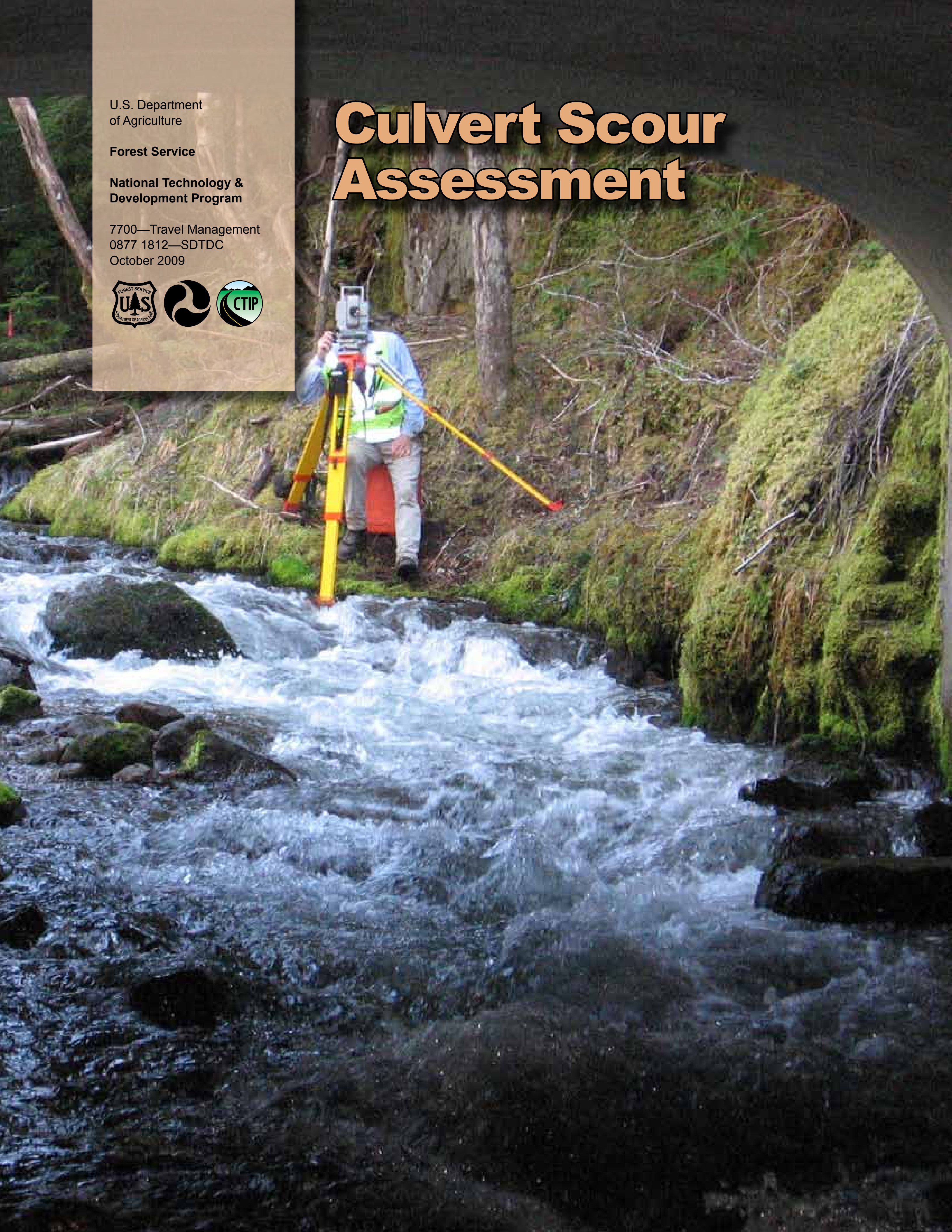

Culvert Scour Assessment

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Culvert Scour Assessment

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1 INTRODUCTION

The purpose of this study is to quantitatively analyze (1) the geomorphic and structure controls on channel-bed and footing scour at road-stream crossings, and (2) the effectiveness of aquatic organism passage (AOP) at these crossings by comparing channel characteristics within the crossing structure to reference channel conditions not influenced by the structure. From this analysis, one can determine the design, construction, stream, and channel conditions that contributed to the success or failure of the installation for AOP and scour resistance.

Background information

Embedded or open-bottom culverts that are designed to mimic natural channel form and function have been used for years at road-stream crossings (McKinnon and Hnytka 1985). Such designs are intended to provide geomorphic continuity through the stream crossing such that the passage of water, sediment, debris, and aquatic organisms occur in a similar fashion to conditions in the adjacent stream channel. This technique is often applied on streams where traditional hydraulic criteria for fish passage cannot be met, such as on mountain streams that often exceed the maximum velocities that are required for fish passage.

Guidelines for stream-simulation design typically include criteria for culvert width, slope, and bed material, but may also include other considerations (Bates et al. 2003, Oregon Department of Fish and Wildlife 2004). Guidelines developed by the Forest Service, U.S. Department of Agriculture, include detailed site assessment and design considerations that relate to channel geomorphology, project alignment, longitudinal profile, reference reach conditions, bed material size and arrangement, structure size and elevation, and stability of the streambed inside the structure (Forest Service Stream-Simulation Working Group 2008).

This study was designed to evaluate past culvert installations to determine how they have adjusted to local flood history and how their modes of response relate to elements of culvert design. It was therefore necessary to include culverts that had been exposed to high flows; otherwise, measured parameters would only reflect constructed features/conditions and not flood-response conditions. This criteria, however, limited the study sites to older installations, most of which were not designed according to the more contemporary stream-simulation design standards described previously. Culvert widths in this study ranged from less than half of 1 bankfull width to greater than 1.1 bankfull width. Culvert slopes ranged from a slope of zero to over 1.7 times the streamslope. Within these ranges of culvert designs, differences can be seen in the modes of adjustment in response to flood events. These results provide insight into the design elements and site considerations that should be addressed during culvert-installation projects.

This study includes an evaluation of differences between individual culvert sites and channel conditions nearby but outside the crossing. Conditions are evaluated with respect to bed scour, flow geometry, hydraulics (velocity and incipient motion), channel complexity, and physical habitat. Causative factors are explored by relating observed and modeled conditions to culvert designs. General discussions are provided regarding the implications of study results to AOP. Management recommendations are provided that we hope will be useful to practitioners involved in culvert designs.

2 METHODS

2.1 Study area and site selection

An interdisciplinary team with expertise in hydraulic engineering, hydrology, fisheries biology, and fluvial geomorphology selected study sites in western Oregon. The team selected sites according to the following criteria:

- Focus on stream-simulation type culverts (may include round, pipe arch, bottomless arch, or box).
- Focus primarily on moderate-to-steep gradients (2 percent to 6 percent), as these are the most common applications that still have fish potential.
- Include a number of low-gradient (less than 2 percent) culverts, particularly if they have experienced significant above-bankfull flows, because such a scenario most likely results in compromised culvert conditions.
- Include a range of stream sizes and gradients (within the constraints specified above) so that results are applicable to the range of likely applications.
- Avoid culverts with internal structures (baffles or ladders) because these are not typical in stream-simulation design.
- Avoid culverts with other special circumstances that are not likely to be part of new designs (secondary pipes for conveying flood flows).
- Include well functioning as well as poorly functioning culverts in order to identify the design elements that favor good performance.
- Focus on older installations (greater than approximately 5 years old) that have experienced a range of high flows and sufficient channel-forming flow durations to make sure culverts have responded adequately to local hydrology. More recent installations can be utilized on a case-by-case basis if the hydrology has been suitable.
- Limit the spatial distribution of the culverts to ensure that adequate sample sizes can be obtained for each region.
- Select sites to represent a range of geomorphic channel types.
- Select sites that have appropriate representative channel conditions upstream and/or downstream of the culvert. Appropriate representative channels should represent similar gradients, planforms, and valley conditions that are present at the culvert crossing.

The team selected 17 sites that met these criteria. The sites range in location from the Coast Range to the east slope of the Cascades. Six sites are located in the Coast Range, nine sites are located in the western Cascades, and two sites are located east of the Cascade crest. A map of the culvert locations is included in figure 2.1-1. Additional details on culvert locations are included in the individual site evaluations in appendix A. Appendix A is contained on a CD inside the back cover of the publication.

The team selected representative channel reaches upstream and/or downstream of each culvert crossing. The criterion for selecting representative reaches was to select reaches close enough to the culvert to have similar valley and geomorphic characteristics (slope, confinement, bed material), but far enough to be outside of the influence of the existing or previous culverts. Within each culvert and representative reach, the team selected cross-section locations that represented characteristic hydraulic, geomorphic, habitat, and substrate conditions of the reach. These sections formed the basis for the hydraulic and bed-mobility analyses. For most sites, the interdisciplinary team identified representative reach boundaries and representative cross-section locations.

Figure 2.1-1. Location of the study sites.

2.2 Acquisition of background information

Where possible, the team obtained background information for culverts to determine design objectives, construction details, flood response history, and maintenance activities. These factors can help to evaluate culvert performance and explain analysis findings. Due to the age of many of the sites and attrition of agency personnel, most of the sites have very limited, if any, available background information. Forest Service personnel involved with the installations provided construction information for six of the culverts. Information was available for three other pipes that were analyzed as part of a 1987 study by the Western Federal Lands Highway Division (WFLHD) (Browning 1990). This study involved field assessment by Oregon Department of Fish and Wildlife (ODFW) fish biologists and hydraulic analysis by WFLHD staff to evaluate fish-passage conditions for a range of culvert installation types. The WFLHD study also includes an evaluation of an older culvert that was replaced by a newer culvert that is included in the present study. This evaluation gives insight into channel conditions that may have existed at the time of culvert installation.

2.3 Analysis framework

The team took measurements to compare conditions at the crossing (including the transition areas immediately upstream and downstream of the culvert) with conditions in the channel upstream and/or downstream of the crossing that are outside the influence of the culvert. They chose metrics that provided insight into the condition of the crossing with respect to scour and AOP. For each site, the team presents the comparison of metrics between the culvert and the channel in this context. They include a site evaluation for all the components of the site analysis for each of the 17 sites.

Comparison metrics included either those estimated from hydraulic modeling (referred to as predicted conditions) or those measured directly in the field (termed observed conditions). Hydraulic metrics included cross-sectional flow area, top width, wetted perimeter, hydraulic radius, maximum depth, flow width-to-depth ratio, velocity, and shear stress at a range of flows. Field-based measures included vertical thalweg sinuosity, depth distribution, cross-section complexity, residual depths, habitat units, large woody debris (LWD), and bed material distributions. The team conducted a bed mobility analysis at selected representative sites.

In order to generate valid comparisons between culverts and representative reaches, the entire longitudinal profile through the site was broken out into separate profile segments, with each segment exhibiting a unique gradient. Section 2.8.2 of this report includes the methods for this analysis. For the hydraulic (modeled) metrics, the team compared the range of values between culvert (and transition) segments and representative segments that exhibited similar gradient. Field-based vertical sinuosity and residual depth measures are presented for all delineated profile segments. For field-based cross-section measures, the team made comparisons between culvert and channel cross sections in similar unit types.

2.4 Culvert and site conditions

The team recorded culvert types and configurations, including corrugation pattern and size, mitering, presence of wingwalls, etc. They observed culvert structural conditions and:

- Documented settlement, leaking, or structural damage to the pipe, fill, or footings.
- Documented culvert corrosion, torn metal, and abrasion.

- Noted roadfill erosion or piping conditions.
- Noted, measured, and photographed footing exposure compared to total footing depth, although at many sites, it was difficult to determine total footing depth.
- Documented and photographed other relevant site conditions including:
    - Debris plugging in culverts and debris, stream, or culvert features that were creating scour.
    - Stream-channel incision related to existing or previous culverts.
    - Areas of significant erosion or sediment aggradation.
    - Construction-related changes to channel pattern or alignment.
    - Potential backwater effects at the crossing from downstream receiving streams.

2.5 Topographic survey

The interdisciplinary team used topographic surveys to obtain channel-geometry and culvert-dimension data that they used in the analysis. They conducted topographic surveys at study sites using a total-station survey instrument. They surveyed thalweg profiles through the culvert and upstream and downstream 20- to 30-channel widths, except for sites that emptied into a receiving water body at a shorter distance downstream of the outlet. The team surveyed thalweg profiles and water-surface profiles at the culvert for each representative reach.

The interdisciplinary team surveyed one to three representative cross sections in the culvert and in each representative reach, depending on site conditions and cross-sections identified for analysis. Additionally, the team surveyed two additional cross sections at the upstream and downstream boundaries of the representative segments. They also surveyed additional cross sections where necessary for hydraulic modeling based on breaks in slope, contraction and expansion, or change in flood-plain conditions. Cross-section surveys included surveys of bankfull boundaries using field indicators of bankfull conditions. In some cases, they surveyed vegetation-change boundaries to assist with identification of flood-plain roughness conditions for hydraulic modeling.

The team also surveyed and monumented:

- Culvert dimensions including footings, crowns, inverts, and sidewalls.
- Road and fillslope locations and dimensions.
- Topographic points, including any significant gradebreaks throughout the site.

Using a Sokkia SDR33 data collector, the team collected total station data at each of the 17 sites. Following the survey, they downloaded all survey data from the data collector onto a computer using Autodesk Land Desktop as .sdr files and converted them to fieldbook (.fbk) files. At this point, any survey errors the team noted (rod height or descriptor) were corrected in the field at the time of the survey. The team imported the corrected fieldbook files into computer-aided design drawings, converting survey data into x, y, z coordinates. Once in a drawing, the team evaluated each survey for coherence and exported it as a text file of coordinates and descriptions. Finally, they imported the text files into ArcMap, and each survey was converted into a shapefile to facilitate hydraulic modeling.

2.6 Pebble counts and bed-material analysis

Pebble-count data provides information on bed-material distributions that team members use for incipient motion analysis to understand bed-mobility thresholds. The team performed pebble counts at each representative cross section within the culvert and in each representative reach. They based the pebble-count methodology on the procedures identified by Wolman (1954) and sampled particles at random at even-spaced paces along the cross-section transect within the bankfull channel. They counted at least 100 particles at each pebble-count location. Then, using either a gravelometer or a ruler, they measured the intermediate axis of each particle.

Team members assigned particles to standard size classes based on the phi-unit scale (Bunte and Abt 2001) and plotted frequency distributions and cumulative frequency distributions for these size classes. They calculated percentiles (percent finer than) for the D_5, D_{16}, D_{50}, D_{84}, and D_{95} and used these values to calculate sorting and skewness coefficients that are used in comparisons between the culvert and the representative channel.

The sorting coefficient characterizes the dispersion of the particle sizes in the sample. A “well-sorted” distribution has a narrow range of particle sizes, whereas a “poorly sorted” distribution has a wide range of particle sizes. The following sorting coefficient, from Folk and Ward (1957), was applied (from Bunte and Abt 2001):

$$S = \frac{\phi_{84} - \phi_{16}}{4} + \frac{\phi_{95} - \phi_{5}}{6.6}$$

where S is the Folk and Ward (1957) sorting coefficient, ϕ_i is the phi-unit for the particle size at which $_i$th percent is finer than; $\phi = -\log_2(D_i)$, where D_i is the particle size in millimeters. Sorting coefficient values greater than 4 indicate a very poorly sorted bed, where there is a wide range of different particle sizes. Values less than 0.35 indicate a very well sorted bed, where particle sizes tend to be similar throughout the distribution.

The skewness coefficient characterizes the skewness of the particle size distribution. Streambed particle sizes typically follow asymmetrical (nonnormal) distributions, and the skewness coefficient represents their degree of deviation from normality. The following skewness coefficient, from Folk and Ward (1957) modified by Warren (1974), was applied (from Bunte and Abt 2001):

$$Sk = \frac{\phi_{84} - \phi_{50}}{\phi_{84} - \phi_{16}} - \frac{\phi_{50} - \phi_{5}}{\phi_{95} - \phi_{5}}$$

where Sk is the skewness coefficient. This equation assumes that the percentile values refer to the percent coarser cumulative frequency distribution. Because the percent finer values were used, the final skewness values were multiplied by -1 to obtain the correct sign. Skewness values range from -1 to 1. Positive skewness values represent skewness towards a tail of fine particles, which means large particles comprise the bulk of the sample. Negative values indicate that fine particles comprise the bulk of the sample.

2.7 Hydrology

The team estimated flows for a range of flood-recurrence intervals for each site using U.S. Geologic Survey (USGS) regional regression equations for western and eastern Oregon, as appropriate (Cooper 2005 and 2006). They used the Oregon Water Resources Department (OWRD) Web-based autodelineation program to calculate peak discharges (http://www.wrd.state.or.us). See appendix B (on enclosed CD) for the equations and parameters used in the regressions.

Team members calculated estimated flows for the following recurrence intervals: 2-year (Q_2), Q_5, Q_{10}, Q_{50}, and Q_{100}. They also calculated 25 percent of the Q_2 to obtain a lower flow value for analysis purposes and used these flow values in hydraulic modeling and throughout the analysis.

They made an estimate of bankfull flow using a combination of hydraulic modeling and field indicators of bankfull flow elevations. More information is provided in section 2.8.3.

2.8 Hydraulics

2.8.1 Hydraulic modeling

The team used the U.S. Army Corps of Engineers 1-dimensional HEC-RAS (version 3.1.3) hydraulic modeling program to estimate hydraulic conditions at a number of flow levels, and they conducted model simulations to predict water-surface elevations, cross-section parameters, velocities, and shear stress.

Geometry data. Incorporation of survey data into a hydraulic model requires the transformation of three-dimensional data (x, y, and z) data into two-dimensional data (x and y) along cross sections that are perpendicular to the stream. While data was collected along cross sections, deviations from a straight line may cause artificial widening of the cross section. In order to avoid this, the scientists exported three-dimensional (x, y, and z) coordinates from the ArcMap shapefiles and entered them into a worksheet that corrects for any deviations from a straight line, providing a two-dimensional cross section. ArcMap measured the downstream channel distance between each cross section, as well as the left and right over-bank downstream distance; the information was entered into the model. Cross-section interpolation created cross sections at no less than 10-foot intervals along the profile. Additional cross sections were interpolated where necessary to account for bedforms not fully captured in the survey.

Using ArcMap shapefiles to extract longitudinal thalweg profiles and water-surface profiles, the team entered the data into spreadsheets. They used the thalweg profile distances and elevations to locate cross sections in the model.

The team identified bank stations, or the location on either bank that defines the active channel width, based on three indicators: (1) an inflection point in the geometry of the channel, (2) a vegetation line, and (3) survey indicators of top of bank. They identified ineffective flow areas where water is present but did not add to the conveyance within a cross section (backwater areas). Additionally, they added levees where a low point in the cross section (generally an overflow channel in the flood plain) conveys flow in the model before water is able to overtop the bank and access the overflow channel. The levee prevents water from occupying the channel until the high point separating the channels is overtopped.

Steady flow data and boundary conditions. The HEC-RAS hydraulic model requires the assignment of boundary conditions at the downstream end (for subcritical flow conditions) and/or upstream end (for supercritical flow conditions) of each site. Four different options exist for defining these boundary conditions; a known water surface, critical depth, normal depth, or a rating curve. Lacking detailed discharge measurements at the time of the survey or a stage-discharge rating curve, normal or critical depth boundary conditions were used for all hydraulic models. The choice of boundary condition used for each site depended on site conditions, but was typically calculated using normal depth; critical depth was used in a few cases where critical-depth conditions were clearly present at the reach boundary. All sites used a mixed flow regime calculation.

Channel and flood-plain roughness. Team members calculated Manning's n for the channel using Jarrett's (1984) equation and used a first approximation (using field-derived values) for initial model runs. Hydraulic radius was output from the model for flows corresponding to bankfull flow (based on field indicators). They obtained a local energy grade slope using measured water surface measurements bounding the cross sections of interest and used the hydraulic radius and energy grade slope in Jarrett's equation to obtain Manning's n for each cross section. Jarrett's equation takes the following form:

$$n = 0.39S^{0.38} R^{-0.16}$$

where n is Manning's roughness coefficient, S is the friction slope (or water surface slope), and R is hydraulic radius (ft). Jarrett (1984) specifies that the equation is applicable to slopes from 0.002 – 0.04 and for hydraulic radii from 0.5 feet to 7 feet. All sites met these criteria except for the upper slope limit, which was exceeded in many cases. Hubbard (1997) (as cited in Barnard 2003) showed that Jarrett's equation performed well on slopes up to 0.08. Based on this information, they applied Jarrett's equation to slopes up to 0.08. For sections with greater slopes, they used the average of the most adjacent cross sections with slopes less than 0.08. They estimated flood-plain roughness values using the approach outlined in Arcement and Schneider (1987), except in cases where channel roughness (using Jarrett's equation) exceeded the estimate of flood-plain roughness, in which case the channel roughness was also applied to the flood plain.

Manning's roughness values predicted by the Jarrett (1984) equation were considerably greater than those typically used for modeling culverts and natural channels. The values predicted by the Jarrett (1984) equation ranged from 0.057 to 0.16. Although the values are large, they are within the range of measured values determined for high-gradient streams by Jarrett (1984). The values are also within the range of other studies that have measured roughness, including a study conducted in northern California by Lang et al. (2004), which recorded values as high as 0.061 for culverts with native streambed material and as high as 0.448 for culverts with baffles.

Culvert modeling. Because of the size of the culverts and the presence of natural streambed material along the bed, team members modeled culverts using an open-channel routine with a lid placed over the channel to simulate the culvert dimensions. They obtained lid dimensions during the topographic survey and applied them to the model using the lid function in HEC-RAS. They modeled Lowe Creek without a lid because of irregular culvert geometry; modeled flows do not exceed the culvert height, so little effect on model results would be expected. The lid function has limitations for modeling culverts as it does not address pressure flow, which possibly occurs for a couple of sites at the highest flows. Using the lid function also means that some values are not reported in the model for high flows that fill the culvert. Values not reported include top width and hydraulic depth. These values were therefore not included in the analysis for the affected cross sections and flows.

Team members determined Manning's n values for culvert walls based on the guidance provided in the HEC-RAS hydraulic reference manual. The range of Manning's n for each site can be found in the individual site evaluations in appendix A. Vertical variation in n was applied to the culvert cross sections by weighting n based on the proportion of wetted perimeter comprised of culvert bed versus culvert walls. In some cases, interpolated sections within the culvert use a composite (average) n as opposed to vertical variation. Sample runs using average n versus vertical variation showed little difference in the results. They determined ineffective flow areas at the culvert inlet and outlet and culvert contraction and expansion coefficients using the guidance provided in the HEC-RAS manual.

Model uncertainty. The HEC-RAS model is a one-dimensional step-backwater model, which uses the energy equation to determine water-surface elevations through a series of cross sections. When using the steady-flow program, as this study exclusively does, it does so under the assumption that flow is (1) steady, (2) gradually varied, and (3) one-dimensional, and that the slope is "small," which is cited as less than 10-percent slope. For natural stream channels, the degree to which these assumptions become less valid increases with channel-bed slope. Large substrate, steep riffles, and steps result in greater turbulence, spatially diverse hydraulic conditions, and areas of rapidly varied flow. Local drops due to steps or steep riffles create short sections with bed slopes that far exceed the 10-percent stated model limit. In these cases the model typically is not able to satisfactorily balance the energy equation, and it returns critical depth as the solution, which indicates there may be considerable uncertainty with the hydraulic calculations. In general, one can assume that the steeper, more complex channels have a greater degree of uncertainty than the lower gradient, more uniform channels. Although model uncertainty was not explicitly quantified in this study, uncertainty was addressed by considering multiple sources of information at each site, including modeled/predicted data, measured data, and qualitative site observations.

2.8.2 Longitudinal profile analysis

In order to generate valid comparisons between culverts and representative reaches, the entire longitudinal profile through the site was broken out into separate profile segments, with each segment exhibiting a unique gradient. The technique generally followed Forest Service guidelines (unpublished). The first step was the identification of hydraulic controls along the channel thalweg profile. The slope of each segment between each hydraulic control was then calculated and adjacent segments with similar slopes (within 20 percent) were combined. In some cases, adjacent slope segments with similar gradients were not combined in order to achieve separate segments for areas of interest to the analysis, including within culverts, and in the inlet and outlet transition areas. Those areas thought to be transition areas were immediately upstream and downstream of the culvert within the area of expansion or contraction of flow, or in areas where other significant culvert effects took place (culvert-related incision or aggradation).

The profile segments formed the basis of comparisons of hydraulic (modeled) variables between the crossing and the representative channel. Only segments in the representative channel with a similar gradient (within 20 percent) were identified as comparable to the culvert or transition segments. In some cases, the 20-percent criterion was relaxed if other observations or data suggested that the segments were reasonably comparable. Segments were not used for comparisons if no measured cross sections were present in the segment. The rationale for identifying comparable segments is discussed in the profile analysis segment summary that is included in each site writeup.

2.8.3 Analysis of hydraulic variables

Peak discharges determined during hydrologic analysis were input into the model. These included the 25-percent Q_2, Q_2, Q_5, Q_{10}, Q_{50}, and Q_{100}. An estimate of bankfull flow (Q_{bf}) was also determined by varying the discharge in the model until the water surface profile best matched the elevation of the field-identified bankfull indicators. In some cases, it was not possible to select a discharge that matched the field-identified bankfull elevations at all of the cross sections. For these cases, the discharge was matched to cross-section bankfull elevations for which the investigators had the greatest confidence.

A number of hydraulic variables were exported from the HEC-RAS model and used in the analysis to compare conditions in the culvert and representative segments. These values included flow area, top width, wetted perimeter, hydraulic radius, maximum depth, channel velocity, and channel shear. These metrics are compared for the following range of flows: 25-percent Q_2, Q_{bf}, Q_5, Q_{10}, Q_{50}, and Q_{100}. For most sites, the Q_2 was not used because of the similarity with the Q_{bf}; however, at Upper and Lower Eightmile Creek, the Q_{bf} was closer to the 25-percent Q_2, and so the following flows were used at those sites: Q_{bf}, Q_2, Q_5, Q_{10}, Q_{50}, and Q_{100}.

Because of the important influence of channel gradient on channel processes and response, hydraulic variables were only compared between culvert (and transition) segments and representative channel segments with similar gradient. The range of values within comparable profile segments is presented in box plots in each site evaluation.

2.8.4 Particle entrainment analysis

Team members performed analyses of particle entrainment (incipient motion) in order to compare the bed-mobilization threshold of the channel with that of the culvert. Culverts performing well as stream-simulation designs would be expected to have bed material that is mobilized at similar flows that mobilize the bed in the natural channel.

They analyzed bed entrainment by comparing the shear stress exerted by the flow to the critical shear stress needed to mobilize bed sediments. If channel shear stress exceeds critical shear stress for a given particle size, then that particle is assumed to be mobile. Mobility of the D_{84} particle size was assumed to represent the threshold at which the bed is mobilized for these channels, which are mostly comprised of step-pool systems. This is based on the concept that the larger, grade controlling particles that make up steps and cascades govern bed mobility and channel form in step-pool streams (only once these particles become mobile does significant bed reshaping occur) (Grant et al. 1990, Chin 1998). The use of the D_{50} particle size may be more appropriate for the few pool-riffle streams in the study, but the D_{84} was applied to these streams to maintain consistency.

The team used the critical shear stress approach for bed-entrainment calculations. It is acknowledged that this method may not be the most appropriate for the steeper streams in the study due to the difficulty in accurately capturing the variability in channel conditions and due to the moderating effects of form resistance (from spill-over steps and LWD) on the shear stress that is available to mobilize particles (Bathurst 1987, Wilcox et al. 2006, Yager et al. 2007). However, in order to maintain a consistent approach at each site, and based on early experimentation with other methods (Costa 1983 and Bathurst 1987) that provided widely variable entrainment flows, they selected the critical shear stress approach for this analysis.

The selection of appropriate Shields parameters can introduce considerable uncertainty in determining entrainment thresholds. Shields parameters in gravel-bed rivers typically range from 0.03 to 0.086 (Buffington and Montgomery 1997), but in steep mountain rivers may be as high as 0.1 (Lenzi et al. 2006). The use of higher values may be appropriate in some cases as it better represents the increased stability of the bed due to particle interlocking and protection provided by the accumulations of large particles (steps) that form in coarse-grained beds (Church et al. 1998). However, in well-graded beds, which often characterize step-pool systems, larger particles may be entrained at lower flow thresholds because of their protrusion above smaller neighboring particles, which increases their exposure to flow and reduces their pivoting angles (Komar and Li 1986).

In order to take into account the potential effect of particle exposure, team members determined critical shear stress through methods that modify the Shields parameter according to the size difference between the D_{50} and the particle size of interest (in our case, the D_{84}). Based on the methods of Komar (1987), they used following equation for critical shear stress:

$$\tau_{ci} = 102.6\, \tau^*_{D50}\, D_i^{0.3}\, D_{50}^{0.7}$$

where τ_{ci} is the critical shear stress (lb/ft^2) at which the D_i particle size is mobile, τ^*_{D50} is the Shields parameter for the D_{50} particle size, D_i is the particle size of interest (feet), and D_{50} is the median particle size (feet). Instead of using the typical 0.045 for τ^*_{D50}, values were obtained from Julien (1995), which vary according to the particle size of interest. The range of critical shear stress values for each site can be found in the individual site evaluations in appendix A.

The team members performed incipient motion analysis at representative cross-section/pebble-count locations and were limited to those cross sections not representing pool units. They excluded pools because grain sizes and hydraulics are variable and do not necessarily represent the principal bed movement dynamics of the reach. In order to further limit the impact of variability of shear stress between cross sections, shear stress was taken as the average of two or more cross sections surrounding the pebble-count location, with the criteria that cross sections had to be within the same channel unit. In most cases, this included the surveyed cross section and the two adjacent interpolated sections.

2.9 Channel complexity and depth distribution

Channel complexity is important for aquatic habitat and passage conditions. Team members evaluated complexity at cross sections and along longitudinal profiles. Profile complexity was assessed by looking at thalweg vertical sinuosity and residual depths. They analyzed cross-section complexity by using the sum of squared height difference method and by conducting a depth-distribution analysis. These methods are discussed below.

Vertical sinuosity and residual depth. They evaluated profile complexity using vertical sinuosity, also known as the chain-and-tape method (Bartley and Rutherford 2005), which is the length of the topographic bed distance divided by the reach distance. This metric reveals how sinuous the bed is in the vertical plane. Uniform, plane-bed reaches will have very low vertical sinuosity, whereas complex step-pool channels will have high vertical sinuosity. Team members calculated vertical sinuosity for each of the longitudinal profile segments.

The team also assessed profile complexity through a comparison of residual depths between longitudinal profile segments. Residual depth is defined as the difference in elevation between the maximum pool depth and the elevation of the downstream hydraulic control.

Cross-section complexity – sum of squared height difference. The team evaluated cross-section complexity by calculating the sum of squared height differences ($\sum dh^2$) along cross sections (Bartley and Rutherford 2005). This metric reflects the degree of variation of the channel bed. Height differences were calculated between each successive surveyed point along the section, squared, and the results summed. In order to remove the potentially spurious effect of channel banks, this analysis was performed only for the channel bed (left toe of bank to right toe of bank).

Depth distribution. In recognition of the value of shallow water habitats, Barnard (2003) developed a method to quantify the amount of shallow-edge habitat that is available in culverts compared to corresponding natural channels. The team performed this “depth-distribution” analysis for this study, generally following the procedures described by Barnard (2003). Depth distribution is calculated as the amount of the cross section that has flow depths less than 0.3 feet. Depth distribution was calculated by interpolating points along the cross section at 0.5-foot increments and calculating depth for each point. The number of points with depths less than 0.3 feet was summed.

The team conducted this analysis for the 25-percent Q_2 flow. For most streams, the 25-percent Q_2 is likely to represent a flow that is meaningful for fish passage. In their study of fish passage at culvert sites in northern California, Lang et al. (2004) found that juvenile salmonids (3 inches to 8 inches fork length) typically tried to pass upstream through culverts between the 8 percent and 26 percent annual exceedance flows (an 8-percent annual exceedance flow is the flow that is exceeded only 8 percent of the time, on average, over the course of a year). For adult anadromous salmon, nearly 60 percent of fish attempted to pass at flows greater than or equal to the 5-percent annual exceedance flow. As a reference, the 25-percent Q_2 flow for the Middle Fork Willamette River near Oakridge, Oregon, (USGS #14144800, nearest long-term gauging station near the upper Willamette River sites) is approximately equivalent to the 5-percent annual exceedance flow.

2.10 Channel units and LWD

Team members performed a channel-unit (or habitat-unit) survey for the culvert and for the natural channel outside the crossing. They identified unit boundaries during the survey of the longitudinal thalweg profile and they were amended in some cases after review of profile characteristics; for instance, after review of residual-depth measurements. Unit types were limited to pools, riffles, steps, and glides. They identified:

- Pools if there was significant residual depth and backwatered conditions from a hydraulic control.

- Riffles for rapid and steeper flow with surface turbulence.
- Steps if there was an abrupt drop or sequence of abrupt drops ending in hydraulic jumps.
- Glides for areas of rapid flow with moderate slopes, little surface turbulence, and no residual depth.

They calculated percent composition by channel unit in order to compare conditions between the culvert and the natural channel.

They counted LWD in each of the study segments. LWD counts followed the Washington timber, fish, and wildlife protocols (Schuett-Hames et al. 1999). Minimum size to qualify as LWD is 10-centimeter diameter over 2 meters of length. They compared wood counts between the culvert and the natural channel and used this data to help explain analysis results.

2.11 Photo documentation

Photos taken at the crossing and throughout the channel outside the crossing documented site conditions and were used by team members as a reference for the assessment. The photos also will be useful for any future assessments of change at the sites. They took photos looking upstream and downstream from the upstream and downstream boundaries of each representative channel segment and the culvert segment. They photographed each representative cross-section/pebble-count location from one or more angles and took other shots to show representative conditions in the natural channel and the culvert.

They took photos of the culvert inlet and outlet as well as from atop the culvert inlet (looking upstream) and atop the culvert outlet (looking downstream). They took close-up photos of footing conditions if scour conditions were present. They photographed other notable conditions throughout the site, as appropriate, to document site conditions that may have relevance to the assessment.

3 RESULTS

3.1 Culvert and representative channel segment conditions

A summary of basic site conditions is included in table 3.1-1. Sites consist of 4 pool-riffle channels and 13 step-pool systems. Stream bankfull widths range from 7 feet to 31 feet. There are 14 open-bottom arch culverts, two embedded pipe-arch culverts, and one embedded round culvert. All culverts are corrugated metal pipe except for one site, Little Zigzag, which is a Con/Span® precast modular concrete culvert. Six of the installations date back to the 1980s or earlier. Four sites were constructed in the 1990s, and the remaining seven sites are year 2000 to 2003 installations.

Each of the 17 sites had 1 or 2 representative channel reaches that were surveyed upstream or downstream of the crossing. A summary of reach conditions, including the number of representative cross-section/pebble-count locations in each reach, is included in table 3.1-2. One site, Pine Creek, had two representative channel reaches upstream of the crossing. In some cases, they chose representative reaches a considerable distance away from the crossing in order to get beyond culvert-related channel incision or to avoid areas where significant human alteration (instream structures) was present. For a couple of sites, hydraulic analysis performed following the survey showed that the upstream representative reach was not entirely free from culvert backwater impacts for some of the modeled flood stages. These instances are discussed in the individual site evaluations. One site in particular, Eames Creek, had backwater effects that impacted the

Table 3.1-1. *Summary of study sites and culvert characteristics.*

Stream	County	Region	Location	Culvert Type	Year Installed	Culvert Gradient[1]	Stream gradient[2]	Span (max width)	Rise (max)	Culvert Length (ft)	Bankful width[3] (ft)	Channel Type
Velvet Creek	Lane	Coast range	Siuslaw NF Rd 32	Open-bottom arch	1981	1.6%	1.3%	16	8	92.5	24.0	pool-riffle
Deadwood Trib North	Lane	Coast range	Deadwood Rd	Open-bottom arch	2000	6.2%	5.9%	8	7.3	56	15.8	step-pool
Deadwood Trib South	Lane	Coast range	Deadwood Rd	Round	2000	12.6%	9.3%	7.5	7.1	63	6.6	step-pool
Buck Creek	Lane	Coast range	Deadwood Rd	Open-bottom arch	2003	0.1%	1.4%	17	12.7	60	19.9	pool-riffle
Falls Creek	Lane	Cascades, south Willamette Valley	Fall Cr Rd west of Eugene	Open-bottom arch	~1999	3.0%	3.6%	19	9.8	80	21.2	step-pool
Hehe Creek	Lane	Cascades, south Willamette Valley	Willamette NF Rd 1831	Open-bottom arch	~1986	4.5%	4.7%	17	11.3	60	19.5	step-pool
Eames Creek	Lane	Coast range	Wolf Creek Trib (~0.6 hr SW of Eugene)	Open-bottom arch	pre-1987	0.03%	0.83%	13	8.2	55	31.0	pool-riffle
Haight Creek	Lane	Coast range	Upper Siuslaw RiverTrib (SW of Eugene)	Open-bottom arch	pre-1987	0.5%	0.8%	19	10	62	18.9	pool-riffle
Pine Creek	Lane	Cascades, south Willamette Valley	Willamette NF Rd 21 (MF Will)	Pipe arch	~1999	5.0%	6.2%	13.5	7	60	13.1	step-pool
Youngs Creek	Lane	Cascades, south Willamette Valley	Willamette NF Rd 21 (MF Will)	Pipe arch	~2002	6.7%	6.4%	14	9	62	13.7	step-pool
Simpson Creek	Lane	Cascades, south Willamette Valley (MF Will)	Willamette NF Rd 21 MP 21.1	Open-bottom arch	1995	8.3%	5.2%	22	13	114	24.8	step-pool
Tire Creek	Lane	Cacades, south Willamette Valley (MF Will)	Willamette NF Rd 5826 MP 2.63	Open-bottom arch	1996	9.4%	5.2%	17	11.8	62	22.0	step-pool
Cool Creek	Clackamas	Cascades, north Willamette Valley (FR 2612)	2.5 Mi off US 26 on Still Ck Rd	Open-bottom arch	1984	2.2%	5.2%	13	6.7	48	19.6	step-pool
Little Zigzag Creek	Clackamas	Cascades, north Willamette Valley	Mt. Hood NF Rd 2639 MP 1.4	Open-bottom arch (concrete)	2000	4.5%	4.2%	15.5	8.7	133	14.2	step-pool
Lowe Creek	Clackamas	Cascades, north Willamette Valley	Mt. Hood NF Rd 4671	Open-bottom arch	pre-1987	5.0%	4.5%	19	15.5	70	23.6	step-pool
Upper Eightmile Creek	Wasco	Cascades, east of Mt. Hood	Mt. Hood NF Rd 4430 150 spur	Open-bottom arch	2000	4.7%	4.2%	12	6.2	42	20.5	step-pool
Lower Eightmile Creek	Wasco	Cascades, east of Mt. Hood	Mt. Hood NF Rd 4440	Open-bottom arch	2000	2.4%	3.7%	12	7.4	56	16.5	step-pool

[1] *Slope of pipe structure.*

[2] *Longitudinal thalweg profile extending up to 20- to 30-channel widths up and downstream of crossing.*

[3] *Bankful width of channel determined through field indicators and cross-section geometry.*

Table 3.1-2. Summary of representative reaches and numbers of representative pebble counts taken in each reach.

Stream	Upstream Representative Reach			Downstream Representative Reach		
	Length	Slope[1] (ft)	No. of Pebble Counts[3]	Length (ft)	Slope (ft/ft)[1]	No. of Pebble Counts[3]
Velvet Creek	200	1.5%	2			
Deadwood Trib North	140	4.8%	3			
Deadwood Trib South	145	10.6%	3			
Buck Creek	394	1.0%	3	208	1.0%	2
Falls Creek	158	3.9%	2			
Hehe Creek	123	4.8%	2	122	4.3%	2
Eames Creek	180	0.7%	2			
Haight Creek	165	1.1%	2			
Pine Creek[2]	98	3.1%	2	67	8.0%	2
Youngs Creek	135	6.2%	2	80	4.4%	1
Simpson Creek	126	6.5%	2	150	4.5%	2
Tire Creek				115	4.8%	2
Cool Creek	128	4.0%	2			
Little Zigzag Creek	118	3.6%	2			
Lowe Creek	110	5.8%	2	95	4.0%	2
Upper Eightmile Creek	125	2.5%	2			
Lower Eightmile Creek	150	3.7%	2	105	1.8%	2

[1] Obtained from water surface profile from survey.

[2] Both representative segments in Pine Creek are upstream of the culvert.

[3] Also corresponds to number of representative cross sections used for critical shear stress, cross-section complexity, and depth distribution analysis.

entire upstream representative reach for nearly all modeled flow levels.

The relationship of culvert width and slope to the channel width and slope is an important factor in stream-simulation culverts, as these are often included in design criteria. Table 3.1-3 displays these relationships for each of the 17 sites. Five culverts have widths that equal or exceed the bankfull width of the natural channel. Two culverts, Deadwood Tributary North and Eames Creek, have widths that are half that of the bankfull channel or less.

3.2 Hydrology

Discharges for the 0.25 Q_2, Q_2, Q_5, Q_{10}, Q_{25}, Q_{50}, and Q_{100} for each site are included in table 3.2-1. Discharges were calculated differently depending on the location and elevation of the site. Detailed hydrologic analysis results are included in the OWRD autodelineation reports in appendix B. Estimates of bankfull flow were calculated by matching HEC-RAS water surface profiles with field-identified bankfull indicators. The bankfull-flow estimates are included in the site evaluations in appendix A.

3.3 Site evaluations

The focus of this study was at the individual-site scale. Site evaluations in appendix A include site-scale results for the 17 sample sites.

The site evaluations in appendix A contain the following information for each site: (1) overview of culvert and site information, (2) site map, (3) history of the site (if known), (4) site description, (5) survey summary, (6) profile analysis segment summary, (7) scour conditions, (8) AOP conditions, and (9) design considerations. Analysis results appear as graphs, tables, and other figures and include longitudinal-profile plots, cross-section plots, HEC-RAS output data, box plots of hydraulics results, tables of complexity and habitat measures, bed-material distributions, and site photos.

The scour and AOP sections summarize and interpret the analysis results with respect to the performance of the structure for scour resistance and AOP. These sections contain the following subsections for presentation of results.

Scour Conditions	**Observed conditions (measured)**
	Footing scour
	Culvert bed adjustment
	Profile characteristics
	Residual depths
	Substrate
	Predicted conditions (modeled)
	Cross-section characteristics
	Shear stress
	Excess shear stress
	Velocity
AOP Conditions	Cross-section complexity
	Profile complexity
	Depth distribution
	Habitat units
	Residual depths
	Substrate/bed material
	Large woody debris

The following sections contain a brief summary of conditions among all sites.

Table 3.1-3. Culvert width and slope ratios.

Site	Bankfull Width (ft)[1]	Culvert Span	Width Ratio (culvert/ BFW)	Culvert Bed Slope	Long Profile Slope[2]	Culvert Slope[3]	Ratio (culvert slope/long profile slope)	Ratio (culvert bed slope/long profile slope)	Ratio (culvert slope/ culvert bed slope)
Velvet Creek	24.0	16	0.7	1.1%	1.3%	1.6%	1.2	0.8	1.5
Deadwood Trib North	15.8	8	0.5	6.3%	5.9%	6.2%	1.0	1.1	1.0
Deadwood Trib South	6.6	7.5	1.1	6.6%	9.3%	12.6%	1.4	0.7	1.9
Buck Creek	19.9	17	0.9	1.5%	1.4%	0.1%	0.1	1.1	0.1
Fall Creek	21.2	19	0.9	3.7%	3.6%	3.0%	0.8	1.0	0.8
Hehe Creek	19.5	17	0.9	4.1%	4.7%	4.5%	0.9	0.9	1.1
Eames Creek	31.0	13	0.4	0.8%	0.8%	0.0%	0.0	0.9	0.0
Haight Creek	18.9	19	1.0	0.1%	0.8%	0.5%	0.6	0.1	5.0
Pine Creek	13.1	13.5	1.0	3.8%	6.2%	5.0%	0.8	0.6	1.3
Youngs Creek	13.7	14	1.0	2.8%	6.4%	6.7%	1.1	0.4	2.4
Simpson Creek	24.8	22	0.9	4.4%	5.2%	8.3%	1.6	0.9	1.9
Tire Creek	22.0	17	0.8	3.3%	5.2%	9.4%	1.8	0.6	2.8
Cool Creek	19.6	13	0.7	1.5%	5.2%	2.2%	0.4	0.3	1.5
Little Zigzag Creek	14.2	15.5	1.1	3.9%	4.2%	4.5%	1.1	0.9	1.2
Lowe Creek	23.6	19	0.8	3.5%	4.5%	5.0%	1.1	0.8	1.4
Upper Eightmile Creek	20.5	12	0.6	3.1%	4.2%	4.7%	1.1	0.7	1.5
Lower Eightmile Creek	16.5	12	0.7	2.6%	3.7%	2.4%	0.6	0.7	0.9

[1] BFW of channel determined through field indicators, cross-section geometry, and hydraulic analysis.

[2] Longitudinal thalweg profile extending up to 20 channel widths up and downstream of crossing.

[3] Slope of pipe.

Table 3.2-1. Hydrology for each site obtained from USGS regional regression equations using OWRD autodelineation process. Hydrology reports for each site are included in appendix B.

Site	Basin Area (sq mi)	Q (cfs) for indicated return interval (year)						
		25% of 2-year	2	5	10	25	50	100
Velvet Creek	1.81	35	140	208	256	318	366	414
Eames Creek	5.53	78	311	486	613	785	919	1060
Haight Creek	3.76	41	165	242	295	365	418	471
Deadwood Trib North	0.43	10	40	58	70	86	99	111
Deadwood Trib South	0.21	5	18	26	32	40	46	52
Buck Creek	1.54	30	119	171	208	255	290	326
Hehe Creek	1.86	45	178	258	310	375	424	471
Pine Creek	1.91	15	58	91	113	142	165	188
Youngs Creek	2.92	21	85	135	170	215	250	286
Simpson Creek	11.30	65	258	407	511	646	751	858
Tire Creek	3.90	48	193	308	388	489	566	644
Cool Creek	1.70	21	83	134	172	222	262	302
Little Zigzag Creek	4.08	30	118	168	204	253	292	333
Lowe Creek	5.99	35	141	227	292	380	448	520
Fall Creek	3.55	67	269	401	491	604	689	774
Upper Eightmile Creek	4.09	43	171	237	285	353	406	460
Lower Eightmile Creek	4.78	43	171	236	287	360	418	478

3.4 Overview of scour conditions

Site evaluations in appendix A include site analysis information. The authors present a brief overview of scour conditions among sites here.

Except for a few sites, the culverts in the survey are in relatively good shape with respect to scour. There are two sites with severe scour; these include Lowe Creek and Deadwood Tributary South. The Lowe Creek culvert has footing scour along the upstream portion of the culvert on the left bank that is severely undermining the left-base footing and is creating a potential risk for structural failure if scour continues. The Deadwood Tributary South culvert is a closed-bottom culvert (pipe arch) that is scoured to the culvert base for the upstream half of the pipe. Structural integrity does not appear to be at risk, but fish-passage conditions are poor. There are a handful of other sites with localized scour, typically at the inlet area or along the footings, but none of these sites are compromised with respect to structure integrity. There are also a few sites where the main flow is along the footing and may scour footings over time. A brief summary of observed scour conditions is included in the table 3.4.1.

Table 3.4-1. Brief summary of observed scour conditions at culvert sites. See site evaluations (appendix A) for additional information.

Velvet Creek	No significant scour. Some bedrock is exposed in the inlet area, which is atypical of conditions in the natural channel outside the influence of the crossing.
Eames Creek	Culvert bed composed of sandstone bedrock. Downstream transition segment composed of bedrock. Little to no bedrock present in upstream channel reach. Unknown if streambed material was placed in culvert during construction. Base footings slightly undermined by scour in places.
Haight Creek	Culvert bed composed of sandstone bedrock. Some bedrock present in upstream channel but not dominant. Unknown if streambed material was placed in culvert during construction. Scour of bedrock along left bank footing in inlet area and along right bank at downstream end.
Deadwood Trib North	No significant scour. Riprap placed on right bank upstream of inlet failed into inlet area. Flow was wall-to-wall at the time of the survey.
Deadwood Trib South	Pipe scoured to base in upper half. Material aggraded in downstream half.
Buck Creek	No significant scour. Footings are exposed up to 3 feet but pipe was constructed that way.
Hehe Creek	No significant scour. Some bedrock present just upstream of inlet may be related to culvert inlet scour but bedrock sections are also found in the natural channel outside the crossing.
Pine Creek	There is currently scour to the culvert base at the inlet of the culvert. Originally placed material scoured out of the pipe after construction but refilled.
Youngs Creek	There is currently scour to the culvert base at the inlet of the culvert. Originally placed material scoured out of the pipe after construction but refilled.

Table 3.4-1. Brief summary of observed scour conditions at culvert sites. See site evaluations (appendix A) for additional information (continued).

Simpson Creek	No significant scour. There has been incision upstream of the culvert and aggradation of material in the downstream portion of the culvert.
Tire Creek	There is scour in the inlet region and associated channel incision upstream of the inlet. Pipe footings are not compromised.
Cool Creek	There is minor inlet scour along the left bank inside the pipe. Material has aggraded along the right bank and in the downstream portion of the pipe, potentially reducing hydraulic capacity.
Little Zigzag Creek	No significant scour. Flow was wall-to-wall at the time of the survey.
Lowe Creek	Severe scour on left bank at inlet and extending downstream 30 feet. Left bank base footing severely undermined.
Fall Creek	No significant scour. Flow was wall-to-wall at the time of the survey.
Upper Eightmile Creek	No significant scour. Flow was wall-to-wall at the time of the survey.
Lower Eightmile Creek	No significant scour. Flow was wall-to-wall at the time of the survey.

A common condition found at many of the sites is the adjustment of the channel bed post installation. Survey measures indicate that many sites have culvert beds that have a flatter slope than the culvert structure itself. Assuming that culvert beds were originally constructed at the same slope as the culvert structure, these sites have adjusted since installation through inlet scour, aggradation in the downstream portion of the pipe, or a combination of the two. At many sites, bed degradation at the upstream portion of the pipe and aggradation of material in the downstream portion were clearly visible. Figure 3.4-1 shows the incidence of culvert-bed flattening among all sites.

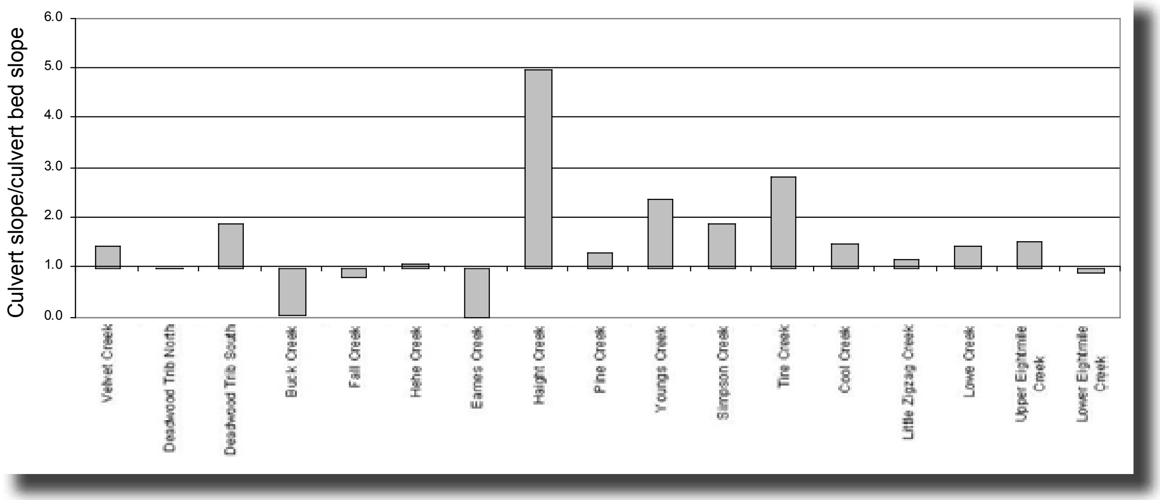

Figure 3.4-1. Ratio of culvert slope to culvert-bed slope. Culvert slope is the slope of the actual culvert structure. Culvert-bed slope is the slope of the thalweg profile through the culvert.

The occurrence of culvert-bed flattening was plotted against the width ratio in order to evaluate the effect of culvert widths on culvert-bed slope (figure 3.4-2). This comparison shows no relationship between culvert-bed adjustment and culvert width as it related to bankfull width. There is no relationship present, suggesting that different culvert widths have little effect on culvert bed slope adjustment.

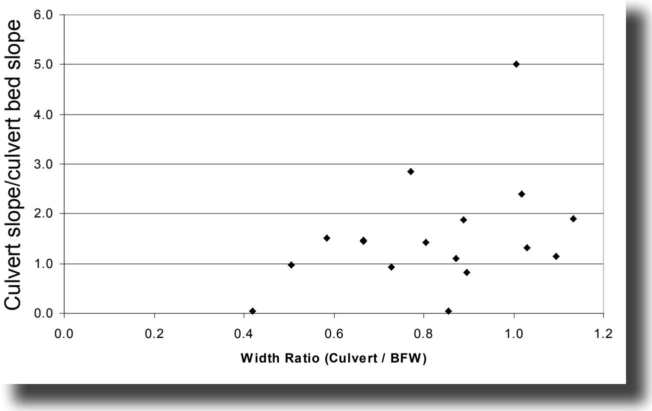

Figure 3.4-2. Relationship of culvert slope/culvert-bed slope ratio to the width ratio.

3.5 Overview of AOP conditions

Site analysis information for AOP is included in the site evaluations in appendix A. A brief overview of AOP conditions among sites is presented here.

Most sites appeared suitable for fish passage at the flow encountered during the survey. The one exception was Deadwood Tributary South, where the upstream half of the culvert was scoured to the base and rapid shallow flow in this section would inhibit fish passage. This site, as well as Deadwood Tributary North, also has potential passage limitations created by large rock steps that were constructed downstream of the outlet in order to maintain grade through the culvert.

Several other sites had conditions that might limit AOP during some flow conditions. At the time of the survey, several sites had shallow wall-to-wall flow without flow concentration that may be necessary to provide fish passage at low flows. These include Velvet Creek, Fall Creek, Deadwood Tributary North, Deadwood Tributary South, Little Zigzag Creek, Eames Creek, Haight Creek, Lower Eightmile Creek, and Upper Eightmile Creek. These sites generally showed a lack of streambed complexity, shallower residual depths, and low depth-distribution values when compared to the natural channel. These sites had no defined streambanks to facilitate terrestrial organism passage and had little or no stable bed elements (steps) to provide complexity.

Vertical sinuosity and residual depth. Vertical sinuosity in the natural channel was consistently greater than that in the culvert except for Simpson Creek and Tire Creek, where culvert-bed sinuosity was greater (figure 3.5-1). This indicates that, in nearly all cases, the culvert beds reviewed have less complex bed topography than their corresponding natural channels. Values generated in the profile complexity analysis are included in appendix A.

Maximum residual depth is greater in the natural channel than in the culvert for all but two sites; Pine Creek and Cool Creek (figure 3.5-2). On average, maximum residual depth in the culverts reviewed was about 0.6 that of the natural channel. This is consistent with the results of the vertical-sinuosity assessment. Greater pool depths would generally be associated with greater vertical sinuosity. Values generated in the residual-depth analysis are included in appendix A. Factors contributing to similarities and differences in residual depths at individual sites are discussed in the site evaluations in appendix A.

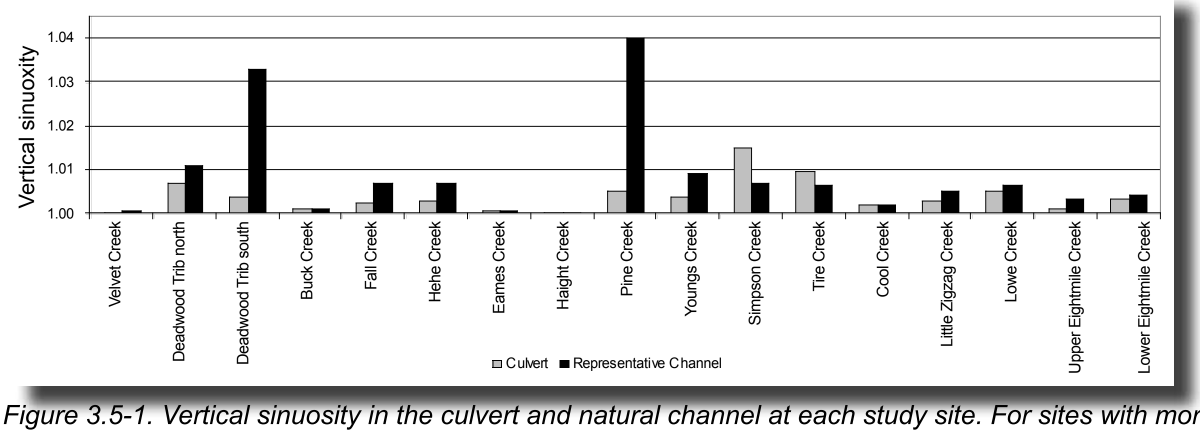

Figure 3.5-1. Vertical sinuosity in the culvert and natural channel at each study site. For sites with more than one reference segment, the vertical sinuosities were averaged. Reference channel values are significantly greater than the culvert values using a one-tailed paired t-test (α = 0.05).

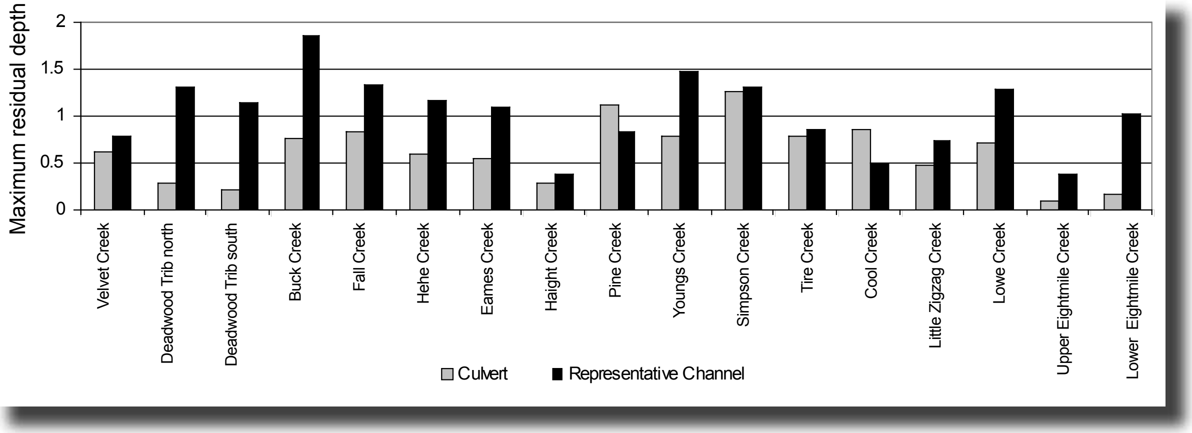

Figure 3.5-2. Maximum residual depth in the culvert and natural channel. For sites with more than one representative natural channel segment, the residual depths were averaged. Values for culverts and reference channels are significantly different using a paired t-test at α = 0.05.

Cross-section complexity – sum of squared height difference. The sum of squared height difference did not show that the measured culvert cross sections were less complex than those measured in natural channel segments. Five sites had higher values in the culvert and seven sites were within the range of the values in the natural channel. At only two sites did the culvert have lower values than the channel, and one of these was Hehe Creek, which site observations suggest has a complex bed.

Depth distribution. At the 25-percent Q_2, the depth distribution analysis showed that at least one cross section in the culvert had less available shallow water habitat at 13 of 17 sites. The following sites had at least one cross section with depth-distribution values within or greater than the range found in the natural channel: Tire Creek, Buck Creek, Little Zigzag Creek, Deadwood Tributary South, Fall Creek, Lowe Creek, Lower Eightmile Creek, Pine Creek, and Youngs Creek.

Four sites had both culvert values within or greater than the range of the channel (Tire, Deadwood Tributary South, Fall, and Youngs). In order to look at broad trends in depth distribution between the culvert and the natural channel, a comparison was made between averaged depth-distribution measures of culvert cross sections and channel cross sections. These comparisons indicate a strong influence of culverts on the availability of shallow flow areas (figure 3.5-3). At 13 of the 17 sites, the natural channel has a greater abundance of shallow channel margin habitat at the 25-percent Q_2. Values generated in the depth-distribution analysis are included in appendix A. Individual depth-distribution measures are presented and discussed further for each site in the site evaluations in appendix A.

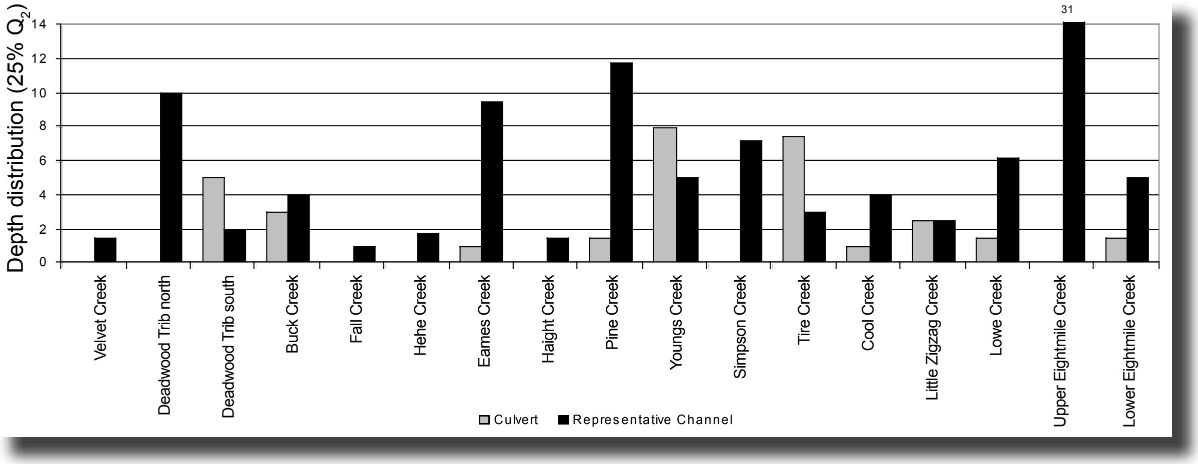

Figure 3.5-3. Depth distribution results for all sites. Bars depict the number of cross-section increments with depths less than 0.3 feet.

Channel units and LWD. The distribution of channel-unit types differs between culverts and natural channels. In general, pools and steps are more common in natural channels, riffles are about equally as common in natural channels and culverts, and glides are more common in culverts. Percent pool values for all sites are displayed in figure 3.5-4. Percentage of pools is greater in natural channels for 13 of 17 sites. Total habitat-unit composition results for all sites are included in appendix A.

These results are consistent with the results of the vertical-sinuosity analysis, which shows that vertical sinuosity is greater in natural-channel reaches. Culverts tend to be dominated by riffle and glide habitat, which is more uniform and shows less vertical variation and complexity.

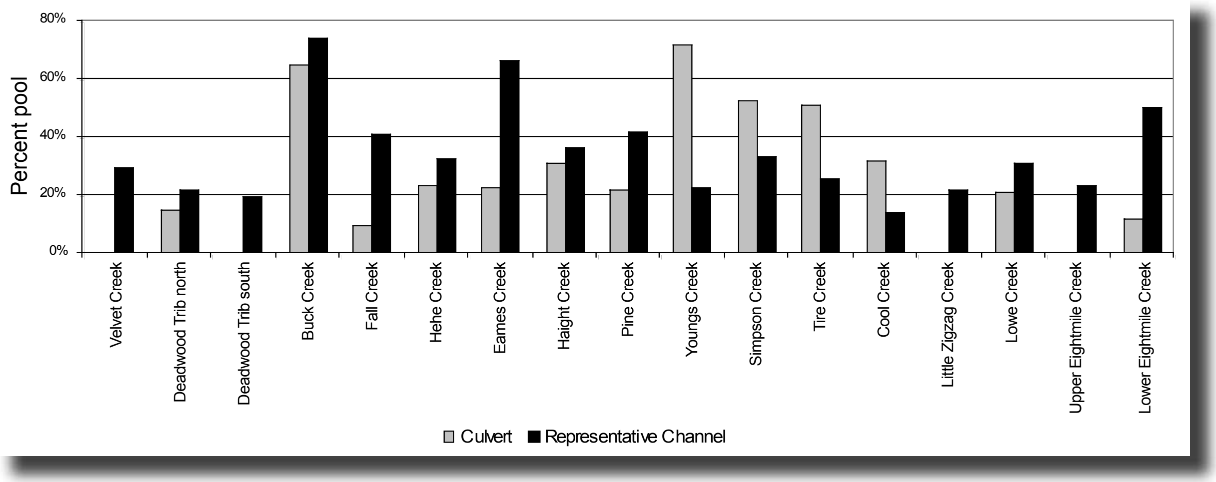

Figure 3.5-4. Percent pool (as percent of total stream-surface area) of natural channels and culverts for all sites. For sites with two representative natural channel segments, percent pool values were averaged. Natural channel values are significantly greater than culvert values using a paired t-test (one-tailed) at α=0.10.

LWD loading is considerably different between the culverts and natural channels. In all cases, LWD per channel width is greater in representative channel segments (figure 3.5-5). The data from the LWD analysis is provided in appendix A. An LWD loading of two pieces per channel width is considered "good" according to the Washington State standards (WFPB 1997). Natural-channel segments in only six sites exceed this target, although several other sites have between one and two pieces per channel width. Wood is absent in most culverts, with only one or two pieces counted at seven of the sites.

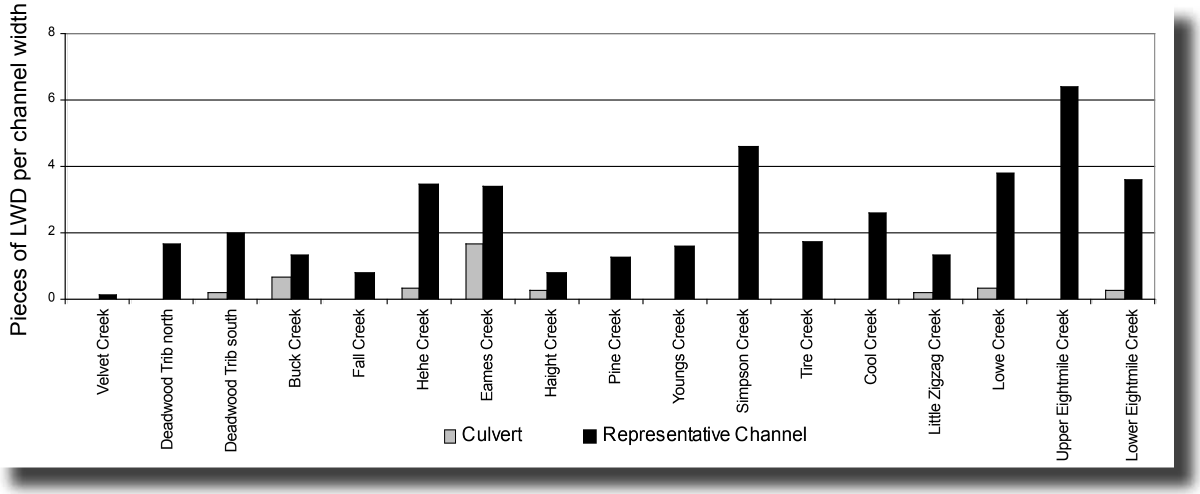

Figure 3.5-5. Counts of LWD per channel width for culverts and natural channels. For sites with two representative natural-channel segments, LWD and channel-width values were averaged.

Low wood counts in culverts are no surprise considering the absence of channel banks, riparian forests, and road maintenance activities. In some culverts, fluvially transported wood had accumulated within the pipe. LWD that is retained in culverts may not be viewed favorably, because wood can create debris jams that plug culverts or create footing scour. Nevertheless, a lack of wood demonstrates that channels at culvert crossings are not functioning like their natural counterparts. The prevalence of riffle-and-glide habitat in culverts may be partially due to a lack of wood that is available to form steps, create scour pools, and generally increase channel complexity.

3.6 Overview of substrate conditions

Grain-size distributions. Pebble-count data for each site are included in the site evaluations (appendix A). When analyzed together, pebble-count data showed some interesting trends. In order to look at broad trends among sites, size-fraction ratios were developed by dividing the size for each size class in the culvert by the size for the same size class in the representative channel. A summary of these ratios for all sites is included in figure 3.6-1. The larger values in the chart indicate that the material in the culvert is larger than the natural channel for the given size fraction. On average, material in culverts is bigger than material in the channels. This is especially true for the smaller size classes. For most sites, the culvert has larger material for the smaller size fractions. This was further analyzed by averaging the ratios for each size class (figure 3.6-2). There are large differences in sizes for the smaller size classes (D_5 and D_{16}) but little differences for the large size classes (D_{84} and D_{95}). The D_{50} shows a moderate difference, with culverts having, on average, about 50 percent larger D_{50}s. D_5 and D_{16}s, however, average more than three times larger in the culvert, indicating that culverts typically have fewer particles in the smaller size classes, which is indicative of armored bed conditions. Results of a paired one-sample t-test show significantly greater values for the culvert for the D_5 and D_{16} size classes ($\alpha = 0.05$) but not for the D_{50}, D_{84}, or D_{95}. The complete substrate data are included in appendix A.

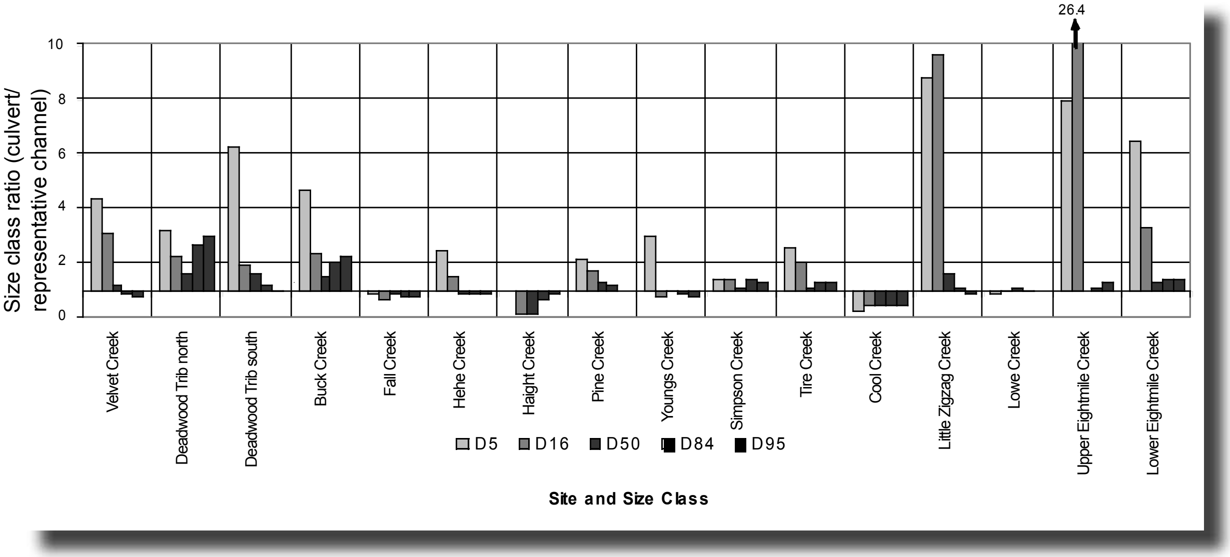

Figure 3.6-1. Size-class ratios for each site (culvert/representative natural channel). Data from pools are excluded.

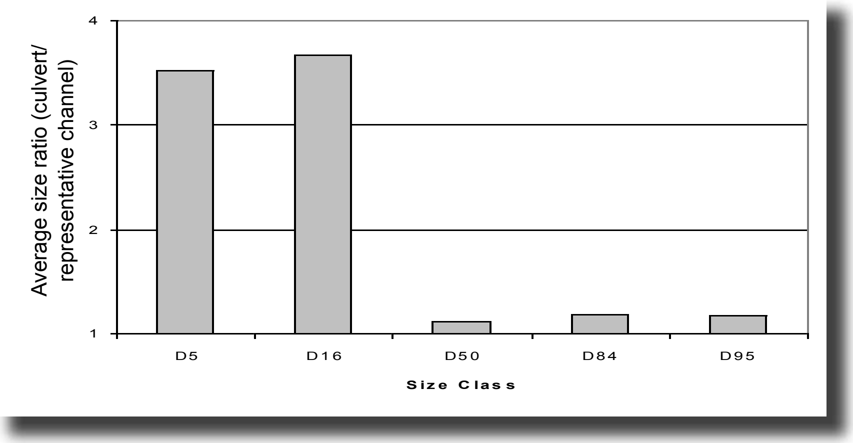

Figure 3.6-2. Ratios (culvert/representative natural channel) for a range of size classes.

Substrate size ratios were compared to stream width ratios to see if culvert width had an impact on the size of material in the culvert. The width ratio did not appear to impact the size of the D_{50} or D_{84} (figure 3.6-3).

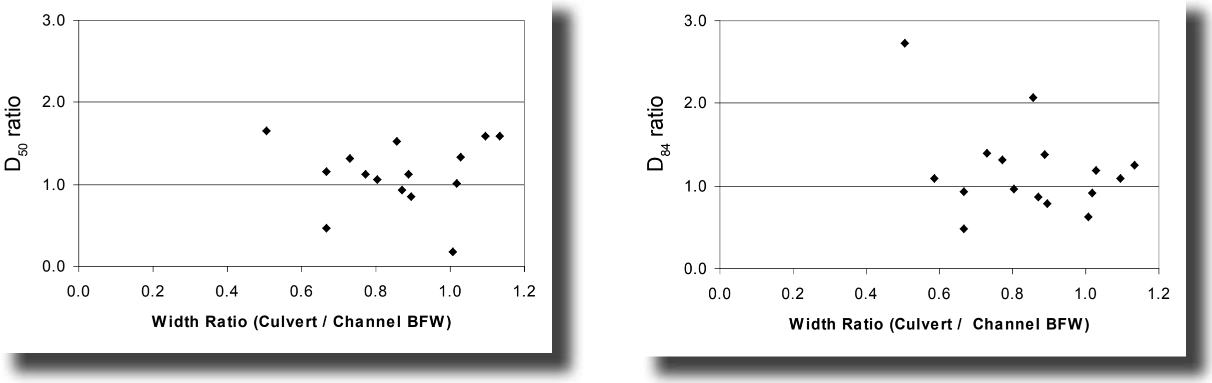

Figure 3.6-3. Effect of width ratio (culvert/natural channel bankfull width) on the D_{50} (left) and D_{84} (right) ratios. There are no significant correlations. Upper Eightmile Creek was removed as an outlier from the D_{50} analysis because of the effect of a large sand deposit on the D_{50} for the natural channel. Pebble-count data in pools are not included in these data.

Sorting and skewness. In order to look at broad trends in bed-material sorting and skewness among all sites, the values for each location (natural channel or culvert) at each site were averaged and ratios were developed for each site. The sorting and skewness coefficients are displayed in table 3.6-1. Guidelines for evaluating these coefficients are included in table 3.6-2 and table 3.6-3. Box plots are also included that show the range of data (figure 3.6-4). Culverts tend to have lower sorting coefficients than the natural channels. This corresponds to a greater degree of sorting; that is, culvert beds tend to be more “well-sorted” than the natural channel. This implies a narrower size range of particle sizes in culverts and broader, more heterogeneous ranges of material in natural channels. Differences between the culvert and representative natural channels are significant using a paired t-test at $\alpha = 0.05$.

Bed-material distributions appear to be slightly more negatively skewed in culverts than in representative channels, which would indicate that culverts have a greater abundance of particles on the fine side of the distribution. These results, however, are not significant using a paired t-test at $\alpha = 0.05$.

Table 3.6-1. Substrate sorting and skewness coefficients.

Site*	Substrate Sorting Coefficient			Substrate Skewness Coefficient		
	Culvert	**Natural Channel**	**Sorting ratio (culv/ref)**	**Culvert**	**Natural Channel**	**Skewness Difference (culv/ref)**
Velvet Creek	1.5	2.3	0.64	0.18	0.30	-0.12
Deadwood Trib North	2.0	2.1	0.97	0.14	0.35	-0.21
Deadwood Trib South	1.6	2.0	0.81	0.29	0.35	-0.05
Buck Creek	1.9	2.1	0.90	0.19	0.46	-0.27
Fall Creek	1.6	1.5	1.03	0.15	0.04	0.11
Hehe Creek	1.9	2.4	0.78	0.24	0.37	-0.13
Haight Creek	2.7	2.4	1.14	-0.03	0.48	-0.51
Pine Creek	1.6	2.0	0.80	0.33	-0.09	0.42
Youngs Creek	1.7	2.0	0.84	0.42	0.40	0.02
Simpson Creek	1.5	1.5	0.99	0.03	0.19	-0.16
Tire Creek	1.3	1.6	0.80	0.00	0.32	-0.33
Cool Creek	1.4	1.3	1.08	0.23	0.16	0.07
Little Zigzag Creek	1.7	3.1	0.55	0.35	0.47	-0.12
Lowe Creek	1.5	1.8	0.82	0.26	0.25	0.00
Upper Eightmile Creek	1.3	2.8	0.45	0.23	-0.15	0.38
Lower Eightmile Creek	1.2	2.4	0.51	-0.15	0.36	-0.51

** Eames Creek was removed from this analysis because of the large effect of the culvert on upstream bed material distributions.*

Table 3.6-2. Interpretation of sorting coefficients. From Folk and Ward 1957

Sorting Coefficient	Characterization
> 4	Extremely poor
2 – 4	Very poor
1 – 2	Poor
0.71 – 1	Moderate
0.5 – 0.71	Moderately well
0.35 – 0.5	Well
< 0.35	Very well

Table 3.6-3. Interpretation of skewness coefficients.

Skewness Value	Characterization	Particle Sizes
-0.3 to -1	Strongly negative skewed	More fine particles
-0.1 to 0.3	Negative skewed	
-0.1 to 0.1	Nearly symmetrical	
0.1 to 3	Positive skewed	
0.3 to 1	Strongly positive skewed	More coarse particles

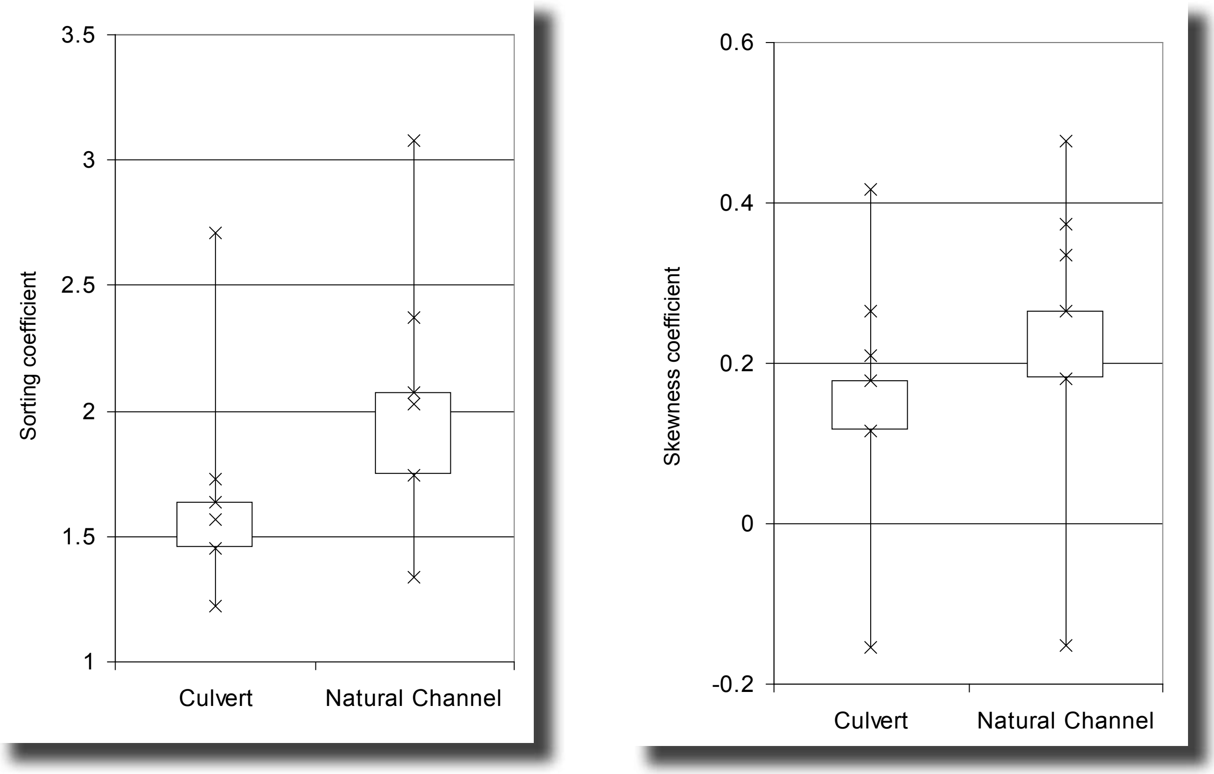

Figure 3.6-4. Box plots of sorting coefficients (left) and skewness coefficients (right).

4 DISCUSSION

Culvert sites included in this study represent a range of culvert types that generally fit the description of stream-simulation design. All of the pipes are either open-bottomed arches or embedded-pipe arches with culvert beds made up of natural streambed materials. Some of the culverts were installed in the 1980s, long before the more contemporary standards for stream simulation were in common use. For most sites, the original design objectives and project constraints are unknown. This evaluation is therefore not intended to be a critique of how well these culverts meet stream-simulation design objectives, but instead is focused on learning from these sites in order to advance the practical application of stream-simulation design techniques.

The following sections discuss patterns of culvert behavior in response to bed-mobilizing flood events that have been observed among all the sites. The effect of culvert characteristics (width) and designs (slope and bed material) are related to modeled and observed culvert bed scour conditions. There are, of course, many variables that affect culvert bed conditions at each site, and these influences may obscure underlying patterns of culvert response. Thus, an attempt is made at identifying trends, while also highlighting specific site conditions that may be influencing the results. A discussion on the implication of designs to AOP is also included. And finally, the results are used to develop recommendations for future culvert design and construction.

4.1 Inlet scour and culvert bed adjustment

Assuming culverts were installed to a similar grade as the channel (except for Buck and Eames, which were placed at zero slope), most culverts have adjusted their profiles since installation. In most cases, the culvert bed has adjusted to a flatter slope (see figure 3.4-1). Thirteen out of 17 sites (76 percent) have culvert bed slopes that are less than the pipe slope, indicating adjustment. This adjustment has occurred through inlet scour and/or aggradation at the downstream end of the culvert. A high incidence of inlet scour has been reported in other regional studies (Lang et al. 2004) and was observed at many of the sites included in the present study. Inlet scour was observed primarily along culvert sides adjacent to footings/stem walls, but was occasionally observed to occupy much of the inlet area.

At least two sites (Pine and Youngs Creek) have lost most if not all of their originally placed bed material; most of the material has subsequently been naturally replaced by new material from upstream. This may be an acceptable or even a desired scenario for a stream-simulation type design; except that in closed-bottom pipes like Pine and Youngs it presents a risk of scour to the culvert base that may not always be replaced by upstream sources. Use of open-bottom arches, or installation of a foundation of stable bed material over which mobile material can move, would ensure that base scour of the culvert does not persist.

Results show that the incidence of culvert bed flattening does not vary with the culvert width ratio (figure 3.4-2), suggesting that other factors may be influencing this condition. Presumably, the degree of bed adjustment would depend on the number of large flow events experienced by the culvert, and so some sites may have adjusted more than others depending on their flood history. The following discussions highlight other potential causes for bed adjustment, which are primarily related to site evaluation, design, and construction.

Culvert elevation. New culvert installations are typically larger than the culverts they are replacing. An increase in the elevation of the culvert crown may require raising the height of the roadfill to accommodate the larger structure, which may add considerable expense to a culvert replacement project. If resources are unavailable to raise the road prism, then culverts may be either undersized or placed at too low an elevation. In cases where culverts are placed too low, the slope may remain similar to the natural stream slope, but the pipe is lower than the channel profile. This condition can create upstream channel incision. Material eroded from the channel and banks upstream is then made available to aggrade within the pipe. This occurs more readily in the downstream portion of the pipe that is free from the contraction scour at the inlet. Based on study results and site observations, this dynamic may be contributing to bed adjustment at Pine Creek, Youngs Creek, Tire Creek, and Hehe Creek.

Backwater-induced sediment aggradation. At some sites, accumulations of coarse material were observed upstream of the culvert inlet (Pine Creek, Youngs Creek). The material was likely deposited during mobile-bed flood events, when the upstream bed was mobilized and contributing material that was then deposited in the backwater created by the culvert (potentially plugged with debris or exceeding capacity). This material appears to have caused localized channel widening in Pine and Youngs Creeks, and also creates an oversteepened section just upstream of the inlet, which may be exacerbating inlet scour.

Maintenance and restoration. Slope adjustment may also be the result of maintenance activities during or following storms, when debris plugs at culvert inlets are removed by heavy machinery to improve conveyance. Debris removal efforts may have a tendency to overexcavate the inlet area to ensure that culverts remain free of debris that can plug culverts and cause roadway overtopping. Other potential management-related causes of culvert bed flattening are grade control structures placed downstream of the culvert outlet that create backwater areas where sediment aggrades, thus reducing slope through the crossing. Such structures are present at Cool Creek and Upper Eightmile Creek.

4.2 Effect of culverts on channel-flow geometry and hydraulics

Culverts have a significant effect on channel-flow geometry and hydraulic variables including width-to-depth ratio, cross-sectional area, velocity, and shear stress. There are many factors that affect hydraulic conditions at each site, and it is difficult to separate out the many variables that are influencing observed conditions. Nevertheless, some trends can be seen from the results of this study, and these are discussed below under their respective headings.

Cross-section geometry. The effect of culverts on cross-section flow geometry indicates considerable flow constriction caused by culverts at every site. Modeling shows that six sites (Tire, Cool, Eames, Lowe, Lower Eightmile, and Upper Eightmile) have some degree of backwater created by the culvert, typically with outlet control characteristics where the water surface is elevated through a portion of the length of the pipe. This condition typically only affects flows above the Q_2 and, for some sites, only affects the Q_{50} and Q_{100}. Backwater conditions have obvious impacts to flow geometry, including increasing the depth and decreasing the width-to-depth ratio. Culverts that were at least 90 percent of bankfull width or greater showed no backwater impacts; however, some culverts as small as 50 percent bankfull width (Deadwood Tributary North) also showed no backwater effects.

All sites have some degree of impact on cross-section flow geometry, at least at the higher flows (Q_{10} and above). Top width and wetted perimeter tend to show the greatest differences from the natural channel.

Velocity. All sites show an effect on velocity at least at the highest modeled flows (Q_{50} and Q_{100}). Even at low-to-moderate flows (25-percent Q_2), most of the sites have average velocities that exceed 2.0 feet per second, which is considered near the upper limit for juvenile salmonid swimming ability (Bell 1990). Even though average velocities are high, there are typically lower velocity areas near culvert margins or within boundary layers adjacent to substrate where fish may be able to pass (see literature review in Kahler and Quinn 1998). However, as average velocities exceed 5 feet per second, which occurs at many sites, low-velocity areas may be limited in the culvert.

Velocity differences between the channel and the culvert are related to flow constriction in the culvert, but the degree of effect on velocity does not necessarily track well with culvert bankfull width ratios. Many other factors, including culvert roughness, culvert slope, culvert cross-sectional area, and the degree of backwater created by the culvert all affect velocity. More investigation is needed to explore the relationships among all sites with respect to velocity. For discussion of velocity results at the site scale, see the site evaluations in appendix A.

Shear Stress. For many sites, shear stress is lower in culverts than in the representative channels, a condition that is attributable to lower culvert bed slopes and backwatered conditions in culverts in some cases. Many of these sites have experienced culvert bed adjustments in the form of inlet scour or locally reduced slopes due to aggradation, resulting in reduced shear stress. Other sites, such as Little Zigzag, are dominated by uniform beds without the step sequences that elevate the shear in the natural channel. Steeper culvert beds tend to show greater shear stress than flatter beds. Judging from the high incidence of culvert bed adjustment (flattening), shear stresses were likely greater in culverts immediately following construction but prior to any bed-mobilizing flows. These initially higher shear stresses would have resulted in scour and bed adjustments that have reduced culvert bed slopes and have therefore moderated shear stresses within culverts. More investigation is needed to explore the relationships among all sites with respect to shear stress. For discussions of shear stress results at the site scale, see the site evaluations in appendix A.

Critical shear stress. Results of the excess shear analysis suggest that the D_{84} particles are mobilized at lower flows than would typically be expected to mobilize the bed in step-pool channels (Grant et al. 1990, Chin 1998). Many of the sites have calculated shear stress that exceeds critical shear stress below the 25-percent Q_2 (appendix A). This runs counter to other regional studies that have estimated that bed mobilizing events in step-pool channels typically occur close to the 50-year event (Grant et al. 1990). The low entrainment thresholds calculated in the analysis may be due to the difficulty in accurately modeling incipient motion of particles in step-pool channels using traditional critical shear stress approaches (Bathurst 1987). Furthermore, applying the Komar (1987) method to estimate critical shear stress assumes that an increase in particle protrusion above the bed (a condition that often occurs in step-pool channels) will increase the potential for particle entrainment. However, the equation does not take into account the increased stability that is provided by the interlocking of particles at stable step structures, nor does it account for high degrees of form resistance (spill resistance and LWD resistance) that may limit the amount of shear stress that is available to initiate particle motion (Wilcox et al. 2006).

In consideration of the factors discussed above, the critical shear stress approach may not be the most appropriate technique to apply to the steep boulder-bed channels in this study. However, applying different methods for the step-pool systems versus the lower gradient pool-riffle systems may have introduced significant variability. Moreover, initial trials using the Costa (1983) and Bathurst (1987) methods, which were developed for step-pool channels, provided widely variable results that made interpretations and comparisons difficult. In summary, even though entrainment thresholds calculated for the steeper sites in this study are potentially lower than the actual entrainment thresholds experienced in these streams, it is assumed that they provide reasonable relative comparisons of bed mobility between culverts and natural channels.

Excess shear stress is typically smaller in culverts than in the representative channels at low flows. This is attributable to lower average shear in the culvert for many sites as discussed previously, but is further influenced by coarser D_{84}s in culverts. Coarser bed material in culverts is a result of a combination of bed coarsening and artificially larger material placed during construction. A few of the sites exhibit an increase in culvert excess shear with respect to the natural channel as flows increase. These include Velvet Creek, Haight Creek, and Cool Creek. This is generally due to more rapid increases in depth of flow as flows rise in the culvert with respect to the natural channel. A few sites have lower excess shear in culverts when compared to natural channels due to a reduction in the energy slope in the culvert as a result of outlet control conditions in the pipe. These include Tire Creek, Lowe Creek, Upper Eightmile Creek, and Lower Eightmile Creek.

4.3 Culvert substrate conditions

Coarser bed material in culverts compared to natural channels is a ubiquitous condition measured at nearly all the study sites (figure 3.6-1). Differences in bed material size are most pronounced for the smaller grain sizes, with culverts typically having much less of the smaller material that is found in the natural channels. In some cases, the differences are severe, such as in Velvet Creek, Deadwood Tributary South, Buck Creek, Little Zigzag Creek, Upper Eightmile, and Lower Eightmile, where the size of the smaller size classes far exceed the natural channel conditions. Only Haight Creek and Cool Creek have culvert material that is significantly smaller than the representative channels. In Haight Creek this is likely the result of backwater influence from the mainstem Siuslaw River, which is a short distance from the culvert outlet.

Culverts have material that is more “well-sorted” (poorly graded or only belonging to a few size classes) than representative channels (table 3.6-1). Culverts therefore do not represent the wide range of size classes that are found in the natural channels. This is likely related to the lack of smaller material in culverts. Even though a lack of smaller material may not have a direct impact on aquatic habitat or passage conditions, it does suggest that there is reduced hydraulic and physical habitat complexity available for sorting and storing smaller material.

The size and gradation of material originally placed in culverts during construction obviously would have a large influence on the material measured at the sites. Larger material than that found in the natural channel is sometimes placed in the culvert in order to ensure that culvert beds do not experience excessive scour. This likely occurred at a number of the sites in this study, based on site observations and discussions with practitioners that were involved in design/implementation. In particular, Deadwood Tributary North and Buck Creek have D_{84} and D_{95} material that is considerably larger than the representative channels, likely due to the size of material placed during construction. These sites show very little incidence of culvert bed flattening, possibly a result of the construction-related bed armoring that is able to resist adjustment.

The pronounced difference in size of the smaller size fractions suggests that bed coarsening has occurred through transport of the smaller material and that flows competent to move the larger material have occurred less frequently. Transport of the smaller material from culverts may be exacerbated by a lack of material sorting or bedform construction during installation. Several culverts have uniform plane-bed type channels where bedform structures (steps) do not appear to have been constructed. Plane-bed channels decrease the presence of low energy areas where smaller material is able to accumulate and remain.

4.4 Channel complexity and depth distribution

Channel complexity was lower in culverts than in representative natural channels. Measures of complexity were evaluated by looking at thalweg (vertical) sinuosity, residual depth, and depth distribution (important for passage). Cross-section complexity, using sum of squared height difference, was also analyzed but the technique does not appear to provide a reliable assessment of complexity in culverts. The various complexity metrics applied to the study sites are discussed below.

Vertical sinuosity and residual depth. Vertical sinuosity is less in culverts than in the representative natural channels at most sites (63 percent). Only two sites have higher vertical sinuosity in the culvert; these include Simpson Creek and Tire Creek. For Deadwood Tributary South and Pine Creek, the vertical sinuosity in the culvert is considerably less than the natural channel (over 7 times less in the case of Pine Creek). Less vertical variation in the culvert is related to more plane-bed type channels that lack the step-pool sequences and residual depths of natural channels. Maximum residual depth in the culverts is, on average, about 60 percent that of the natural channel outside the crossing. Sites with low values for residual depth also show big differences in substrate when compared with their natural channels, particularly with respect to the presence of small material. This may reflect a lack of complexity that is needed to retain smaller material. The clear differences in residual depths and vertical sinuosity demonstrate differences in complexity between culverts and natural channels. This has implications for fish habitat and passage conditions.

Cross-section complexity – sum of squared height difference. Sum of squared height difference did not appear to be a good metric for evaluating complexity. In many cases, results did not match visual estimates of complexity. This may be an artifact of where the boundaries were chosen for this metric. Use of this metric may require more detailed cross-section measures to make sure the detailed bed topography is captured and included in the calculation.

Depth distribution. In general, the culverts in this study tended to have less available shallow channel margin habitat than natural channels at the 25-percent Q_2. These results have important implications for AOP because of the effects of shallow flows on velocity. Velocity profiles in culverts show lower velocity areas closer to the bed (Ead et al. 2000; Lang et al. 2004; House et al. 2005). In addition, areas of shallower flow (areas closer to the culvert sides) have lower velocities at a given depth than areas of deeper flow. This follows the classic Prandtl Von Karmen universal velocity distribution law (Chow 1959). Velocity in shallow flow areas may be further reduced through increased boundary roughness as one approaches obstructions along flow margins, or from secondary currents near the surface (Ead et al. 2000).

Because juvenile fish have been shown to seek out low velocity areas in culverts for passage (Belford and Gould 1989), passage conditions may be degraded if shallow, low energy areas are less available, such as occurs due to a reduction in width-to-depth ratios in culverts. Not only is this important for fish that rely on the low velocity habitat, but it may also be important for passage of other organisms, including amphibians and mammals that may use shallow areas for migration through culverts.

The two culverts with the most available shallow channel margin habitat with respect to their natural counterparts are Youngs Creek and Tire Creek. These culverts both have well-developed banks within the pipe that allow for the presence of shallow channel margin flow. Well-developed banks constructed within a culvert will increase the availability of shallow channel-margin habitat and will provide more boundary roughness and complexity that can provide velocity refuge for passage.

4.5 Channel units and LWD

Channel-unit and LWD analysis indicates that aquatic habitat conditions are less favorable in culverts compared to natural channels. The channel-unit and LWD results and implications are discussed below.

Channel units. Percentage of pool habitat is often used as an indicator of habitat quality and complexity. In 13 of 17 sites, the natural channel had greater percentage of habitat in pools than the culvert; however, 4 of these have percent pool within 10 percentage points of the natural channel, which indicates fairly good simulation of natural pool abundance. Youngs Creek, Simpson Creek, Tire Creek, and Cool Creek have greater percent pools in the culvert than the natural channel; all with pool abundance that is at least 19 percentage points greater than the natural channel. These sites are among the best of all of the sites with respect to bedforms or banks that simulate natural channel conditions. Simpson Creek, which is a long culvert with high pool abundance, has many constructed step-pool sequences that contribute to the high number of pools.

Most culverts have less pool abundance due to plane-bed channels, lack of constructed step-pool sequences, and a prevalence of glide-like habitat. For short culverts, a lack of pool habitat may not significantly impact passage conditions, and it may actually serve to reduce the potential for footing scour. However, for long culverts, a lack of pool habitat may reduce resting areas that are important for migrating fish.

Large woody debris. LWD frequency is much less in the culverts than in the channel. Stream-simulation designs should be capable of transporting some wood; however, large logs, especially those with attached root wads, may be too large to be transported through the pipe. This is because at high flows the stream hydraulics may be able to transport wood of a length that exceeds the width of the culvert, even if designed under contemporary design standards. Wood transport is therefore an issue that is not adequately addressed by stream-simulation design criteria. During large flood events, there will continue to be the potential for plugging of the culvert with wood. Even small wood can plug the pipe or reduce capacity. In natural channels, the stream can adjust laterally or vertically to accommodate in-channel wood. In a culvert, this is not possible. For these reasons, wood collecting within culverts or at culvert inlets will continue to be a maintenance issue for all but the largest of pipes. Capacity will be maintained at many sites by removing wood from culvert barrels and inlet areas during or following large floods. In order to compensate for the lack of wood in culverts, the structural and habitat benefits of wood will need to be met in other ways, such as building rock steps and bank features that simulate the geomorphic function and habitat complexity provided by wood.

4.6 Implications to AOP

A number of studies have demonstrated the importance of low velocity areas in culverts for fish passage (Kahler and Quinn 1998). It is important that these low-velocity areas are available at relatively large flows since fish are motivated to migrate through culverts during the rising and falling limbs of flood hydrographs. Lang et al. (2004) demonstrated that most juvenile fish migration through culverts occurred between the 11-percent and 15-percent annual exceedance flows (flows exceeded only 11 percent to 15 percent of the time) and that adults tended to pass at even greater flows, with the peak between the 1-percent and 2.5-percent annual exceedance flows. As a reference, the 25-percent Q_2 flow for the Middle Fork Willamette River near Oakridge, Oregon, (USGS #14144800, nearest long-term gauging station near the upper Willamette River sites) is approximately equivalent to the 5-percent annual exceedance flow. Maintaining low-velocity areas at these higher flows is difficult because of the increased constriction of flow at higher discharges. Modeled velocities in culverts for the study sites in this study exceeded 2.0 feet per second for all but one site at the 25-percent Q_2. All sites had velocities that exceeded 2.0 feet per second at the 25-percent Q_2 in the natural channel. Juvenile fish swimming capabilities are typically 2.0 feet per second or less (Bell 1990). Although velocities at the study sites exceed this threshold, lower velocity areas near culvert/channel boundaries or in shallow flow areas may be within the range of fish swimming abilities. It was beyond the scope of this study to evaluate the spatial distribution of velocities in channels and culverts.

Channel complexity and habitat quality were lower in culverts than in natural channels. Lack of habitat complexity is partially a result of culvert design and construction methods but is also related to the inherent constraints imposed on streams by culverts. The lack of channel sinuosity, channel migration zones, streambanks, and adjacent riparian areas limits the ability of culverts to provide functional habitat and passage conditions. The individual site evaluations (appendix A) discuss the factors affecting AOP conditions at each site.

4.7 Comparison of results with WFLHD study

Several sites analyzed as part of this study were also analyzed as part of a culvert study conducted by the Western Federal Lands Highway Division (WFLHD) in the late 1980s (Browning 1990). The two studies have five sites in common. However, for one of the sites (Pine Creek), the structure was replaced since the early study, and for another site (Eames Creek), two very similar culverts in close proximity made it impossible to tell which culvert was included in the original study. The three remaining culverts that were included in both studies include Haight Creek, Cool Creek, and Lowe Creek. The WFLHD study only looked at hydraulic variables for two flow events; the 2-year recurrence interval and the 50-year recurrence interval event. A comparison of the results of the two studies is provided in table 4.7-1.

Table 4.7-1. Comparison of results of present study with results of the WFLHD study (Browning 1990) for the three sites assessed in both studies.

		Flow Depth (ft)		Velocity (ft/s)		Shear Stress (lb/ft^2)	
Site	**Flow Event**	**WFLHD Study**	**Present Study (range)**	**WFLHD Study**	**Present Study (range)**	**WFLHD Study**	**Present Study (range)**
Haight	2-year	2.1	2.68 – 3.08	3.06	2.99 – 3.43	0.66	0.13 – 0.24
	50-year	3.1	4.56 – 5.11	3.99	4.99 – 5.6	0.97	0.29 – 0.57
Cool	2-year	2.5	1.64 – 2.67	4.31	2.78 – 4.36	1.56	0.61 – 2.18
	50-year	3.8	3.9 – 6.06	5.51	5.39 – 7.28	2.37	1.61 – 4.01
Lowe	2-year	2.5	1.21 – 3.05	9.65	2.42 – 5.6	7.8	0.7 – 7.51
	50-year	3.9	1.03 – 9.75	12.12	1.43 – 22.15	12.17	0.25 –123.26

There is fairly good correlation of values for some parameters at some flows, but many parameters diverge considerably. There are several reasons related to the different methods of the two studies that would explain much of the difference in the values:

1. The use of different regional regression equations. The older study used equations from an earlier USGS publication (USGS 1979). The estimated flows in the WFLHD study are larger than those using the newer USGS equations. In Lowe Creek, the estimated flows are over twice as large as in the current study.
2. Different calculations for watershed area. Older calculations for Lowe and Haight Creek were larger than the more recent calculations, resulting in larger flow estimates.
3. Different assumptions for roughness. The WFLHD study assumed Manning's roughness values of 0.040 or 0.045, whereas the present study used Jarrett's equation to determine roughness (see section 2.8.1).
4. Different methods for modeling. WFLHD study used a normal depth approach (Manning's equation) and assumed trapezoidal channel dimensions to represent the culvert bed.

It is also probable that the culvert beds have adjusted since the late 1980s, thus changing the hydraulic conditions. However, short of recreating the original methods used in the WFLHD study, it is impossible to separate out the influence of the methods versus the influence of channel adjustments.

5 RECOMMENDATIONS

The following recommendations and considerations for culvert design were developed from study results and site observations.

Design for a bed mobility threshold in the culvert that equals or exceeds that of the natural channel. If bed mobilization occurs more readily in the culvert than in the natural channel, then scour of culvert beds or footings will occur. This appears to have occurred in Deadwood Tributary South and may be responsible for scoured portions of other culverts including Pine, Youngs, Eames, Haight, and Lowe. In the majority of culverts in this study, even those that exceed bankfull channel width, flow constriction occurs even at relatively frequent flood recurrence intervals. It therefore must be acknowledged that there will often be more energy available to cause bed scour in culverts than in natural channels during high flows.

An important step in culvert design is the determination of the different thresholds for bed mobilization in the culvert and the natural channel. This information can be used to select appropriate culvert sizes and bed-material gradations. The objective should be designing for bed mobility in the culvert that occurs at similar flows as in the natural channel. This will simulate natural channel adjustment and will reduce bed degradation or aggradation in the vicinity of the crossing.

Compensating for higher energy in culverts (shear and velocity) by increasing rock sizes comes with some risk at higher flows. If and when the placed material is transported out of the culvert (during large flows), new material recruited from upstream may be too small to be retained in the culvert; resulting in persistent instability and scour potential from future floods. This is especially a concern in step-pool channels, where significant bed mobilization occurs only when the key step-forming particles are entrained (Grant et al. 1990) and bed mobility ceases once they become stable again. The lack of continued recruitment of material into the culvert at the descending limb of the flood hydrograph, or during subsequent lower magnitude flow events, may perpetuate culvert bed scour conditions. This may be a concern for the Buck Creek site, where culvert shear stress and velocity are higher in the culvert at high flows. So far, the bed has been stabilized because there is coarser material in the culvert than in the natural channel. However, if this material is transported out of the pipe during a large flow event, there will be no material of this size available to replace it, leading to potential culvert bed scour and channel incision.

Create bedforms in culverts that simulate natural channel bedforms. A number of sites in this study had uniform culvert beds that did not resemble the natural channel outside the crossing. These include Velvet Creek, Fall Creek, Deadwood Tributary North, Deadwood Tributary South, Little Zigzag Creek, Eames Creek, Haight Creek, Lower Eightmile Creek, and Upper Eightmile Creek. These sites were characterized by plane-bed or bedrock channels with shallow wall-to-wall flow at the time of the survey. A lack of bedforms or banks that mimic those in the natural channel reduces complexity and depth distribution and likely results in adverse impacts to AOP. Sites with bedforms that better mimic those in the natural channel include Tire Creek, Simpson Creek, and Hehe Creek.

Creating bedforms akin to those in the natural channel not only benefits AOP, but also helps to achieve bed stability that is similar to the natural channel. This is especially the case for step-pool channels, where stability is provided by rock steps that consist of interlocked particles. The interlocking of the particles increases particle stability above what would be expected if the rocks were arranged in an unsorted pattern on the streambed. Bedform construction in step-pool systems may include creating embedded rock steps that mimic natural steps or using large rocks to mimic the function of wood in a wood-forced system. The Forest Service guidelines (Forest Service Stream-Simulation Working Group 2008) outline several considerations and techniques for designing culvert beds that satisfy these objectives. Step height and spacing should also be similar to the natural channel. Step dimensions can be measured using an appropriate reference reach or can be determined through the use of empirical equations and relationships measured in other streams (Grant et al. 1990, Papanicolaou and Maxwell 2000). Bedforms should ideally be constructed before the culvert is placed on the footings. In closed-bottom pipes, constructing bedforms within the pipe will be necessary except in cases where the top portion of the culvert can be removed or left off for access (on structural plate culverts).

Create stable channel banks in wide culverts. Most sites showed a lack of defined streambanks within the culvert. Constructed streambanks can protect footings, concentrate flow for low-flow fish passage, create greater habitat complexity and velocity refuge, create shallow flow on channel margins at a range of flows, and allow for passage of terrestrial organisms. Pine Creek, Tire Creek, Buck Creek, Cool Creek, Lowe Creek, Hehe Creek, and Youngs Creek all had some degree of exposed streambanks at the survey flow, but most of these only had a bank on one side, with flow along the culvert wall on the other side.

Banks should consist of stable configurations of rocks that are placed along culvert margins in a manner that simulates conditions found in the natural channel. Construction of banks will only be feasible in wide culverts. It may be counter-productive to provide banks in narrower culverts where preserving flow capacity may outweigh the benefits of banks.

In several culverts in this study, flow was observed to concentrate along the concrete footings on one or both sides of the culvert. This is a result of the lower resistance of the smooth wall of the footing; but it is undesirable as it can contribute to footing scour and abrasion. Placed bank features can protect footings and culvert walls from scour and other damage.

Control for inlet scour. Many of the sites in this study have experienced at least some degree of inlet scour. These include Lowe Creek, Deadwood Tributary South, Eames Creek, Haight Creek, Tire Creek, Pine Creek, Youngs Creek, and Cool Creek. Significant outlet scour was not observed. Because of the predisposition for inlet scour, special precautions should be taken to address it. These include placing larger than normal bed material or stable steps in the upstream portion of the culvert, or making sure that at least the upstream portion of the pipe has a solid foundation of stable material. For closed-bottom pipes, bed retention sills near the inlet may be necessary. Modified culvert inlets such as wingwalls may reduce the incidence of inlet scour.

Design for bed adjustments. Most of the sites in this study had evidence of bed adjustment post-installation. Ten of the 17 sites experienced a flattening of the culvert bed through inlet scour and/or aggradation in the downstream portion of the pipe (see section 3.4). Inlet scour has been identified as a common occurrence in other studies (Lang et al. 2004). The width of the culvert with respect to the natural channel does not appear to be a good predictor of bed adjustment. There are many other contributing factors, and bed adjustment may be difficult to predict. Designs should therefore anticipate potential adjustments by installing culverts that are large enough to accommodate aggradation and deep enough to accommodate scour. This may include the use safety factors for culvert size and embedment/footing depth. The Forest Service guidelines (Forest Service Stream-Simulation Working Group 2008) outline considerations and techniques for sizing and placing culverts that satisfy these objectives.

Alignment considerations. Scour in several of the pipes in this study was at least partially related to the culvert alignment where tight bends at the inlet were contributing to scour of culvert beds or footings. This includes Pine Creek, Youngs Creek, Eames Creek, and Haight Creek. Deadwood Tributary North experienced failure of bank material into the inlet due to a sharp bend at the inlet. At Pine and Youngs Creeks, aggradation of bed material upstream of the inlet (assumed to be a result of backwatered conditions during floods) induced lateral channel migration that resulted in a skewed alignment. Designers should recognize the potential for this dynamic and select culvert sizes accordingly.

Culvert replacements may mistakenly assume that the observed alignment of the stream at the time of replacement is the correct alignment, when in reality the original culvert installation may have changed the alignment. Alignments are often changed to allow for culverts that are perpendicular to the stream and therefore have the least possible length and road fill requirements. These situations not only change stream alignments, but they also increase the slope of the channel at the crossing. Efforts should be made to determine the natural stream alignment and to place structures as close to this alignment as possible.

Channel-unit considerations. Although pool habitat is generally viewed as a benefit for fish rearing and spawning, pool habitat in culverts may not be considered a positive attribute because of potential scour issues. During large flows, scour in step-pool channels occurs in pools due to local high slopes and shear stresses created by the steep channel units located just upstream (Grant et al. 1990). If these conditions occur in culverts, then the incidence of footing or culvert base scour may be increased. For long culverts, it would be unreasonable to design culvert beds without pool sequencing similar to that of the natural channel, since designing otherwise might create passage issues (long, uniform plane-bed channels). However, for short culverts, placement of the pipe can take channel units into consideration to ensure that scour potential is minimized. For example, if location options are available, culverts can be placed in sections of long riffles to avoid potential issues with scour in pool units.

Recommendations for future assessments. This assessment was focused primarily on conditions at the individual-site scale. A further examination of trends among all sites would help to further the understanding of the response of culvert sites to elements of design. Predictor variables such as culvert size, culvert shape, culvert slope, and the size of placed bed material can be related to observed scour, predicted scour, and AOP conditions in order to evaluate how components of culvert design affect scour and AOP among all sites.

Future assessments should look at how culvert designs affect species-specific fish passage requirements. This would include detailed measures of the spatial extent of velocity and depth throughout the culvert and in adjacent natural channels outside the crossing at fish-passage flows.

One of the objectives of this study was to examine sites that had adjusted to local flood history (all sites were at least 5 years old); therefore newer sites constructed according to more contemporary stream-simulation design criteria were not included. Future studies should attempt to include newer pipes constructed with the more recent criteria. Although these culverts may not have fully responded to local hydrology, modeling can be used to predict channel response, which can later be compared to observed adjustments.

Modes of culvert response will vary depending on channel type, sediment conditions, and regional differences in hydrology and geomorphic setting. Future studies should attempt to represent the range of conditions in which culvert installation projects are likely to occur, so that appropriate prescriptions can be developed for particular site conditions.

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SDTDC's national publications are available on the Internet at: http://www.fs.fed.us/eng/pubs/

Forest Service and U.S. Department of the Interior, Bureau of Land Management employees also can view videos, CDs, and SDTDC's individual project pages on their internal computer network at: http://fsweb.sdtdc.wo.fs.fed.us/

For additional information on culvert scour, contact Greg Napper at SDTDC. Phone: 909–599–1267 ext. 290. Email: gnapper@fs.fed.us

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