct pools in which energy of the flow entering the pool is entirely dissipated.

Fishway steps for adult fish that will leap (chinook, coho, sockeye, steelhead, trout) shall not exceed 12 inches. Fishway steps for adult fish that do not leap (chum, pink) shall not exceed 9 inches. Flow condition at weirs for non-leaping fish shall be optimized to allow swim-through conditions at notches by creating streaming rather than plunging flow and a velocity appropriate for the species requiring passage.

Fishway pools and corners shall be designed to minimize unnecessary turbulence and upwelling. Fishway pools shall be designed with enough effective volume for adequate dissipation of the energy entering the pool. The effective pool volume must be at least enough to dissipate four foot-pounds per second per cubic foot. Pool volume more than eight feet away from a plunge does not effectively contribute to energy dissipation. Exceptions to this volume standard might be appropriate at facilities where fish passage is isolated from a high energy flow bypass. The minimum depth in the fishway pools shall be three feet. Minimum wall freeboard shall be three feet to prevent fish from leaping out of the fishway.

Maintenance

The risk of obstructions or hydraulic interference by debris must be minimized by providing adequate clearance at slots and access for inspection and maintenance. Fishways should be protected by a trash rack or trash boom where appropriate.

OTHER PASSAGE AND HABITAT CONSIDERATIONS

Regardless of successful fish passage, the placement of culverts often result in habitat losses that must be mitigated. These impact are associated with the culvert itself and some may also be associated with channel modification necessary to install or retrofit a culvert for fish passage. There are, for example, habitat losses often associated with steepening a channel to achieve fish passage. Following are habitat considerations that may control the siting, sizing and design of culverts and/or fish passage improvements.

Direct habitat Loss

Salmonid habitat includes all areas of the aquatic environment where the fish spawn, grow, feed, and migrate. Culvert installations require some level of construction in the stream channel which replaces native streambed material and diversity with the culvert structure.

Spawning Habitat

Each species of salmon and trout require specific spawning conditions related to the water velocity, depth, substrate size, gradient, accessibility and space. All salmonids require cool, clean water to spawn in. In the stream environment most salmonid spawning will occur in pool tail-outs and runs. Spawning habitat can be lost or degraded by culvert installations in the following ways.

- Culvert placement in a spawning area replaces the natural gravel used for spawning with a pipe. This is a direct loss of spawning habitat.
- Culvert construction can require significant channel realignment that eliminates natural meanders, bends and spawning riffles and other diversity in the channel that serve as valuable habitat.
- Culverts shorten channels leading to increased velocities and bed instability that reduce spawning opportunities and decrease egg survival.
- Riffles and gravel bars immediately downstream of the culvert can be scoured if flow velocity is increased through the culvert. Gravel mobilization when eggs are incubating in redds (nests) results in high egg mortality.
- Any release of sediment into the stream may smother spawning gravel with silt and is considered as a direct habitat impact to that project. In the case of culverts, sediment releases may be due to construction or due to change in hydraulics due to the alignment, siting or design of the culvert. Appropriate mitigation is to prevent the release the sediment in the first place by design and implementation of a good erosion and sediment control plan and by project timing and strict adherence to best management practices.

Rearing Habitat

Juvenile salmonids utilize almost all segments of the stream environment during some stage of their freshwater residence. Habitat usage is highly variable depending upon the species, life stage, and time of year. Pools with large woody debris are especially valuable habitat. Trees on the streambank provide cover and a source of insects and large woody material which are critical to rearing fish. Culvert construction can negatively impact rearing habitat in the following ways:

- There is a direct loss of rearing habitat when it is replaced with a pipe.
- Woody debris at the culvert site is removed to install a culvert. Woody debris provides many benefits to channel structure, function, stability and food production which all contribute to healthy salmonid populations.
- Riparian vegetation is removed from the stream bank to make way for the culvert installation and is often removed for the entire right-of-way width as a regular maintenance activity.
- Cutting off of natural bends, meanders, side channels and backwater channels directly eliminates usable habitat. Similarly, any reduction in stream length by a culvert is a reduction in rearing habitat. Most side channels and back water channels are more productive with higher fish usage than the main stream channel, especially during winter flood flows.
- Culvert placement that lowers the natural water level of pools, ponds, backwaters, or wetlands within or adjacent to the stream can significantly decrease valuable rearing habitat.

Loss of Food Production

Fish, like all other organisms need food in order to survive, grow and reproduce. Juvenile salmonids feed on aquatic invertebrates and terrestrial insects that fall into the water. The food chain in the aquatic environment begins with the primary producers like algae and diatoms (periphyton) which require organic material and sunlight to fuel the photosynthetic process. Benthic invertebrates like mayflies, stoneflies and caddisflies feed on the primary producers. Invertebrates require some of the same conditions as salmonids such as clean water and stable gravel. The inside of a culvert is dark and the absence of sunlight prohibits primary production. Reduction in the number of invertebrates that are a source of food for salmonids can reduce growth rates. It is generally recognized that faster growth rates that produce larger salmonids is a competitive advantage that increases their survival rate at sea.

Removal of riparian vegetation for culvert placement reduces the organic debris like leaves, wood, bark, flowers, fruit etc. that enters the stream and fuels primary production. Terrestrial insects that drop from overhanging vegetation into the water where they are consumed by salmonids are removed from the food base when the vegetation is lost.

Mitigation of direct habitat losses

Mitigation for impacts of loss of cover and pools might include adding diversity and structure such as woody debris to the channel in an appropriate location.

Placement of a culvert in a spawning area results in a direct loss of that habitat. Gravel spawning beds are also valuable as invertebrate habitat. Spawning habitat in most Pacific Northwest streams is not limited by the supply of gravel, it is limited by the structure and diversity of channel forms that sort and distribute bed material to create spawning and other habitats. The only effective mitigation in most situations is to avoid loss of the spawning habitat in the first place. In streams that are deficient in spawning gravel, a loss of spawning habitat might be mitigated off site by gravel supplementation. Several techniques might be used.

Gravel merely placed over an existing streambed, whether inside or outside of a culvert, may be an attractive nuisance in that it is attractive to fish for spawning but not stable enough for eggs to survive winter floods. Once the gravel is redistributed by high flows, it can be valuable habitat.

Gravel supplementation should be done to mimic natural gravel deposits or gravel banks. Natural deposits that can be copied are pool tailouts and gravel banks. The downstream end of stable pools and stable riffles might be supplemented with a layer of gravel to mimic tailout deposits. Gravel can be placed upstream of streambed controls installed as part of the fish passage project. A channel constriction made of mounds of gravel will, in the right situation, create a pool and a tailout. Gravel can be supplied to a bankline to mimic a natural eroding gravel bank. The gravel is redistributed most efficiently by high stream flows.

If several feet of washed gravel is placed in steeper culverts there is the potential for low flows to go subsurface and create a barrier. This is especially problematic when there is no input of bedload from upstream to seal the gravels, such as when there is a wetland or pond immediately above the culvert.

Another common reason for placing gravel in culverts is to fill the void created by countersinking the culvert. If the purpose is to prevent an upstream headcut, the material should be sized according to the discussion in the section on **Channel Profile** or **APPENDIX E**.

Water quality

To extend the life span of culverts in acidic water, they are sometimes treated with an asphalt coating. It is unknown what affect this may have on fish or invertebrates in the water. Until it can be shown that these type of treatments are not a risk to fish health they should not be used.

Quality and quantity of road stormwater runoff shall be mitigated as determined appropriate by local jurisdiction or the Department of Ecology. In addition, all stormwater discharges into a stream must be designed to prevent scour during higher flows.

Upstream and downstream channel impacts

Increased velocity from a culvert can erode downstream banks and thus promulgate the need for bank protection and extended impacts of the culvert. It is recommended that the culvert exit velocity should not exceed the pre-project channel velocity at the outlet location by more than 25% at the same stream flow.

An undersized culvert creates a bed instability upstream. At high flows the culvert creates a backwater and bed material deposits in the channel upstream. With receding flows, the bed and/or banks erode through or around the deposition. The result is either a chronically unstable channel bed or increased bank erosion and the need for bank clearing and protection. It is recommended that the culvert inlet be designed to limit head loss to less than 1.0 foot during a 10-year flood.

The upstream and downstream impacts listed above are normally mitigated by the design process described in this manual. Typically, the size and elevation of culverts required by this manual are such that velocities leaving the culvert are not excessive. Sites with banks or beds susceptible to erosion may require special consideration.

A culvert placed into a stream with an actively migrating channel can result in an acceleration of the channel migration and substantial maintenance effort to keep the channel at the culvert location. Channel migration is a natural geomorphic process though it might be exacerbated by upstream activities; it is part of ecological connectivity.

Additional impacts due to channel headcut and regrade must be considered in the design. Refer to the section on **Channel Profile** for details on design and mitigation for those impacts.

Ecological connectivity

The term *connectivity* refers to the capacity of a landscape to support the movement of organisms, materials, or energy (cited by Peck, 1998). In terms of culvert design, it is the linkage of organisms and processes between upstream and downstream channel reaches. The health of fish populations ultimately depend on the health of their ecosystems which includes migrations and processes dependent on the connectivity. Biotic linkages might include upstream and/or downstream movement of mammals and birds, non-target fish species, and the upstream flight, and downstream drift of insects. Physical processes include the movement and distribution of debris and sediment and migration of channel patterns. Some of these functions may be blocked by road fills and culverts that are small relative to the stream corridor

These issues are difficult to quantify and generalize but may ultimately be significant to the health of aquatic ecosystems. More development of the concept of ecological connectivity in relation to road culverts is expected and encouraged.

Debris and bed material should be managed by allowing them to pass unhindered through the culvert. When debris is trapped fish passage barriers are created, the debris is not passed to the channel downstream, and a backwater is created upstream that extends the effect of the culvert. Usually the size of the culvert as developed by the design processes described in this manual will be adequate to pass most debris and bed material. There may be special cases where the culvert size should be increased to not capture debris.

Trash racks and multiple parallel culvert pipes racks are generally not acceptable because they trap debris, create barriers to fish migration and increase the risk of culvert failure. In the case of low road profiles, instead of multiple culverts, alternative low clearance culvert structures should be considered.

Debris racks might be a reasonable temporary solution in special cases of existing culverts with high risk of debris plugging and a clear responsibility and committed schedule of future culvert replacement. The debris rack for this situation should be mounted high on the culvert, above the ordinary high water. The rack itself is only functional at high flows when debris is moving. The space below it is left open for flow. Openings within the bar rack should be no smaller than nine inches. A specific monitoring and maintenance plan should be developed for any debris rack and convenient access for these activities must be provided.

Channel maintenance

Other than fish passage, likely the greatest impact posed by culverts to aquatic habitats is the need for channel maintenance created by poor siting of road crossings and culverts. Highways are often placed at the fringe of river floodplains and must therefore cross the alluvial fans of small streams entering the floodplain. As the stream enters the relatively flat floodplain a natural deposition zone is created and the channel is prone to excursions and avulsions across its alluvial fan. Culverts placed in these locations tend to fill with bed material. To keep the culvert from plugging and the road overtopping, periodic and in some cases annual channel dredging becomes necessary. Bed material removal becomes a major impact of channel instability and spawning and rearing habitat losses for some distance upstream and downstream. It is also an ecological connectivity impact to not allow bed material and the channel aggrading process to migrate through the reach.

Mitigation for these channel maintenance impacts include installing a bridge or a culvert large enough that the aggradation and channel evolution processes can continue. A bedload sump might be appropriate in some situations to localize the dredging need and to eliminate at least the upstream impacts of dredging. Relocating the road may be possible and should be considered where feasible.

Construction impacts

Construction impacts might include the release of sediment or pollutants, temporary fish passage barrier during construction, removal of bankline vegetation, blocking of the flow or stranding of fish. These issues are all dealt with in the WAC 220-110-070 by provisions for timing of construction, care of water, erosion and sediment control planning, and revegetation. The construction plans submitted for Hydraulic Project Approval should include, in addition to plans and specifications, a sediment and erosion and control plan covering these items. The provisions of the WAC may be modified for specific projects.

Risk of culvert failure

Structural failure of culverts can cause extensive and massive damage to habitat that persist for a long time. Failures can be a result of inadequate design, poor construction, beaver damming, deterioration of the structure, or extreme natural events. Risks of failure can be minimized by sizing the culvert for passage of extreme events and debris, including appropriate inlet and/or outlet armoring and use of proper backfill and compaction during In some cases fords or alternate road overflow points may be useful. This should be considered at forest roads that are susceptible to debris flows, or at roads that cross alluvial fans. construction.

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APPENDIX A

DEFINITIONS

Aggradation - The geologic process by which stream bed is raised in elevation by the deposition of additional material transported from upstream. (Opposite of degradation).

Armor - A surficial layer of course grained sediments that are rarely transported and protect the underlying sediments from erosion and transport.

Backwater - Water backed-up or retarded in its course as compared with it's normal open channel flow condition. Water level is controlled by some downstream hydraulic control..

Baffle - Wood, concrete or metal mounted in a series on the floor and/or wall of a culvert to increase boundary roughness and thereby reduce the average water velocity in the culvert.

Bed - The land below the ordinary high water lines of state waters. This definition shall 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 not in suspension consisting of coarse material moving on or near the channel bed.

Bed Roughness - Irregularity of streambed material (i.e. gravel, cobbles) that contributes resistance to streamflow. Commonly measured as Manning's roughness coefficient.

Burst Swimming Speed - The highest rate of speed that a fish can generate for a short period of time (usually several seconds) . Also called Darting Speed.

Cascade - A series of small vertical drops within a channel that may be natural or man made.

Channel - A natural or man made waterway that has definite bed and banks that confine water.

Channel Bed Slope - Vertical change with respect to horizontal distance within the channel (Gradient). Refer to Appendix E for information on how to measure.

Channel Bed Width - Refer to Appendix E for definition and information on how to measure.

Channelization - Straightening or diverting a waterway into a new channel.

Cruising Speed - See Sustained Swimming Speed.

Debris - Includes gravel, cobble, rubble, and boulder-sized sediments as well as trees and other organic detritus scattered about by either natural processes or human influences.

Degradation - Erosional removal of streambed material that results in a lowering of the bed elevation throughout a reach. (Opposite of *aggradation.*)

Deposition - Settlement of material onto the channel bed.

Dewatering - Removing water from an area.

Filter Fabric - A natural or synthetic fabric used to block sediment from water flowing through a subsurface or surface area such as through a revetment or through a channel.

Fishway- A system that may include special attraction devices, entrances, collection and transportation channels, a fish ladder, exit and operation and maintenance standards.

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.

Intergravel Flow - That portion of the surface water that infiltrates the stream bed and moves through the substrate interstitial spaces.

Geomorphology - The study of physical features associated with landscapes and their evolution. Includes factors such as; stream gradient, elevation, parent material, stream size, valley bottom width, and others.

Grade Stabilization or Grade Control - Stabilization of the streambed elevation against degradation. Usually a natural or man made hard point in the channel that holds a set elevation.

Headcut - The erosion of the channel bed progressing in an upstream direction creating an incised channel.

Incision - The resulting change in channel cross section from the process of degradation.

Jute - Fiber used to make rope, twine or burlap. It is used in the construction of some geotextile fabrics.

Large Woody Debris (LWD) - Any large piece of woody material such as root wads, logs, and trees in or intruding into a stream channel.

Mitigation - Actions to avoid or compensate for the impacts to fish life resulting from the proposed project activity. (WAC 220-110-050).

Ordinary High Water Mark (OHW) - Generally, the lowest limit of perennial vegetation. There are also legal definitions of OHW that include characteristics of erosion and sediment.

The Ordinary High Water mark can usually be identified by physical scarring along the bank or shore, or by other distinctive signs. This scarring is the mark along the bank where the action of water is so common as to leave a natural line impressed on the bank. That line may be indicated by erosion, shelving, changes in soil characteristics, destruction of terrestrial vegetation, the presence of litter or debris, or other distinctive physical characteristics.

The legal definition of OHW as defined in the 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".*

Considerable judgment is required to identify representative OHW marks. It may be difficult to identify the mark on cut banks. In warm months grasses or hanging vegetation may obscure the OHW mark. Artificial structures (culverts, bridges, or other constrictions) can affect the OHW mark in their vicinity by creating marks on the shore which are consistent with OHW marks, but above the elevation that is usually found in undisturbed river reaches.

Where the OHW mark cannot be determined reliably, the surveyor should move to a location where the channel section will allow for a more precise measurement. At a location beyond the influence of artificial structures, measure the OHW indicators at 5 different places (spaced about 5 channel widths apart straight channel sections), and take the average of these distances.

Perching- The tendency to develop a falls or cascade at the outfall of a culvert due to erosion of the stream channel downstream of the drainage structure.

Prolonged Swimming Speed - The speed at which a fish can swim for an extended period of time (several minutes or more). Results in fatigue.

Reach - A section of a stream having a similar physical and biological characteristics.

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 - 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. *Source: WDFW Riparian Document*

Riprap - Large, durable materials (usually rocks; sometimes broken concrete, etc.) used to protect a stream bank or lake shore from erosion; may also refer to the materials used.

Scour - Localized erosion caused by flowing water.

Shear Strength - The characteristic of soil, rock and root structure that resists one unit of material sliding along another.

Shear Stress - Hydraulic force of water created by its movement on a parallel submerged surface such as the channel bed or channel bank.

Substrate - Mineral and organic material that forms the bed of a stream.

Sustained Swimming Speed- The swimming speed fish can maintain indefinitely without fatigue. Also called Cruising Speed.

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 break in slope at the foot of a bank where the bank meets the bed.

Weir- A small dam that causes water to back up behind it and flow over or through it. Often has a notch used to control or regulate flows over it.

APPENDIX B

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:

> *NOTE: Bridges section (1) not included in this printing of WAC for WDFW culvert manual.*

(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.

Table 1. Fish Passage Design Criteria for Culvert Installations

	Adult Trout >6 in. (150 mm)	Adult Pink, Chum Salmon	Adult Chinook, Coho, Sockeye, Steelhead
Culvert Length	Maximum velocity (fps)		
10 - 60 feet	4.0	5.0	6.0
60 - 100 feet	4.0	4.0	5.0
100 - 200 feet	3.0	3.0	4.0
Greater than 200 feet	2.0	2.0	3.0
	Minimum water depth (ft)		
	0.8	0.8	1.0
	Maximum hydraulic drop in fishway (ft)		
	0.8	0.8	1.0

(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.

(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

FISH PASSAGE DESIGN FLOWS FOR UNGAGED CATCHMENTS IN WASHINGTON

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LANDS AND RESTORATION SERVICES PROGRAM
Environmental Engineering Services

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Department of Transportation

Introduction

Successful upstream passage of adult and juvenile fish through artificial structures (channels, culverts, fishways) depends on the selection of appropriate passage design flows. It is recognized that fish passage through artificial structures cannot practically be provided at all flows. A high design flow is selected to be the upper limit of the range through which upstream fish passage criteria are satisfied. The limitation of passage above the passage design flow may be due to velocity, drop height or turbulence. Structural design flows are also important, especially in terms of passage of debris and bed material. WAC 220-110-070 (Water Crossing Structures) requires that the high flow design discharge be the flow that is not exceeded more than 10 percent of the time during the months of migration. This report provides regional regression equations for ungaged catchments to estimate this flow.

For gaged catchments the 10 percent exceedance flow for any month can be easily determined by developing a flow duration curve. For ungaged catchments, the two-year peak flood can be used to estimate this flow (Cummans, 1975). The two-year peak flow is often much higher (300 to 400 percent) than the 10 percent exceedence flow. Bates (1988), reviewed current agency criteria and developed two regression equations relating basin parameters to the 10 percent exceedence flow.

The U.S. Geological Survey (USGS) are in the process of updating regional regression equations for flood frequencies in Washington. This report utilizes the same regions and basin parameters to develop regression equations for the 10 percent exceedence 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 (Peterson, 1982) and (Cederholm, 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 1). Data was also analyzed for Eastern Washington, but no correlation between design flows and basin parameters could be found.

Description of Regions

The state of Washington was divided into subsections based on their drainage flow characteristics. These regions were derived from "The Catalog of Information on Water Resources Data" (1972), "Water Resources Regions and Subregions for the National Assessment of Water and Related Land Resources" by the U.S. Water Resources Council (1970), "River Basins of the United States" by the Inter-Agency Committee on Water Resources, Subcommittee on Hydrology (1961), and State planning maps. The regions defined are those regularly employed by the U.S. Water Resources Council and USGS for water resources planning.

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

The Puget Sound Region (Region 2) includes sections of Clallam, Jefferson, Mason, Thurston, Pierce, and all of King, Snohomish, Whatcom, and Skagit counties. Region two consists of streams that drain into the Puget Sound. In order to find the best correlation, the Region 2 data was divided into highland and lowland streams. The division was defined at gage elevations of 1000 feet. In addition, Region 2 had a high percentage of urbanized streams (defined arbitrarily as greater than 20 percent impervious surfaces). Separate regression equations were run for this data.

The Lower Columbia Region (Region 3) is based on rivers that flow west of the Cascade Mountain Range and drain into the Columbia River. This region includes Wahkiakum, Cowlitz, Clark, and sections of Skamania, Pacific, and Lewis Counties. Again the best correlation was found when the region was divided into highland and lowland subregions. Again, the classification was based on the gage elevation.

Region four (Eastern Washington) is defined as the rivers in counties east of the Cascade Mountain Range. As defined by the USGS and U.S. Water Resources Council, Eastern Washington is divided into six regions. Too few fluvial systems fit the required criteria however to analyze any one region as a whole. Therefore, it was necessary to condense all of Eastern Washington into one region. No correlation was found amongst the small, unrepresentative data pool gathered within this large, diverse region.

Methodology

To create a usable model for estimating fish passage design flows, a data selection process was necessary. Parameters selected required the drainage areas to be less than 50 square miles with at least five years of data compiled by the USGS for January and May. All selected data were reported by USGS as either fair, good or excellent. Sites where the measured data was reported 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 was compiled from USGS Hydrodata (Daily Values) and USGS Open File Reports 84-144-A, 84-144-B, 84-145-A, and 84-145-B. Basin drainage areas were gathered from the USGS Hydrodata. Mean annual precipitation and precipitation intensity were gathered from the USGS Open File Reports. When figures were not available in the Open File Reports, values were determined by locating the latitudinal and longitudinal coordinates of the gage stations on Plates 1 and 2. The 10 percent exceedence 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 USGS report.

Reasonable correlations were found within the Western Washington regions. Correlation improved upon further division of the individual regions. Gage less than 1000 feet were classified lowland, gages more than 1000 feet were classified highland. Separate analyses were run for the high passage flows during January and May migration periods for each region/subregion defined. Percent standard error (Tasker 1978), was derived from the formula;

$$SE_{percent} = 100(e^{\text{mean squared}} - 1)^{½},$$

where the units of the mean are natural log units. A table was included in the paper by Tasker that allowed for simple derivation of standard error in percent from logarithmic units.

The user is reminded of the non-symmetrical nature of the log-normal distribution. The higher the calculated design flow, the greater 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. The above statement remains to maintain scientific accuracy.

Results and Applications

Table 1 is a summary of the regression equations that were developed. Region one stations were all lowland (elevation <1000 ft), Region 2 had lowland, highland (elevation > 1000 ft) and urbanized stations, and Region 3 has lowland and highland stations.

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

1. From the map showing hydrologic regions (Figure 1), select the region in which the site is located.

2. From Table 1 select the appropriate equation from the region, elevation or land use condition and month.

3. From a USGS topographic map measure the drainage area above the site, latitude and longitude and estimate the basin parameters from plates 1 and 2.

4. Substitute the values determined from step three into the equation from step two and solve for the fish passage design flow.

5. 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 1: Lake Creek Tributary (Lake Cavanaugh Road)

From Table 1: Region 2, Elev <1000 ft, January

A = 1.82 sq mi

Latitude: 48°22' Longitude: 122°11'

From Plate 2: P = 80 in/yr

$Q_{fp} = 0.125(A)^{.93}(P)^{1.15}$

$Q_{fp} = 0.125(1.82)^{.93}(80)^{1.15}$

Q_{fp} = 34 cfs, Standard Error is 48.6%

Q_{fp} = 18 to 50 cfs .... Answer

Example 2: S. Branch Big Creek (SR 101)

From Table 1: Region 1, May

A = 0.87 sq mi

Latitude: 47°09' Longitude: 123°53'

From Plate 1: $I_{24,2}$= 4.5 in/24 hours

$Q_{fp} = 2.25(A)^{.85}(I_{24,2})^{0.95}$

$Q_{fp} = 2.25(0.87)^{.85}(4.5)^{0.95}$

Q_{fp} = 8.3 cfs, Standard Error is 30.6%

Q_{fp} = 6 to 11 cfs.. Answer

Table 1. - Regional regression equations for fish passage design flows in Washington. Q_{fp}, fish passage design flow; A, drainage area, square miles; I, 2-year, 24-hour precipitation, in inches; P, mean annual precipitation, in inches.

	Equation	Constant a	Coefficients b	c	Standard error of prediction (%)
REGION 1					
January	$Q_{fp}=aA^bI^c$	6.99	0.95	1.01	25.7
May	$Q_{fp}=aA^bI^c$	2.25	0.85	0.95	30.6
REGION 2					
Lowland Streams < 1000 feet Elevation					
January	$Q_{fp}=aA^bP^c$	.125	0.93	1.15	48.6
May	$Q_{fp}=aA^bP^c$	.001	1.09	2.07	75
Highland Streams > 1000 feet Elevation					
January	$Q_{fp}=aA^b$	141	0.72		59.8
May	$Q_{fp}=aA^bP^c$	3.25	0.76	0.48	56.9
Urban Streams > 20% Effective Impervious Area					
January	$Q_{fp}=aA^bP^c$	.052	0.96	1.28	40.7
May	$Q_{fp}=aA^bP^c$	.003	1.10	1.60	43.3
REGION 3					
Lowland Streams < 1000 feet Elevation					
January	$Q_{fp}=aA^bP^c$	.666	0.95	0.82	38.1
May	$Q_{fp}=aA^bP^c$	.014	0.87	1.42	38.1
Highland Streams > 1000 feet Elevation					
January	$Q_{fp}=aA^bP^c$	.278	1.41	0.55	59.8
May	$Q_{fp}=aA^bP^c$	3.478	0.85	0.38	28.2

Table 2. - Maximum and minimum values of basin characteristics and R squared values used in the regression analysis, by region and land type.

	Drainage Area (sq mi)	Mean Annual Precipitation (inches)	2-year 24-hour Precipitation (inches)	R^2 (January/ May)
REGION 1				
Maximum	48	--	7.5	(0.91/0.84)
Minimum	2.72	--	2.5	
REGION 2				
Lowland Streams < 1000 ft Elevation				
Maximum	48.6	160	--	(0.81/0.77)
Minimum	1	28	--	
Highland Streams > 1000 ft Elevation				
Maximum	45.8	170	--	(0.68/0.76)
Minimum	.19	60	--	
Urban Streams > 20% Effective Impervious Area				
Maximum	24.6	47	--	(0.74/0.76)
Minimum	3.67	35	--	
REGION 3				
Lowland Streams < 1000 ft Elevation				
Maximum	40.8	130	--	(0.84/0.86)
Minimum	3.29	56	--	
Highland Streams > 1000 ft Elevation				
Maximum	37.4	132	--	(0.73/0.81)
Minimum	5.87	70	--	

Limitations and Comments

The equations presented in this study can be used within certain limitations to predict fish passage design flows for Western Washington. With the exception of urbanized streams in region two, the relationships were determined from gaging-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 gaged data. Extrapolations beyond the limits of the basic data used in each region is not advised. Relationships can be used with the most confidence in lowland areas with runoff dominated by rainfall, and with 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.

For Eastern Washington, since no correlation was found it is recommended that the two year peak flood flow (USGS, 1996) be used as the high fish passage design flow.

PROVISIONAL DATA
SUBJECT TO REVISION

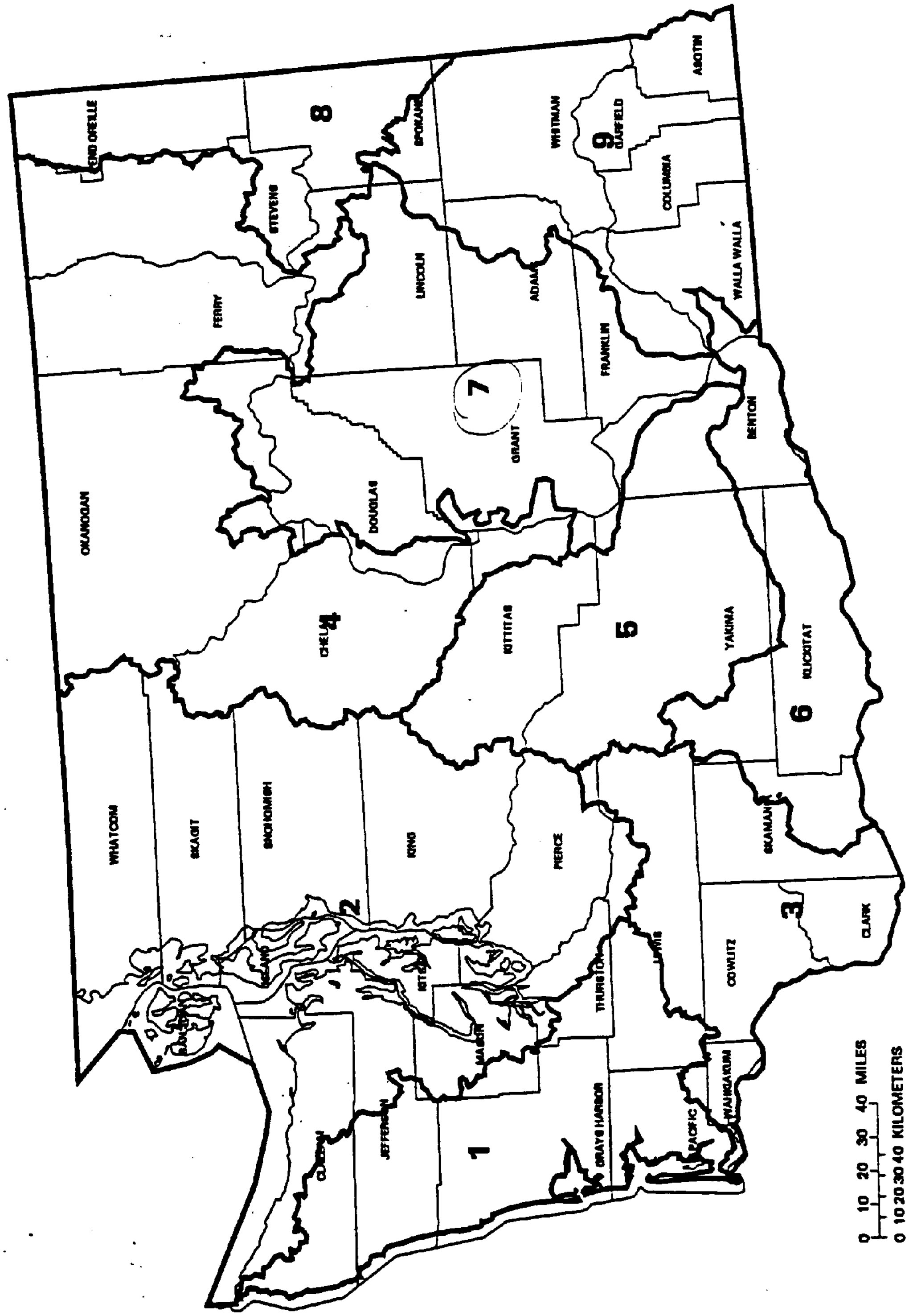


Figure 1 - Regions in Washington State used for development of regression equations (Source, USGS 1996)

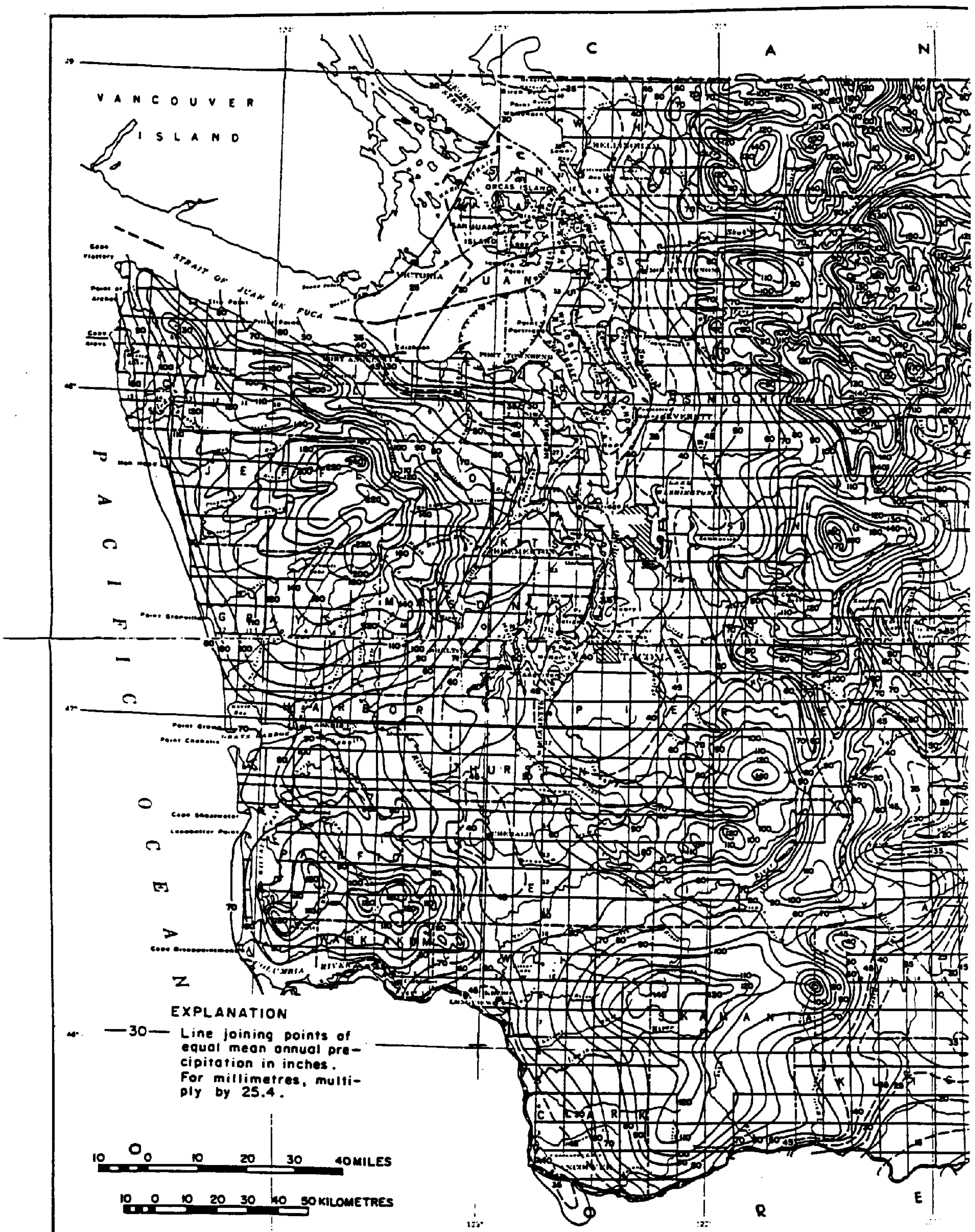
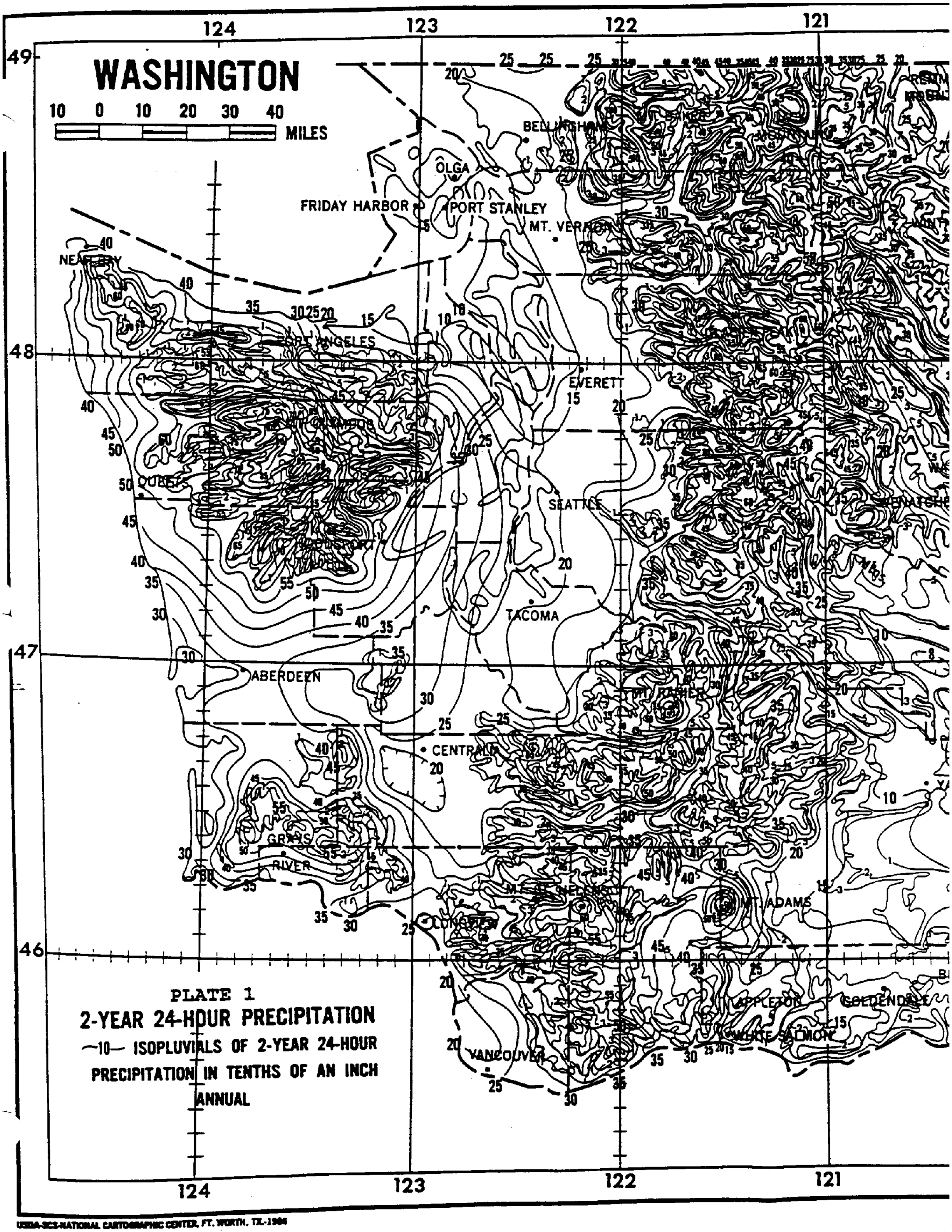


PLATE 2.-- Mean annual precipitation in Washington, 1930-57. From U.S. Weather Bureau (196



WASHINGTON
10 0 10 20 30 40
MILES
PLATE 1
2-YEAR 24-HOUR PRECIPITATION
—10— ISOPLUVIALS OF 2-YEAR 24-HOUR PRECIPITATION IN TENTHS OF AN INCH
ANNUAL
BELLINGHAM
OLGA
FRIDAY HARBOR
PORT STANLEY
MT. VERNON
NEAH BAY
PORT ANGELES
EVERETT
SEATTLE
TACOMA
ABERDEEN
CENTRALIA
GRAYS RIVER
MT. ST. HELENS
MT. ADAMS
APPLETON
GOLDENDALE
WHITE SALMON
VANCOUVER
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APPENDIX D

Hydraulics of Culvert Baffles

Baffles are added to culvert as roughness elements to reduce the water velocity in a culvert to a level acceptable for fish passage. Baffles must satisfy two hydraulic criteria at all flows up to the fish passage design flow. The velocity created by them must comply with WAC 220-110-070 and described in the manual and the turbulence must not be so much that it creates a barrier to passage.

There are three aspects of hydraulic analysis discussed here 1) velocity and 2) turbulence analyses for fish passage, and 3) culvert capacity with baffles. Details of baffle installation are also discussed.

Fish Passage and Culvert Capacity Hydraulic Analysis

The velocity of flow associated with culvert baffle systems can be derived from hydraulic laboratory work by several groups. Rajaratnam and Katopodis (1990), and Rajaratnam et al (1989) studied studied various combinations of baffle geometries, heights, spacings, slope and flow in models of circular culverts. Hydraulic model studies for weir baffles in square box culverts were studied by Shoemaker (1956). These models can be used for both the fish

$$Q = C(y_0/D)^a \sqrt{gS_0 D^5} \qquad \textbf{Equation 1}$$

passage velocity and culvert capacity analyses.

Flow equations were developed by Rajaratnam and Katopodis for all the styles they tested. Those equations are simplified here to the form of **Equation 1**. In the equation, C and a are the coefficient and exponent that depend on the baffle configuration and were determined experimentally. Q is the discharge in cfs, Y_0 is the depth of water, g is the gravitational acceleration in ft/sec/sec and S_o is the non-dimensional slope of the culvert. The dimension z_o is the height of the baffle as shown in **Figure 1**.

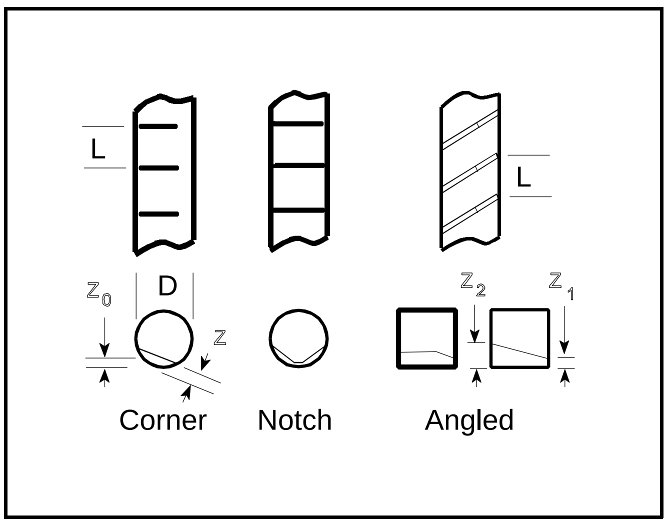

Figure 1. Recommended styles of baffles for round and box culverts.

The dimensions and their respective coefficients and exponents for **Equation 1** are shown in

Table 1. The first column are the labels of experimental baffles provided by the authors; data for those without labels have been extrapolated. The difference in styles are represented by the dimensions in the next two columns; Z_0 is the average height of the baffle, L is the spacing between baffles and D is the diameter of the culvert. The limits shown in the table are the limits of experimental data or valid correlation for the coefficients and exponents. From **Equation 1**, calculate the depth of flow. The resulting velocity is the flow divided by the cross section flow area between the baffles.

The weir baffles studied by Rajaratnam an Katopodis were actually horizontal weirs rather than sloping baffles as shown in **Figure 1** This is the best information available for predicting the roughness of baffles like those recommended in the manual and must be used with sound judgement. Box culverts were not included in this study. The models presented below for culvert capacity with baffles can be used for fish passage analysis in box culverts.

Table 1 Baffle hydraulics

	z_o	L	C	a	Limits
WB-2	0.15D	0.6D	5.4	2.43	$0.25 \leq y_0/D < 0.8$
WB-1	0.15D	1.2D	6.6	2.62	$0.35 \leq y_0/D < 0.8$
	0.15D	2.4D	8.5	3.0	
WB-3	0.10D	0.6D	8.6	2.53	$0.35 \leq y_0/D < 0.8$
WB-4	0.10D	1.2D	9.0	2.36	$0.20 \leq y_0/D < 0.8$
	0.10D	2.4D	9.6	2.5	

Hydraulic model studies for weir baffles in square box culverts were studied by Shoemaker (1956). Internal culvert friction loss and entrance losses were calculated from hydraulic model studies. Shoemaker used the Darcy-Weisbach friction equation, **Equation 2**, as a hypothetical model for a culverts with baffles. The head loss caused by friction is h_f, f is the friction coefficient, L_c the length of culvert, D the diameter of pipe (4 times the hydraulic radius of noncircular pipes), and $V^2/2g$ is the gross section velocity head in the culvert where V is the average velocity in ft/sec.

The baffles tested were full-width level baffles with a rounded leading edge at a radius equal to one tenth of the culvert height. Baffle heights of 0.10, 0.20 and 0.30 times the culvert height and spacings of 1.0, 2.0 and 4.0 times the culvert height were studied.

Shoemaker's variation of the Darcy-Weisbach friction factor is depicted in **Figure 2** from Shoemaker where Z is the baffle depth and L is the baffle spacing.

Friction factors for short baffle spacings should be used cautiously. As would be expected, as the baffle spacing approaches zero, the baffle roughness actually decreases and the effective cross sectional area of the culvert becomes the area of the culvert remaining above the baffles. Shoemaker, in his calculation of velocity head, used the gross culvert area.

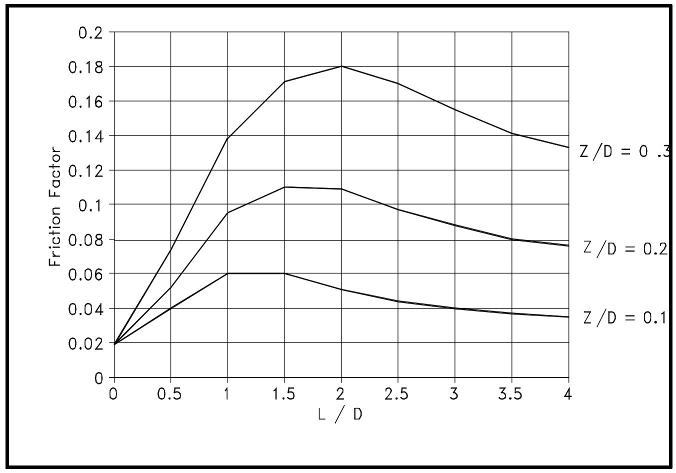

Figure 2. Variation of Darcy-Weisbach friction factor with baffle spacing.

A second analysis by Shoemaker is intended specifically for estimating culvert capacity. It provides a means for evaluation of other energy components making up the hydraulic grade line through a culvert. The assumption was made that entrance and outlet losses, as well as the friction losses, are

$$HW = (K_e + C_e + f\frac{L_c}{D})\frac{V^2}{2g} + P - S_o L_c \qquad \textbf{Equation 2}$$

proportional to the velocity head. With these assumptions, the energy equation for flow through the culvert can be written as **Equation 2** where HW is the headwater elevation above the invert at the culvert entrance, K_e and C_e are the culvert entrance and exit head loss coefficients respectfully, P is the outlet water surface elevation, and S_o is the slope of the culvert. Other parameters are as previously defined. Shoemaker describes a reasonable approximation of P as the distance from the culvert invert to the center of the flow in the opening above a baffle.

Combined values of the head loss coefficients K_e and C_e were derived by Shoemaker as a single coefficient C_a and is shown in **Figure 3** as a function of baffle spacing and height. In Shoemaker's model, the culvert entrance and exit had aprons extending 2.5 times the culvert width, wing walls flared at 34° from the culvert line and mitered at a 2:1 slope. The most upstream baffle was consistently placed one culvert

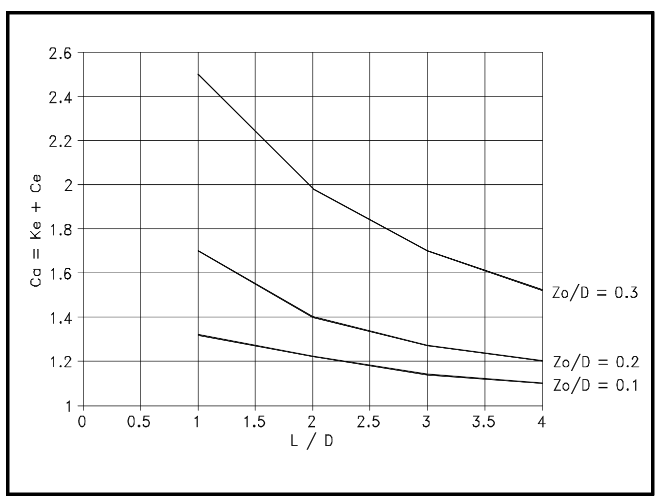

Figure 3. Energy coefficients for various baffle arrangements.

height downstream from the culvert entrance and the downstream-most baffle was placed at the edge of the apron.

Energy dissipation factor

In order to maintain a desired velocity, energy must be dissipated. Energy of falling water is dissipated by turbulence. Turbulence in the culvert is defined by the energy dissipation per unit volume of water and is referred to as the energy dissipation factor (EDF). There is little research data available to determine the appropriate maximum EDF for fish passage. Based on field experience, it is recommended that the EDF be kept below a threshold of 3.0 foot-pounds per cubic foot per second (ft-lb/ft^3/sec) for passage of adult salmon and below 2.25 ft-lb/ft^3/sec for adult trout.

The energy dissipation factor is calculated by **Equation 3** where EDF is the energy dissipation factor in ft-lb/ft^3/sec, γ is the unit weight of water (62.4 pounds per cubic foot), Q is the flow in cubic feet per second, S is the dimensionless slope of the culvert (eg: ft/ft), and

$$EDF = \frac{\gamma QS}{A} \qquad \textbf{Equation 3}$$

A is the cross sectional flow area at that flow between baffles in square feet.

Baffle Installation

Baffles in concrete culverts can be made of wood timbers, steel plate or precast concrete. Wood timber baffles have lasted nearly twenty years in high gradient streams with heavy rates of cobble and boulder bed load. Bent steel plates work well with one leg bolted to the floor and pointing downstream. Example sketches of an anchor bolting are included in Appendix I.

Expansion ring anchors work well in round pipes and can be installed without diverting flow from the work area. The rings are expanded out against the entire pipe circumference. Rods are rolled to the shape of the culvert interior and are attached to an anchor plate. The rod and anchor plate are attached to the culvert by expanding the rod into the recess of a corrugation. This is done by tightening a nut on one end of the rod against a sleeve attached to the other end of the rod. Once the rod and anchor plate are secured, the baffle is bolted to the anchor plate. This system will also work in smooth culverts. A set of shear bolts must first be anchored to the culvert wall; the expansion ring is then installed against the upstream side of the shear bolts. An example sketch of an expansion ring anchor is included in Appendix I.

Bolt anchor systems for existing circular or arch culverts need further development. Anchor bolt and J-bolt systems have worked as anchor systems but are difficult to install and consequently have often failed.

Generally 3/16" steel is adequate for baffles though 1/4" plate can be used as a conservative design for long baffle life especially in areas with corrosive water or high bed load movement. Gussets should be added to stiffen and strengthen baffles when the baffles are greater than nine inches deep.

APPENDIX E

Design of Roughened channels

Roughened channels are a graded mix of rock and sediment built into a culvert to create enough roughness and diversity to achieve fish passage. The roughness controls the velocity and the diversity provides migration paths and resting areas for a variety of fish sizes. The design process described here is complex and requires substantial knowledge of hydraulic modeling and understanding of models and methods suggested.

The same design principles can be used for the design of channels outside of culverts, though it should be done very cautiously where they are located downstream of a fixed structure, such as a culvert, and any degrading of the channel will result in the culvert countersink or velocity criteria to be exceeded. The roughened channel is acceptable upstream of culverts to control channel headcutting as described in the manual. The stream simulation option gives a much more conservative design for fish passage than roughened channels and should be investigated before roughened channels.

Installations of this technique inside of culverts have had mixed results with regards to fish passage and stability. Because of this, **culverts designed as roughened channels are viewed as experimental at this time.** Being experimental, several conditions should be applied to culverts designed by this process. A contingency plan and a commitment to upgrade the facility if it fails in function or structure should be provided. A study plan that includes specific experimental objectives that will further the development or acceptance of the concept should be developed. There should be commitment to a monitoring plan including reporting and peer critique of findings. At the conclusion of the study, the facility would either be accepted as adequate by WDFW or be considered an unresolved passage barrier.

Some history of monitoring experimental installations will be required before the technique is accepted as a standard method and specific design details are provided. In the meantime, details of current design principles are provided here. Changes in the recommendations given are likely as new observations and data becomes available. Because of the experimental consideration, background literature citations are provided in the text and references are listed at the end of this appendix.

Generally, the **roughened channel design** might be applied in the following situations:

- Replacement culvert installations,
- Moderate to high culvert slopes,
- Target species identified for passage,
- Limited work area, *e.g.* limited to right-of-way only,
- Special design expertise, hydrology, and survey information required.

Roughened channels are designed to control velocity within the culvert utilizing large scale roughness. Ideally, channels are roughened to the point where the potential energy available at the upstream end is dissipated in turbulence through the pipe and that no excess kinetic energy of flow is present at the downstream end. It should be recognized that these culverts will have greater flow per unit width than the adjacent upstream channel and therefore higher bed stress, turbulence and velocity. As a result, roughened channel culverts have higher sediment transport rates than the natural stream and tend to become scoured and non-alluvial. This situation is less likely where roughened channels are built without the confinement of culvert walls.

Roughened Channel Design

Maximum average velocity is a basic criteria of the hydraulic option. The bed materials inside the culvert create the fish passage structure to produce the required maximum velocity. Their stability is fundamental for the permanence of that structure. The effect of turbulence on fish passage can be approximated by limiting the energy dissipation factor (EDF). In order for low flows to remain on the surface of the culvert bed and not percolate through a course, permeable substrate, bed porosity must be minimized. A section is devoted to each of these considerations below.

The most important aspects to consider in the design of roughened channels are;

- Bed stability,
- Average velocity at flows up to the fish passage design flow,
- Turbulence,
- Bed porosity.

Following is an outline of a suggested roughened channel design procedure. These steps are iterative; several trials may have to be calculated to determine a final acceptable design. Additional details of these steps are provided in the following sections.

1. Assume a culvert span; begin with a stream bed width equal to the culvert bed width as defined in the manual.
2. Size the bed material for stability on the basis of unit discharge for the 100 year event (Q_{100}).
3. Check to see that the largest bed particle size, as determined by stability is less than one quarter the culvert span. If not, increase culvert span.

4. Create a bed material gradation to control porosity.
5. Determine average velocity and energy dissipation factor (EDF) at the fish passage design flow on the basis of culvert width and the bed D_{84} from gradation in Step 4. If the velocity or EDF exceed the criteria, increase the culvert span.
6. Check culvert capacity for extreme flood events. This step is not detailed here but is required as it is for any new culvert or retrofit culvert design that affects the culvert capacity.

Bed Stability

In order for the roughened channel to be reliable as a fish passage facility, it is essential that the bed material remains in the channel more or less as placed. It is expected that the bed material will shift slightly but not move any appreciable distance or leave the culvert. Bed stability is essential because these channels are not alluvial. Since they are often steeper and more confined than the adjacent natural channel, recruitment of the larger bed elements from upstream cannot be expected to occur. Any channel bed elements lost therefore will not be replaced and the entire channel will degrade. The 100 year recurrence interval flood is suggested as a high structural design flow.

The design of the bed material composition is usually dominated by bed stability considerations rather than fish passage velocities. It is therefore recommended that bed stability analysis should be performed before calculating the fish passage velocity.

There are a variety of approaches available for sizing the bed material. Sizing methods for rip rap channel linings are a conservative approach to this problem. Some are not suited to steep, rough channels and give questionable results. Two methods appear to be appropriate;Federal Highway Administration (Norman, 1975), USACOE (1994) steep slope design. Those methods are not summarized here; the designer is responsible for obtaining the current design standards. Copies of the papers can be obtained from WDFW at the email or address listed in the beginning of the manual. The stability of this type of bed is currently being further researched.

The width of the culvert bed should, as a design starting point, be at least the width of the natural stream channel bed as defined in the manual. When the width of the bed in roughened channel culverts is less than the bed width of the stream, hydraulic conditions are very turbulent and the channel inside the culvert is more likely to wash out.

To our knowledge, these methods have not been applied to specific roughened channel designs or tested in the field in this application. A number of existing pipes have been analyzed using these three methods and they give similar D_{50} and/or D_{30} bed material dimensions for stability during the 100 year recurrence interval storm. The results appear to be reasonable when related to the current condition of those culvert beds.

In addition, there is theoretical work done by Bathurst (1987), Apt (1988), Parker et. al. (1982), Wiberg and Smith (1987), Nelson (1991 and 1993) and well as others, on the initial movement and general bedload discharge for sediment in steep, rough natural channels.

Bathurst (1987) can be applied directly to the initial motion of individual particle sizes. Bathurst compares well with the rip rap sizing methods suggested above for bed stability design.

The bed stability analysis is especially important at sites where the culvert will become pressurized or backwatered during the design flood event. The WinXSPRO hydraulic model and the riprap design methods suggested here assume open channel flow and were not developed for the high velocity and turbulence under pressure. WinXSPRO is not a backwater model and really only applies to natural stream channels. Reasonable results from it can only be expected at fairly shallow depth inside a culvert. A conservative stability analysis would model the culvert using a complete culvert analysis program and/or a backwater model. The hydraulic results are then used to estimate shear stress conditions.

Fish Passage Velocity

The point of roughening the channel is to create an average cross sectional velocity within the limits of the fish passage criteria and the hydraulic design option. The average velocity of a roughened channel culvert is essentially a function of

- Streamflow,
- Culvert bed width and,
- Bed roughness.

The flow used to determine the fish passage velocity is the fish passage design flow as described in the manual under hydrology of the hydraulic design option. As with the stability analysis, the width of the culvert bed should, as a design starting point, be at least the width of the natural stream channel bed as defined in the manual.

Steep and rough conditions present a unique challenge for hydraulic modeling. Traditional approaches to modeling open channel flow assume normal flow over a bed with low relative roughness. In roughened channels the height of the larger bed materials are comparable with the flow depth and complex turbulence dominates the flow (Wiberg and Smith, 1991). A number of equations are available for an analysis of these conditions but they are crude with widely varying results. The research has centered on estimating flow in natural cobble/boulder streams and are not intended for engineering artificial channels. Bathurst (1978) developed a semi-empirical equation for channels with relative roughness less than 1.0 ($R/D_{84}<1$ where R/D_{84} is the ratio of hydraulic radius to the intermediate axis of an 84th percentile bed particle). Hey's (1979) equation was developed for cobble and gravel bed streams and has been tested and shown successful on boulder beds (Thorne and Zevenbergen, 1986). This equation is reasonable for relative roughness of $R/D_{84}>1$. Nelson et. al. (1991) used a theoretical approach that uses specific channel and sediment geometry to come up a with spatially averaged velocity profile. All of these equations are featured in the computer program WinXSPRO produced by the USFS. This program is recommended as a design tool for this option. It still being tested but is available for use at ftp.westca.com/outgoing/Winxspro.

It is recommended that the designer obtain a copy of the relevant articles mentioned in this section to make sure that the basis and limitations of these equations are fully understood. We have not field-verified their conclusions at this point in time but pending and proposed research will address this in the near future.

The bed material is placed so that a low flow channel meanders down the center of the culvert with side slopes next to it approximately six horizontal to one vertical.

Bed Porosity

The gradation of the mix used for the bed inside roughened channel culverts should have enough fine materials to seal the bed. The standard rip rap gradation recommended by the Army Corps of Engineers (USACOE 1994) where $D_{100}/D_{30} < 2$, is very permeable. This leads to subsurface flow during low flow periods and does not create a very “stream like” character. Even after five years of seasoning, some culverts have experienced substantial loss of

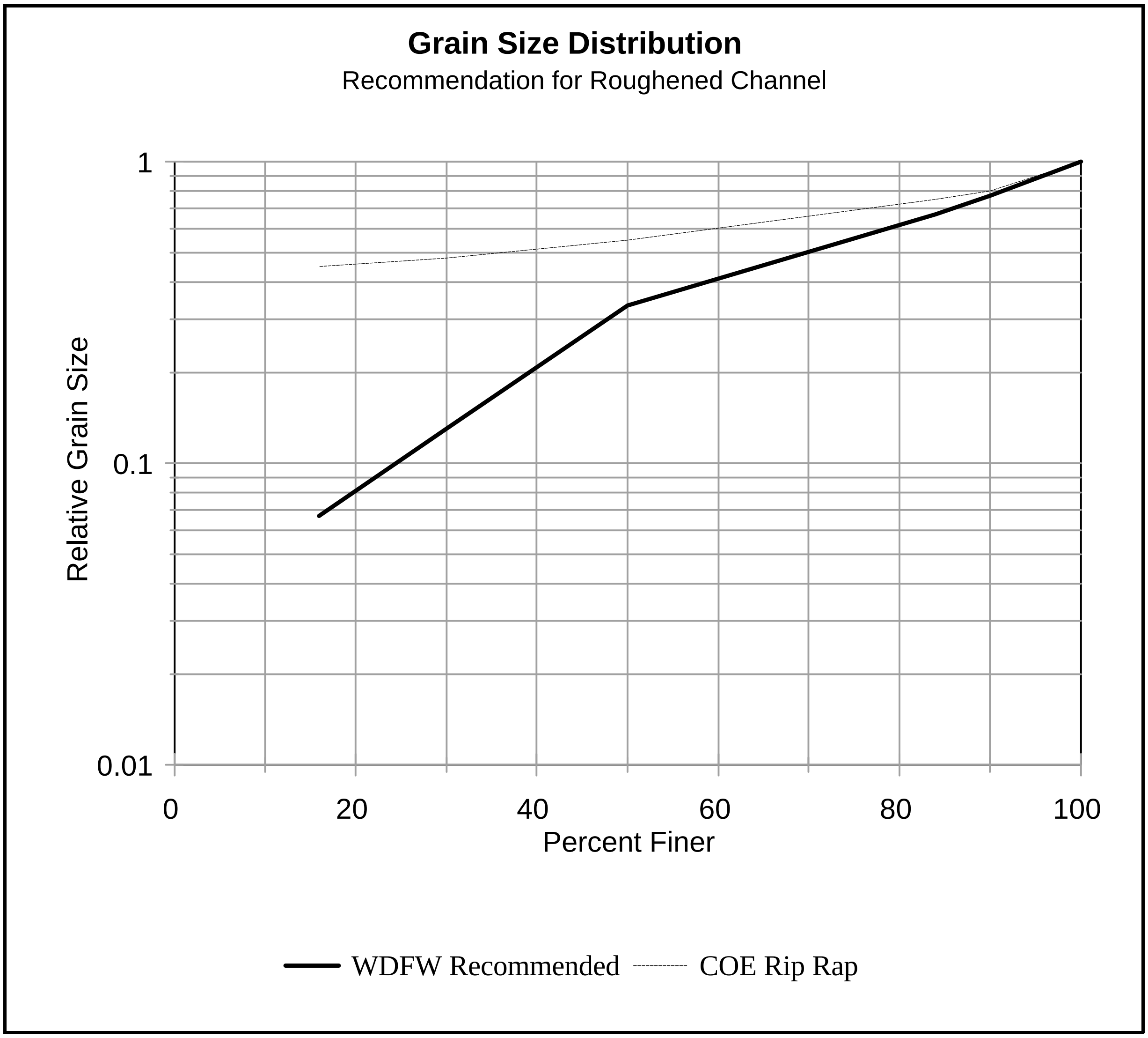

Figure E-1. Grain size distribution recommended for roughened channel culverts.

surface flow. Specifying a well graded mix reduces permeability but at the same time reduces stability by filling, or even overfilling, the voids. The fill must be designed to limit the reduction of stability and the risk of failure. At this point we recommend that the ratio D_{100}/D_{50} be about 3.0, and D_{100}/D_{16} be about 15. This gradation is shown in relation to the standard riprap in **Figure E-1**. The recommended mix is also described in **Table E-1.**

Table E-1. Particle size distribution for porosity design

D_{100} (inches)	Particle size distribution (inches)			
			30%	30%
9		40%<2	2 - 5	5 - 9
12		40%<3	3 - 7	7 - 12
18	15%<1	25% 1 - 5	5 - 11	11 - 18
24	10%<1	30% 1 - 6	6 - 14	14 - 24
30	10%<1	30% 1 - 8	8 - 18	18 - 30

When using the riprap sizing methods mentioned above, the result is a D_{50} or D_{30} representative of a standard rip rap gradation. D_{100} should then be determined for that rip rap mix as 2 times D_{30} or 1.8 times D_{50}. This D_{100} is then the largest particle of the well graded mix recommended in the previous paragraph and **Figure E-1** and **Table E-1**.

For the specification of a practical and economical culvert bed mix **Table E-1** gives a broader range for given particle sizes than **Figure E-1.** Given the maximum D_{100} dimension, as determined above, particle sizes are shown in distribution brackets. The brackets contain as well-graded a range as possible. This is particularly true of the smallest size classes. For instance, 40%<2 inches means that fines, sands and gravels less than about 2 inches are all present. Their relative abundance is not stated so that a variety of well graded combinations are possible. It does not mean that just gravel less than 2 inches is acceptable. The heterogeneous mixture is important for the bed to seal. In the larger classes gaps in the gradation are less important as far as porosity is concerned. **Table E-1** should be used with sound engineering judgement and consideration of its intent.

<u>Turbulence</u>

In order to maintain a desired velocity, energy must be dissipated; energy of falling water is dissipated by turbulence. Theoretically, culvert diameter could be continually reduced and roughness comparably increased so the average velocity meets fish passage criteria but in that process the intensity of the turbulence increases and becomes a barrier to fish passage. Turbulence in the culvert is defined by the energy dissipation per unit volume of water and is referred to as the energy dissipation factor (EDF). It is unclear at this time what the specific numerical value for EDF should be for fish passage in roughened channels and is one of reasons roughened channel culverts are considered experimental.

Based on an examination of existing roughened channel culverts we conservatively recommend that EDF be equal or less than 7.0 foot-pounds per cubic foot per second ($ft\text{-}lb/ft^3$ /sec). The recommended EDF for roughened channel culverts is significantly greater than that recommended for baffled culverts (EDF 2.25 to 3.0) and fishways (EDF 4.0). This is because the diversity of the turbulence scale and flow patterns in a roughened channel provides more opportunities for low turbulence zones for resting and passage. As research and experience in the hydraulics and fish passage characteristics of roughened channel culverts broadens, this value may be modified.

The energy dissipation factor is calculated by **Equation 1** where EDF is the energy dissipation factor in ft-lb/ft^3/sec, γ is the unit weight of water (62.4 pounds per cubic foot), Q is the flow in cubic feet per second, S is the dimensionless slope of the culvert (eg: ft/ft), and

$$EDF = \frac{\gamma QS}{A}$$ **Equation 1**

A is the cross sectional flow area at that flow in square feet.

Fish rocks and bed retention sills

A dominant style has emerged in recent designs of roughened channels inside culverts. This style is designed using the stability, velocity, turbulence and porosity considerations described in the previous pages and then large boulders (“fish rocks”) are placed in a scattered pattern on the channel bed and bed retention sills are installed in the bed. The boulders and sills are essentially added safety factors to the fish passage and stability design and reflect the poor understanding of fish passage and stability analyses of the purely engineered bed described in the previous pages. The boulders provide holding areas for fish. The sills prevent the bed from scouring out of the culvert. This style is pictured in **Figure E-2**.

The bed material fills 30% of the culvert rise in the case of round or squashed pipes. For bottomless culverts the bed elevation is 20% of the rise above the footings. The bed material is placed so that a low flow channel meanders down the center of the culvert with side slopes next to it approximately six horizontal to one vertical. Bed retention sills may be placed 10% of the culvert rise above the culvert invert. The crest of the sills should also have a minimum slope also of six horizontal to one vertical. The sills are typically made of the same material as the culvert, e.g. steel, aluminum or concrete and are connected to the culvert.

Referring to the profile, the lowest point of the bed at the outlet of the culvert must be at the elevation of the downstream control point. This insures that the bed retention sills are below the downstream control point and will not become exposed and create an outfall drop. This control should be either a stable natural bed feature or a permanent constructed control, placed at least 20 feet from the outlet and as defined in the manual.

Other styles of roughened channel culverts may also be appropriate but appreciable experience is available with this style and it is therefore less risky.

By this method it is assumed that the bed material creates the dominant form of roughness and that the boulders placed on the bed act only to enhance the fish passage. It is clear that these boulders have some role in general resistance to flow but it is not clear how to quantify this. Obviously, they act as constrictions or obstructions to flow. It is not possible to know without additional studies whether bed roughness or constriction losses are the dominant roughness factor. To design conservatively for fish passage we recommend not including the boulders in the velocity calculation. In cases there may be little or no difference in the roughness boulders and the largest bed element, in which case they are combined in the analysis.

The depth of flow at the fish passage design flow should be less than or equal to two thirds of the exposed height of the boulder. Boulders should be embedded at least one third of their diameter. (Diameter of boulders is here considered to be roughly equal to the intermediate axis of the particle). The result of applying these constraints to the boulder size and water

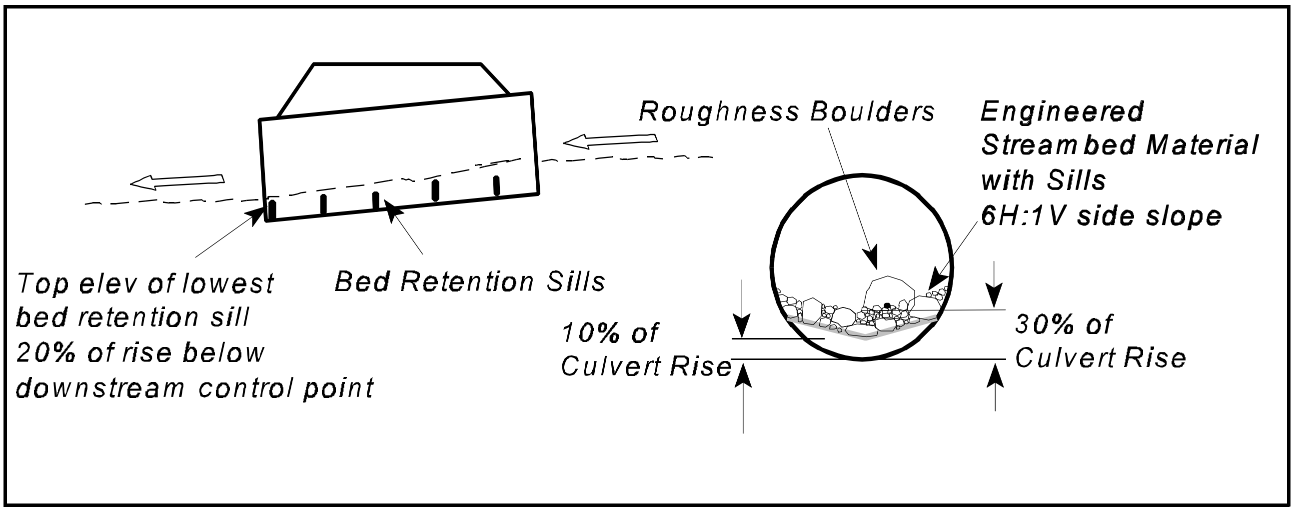

Figure E-2. Roughened channel with bed retention sills.

depth leads to a boulder diameter which is roughly two times the water depth at the fish passage design flow. A final requirement is that the size of boulders should not be greater than one quarter of the culvert span. This is to prevent the confinement of flow into a narrow, high velocity jet between the boulder and the culvert wall or other boulders.

Generally, rounded material is preferred for fish passage culverts. If one portion of the gradation is not available in rounded rock, fractured rock is acceptable. In many areas gravel and cobble is available but boulder sized rock must be reduced from bedrock. In the interest of creating designs and specifications that are practical and economical, gradations should not be too restrictive. As long as all the broad ranges of size are represented, a good bed material can result. For instance, a select pit run can be combined with cobble and large fractured rock, delivered in truck load units and mixed on site with an excavator or front end loader. This material is then loaded into the pipe with a small “Bobcat” style front end loader, conveyor belt, rail mounted cart or pushed into the culvert with a log manipulated by an excavator.

Other styles of roughened channel culvert are possible, although untried. Eliminating the bed retention sills will become more practical as we better understand the implications and limits of culvert width and sediment sizing.

ROUGHENED CHANNEL DESIGN BACKGROUND REFERENCES

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Wiberg, P.L., and Smith, J.D. 1987a. "Initial motion of coarse sediment in streams of high gradient." *Erosion and Sedimentation in the Pacific Rim, Proc. of Corvallis Symp.*, IAHS Publ. 165, pp. 299-308.

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APPENDIX F

Culvert Fish Passage Design Data Summary

The following information describes the process of a specific culvert design for fish passage. The purpose of the form is to document the final design of a culvert and help permit reviewers and funding entities verify compliance with fish passage regulations and expedite permitting. Not all sections will apply to any culvert; chose the sections relevant to your culvert design process. This form should be submitted with project plans that show, at a minimum, project layout, channel and culvert profiles, details of unique features, care of water (erosion control, water diversion etc.), and road runoff treatment. Additional review information may be needed for specific situations. Data required on this form is defined in the publication 'Fish Passage Design at Road Culverts' and must be developed by acceptable methods such as those described in that manual. Refer to the Explanation of Data at the end of this form for additional information.

Culvert Fish Passage Design Data Summary Form

Site and Designer:

Date____________

Stream name __________________ WRIA __________ Tributary to____________________
Name of road crossing ___________________________ Road owner___________________
Designer _____________________________ Contact (phone, email) ____________________

Brief Narrative of Project:

____
____
____
____
____

Design Option Used:______________________

No Slope design option candidates need only provide Items marked **(N)** for proposed culvert.

Description of Culvert

Culvert Information			**Existing**	**Proposed**	
Shape:			__________	__________	**(N)**
Material:			__________	__________	
Corrugation Dimensions:		Depth	______ (in.)	______ (in.)	
		Spacing	______ (in.)	______ (in.)	
Size:	Diameter:		______ (ft)	______ (ft)	**(N)**
	Rise:		______ (ft)	______ (ft)	**(N)**
	Span:		______ (ft)	______ (ft)	**(N)**
Culvert Elevations	Elevation Datum Used:		__________		
	Upstream Invert Elevation:		______	______	
	Downstream Invert Elevation:		______	______	
Culvert Length:			______ (ft)	______ (ft)	**(N)**
Slope:			______ (ft/ft)	______ (ft/ft)	**(N)**
Culvert Countersink (Upstream):			______	______	**(N)**
Culvert Bed Width (Upstream):			______ (ft)	______ (ft)	**(N)**
Culvert Countersink (Downstream):			______	______	**(N)**
Culvert Bed Width (Downstream):			______ (ft)	______ (ft)	**(N)**
Skew angle:			______ (deg)	______ (deg)	
Roughness of culvert used in calculations: (Manning's n or other)			______	______	
Road fill					
Height of fill on upstream face:			______ (ft)	______ (ft)	
Lowest elevation at top of fill:			__________	__________	

Culvert Treatment Specifications

Upstream End Treatment:
____

Baffles:
____

Streambed Retention Sills:
____

Stream Bed Material Within Culvert:
____

How is Imported Bed Material Designed for Stability?
____

Additional culvert information, other conditions or concerns
____
____
____

Fish

Species of migratory fish designed for and migration timing

	Present (Y,N)	Timing Month(s)
Adult Chinook, Coho, Sockeye Salmon, or Steelhead		
Adult Pink or Chum Salmon		
Adult Trout		
Juvenile Salmon, Steelhead, or Trout		

Source of information:

Hydrology

Estimated Low and Peak Flood Flows (cfs)

	Q7L2	Q2	Q100
Current Watershed Conditions			
Future Watershed Conditions			

Estimated Fish Passage Flows (cfs)

Species	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Current Watershed (Qfp)				
Future Watershed (Qfp)				

Describe how flows were estimated and assumptions of future conditions:

Hydraulics

Maximum water velocity (fps) in culvert at fish passage design flows (Qfp)

Species / Size	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Design Velocity(Current)				
Design Velocity(Future)				
Velocity Allowable				

Describe how velocity was calculated:

Water Surface Elevations

Upstream of Culvert — Q100 _______
Hw/D (Q100) _______
Is culvert under Inlet or Outlet Control?(Q100) _______
Qfp (Current) _______
Qfp (Future) _______

Downstream of culvert — Q7L2 _______
OHW _______
Qfp (Current) _______
Qfp (Future) _______

Describe how water surface elevations were determined.

Upstream Channel Description

Elevations

Elevation of stream bed at upstream end of culvert: ______

Upstream channel slope: ______ (ft/ft) **(N)**

Channel

Channel bed width: _______ (ft) **(N)**

Stream bed material type: __________ **(N)**

Is there evidence of a significant amount of bed material transport? (Y,N) __________ **(N)**

Is there a significant amount of mobile woody debris present? (Y,N) __________

Exposed or expected bed scour controls and distance from culvert: **(N)**

____

____

Structures in bed or channel that could be adversely impacted by upstream channel regrade: **(N)**

____

____

Additional upstream information, other conditions or concerns **(N)**

____

____

Downstream Channel Description

Elevations

Elevation of stream bed at downstream end of culvert: ______ **(N)**

Elevation of stream bed at downstream control point: ______

Downstream channel slope: ______ (ft/ft)

Channel

Channel bed width: _______ (ft) **(N)**

Stream bed material type: __________

Manning's "n": for downstream channel: _____

Channel capacity : _______ (cfs)

Structures in stream bed or channel that could be adversely impacted by project:

____

____

Additional downstream channel information, other conditions or concerns

____

____

____

Explanation of Data

These are definitions, descriptions, and standards for the data in the Culvert Fish Passage Design Data Summary Form. These terms are discussed in the publication 'Fish Passage Design at Road Culverts'.

Site and Designer

Indicate the Stream name, Water Resource Inventory Area(WRIA), body of water that stream is tributary to, name of road culvert is located on, owner of the road, designer of culvert improvement, and contact information in the spaces available.

Brief Narrative of Project

Summarize the project with a problem / solution statement.

Design Option Used

Indicate design option for culvert (Default, Hydraulic, or Stream Simulation) as defined in the design manual.

Description of Culvert

Culvert Information

Shape:

Indicate culvert shape (Circular, Rectangular, Arch, Elliptical, Bottomless, or Other)

Material:

Indicate culvert material (Corrugated Metal, Concrete, Smooth Plastic or Metal)
If corrugated, indicate corrugation dimensions for Depth and Spacing

Size:

Diameter: Indicate diameter for circular culverts.
Rise: Indicate the dimension from culvert invert to crown.
Span: Indicate the maximum width of culvert.

Culvert Elevations:

Elevation Datum Used: Describe elevation datum used (Assumed, MSL, etc.),
Upstream invert elevation: Elevation of the lowest point on the inner surface of the culvert at the upstream end.
Downstream invert elevation: Elevation of the lowest point on the inner surface of the culvert at the downstream end.

Culvert Length:

Indicate culvert length including aprons if present.

Slope:

Use Standard survey methods to determine the horizontal length of the culvert including aprons, and the difference between its invert elevations. If slope varies within culvert, provide maximum. Describe the slope with surveyed profile.

Culvert Countersink:

Indicate the culvert countersink at each end of culvert (ratio of depth of burial to culvert rise as %)

Culvert Bed Width:

Indicate culvert width at depth of countersink at each end of culvert.

Skew angle:

Indicate the angle of the culvert to the upstream channel.

Roughness of culvert used in calculations: (Manning's n or other, if other describe)

Use appropriate sources to select a Manning's n value for culverts without bed material.

To determine a Manning's n value for the bed material, either use appropriate sources that list the bed material, sound judgement based on experience, or a roughness element calculation based on lab data.

A weighted Manning's n value will be required for culverts with stream bed material in order to account for each segment of the wetted perimeter. For example if the bed roughness is determined to be .040 for a ten foot wide bed and the culvert wall is 0.012 for two feet of submerged wall on each side of the culvert, the combined Manning's n is 0.032. [10 x 0.040 + 2 x 0.012 + 2 x 0.012] / [10 + 2 + 2]=0.032

Road Fill

Height of fill on upstream face:

Measure height of material from top of culvert to top of fill.

Lowest elevation at top of fill:

Indicate elevation of low point of fill.

Culvert Treatment Specifications

Upstream End Treatment:

Indicate wether the upstream end is beveled, protruding, beveled at upstream face, has flared wing walls etc.

Baffles:

If Baffles are present describe the type of material used, shape, height and spacing.

Streambed Retention Sills:

If Streambed Retention Sills are present describe the type of material used, shape, height and spacing.

Stream Bed Material Within Culvert:

Indicate material to be used as stream bed material from list below:

Bare: No material will be placed within culvert.

Natural Bed: Material with similar gradation to existing stream bed material will be placed in culvert or channel section is expected to regrade and deposit existing stream bed materials within culvert.

Engineered Bed: Engineered materials will be placed within culvert.

Describe the gradation of any imported bed material with D90, D50, D10, and the placement of these materials. For example Strata, Placement patterns for large boulders etc. Is the material uniformly graded from fines to maximum size. Describe specification used.

How is imported Stream Bed Material Designed for Stability?

Describe methods used to eliminate scour and transport of stream bed materials within culvert.

Additional culvert information, other conditions or concerns:

Describe any information not covered on the form that is relevant to the project.

Fish

Species of migratory fish designed for and migration timing

Indicate fish species found in stream and the months they require upstream passage.

Source of information:

Indicate where you obtained this information (suggest contact with WDFW Area Habitat Biologist or regional Fish Biologist)

Hydrology

Estimated Low and Peak Flood Flows (cfs)

Enter information in the table for the 7 day 2 year low flow (Q7L2), 2 year peak flood flows (Q2) and 100 year peak flood flows (Q100) in cubic feet per second for current and future (if available) watershed conditions.

Estimated Fish Passage Flows (cfs)

Enter information in the table for the fish passage flows for each species present in cubic feet per second for current and future (if available) watershed conditions.

Describe how flows were estimated and assumptions of future conditions:

Provide information on how flood and fish passage flows were obtained. Describe calculations, data sources, hydrologic models, monitoring efforts, or predictions.

Hydraulics

Maximum water velocity (Q/A) in culvert at fish passage design flows (Qfp)

Enter information in the table for the fish passage velocity for each species present in feet per second for current watershed conditions, future watershed conditions (if available), and velocity allowable per WAC.

Describe how velocity was calculated:

Indicate how velocities were derived. Describe calculations used (normal depth, backwater analysis, with or without bed material deposition, etc.)

Water surface elevations

Upstream of Culvert:

Provide water surface elevations for 100 year flood flows (including Headwater to Depth Ratio Hw/D, and wether culvert is under inlet or outlet control), current and future fish passage flows at the upstream end of the culvert.

Downstream of culvert:

Provide water surface elevations for minimum flows, ordinary high water(OHW), current and future fish passage flows at the downstream end of the culvert.

Describe how water surface elevations were determined:

Provide information on how water surface elevations were obtained and describe calculations used.

Upstream Channel Description

Elevations

Elevation of bed at upstream end of culvert:

Indicate stream bed elevation at upstream end of culvert.

Upstream Channel Slope:

Calculate the average channel slope based on bed elevations and distance along the channel thalweg (the lowest point in the channel cross section). Measure the channel elevations at the head of riffles; specifically, in a riffle and pool channel, the point that would create a pool of water upstream if there were no water flowing in the channel. Consistently measure the same point relative to each riffle. If there are no distinct pools and riffles, measure points at regular intervals about two channel widths apart. For slope calculations, do not measure points in pools or points that are uniquely controlled by debris or other unique features. Survey and provide channel slopes for a minimum distance of twenty channel widths upstream of the culvert.

Channel

Channel Bed Width:

The channel bed width is the dimension across the channel between ordinary high water marks. For design, use the average of at least three typical widths both upstream and downstream. Measure widths that describe normal conditions at straight channel sections between bends and outside the influence of any culvert or other artificial or unique channel constrictions.

Stream Bed Material Type:

Determine the size and type of bed material present. Catagorize it as: clay, sand, gravel, cobbles, boulders, bedrock etc. .

Is there evidence of a significant amount of bed material transport?:

Listen to the stream bed for moving material and check for stability. Look for signs of disturbance, such as: scour; or deposition of material. Look at the configuration of the channel. Are there sharp bends? Pools? Riffles? Sand or gravel bars? All of these signs are indicators of stream energy, sediment transport, debris collection, grade breaks or stream stability. It may help you determine if the stream is re-grading or becoming channelized due to either natural or human actions.

Is there a significant amount of mobile woody debris present?:

Look for debris at the site. Estimate the size and amount of it. Determine if it will move. This may drive the size and design of the culvert. If there is a lot of debris movement, baffles within the culvert may not be a good idea. This debris movement will have to be taken into account when the height of the culvert is planned. Will it pass through the culvert? Will it get hung up? Try to determine why the debris is located where it is. Are the banks failing?

Exposed or expected bed scour controls and distance from culvert:

Indicate items such as bedrock, large rocks, logs etc. that would help prevent scour and sediment transport and indicate distance upstream of culvert.

Structures in bed or channel that could be adversely impacted by upstream channel regrade:

Indicate items that could be impacted by upstream channel regrade such as pipes, intakes, weirs, bridge footings etc.

Additional upstream information, other conditions or concerns:

Describe any information not covered on the form that is relevant to the project.

Downstream Channel Description

Elevations

Elevation of bed at downstream end of culvert:

Indicate stream bed elevation downstream of culvert. The downstream bed elevation, used for culvert placement is taken at a point downstream at least four times the average width of the stream but not necessarily more than twenty-five feet from the culvert. Thalweg elevations may be higher further than that from the culvert; they are appropriate to use.

Elevation of bed at downstream control point:

Indicate stream bed elevation at the downstream control point.

Downstream Channel Slope:

Calculate the average channel slope based on bed elevations and distance along the channel thalweg (the lowest point in the channel cross section). Measure the channel elevations at the head of riffles; specifically, in a riffle and pool channel, the point that would create a pool of water upstream if there were no water flowing in the channel. Consistently measure the same point relative to each riffle. If there are no distinct pools and riffles, measure points at regular intervals about two channel widths apart. For slope calculations, do not measure points in pools or points that are uniquely controlled by debris or other unique features. Survey and provide channel slopes for a minimum distance of twenty channel widths downstream of the culvert.

Channel

Channel Bed Width:

The channel bed width is the dimension across the channel between ordinary high water marks. For design, use the average of at least three typical widths both upstream and downstream. Measure widths that describe normal conditions at straight channel sections between bends and outside the influence of any culvert or other artificial or unique channel constrictions.

Stream Bed Material Type:

Determine the size and type of bed material present. Catagorize it as: clay, sand, gravel, cobbles, boulders, bedrock etc.

Manning's n for Downstream Channel:

Selection of an appropriate value for Manning's n is very significant to the accuracy of the computed water surface profiles. The value of Manning's n is highly variable and depends on a number of factors including: surface roughness; vegetation; channel irregularities; channel alignment; scour and deposition; obstructions; size and shape of the channel; stage and discharge; and suspended material and bedload.

In general, Manning's n values should be calibrated whenever observed water surface profile information (gaged data, as well as high water marks) is available. When gaged data are not available, values of Manning's n computed for similar stream conditions or values obtained from experimental data should be used as guides in selecting n values. There are several references a user can access that show Manning's n values for typical channels.

Channel capacity:

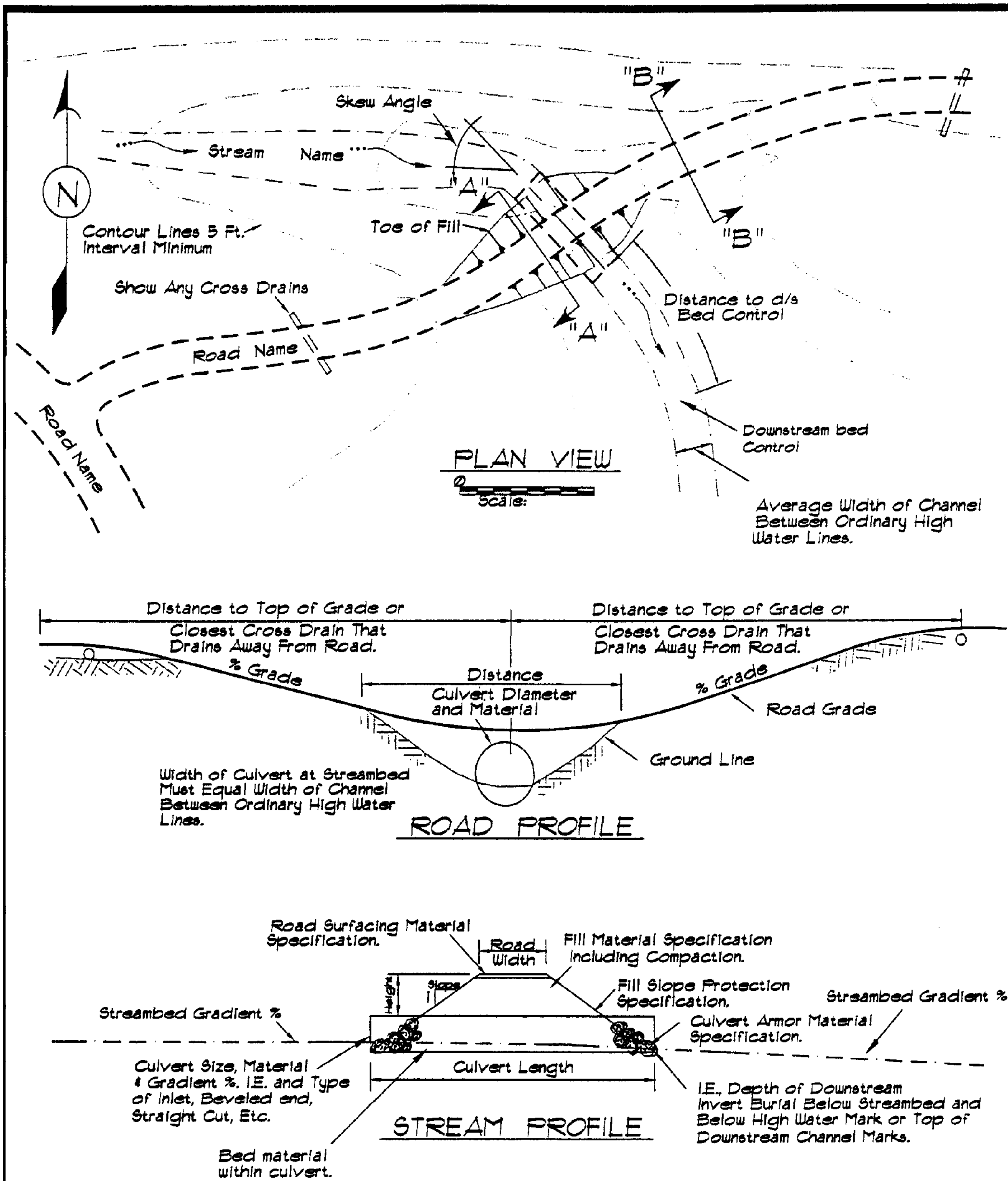
Calculate the channel capacity to determine the flood carrying capacity of the stream. Use open channel flow calculations to determine if the stream will rise above its banks. If there is a potential for this, assess the impact to the project, road, and adjacent land.

Structures in stream bed or channel that could be adversely impacted by project:

List items that could be impacted by the project such as pipes, intakes, weirs, bridge footings etc. Indicate the structure, the distance from the culvert, and the elevation.

Additional upstream information, other conditions or concerns:

Describe any information not covered on the form that is relevant to the project.



Title & Stream Name: ____________________

PURPOSE OF ROAD

Date: __________

IN ¼Sec.____, Sec.____, T.____N, R.____

COUNTY OF ____________________

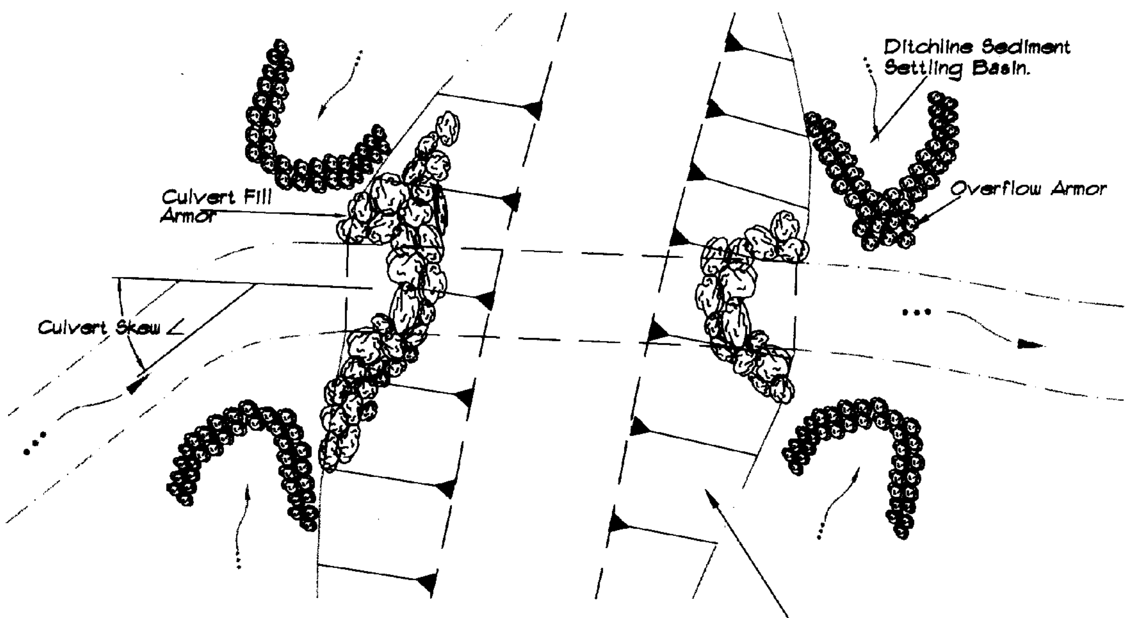
APPLICATION BY ____________________

ADDRESS: ____________________

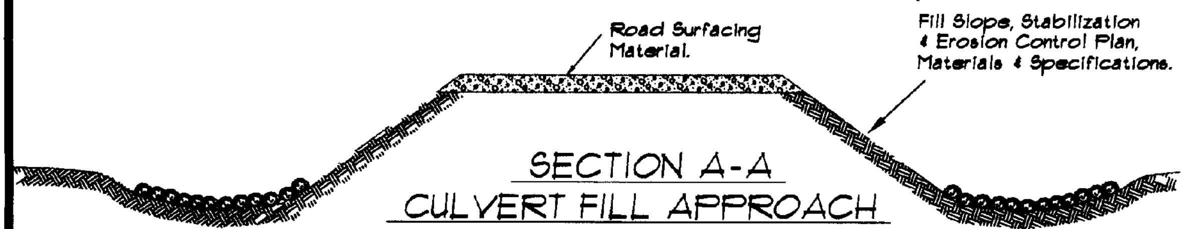
SHEET____OF________

THIS IS AN EXAMPLE OF THE INFORMATION REQUIRED FOR A CULVERT HPA.

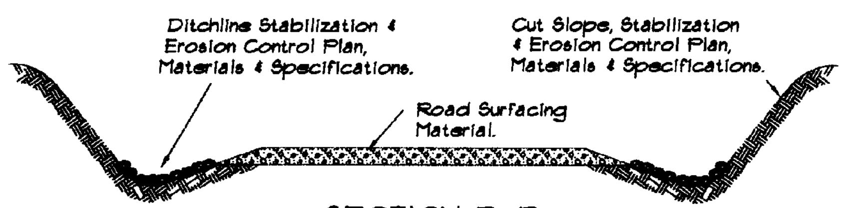
PROVIDE DIMENSIONS,DETAILS & SPECIFICATIONS AS APPROPRIATE FOR PROPOSED ROAD & CULVERT.



CULVERT DETAIL



SECTION A-A
CULVERT FILL APPROACH



SECTION B-B
DITCHLINE APPROACH

Erosion Control Plan Narrative:

Attach if necessary and include:

1. Construction Erosion Control
   example: A. Dry weather work
   B. Water bypass plan
   C. Sequence of stabilization
2. Long Term Erosion Control
   example: A. Vegetation plan
   B. Maintenance plan
   C. Inspection plan

Title & Stream Name: ____________

Date: ________

IN ¼Sec.___, Sec.___, T.___N, R.___

COUNTY OF ____________

APPLICATION BY ____________

ADDRESS: ____________

SHEET___OF______

THIS IS AN EXAMPLE OF THE INFORMATION REQUIRED FOR A CULVERT HPA.

PROVIDE DIMENSIONS, DETAILS & SPECIFICATIONS AS APPROPRIATE FOR PROPOSED ROAD & CULVERT.

APPENDIX G

Case Studies

Five case studies are presented which cover a range of solutions to fish passage problems at culverts. They are presented to demonstrate the three design options and to provide examples of how to solve fish passage problems. The first is a No Slope Option process; the next three are using the Hydraulic Option and the last one shows the Stream Simulation Option process. These projects were designed and constructed by Washington Department of Fish and Wildlife (WDFW) in cooperation with the landowners. Each project is presented in the form of a short problem description, how a solution was selected, and the completed Data Summary Form. Construction drawing details are available upon request.

A summary of unit costs for recent projects constructed by WDFW is provided at the end of the case studies.

No Slope Design - Kinman Creek

Problem

Kinman Creek is a tributary to Hood Canal and located in Kitsap County; Section 23, Township 27N, Range 1E W.M. The culvert is located under a private driveway at river mile 1.0. The existing culvert was a 18-inch aluminum Corrugated Metal Pipe (CMP), 25-feet long, placed on a 3.2 percent slope with a 0.5 foot drop at the outfall. There was only two feet of fill over the existing pipe. The culvert was a velocity barrier to fish passage, and was undersized. Historically, flows had overtopped the road several times a year.

Target Species

Coho and six inch (150 mm) Trout

Solution

The channel bed width at the Ordinary High Water Mark (OHWM) was measured to be five feet. Therefore, a six foot diameter CMP culvert, 40 feet long was selected. The culvert invert was placed flat with the outlet at 20 percent of the diameter below the downstream control. Since the upstream and downstream bed elevations were the same, upstream grade controls such as log or rock sills were not needed to address head cutting.

Permits

HPA, Landowner agreement, SEPA

Total Cost

$33,145 (1997)

Culvert Fish Passage Design Data Summary Form

Site and Designer:

Date____________

Stream name _**Kinman Cr.**________ WRIA __________ Tributary to__**Hood Canal**________
Name of road crossing ___________________________ Road owner___________________
Designer _____________________________ Contact (phone, email) ____________________

Brief Narrative of Project:

____
____
____
____
____

Design Option Used:_No Slope____________

No Slope design option candidates need only provide Items marked **(N)** for proposed culvert.

Description of Culvert

Culvert Information			**Existing**	**Proposed**	
Shape:			___________	_**Circular**_	**(N)**
Material:			___________	___________	
Corrugation Dimensions:		Depth	______ (in.)	______ (in.)	
		Spacing	______ (in.)	______ (in.)	
Size:	Diameter:		______ (ft)	___**6**__ (ft)	**(N)**
	Rise:		______ (ft)	___**6**__ (ft)	**(N)**
	Span:		______ (ft)	___**6**__ (ft)	**(N)**
Culvert Elevations	Elevation Datum Used:		___________		
	Upstream Invert Elevation:		______	______	
	Downstream Invert Elevation:		______	______	
Culvert Length:			______ (ft)	___**40**_ (ft)	**(N)**
Slope:			______ (ft/ft)	____**0**_ (ft/ft)	**(N)**
Culvert Countersink (Upstream):			______	______	**(N)**
Culvert Bed Width (Upstream):			______ (ft)	______ (ft)	**(N)**
Culvert Countersink (Downstream):			______	__**20%**_	**(N)**
Culvert Bed Width (Downstream):			______ (ft)	____**5**_ (ft)	**(N)**
Skew angle:			______ (deg)	______ (deg)	
Roughness of culvert used in calculations: (Manning's n or other)			______	______	
Road fill					
Height of fill on upstream face:			______ (ft)	______ (ft)	
Lowest elevation at top of fill:			___________	___________	

Culvert Treatment Specifications

Upstream End Treatment:

____

Baffles:

____

Streambed Retention Sills:

____

Stream Bed Material Within Culvert:

___**Imported Gravel**____

How is Imported Bed Material Designed for Stability?

____

Additional culvert information, other conditions or concerns

____
____
____

Fish

Species of migratory fish designed for and migration timing

	Present (Y,N)	Timing Month(s)
Adult Chinook, Coho, Sockeye Salmon, or Steelhead	**Y**	**Oct-Jan**
Adult Pink or Chum Salmon		
Adult Trout		
Juvenile Salmon, Steelhead, or Trout		

Source of information:

Hydrology

Estimated Low and Peak Flood Flows (cfs)

	Q7L2	Q2	Q100
Current Watershed Conditions			
Future Watershed Conditions			

Estimated Fish Passage Flows (cfs)

Species	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Current Watershed (Qfp)				
Future Watershed (Qfp)				

Describe how flows were estimated and assumptions of future conditions:

Hydraulics

Maximum water velocity (fps) in culvert at fish passage design flows (Qfp)

Species / Size	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Design Velocity(Current)				
Design Velocity(Future)				
Velocity Allowable				

Describe how velocity was calculated:

Water Surface Elevations

Upstream of Culvert — Q100 _______
Hw/D (Q100) _______
Is culvert under Inlet or Outlet Control?(Q100) _______
Qfp (Current) _______
Qfp (Future) _______
Downstream of culvert — Q7L2 _______
OHW _______
Qfp (Current) _______
Qfp (Future) _______

Describe how water surface elevations were determined.

Upstream Channel Description

Elevations

Elevation of stream bed at upstream end of culvert: _**67.8**_

Upstream channel slope: _**0.017** (ft/ft) **(N)**

Channel

Channel bed width: ___**5**___ (ft) **(N)**

Stream bed material type: _**Sand**_____ **(N)**

Is there evidence of a significant amount of bed material transport? (Y,N) ____**N**_______ **(N)**

Is there a significant amount of mobile woody debris present? (Y,N) ____**N**______

Exposed or expected bed scour controls and distance from culvert: **(N)**

____

____

Structures in bed or channel that could be adversely impacted by upstream channel regrade: **(N)**

____

____

Additional upstream information, other conditions or concerns **(N)**

____

____

Downstream Channel Description

Elevations

Elevation of stream bed at downstream end of culvert: _**67.7**_ **(N)**

Elevation of stream bed at downstream control point: ______

Downstream channel slope: _**0.017** (ft/ft)

Channel

Channel bed width: ___**5**___ (ft) **(N)**

Stream bed material type: __________

Manning's "n": for downstream channel: _____

Channel capacity : _______ (cfs)

Structures in stream bed or channel that could be adversely impacted by project:

____

____

Additional downstream channel information, other conditions or concerns

____

____

____

Hydraulic Design - South Branch Big Creek

Problem

South Branch Big Creek is a tributary to the Humptulips River in Grays Harbor County; Section 35, Township 20N, Range 10W, W.M. The existing 3-foot diameter Portland Cement Concrete (PCC) culvert is 80 feet long and located under SR-101 at MP 101.1. The undersized culvert was placed on a 2.4 percent slope, is 80 feet long with a 0.5 foot drop at the outfall. There is 3 feet of fill over the pipe. Hydrologic calculations indicate at 45 cfs, available headwater depth is at the elevation of the road. The estimated two year flood was 76 cfs. Maintenance personnel indicate they have no history of the road being overtopped at this location. At low flow, this culvert was a depth barrier to fish passage and at high flow a velocity barrier.

Targeted Species Adult & Juvenile coho, steelhead and cutthroat trout

Solution

The Hydraulic Design Option was selected over the Default Design Option or the Stream Simulation Option because of the length of pipe needed, the channel slope and the lack of adequate cover. Other factors included relative replacement costs of installing a new culvert; costs associated with a traffic detour and open cut. It was decided to hydraulicly jack a 5-foot diameter steel pipe through the fill parallel to the existing pipe. The cost of jacking a larger pipe to meet the Default Design Option or the Stream Simulation Option would have been cost prohibitive. A 5-foot diameter pipe, 100 feet long, placed on a flat slope was selected to meet the velocity criteria with the understanding that during high flows bypass would be provided by the existing pipe. The downstream invert elevation was set 1.6 feet below the existing pipe invert and was based on a calculated tailwater rating curve to achieve outlet control. The upstream channel was excavated for a distance of 40 feet to address three feet of down cutting. Three rock control weirs were placed on 15-foot centers to control the regrade.

Permits HPA, Landowner agreement, SEPA, ACOE, Fill & Grade

Total Cost $244,400 (1997)

Culvert Fish Passage Design Data Summary Form

Site and Designer:

Date____________

Stream name **S. Branch Big Cr.** WRIA __________ Tributary to **Humptulips River**

Name of road crossing **SR 101** Road owner **WS DOT**

Designer ______________________________ Contact (phone, email) ____________________

Brief Narrative of Project:

____

____

____

____

____

Design Option Used: Hydraulic

No Slope design option candidates need only provide Items marked **(N)** for proposed culvert.

Description of Culvert

Culvert Information			**Existing**	**Proposed**	
Shape:			___________	**Circular**	**(N)**
Material:			___________	**Steel**	
Corrugation Dimensions:		Depth	______ (in.)	______ (in.)	
		Spacing	______ (in.)	______ (in.)	
Size:	Diameter:		______ (ft)	**5** (ft)	**(N)**
	Rise:		______ (ft)	**5** (ft)	**(N)**
	Span:		______ (ft)	**5** (ft)	**(N)**
Culvert Elevations	Elevation Datum Used:			__________	
	Upstream Invert Elevation:		______	**86.5**	
	Downstream Invert Elevation:		______	**86.5**	
Culvert Length:			______ (ft)	**100** (ft)	**(N)**
Slope:			______ (ft/ft)	**0** (ft/ft)	**(N)**
Culvert Countersink (Upstream):			______	______	**(N)**
Culvert Bed Width (Upstream):			______ (ft)	______ (ft)	**(N)**
Culvert Countersink (Downstream):			______	**30%**	**(N)**
Culvert Bed Width (Downstream):			______ (ft)	**4** (ft)	**(N)**
Skew angle:			______ (deg)	**0** (deg)	
Roughness of culvert used in calculations: (Manning's n or other)			______	**0.012**	
Road fill					
Height of fill on upstream face:			______ (ft)	**10** (ft)	
Lowest elevation at top of fill:			___________	**101.0**	

Culvert Treatment Specifications

Upstream End Treatment:

____

Baffles:

None

Streambed Retention Sills:

None

Stream Bed Material Within Culvert:

None

How is Imported Bed Material Designed for Stability?

N/A

Additional culvert information, other conditions or concerns

5' steel pipe was jacked through road fill to eliminate need for traffic detour

____

____

Fish

Species of migratory fish designed for and migration timing

	Present (Y,N)	Timing Month(s)
Adult Chinook, Coho, Sockeye Salmon, or Steelhead	**Y**	**Jan**
Adult Pink or Chum Salmon		
Adult Trout	**Y**	**April**
Juvenile Salmon, Steelhead, or Trout	**Y**	**May**

Source of information:
WDFW Project Biologist

Hydrology

Estimated Low and Peak Flood Flows (cfs)

	Q7L2	Q2	Q100
Current Watershed Conditions		**98**	**194**
Future Watershed Conditions			

Estimated Fish Passage Flows (cfs)

Species	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Current Watershed (Qfp)	**22**			**7**
Future Watershed (Qfp)				

Describe how flows were estimated and assumptions of future conditions:
Developed flow correlation between Big Creek at Grisdale (12035450) and S. Branch Big Creek by measuring four flows simultaneously at each.

Hydraulics

Maximum water velocity (fps) in culvert at fish passage design flows (Qfp)

Species / Size	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Design Velocity(Current)	**2.9**			
Design Velocity(Future)				
Velocity Allowable				

Describe how velocity was calculated:
Velocity is maximun at outlet w/o bed material. Backwater analysis using Culvert Master.

Water Surface Elevations

Upstream of Culvert	Q100	**93.5**
	Hw/D (Q100)	
Is culvert under Inlet or Outlet Control?(Q100)		
	Qfp (Current)	**88.8**
	Qfp (Future)	
Downstream of culvert	Q7L2	**87.9**
	OHW	**89.0**
	Qfp (Current)	**88.5**
	Qfp (Future)	

Describe how water surface elevations were determined.

Upstream Channel Description

Elevations

Elevation of stream bed at upstream end of culvert: **90.5**

Upstream channel slope: **0.007** (ft/ft) **(N)**

Channel

Channel bed width: **10** (ft) **(N)**

Stream bed material type: **Sm.Gravel/Sand** **(N)**

Is there evidence of a significant amount of bed material transport? (Y,N) **N** **(N)**

Is there a significant amount of mobile woody debris present? (Y,N) **Y**

Exposed or expected bed scour controls and distance from culvert: **(N)**

Soft Bedrock 20' downstream of culvert at 88.0

Structures in bed or channel that could be adversely impacted by upstream channel regrade: **(N)**

Additional upstream information, other conditions or concerns **(N)**

40' of new channel was constructed upstream to tie into new culvert.

Downstream Channel Description

Elevations

Elevation of stream bed at downstream end of culvert: **87.4** **(N)**

Elevation of stream bed at downstream control point: **88.0**

Downstream channel slope: **0.01** (ft/ft)

Channel

Channel bed width: **10** (ft) **(N)**

Stream bed material type: **Bedrock/Clay**

Manning's "n": for downstream channel: **0.03**

Channel capacity : **179** (cfs)

Structures in stream bed or channel that could be adversely impacted by project:

Additional downstream channel information, other conditions or concerns

Channel is mainly bedrock(loose with a lot of clay but seems stable). Appears channel was excavated at one time and relocated when highway was constructed.

Hydraulic Design - Green Cove Creek

Problem

Green Cove Creek is a tributary to Eld Inlet in Thurston County; Section 32, Township 19N, Range 2 W, W.M. The two existing four foot diameter culverts are 88 feet long and under 36th Avenue NW. The right barrel has a slope of 1.55 percent with a 1.4 foot drop at the outlet. The left barrel has a slope of 1.9 percent with a 1.7 foot drop at the outlet. There is 29 feet of road fill over the pipes. At low flow this culvert was a depth barrier to fish passage and at high flow a velocity barrier. This is a highly urbanized stream that has a calibrated rating curve and is heavily monitored for flows.

Targeted Species

Adult & Juvenile coho, steelhead and cutthroat trout

Solution

Two options were considered; replacement using the default method, or construction of a fishway using the Hydraulic Option. Given the concerns of a road closure and the cost of removing 29 feet of fill associated with replacing the culvert, it was decided to construct a pool & chute fishway to backwater the culvert, to meet the velocity criteria. Survey information indicated the fishway would have to be so long it would submerge the culvert outlet and extend downstream beyond the landowner's property line. As this was unacceptable, an alternative was selected that entailed lowering the fishway and meeting the velocity criteria by placing baffles through the culvert. The fishway then becomes the tailwater control for the baffle design. Twelve steel baffles (3/16" galvanized plate) were field bolted in each pipe on 8-foot centers. Baffles were bolted to the concrete pipe wall using 3/4" diameter threaded rods anchored with a epoxy adhesive.

Note that the hydrology described in the design data form does not comply with current standards; it was developed using a hydrology model that is now obsolete.

Permits

HPA, Landowner agreement, SEPA, Shorelines

Total Cost

$95,644 (1996)

Culvert Fish Passage Design Data Summary Form

Site and Designer:

Date____________

Stream name **Green Cove Cr.** WRIA **13.0133** Tributary to **Eld Inlet**

Name of road crossing **36th Street** Road owner **Thurston County**

Designer ______________________________ Contact (phone, email) ____________________

Brief Narrative of Project:

____

Design Option Used: Hydraulic

No Slope design option candidates need only provide Items marked **(N)** for proposed culvert.

Description of Culvert

Culvert Information			**Existing**	**Proposed**	
Shape:			______	**2 Circular**	**(N)**
Material:			______	**2 Concrete**	
Corrugation Dimensions:		Depth	______ (in.)	______ (in.)	
		Spacing	______ (in.)	______ (in.)	
Size:	Diameter:		______ (ft)	**4** (ft)	**(N)**
	Rise:		______ (ft)	______ (ft)	**(N)**
	Span:		______ (ft)	______ (ft)	**(N)**
Culvert Elevations	Elevation Datum Used:		______		
	Upstream Invert Elevation:		______	______	
	Downstream Invert Elevation:		______	______	
Culvert Length:			______ (ft)	**90** (ft)	**(N)**
Slope:			**0.019** (ft/ft)	**0.016** (ft/ft)	**(N)**
Culvert Countersink (Upstream):			______	______	**(N)**
Culvert Bed Width (Upstream):			______ (ft)	______ (ft)	**(N)**
Culvert Countersink (Downstream):			______	______	**(N)**
Culvert Bed Width (Downstream):			______ (ft)	______ (ft)	**(N)**
Skew angle:			______ (deg)	**45** (deg)	
Roughness of culvert used in calculations: (Manning's n or other)			______	______	
Road fill					
Height of fill on upstream face:			______ (ft)	**26** (ft)	
Lowest elevation at top of fill:			______	**120.0**	

Culvert Treatment Specifications

Upstream End Treatment:

____

Baffles:

Steel, sloping, 3 to 9 inches, 8 feet apart

Streambed Retention Sills:

____

Stream Bed Material Within Culvert:

____

How is Imported Bed Material Designed for Stability?

____

Additional culvert information, other conditions or concerns

Concrete pool and chute fishway downstream

____

Fish

Species of migratory fish designed for and migration timing

	Present (Y,N)	Timing Month(s)
Adult Chinook, Coho, Sockeye Salmon, or Steelhead	**Y**	**Jan**
Adult Pink or Chum Salmon		
Adult Trout	**Y**	**March**
Juvenile Salmon, Steelhead, or Trout	**Y**	**Jun**

Source of information:

Hydrology

Estimated Low and Peak Flood Flows (cfs)

	Q7L2	Q2	Q100
Current Watershed Conditions		**40**	**150**
Future Watershed Conditions		**70**	**170**

Estimated Fish Passage Flows (cfs)

Species	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Current Watershed (Qfp)	**43**			
Future Watershed (Qfp)	**47**			

Describe how flows were estimated and assumptions of future conditions:

Thurston County HSPF basin model data.

Hydraulics

Maximum water velocity (fps) in culvert at fish passage design flows (Qfp)

Species / Size	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Design Velocity(Current)	**3.9**			
Design Velocity(Future)				
Velocity Allowable	**5.0**			

Describe how velocity was calculated:

Mannings Equation, Normal Depth, Flow Master

Water Surface Elevations

Upstream of Culvert	Q100	**103.5**
	Hw/D (Q100)	______
Is culvert under Inlet or Outlet Control?(Q100)		**Outlet**
	Qfp (Current)	**97.41**
	Qfp (Future)	______
Downstream of culvert	Q7L2	**94.3**
	OHW	**96.0**
	Qfp (Current)	**96.2**
	Qfp (Future)	______

Describe how water surface elevations were determined.

Upstream Channel Description

Elevations

Elevation of stream bed at upstream end of culvert: _**95.6**_

Upstream channel slope: _**0.012** (ft/ft) **(N)**

Channel

Channel bed width: __**12**___ (ft) **(N)**

Stream bed material type: **Sand/Gravel** **(N)**

Is there evidence of a significant amount of bed material transport? (Y,N) ___**N**______ **(N)**

Is there a significant amount of mobile woody debris present? (Y,N) ___**Y**______

Exposed or expected bed scour controls and distance from culvert: **(N)**

____

____

Structures in bed or channel that could be adversely impacted by upstream channel regrade: **(N)**

__**Thurston County operates a stream gage 50' +/- upstream of culvert**______________________

____

Additional upstream information, other conditions or concerns **(N)**

____

____

Downstream Channel Description

Elevations

Elevation of stream bed at downstream end of culvert: **(Fishway)** _**94.3**_ **(N)**

Elevation of stream bed at downstream control point: **(Fishway)** ______

Downstream channel slope: _**0.012** (ft/ft)

Channel

Channel bed width: __**12**___ (ft) **(N)**

Stream bed material type: **Sand/Gravel**

Manning's "n": for downstream channel: _____

Channel capacity : _______ (cfs)

Structures in stream bed or channel that could be adversely impacted by project:

____

____

Additional downstream channel information, other conditions or concerns

__**There was a 2' outfall drop so a fishway was constructed downstream. The road shoulder was failing because of the outfall scour. The constructed fishway supported the failing slopes.**______

____

Hydraulic Design - Percival Creek

Problem

Percival Creek is a tributary to Capital Lake and Budd Inlet in the City of Olympia; Section 21, Township 18N, Range @w, W.M. The 5 foot diameter concrete pipe is 170 feet long and located under Mottman Road in Tumwater. The culvert is on a 0.96 percent slope under 35 feet of road fill with a 3.2 foot drop at the outlet. Baffles were previously installed (in 1995) so the culvert was passable with regard to velocity, except for the problem at the outfall. This is a highly urbanized stream that has a calibrated rating curve and is heavily monitored for flows.

Targeted Species

Adult & Juvenile coho, steelhead and cutthroat trout

Solution

Before the baffles were installed, an analysis of the culvert's future flood capacity was made using the county's calibrated stream gauging data and their hydrologic simulation program (HSPF). At the estimated future 100 year flood event, the ratio of the available depth of water to the diameter of the pipe was 1.3. This indicated the culvert was not undersized even with baffles. The two options considered to address the drop at the outlet were log control sills or a fish ladder. The structure is located in a ravine with no access for heavy equipment to install the log control sills. Because the outfall drop was less than four feet, a 10-foot wide pool and chute style fish ladder was selected. Concrete was pumped and materials were lowered by a crane.

Note that the hydrology described in the design data form does not comply with current standards; it was developed using a hydrology model that is now obsolete.

Results

During the fall of 1996 WDFW personnel conducted spawner surveys above the newly developed fishway. Results indicate a peak count of 372 chinook were observed spawning above Mottman Road. This is the first time in many years that fish have been able to freely migrate through the Mottman Road culvert.

Permits

HPA, Landowner agreement, SEPA, Shorelines

Total Cost

$84,872 (1996)

Culvert Fish Passage Design Data Summary Form

Site and Designer:

Date____________

Stream name **Percival Creek** WRIA __________ Tributary to **Budd Inlet/Capital Lake**
Name of road crossing **Mottman Road** Road owner **City of Tumwater**
Designer ______________________________ Contact (phone, email) ____________________

Brief Narrative of Project:

____
____
____
____
____

Design Option Used: **Hydraulic**

No Slope design option candidates need only provide Items marked **(N)** for proposed culvert.

Description of Culvert

Culvert Information			**Existing**	**Proposed**	
Shape:			______	**Circular**	**(N)**
Material:			______	**Concrete**	
Corrugation Dimensions:		Depth	______ (in.)	______ (in.)	
		Spacing	______ (in.)	______ (in.)	
Size:	Diameter:		______ (ft)	**5** (ft)	**(N)**
	Rise:		______ (ft)	______ (ft)	**(N)**
	Span:		______ (ft)	______ (ft)	**(N)**
Culvert Elevations	Elevation Datum Used:			______	
	Upstream Invert Elevation:		______	**102.5**	
	Downstream Invert Elevation:		______	**100.9**	
Culvert Length:			______ (ft)	**170** (ft)	**(N)**
Slope:			______ (ft/ft)	**.0096** (ft/ft)	**(N)**
Culvert Countersink (Upstream):			______	______	**(N)**
Culvert Bed Width (Upstream):			______ (ft)	______ (ft)	**(N)**
Culvert Countersink (Downstream):			______	______	**(N)**
Culvert Bed Width (Downstream):			______ (ft)	______ (ft)	**(N)**
Skew angle:			______ (deg)	**10** (deg)	
Roughness of culvert used in calculations: (Manning's n or other)			______	**0.06**	
Road fill					
Height of fill on upstream face:			______ (ft)	**35** (ft)	
Lowest elevation at top of fill:			______	**142**	

Culvert Treatment Specifications

Upstream End Treatment:
____

Baffles:
Height 9", Spacing 8'

Streambed Retention Sills:
____

Stream Bed Material Within Culvert:
____

How is Imported Bed Material Designed for Stability?
____

Additional culvert information, other conditions or concerns
____
____
____

Fish

Species of migratory fish designed for and migration timing

	Present (Y,N)	Timing Month(s)
Adult Chinook, Coho, Sockeye Salmon, or Steelhead	**Y**	**Jan**
Adult Pink or Chum Salmon		
Adult Trout	**Y**	**Feb-April**
Juvenile Salmon, Steelhead, or Trout	**Y**	**May/June**

Source of information:

WDFW Project Biologist Tom Burns

Hydrology

Estimated Low and Peak Flood Flows (cfs)

	Q7L2	Q2	Q100
Current Watershed Conditions		**80**	**172**
Future Watershed Conditions		**95**	**231**

Estimated Fish Passage Flows (cfs)

Species	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Current Watershed (Qfp)	**35**			
Future Watershed (Qfp)				

Describe how flows were estimated and assumptions of future conditions:

Thurston County HSPF data and WDFW Regression Equation.

Hydraulics

Maximum water velocity (fps) in culvert at fish passage design flows (Qfp)

Species / Size	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Design Velocity(Current)	**3.9**			
Design Velocity(Future)				
Velocity Allowable	**4.0**			

Describe how velocity was calculated:

Mannings Equation.

Water Surface Elevations

Upstream of Culvert	Q100	**109.1**
	Hw/D (Q100)	**1.3**
Is culvert under Inlet or Outlet Control?(Q100)		**Outlet**
	Qfp (Current)	**105.3**
	Qfp (Future)	
Downstream of culvert	Q7L2	**99.9**
	OHW	**102.0**
	Qfp (Current)	**103.1**
	Qfp (Future)	

Describe how water surface elevations were determined.

Upstream Channel Description

Elevations

Elevation of stream bed at upstream end of culvert: **102.6**

Upstream channel slope: **0.020** (ft/ft) **(N)**

Channel

Channel bed width: **13** (ft) **(N)**

Stream bed material type: **Sand/Gravel** **(N)**

Is there evidence of a significant amount of bed material transport? (Y,N) **N** **(N)**

Is there a significant amount of mobile woody debris present? (Y,N) **Y**

Exposed or expected bed scour controls and distance from culvert: **(N)**

Structures in bed or channel that could be adversely impacted by upstream channel regrade: **(N)**

Additional upstream information, other conditions or concerns **(N)**

Downstream Channel Description

Elevations

Elevation of stream bed at downstream end of culvert: **(Deep Pool)** **94.7** **(N)**

Elevation of stream bed at downstream control point: **98.8**

Downstream channel slope: **0.02** (ft/ft)

Channel

Channel bed width: **13** (ft) **(N)**

Stream bed material type: **Bedrock/Gravel**

Manning's "n": for downstream channel: **0.04**

Channel capacity : **>200** (cfs)

Structures in stream bed or channel that could be adversely impacted by project:

Thurston County has maintained a stream gage in the plunge pool for several years. USGS has used this data

Additional downstream channel information, other conditions or concerns

The Downstream channel is in a 35' deep ravine with steep side slopes.

Roughened Channel Design - Dazzling Howie Creek

Problem

Dazzling Howie Creek is a tributary to the South Fork Stillaguamish River in Snohomish County; Section 24, Township 30 N, Range 10E. The six by five foot wooden box culvert was located under 2 feet of road fill on the Mountain Loop Highway at MP 21.5. The culvert was 60 feet long and placed on a 1.2 percent slope with a 2.3 foot drop at the outfall. The channel bed width was measured to be 11 feet at the OHW mark. The culvert was a outfall and velocity barrier to fish passage.

Targeted Species

Adult coho

Solution

All three options were considered: Default, Hydraulic and Stream Simulation. Under the Default method the culvert would have been replaced with a pipe at a flat gradient. Using the Hydraulic method a fish ladder would be constructed to backwater the culvert outlet. Stream Simulation would require replacement of the existing wooden box culvert with much larger culvert. The Default Option was not selected, because of the 4.6 feet of drop through the culvert (including the 2.3 drop at the outlet), and the 4 percent downstream channel gradient combined with the required length of the culvert made the inlet constricted. The Hydraulic Design Option was not selected because it would require the land owner to take on additional maintenance responsibilities and the distance to the Stillaguamish River was too short.

A 117-inch by 79-inch pipe arch culvert with a roughened channel was constructed. The bed material placed inside the culvert was sized to simulate the substrate material size found in the natural channel, and bedload retention sills were welded into the culvert. Three upstream rock control weirs were placed on 15-foot centers to control the regrade.

Note that the final design does not comply with current Stream Simulation design method; this design was based on a design process that is now obsolete. The current design process would require an arch culvert with a 15-foot span or an equivalent round culvert and no bed retention sills would have been required.

Permits

HPA, Landowner agreement, SEPA

Total Cost

$103,000 (1997)

Culvert Fish Passage Design Data Summary Form

Site and Designer:

Date____________

Stream name **Dazzling Howie Cr.** WRIA ________ Tributary to **S. Fork Stillaquamish River**
Name of road crossing **Mountain Loop Highway** Road owner **Snohomish County**
Designer ______________________________ Contact (phone, email) ____________________

Brief Narrative of Project:

____
____
____
____
____

Design Option Used: Stream Simulation

No Slope design option candidates need only provide Items marked **(N)** for proposed culvert.

Description of Culvert

Culvert Information			**Existing**	**Proposed**	
Shape:			Rect.	Arch	**(N)**
Material:				Corrugated Metal	
Corrugation Dimensions:		Depth	______ (in.)	1 (in.)	
		Spacing	______ (in.)	3 (in.)	
Size:	Diameter:		______ (ft)	______ (ft)	**(N)**
	Rise:		5 (ft)	6.6 (ft)	**(N)**
	Span:		6 (ft)	9.8 (ft)	**(N)**
Culvert Elevations	Elevation Datum Used:		______		
	Upstream Invert Elevation:		______	90.5	
	Downstream Invert Elevation:		______	87.5	
Culvert Length:			______ (ft)	60 (ft)	**(N)**
Slope:			0.012 (ft/ft)	0.05 (ft/ft)	**(N)**
Culvert Countersink (Upstream):			______	______	**(N)**
Culvert Bed Width (Upstream):			______ (ft)	______ (ft)	**(N)**
Culvert Countersink (Downstream):			______	38%	**(N)**
Culvert Bed Width (Downstream):			______ (ft)	10 (ft)	**(N)**
Skew angle:			______ (deg)	______ (deg)	
Roughness of culvert used in calculations: (Manning's n or other)			______	0.04	
Road fill					
Height of fill on upstream face:			3 (ft)	2.5 (ft)	
Lowest elevation at top of fill:			______	99.5	

Culvert Treatment Specifications

Upstream End Treatment:

____

Baffles:

____

Streambed Retention Sills:

.25" steel plates, 24" high, 20' spacing

Stream Bed Material Within Culvert:

D90 = 18", D50 = 9", D10 = 3"

How is Imported Bed Material Designed for Stability?

Use of Streambed Retention sills

Additional culvert information, other conditions or concerns

Fish Passage is based on maintaining a natural streambed in the culvert.

____
____

Fish

Species of migratory fish designed for and migration timing

	Present (Y,N)	Timing Month(s)
Adult Chinook, Coho, Sockeye Salmon, or Steelhead	**Y**	**Jan**
Adult Pink or Chum Salmon		
Adult Trout	**Y**	**March**
Juvenile Salmon, Steelhead, or Trout	**Y**	**April**

Source of information:

Hydrology

Estimated Low and Peak Flood Flows (cfs)

	Q7L2	Q2	Q100
Current Watershed Conditions		**33**	**90**
Future Watershed Conditions			

Estimated Fish Passage Flows (cfs)

Species	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Current Watershed (Qfp)	**14**			
Future Watershed (Qfp)				

Describe how flows were estimated and assumptions of future conditions:

Regression equations with standard error adjusted based on one year of flow monitoring.

Hydraulics

Maximum water velocity (fps) in culvert at fish passage design flows (Qfp)

Species / Size	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Design Velocity(Current)	**4.0**			
Design Velocity(Future)				
Velocity Allowable				

Describe how velocity was calculated:

Mannings Equation using bed inside culvert.

Water Surface Elevations

Upstream of Culvert	Q100	**94.1**
	Hw/D (Q100)	
Is culvert under Inlet or Outlet Control?(Q100)		
	Qfp (Current)	**93.3**
	Qfp (Future)	
Downstream of culvert	Q7L2	**89.0**
	OHW	**90.5**
	Qfp (Current)	**90.3**
	Qfp (Future)	

Describe how water surface elevations were determined.

Upstream Channel Description

Elevations

Elevation of stream bed at upstream end of culvert: **93.0**

Upstream channel slope: **0.04** (ft/ft) **(N)**

Channel

Channel bed width: **11** (ft) **(N)**

Stream bed material type: **Gravel/Cobble** **(N)**

Is there evidence of a significant amount of bed material transport? (Y,N) **N** **(N)**

Is there a significant amount of mobile woody debris present? (Y,N) **N**

Exposed or expected bed scour controls and distance from culvert: **(N)**

Stable Cobble Channel.

Structures in bed or channel that could be adversely impacted by upstream channel regrade: **(N)**

Additional upstream information, other conditions or concerns **(N)**

Downstream Channel Description

Elevations

Elevation of stream bed at downstream end of culvert: **88.4** **(N)**

Elevation of stream bed at downstream control point: **89.4**

Downstream channel slope: **0.044** (ft/ft)

Channel

Channel bed width: **11** (ft) **(N)**

Stream bed material type: **Gravel/Cobble**

Manning's "n": for downstream channel: **0.04**

Channel capacity : **560** (cfs)

Structures in stream bed or channel that could be adversely impacted by project:

Additional downstream channel information, other conditions or concerns

Culvert is 60' upstream of the confluence with the S. fork Stilliguamish River.

Stream Simulation Design - Pringle Creek

Problem

Pringle creek is a tributary of Turner creek, east of Mt. Vernon in Skagit county, Sec 17, T34N R5E. The creek passes under a private gravel road at an inclined bend in the road. Before replacement there were two 24 inch round CMP culverts on a 5.6% overall slope. Since much of the drop through these culverts occurred in the last third or so of their 36 foot length, they were a total barrier to fish passage because of velocity. The upstream end of the road fill was held up by a decaying log headwall and portions of the road were washing out before replacement. Immediately upstream of the culvert the stream ran at the base of a very steep soil face. The slope was vegetated but experiencing some erosion at the toe. Downstream, the channel is confined along side the road in a narrow deep ditch. This section had log controls installed at least 5 years ago and it appeared stable with a fair number of small alders growing on the banks. Upstream of the culvert the channel passes into a steep valley with a mature riparian zone. The watershed is lightly developed and habitat appeared to be good for coho and trout. No habitat survey was done nor was the culvert part of an inventory and prioritization program.

Targeted Species

Adult and juvenile coho and cutthroat trout.

Solution

The stream simulation option was chosen for a number of reasons. The default option would have required substantial grade control downstream of the culvert to make up for the drop (7 log controls in 140 feet of channel). The stream width is relatively small and as a result the stream simulation culvert would not represent a substantial increase in cost. The grant program, project manager and contractor could accept this design and were willing to try it. The downstream grade control was examined and appeared to be reliable so it was left in place. Ten feet was chosen as the culvert diameter (30% greater than the 7 foot stream bed width), countersunk to 50% of its diameter and placed on a 4% gradient. It was filled with a “boulder/cobble mix with fines to seal” which turned out to be 1.5 foot maximum sized material graded fairly well to silt as the finest. There was a gap between the coarsest and finest fractions, largely in the 7 to 12 inch range, but none of this was quantified. This fill was placed in the culvert with a small front end loader of the “Bobcat” variety. The same mixture that was placed in the bottom of the pipe was the same as that on the top. No attempt was made to selectively place it. The mixture sealed almost immediately and fish passage was restored as soon as flows returned to the creek. The channel upstream of the pipe was moved away from the hillside and steepened slightly from 4 to 5% with log controls and a coarse cobble bed material. Large woody debris was added to the banks and channel to provide habitat and the site was revegetated with ground cover and native woody species. The bed in the pipe remains stable after a number of high flow events and fish passage is considered good.

Permits HPA

Total Cost $31,000 (1998)

Culvert Fish Passage Design Data Summary Form

Site and Designer:

Date____________

Stream name **Pringle Creek** WRIA **3** Tributary to **Walker**
Name of road crossing ____________ Road owner ____________
Designer **Bob Barnard** Contact (phone, email) ____________

Brief Narrative of Project:

Design Option Used: Stream Simulation

No Slope design option candidates need only provide Items marked **(N)** for proposed culvert.

Description of Culvert

Culvert Information			**Existing**	**Proposed**	
Shape:			**2 round**	**round**	**(N)**
Material:			**cmp**	**cmp**	
Corrugation Dimensions:		Depth	___ (in.)	**1** (in.)	
		Spacing	___ (in.)	**3** (in.)	
Size:	Diameter:		**2-2** (ft)	**10** (ft)	**(N)**
	Rise:		___ (ft)	___ (ft)	**(N)**
	Span:		___ (ft)	___ (ft)	**(N)**
Culvert Elevations	Elevation Datum Used:		**Assumed 100**		
	Upstream Invert Elevation:		**104.2**	**98.5**	
	Downstream Invert Elevation:		**102.2**	**96.7**	
Culvert Length:			**36** (ft)	**50** (ft)	**(N)**
Slope:			**0.056** (ft/ft)	**0.036** (ft/ft)	**(N)**
Culvert Countersink (Upstream):			___	**50%**	**(N)**
Culvert Bed Width (Upstream):			___ (ft)	**10** (ft)	**(N)**
Culvert Countersink (Downstream):			___	**50%**	**(N)**
Culvert Bed Width (Downstream):			___ (ft)	**10** (ft)	**(N)**
Skew angle:			**53** (deg)	**57** (deg)	
Roughness of culvert used in calculations: (Manning's n or other)			___	___	
Road fill					
Height of fill on upstream face:			**4** (ft)	**2** (ft)	
Lowest elevation at top of fill:			**110.3**	**110.3**	

Culvert Treatment Specifications

Upstream End Treatment:
Protruding

Baffles:

Streambed Retention Sills:

Stream Bed Material Within Culvert:
D90 = 18", D50 = 8", D10 = 1.0"

How is Imported Bed Material Designed for Stability?
Comparison to existing bed material and professional judgement.

Additional culvert information, other conditions or concerns
u/s & d/s bed channel width approx 7' ; culvert bed width = 1.2 * 7 + 2 = 10.4

Fish

Species of migratory fish designed for and migration timing

	Present (Y,N)	Timing Month(s)
Adult Chinook, Coho, Sockeye Salmon, or Steelhead		
Adult Pink or Chum Salmon		
Adult Trout		
Juvenile Salmon, Steelhead, or Trout		

Source of information:

Hydrology

Estimated Low and Peak Flood Flows (cfs)

	Q7L2	Q2	Q100
Current Watershed Conditions		**12**	**37**
Future Watershed Conditions			

Estimated Fish Passage Flows (cfs)

Species	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Current Watershed (Qfp)			**12**	
Future Watershed (Qfp)				

Describe how flows were estimated and assumptions of future conditions:

Regional Regression Equation.

Hydraulics

Maximum water velocity (fps) in culvert at fish passage design flows (Qfp)

Species / Size	Adult Chinook, Coho, Sockeye, Steelhead	Adult Pink, Chum	Adult Trout	Juvenile Salmon, Steelhead, Trout
Design Velocity(Current)				
Design Velocity(Future)				
Velocity Allowable				

Describe how velocity was calculated:

Water Surface Elevations

Upstream of Culvert	Q100	**105.0**
	Hw/D (Q100)	**1/5**
Is culvert under Inlet or Outlet Control?(Q100)		
	Qfp (Current)	**104.7**
	Qfp (Future)	**104.7**
Downstream of culvert	Q7L2	
	OHW	**102.5**
	Qfp (Current)	**102.5**
	Qfp (Future)	**102.5**

Describe how water surface elevations were determined.

Bed roughness assumed to control water depth. Used WinXSPro and large scale roughness equation (Rathurst) to determine water depth.

Upstream Channel Description

Elevations

Elevation of stream bed at upstream end of culvert: **104**

Upstream channel slope: **0.05** (ft/ft) **(N)**

Channel

Channel bed width: **7** (ft) **(N)**

Stream bed material type: **Gravel** **(N)**

Is there evidence of a significant amount of bed material transport? (Y,N) **N** **(N)**

Is there a significant amount of mobile woody debris present? (Y,N) **N**

Exposed or expected bed scour controls and distance from culvert: **(N)**

4 Log controls. 1st one about 17' u/s of channel(about 2 channel widths)

Structures in bed or channel that could be adversely impacted by upstream channel regrade: **(N)**

u/s channel reconstructed to steeper grade w/log controls. Good riparian and instream habitat u/s.

Additional upstream information, other conditions or concerns **(N)**

Landowner committed to preserving existing riparian and natural conditions.

Downstream Channel Description

Elevations

Elevation of stream bed at downstream end of culvert: **101.7** **(N)**

Elevation of stream bed at downstream control point: **101.45**

Downstream channel slope: **0.034** (ft/ft)

Channel

Channel bed width: **5-7** (ft) **(N)**

Stream bed material type: **Gravel**

Manning's "n": for downstream channel: **0.05-0.06**

Channel capacity : **>Q100** (cfs)

Structures in stream bed or channel that could be adversely impacted by project:

Additional downstream channel information, other conditions or concerns

Project Unit Costs

Since 1991 Washington Department of Fish and Wildlife has tracked fish passage project costs relative to design parameters. This section summarizes those costs. The projects were designed and constructed by WDFW staff. The costs represent the cost of the entire project development including survey, design, permits, construction, and initial monitoring. To separate out just the construction costs, use about 50% of the total costs. The costs have been inflated 3.0% per year to produce 1998 costs. These costs should only be used for initial project planning purposes to compare project types; site conditions will certainly greatly affect actual project costs.

Project Type	Units	Cost / Unit	Cost / Ft. Drop	No of projects
Pipe jacking, channel mods	Length	$2,200	$91,000	3
Culvert replacement	Length	$1,300	$34,400	9
Log controls	No of weirs	$11,500	$13,000	5
Concrete fishway			$16,000	5
Baffles	Baffle	$1,400	$3,500	5

In the table, drop is the vertical distance measured from the downstream water surface to the water surface elevation upstream of the project. For baffles this would be the upstream culvert invert elevation minus the downstream culvert invert elevation. For log controls or fishways, this is the upstream water surface elevation minus the elevation of the water surface in the channel just below the last log control or fishway weir.

APPENDIX H

Fish Passage Analysis

Not all culverts are barriers to fish migration. Often, a passage analysis is needed to document the percent of time a culvert is passable for different species and life stages of fish. Following is a detailed fish passage analysis for the Fairchild Creek Culvert under SR 101 near the Humptulips River. The culvert is a 72 inch corrugated metal pipe placed on a 0.005 ft/ft slope, 180 feet long.

The target hydraulic condition for determining whether a culvert is passable is the velocity criteria of the hydraulic design option from Table 1 of WAC 220-110-070. Therefore, if at the high passage design flow the maximum velocity is less than or equal to the allowable velocity 90 percent of the time, the WAC criteria it met. If not, the culvert is considered a barrier. This only determines the amount of time a culvert is or is not passable; it does not determine the percentage of fish that pass or are blocked. Another level of analysis would be required including the number of fish present at specific flows. In fact, salmonids are adapted to attempt passage at higher flows; the passability by this method of analysis would over-estimate the number of fish passing or blocked by a culvert.

The following steps can be used to make the percent passage calculations.

1) Determine species, life stage and migration timing.

2) Determine maximum design velocities for culvert from Table 1 of WAC 220-110-070 fish passage design criteria. For coho fry and fingerlings maximum velocity values were estimated from Powers, 1998.

3) Develop monthly flow duration curves.

   Since there was no stream gage data for Fairchild Creek. Flows in Fairchild Creek were correlated to flows in a nearby gaged stream. The gage used was Big Creek near Grisdale (USGS Gage #12035450), a tributary to the Wynoochee River.

4) Use a program such as Flow Master™ to analyze the culvert velocities to determine velocity as a function of flow. Two velocities were actually measured to verify the results.

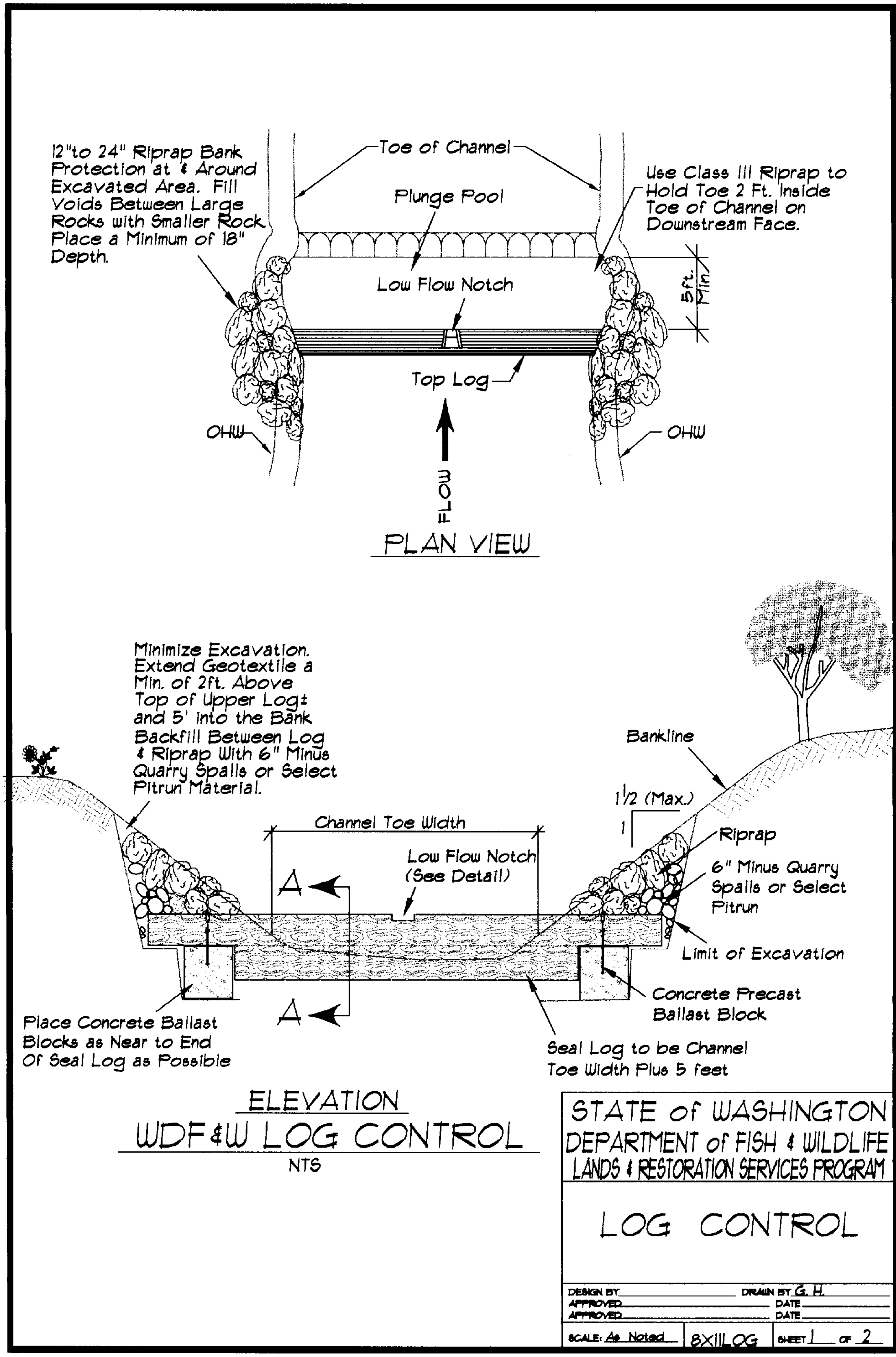
5) Taking the maximum velocity from Table 1, for the desired species, determine the discharge at which that velocity occurs in Fairchild Creek. Relate that discharge to the discharge in Big Creek, and determine from the flow duration curves the percent of time that value is equaled or exceeded. That is the value shown in the table below. A value of 60 percent means that the culvert is passable 60 percent of the time during the selected month. WDFW fish passage criteria requires passage 90 percent of the time.

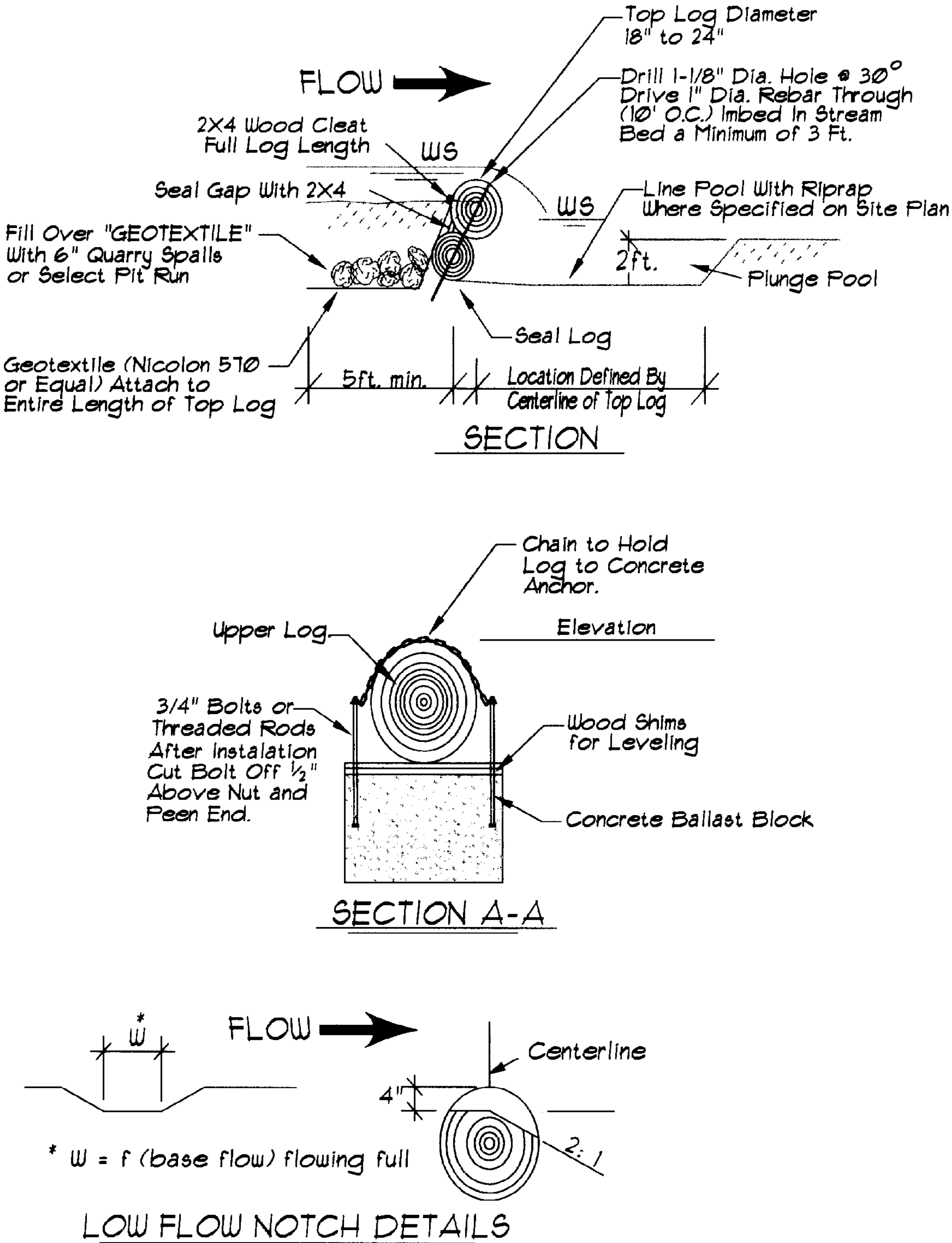
Species	Migration Timing	Velocity (fps)	Percent Passing
Adult coho	November	4.0	37
	December	"	50
	January	"	44
	average		44
Fry coho	March - May	1.2	2
Fingerling coho	October	2.1	45
	November	"	3
	December	"	3
	average		17
Adult Trout	March	3.0	10

For adult coho, the culvert is passable 44 percent of the time, for adult trout 10 percent of the time and for coho fry and fingerlings, 2 and 17 percent respectively. These values do not meet the 90 percent criteria therefore the culvert would be considered a barrier.

APPENDIX I

Example Design Sketches


12"to 24" Riprap Bank Protection at & Around Excavated Area. Fill Voids Between Large Rocks with Smaller Rock. Place a Minimum of 18" Depth.
Toe of Channel
Plunge Pool
Use Class III Riprap to Hold Toe 2 Ft. Inside Toe of Channel on Downstream Face.
Low Flow Notch
5 ft. Min.
Top Log
OHW
OHW
FLOW
PLAN VIEW
Minimize Excavation. Extend Geotextile a Min. of 2ft. Above Top of Upper Log & and 5' into the Bank
Backfill Between Log & Riprap With 6" Minus Quarry Spalls or Select Pitrun Material.
Bankline
1½ (Max.)
1
Channel Toe Width
Low Flow Notch (See Detail)
A
A
Riprap
6" Minus Quarry Spalls or Select Pitrun
Limit of Excavation
Concrete Precast Ballast Block
Place Concrete Ballast Blocks as Near to End Of Seal Log as Possible
Seal Log to be Channel Toe Width Plus 5 feet
ELEVATION
WDF&W LOG CONTROL
NTS
STATE of WASHINGTON
DEPARTMENT of FISH & WILDLIFE
LANDS & RESTORATION SERVICES PROGRAM
LOG CONTROL
DESIGN BY
DRAWN BY G. H.
APPROVED
DATE
APPROVED
DATE
SCALE: As Noted
8XIILOG
SHEET 1 OF 2



$$\frac{0.29D^2 \times (2L-10)}{2} =$$ Concrete Anchor Volume Needed at each end, (Cubic Feet).

Where:

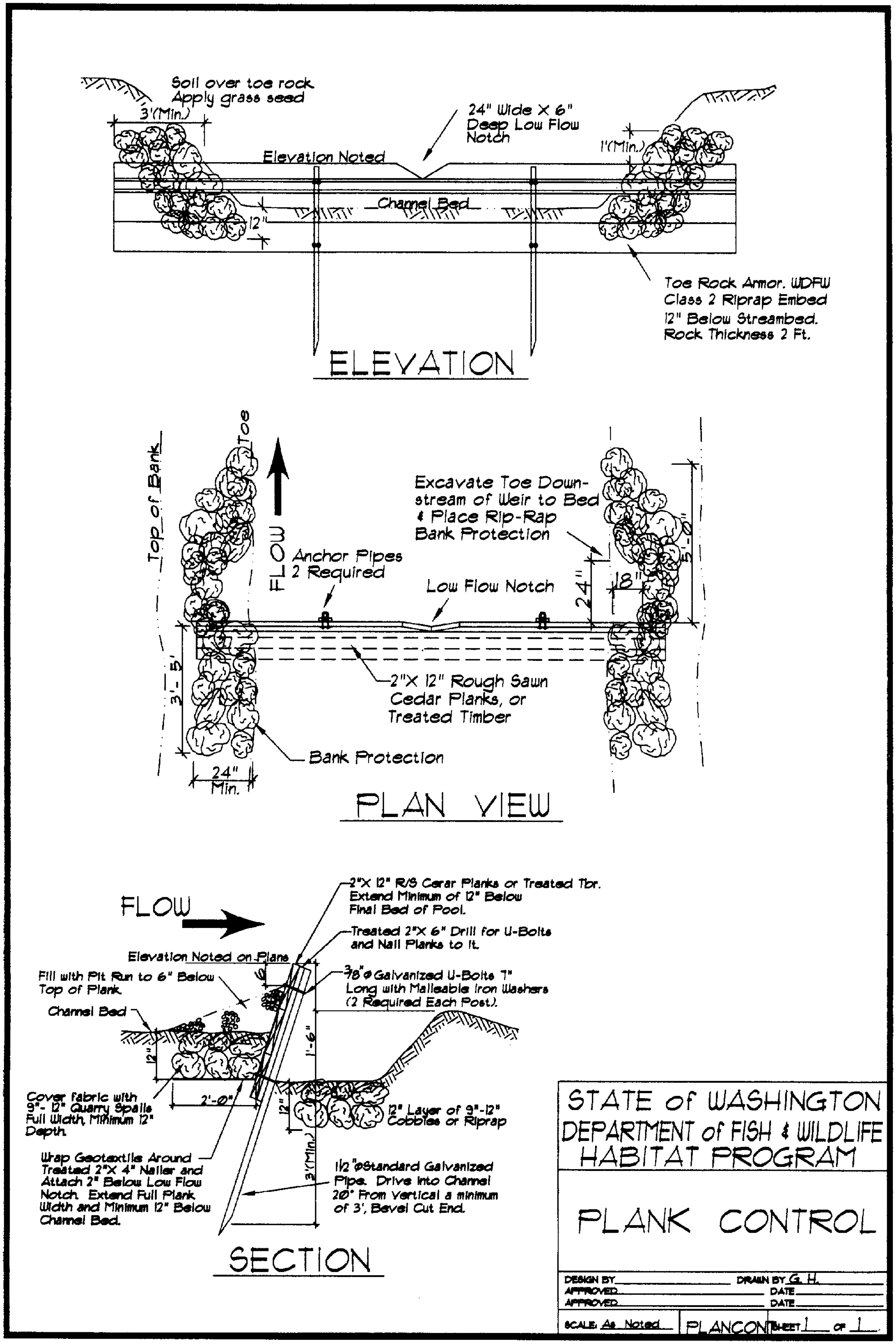
D = Diameter of Log in Feet

L = Length of Log in Feet.

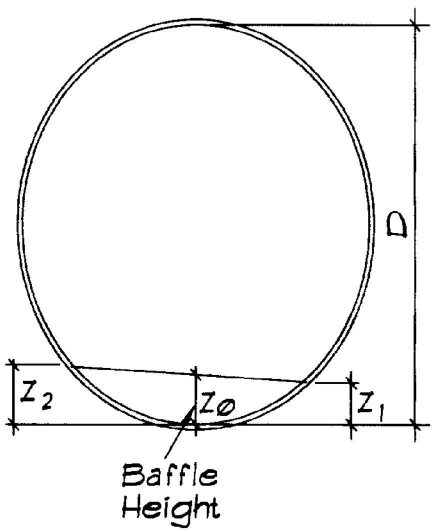
STATE of WASHINGTON
DEPARTMENT of FISH & WILDLIFE
LANDS & RESTORATION SERVICES PROGRAM

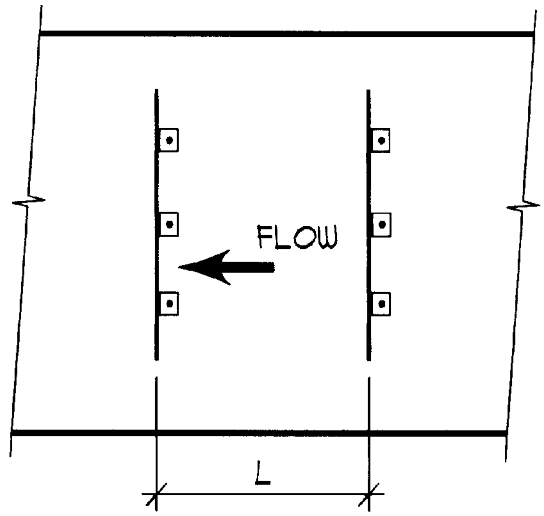
LOG CONTROL

DESIGN BY ________ DRAWN BY G. H.
APPROVED ________ DATE ________
APPROVED ________ DATE ________
SCALE: As Noted | 8X11LOG | SHEET 2 OF 2



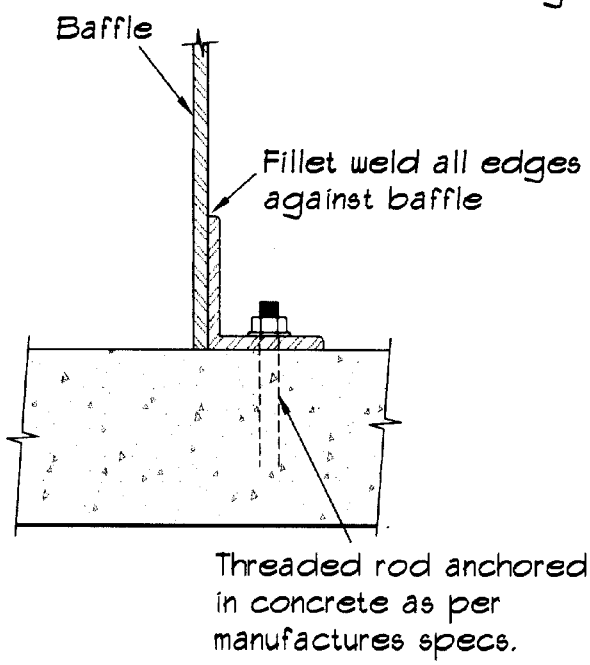
Soil over toe rock
Apply grass seed
3'(Min.)
24" Wide X 6" Deep Low Flow Notch
1'(Min.)
Elevation Noted
Channel Bed
12"
Toe Rock Armor. WDFW Class 2 Riprap Embed 12" Below Streambed. Rock Thickness 2 Ft.
ELEVATION
Top of Bank
Toe
FLOW
Excavate Toe Down-stream of Weir to Bed & Place Rip-Rap Bank Protection
Anchor Pipes 2 Required
Low Flow Notch
24"
18"
3'-5'
2"X 12" Rough Sawn Cedar Planks, or Treated Timber
Bank Protection
24" Min.
PLAN VIEW
FLOW
2"X 12" R/S Cerar Planks or Treated Tbr. Extend Minimum of 12" Below Final Bed of Pool.
Treated 2"X 6" Drill for U-Bolts and Nail Planks to It.
Elevation Noted on Plans
Fill with Pit Run to 6" Below Top of Plank
3/8"ø Galvanized U-Bolts 7" Long with Malleable Iron Washers (2 Required Each Post).
Channel Bed
12"
1'-6"
2'-0"
Cover fabric with 9"- 12" Quarry Spalls Full Width, Minimum 12" Depth
12" Layer of 9"-12" Cobbles or Riprap
Wrap Geotextile Around Treated 2"X 4" Nailer and Attach 2" Below Low Flow Notch. Extend Full Plank Width and Minimum 12" Below Channel Bed.
3'(Min.)
1½"ø Standard Galvanized Pipe. Drive into Channel 20° From Vertical a minimum of 3', Bevel Cut End.
SECTION
STATE of WASHINGTON
DEPARTMENT of FISH & WILDLIFE
HABITAT PROGRAM
PLANK CONTROL
DESIGN BY
DRAWN BY G. H.
APPROVED
DATE
APPROVED
DATE
SCALE As Noted
PLANCONT
SHEET 1 OF 1





NOTE:

Attachment method shown is for concrete pipes. For corrugated pipes use expansion ring as shown in seperate detail. Expansion rings may be used in pipe arches.

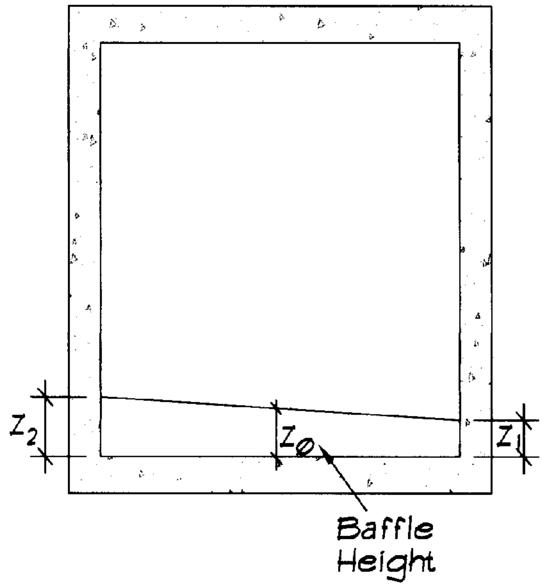


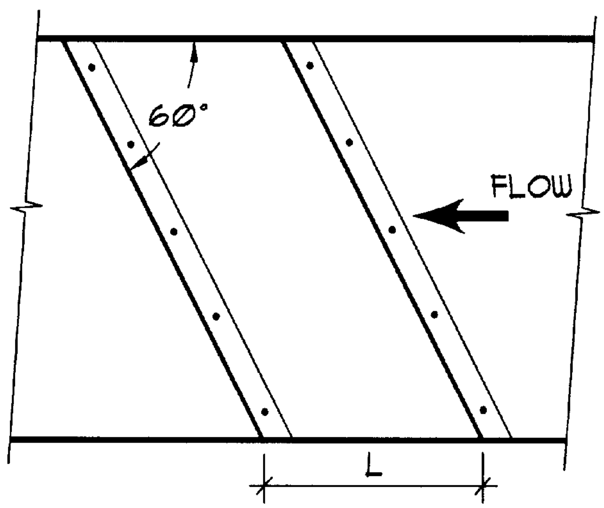
BAFFLE HEIGHT Zø	Z_1	Z_2
6"	3"	9"
9"	6"	12"
12"	9"	15"

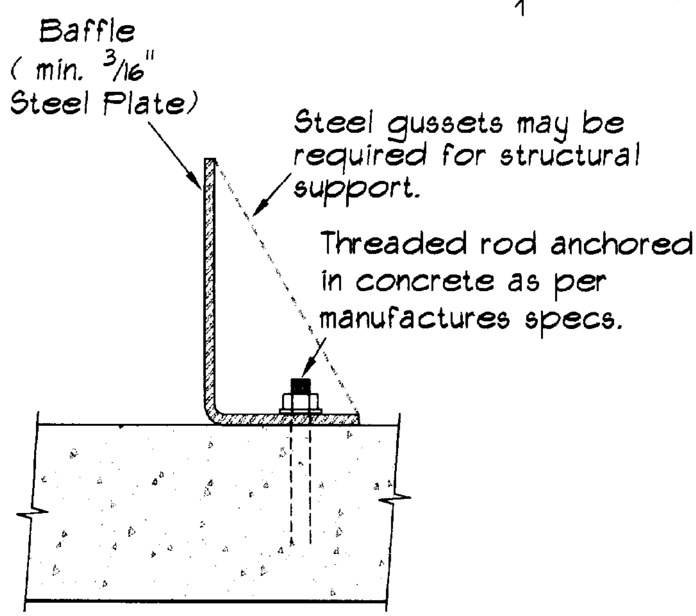
STATE of WASHINGTON
DEPARTMENT of FISH & WILDLIFE
ENVIRONMENTAL ENGINEERING SERVICES

SLOPING BAFFLE
CIRCULAR CULVERTS

DESIGN BY P. Powers DRAWN BY G. H.
REVIEWED BY DATE 09/98
APPROVED DATE
SCALE: As Noted | S-BAFFLE | SHEET 1 OF 1







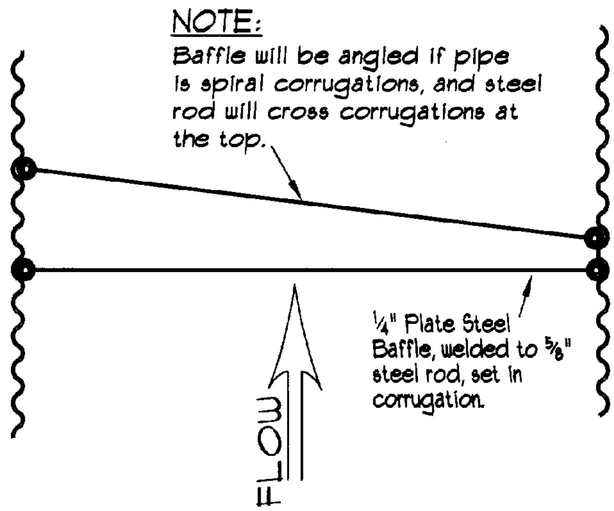
STEEL BAFFLE SECTION

BAFFLE HEIGHT $Z_\emptyset$	Z_1	Z_2
6"	3"	9"
9"	6"	12"
12"	9"	15"

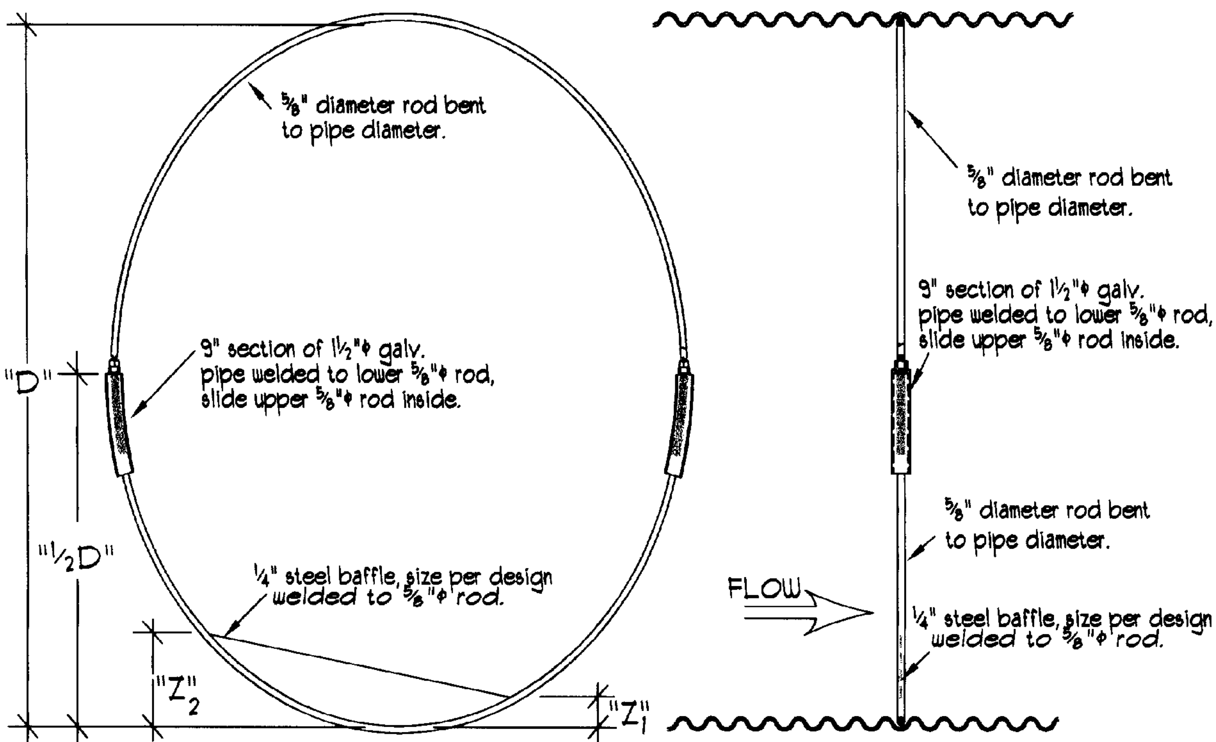
STATE of WASHINGTON
DEPARTMENT of FISH & WILDLIFE
ENVIRONMENTAL ENGINEERING SERVICES

SLOPING / ANGLED BAFFLES
BOX CULVERTS

DESIGN BY P. Powers DRAWN BY G. H.
REVIEWED BY DATE 09/98
APPROVED DATE
SCALE: As Noted SABAFFLE SHEET 1 OF 1



PLAN VIEW



SECTION

ELEVATION

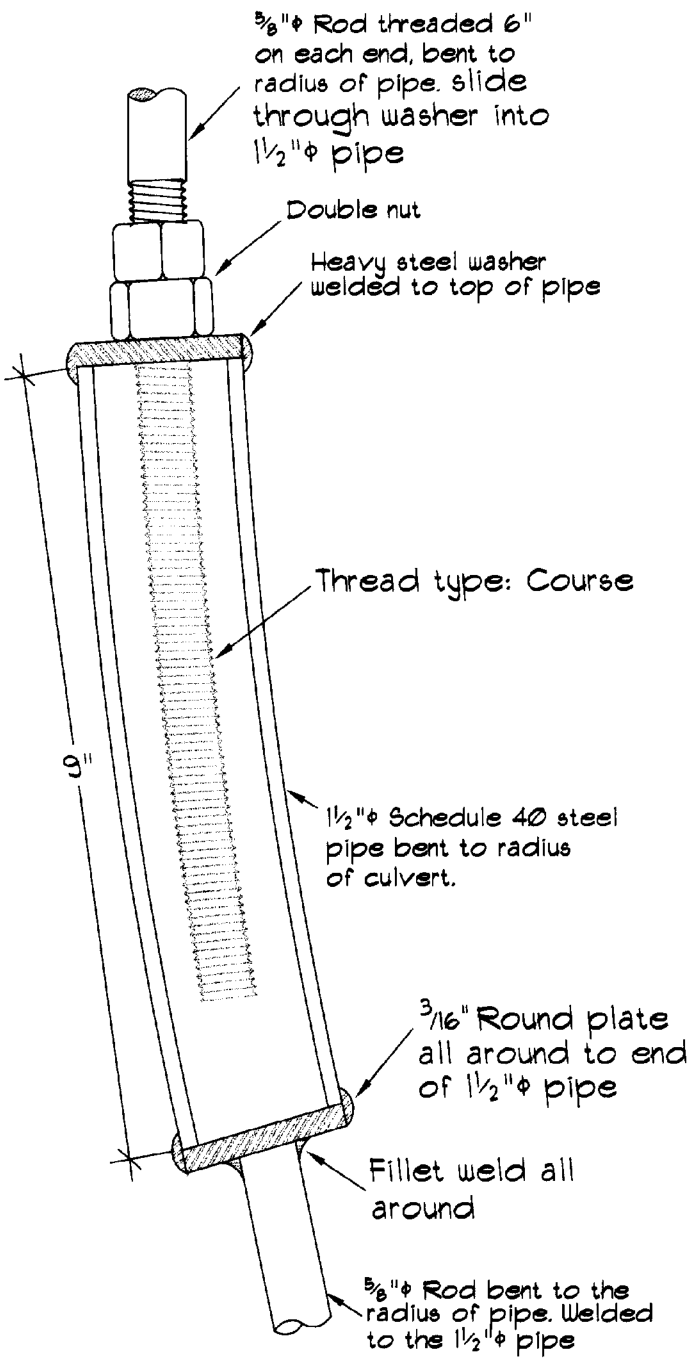
NOTE:

1. All steel to be galvanized after fabrication.
2. Due to possable deformation in corrugated metal pipes the actual shape of each baffle will need to be cofirmed in the field prior to fabrication.

STATE of WASHINGTON
DEPARTMENT of FISH & WILDLIFE
ENVIRONMENTAL ENGINEERING SERVICES

SLOPING BAFFLE
EXPANSION RING

DESIGN BY K. Bates DRAWN BY G. H.
REVIEWED BY ____ DATE 09/98
APPROVED ____ DATE ____
SCALE: As Noted | EXPRING | SHEET 1 OF 2



PIPE CONNECTION

EXPANSION RING
CULVERT BAFFLE

STATE of WASHINGTON DEPARTMENT of FISH & WILDLIFE ENVIRONMENTAL ENGINEERING SERVICES		
SLOPING BAFFLE EXPANSION RING		
DESIGN BY K. Bates	DRAWN BY G. H.	
REVIEWED BY	DATE 09/98	
APPROVED	DATE	
SCALE: As Noted	EXPRING	SHEET 2 OF 2