An Abstract of the Thesis of

Dale White for the degree of Master of Science in Forest Engineering presented on November 26, 1996. Title: Hydraulic Performance of Countersunk Culverts in Oregon.

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Marvin Pyles

Twenty eight countersunk culverts in Oregon were evaluated to assess current conditions and hydraulic performance. The culverts were also assessed with respect to their stability, particularly when subjected to high flows. In general, the culverts were found to be resistant to erosion and effective at conveying large discharges. Based on study results and reviewed literature, recommendations are given for design of countersunk culverts. Recommendations include countersinking culverts at least 20% of their height and using boulder weirs or bed riprap to stabilize channel bed elevation downstream from culvert outlets.

Water velocity within the barrels of selected culverts was examined. Detailed measurement of water velocity distributions in several culverts during fall and winter discharges documented the presence of zones of velocity of a magnitude currently accepted in the literature as passable by juvenile salmonids. A method for predicting the extent of low velocity zones within the flow cross-section, based on commonly used hydraulic parameters such as normal depth, channel slope, and average cross-sectional velocity, was explored. The extent of low velocity zones was under-predicted in most cases. In all cases the relationship between predicted and measured areas of low velocity appeared linear, suggesting that the development of such a method for use in culvert design may be possible.

Hydraulic Performance of Countersunk Culverts in Oregon

by

Dale White

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Chair of the Forest Engineering Department

Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Dale White, Author

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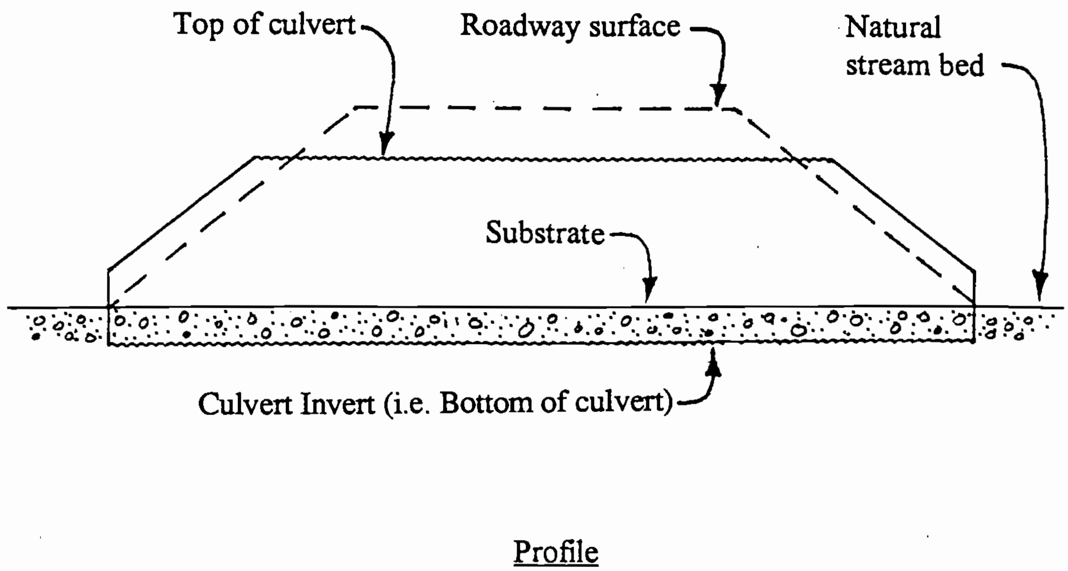
Hydraulic Performance of Countersunk Culverts in Oregon

Introduction

Providing for passage of anadromous salmonids and resident game fish at stream-crossings has long been recognized as vital to the survival of those species. Past efforts at improving migration have been aimed at adult fish traveling upstream to spawn and at smolts traveling downstream from rearing areas to the sea. More recently, concern has been extended to the migratory and re-distributional movements of juvenile anadromous salmonids during their fresh-water life stage and to resident game fish. Recognizing the importance of upstream movement during the juvenile phase, the Oregon Department of Forestry has recently added provisions for juvenile fish passage to Oregon forest practice laws. Adopted in 1994, these regulations require that every crossing of a fish-bearing stream be built so as "to allow migration of both adult and juvenile fish during conditions when fish movement in that stream normally occurs" (ODF, 1994). The adoption of this regulation reflects the concern over providing for passage of juvenile fish at stream-crossings.

The increasingly stringent fish passage regulations in Oregon have generated increased interest in the capability of culverts to provide fish passage at road crossings. Structures which provide a streambed of natural substrate are currently believed to be effective fish passage designs. These structures include countersunk culverts, open-arch crossings, and bridges. Countersunk culverts are constructed with their invert at a lower elevation than the streambed (Figures 1 and 2). Countersunk culverts can be back-filled to streambed level with stream substrate or riprap, or natural stream processes may be allowed to do the back filling. The natural streambed material within the culvert is thought to aid in fish passage by reducing average stream velocity and by creating low velocity pockets.

Open-arch crossings are bottomless sections of steel culvert material or pre-cast concrete mounted on footings. They are well-suited to sites which are underlain by exposed or shallow bedrock. At such sites, open-arch culverts with footings tied to underlying bedrock form stable structures which are resistant to scour. Because open-



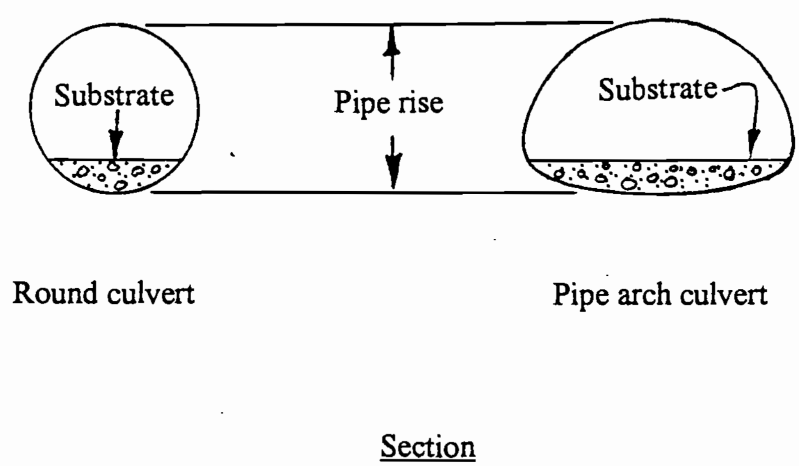


Figure 1. Diagram of a countersunk culvert.

Figure 2. Countersunk culvert on Middle Fork Canyon Creek near John Day, Oregon.

arch crossings require footings, they tend to be more expensive than countersunk culverts. Since both open-arch culverts and deeply countersunk culverts provide an arch-shaped crossing over a streambed of natural materials, there is little functional difference between them (Bates, 1994).

Open-arch crossings and countersunk culverts alter channel hydraulics by constricting the natural channel. Although bridges are thought to be the best alternative for providing passage for aquatic species because they typically do not constrict the natural channel at most discharges, bridges also tend to be far more expensive than either open-arch crossings or countersunk culverts.

Although countersunk culverts have long been recommended as crossing structures where fish passage is desired (Browning, 1990; USDA, 1974; USDOT, 1985), the design and performance of countersunk culverts has received relatively little attention from researchers. This project was designed to provide information on existing countersunk culverts in Oregon and to explore factors regarding their design. Three issues were focused upon:

1) assessment of the ability of countersunk culverts to provide for passage of target species and age groups;
2) evaluation of the stability of the countersunk configuration; and
3) derivation and critical analysis of a method of predicting the extent of low velocity zones within the flow cross-section.

The culvert inventory is intended to serve both as an assessment of the performance of existing culverts and as a basis for future study. The velocity analysis examined the possibility of predicting the extent of low-velocity zones in countersunk culverts using standard hydraulic parameters such as average cross-sectional velocity and depth.

Current state forest practice guidelines specify countersunk culverts as an alternative stream-crossing design to facilitate fish passage. The need for information on the capability of countersunk culverts to provide for fish passage and maintain their intended configuration while effectively conveying stream flow is needed. Information on the design and field performance of countersunk culverts will potentially aid land managers meet current fish passage requirements.

Literature Review

Biological issues

Introduction

The subject of anadromous and resident fish migration in Oregon streams involves several important issues including migration timing and direction, allowable delay at human-made structures, and physical ability of fish to overcome obstacles (Bates, 1994). Research on these topics, particularly with respect to juvenile fish, is lacking. The species and age-specific nature of these issues, as well as their location-specific nature, further complicate the fish migration topic.

There are several issues concerning fish migration that are of particular concern to culvert designers. The hydraulic conditions under which the fish can proceed upstream depend on the swimming ability of the target species (and age class). The timing and allowable delay of upstream movement determine the discharge at which favorable hydraulic conditions must be produced. These needs must be balanced against the need to provide a long lasting, economical structure which also provides for the conveyance of large storm discharges.

Migration timing and allowable delay

Information on migration timing and allowable delay for adult salmonids is relatively abundant (Bates, 1994; Behlke, 1991; G. N. McDonald & Associates, 1994; USDOT, 1990). Timing varies by species and region. Allowable delay, which is the maximum time that fish can be expected to be blocked by a passage barrier, is prescribed by government agencies and varies with species and region.

Regarding juvenile salmonids, numerous studies indicate that upstream movement into tributaries and ponds by pre-smolt juveniles is an important characteristic of the life cycle of coho salmon and steelhead trout in coastal Pacific Northwest streams (Bustard and Narver, 1975; Cederholm and Scarlett, 1982; Everest, 1973; Peterson, 1980; Peterson, 1982, Scarlett and Cederholm, 1984; Skeesick, 1970). This movement occurs primarily in the fall and early winter (Bustard and Narver, 1975; Cederholm and Scarlett, 1982; Peterson, 1980; Skeesick, 1970). It is usually initiated with the first fall freshet, and thereafter primarily occurs during freshets (Bustard and

Narver, 1975; Cederholm and Scarlett, 1982; Everest, 1973; Peterson, 1980; Peterson, 1982, Scarlett and Cederholm, 1984, Skeesick, 1970). The strong correlation between freshets and movement of juvenile fish suggests that the fish move into tributaries and ponds during the fall and early winter seeking high flow refuge and/or relief from high mainstem turbidity levels (Bustard and Narver, 1975; Cederholm and Scarlett, 1982; Peterson, 1980; Peterson, 1982, Scarlett and Cederholm, 1984, Skeesick, 1970). Upstream movement is less prevalent during the late winter and spring (Bustard and Narver, 1975; Cederholm and Scarlett, 1982; Peterson, 1980; Skeesick, 1970). Movement into tributaries and ponds during this period is not as strongly correlated with freshets as is movement in the fall and early winter (Bustard and Narver, 1975; Cederholm and Scarlett, 1982; Peterson, 1980; Peterson, 1982, Scarlett and Cederholm, 1984, Skeesick, 1970). This suggests that late winter and spring upstream movement represents a redistribution in preparation for summer (Cederholm and Scarlett, 1982) rather than escape from high flows. There is relatively little upstream movement of coastal coho and steelhead during the summer (Cederholm and Scarlett, 1982).

All of the studies discussed above took place in coastal Pacific Northwest streams. Because fish in other areas may be subject to different environmental pressures, behavior may differ by location. For instance; summer upstream movement for thermal refuge in warmer, inland streams has been reported anecdotally. No studies were found which addressed this issue.

Size and age classes of juvenile upstream migrants

Juvenile coho salmon and steelhead trout observed in the reviewed studies were of the 0 and 1+ age groups (Bustard and Narver, 1975; Cederholm and Scarlett, 1982; Everest, 1973; Peterson, 1980; Scarlett and Cederholm, 1984; Skeesick, 1970). The mean fork lengths of the coho salmon ranged from approximately 50 mm to 100 mm (Bustard and Narver, 1975; Cederholm and Scarlett, 1982; Peterson, 1980; Scarlett and Cederholm, 1984; Skeesick, 1970). Lengths were not reported for the steelhead trout.

Distances traveled by upstream juvenile migrants

Mark and recapture data indicates that juvenile coho are capable of traveling considerable distances upstream. Fish that were captured and cold branded at the mouths of two tributaries of the Clearwater River were recaptured as far as 1.1 km upstream in one tributary and 1.4 km upstream in the other (Scarlett and Cederholm, 1984). These distances represented the upstream limit of the recapture effort, suggesting that the fish may have been capable of traveling farther upstream. The upper 0.5 km of one tributary was dry during the summer low flow season. These results illustrate the capability of coho juveniles which "summer" in the main stem to utilize habitat far up the tributaries, including intermittent reaches, during the rainy season. Distances traveled by steelhead trout were not reported in the reviewed literature.

Swimming speeds

Since fish traveling upstream move against the flow, water velocity is a critical factor at all points in their journey. Successful negotiation of a culvert generally requires the continuous presence of velocity zones in the flow cross-section against which the fish can make upstream progress at sustained swimming speed (Behlke, 1991). Bates (1994) recommends providing continuous zones within the channel cross-section with a maximum water velocity of 2 fps for effective passage of adult and juvenile salmonids. Bates (1994) also reports that "passage design criteria among species of salmon and steelhead vary little," implying that variation in swimming performance among these species is small enough as to be insignificant from the point of view of the culvert designer.

Behlke (1991) presented equations for computing the sustained swimming speeds of fish species as a function of fish length and duration of effort. The equations resulted from regression analysis of data from numerous studies of the swimming capabilities of adult and juvenile North American trout and salmon. According to these equations, at 15° C a 50 mm juvenile coho salmon (see "Size and age classes of juvenile upstream migrants" above) could pass through a 60 ft long culvert against a water velocity of 1 fps in approximately 55 minutes [Kane et al.(1989) observed Arctic greyling taking less than one minute to over 80 minutes to pass through a 60 ft long culvert]. The 50 mm coho salmon could pass through the same culvert against a 0.8 fps current in approximately 3 minutes. A 100 mm coho salmon could pass through the same culvert against a 1 fps current in less than 1 minute. It could also pass against a velocity of 1.9 fps in approximately 5 minutes. According to Behlke's (1991) equations, the 100 mm coho salmon would be unable to negotiate the culvert against a current of 2.0 fps.

The information presented above suggests that the "target velocity" for passage of juvenile salmonids lies roughly in the 1 fps to 2 fps range, depending on the size of fish for which passage conditions are desired. While this velocity estimate is based on available data - more research is needed before the swimming capabilities of these fish in the wild can be defined with confidence. In addition, it is possible that within-species swimming abilities may vary with geographical location. Information on such variability was not available in the reviewed literature.

Negotiating "perched" outlets

Two other concerns of the culvert designer are "perching" of the outlet and a locally steep gradient at the inlet. Either of these conditions require fish to leap or greatly accelerate to enter/exit the culvert. Several authors suggest a 1 ft maximum drop for adult trout and salmon (Bates, 1994; Behlke, 1991; USDOT, 1990). Behlke (1991) states that the supercritical flow induced by any abrupt drop in bed elevation, whether caused by a culvert or any other instream structure, can result in water velocities that are impassable to juvenile salmonids and other weak-swimming fish. Bates (1994) notes that resident species tend to be poor leapers, suggesting that drops may adversely impact them more than anadromous species.

Observations of Arctic Grayling negotiating a culvert

Kane et al (1989) observed Arctic Grayling moving upstream through a 9.6 foot diameter round steel culvert in Alaska. The two points in the culvert which appeared to present the most difficulty to the fish were the slightly perched outlet and the inlet, where non-uniform flow existed. In negotiating the barrel the fish most often swam in zones of relatively low velocity near the outside edges of the flow cross-section. They typically held their bodies perpendicular to the curved sides of the culvert. Smaller grayling (75 to 150 mm) were observed to rest by holding stationary in pipe corrugations while negotiating the culvert at an average water velocity of 5.8 feet per second.

Engineering issues

Countersunk culvert design recommendations

Several of the reviewed papers provide design recommendations for countersunk culverts (Behlke et al, 1991; Bates, 1994, Browning, 1990; G. N. McDonald & Associates; 1994). Behlke et al (1991) presents a procedure and computer program for the design of countersunk culverts for passage of weak-swimming fish (including juvenile salmonids) in Alaska. This design procedure may be applicable in Oregon if the method used to determine the design discharge is modified to address conditions and fish found in Oregon. Bates (1994) also recommends that culverts be countersunk at least 20% of their diameter as protection against channel degradation and scour pool formation and as a means of increasing bed roughness within the culvert. Browning (1990) presents a detailed list of design criteria including:

1) a headwater-to-rise ratio of ≤ 1

2) a culvert barrel velocity which exceeds the natural stream velocity by no more than 25% during a discharge magnitude with return period of 2 years

3) outlet scour not exceeding 0.5 feet during a discharge magnitude with return period of 2 years

4) placement of the culvert inlet 12 to 24 inches below natural streambed level for culverts with effective diameter 10 feet or less

5) placement of the culvert invert a distance of at least 20% of the culvert rise below the natural streambed level for culverts with equivalent diameters of more than 10 feet

6) filling of the culvert to streambed level with materials similar to the natural streambed materials

7) placement of the culvert barrel on as flat a slope as possible to promote recruitment and retention of substrate.

G. N. McDonald & Associates (1994) recommends countersinking culverts by at least 20% of their diameter and placing them at a slope of no more than 0.5%.

Countersunk culvert performance evaluation

McKinnon and Hnykta (1985) evaluated the field performance of countersunk culverts at four streams tributary to the Liard River in Canada. The culverts were countersunk and filled to the natural bed level with riprap. The goal was to provide a large enough zone of low velocity (≤ 3 fps) to allow fish passage at the passage design discharge. Data on fish species composition, habitat use, migration patterns and timing as well as hydraulic and hydrologic data are reported in this study. Fish species present included Arctic Grayling, Longnose Sucker, Brook Stickleback, Slimy Sculpin, Northern Pike, Lake Chub, and Finescale Dace. Discharges during the study period did not exceed the mean annual flood. With respect to fish passage, the authors concluded that the culverts appeared to have areas of sufficient low velocity to allow passage of the observed fish species and sizes, and that no spawning migration delays due to the culverts were apparent.

McKinnon and Hnykta constructed detailed velocity maps at cross-sections in the culverts for use in analysis of velocity distributions. Conclusions made by the authors concerning the hydraulic performance of the examined countersunk culverts included:

1) the culverts appeared to have areas of sufficiently low velocity to allow passage of the fish species and sizes that were present;
2) the riprap material placed on the culvert floor appeared to be stable under the examined discharges;
3) velocities within the culverts were comparable to those in the natural stream;
4) the stream simulation approach (countersinking and back-filling the culverts with riprap) "appears to be a valid concept."

<u>Designing for fish passage in conventional culverts</u>

Many references exist which describe the hydraulic characteristics and design of standard, non-countersunk culverts (e.g. USDOT, 1985; USDOT, 1990; Pyles, 1992; Bates, 1994; G. N. McDonald & Associates, 1994). All of the reviewed references on culvert design include discussions of fish passage considerations. Bates (1994) focuses specifically on fish passage in culverts. The USDOT (1985) publication is a detailed culvert design manual intended for use by federal agency engineers.

The reviewed culvert design references for standard culverts agreed on several important points regarding fish passage. These include: 1) acceptable flow types; 2) the importance of maintaining continuous zones of velocity against which fish can pass at their respective sustained swimming speed; and 3) the importance of preventing channel degradation at the culvert outlet. The flow type at a given discharge (a rough indicator of velocity) affects fish passage success at that discharge. Inlet control flow conditions, which indicate supercritical flow conditions, are generally considered to be an unacceptable flow type for fish passage because of the associated high water velocities (Behlke, 1991; Bates, 1994; G. N. McDonald & Associates, 1994). Outlet control flow conditions are preferable to inlet control conditions when fish passage is desired (Bates, 1994). The ideal flow type for fish passage is "tranquil" flow, where flow depth exceeds critical depth throughout the pipe (G. N. McDonald & Associates, 1994).

Protection against scour

Scour holes tend to develop at the exit of any culvert (G. N. McDonald & Associates, 1994), and such degradation of the channel bed below the outlet of a culvert can adversely affect the fish passage capabilities of the culvert (USDOT, 1990; Behlke, 1991; Bates, 1994; G. N. McDonald & Associates, 1994). This lowering of the bed level below the outlet can cause an increase in water velocity in the pipe (Behlke, 1991), and in extreme cases of downstream erosion, the culvert outlet can become perched (USDOT, 1990; Bates, 1994). To negotiate a perched culvert outlet a fish must leap as well as overcome potentially high velocities. Placing riprap as a scour mat downstream is a commonly recommended solution to the outlet scour problem (Behlke, 1991; Bates, 1994; G. N. McDonald & Associates, 1994). Another preventative measure against excessive scour is to increase the size of the culvert in order to reduce water velocity in the culvert (Behlke, 1991). Several of the references recommend the construction of low weirs downstream of the culvert outlet as a means of raising the outlet water level to prevent channel degradation below the culvert outlet (USDOT, 1990; Behlke, 1991). USDOT (1990) indicates that scour around the culvert inlet may result from the culvert barrel not being aligned with the incoming flow. Proper alignment or streambank protection are suggested as remedies to this problem.

Velocity distribution in open channels

Many researchers have attempted to model velocity distributions in the water columns of open channels (Chow, 1959; Song and Yang, 1979; Vanoni, 1941). Some authors presented logarithmic or simple polynomial functions to relate velocity to distance above the channel bed (Chow, 1959; Vanoni, 1941). A recent model divides velocity distribution in the water column into three layers: a "laminar sublayer" nearest the bed, which can be modeled as a linear function; an "inner turbulent layer" further above the bed, which follows a logarithmic function; and an "outer turbulent layer" extending to the water's surface, which follows a polynomial function (Song and Yang, 1979). Figure 3 illustrates the three layers of the velocity profile presented by Song andYang (1979). The descriptive equations presented for the three layers of the water column are

Laminar sublayer: $V/(gDS)^{0.5} = [y * (gDS)^{0.5}]/\nu$

Inner turbulent layer: $V/(gDS)^{0.5} = A_1 * LN(y/D) + A_2$

Outer turbulent layer: $V/(gDS)^{0.5} = A_3 + A_4(y/D) + A_5(y/D)^2$

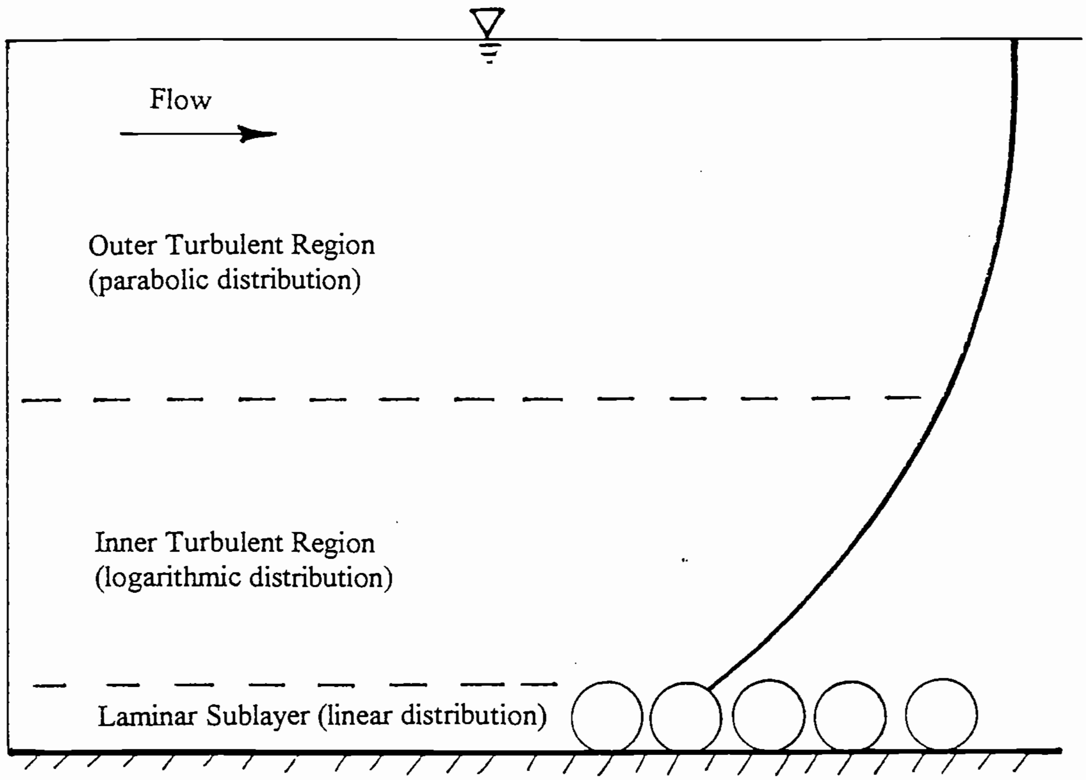


Figure 3. The three layers of velocity distribution in turbulent flow (after Song and Yang, 1979).

where V = velocity; g = the gravitational constant; D = water depth; y = distance above bed; ν = kinematic viscosity; and A_1, A_2, A_3, A_4, and A_5 are constants (Song and Yang,1979). The laminar sublayer extends to the top of the substrate (Song and Yang assume substrate of uniform size), and the boundary between the inner and outer turbulent layers lies approximately midway between the water surface and the bed for turbulent flow.

Methods

Introduction

This study of countersunk culverts in Oregon focused on three issues.

1) The ability of countersunk culverts to provide for passage of target species and age groups was assessed. This issue might be best addressed through mark and recapture studies of fish. Because this approach was beyond the scope of this study, hydraulic conditions were examined instead. Velocity distributions within several countersunk culverts were measured and compared to published information on fish swimming capabilities. This allowed for the assessment of whether the countersunk configuration results in hydraulic conditions which might reasonably be expected to provide for adequate passage of target species and age groups.

2) The stability of the countersunk configuration was evaluated. The question of whether countersunk culverts are capable of maintaining their intended configuration over time was addressed through an assessment of the condition of the culverts. This included consideration of the largest estimated discharge that the culvert had been subjected to since construction and the effects of the large storm event of February 1996.

3) A method for the prediction of the extent of low velocity zones within the flow cross-section was explored. Prediction of the extent of low velocity zones was examined through a detailed analysis of velocities in several culverts.

The culvert inventory

Countersunk culvert locations were determined through a telephone survey of National Forest Headquarters in Oregon, the Oregon Department of Forestry , the Oregon Department of Fish and Wildlife, the USDOT Federal Highway Administration, and Oregon offices of the Bureau of Land Management. The telephone survey was followed by a field inspection of each identified culvert. In some cases, the culverts were found not to be countersunk. Those culverts that were countersunk were subjected to a detailed site survey. In total, 28 countersunk culverts located throughout Oregon were included in the study (Figure 4).

The site survey of each culvert was conducted during the summer of 1995. Details of culvert structure including culvert type, culvert dimensions, corrugation size, and inlet and outlet configurations were recorded. The alignment of pipe with respect to

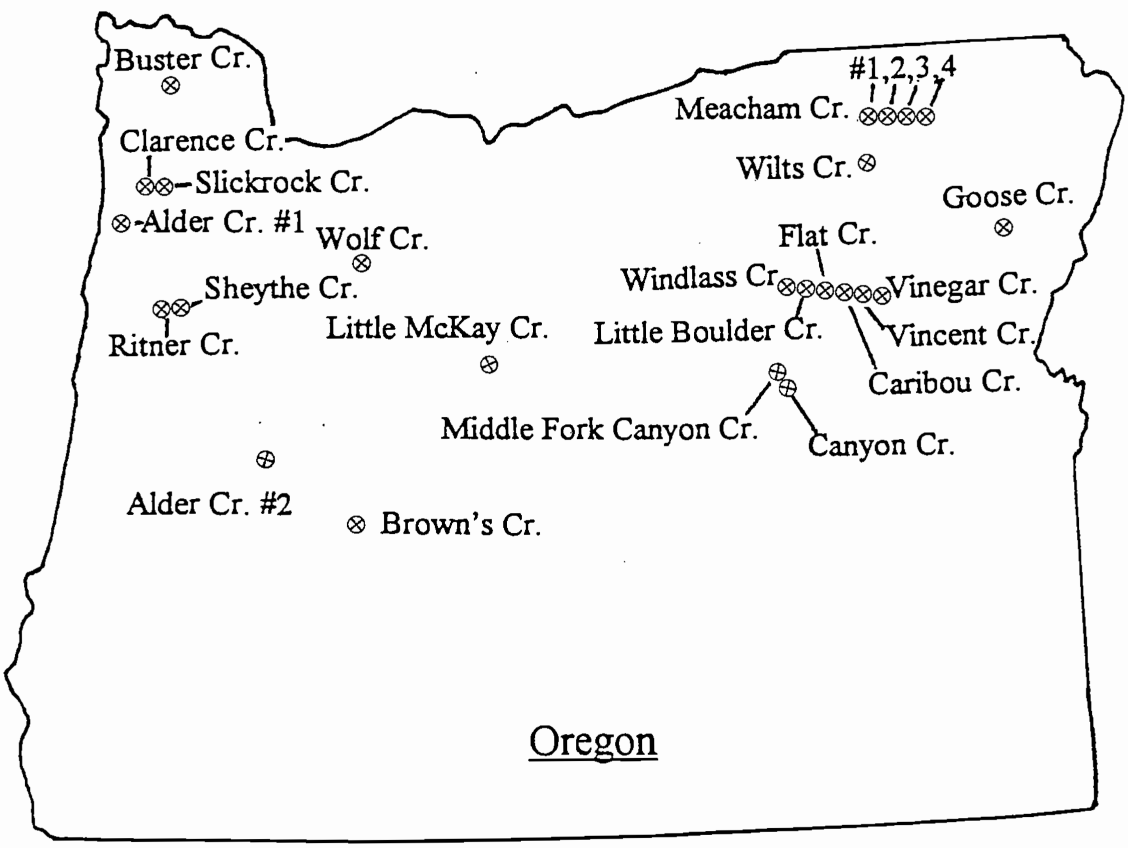


Figure 4. Culvert locations.

the upstream channel (incident angle) was measured using a compass. A level survey was conducted at each culvert site using an engineer's level and stadia rod. The survey followed the channel thalweg from approximately 100 ft above the culvert inlet to approximately 100 ft below the outlet. This distance was shortened to approximately 50 ft when heavy brush was present. The survey terminated if the stream entered a larger stream or river within 100 ft of the culvert outlet. Substrate in the mid-section (middle 50% of the length of the culvert) of the culvert was characterized using the "random walk" sampling method described in Wolman (1954).

A qualitative assessment of site conditions was made. It included assessment of the structural integrity of the culvert, the substrate in the culvert barrel, and the riprap on fill slopes near the inlet and outlet. Areas of scour and deposition and presence of woody debris were noted. The presence of bed riprap, boulder weirs, or bedrock sills downstream of the outlet was also noted. Active channel width (defined as that portion of the channel which is commonly occupied by winter or spring high flows and, consequently, is unvegetated) was measured above and below the culvert. A site sketch was drawn which included the locations of all important features and observations. Photographs were taken of the inlet, outlet, and any other points of interest. The age of the culvert structure was obtained from design plans, from dates written into concrete rip-rap, or from estimates by local Forest Service hydrologists and engineers.

A large storm during February, 1996 resulted in discharges in excess of the 20-yr event on many Oregon streams. All of the sites were re-visited during the spring of 1996 and changes due to winter high flows were recorded. Field notes and photographs were used to determine these changes. A "score sheet" was devised for the spring 1996 survey which provided a protocol for evaluating the inlet, outlet, and entire culvert. The Appendix contains a sample score sheet with complete definitions of the scoring categories, criteria, and matrices used to determine composite scores. The inlet was assigned a score from 1-4 depending on the degree of scour observed; with a score of 1 indicating severe scour and a score of 4 indicating no appreciable scour. Stability (the apparent susceptibility to change) was rated in a similar manner as scour; based on subjective observation of current conditions and comparison with conditions observed during summer 1995. A matrix was then employed to determine an overall score for the inlet. Certain variables such as the presence of natural features providing downstream bed elevation control were not incorporated into the matrices. In several instances such variables were deemed important. In those instances the guidance of the matrices was disregarded and an alternate rating was assigned which better fit the situation in the spirit of the rating definitions. After the inlet was rated, a similar procedure was utilized to assign an overall score to the outlet. Finally, a third matrix was used to determine a general score for the culvert. General score values ranged from 0 to 4, with 0 indicating culvert failure and 4 indicating an installation that appears to be stable and has a good bed configuration. General observations about the effects of the 1996 winter flows were also recorded during the spring 1996 survey.

Culvert crown slope and local streambed slope were determined from the surveyed thalweg profiles. Inlet, outlet, and average fill depths of substrate in the culvert barrel were calculated using survey data. Relative fill depths, defined as (depth of substrate)/(height of culvert pipe), were calculated. Inlet constriction and outlet flow expansion variables, defined as (culvert width)/(upstream channel width) and (downstream channel width)/(culvert width) respectively, were also calculated. D_{50} and D_{84} sizes were determined from b-axis size vs. cumulative frequency plots of substrate sample data. Local stream slopes (from culvert inlet to 1/4 mile upstream) and drainage areas were measured on USGS topographic maps using a map wheel and planimeter. The return periods of the largest discharge events that the culverts had been subjected to since construction were estimated using USGS data, National Weather Service data, and a statistical summary of Oregon stream flow data (Wellman et all, 1993). In several cases stream gages were too distant from culvert sites to provide reasonable estimates of discharges at the sites. Estimates by local Forest Service hydrologists were used in these cases.

A table incorporating all of the culvert inventory data was constructed. Using this table, "score sheet" values were plotted against measured or calculated variables such as incident angle of flow or channel constriction at inlet. Statistical analysis (such as multivariate analysis) was not employed due to low correlation between score sheet values and measured or calculated variables.

The velocity study

Velocity study sites

Three countersunk culvert sites in the coast range of Oregon were selected for detailed velocity measurements. The Ritner Creek and Sheythe Creek culvert structures each consist of three parallel, single-piece, round culverts. The Clarence Creek culvert is a single, multi-plate, pipe arch culvert. Detailed descriptive information on these culverts can be found in the Culvert Inventory Data Table in the Appendix.

Classification of roughness in study culverts

Bathurst (1982) characterized roughness in boulder bed streams as small, medium, and large scale based on relative submergence. Large scale roughness imparts significant form resistance on flow, as well as inducing high levels of internal distortion resistance associated with turbulence. Resistance under small scale roughness conditions is dominated by skin resistance imposed by the channel bed and banks (Bathurst, 1982)(Figure 5). The approach to predicting hydraulic conditions in countersunk culverts is different under the different roughness regimes. Sites with medium and large scale roughness probably represent "fish ladder" type problems. Under such conditions fish rely upon the presence of relatively low velocity resting sites and burst swimming to negotiate a culvert (Behlke, 1991). The Clarence Creek culvert is an example of this kind of passage situation. Solutions to this problem were not explored in this report. Instead, velocities present under the small scale roughness conditions such as those found at the Ritner and Sheythe Creek culverts were examined.

Data collection and reduction

Each of the culvert sites was visited on multiple occasions during fall 1995 and winter 1996 for detailed velocity measurements. Velocities were measured on cross-sections at the mid-point and outlet of each pipe (at the outlet only at Sheythe Creek) using a Marsh McBirney Flowmate 2000 velocity meter. Measurements were taken at 1 ft horizontal intervals near the center of the channel and at minimum 0.5 ft horizontal intervals near the walls of the culvert. At each of these stations velocity were measured at 0.1, 0.2, 0.4, 0.6, 0.8, 1.2, 1.6, 2.0, 2.4, and 2.8 feet above the streambed.

Cross-sections were plotted using Excel spreadsheet software. Included were bed surface, water surface, and locations of the velocity measurement points. Measured velocity values were inserted and isovels were drawn by hand. Cross-sectional area of flow and area between isovels was measured using a planimeter. Average velocity for each cross-section was calculated as discharge divided by total cross sectional area of flow. Hydraulic depth was calculated as the total cross-sectional area of flow divided by the top width of the wetted channel.

Application of Manning's equation to calculate average cross-sectional velocity

Manning's equation was applied to culvert geometry data in an attempt to predict average cross-sectional velocity. This procedure was conducted twice: once using the

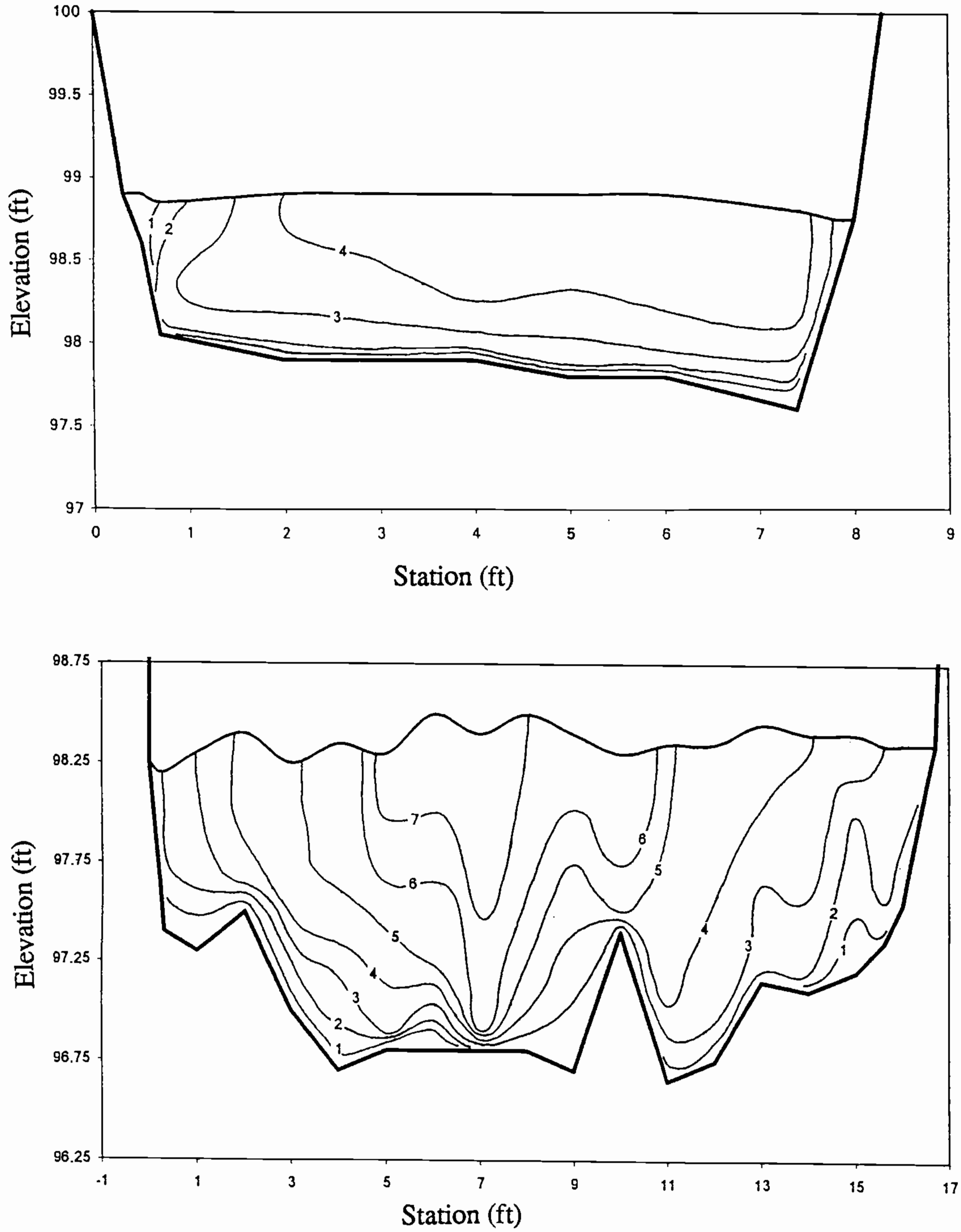


Figure 5. Isovels (fps) illustrating small-scale roughness on Ritner Creek (top) and large-scale roughness conditions on Clarence Creek (bottom).

individual culvert slopes of 1.1, 1.2, and 1.5% for the left, middle, and right culverts respectively, and once using the local streambed slope of 1.1% for all three culverts. In both cases, numerous values of Manning's "n" were tried. The results were compared to the measured average cross-sectional velocity in order to determine the "n" value which produced the best agreement between the predicted and measured average velocities.

McKinnon and Hnytka (1985) included detailed velocity data for 21 cross-sections from three countersunk culverts which exhibited small scale roughness. The culvert diameters were 17, 15, and 16 ft, with corresponding slopes of 0.13, 0.0, and 0.04% respectively. Substrate in all three culverts was gravel and silt. An attempt was made to apply the procedure involving Manning's equation outlined above to these culverts. Because the individual slopes of the three culverts were zero (or very near to zero) the Manning's equation gave highly inaccurate results. Local streambed slopes were not reported by McKinnon and Hnytka (1985). Thus, prediction of average cross-sectional velocity using Manning's equation was not possible for the McKinnon and Hnytka (1985) data.

<u>Development of an equation for prediction of low velocity zones in cross-sections based on average cross-sectional velocity</u>

For each of the 19 Ritner Creek cross-sectional data sets, velocity profiles were plotted for each of the vertical stations. Because of the shallow, roughly rectangular shape of the flow cross-section, the "wide channel" approximation was used (the relatively small, triangular shaped portions of the cross-section lying beyond the substrate edges were disregarded). Chow (1959) stated that this wide channel approximation can be used with certainty when the channel width to depth ratio exceeds 10. Ritner Creek culvert width to depth ratios averaged approximately 7, falling short of the range of certainty proposed by Chow (1959). Due to the exploratory nature of the velocity analysis, however, the wide channel approximation was considered appropriate and was utilized.

By averaging the velocity profiles, a "representative" velocity profile was created for each of the nineteen cross-sections. These "representative" velocity profiles were normalized as follows: depth was normalized by dividing measured depth by the hydraulic depth of the cross-section, and velocity was normalized by dividing measured velocity by the average velocity for the cross-section. The normalized profiles were plotted on semi-log paper and the equation of a linear regression line fitting the data points was obtained. This equation modeled the relationship between normalized velocity (V/V_{ave}) and the log of normalized depth [Log(y/D)]. This procedure was repeated using the data for 21 cross-sections supplied by McKinnon and Hnytka (1985) and 3 cross-sections from Sheythe Creek. A regression line was fit to this data, in the manner described above for the Ritner Creek culvert data analysis.

<u>Prediction of low velocity zones in the cross-sections based on average cross-sectional velocity</u>

Based on the relatively shallow, rectangular shape of the flow cross-sections, the following assumption was made: the proportion of the two dimensional "representative" velocity profile which has a velocity less than or equal to a given velocity is an accurate approximation of the proportion of the entire three dimensional flow cross-section which has a velocity less than or equal to that given velocity. Adopting this assumption, the regression equation relating (V/V_{ave}) and Log(y/D) was used to calculate the predicted proportion of the water column with velocity less than or equal to 1 fps (and 2 fps) for each of the nineteen Ritner Creek cross-sectional data sets. The 1 fps and 2 fps velocities were chosen as representative velocities based on fish passage literature, which suggests that the upper velocity limit for passage of juvenile salmonids falls between these values (Bates, 1994; Behlke, 1991). The measured proportion of the cross-sectional area with velocity less than or equal to 1 fps was plotted against the proportion predicted by the regression equation. The analysis was repeated with 2 fps as the given velocity.

The regression equations were applied to the Ritner Creek data using three sets of average cross-sectional velocity values:

1) measured average cross-sectional velocity;
2) average cross-sectional velocities predicted by Manning's equation, using individual culvert slopes, and;
3) average cross-sectional velocities predicted by Manning's equation, using local streambed slope.

The measured average cross-sectional velocity was used in order to assess the accuracy of the regression equation prediction without the introduction of error associated with application of Manning's equation. Average cross-sectional velocities predicted by Manning's equation were used in order to test the accuracy the predictive method using hydraulic parameters available to the culvert designer during the design stage.

The predictive procedure described above was applied to the data supplied by McKinnon and Hnytka (1985). Since application of Manning's equation to this data yielded inaccurate results, the predictions were based on measured average cross-sectional velocity.

Results

Culvert inventory data

A total of twenty eight countersunk culverts were inventoried in locations throughout the northern half of Oregon (Figure 4). It is unknown what proportion of the existing countersunk culverts in Oregon is represented by this sample. Based on the search methods used to locate the sample, however, it is likely that it includes a significant proportion of the countersunk culverts in Oregon. Sixteen of the culverts were on the east side of the Cascade crest and the remaining twelve were to the west. Drainage basin sizes ranged from less than 0.5 to 23 square miles, with an average of 7.5 square miles. A summary of the culvert inventory data is presented in the Appendix.

Stream and culvert gradients

Local stream gradients ranged from 0.4% to 7.4% (Figure 6). Culvert gradients (inlet crown to outlet crown) ranged from -0.7% to 7.6%(Figure 6). Eight of the culverts had gradients greater than 2%; three of the culverts had gradients exceeding 4%.

Culvert installation types and sizes

Twenty-two of the culverts were in single-pipe installations. The remaining six culverts belonged to the three-parallel-pipe installations at Ritner and Sheythe Creeks. Twenty of the culverts were pipe-arch style and eight were round. Heights ranged from 4.6 to 19.5 ft, widths ranged from 6.1 to 20.8 ft, and lengths ranged from 50 to 160 ft (Figure 7). Nineteen of the culverts were of multi-plate construction and the remaining nine were of single-piece construction. All but three of the culverts had mitered ends at the inlet and outlet. Several of the culverts with mitered ends had inlet or outlet walls which had been bent in by rip-rap, potentially lowering the conveyance capacity of the culvert (Figure 8).

Substrate sizes and depths of fill within culvert barrels

D_{50} sizes for substrate within the culvert barrels ranged from less than 1 mm (silt) to 120 mm (Figure 9). The average (over the length of the culvert) depth of fill ranged from 0.2 ft to 5.6 ft and averaged 1.75 ft (Figure 7). Relative depths of fill,

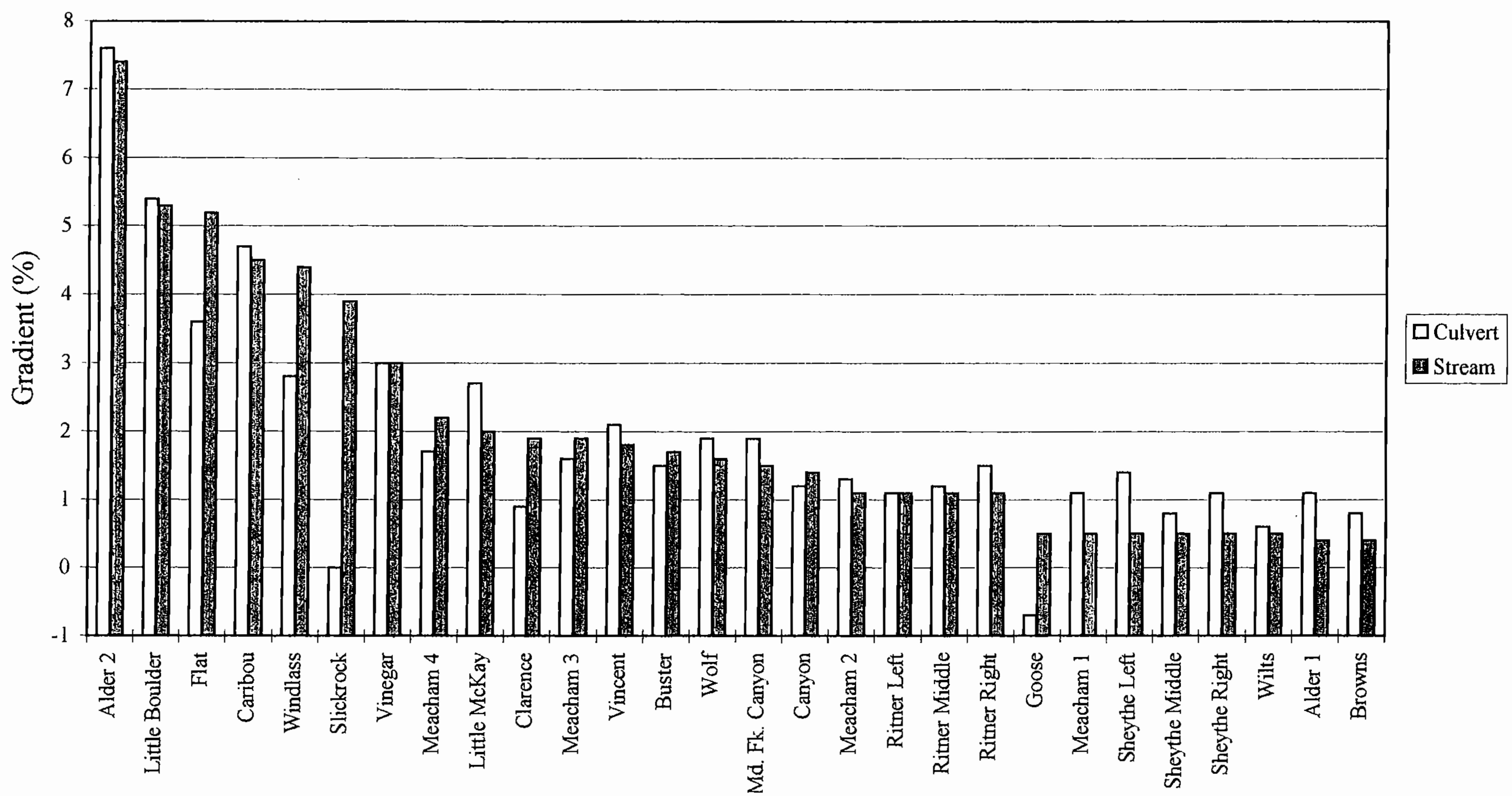


Figure 6. Local stream gradient and culvert gradient.

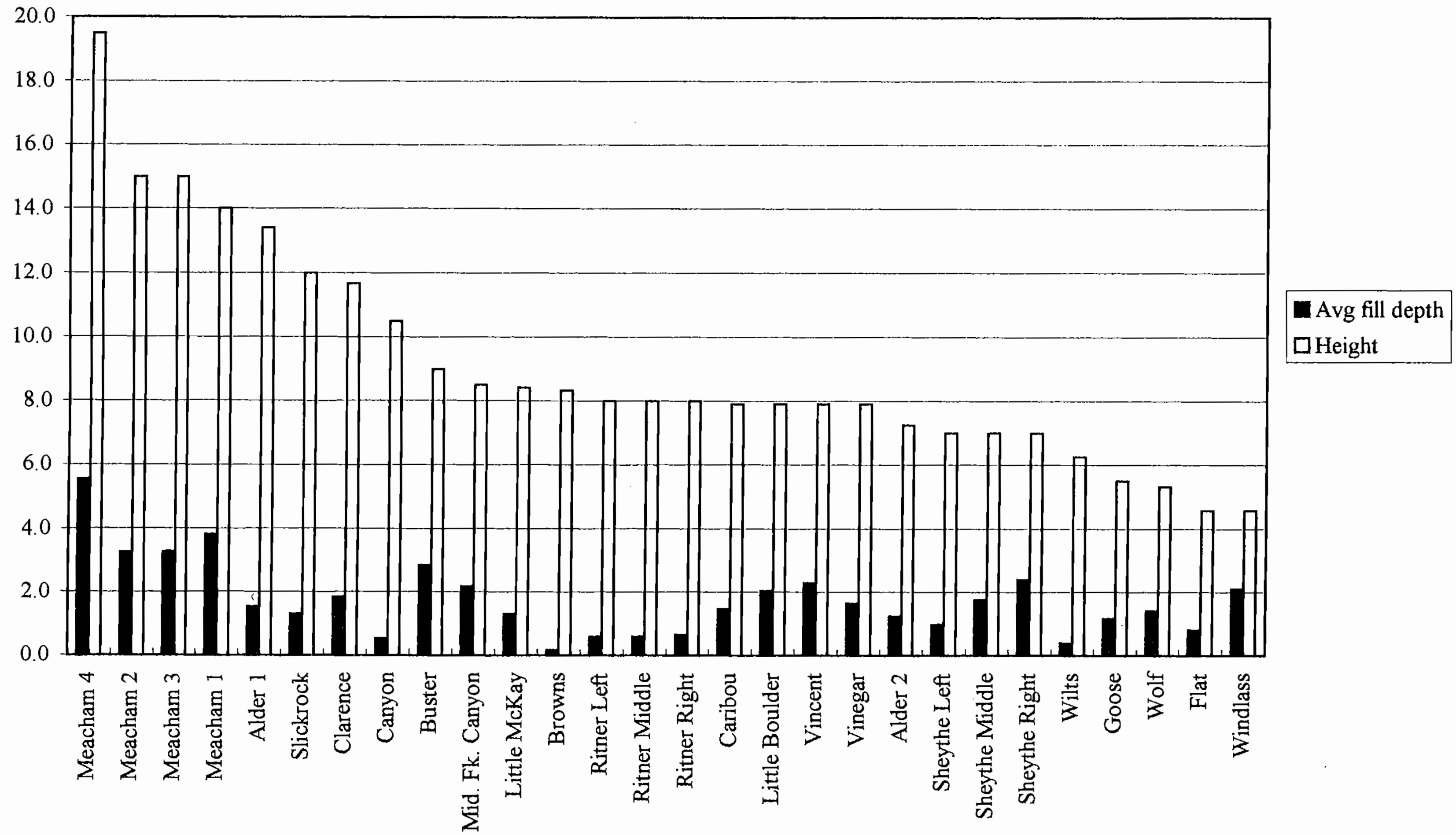


Figure 7. Culvert height and average fill depth.

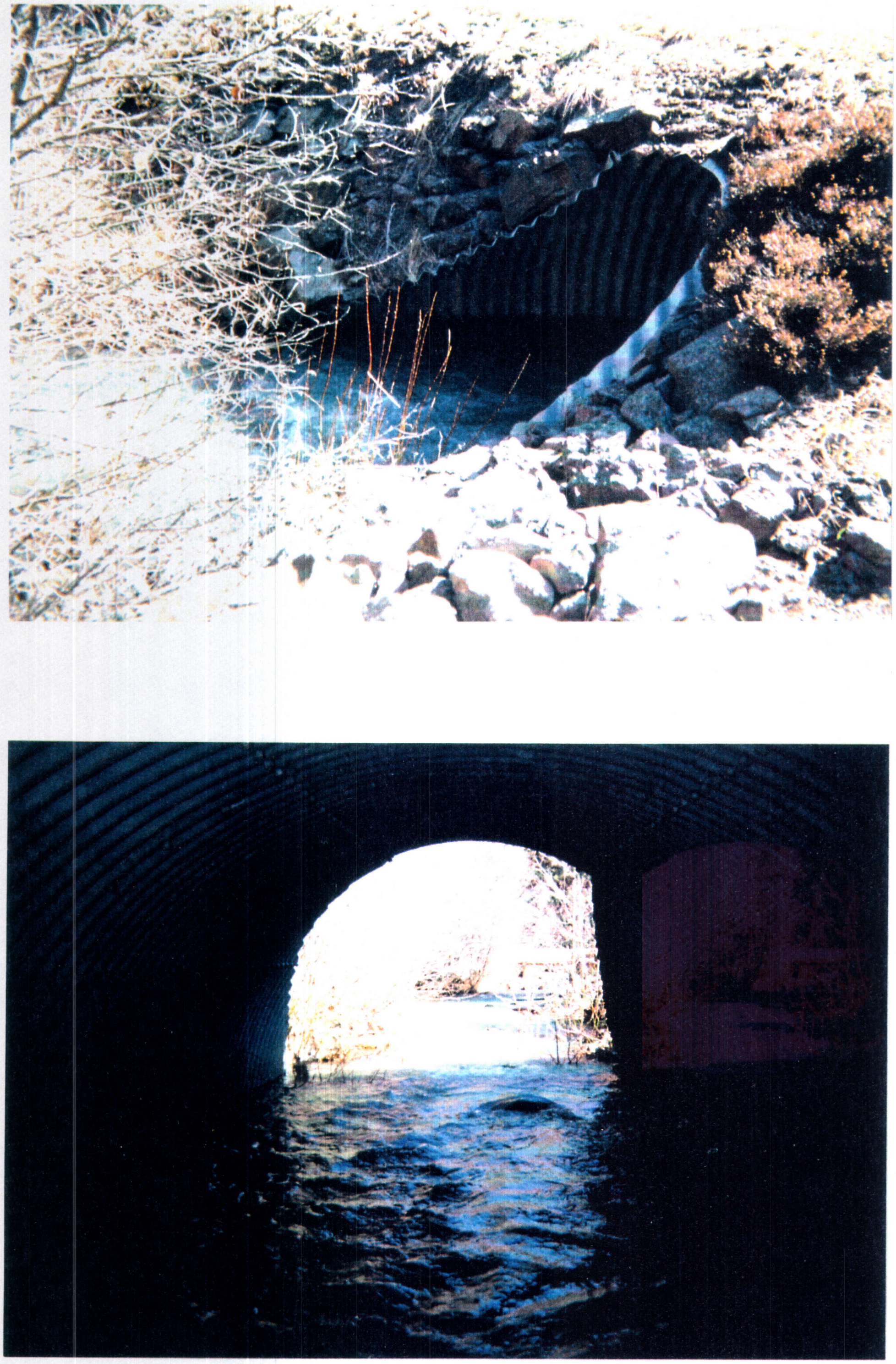


Figure 8. Damaged inlet on Little McKay Creek culvert.

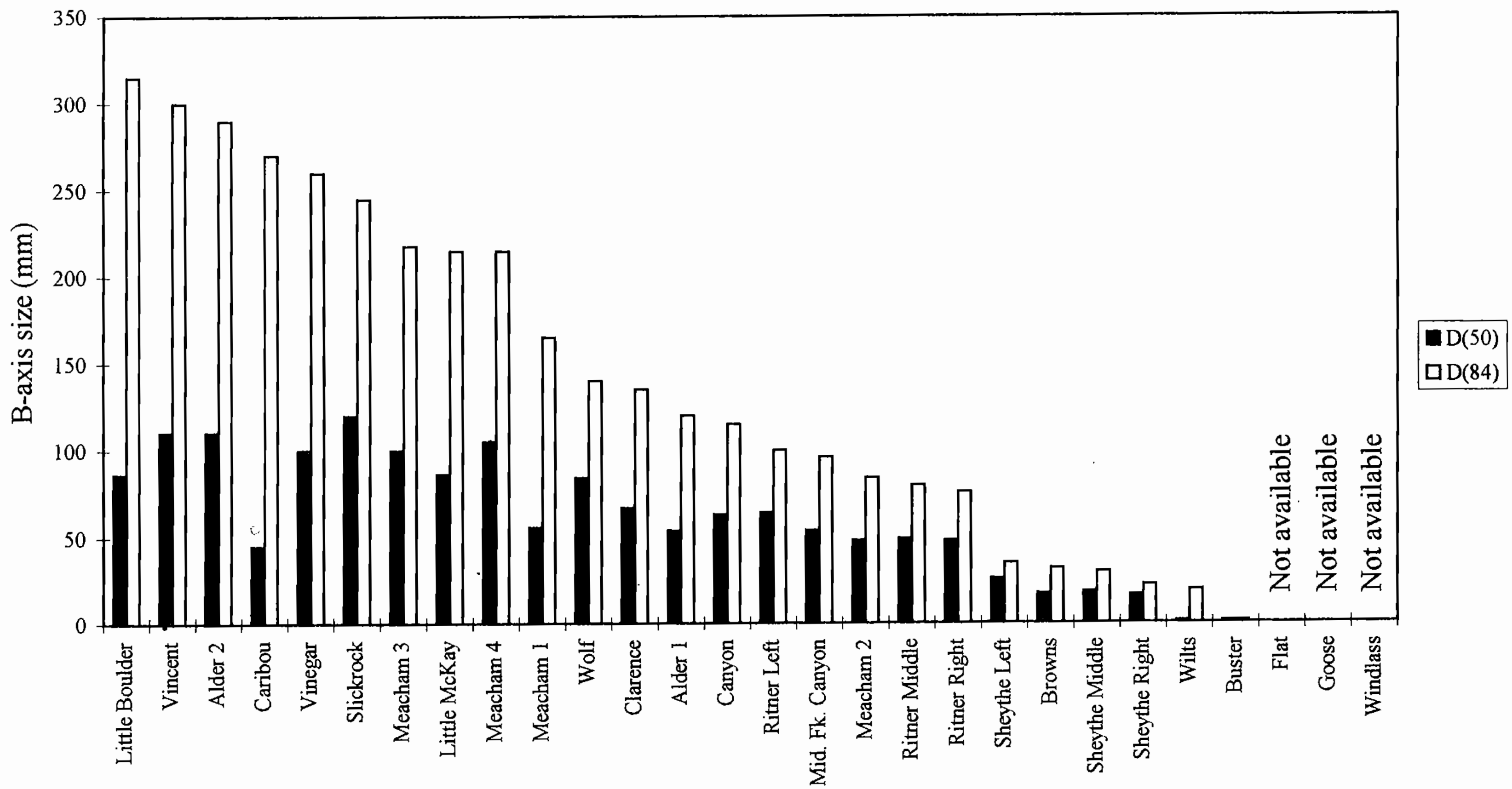


Figure 9. Substrate size.

defined as the actual depth of fill divided by the height of the empty culvert, ranged from 0.02 to 0.46. The average relative depth of fill was 0.19 with a standard deviation of 0.1.

Incident angle of stream channel

The incident angle of the stream channel is defined as the angle between the incoming channel thalweg and the longitudinal axis of the culvert barrel. The maximum incident angle observed was 60 degrees. The minimum was 0 degrees and the average was 22 degrees (Figure 10). The possibility that incident angle might be related to scour at culvert inlets was examined. Because the deflection of incoming stream flow by a culvert wall may cause the formation of a lateral scour zone as would flow impinging on a boulder bank of a natural channel. Figure 11 shows the inlet scour "score" vs. incident angle. A least squares regression line through the data shows increased scour (i.e., lower "scour score") with increased incident angle ($P < 0.05$). However, the low r-squared value reflects the low predictive power of the regression line.

Effects of woody debris on inlet hydraulics

Although woody debris was not present (or was present with no effect on inlet hydraulics) at 21 culverts, it had a moderate to major effect on the inlet hydraulics of seven culverts. Typically, logs lying across inlet mouths deflected flow, causing increased scour of substrate. Figure 12 shows an accumulation of woody debris spanning the inlet of Meacham Creek 3 culvert at an elevation several feet above the bed. The log jam appears to have deflected streamflow downwards towards the bed and caused the excavation of a 1.75 ft deep scour pool. Figure 12 also shows a debris jam across the inlets of the Ritner Creek culverts. The right culvert at the Ritner Creek installation provided another example of inlet scour induced by a debris jam. In this case the debris jam lay directly on the streambed. The action of the streamflow pouring over this debris "weir" apparently scoured the culvert floor bare for a distance of approximately 20 ft below the inlet.

Debris jams affected distribution of flow among the three pipes of the installations at Ritner and Sheythe Creeks. At Ritner Creek a debris jam formed across the middle culvert inlet in fall 1995 and protected it from scour during the winter. Meanwhile the right culvert, which was forced to convey more water due to the partial blockage of the middle culvert, experienced a significant amount of bed scour along its

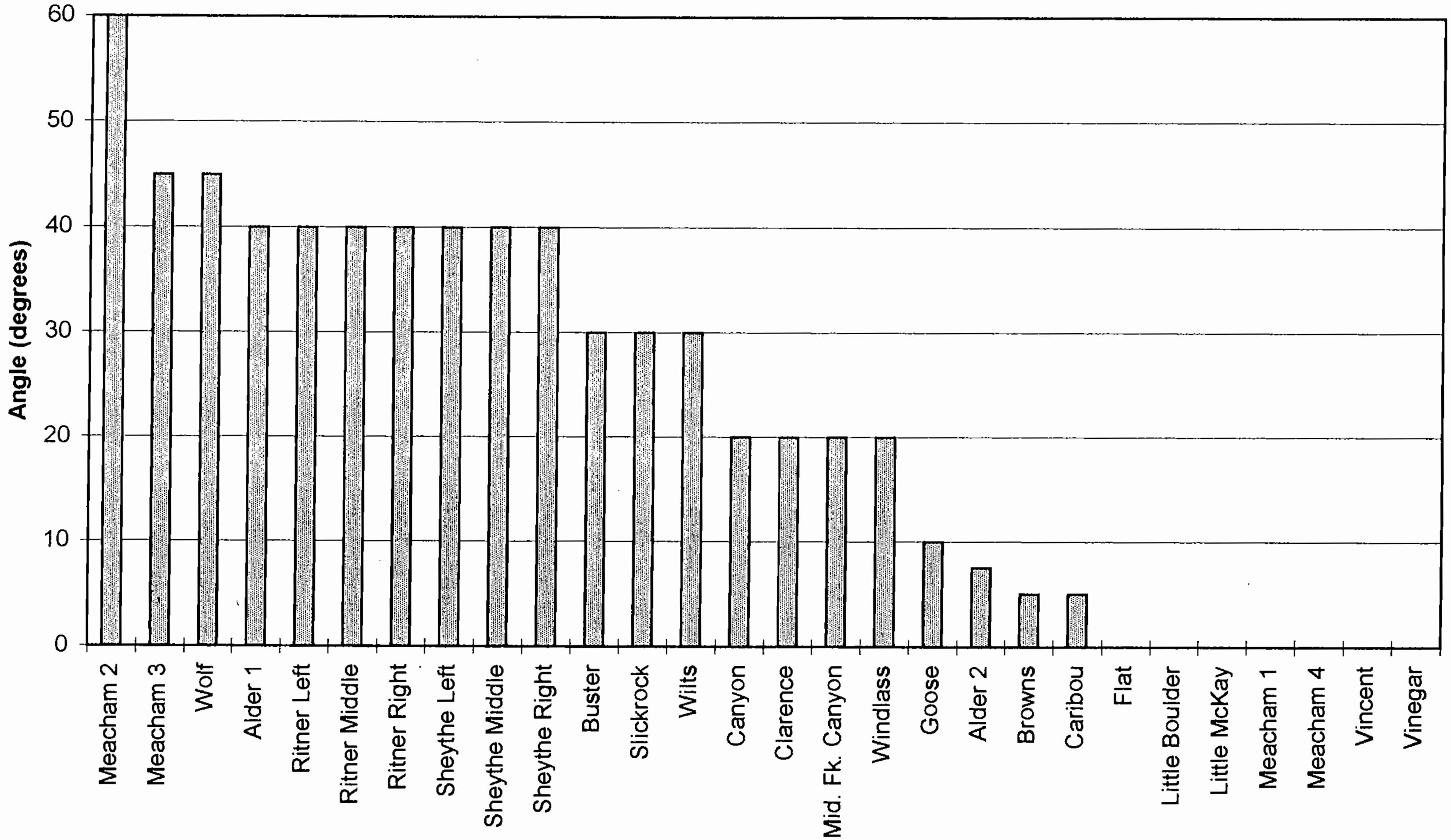


Figure 10. Incident angle of stream channel.

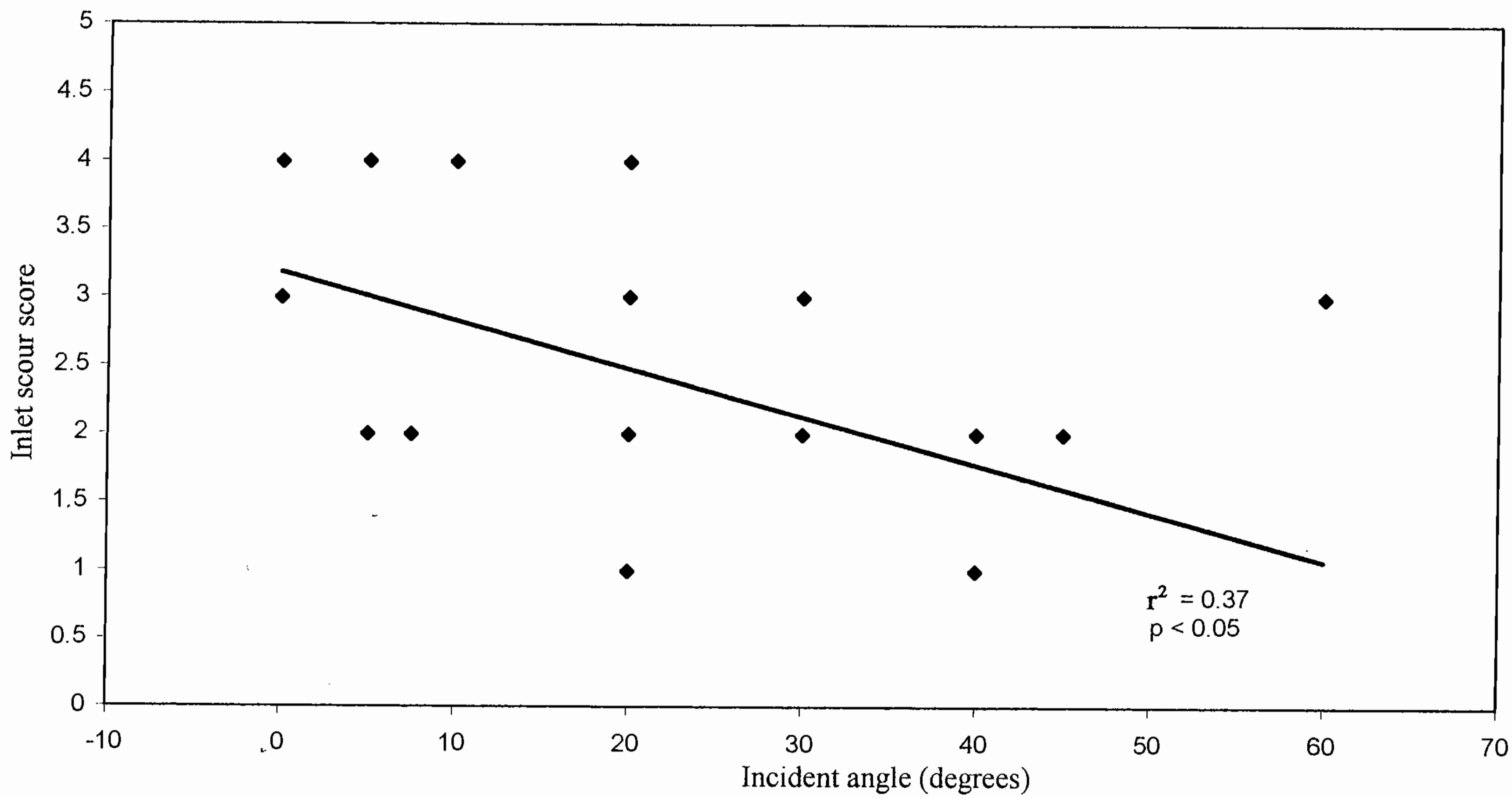


Figure 11. Inlet scour score vs. incident angle of flow.

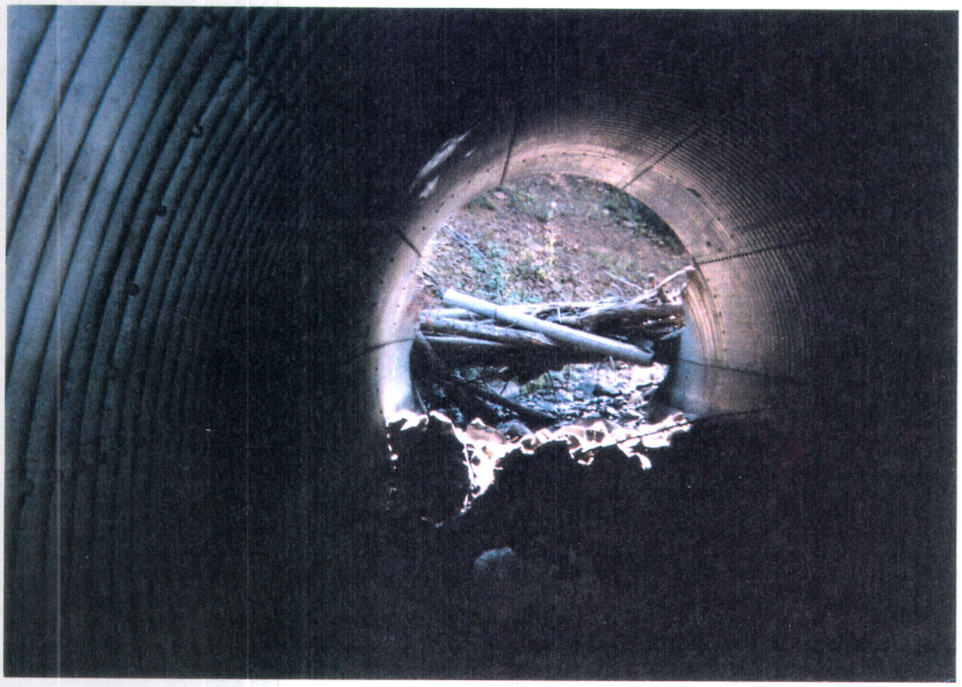


Figure 12. Debris jams across culvert inlets. Top: Meacham Creek culvert #3. Bottom: Ritner Creek culverts.

entire length. Observations indicate that woody debris affected the Sheythe Creek culverts in a similarly variable manner.

Boulder weir or rip-rap protection downstream of outlet

Sixteen of the culverts had bed rip-rap, boulder weirs, or both placed downstream of their outlets at the time of construction. In all cases but one the rip-rap and weirs appeared to effectively prevent destabilizing bed scour at culvert outlets. The one exception was Clarence Creek culvert. This culvert installation included a downstream weir of boulders drilled and cabled together. The weir appeared to be effective at maintaining the stability of the streambed during the fall of 1995 and early winter of 1996. After one boulder was washed from the weir in the storm of February 1996 (estimated return period of 10 yr.) the local bed degraded (Figure 13) and by the spring of 1996 the bed elevation within the outlet of the culvert had dropped approximately 0.5 ft. It is apparent that the outlet has been altered and the potential for the development of a scour pool and perching of the outlet has increased since the failure of the weir.

A relatively high boulder weir was installed below the Windlass Creek culvert, resulting in deposition in the lower portion of the culvert. Figure 14 shows the outlet of Windlass Creek culvert. The flow conveyance capacity of this culvert has been greatly reduced by high weir placement and resulting deposition.

Downstream elevation control by natural features

Natural features provided downstream elevation control (a bed elevation higher than the culvert invert at the outlet) at three of the culvert sites. At Brown's and Alder 1 culverts the natural streambeds provided elevation control at distances of 4-5 stream-widths downstream of the outlets. Both of these culverts formed deep "runs" during observed flow conditions. Water velocities averaged 1.5 fps in Alder 1 culvert under winter a low flow discharge of approximately 68 cfs. The average depth was 2.3 ft. Brown's Creek Culvert, lying on a spring-fed stream on the east side of the Cascade crest, contained deep water moving at 1.1 fps (average depth = 1.4 ft) when visited during mid-June 1995.

A bedrock sill, approximately 15 ft downstream of the Buster Creek Culvert outlet, controlled streambed elevation downstream. Due to the presence of the sill, the space within this culvert formed a deep, low-velocity pool in summer of 1995 (one year after construction). Substrate was not placed within Buster Creek culvert at the time of

Figure 13. Outlet of Clarence Creek culvert. Top: July, 1995. Bottom: March, 1996 (note failed weir and degraded bed at outlet).

Figure 14. Culvert at Windlass Creek. Top: Inlet. Bottom: Outlet showing aggredation due to high placement of downstream weir.

construction, and the bed within the culvert was covered by a deep layer of silt in 1995. The 1996 storm filled the culvert with gravel/rubble sized substrate to the level of the natural channel bed. The bedrock sill appears to have acted as a weir, trapping and holding the substrate in place.

Culvert ages and estimated largest flow events

Culvert ages in 1995 ranged from 2 years to an estimated 25 years (Figure 15), with a mean age of 8.7 years. It was assumed that the largest flow event experienced by a culvert, rather than its age, would be the best indicator of its relative stability. Estimated return periods of the largest storm events experienced by the culverts (including winter 1996) ranged from 5 to 100 years (it should be re-iterated that these figures are estimates based on gages which were in many cases far downstream of the relatively small watersheds examined in this study). Estimated largest discharge events for the culverts are presented in Figure 15. Six culverts had been subjected to discharges of estimated return period 50 years or greater. Thirteen culverts had weathered storms with estimated return periods of 20 years or more.

Unfortunately, the steeper culverts had, in general, experienced storms of shorter return periods. Of the eight culverts which had slopes greater than 2%, only one, at Little McKay Creek, had been subject to a discharge estimated to have greater than a 5 year return period. The 10^+ year estimate for Little McKay Creek was based on the estimated peak flow computed from the measured peak headwater depth. This peak flow estimate equaled that of the predicted 10 year flood discharge according to Campbell and Sidle (1984). Forest Service employees estimated that the return period of the discharge at Little McKay Creek culvert may have been as high as 20-25 years. Aside from the Little McKay Creek culvert, the remaining six culverts had been tested by discharges estimated to have a 5 year return period. The three culverts with slopes greater than 4% had been subjected to discharges estimated to have a 5 year return period.

Scour and stability at culvert inlets

The highest incidence of scour and removal of substrate from the bed typically occurred at the upstream end of a culvert invert, often exposing the upstream lip of the invert, and continued for a short distance into the pipe. Eight culverts had inlet scour which exposed invert steel. In all eight cases, invert steel was exposed for a distance greater than one culvert width. Contributing causative factors appeared to be high

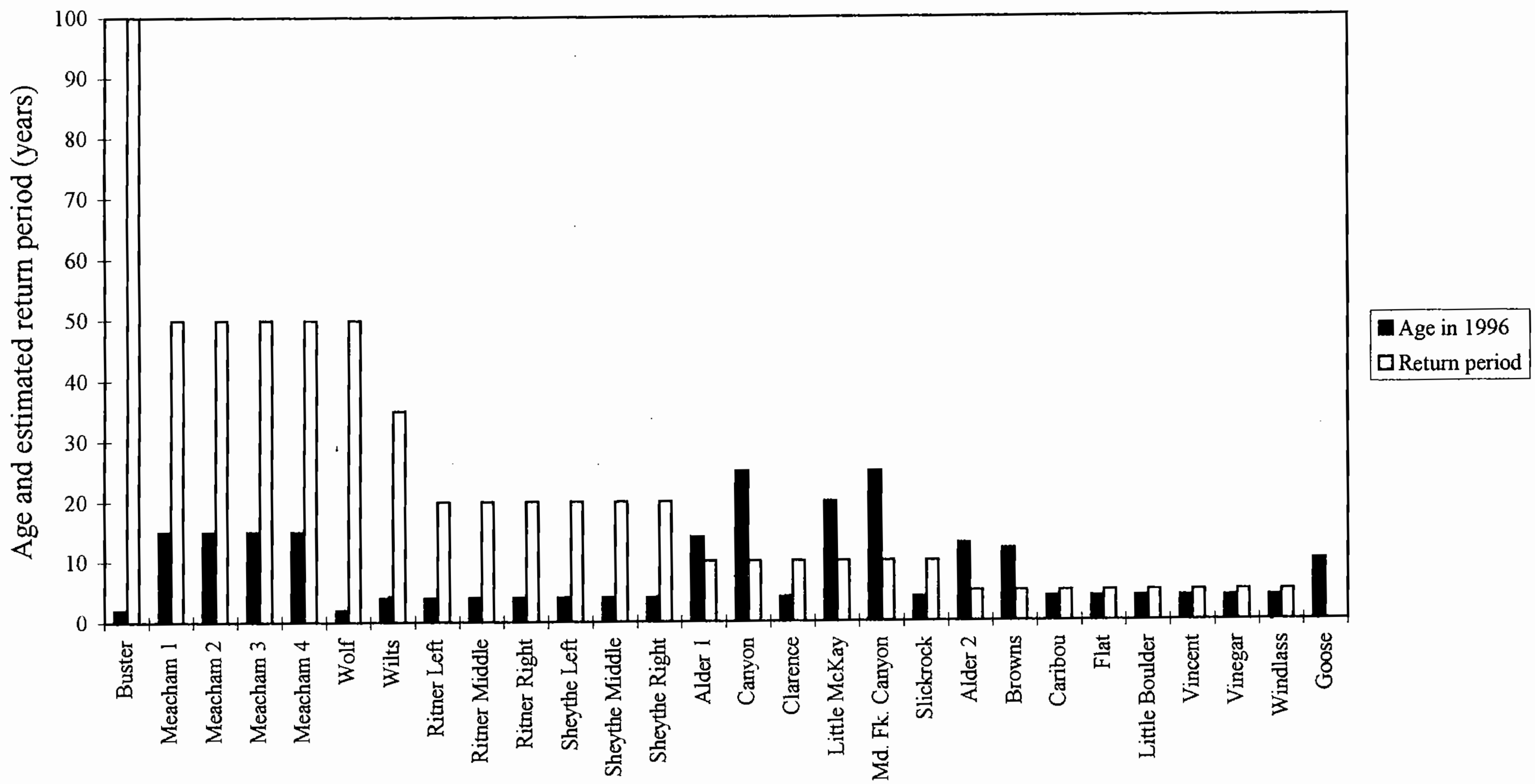


Figure 15. Culvert age and estimated return period of largest discharge since construction.

incident angle of incoming stream flow and/or the presence of woody debris across the culvert inlet. Many other culverts had shallower depressions which did not expose invert steel.

In the spring of 1996 the culvert inlets were rated based on a subjective analysis of the degree of inlet scour, the apparent stability of the inlet configuration, and the overall apparent effectiveness of the inlet. The average rating for the degree of inlet scour was "minor" to "moderate". The average rating for inlet stability was "stable" to "very stable". The average overall rating for the culvert inlets based on scour and stability was "good".

Scour and stability at culvert outlets

Scour and stability at culvert outlets was considered more detrimental to the stability and function of the culverts than scour at the inlets for two reasons; 1) outlet scour can lead to perching of the outlet, requiring fish to leap to get into the culvert, and 2) to the degree that substrate at or downstream of the outlet holds upstream substrate in place, its removal threatens the stability of substrate throughout the culvert.

Outlet scour was not found to be a major concern for most of the culverts. Outlet scour and stability scores assigned in the spring of 1996 averaged "minor" to "moderate" and "stable" to "very stable" respectively. The average overall rating for culvert outlets based on scour and stability was "good" (Figure 16).

There were eight culverts which received overall outlet scores of "fair" or "poor". The Alder Creek 1 culvert outlet received a "fair" rating because it lost approximately 0.7 ft of its 2.6 ft deep substrate in the February 1996 storm event. The Clarence Creek culvert outlet received a "poor" rating due to streambed degradation and destabilization which resulted from failure of its boulder weir during the February 1996 storm event. The six culverts at the Ritner and Sheythe Creek sites received "fair" and "poor" ratings due to downstream channel bed degradation which threatens to eventually result in perched outlets.

Overall rating of culverts in the spring of 1996 survey

Overall ratings, which represented the observed condition of the culvert (including the effects of the February, 1996 discharge), were high. Sixteen of the twenty-eight culverts received a score of "very good" based on the rating criteria (Figure 17). An additional five culverts received a score of "good." Five culverts received "fair" ratings. These were the Clarence Creek culvert, the three Ritner Creek culverts,

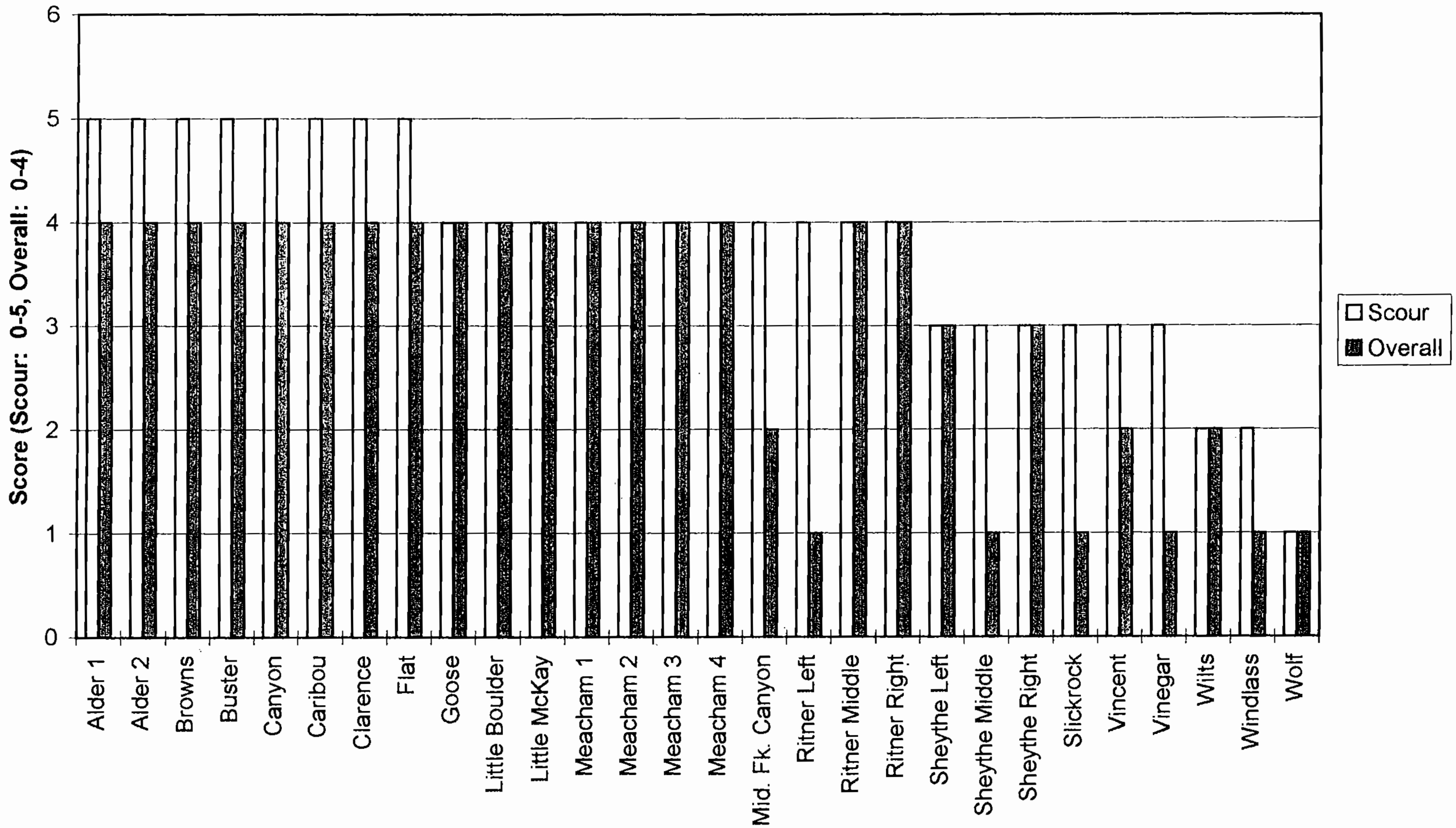


Figure 16. Outlet scour score and outlet overall score.

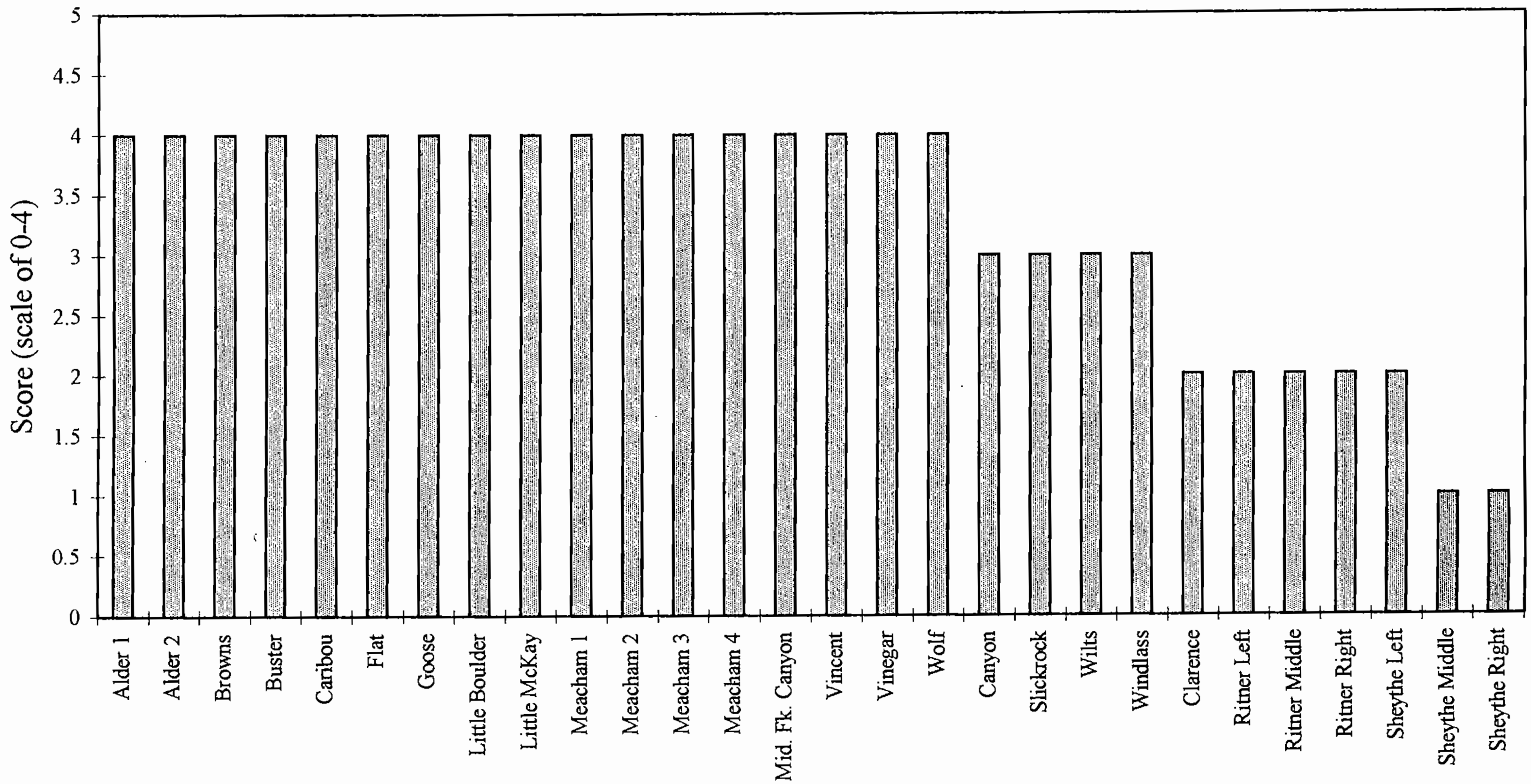


Figure 17. Overall culvert rating score.

and one of the Sheythe Creek culverts. Two culverts (the remaining Sheythe Creek culverts) received "poor" ratings.

Changes in channel morphology in and around the Ritner Creek site, 1995-1996

Channel thalwegs through the Ritner Creek culverts were surveyed in July, 1995 and in March, 1996. A comparison of the summer 1995 and spring 1996 longitudinal bed profiles is shown in Figure 18. As mentioned previously, debris jams affected distribution of flow among the three culverts during the fall and winter. A debris jam formed across the middle culvert inlet in fall 1995 and partially protected it from scour during the ensuing winter high flows. Meanwhile the right (to the downstream-facing observer) culvert, which was forced to convey more water due to the partial blockage of the middle culvert, experienced a significant amount of bed scour along its entire length (Figure 18). Changes to the right culvert illustrated in Figure 18 (bottom) include severe scour of the bed downstream of the outlet, which threatens to "perch" the outlet, and the effects of scour caused by a debris jam which formed at the inlet during the winter season. Changes in bed elevation in the middle culvert were less uniform and less dramatic. Minor, net aggregation may have occurred in this culvert (Figure 18, middle).

The left culvert consistently conveyed a larger percentage of the total stream discharge than either the middle or right pipe. The left culvert discharge averaged 47% of the total stream discharge at moderate to high flows and 100% of total stream discharge at flows less than 10 cfs. This may be attributable to its position as the outermost of the three pipes on the stream bend which the culvert installation spans. Figure 18 (top) shows the bed changes in the left culvert between summer 1995 and spring 1996. Net scour in the upstream region of the culvert and deposition below the outlet are evident.

On a larger scale, the bed morphology of Ritner Creek in the vicinity of the Ritner Creek culverts underwent a dramatic transformation between summer 1995 and spring 1996. In the summer of 1995 the bed of Ritner Creek included a point bar on the inside of the stream bend on which the culvert installation lies. The left culvert, on the outside of the bend, carried all of the summer discharge. At that time the middle and right culverts had higher bed elevations and smaller substrate particles than the left culvert. In spring 1996, after significant downcutting of the channel through the right culvert, the point bar had been eroded (Figure 19). The right culvert carried a larger proportion of the total stream flow than it had previously carried, and the substrate

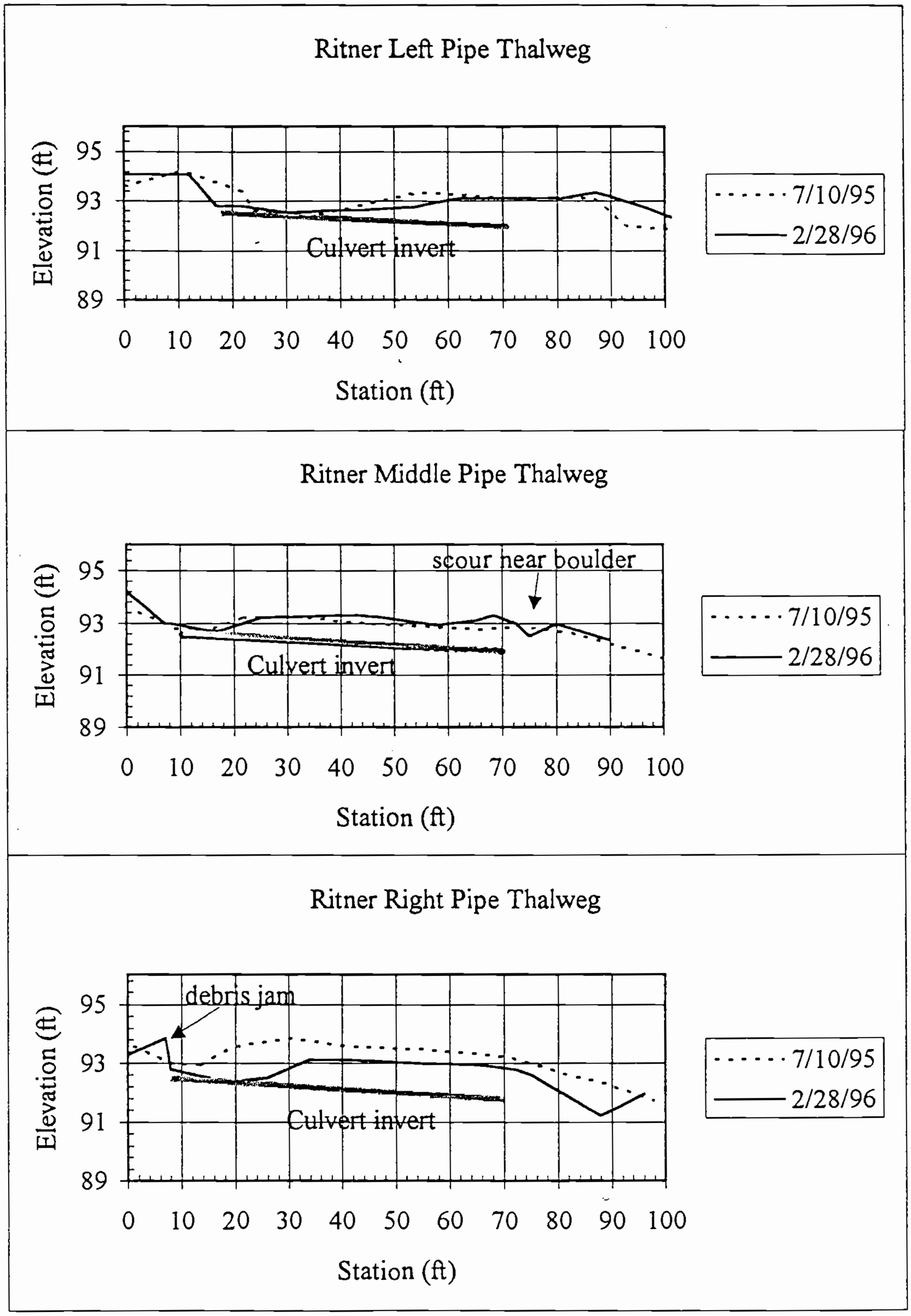


Figure 18. Ritner Creek culvert bed profiles.

Figure 19. Ritner Creek culvert outlets. Top: July, 1995. Bottom: March, 1996.

within the right culvert appeared to be about the same size as that in the left culvert. An almost identical process occurred on the three-pipe installation on Sheythe Creek (Figure 20). The Sheythe Creek installation also lies on a bend, contained a well-developed point bar in summer 1995, and experienced significant downcutting and erosion of the bar during the winter season.

Culvert barrel slope versus local streambed slope

Browning (1990) suggested placing culvert barrels at a flatter slope than the local streambed to retain substrate. The majority of the culverts examined in this study were set at slopes within 1% of the local streambed slope. Other than on the Slickrock Creek culvert, which was disregarded from much of this analysis because of its non-typical configuration, the maximum observed slope difference was 1.6%. The two culverts which had been set 1.6% flatter than the local stream gradient suffered no apparent detrimental effects due to their slope configuration.

Culverts not back-filled with substrate at time of construction

Two of the culverts included in the study were not back-filled with substrate at the time of construction. Buster Creek culvert was placed with its invert approximately 3 ft below streambed level. No fill was introduced into the barrel of the culvert during construction in 1994. In the summer of 1995 a lateral gravel bar extended about 20 ft into the inlet of the 60 ft long culvert (Figure 21). Downstream of the gravel bar the floor of the culvert was covered in a thick layer of silt. In the winter of 1996 Buster Creek experienced a flow event with an estimated return period of 100 years. In spring 1996 the floor of the Buster Creek culvert was filled with gravel and rubble sized substrate to a depth of approximately 3 ft (Figure 21). The bedrock sill lying approximately 15 ft downstream of the culvert outlet had apparently retained the substrate at this level during the high discharge event.

The Brown's Creek culvert lies on a low gradient, spring-fed stream with relatively low fluctuations in water surface elevation throughout the year. This culvert was only slightly countersunk. The inlet invert was placed slightly below the existing bed elevation when the culvert was installed in 1984. The outlet was placed at streambed elevation. In 1995 the culvert barrel contained a plume of substrate which filled the width of the inlet and tapered off to a point at a distance of approximately one-half of the culvert length downstream. The depth of the substrate plume averaged less than 0.5 ft at the inlet. Another, shorter plume of substrate filled the width of the outlet

Figure 20. Sheythe Creek culvert outlets. Top: September, 1995. Bottom: March, 1996.

Figure 21. Buster Creek culvert inlet. Top: August, 1995. Bottom: March, 1996.

and extended several feet upstream. Due to a lack of recent streamflow data, the largest discharge that this culvert had experienced since its construction was difficult to estimate. Based on the nearest available stream flow records, and on the recent string of "dry years", it is likely that the largest discharge this culvert has been subject to is that with a return period of 5 years.

Bed features within culvert barrels

Hydraulically-formed bed features were present in all of the examined culverts. Typically these included areas of deposition, scour, and a channel thalweg (Figure 22). It is possible that the formation of a thalweg, which concentrates flow into a relatively narrow channel at low flows, facilitates low-flow passage by increasing water depth (as compared to a bare culvert bottom).

Observed bedload transport

Transport of natural substrate within culvert barrels was observed on two occasions. Material approaching cobble size was mobile during velocity measurements on the Ritner Creek left culvert on November 11, 1995. The discharge at this time was roughly 45% of the estimated 10 year return period discharge (Campbell and Sidle, 1984). Substrate up to gravel size was mobile in the Goose Creek culvert on August 24, 1995. Discharge in Goose Creek is greatly augmented by diversion flow from another drainage. In both of these cases the bedload transport appeared to be occurring in a continuous fashion upstream, through, and downstream of the culverts.

Subsurface discharge during low-flow season

Low-flow season discharge infiltrated culvert substrates and traveled sub-surface for the length of the Caribou Creek culvert in late July, 1995. This was apparently due to the (necessary) excavation of streambed materials and their replacement by highly permeable layers of foundation and substrate materials during construction in 1992. A juvenile salmonid was observed in a shallow pool formed where the stream flow resurfaced at the outlet of the culvert. Whether or not the fish was attempting to move upstream is not known. Obviously, the situation observed in summer 1995 represented a barrier to movement through the Caribou Creek culvert.

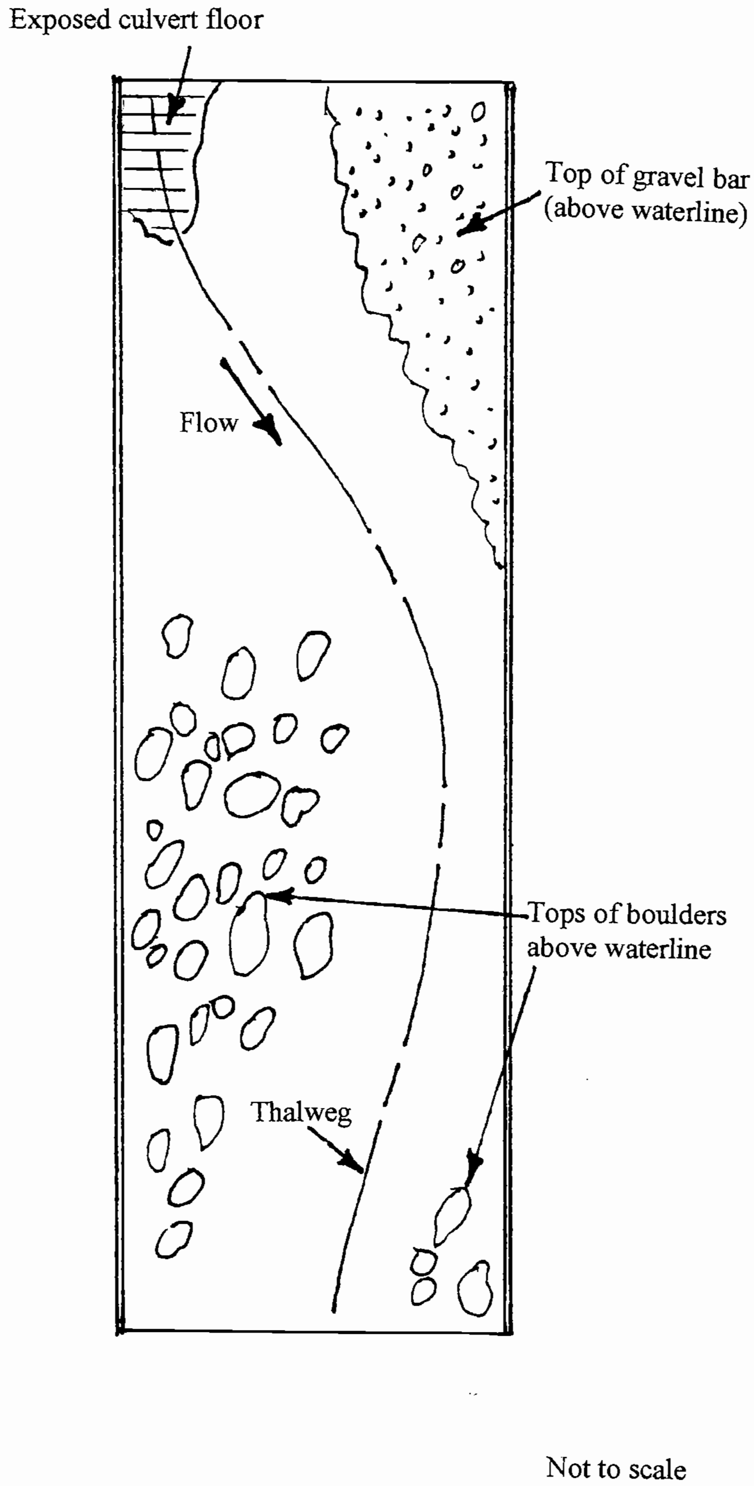


Figure 22. Diagram of bed within Clarence Creek culvert, July, 1995.

Round versus pipe arch culverts

The round culverts observed in this study tended to constrict the channel more than the pipe arch culverts. As can be seen in Figure 1, differences in geometry between the two culvert styles results in pipe arch culverts providing a much wider bed level channel width at a given countersinking depth. At deep countersinking depths, round culverts offer the above-ground width and height similar to that offered by pipe arch culverts. The culvert at Buster Creek, which was a very deeply countersunk round culvert, provided a geometry comparable to a countersunk pipe arch culvert (Figure 21).

The culvert at Canyon Creek provides an example of another potential drawback to round culverts. Two very large boulders, of size far greater than is necessary to provide roughness), lie on the invert of this culvert. It is unknown whether the boulders were placed in the culvert or whether they washed into the culvert. Concerned that velocities in the constricted areas between the edges of the boulders and the culvert walls might impair juvenile fish passage, Oregon Department of Forestry personnel measured velocities in these constricted areas near the end of spring melt in May 1996. The lowest velocity measured was 8 fps (George Robison, personal communication). It is possible that a juvenile salmonid would be unable to negotiate that section of the culvert under those conditions. The wider, flatter invert configuration of countersunk arch-type culverts are better able to accommodate large substrate elements without excessive constriction of flow. Thus, it is less likely that a pipe arch culvert would suffer from this problem.

Flow velocity

Data collection and reduction

Velocity data was collected at the Ritner and Sheythe Creek culverts five times during the summer, fall, and winter 1995. Dates of measurement and flows measured are presented in the Appendix. Measured discharges for Ritner Creek ranged from a summer discharge of 2.2 cfs to a winter storm flow of 147 cfs. The 146 cfs flow equaled 45% of the estimated 10-year discharge of 325 cfs (Campbell and Sidle, 1984). The lowest and highest observed per-culvert discharges were 2.5 and 62 cfs. Both of these discharges occurred in the left culvert. Discharges at the Sheythe Creek left culvert, which was the only of the three culverts at that site which conveyed water during all five visits, ranged from 1 cfs to 28 cfs. Measured Sheythe Creek discharges ranged from 1 cfs to 72 cfs. The estimated 10-year return period discharge on Sheythe

Creek is 253 cfs (Campbell and Sidle, 1984). Clarence Creek was visited three times during winter 1996. The discharge was approximately 30 cfs on two occasions and 94 cfs on the third. The estimated 10-year return period discharge on Clarence Creek is 686 cfs (Campbell and Sidle, 1984).

Ritner Creek culvert data was used for intensive velocity analysis. There were two reasons data from this site was chosen for analysis. First, the relative uniformity in substrate depths and sizes in the three culverts allowed for direct comparison between culverts. Second, the amount of data collected at this site covered a much larger range of discharges than that of the Sheythe or Clarence Creek sites. An example of a cross-section with plotted isovels is presented in Figure 23.

Water velocities measured at the Ritner Creek left culvert on August 10, 1995 were low. Under the low flow conditions of August, 1995 the left culvert was the only one of the three culverts which carried water, the other two having had slightly higher bed elevations. Average cross-sectional velocity at that time was less than 1 fps. Summer discharge measurements were excluded from the analysis in order to focus on higher flows, which had the potential to cause passage problems due to high water velocities.

Application of Manning's equation to calculate average cross-sectional velocity

Manning's equation was applied to discharge and cross-sectional profile data from Ritner Creek in order to predict average cross-sectional velocity. The results of this computation using the individual culvert slopes of 1.1, 1.2, and 1.5% for the left, middle, and right culverts respectively, are shown in Figure 24. A Manning's "n" of 0.06 provided the best agreement between the predicted and measured values of average cross-sectional velocity. Although most field data indicate that "n" values tend to decrease with increased flow, this value of 0.06 represented a reasonable value for the observed range of flows. Application of Manning's equation with the local streambed slope of 1.1% used at all cross-sections had similar results except the 1.1% slope resulted in a "best fit" Manning's "n" of 0.055.

As mentioned previously, an attempt was made to apply the technique described above to the 21 cross-sections from McKinnon and Hnytka (1985). However, due to the zero (or nearly zero) gradient of the culverts included in the McKinnon and Hnytka (1985) study and the absence of information on local streambed slope, it was not possible to accurately calculate average cross-sectional velocities using Manning's equation.

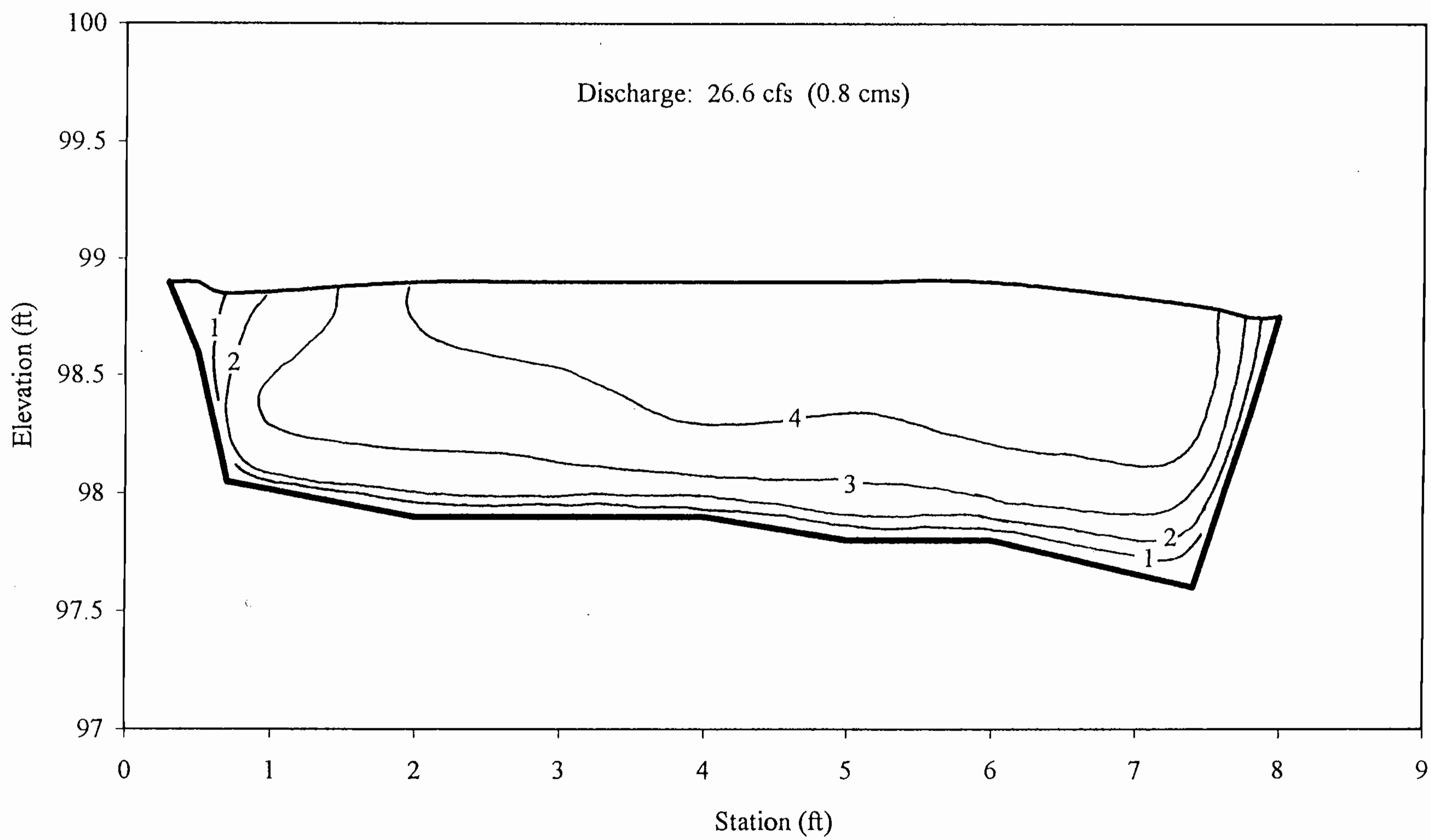


Figure 23. Water velocity (fps) at Ritner left culvert outlet, 12/20/95.

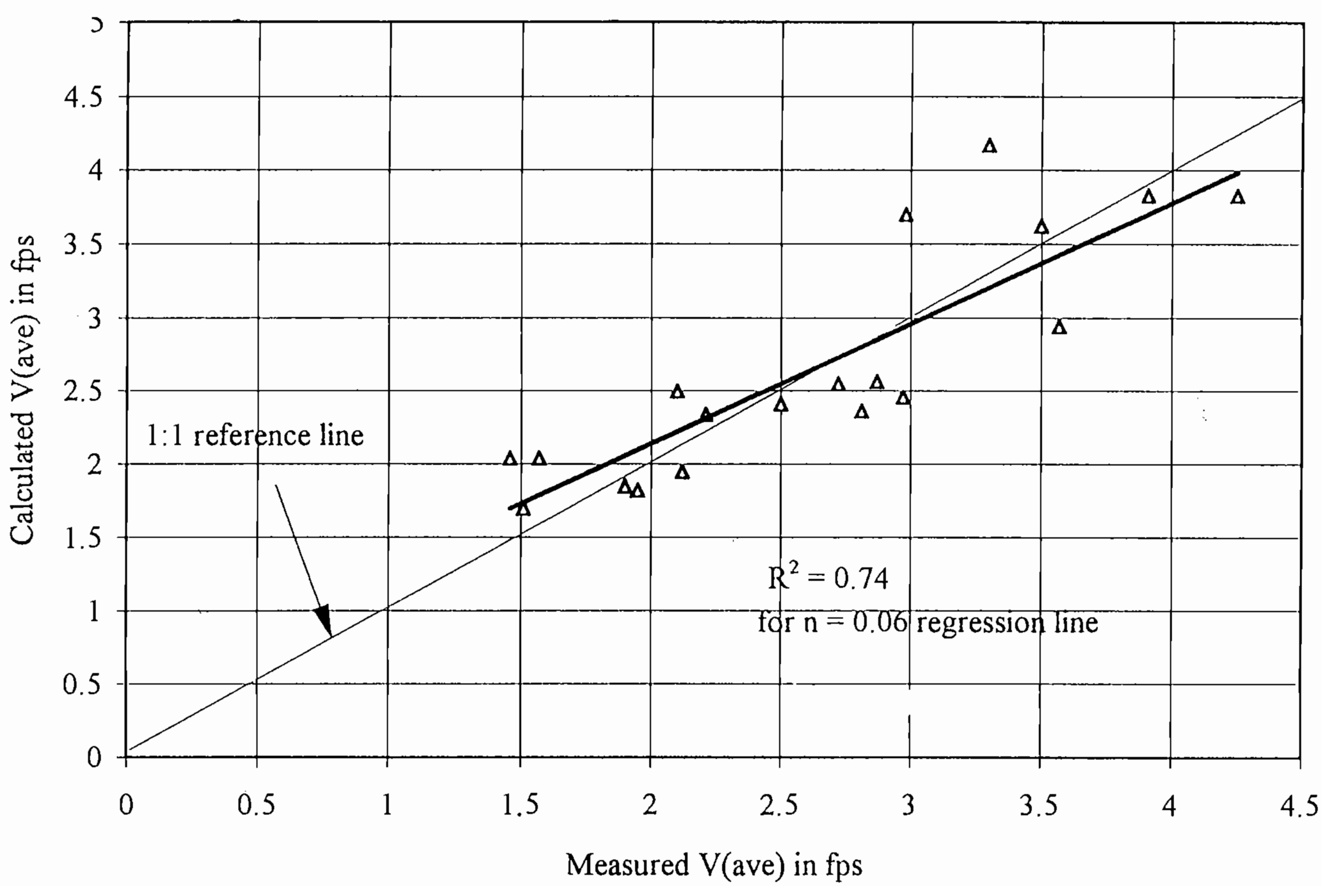


Figure 24. Calculated vs. measured average cross-sectional velocity (individual culvert slopes).

Development of equations for estimating the extent of low velocity zones in cross-sections based on average cross-sectional velocity

Two dimensional velocity profiles were plotted for nineteen of the Ritner Creek cross-sectional data sets (Figure 25). The semi-log graph of normalized velocity versus normalized depth for all nineteen profiles is presented in Figure 26. The formula for the regression line was

$$V/V_{ave} = 0.64 * LOG(y/D) + 1.25 \qquad (r^2 = 0.88,\ p < 0.05)$$

where V = velocity (fps); V_{ave} = average cross-sectional velocity (fps); y = distance above bed (ft); and D = hydraulic depth (ft).

Two dimensional velocity profiles were plotted for 21 of the cross-sections from three countersunk culverts on Liard River tributaries (McKinnon and Hnytka, 1985). A plot of these profiles is presented in Figure 27. Initially, data from the three McKinnon and Hnytka (1985) culverts was plotted separately. Visual assessment of these plots showed no apparent differences between the three culverts, apparently due to the similarity in culvert sizes, slopes, and substrate. The data for the 21 Liard River cross-sections was combined and the following regression line resulted:

$$V/V_{ave} = 0.53 * LOG(y/D) + 1.24 \qquad (r^2 = 0.52,\ p < 0.05)$$

The regression line resulting from the 3 Sheythe Creek cross-sections (Figure 28) was:

$$V/V_{ave} = 0.80 * LOG(y/D) + 1.27 \qquad (r^2 = 0.56,\ p < 0.05)$$

Figure 29 shows the regression equations developed with velocity data from Ritner Creek, Sheythe Creek, and Liard River tributaries. The lines are similar in slope and have almost identical Y-axis intercepts, indicating that V/V_{ave} values for the three data seta were similar near the water surface and diverged with depth.

Prediction of low velocity zones in the cross-sections based on average cross-sectional velocity

The regression equation developed for the Ritner Creek culverts was used to predict the proportion of the water column with velocity less than or equal to 1 fps at the

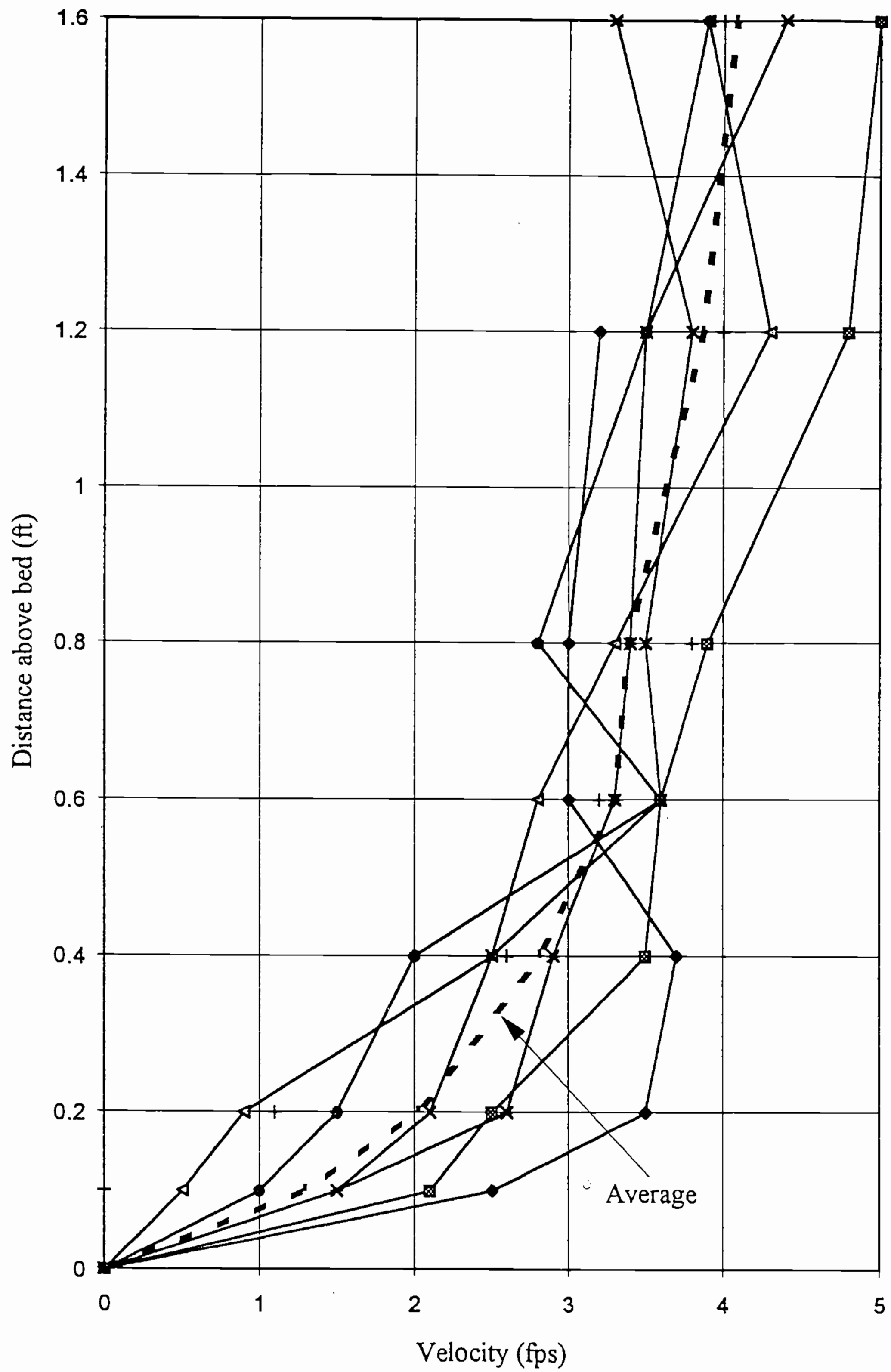


Figure 25. Velocity profile: Ritner middle culvert, midpoint, November 11, 1995.

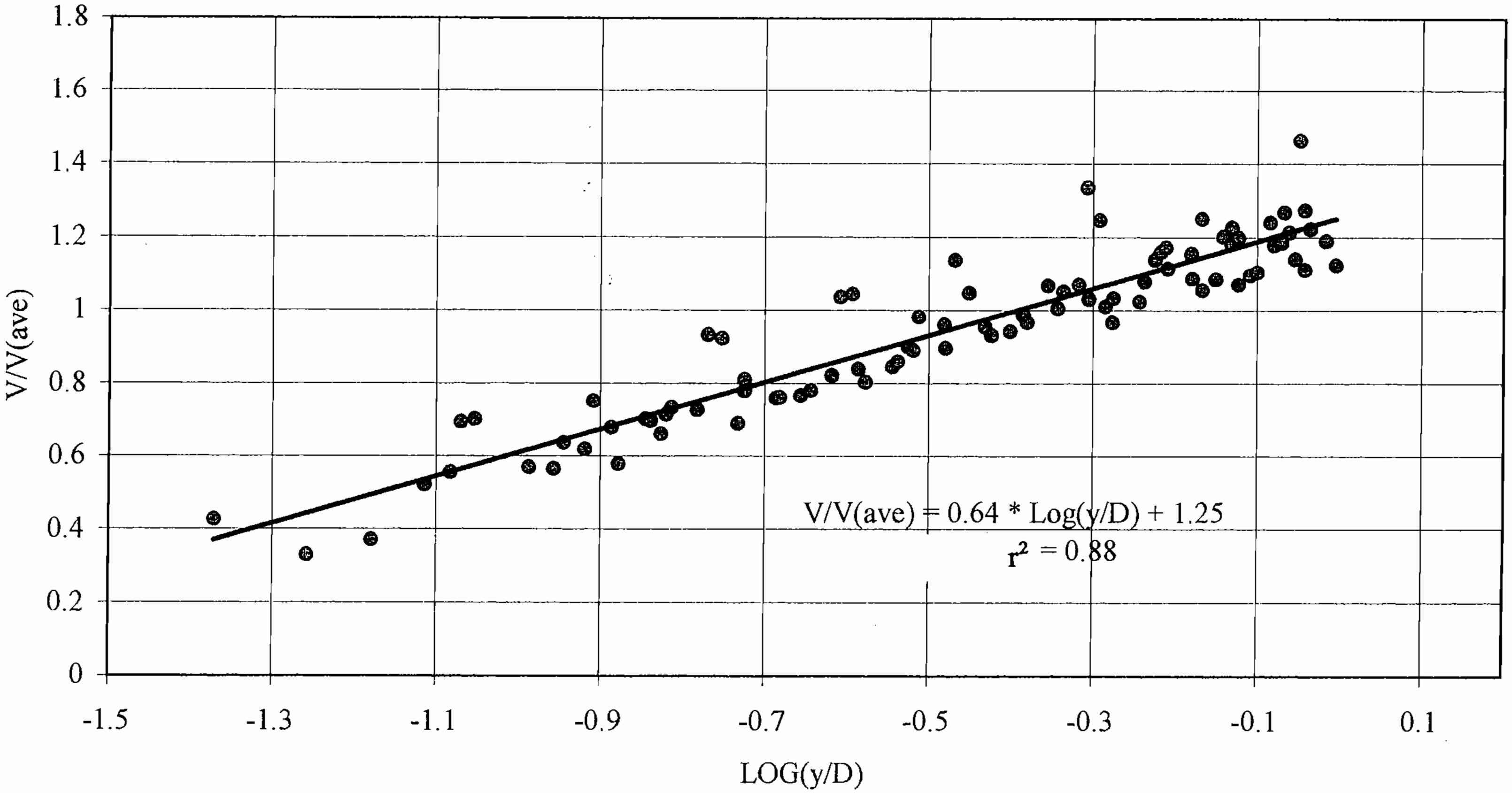


Figure 26. Ritner Creek culverts: V/V(ave) vs. Log(y/D).

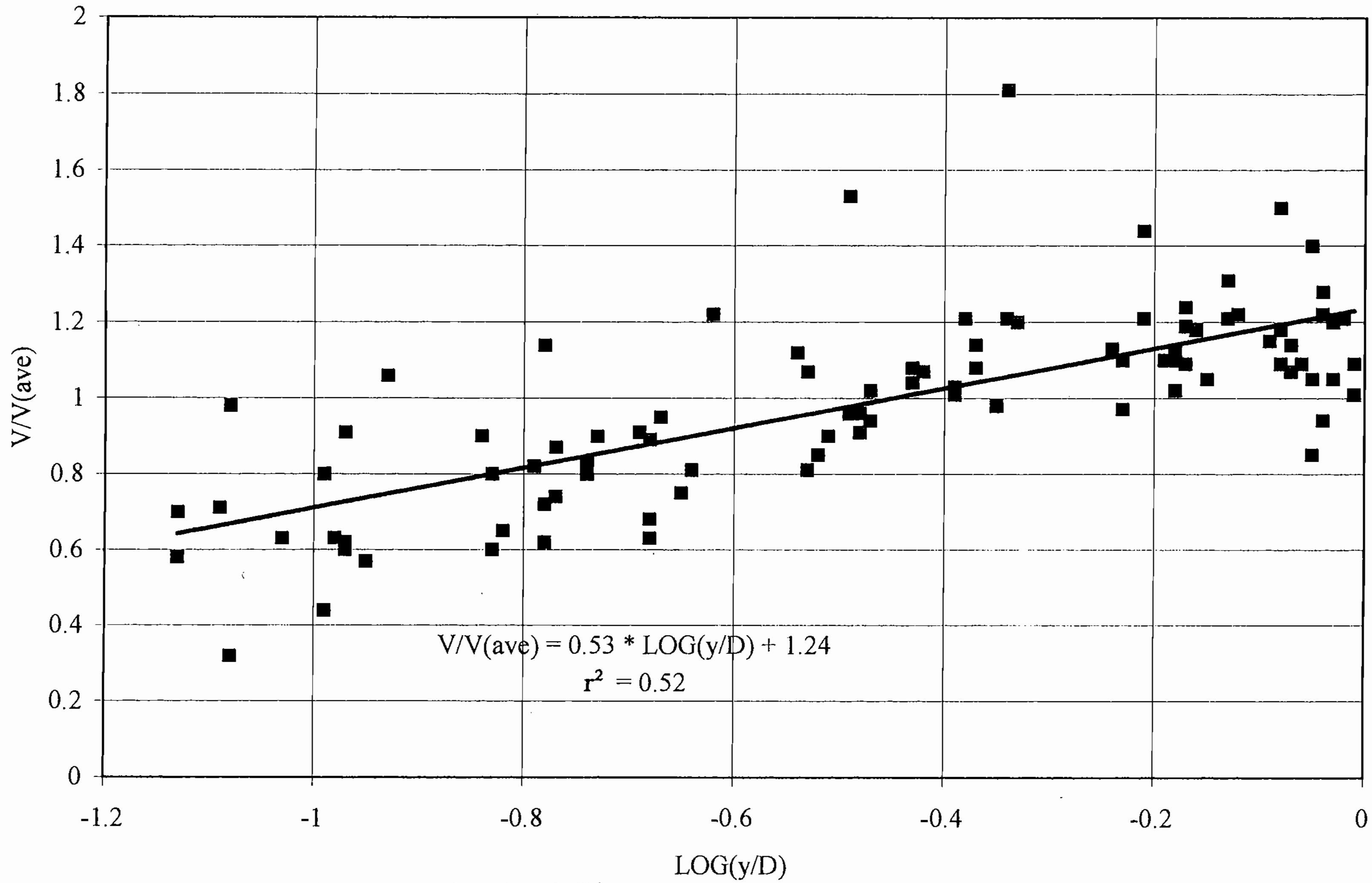


Figure 27. Liard River tributaries: V/V(ave) vs. Log(y/D).

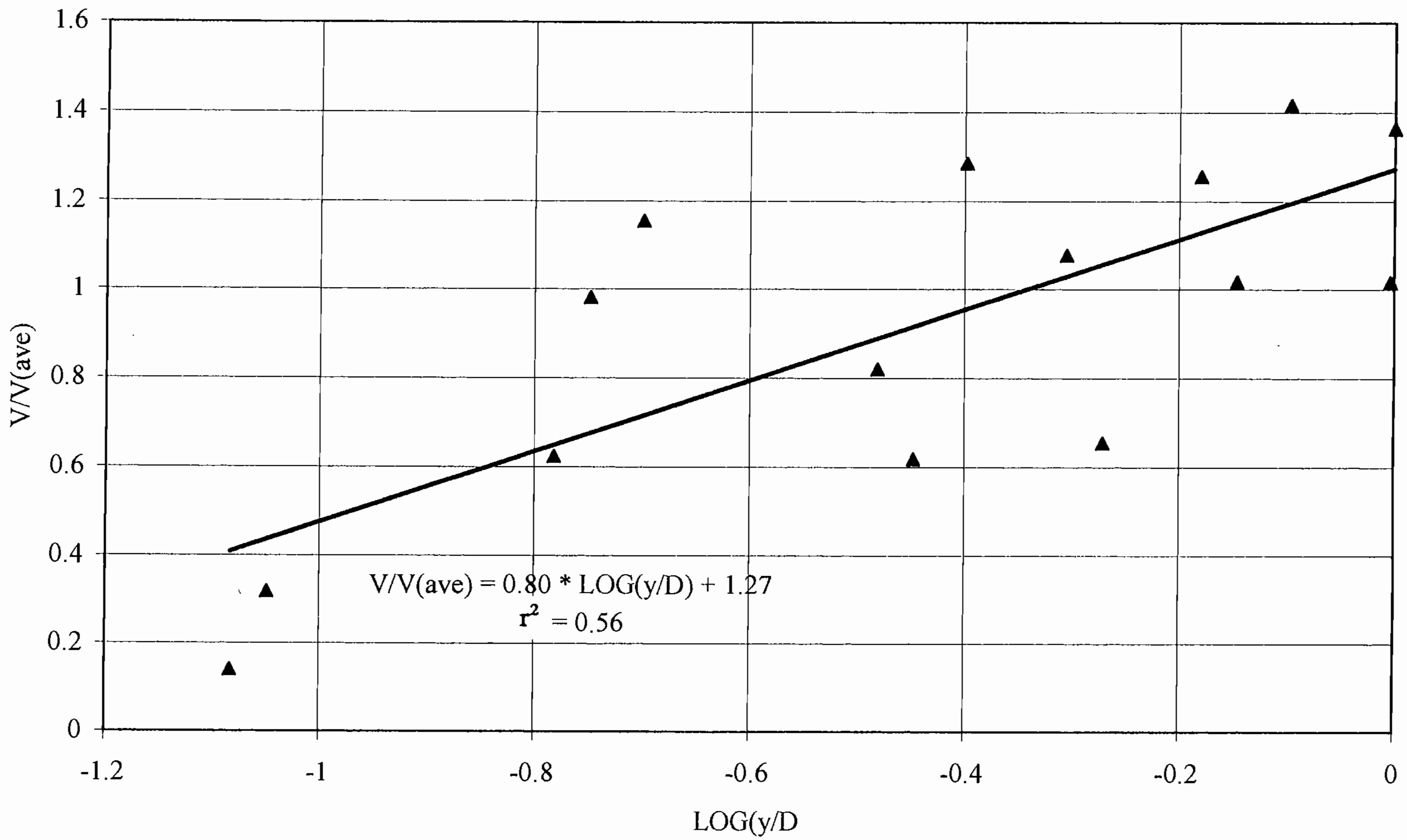


Figure 28. Sheythe Creek culverts: V/V(ave) vs. Log(y/D).

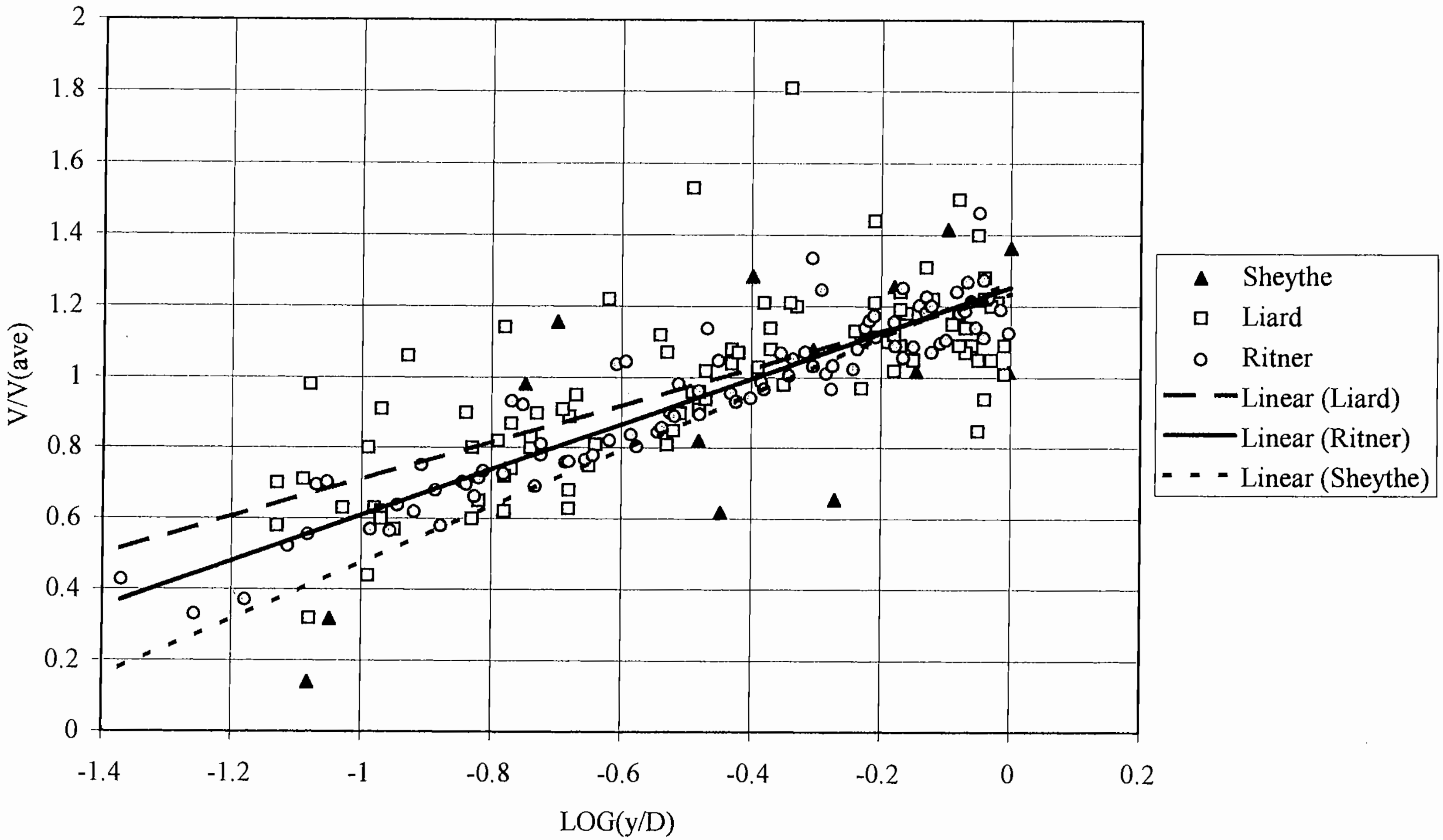


Figure 29. Ritner Creek, Sheythe Creek, and Liard River tributaries: V/V(ave) vs. Log(y/D).

nineteen cross-sectional velocity data sets. Based on the roughly rectangular shape of the channel, the assumption was made that the proportion of the average two-dimensional velocity profile with velocity ≤ 1 fps (and 2 fps) represented an accurate approximation of the proportion of the three dimensional flow cross-section with velocity ≤ 1 fps (and 2 fps). These predictions (from velocity measurements) and measured cross-sectional area with ≤ 1 fps, are presented in Figure 30. For seventeen of the cross-sections the equation under-predicted or accurately predicted the amount of cross-sectional area with velocity less than or equal to 1 fps. For the remaining two cross-sections the equation greatly over-predicted. Both cross-sections for which the equation over-predicted were measured during the highest flow observed; on November 11, 1995. Discharge during that event equaled 45% of the estimated 10 year return period discharge, exceeding reasonable passage design discharge. The fourth over-prediction resulted from data that was obtained during the second highest discharge observed.

A second prediction of cross-sectional area with velocity of 1 fps or less was carried out using average cross-sectional velocities predicted by Manning's equation. Individual culvert slopes and local bed slopes were used to produce these two additional predictions. The results were similar to those discussed above, although over predictions were more numerous (Figure 31). The method under-predicted the proportional area of flow with velocity less than or equal to 1 fps for 14 of the 19 cross-sectional velocity data sets. The method significantly over-predicted for two cross-sections, both of which were measured during the November 11, 1995 discharge.

Using the Ritner Creek culvert data, this predictive method provided a conservative estimate of the proportion of cross-sectional area of flow with velocity less than or equal to 1 fps for the majority of the cross-sections. The discharges for which the equation significantly over-predicted this proportion corresponded to a flow which probably exceeds reasonable passage design discharge at this site. These observations were true for predictions made using both measured average cross-sectional velocity and average velocity calculated by Manning's formula.

The same predictive method was applied using with 2 fps as the maximum velocity. Results based on measured average cross-sectional velocity were similar to those for the 1 fps target velocity analysis (Figure 32). In this case the proportion of

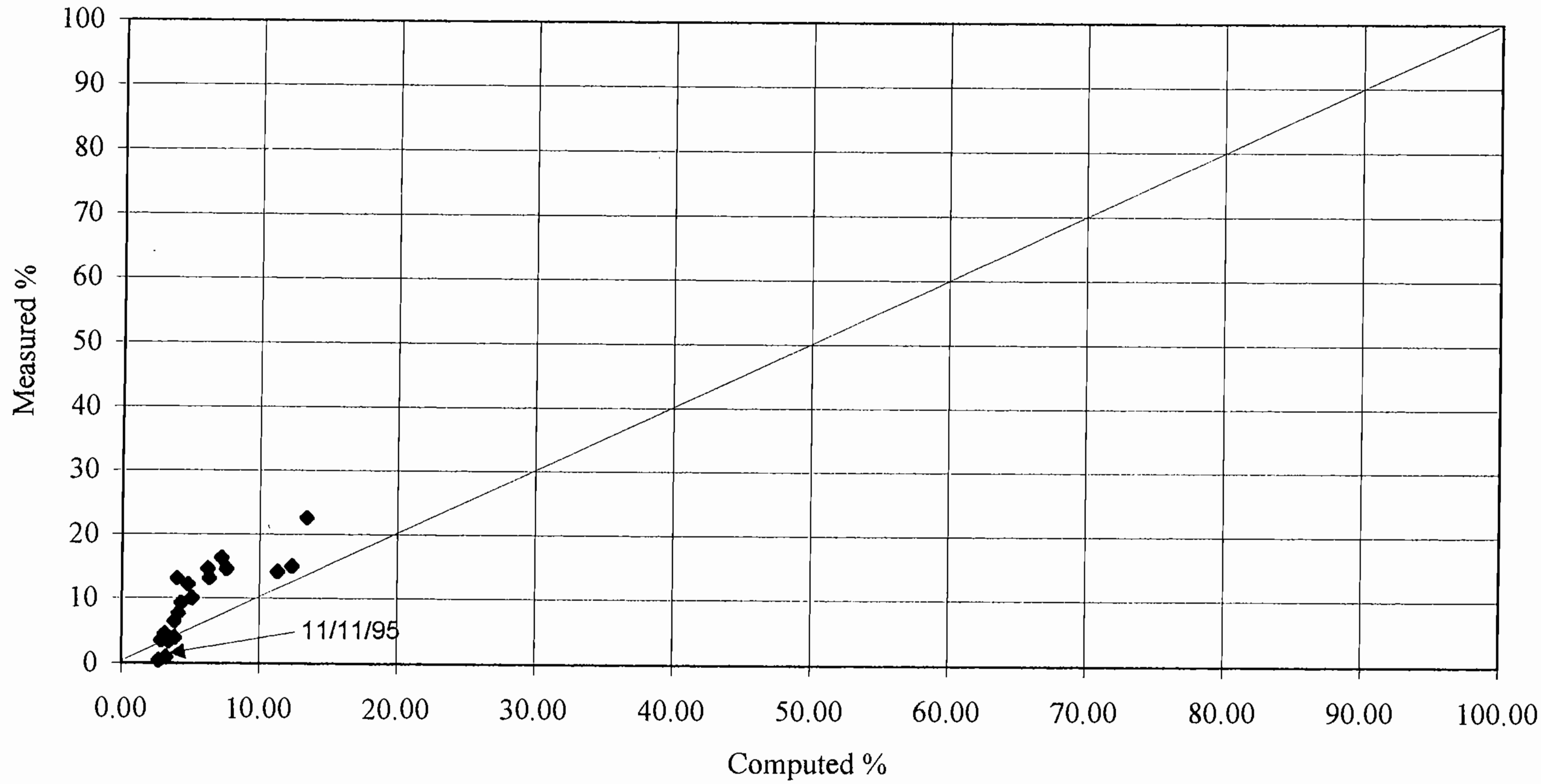


Figure 30. Ritner Creek: Percentage of cross-sectional area of flow with velocity ≤ 1 fps (predicted values based on observed average cross-sectional velocity).

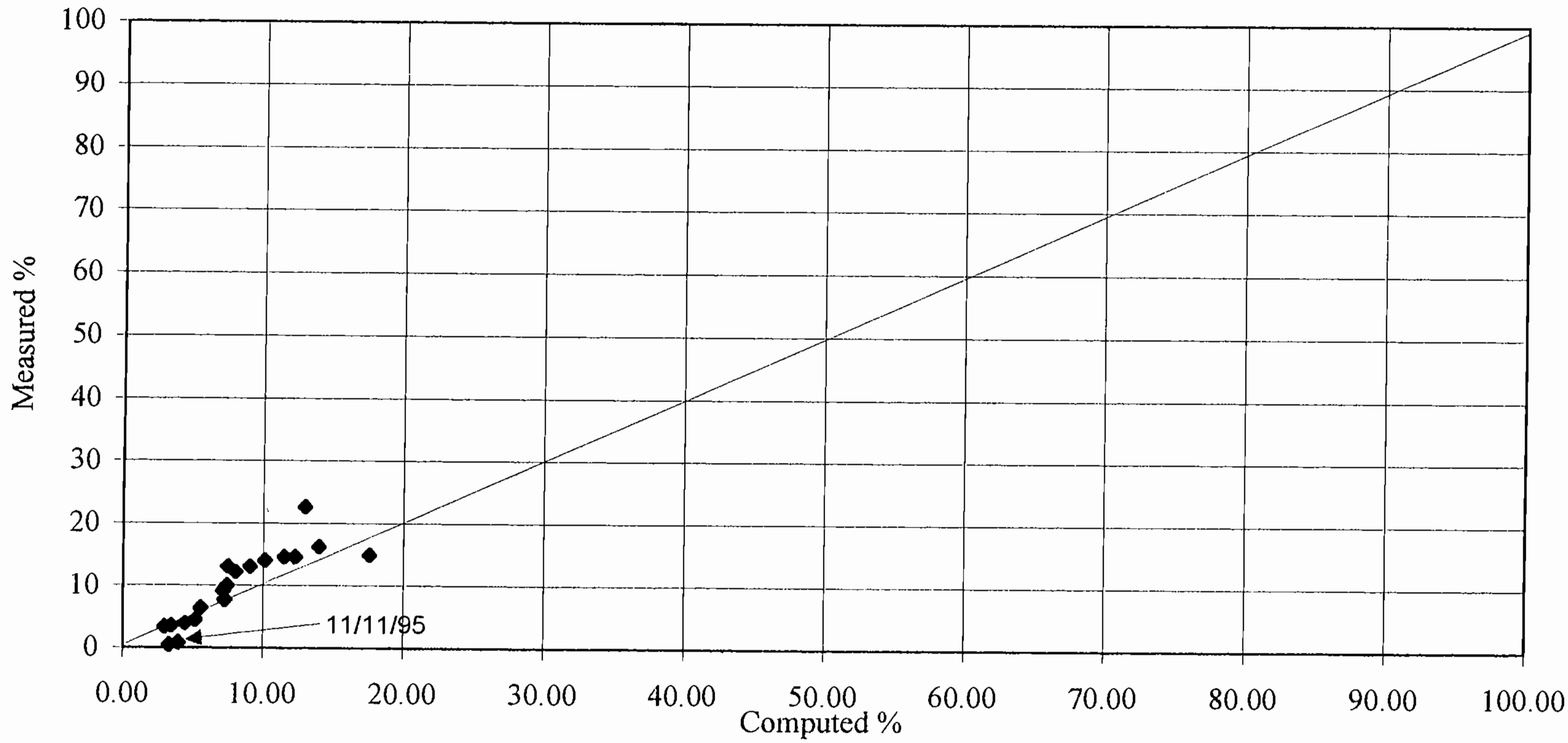


Figure 31. Ritner Creek: Percentage of cross-sectional area of flow with velocity ≤ 1 fps (predicted values based on "Manning's" average cross-sectional velocity).

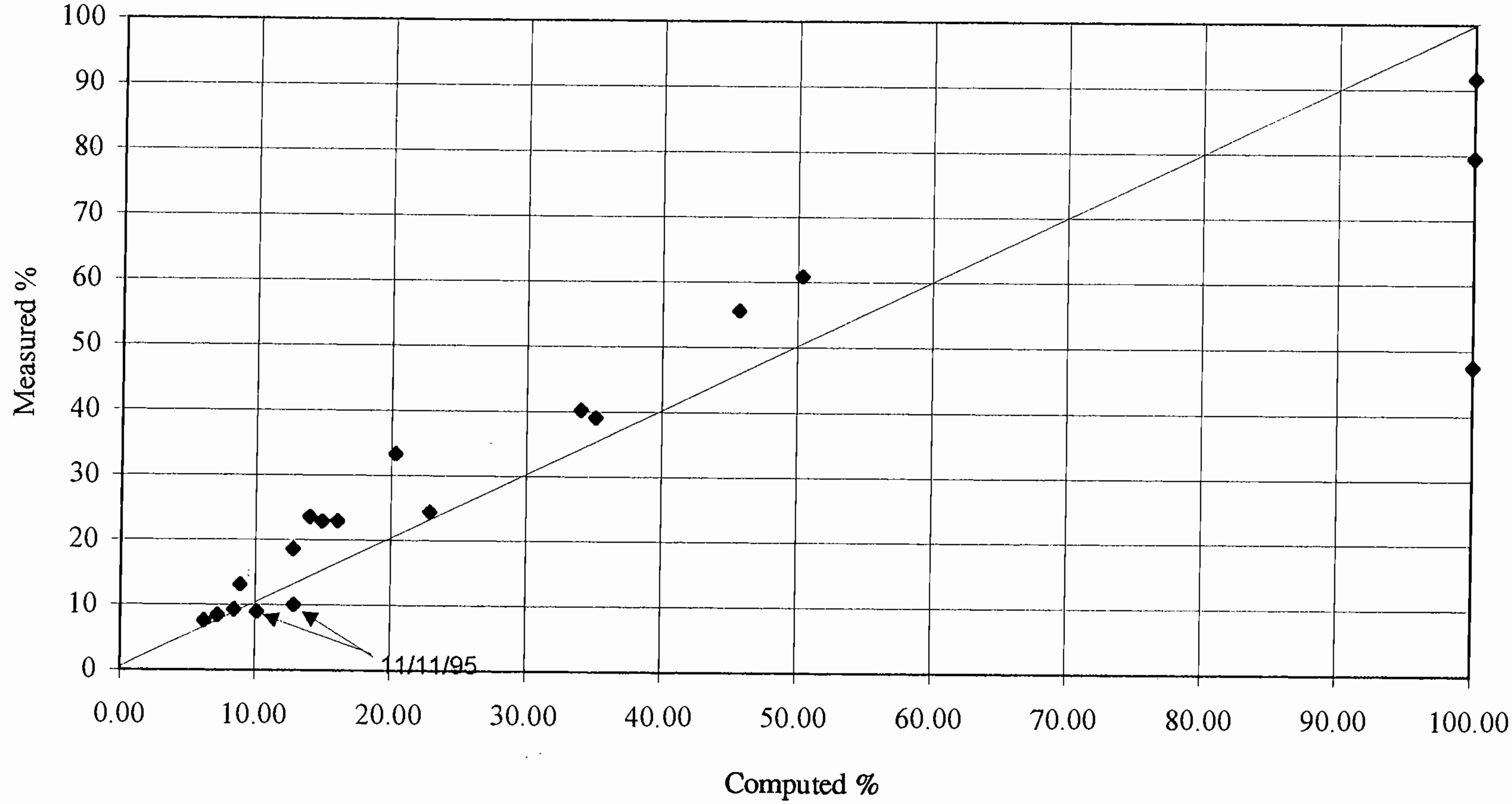


Figure 32. Ritner Creek: Percentage of cross-sectional area of flow with velocity ≤ 2 fps (predicted values based on observed average cross-sectional velocity).

cross-sectional area with velocity of less than or equal to 2 fps was over-predicted for 5 cross-sections. Two of the cross-sections for which the method over-predicted corresponded to the November 11, 1995 discharge. For the remaining three over-predictions, the method predicted that 100% of cross-sectional area had velocity of 2 fps or less.

The measured values for these three cases ranged from approximately 47% to 92%. Examination of the plotted isovels revealed that flow with velocity exceeding 2 fps existed in small cells in each of these cross-sections (Figure 33). Since the prediction method relies on average velocity over the entire depth of the water column, it is not sensitive to small cells of higher velocity flow which do not span the entire channel width. For that reason, it appears that the method may over-predict as the proportion of area at or below the given velocity exceeds approximately 40%. For practical purposes this is not a problem, as the occupation of 40% of the cross-section by low velocity flow should allow for fish passage. For the remaining fourteen cross-sections the equation consistently under-estimated the proportion of cross-sectional area of flow with velocity less than or equal to 2 fps.

The predictive method was repeated, again with 2 fps as the target velocity, using average cross-sectional velocities calculated by Manning's equation. This analysis resulted in more instances of over-prediction of proportional cross-sectional area of flow with velocity less than or equal to 2 fps than did the analysis employing measured average cross-sectional velocities. It is notable, however, that predicted values appear to be related to measured values in a consistent, roughly linear manner.

Cross-sectional data presented by McKinnon and Hnytka (1985) included measurements of the proportion of cross-sectional area with velocities of less than or equal to 0.2 m/s (0.7 fps), 0.4 m/s (1.3 fps), and 0.6 m/s (2.0 fps). Using the same technique as above, the regression line relating (V/V_{ave}) and Log(y/D) developed for the McKinnon and Hnytka (1985) data was used to predict proportional cross-sectional area of low velocity zones. Since Manning's formula could not be meaningfully applied to the available data, only measured average cross-sectional velocities were used in the analysis. Predictions of cross-sectional area with velocity less than or equal to 0.7 fps were lower than the measured values in 19 cases and only slightly higher in the remaining two cases. Predictions with respect to 1.3 fps and 2.0 fps were less conservative. Still, the majority of these predictions were lower than the measured values (Figure 34). As observed in the Ritner Creek results, predicted values appear to

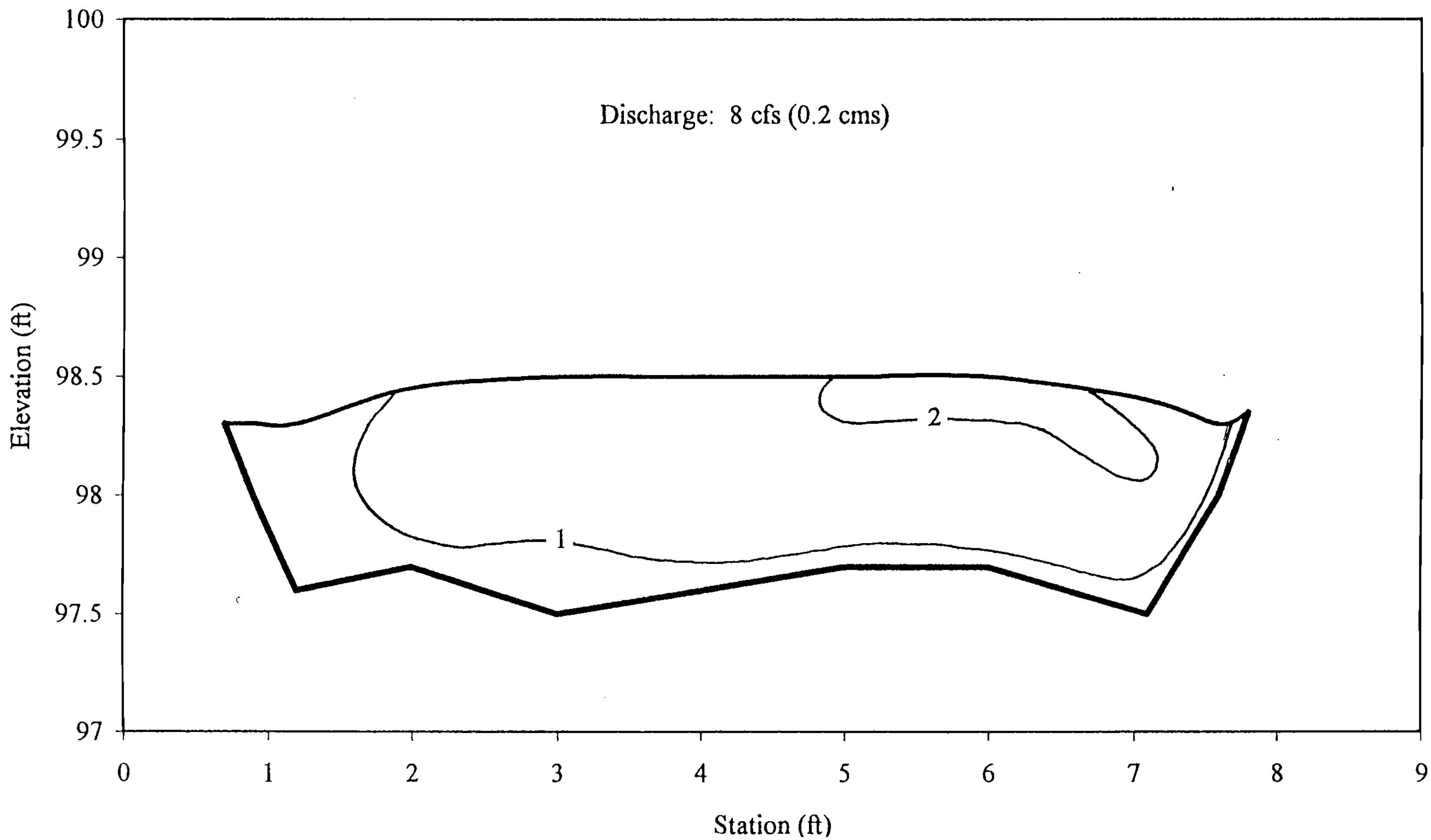


Figure 33. Water velocity (fps) at Ritner Creek left culvert outlet, 10/26/95.

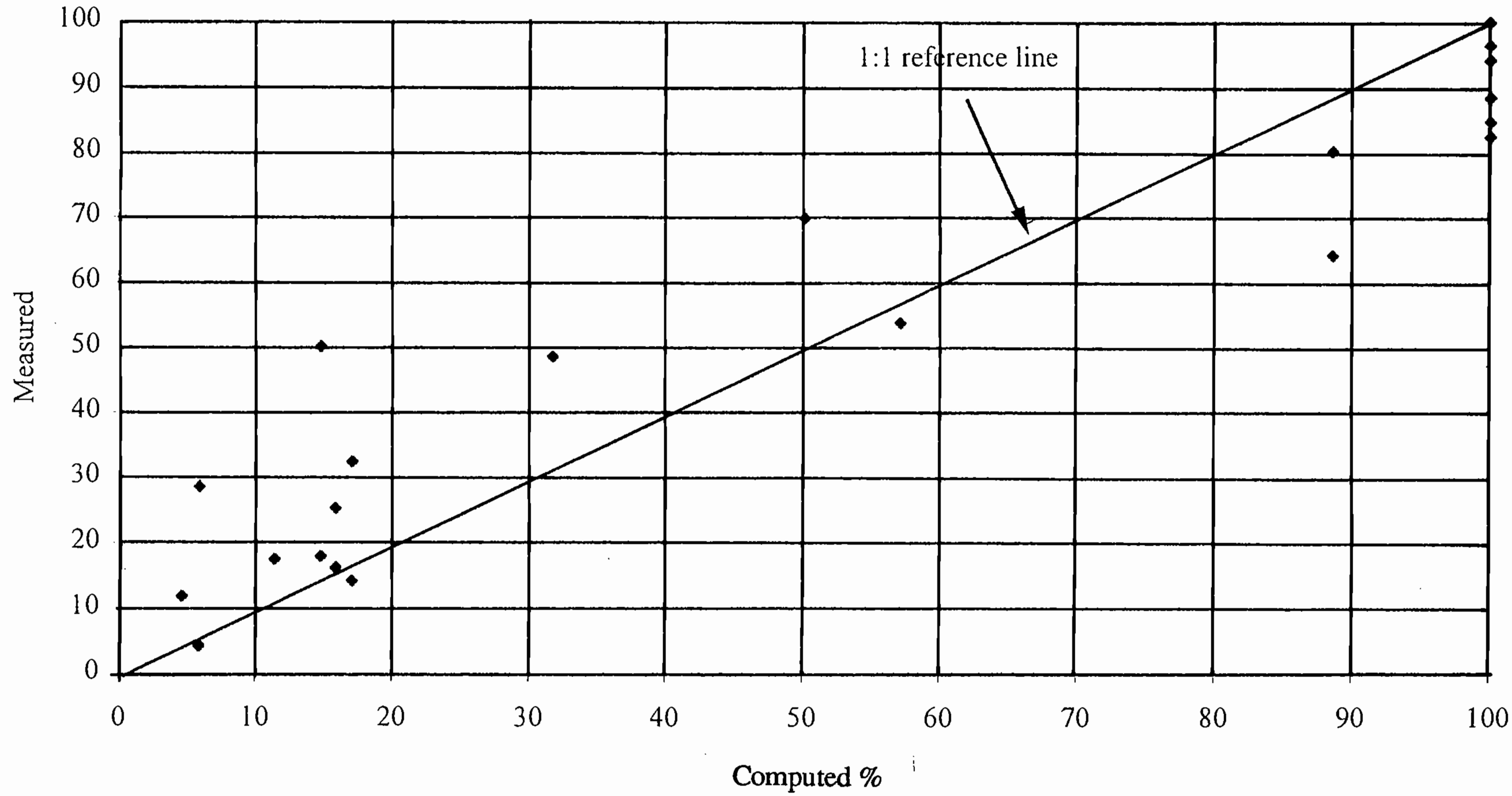


Figure 34. Liard River Tributaries: Percentage of cross-sectional area of flow with velocity ≤ 1.3 fps (predicted values based on observed average cross-sectional velocity).

be related to measured values in a consistent, roughly linear manner. In addition, as with the Ritner Creek results, the most significant over-prediction of low velocity area occurred when measured low velocity area exceeded 40%.

Discussion

The culvert inventory

General observations

In general, the 28 countersunk culverts examined in this study appeared structurally sound. Twenty one of the culverts were rated as "very good" or "good" based on scour and stability. The remaining seven culverts, which rated "fair" or "poor," all had identified problems in their design and/or construction to which their low performance can be attributed. Important issues included: effects of woody debris trapped at inlets, characteristics of multiple-pipe installations, the role of rip-rap and weir protection at culvert outlets, depth of countersinking, effects of the incident angle of flow, slope difference between the culvert and the local streambed, subsurface flow under low discharge conditions, performance of high-gradient culverts, performance of culverts not back-filled with substrate at time of construction, observed bedload transport, round versus pipe arch culverts, and the effects of design and construction practices. Each of these issues is addressed in the following paragraphs.

Effects of woody debris

Although it significantly affected culverts at only a few sites, woody debris exerted a major influence on those culverts. Substantial scour occurred where debris jams formed across culvert inlets. The partitioning of flow through parallel culvert installations was altered by the formation of debris jams across inlets at both of the multiple culvert installations examined in this study. It was apparent from observations of the debris jams at these sites that many of the logs would have passed through a single culvert of equivalent end area to the three existing culverts. It is possible that the influence of woody debris at these sites could have been minimized by the installation of one large culvert rather than three smaller culverts in parallel. In these situations, designs employing larger, single culverts rather than smaller, multiple culverts may have lowered the incidence of debris jams. It is likely, however, that other constraints such as a limit on the height of the road fill influenced the designer's choice of multiple culvert installations.

A large debris jam also formed across the inlet of Meacham 3 culvert, which is a single culvert with a width of 14 ft, showing that multiple-pipe installations are not the only configuration susceptible to this problem. The likelihood of woody debris affecting the performance of a culvert depends on the availability and size of woody debris, the ability of the stream to transport woody debris, and the size (especially width) of the inlet.

Characteristics of multiple-pipe installations

Streambed morphology in and around multiple-pipe installations is dynamic. Study of the Ritner and Sheythe Creek sites show how the effects of woody debris and non-uniform scour and deposition can result in relatively rapid changes in bed morphology and sediment size within countersunk culverts placed in parallel. At times this may be desirable. For example, in some cases it is desirable to allow for lateral channel adjustment in a wide flood plain. In general, however, the tendency for multiple-pipe installations to collect debris jams, and the associated effects of the unequal partitioning of discharge between the culverts, make multiple-pipe installations less desirable than single culverts in many situations. Advantages to multiple-pipe installations include lower road bed elevation and, in some cases, lower cost.

The role of rip-rap and weir protection at culvert outlets

Armoring of the bed by riprap and/or weir is important to the structural integrity of countersunk culverts. All seven of the lowest rated culverts in this study had scour and stability problems directly related to either the lack of such protection or its failure. Another culvert had the opposite problem; excessive substrate deposition in the lower end of the culvert due to the boulder weir being too high. This case illustrates the link between countersinking depth and downstream bed elevation control, which must be synchronized in order to prevent excessive scour or deposition in the culvert barrel. In some cases the presence of natural downstream bed elevation controls made the construction of bed protection structures unnecessary.

Depth of countersinking

Sufficient depth of countersinking appears to be critical to countersunk culvert performance. The combination of countersinking and downstream bed elevation control are what allow these culverts to recruit and retain sediment. The average relative fill depth of the culverts in this study was approximately 20%. This depth, in conjunction with effective downstream bed elevation control, appears to be effective at maintaining an adequate amount of substrate within the culvert barrel. It is worth noting that the Ritner and Sheythe Creek culverts, which all received overall ratings of "fair" to "poor" primarily due to streambed degradation at the outlet, were countersunk less than 20% and had ineffective or non-existent downstream bed elevation controls. Had these culverts been countersunk more deeply or been better protected from downstream bed degradation they might have performed better.

Effects of the incident angle of flow

The results of this study support the assertion made in USDOT (1990) that flow entering a culvert at an angle will result in scour. Orientation of the culvert barrel in line with the incident stream flow would minimize such scour.

Culvert barrel versus local streambed slope

The majority of the culverts examined in this study were set at slopes within 1% of the local streambed slope. The two culverts which had been set at 1.6% flatter than the local stream gradient suffered no apparent detrimental effects due to their slope. From this it would appear that culverts set at slopes 0-1.6% less than the local streambed slope will function effectively. No relationship was apparent between substrate retention and the degree to which culvert barrels were set counter to the natural bed slope. It is therefore questionable whether "counter-sloping" of the culvert barrel against the streambed gradient aids in substrate retention. The downstream bed elevation control probably plays a much more important role in retention of substrate within the culvert.

Subsurface flow under low discharge conditions

Until the foundation and substrate materials "seal" with fine particles, a newly constructed countersunk culvert may be a migration barrier at low-flow due to subsurface transmission of stream flow through the culvert. This phenomenon was observed at Caribou Creek in July 1995. Browning (1990) addressed this issue and suggested the placement of a sediment barrier such as geotextile fabric between the foundation and streambed materials during construction in order to accelerate the "sealing" process.

Performance of high-gradient culverts

It would be valuable to determine the maximum gradient at which countersunk culverts retain substrate. Unfortunately, in this study the highest gradient culverts tended to have been subjected to discharges of relatively low return periods. The results still bear examination. Three culverts had slopes of over 4%. All three culverts had been exposed to the 5 year discharge. All three culverts were stable with good bed configurations. The steepest culvert was Alder 2 culvert at 7.6%. The substrate in this culvert was deliberately sized to remain stable at the 20 year return period design discharge. In 1995 and 1996 a portion of the inlet invert was found to be scoured to bare steel. This scour was considered to be moderate but stable. The other two culverts were on Little Boulder and Caribou Creeks and had slopes of 5.4% and 4.7% respectively. Both of these culverts were free of major scour and appeared to be in good condition. The bed within the Little Boulder culvert had obviously been re-worked by flows since construction and had the look of a natural streambed. Other than the deposition of fine sediment behind boulders, the bed within Caribou Creek culvert appeared to have been re-worked by stream flow very little since construction.

There were five culverts with slopes between 2% and 4%. Of these, the culverts at Flat, Vinegar, and Vincent Creeks had all been subjected to a 5 year return period discharge. All three received an overall culvert score of "very good." It was evident that these culverts had not received large enough discharges to re-work the constructed bed into a natural-looking bed form. The Windlass Creek culvert, also having been subjected to a 5 year return period discharge, had aggraded significantly towards its downstream end as discussed previously. The remaining culvert, at Little McKay Creek, had a slope of 2.7%. The 1996 storm discharge reached bank full at the Little McKay site; a 10^{+} year return period discharge. With the exception of the deposition of rubble-sized material in the formerly open interstices of the boulder/cobble substrate, the 1996 storm had little apparent effect on this culvert.

With the exception of Little McKay Creek culvert, the results of this study provide limited information about the effects of higher flows (approaching design flow magnitude) on countersunk culverts with slopes greater than 2%. Examination of the effects of the 1996 storm on Little McKay Creek culvert, however, shows that a well-constructed countersunk culvert of slope greater than 2% can weather a large storm discharge without damage.

Performance of culverts not back-filled with substrate at time of construction

The Brown's Creek and Buster Creek culverts were not back-filled with substrate at the time of their construction. Both sites had natural bed elevation controls downstream of the culvert outlet. The culverts had become filled with substrate to the approximate natural streambed level by spring 1996. These two examples show that countersunk culverts at sites with natural streambed elevation controls can become filled to the desired level with substrate through natural processes. It is likely that human-made bed elevation control structures would produce the same result.

Observed bedload transport

Bedload transport observed at the Ritner Creek and Goose Creek culverts appeared to be occurring in a continuous fashion upstream, through, and downstream of the culverts. This suggests that in countersunk culverts, at least in those on streams with relatively small substrate such as Goose and Ritner Creeks, some degree of the natural bedload transport process is preserved. This process may be more difficult to preserve on steeper streams with larger, less mobile substrate. This would be particularly true when concern over loss of bed substrate from the culvert barrel prompts the placement of in-culvert substrate which is larger than that of the natural stream. In this case, placement of the "oversized" substrate at an elevation slightly lower than that of the local streambed may allow for natural transport of stream substrate. Under this configuration, the natural stream substrate would constitute a mobile, upper layer of the bed while the "oversized" material would provide an underlying layer that is resistant to scour at higher discharges.

Round versus pipe arch culverts

The pipe arch design was developed to provide the same peak flow capacity as round culverts at lower head water depth and a lower culvert height (important at crossings with "head room" limitations). Differences in geometry between the two culvert styles result in pipe arch culverts providing a much wider channel at bed level given equal countersinking depths. The wider channel should result in lower water velocity at most discharges. Large, deeply countersunk round culverts provide a functional configuration comparable to a countersunk pipe arch culvert. If a round culvert is countersunk by approximately 40% of its depth it will constrict the channel no more than a pipe arch culvert of the same diameter. A deeply countersunk round culvert would accommodate greater lowering of the streambed elevation than a pipe arch culvert of equivalent diameter. In many cases, however, it would be more economical to use a pipe arch culvert sunk to a more shallow depth.

The culvert at Canyon Creek provides an example of high velocity zones between culvert walls and the edges of large boulders (boulders of much larger size than is necessary to provide roughness) lying in the invert of a round culvert. Such high velocity zones may seriously affect the ability of juvenile fish to pass upstream. It is less likely that a pipe arch culvert would suffer from this problem. The wider, flatter inverts of countersunk culverts are better able to accommodate very large substrate elements without excessive constriction of flow.

Effects of design and construction practices

The seven culverts which received "fair" or "poor" overall ratings had inherent problems resulting from design and/or construction methods. The Ritner and Sheythe Creek culverts, four of which were rated as "fair" and two of which were rated as "poor," appear not to have been countersunk deeply enough. The design drawings for these installations calls for a countersinking and backfilling depth of 1 ft. This countersinking depth does not meet the depth criteria suggested by Bates (1994) or G. N. McDonald & Associates (1994) and minimally meets those of Browning (1990). These installations may also have suffered from problems related to construction practices. The contractors who placed the culverts, perhaps because of the unconventional, countersunk design, were reluctant to countersink them to the design depth and may have set them shallower than 1 ft (Steve Mamoyak, personal communication). In addition, the placement of boulders to stabilize the bed downstream of the culvert outlets was done in an unsatisfactory manner. It is likely that the destabilizing effects of channel bed degradation downstream of the outlets of the Ritner and Sheythe Creek culverts would have been avoided by countersinking the culverts deeper and/or providing better bed stabilization such as a weir or bed rip-rap at the culvert outlets.

The Clarence Creek culvert received a "fair" overall rating. If not for the failure of the downstream weir, this culvert would have received an overall rating of "very good." It was observed in summer 1995 that the weir was constructed of visibly weak rock held together by cables epoxied into drilled holes. One of the rocks broke loose during the February 1996 high flows, causing destabilization and degradation of the bed at the outlet. The exact cause of the weir failure is unknown. The problem may have been avoided by a more sound weir design and/or the use of better materials.

The velocity study

Types of roughness in countersunk culverts

The examined culverts can be categorized by relative bed roughness. The Ritner and Sheythe Creek culverts clearly fell into the small scale roughness category at the examined discharges. Clarence Creek culvert, with its wider, more shallow channel and large substrate elements, exhibited medium/large scale roughness at the examined discharges. Of the 28 culverts examined in the culvert inventory, 10 can be expected to exhibit small scale roughness under normal conditions. The remaining 18 culverts have larger sized substrate and can be expected to exhibit medium or large scale roughness.

The approach to predicting hydraulic conditions in countersunk culverts is different under the different roughness regimes. Sites with medium and large scale roughness probably represent "fish ladder" type problems. Under such conditions fish rely upon the presence of relatively low velocity resting sites and burst swimming to negotiate a culvert (Behlke, 1991). The Clarence Creek culvert is an example of this kind of passage problem. Solutions to this problem will not be explored further in this report. Instead, velocities present under the small scale roughness conditions found at the Ritner Creek culverts will be examined.

Application of Manning's equation to calculate average cross-sectional velocity

Average cross-sectional velocities calculated using Manning's equation agreed relatively closely with measured values (Figure 24). This was true whether individual culvert crown slopes or local streambed slope were used in the calculation (the individual culvert slopes at Ritner Creek culverts were very close to the local stream slope). Values of Manning's "n" which gave the best fit to the measured data were 0.06 and 0.055 for calculations utilizing individual culvert crown and local bed slope respectively. These values are on the high end published ranges of Manning's "n" values for the gravel/rubble sized substrate found in the culverts (Dunne and Leopold, 1978; Pyles, 1992). The slope of the regression line through the predicted values in Figure 24 is noticeably less than 1.0. This is expected, since effective channel roughness generally decreases with increased depth (and associated average velocity) in rectangular or trapezoidal channels (Thorne and Zevenbergen, 1985).

The application of Manning's formula to the Ritner Creek culvert data demonstrated that Manning's formula can give an approximate estimate of average cross-sectional velocity in countersunk culverts. As with other open-channel flow problems, application of Manning's formula to the solution of hydraulics problems in countersunk culverts requires the careful choice of the correct Manning's "n" for the channel and examined discharge conditions. In this analysis a representative value of "n" was used which agreed with published values of "n" for the given conditions. Further development of the application of Manning's equation to this problem is necessary if it is to become an accurate aid in countersunk culvert design.

Development of equations for estimating the extent of low velocity zones in cross-sections based on average cross-sectional velocity

Song and Yang (1979) describe three layers to two dimensional velocity distribution in turbulent flow. Velocity distribution in the laminar sublayer, which occupies a thin layer at the bottom of the water column, can be approximated by a linear equation. Above the laminar sublayer lies the inner turbulent region, followed by the outer turbulent region. Within the inner turbulent region velocity distribution can be approximated by the logarithmic profile

$$V/(gDS)^{0.5} = A_1 * LN(y/D) + A_2 \tag{1}$$

where V = velocity; g = the gravitational constant; D = water depth; y = distance above bed; and A_1 and A_2 are constants (Song and Yang, 1979). The term $(gDS)^{0.5}$ can be replaced by using a variation of the Darcy-Weisbach equation

$$V_{ave} = k(gDS)^{0.5} \tag{2}$$

where k is a constant; V_{ave} is the average cross-sectional velocity; and the other variables are as described above (Thorne and Zevenbergen, 1985). Making the substitution, the resulting equation is:

$$V/ V_{ave} = B_1 * LN(y/D) + B_2 \tag{3}$$

where B_1 and B_2 are constants. The equation resulting from analysis of the Ritner Creek culvert velocity data is

$$V/V_{ave} = 0.64 * LOG(y/D) + 1.25. \quad (4)$$

The corresponding equation resulting from analysis of the McKinnon and Hnytka (1985) data is

$$V/V_{ave} = 0.53 * LOG(y/D) + 1.24. \quad (5)$$

That resulting from the Sheythe Creek data is

$$V/V_{ave} = 0.80 * LOG(y/D) + 1.27. \quad (6)$$

Thus, the equations resulting from the analysis of the Ritner Creek culvert, Sheythe Creek culvert, and McKinnon and Hnytka (1985) velocity data agree in form with the equation for velocity distribution in the inner turbulent region presented by Song and Yang (1979). As seen in Figure 29, the regression lines based on data from these three locations have similar slope and almost identical intercept values. These results suggest that published velocity profile equations effectively approximate velocity profiles in countersunk culverts with small scale roughness, and that the formulation of a general method for predicting velocity profiles in countersunk culverts with small scale roughness may be possible.

Prediction of low velocity zones in the cross-sections based on measured average cross-sectional velocity

Application of equation (4) to predict the proportion of cross-sectional area of flow with velocity less than or equal to 1 fps (and 2 fps), based on measured average velocities of Ritner Creek culvert cross-sections, resulted in under-estimation for most cross-sections (Figures 25-26). The relatively few over-predictions occurred primarily under a discharge estimated to be approximately 40% of the 10-yr discharge. In the majority of cases the equation provided a conservative estimate of the proportion of the flow cross-section with velocity less than or equal to the given target velocity. Application of this method to the Liard River tributary data presented by McKinnon and Hnytka (1985) resulted in less consistent results (Figure 27). In this case, proportional area at or below a given velocity were often under-predicted. This was particularly true for the higher values of target velocity. The variation in the sizes, substrate, and slopes of the Liard River tributary culverts may account for the inaccuracy of predictions as compared to those of the Ritner Creek culvert data analysis. Despite the unexplained differences between the Ritner Creek culvert and Liard River tributary results, it is notable that predicted values for both the Ritner Creek culverts and the McKinnon and Hnytka (1985) data appear to be related to measured values in a consistent, roughly linear manner and that over-prediction of low velocity areas tended to occur when the measured extent of such areas exceeded 40% of the total cross-sectional area of flow.

These results of this analysis show that two dimensional velocity zones, expressed as proportions of the water column, can result in a useful approximation of the proportional extent of corresponding three dimensional velocity zones in countersunk culverts with small scale roughness. The variability in the results, however, suggest that further development is required before this or a similar method is of practical use in countersunk culvert design.

Prediction of low velocity zones in the cross-sections based on average cross-sectional velocity predicted by Manning's equation

To facilitate its practical use in culvert design, a predictive procedure should be based on commonly used hydraulic parameters such as channel slope, normal depth, and average velocity. A two-step procedure was used to predict the extent of low velocity zones within the Ritner Creek culvert cross-sections (this procedure was not repeated on Lliard river cross-sections due to insufficient data). First, Manning's formula was used to predict average velocity. Second, the regression relationship relating (V/V_{ave}) and Log(y/D) developed for the Ritner Creek culverts was used to predict the proportional extent of cross-sectional area with velocity of 1 fps (and 2 fps) or less.

This procedure resulted in conservative estimates of the proportion of cross-sectional area of flow with velocity less than or equal to 1 fps for the majority of the cross-sections. The proportional area of flow with velocity less than or equal to 1 fps was under-predicted at 17 of the 19 cross-sections. The procedure over-predicted for two cross-sections, which were measured during the highest discharge observed; a flow which probably exceeds reasonable passage design discharge at this site.

The same predictive procedure was repeated using with 2 fps as the maximum velocity. This analysis resulted in more instances of over-prediction than did the analysis using a 1 fps maximum velocity. It is notable, however, that predicted values appear to be related to measured values in a consistent, roughly linear manner.

This exercise was carried out with the knowledge of the most accurate Manning's "n" value and the regression relationship relating (V/V_{ave}) and Log(y/D) for the given conditions. In reality, the culvert designer would know neither of these with certainty. Nonetheless, the results of this analysis suggest that it may be possible to develop a procedure to accurately estimate the proportional extent of low velocity zones, or the lower limit to the proportional extent of these zones, in countersunk culverts based on common hydraulic parameters. In particular, the apparent linear relationship between predicted and measured values suggests that inclusion of a multiplicative constant might yield a useful predictive equation.

Conclusions and Recommendations

Conclusions

The examination of 28 countersunk culverts in Oregon showed them to be structures which resist erosion and effectively convey high discharges. Conditions within the culverts considered favorable to fish passage were documented both qualitatively and quantitatively. Detailed documentation of water velocity distributions in several culverts under fall and winter discharges showed the presence of zones of velocity of a magnitude currently accepted in the literature as passable by juvenile salmonids. Results of the velocity data analysis suggest that the extent of low velocity zones, or perhaps the lower limit of their extent, in the channel cross-sections of countersunk culvert with small scale roughness may be predictable using common parameters such as cross-sectional area of flow and hydraulic depth. This issue and others, including prediction of velocity under medium and large scale roughness conditions, regarding juvenile salmonid migration, bear further research.

Recommendations

<u>The following recommendations are those of reviewed authors which were supported by observations made in this study.</u>

Countersinking depth. Culverts should be countersunk at least 20% of their height. The possibility of countersinking round culverts more than 20% of the culvert diameter should be considered. When countersinking culverts heights less than about 5 ft, special care should be taken to countersink deeply enough to allow for natural adjustment of the streambed without destabilizing disruption of the substrate within the culvert barrel.

Bed rip-rap and bed elevation control downstream of outlet. Whenever possible natural features should be used to aid in culvert placement (including consideration of using open-arch culverts instead of countersunk culverts on sites where bedrock is at or near the surface). In most cases natural features will not provide the necessary bed protection downstream of the outlet. Bed rip-rap and boulder weirs should be used in these cases, unless it is known with certainty that fluctuations in bed elevation will not result in scour to level of the culvert invert (e.g., an extremely deeply countersunk culvert). The bed elevation control structures should not be considered as "accessories," but rather as vital components necessary for proper functioning of the culvert. In general, for culverts that are countersunk 20% of their diameter, weirs should be built so as to promote retention of substrate in culvert outlet without causing excess deposition which could decrease conveyance capacity. Weir height and countersinking depth are not independent. The two must be synchronized to achieve the desired bed configuration.

Maximum culvert slopes. Well designed and constructed countersunk culverts at slopes of over 2% can sustain floods of 5 year return period and retain their intended configuration. It is recommended that bed material sized and placed such that bed material will be immobile at design discharge in culverts with slope greater than 2%. However, little is known about the effects of larger storms on culverts with slope greater than 3%.

Culvert slope vs. local bed slope. Results of this study indicate that culverts with slopes 0-1.6% flatter than the local streambed gradient retain sediment well. Browning (1990) asserts that placement of culverts at a slope flatter than the natural local gradient will aid in substrate recruitment and retention. Results of this study neither prove nor refute this assertion. It is recommended that culvert barrels be placed at or near local stream gradient on lower gradient streams and slightly flatter than local stream gradient on steeper streams. If a culvert is placed slightly flatter that the local stream gradient, the outlet should be countersunk at least 20% of the culvert height.

Avoidance of "submergence" of stream discharge during low flow periods. When extensive excavation is done for the culvert foundation, or if local factors suggest that low flow season discharge may run subsurface for the length of the culvert, a non-permeable barrier should be placed between the foundation and streambed materials as suggested by Browning (1990). Alternatively, if water quality restrictions permit, fine sediment can be included in the excavation backfill.

Round versus pipe arch culverts. Pipe arch culverts provide a wider channel at bed level than similar sized round culverts given equal countersinking depths, thus resulting in a lower water velocity and less constriction of flow at most discharges. A larger, deeply buried round culvert, however, offers a greater margin of error with respect to the lowering of streambed elevation. When economically feasible, a deeply buried round culvert represents the more conservative choice. If excavation and material costs preclude the use of a large, deeply buried round culvert, a pipe arch culvert should be used.

The following are recommendations based on the results of this study

Use of multiple-pipe installations. Use of multiple, parallel culverts in place of a larger, single culvert is discouraged except in special cases. Problems associated with debris jams and unequal distribution of flow may cause multiple-pipe emplacements to be more prone to failure, and to require more maintenance than single culverts. A multiple-pipe emplacement may allow greater lateral movement of the channel than would a single culvert. Such an emplacement might help preserve the dynamic nature of some channels. Occasionally a multiple-pipe emplacement may be desired due to roadbed elevation limitations. In these cases the installation of one, larger countersunk culvert in parallel with one or more smaller, conventionally placed "overflow" culverts should be considered. The invert elevation of the overflow culverts should be high enough above the natural channel elevation such that they cannot inadvertently become the main channel. The likelihood and consequences of blockage by debris should be examined whenever one considers using of multiple culverts.

Substrate depth. If the bed within a countersunk culvert is intentionally composed of substrate which is larger than local stream substrate, the culvert should be filled to a level slightly below the natural streambed elevation. A layer of local streambed substrate can be placed on top, or the bed can be allowed to naturally fill. This configuration will allow for natural downstream transport of sediment.

Incident angle of streamflow. The culvert barrel should be placed as coincident with the direction of the incident streamflow as possible. This will minimize the possibility of lateral scour within the inlet due to deflection of streamflow by the culvert walls. In cases where the incident angle is significant and cannot be remedied by re-orienting the culvert, measures to re-align the stream so as to enter the culvert at a shallow incident angle might be considered.

Mitering of inlet and outlet. Unless mitering is necessary to enhance the conveyance capacity of the culvert, the inlet should not be mitered. The outlet need not be mitered. Leaving the inlet and outlet un-mitered will protect them from damage by rip-rap sliding down the fill slope.

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Appendix

Culvert Score Sheet: Spring 1996

Culvert:______________________

Date surveyed in 1995:__________

Date surveyed in 1996:__________

Inlet Scores

Scour	

4 - No appreciable scour
3 - Minor scour, invert steel not exposed
2 - Moderate scour, may have small amount of invert steel exposed
1 - Severe scour, significant amount of invert steel exposed

Stability	

4 - Very stable: apparently unaffected by 1996 flood
3 - Stable: inlet condition not likely to degrade in subsequent flood of 1996 magnitude
2 - Unstable: inlet condition likely to degrade in subsequent flood of 1996 magnitude
1 - Very unstable: inlet cond likely to degrade in future flood smaller than 1996 flood

Overall	

4 - Very good
3 - Good
2 - Fair
1 - Poor

Suggested overall score based on scour and stability scores:

Scour	Stability	Overall
4	4	4
3	3	3
3	2	2
3	1	1
2	3	3

Scour	Stability	Overall
2	2	2
2	1	1
1	3	2
1	2	2
1	1	1

Mid-pipe bed conditions

Notes:

Outlet Scores

Scour	

5 - No appreciable scour
4 - Minor scour, invert steel not exposed
3 - Moderate scour, invert steel not exposed
2 - Moderate to severe scour, invert steel exposed, no drop-off
1 - Moderate to severe scour, invert steel exposed, drop-off

Stability	

4 - Very stable: apparently unaffected by 1996 flood
3 - Stable: outlet cond. not likely to degrade in subsequent flood of 1996 magnitude
2 - Unstable: outlet condition likely to degrade in subsequent flood of 1996 magnitude
1 - Very unstable: outlet cond. likely to degrade in future flood smaller than 1996 flood

Culvert Score Sheet: Spring 1996

Outlet Scores: Continued

Overall	

4 - Very good
3 - Good
2 - Fair
1 - Poor

Suggested overall score based on scour and stability scores:

Scour	Stability	Overall
5	4	4
4	3	3
4	2	2
4	1	1
3	3	2
3	2	1
3	1	1

Scour	Stability	Overall
2	3	1
2	2	1
2	1	1
1	3	1
1	2	1
1	1	1

General culvert score

Score	

Key: 4 - Very good: Stable, good bed configuration
3 - Good: Stable, fair bed condition
2 - Fair: Unstable, bed condition fair to good but likely to worser
1 - Poor: Poor bed configuration, stable or unstable
0 - Failed: Culvert failure

Suggested overall score based on inlet and outlet scores:

Inlet	Outlet	Overall
4	4	4
4	3	4
4	2	2
4	1	1
3	4	4
3	3	4
3	2	2
3	1	1

Inlet	Outlet	Overall
2	4	3
2	3	3
2	2	2
2	1	1
1	4	1
1	3	1
1	2	1
1	1	1

Woody debris influence

Score	

Key: 3 - Major influence
2 - Moderate influence
1 - Minor influence
0 - No apparent influence

Notes:

Culvert Inventory Data Table

Culvert	Township	Range	Section	Road name or number
Alder 1	T5S	R9W	4	HWY 22
Alder 2	T19S	R1E	23	#1802
Browns	T21S	R8E	29	#4280
Buster	T5N	R6W	22	Buster
Canyon	T16S	R32E	1	#16
Caribou	T11S	R34E	12	Upper Middle Fork Road
Clarence	T4S	R8W	2	Upper Nestucca
Flat	T11S	R34E	11	Upper Middle Fork Road
Goose	T7S	R43E	14	#70
Little Boulder	T11S	R34E	11	Upper Middle Fork Road
Little McKay	T13S	R17E	5	McKay Creek Road
Meacham 1	T1S	R35E	3	Union Pacific Railroad tracks
Meacham 2	T1N	R35E	35	Union Pacific Railroad tracks
Meacham 3	T1N	R35E	35	Union Pacific Railroad tracks
Meacham 4	T1N	R35E	35	Union Pacific Railroad tracks
Mid. Fk. Canyon	T16S	R32E	2	#16
Ritner Left	T9S	R7W	35	Gage Road
Ritner Middle	T9S	R7W	35	Gage Road
Ritner Right	T9S	R7W	35	Gage Road
Sheythe Left	T9S	R7W	36	Gage Road
Sheythe Middle	T9S	R7W	36	Gage Road
Sheythe Right	T9S	R7W	36	Gage Road
Slickrock	T4S	R8W	1	Upper Nestucca
Vincent	T11S	R35E	18	Upper Middle Fork Road
Vinegar	T11S	R35E	20	Upper Middle Fork Road
Wilts	T3S	R35E	36	#51
Windlass	T11S	R34E	4	Upper Middle Fork Road
Wolf	T6S	R7E	36	#46

Culvert Inventory Data Table

Culvert	length (ft)	Height (ft)	Width (ft)	Pipe Arch (1=yes)	Multiplate (1=yes)	Mitered (1=yes)	Age in 1996 (yr)	Largest storm (yr)
Alder 1	70	13.4	20.8	1	1	1	14	10
Alder 2	50	7.25	11.42	1	1	1	13	5
Browns	80	8.33	12.83	1	1	1	12	5
Buster	78	9	9	0	0	1	2	100
Canyon	113	10.5	10.5	0	1	1	25	10
Caribou	68.7	7.92	12.5	1	1	0	4	5
Clarence	87	11.67	17.92	1	1	1	4	10
Flat	54	4.58	6.08	1	1	1	4	5
Goose	65	5.5	11.5	1	1	1	10	
Little Boulder	72	7.92	12.5	1	1	1	4	5
Little McKay	94.5	8.42	13.42	1	1	1	20	10
Meacham 1	120	14	13.5	1	1	1	15	50
Meacham 2	143	15	14	1	1	1	15	50
Meacham 3	135	15	14	1	1	1	15	50
Meacham 4	160	19.5	19.5	1	1	1	15	50
Mid. Fk. Canyon	90	8.5	13.5	1	1	1	25	10
Ritner Left	65	8	8	0	0	1	4	20
Ritner Middle	65	8	8	0	0	1	4	20
Ritner Right	65	8	8	0	0	1	4	20
Sheythe Left	55	7	7	0	0	1	4	20
Sheythe Middle	55	7	7	0	0	1	4	20
Sheythe Right	55	7	7	0	0	1	4	20
Slickrock	86	12	18.6	1	1	1	4	10
Vincent	78	7.92	12.5	1	1	0	4	5
Vinegar	78	7.92	12.5	1	1	1	4	5
Wilts	140	6.25	9.3	1	0	1	4	35
Windlass	56	4.58	6.1	1	1	1	4	5
Wolf	50	5.33	6.33	1	0	0	2	50

Culvert Inventory Data Table

Culvert	drainage area (sq mi)	% ulvert grad	% Local grad.	Local upstream slope (%)	local-pipe slope (%)	Slope change at inlet (%)
Alder 1	5.82	1.1	0.4	0.4	-0.7	-0.7
Alder 2	1.61	7.6	7.4	10.4	-0.2	2.8
Browns	19.9	0.8	0.4	0.7	-0.4	-0.1
Buster	1.44	1.5	1.7	3.1	0.2	1.6
Canyon	11.65	1.2	1.4	1.4	0.2	0.2
Caribou	2.46	4.7	4.5	4.5	-0.2	-0.2
Clarence	3.32	0.9	1.9	1.5	1	0.6
Flat	1.07	3.6	5.2	4.8	1.6	1.2
Goose		-0.7	0.5	1.1	1.2	1.8
Little Boulder	4.59	5.4	5.3	6.3	-0.1	0.9
Little McKay	12.15	2.7	2	3.3	-0.7	0.6
Meacham 1	16.72	1.1	0.5	0.9	-0.6	-0.2
Meacham 2	22.88	1.3	1.1	2	-0.2	0.7
Meacham 3	22.95	1.6	1.9	2	0.3	0.4
Meacham 4	23.06	1.7	2.2	2.3	0.5	0.6
Md. Fk. Canyon	10.97	1.9	1.5	1.6	-0.4	-0.3
Ritner Left	3.39	1.1	1.1	1	0	-0.1
Ritner Middle	3.39	1.2	1.1	1	-0.1	-0.2
Ritner Right	3.39	1.5	1.1	1	-0.4	-0.5
Sheythe Left	2.47	1.4	0.5	0.4	-0.9	-1
Sheythe Middle	2.47	0.8	0.5	0.4	-0.3	-0.4
Sheythe Right	2.47	1.1	0.5	0.4	-0.6	-0.7
Slickrock	3.56	0	3.9	3.7	3.9	3.7
Vincent	5.43	2.1	1.8	1.7	-0.3	-0.4
Vinegar	11.84	3	3	2.3	0	-0.7
Wilts	0.42	0.6	0.5	0.7	-0.1	0.1
Windlass	2.09	2.8	4.4	11.2	1.6	8.4
Wolf	0.8	1.9	1.6	2	-0.3	0.1

Culvert Inventory Data Table

Culvert	Steam slope (1/4 mi) from topo map (%)	Upstream channel width (ft)	Downstream channel width (ft)	constriction at inlet
Alder 1	1.3	30	32	0.69
Alder 2	12.4	14.6	13.2	0.78
Browns	0.2			
Buster	2.5		7	
Canyon	3	19.6	24	0.54
Caribou	3.2	13.8	12	0.91
Clarence	3.9	15.8	16.4	1.13
Flat	3.8	6.6	12	0.92
Goose	1.5	14	16	0.82
Little Boulder	4.7	11	12.6	1.14
Little McKay	2.4	14.6	20.2	0.92
Meacham 1	1	45	34	0.30
Meacham 2	1.5	33	37	0.42
Meacham 3	2.4	20.8	20	0.67
Meacham 4	2.7	25	30	0.78
Mid. Fk. Canyon	2.4	26	19.2	0.52
Ritner Left	1.1	7.07	7.73	1.13
Ritner Middle	1.1	7.07	7.73	1.13
Ritner Right	1.1	7.07	7.73	1.13
Sheythe Left	0.9	8.4	8.4	0.83
Sheythe Middle	0.9	8.4	8.4	0.83
Sheythe Right	0.9	8.4	8.4	0.83
Slickrock	2.6	17	22.5	1.09
Vincent	2.1	17.4	26.8	0.72
Vinegar	1.9	20.4		0.61
Wilts	10.4	32	18	0.29
Windlass	5.5	5.8	4.8	1.05
Wolf	7.4	7.2	21	0.88

Culvert Inventory Data Table

Culvert	Outlet relative fill depth	Average relative fill depth	D50 (mm)	D84 (mm)	Incident angle (degrees)	West Oregon (1=yes)
Alder 1	0.19	0.11	54	120	40	1
Alder 2	0.24	0.17	110	290	7.5	1
Browns	0.00	0.02	17	32	5	0
Buster	0.28	0.32	1	1	30	1
Canyon	0.02	0.05	63	115	20	0
Caribou	0.14	0.19	45	270	5	0
Clarence	0.10	0.16	67	135	20	1
Flat	0.24	0.18			0	0
Goose	0.21	0.21			10	0
Little Boulder	0.31	0.26	86	315	0	0
Little McKay	0.13	0.16	86	215	0	0
Meacham 1	0.27	0.27	56	165	0	0
Meacham 2	0.26	0.22	48	84	60	0
Meacham 3	0.22	0.22	100	218	45	0
Meacham 4	0.30	0.28	105	215	0	0
Mid. Fk. Canyon	0.28	0.26	54	96	20	0
Ritner Left	0.14	0.07	64	100	40	1
Ritner Middle	0.15	0.07	49	80	40	1
Ritner Right	0.16	0.08	48	76	40	1
Sheythe Left	0.19	0.14	26	35	40	1
Sheythe Middle	0.25	0.25	18	30	40	1
Sheythe Right	0.36	0.34	16	22	40	1
Slickrock	0.00	0.11	120	245	30	1
Vincent	0.24	0.29	110	300	0	0
Vinegar	0.20	0.21	100	260	0	0
Wilts	0.07	0.06	1	19	30	0
Windlass	0.55	0.46			20	0
Wolf	0.31	0.26	84	140	45	1

Culvert Inventory Data Table

Culvert	expansion at outlet	Avg. Inlet fill depth (ft)	Avg. Outlet fill depth (ft)	Average fill depth	Inlet relative fill depth
Alder 1	1.54	0.5	2.57	1.5	0.04
Alder 2	1.16	0.75	1.71	1.2	0.10
Browns		0.34	0	0.2	0.04
Buster	0.78	3.2	2.5	2.9	0.36
Canyon	2.29	0.87	0.2	0.5	0.08
Caribou	0.96	1.82	1.12	1.5	0.23
Clarence	0.92	2.5	1.17	1.8	0.21
Flat	1.97	0.51	1.11	0.8	0.11
Goose	1.39	1.14	1.18	1.2	0.21
Little Boulder	1.01	1.67	2.42	2.0	0.21
Little McKay	1.51	1.52	1.1	1.3	0.18
Meacham 1	2.52	3.8	3.8	3.8	0.27
Meacham 2	2.64	2.62	3.9	3.3	0.17
Meacham 3	1.43	3.22	3.32	3.3	0.21
Meacham 4	1.54	5.3	5.8	5.6	0.27
Mid. Fk. Canyon	1.42	2.01	2.34	2.2	0.24
Ritner Left	0.97	0	1.14	0.6	0.00
Ritner Middle	0.97	0	1.17	0.6	0.00
Ritner Right	0.97	0	1.28	0.6	0.00
Sheythe Left	1.20	0.64	1.3	1.0	0.09
Sheythe Middle	1.20	1.75	1.78	1.8	0.25
Sheythe Right	1.20	2.28	2.51	2.4	0.33
Slickrock	1.21	2.6	0	1.3	0.22
Vincent	2.14	2.68	1.91	2.3	0.34
Vinegar	0.00	1.67	1.62	1.6	0.21
Wilts	1.94	0.35	0.45	0.4	0.06
Windlass	0.79	1.69	2.52	2.1	0.37
Wolf	3.32	1.18	1.63	1.4	0.22

Culvert Inventory Data Table

Culvert	Single pipe (1=yes)	Woody debris influence	Natural downstream elevation control	Boulder weir or bed riprap
Alder 1	1	0	1	0
Alder 2	1	0	0	1
Browns	1	0	1	0
Buster	1	0	1	0
Canyon	1	0	0	0
Caribou	1	0	0	1
Clarence	1	0	0	1
Flat	1	0	0	1
Goose	1	0	0	0
Little Boulder	1	0	0	1
Little McKay	1	0	0	0
Meacham 1	1	0	0	1
Meacham 2	1	0	0	1
Meacham 3	1	3	0	1
Meacham 4	1	0	0	1
Mid. Fk. Canyon	1	0	0	0
Ritner Left	0	2	0	1
Ritner Middle	0	3	0	1
Ritner Right	0	3	0	0
Sheythe Left	0	3	0	1
Sheythe Middle	0	3	0	0
Sheythe Right	0	3	0	0
Slickrock	1	0	0	1
Vincent	1	0	0	1
Vinegar	1	0	0	1
Wilts	1	0	0	0
Windlass	1	0	0	1
Wolf	1	0	0	0

Culvert Inventory Data Table

Culvert	Man-made structures near inlet	Inlet scour	Inlet stability	Inlet overall	Outlet scour
Alder 1	0	1	4	3	2
Alder 2	0	2	4	3	5
Browns	0	2	4	4	4
Buster	0	3	3	3	3
Canyon	0	2	4	3	4
Caribou	0	4	4	4	5
Clarence	1	1	2	2	3
Flat	0	4	4	4	4
Goose	0	4	4	4	5
Little Boulder	0	3	4	4	4
Little McKay	0	3	4	4	5
Meacham 1	0	3	4	4	5
Meacham 2	1	3	4	4	4
Meacham 3	0	2	3	3	3
Meacham 4	1	3	4	4	4
Mid. Fk. Canyon	0	3	4	4	4
Ritner Left	0	1	3	2	4
Ritner Middle	0	1	2	2	2
Ritner Right	0	1	2	2	3
Sheythe Left	0	1	1	1	3
Sheythe Middle	0	1	1	1	4
Sheythe Right	0	2	2	2	3
Slickrock	0	2	4	3	1
Vincent	0	4	4	4	5
Vinegar	0	3	4	4	4
Wilts	0	2	3	3	4
Windlass	0	4	4	4	5
Wolf	0	2	3	3	5

Culvert Inventory Data Table

Culvert	Outlet stability	Outlet overall	Pipe overall	Notes
Alder 1	3	2	4	
Alder 2	4	4	4	
Browns	4	4	4	
Buster	4	3	4	1996 fill depths
Canyon	4	4	3	estimated age
Caribou	4	4	4	
Clarence	1	1	2	
Flat	4	4	4	
Goose	4	4	4	estimated age
Little Boulder	4	4	4	
Little McKay	4	4	4	estimated age
Meacham 1	4	4	4	
Meacham 2	4	4	4	
Meacham 3	4	3	4	
Meacham 4	4	4	4	
Mid. Fk. Canyon	4	4	4	estimated age
Ritner Left	2	2	2	
Ritner Middle	1	1	2	
Ritner Right	1	1	2	
Sheythe Left	2	2	2	
Sheythe Middle	1	1	1	
Sheythe Right	1	1	1	
Slickrock	4	1	3	non-typical config.
Vincent	4	4	4	
Vinegar	4	4	4	
Wilts	4	4	3	
Windlass	4	4	3	
Wolf	4	4	4	

Culvert Inventory Data Table

Culvert	Outlet stability	Outlet overall	Pipe overall	Notes
Alder 1	3	2	4	
Alder 2	4	4	4	
Browns	4	4	4	
Buster	4	3	4	1996 fill depths
Canyon	4	4	3	estimated age
Caribou	4	4	4	
Clarence	1	1	2	
Flat	4	4	4	
Goose	4	4	4	estimated age
Little Boulder	4	4	4	
Little McKay	4	4	4	estimated age
Meacham 1	4	4	4	
Meacham 2	4	4	4	
Meacham 3	4	3	4	
Meacham 4	4	4	4	
Mid. Fk. Canyon	4	4	4	estimated age
Ritner Left	2	2	2	
Ritner Middle	1	1	2	
Ritner Right	1	1	2	
Sheythe Left	2	2	2	
Sheythe Middle	1	1	1	
Sheythe Right	1	1	1	
Slickrock	4	1	3	non-typical config.
Vincent	4	4	4	
Vinegar	4	4	4	
Wilts	4	4	3	
Windlass	4	4	3	
Wolf	4	4	4	

Summary of velocity data collection dates and discharges

Estimated 10-yr discharges based on equations from Campbell and Sidle (1984):

Ritner Creek: 325 cfs
Sheythe Creek: 253 cfs
Clarence Creek: 686 cfs

Culvert(s)	Date	Discharge		Culvert(s)	Date	Discharge
Ritner left	7/10/95	2.2		Sheythe left	9/5/95	1
Ritner middle	7/10/95	0		Sheythe middle	9/5/95	0
Ritner right	7/10/95	0		Sheythe right	9/5/95	0
Total	7/10/95	2.2		Total	9/5/95	1
Ritner left	10/26/95	8		Sheythe left	10/26/95	4.8
Ritner middle	10/26/95	0		Sheythe middle	10/26/95	0
Ritner right	10/26/95	0		Sheythe right	10/26/95	0
Total	10/26/95	8		Total	10/26/95	4.8
Ritner left	11/11/95	62		Sheythe left	11/11/95	28.1
Ritner middle	11/11/95	44.2		Sheythe middle	11/11/95	28.8
Ritner right	11/11/95	40.6		Sheythe right	11/11/95	14.8
Total	11/11/95	146.8		Total	11/11/95	71.7
Ritner left	12/6/95	14.8		Sheythe left	12/6/95	17.3
Ritner middle	12/6/95	7.5		Sheythe middle	12/6/95	--
Ritner right	12/6/95	14.3		Sheythe right	12/6/95	--
Total	12/6/95	36.6		Total	12/6/95	--
Ritner left	12/20/95	26.6		Sheythe left	12/20/95	23.1
Ritner middle	12/20/95	5.9		Sheythe middle	12/20/95	--
Ritner right	12/20/95	13.1		Sheythe right	12/20/95	--
Total	12/20/95	45.6		Total	12/20/95	--
Clarence	1/4/96	31.8				
Clarence	1/15/96	30.6				
Clarence	1/21/96	94.2				