AN ABSTRACT OF THE THESIS OF

Michele L. Reba for the degree of Master of Science in Forest Engineering and Civil Engineering presented on December 4, 2001.
Title: The Design and Evaluation of Three "Stream Simulation" Culverts in South Central Oregon.

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Three culverts, judged to be fish barriers, were replaced with "stream simulation" culverts on the Fremont National Forest of south central Oregon. The culvert sites are located in the Fort Rock Basin in streams that are home to resident Great Basin redband trout (*Oncorhynchus mykiss*). Great Basin redband trout is the common name for the native trout in the Great Basin and is informally recognized as *O.m. newberrii*.

The design process is discussed and documented for the three culvert replacements. The fish passage conditions in the new culverts were compared to the old culverts both quantitatively and qualitatively. One assumption with stream simulation culverts is that fish will be able to move through a culvert if the flow conditions are similar to that of the natural channel. Velocity measurements and channel characteristics were compared between the natural stream and the culvert. The comparisons were used to define whether similarity was achieved between the culvert and the natural stream. Velocity and channel characteristic measurements were taken during one discharge condition of spring snowmelt, the migration period for spawning redband trout. The comparisons were further examined to determine which would be appropriate metrics in the determination of success or

failure of the installation. Channel stability was quantified at each culvert through three systems of channel stability measurements.

Regional design guidelines were found to lack information regarding the invert elevation placement for designing a stream simulation culvert. Invert placement is likely to be critical in terms of permanence of placed streambed material in a culvert. There was a qualitative and quantitative improvement of flow conditions at the replacement culverts over the old culverts. All new culverts satisfied the regulatory criteria for fish passage. Two of the three culverts appeared to be similar to the natural stream when comparing similar habitat unit types. The comparisons at the third culvert site were statistically different from the natural stream. The differences may be attributed to the narrow low flow channel that existed through the culvert. Longitudinal thalweg velocity, cross-sectional velocity, and thalweg velocity distribution comparisons between the culvert and the natural stream appear to be appropriate metrics in the determination of success or failure of stream simulation culverts. Streambed material in the culverts exhibited limited evidence of movement after a minimal spring snowmelt discharge. Stability of streambed material in the culverts at higher discharges was not tested.

The Design and Evaluation of Three "Stream Simulation" Culverts in South Central Oregon.

by

Michele L. Reba

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Table of Contents

Table of Contents, Continued

List of Figures

List of Figures, Continued

List of Figures, Continued

List of Figures, Continued

List of Tables

List of Appendix Figures

List of Appendix Figures, Continued

List of Appendix Figures, Continued

List of Appendix Figures, Continued

The Design and Evaluation of Three "Stream Simulation" Culverts in South Central Oregon.

Introduction

Resource management, resource extraction and recreational activities use forest roads on managed landscapes. On U.S. National Forest land in Oregon and Washington, there were 93,900 miles of road in 1997 (Coghlan and Sowa, 1998). Additional thousands of miles of road are on state and private managed land. At any intersection of a road and a stream, there is typically some type of stream crossing structure. These structures range from low water fords to culverts to bridges. An overlay of a road system with a stream system provides an index of the number of stream crossings. In most landscapes, the majority of these stream crossings are culverts. Culverts allow for level crossing of a stream, which low water fords do not permit, and are typically less expensive than bridges. Bridges are typically located on larger stream systems, are more expensive and therefore less common. Low water fords typically do not allow for year round or heavy traffic use and their use may be further limited by the timing of fish spawning.

A challenging issue, when added to the sheer number of culverts, is the obligation to provide fish passage at any stream crossing used by fish during any significant period of the year (ODFW, 1997). Partial or complete barriers to fish passage through culverts often make suitable habitat unreachable, may result in decreased spawning of fish, and may increase predation. Fish passage guidelines for conventionally designed culverts are based on average water velocity for the species of interest, life stage, and timing of migration. A recent survey of culverts on fish bearing streams located on the Fremont National Forest showed that 86% of the 329 surveyed culverts did not meet the fish passage guidelines set by the US Forest Service. Of the culverts that satisfied the guidelines, 67% were bottomless arches. A bottomless arch is a metal arch or a bottomless concrete culvert placed on footings with a natural streambed underneath and fill material on top of the culvert. A limitation to the use of bottomless arches is that they should be used only where the footings can be placed near surficial bedrock (Browning, 1990) or where modifications can be made in order to stabilize the footings. Additional disadvantages to bottomless arches are the added difficulty and expense in the construction and design of these culvert types. The advantages of bottomless arches are the natural substrate bottom and, if they are sized properly, they will have conditions within the culvert that are similar to those in the natural stream. Stream simulation culverts share the same advantages. A stream simulation culvert is a complete round or pipe-arch culvert embedded or buried below the streambed. The culvert is over-sized, compared to a conventionally designed culvert, in order to maintain the natural stream channel width. Stream simulation culverts have several advantages over bottomless arches. They do not require footings for structural integrity, are simpler in their design and construction, and typically are more cost effective than bottomless arches. However, the pipe sizes that are available for stream simulation designs are limited to approximately 15 ft to 20 ft wide for pipe arches where as those available for bottomless arches are available up to widths of approximately 40 ft.

Stream simulation culverts are designed to have the same physical channel characteristics in the culvert barrel as in the natural stream. These physical channel characteristics are average cross-section, width, slope, and substrate for flows up to migration discharge (McKinnon and Hyntka, 1985). The biological aspects within the culvert are not considered in this study. Currently, stream simulation culverts or structures with a natural bed are not bound by the specific fish passage velocity requirements of regulatory criteria (ODFW, 1997; WDFW, 1999). The requirements state that natural channel beds and their formations provide "paths of access with suitable depths, velocities and resting opportunities with only brief exposure to excessive conditions" (ODFW, 1997). The lack of design specific information regarding fish swimming ability and the specific addition of juvenile passage to state guidelines (ODF, 1994) has led designers to use stream simulation culverts more often. However, there is limited information regarding the performance of these culverts. One study in Oregon inventoried the performance of 28 countersunk culverts, constructed with the invert of the culvert lower than the streambed and with culvert widths that were narrower than the current criteria, but the study did not review the design process of the culverts due to limited information regarding design specifics of each culvert (White, 1996).

This project tracks the replacement of three stream crossing culverts, judged to be fish barriers, from the design and construction phase through a detailed review of their performance after one spring snowmelt. The three culverts were replaced with stream simulation designed culverts on the Fremont National Forest of south central Oregon. The culvert sites are located in the Fort Rock Basin in streams that are home to resident Great Basin redband trout (*Oncorhynchus mykiss*). The Great Basin redband trout is the common name for the native trout in the Great Basin and is informally recognized as *O.m. newberrii*. This study documents, through examples, the steps in the design process of three stream simulation culverts, investigates various metrics to explore the degree of similarity between stream simulation culverts and the natural stream, and investigates various systems to track channel stability within stream simulation culverts.

Objectives

The main goal of this study was to determine to what degree the natural stream was simulated within the confines of the culvert. The premise of this idea is simple. If a fish can move freely through a natural stream, the same fish should be able to move freely through a physically similar section of the same stream that is within the confines of a culvert. The objectives of this study were to:

1) Design and install three stream simulation culverts,
2) Quantify and qualify the improvement over the old culverts with the newly installed stream simulation culverts,
3) Quantify and compare several stream characteristics of each culvert with the natural stream, and
4) Quantify channel stability at each stream simulation culvert after one spring snowmelt.

The design process is discussed and documented through the three culvert replacements. Objectives two, three, and four address the research objectives of the study. The second objective of the study was to investigate the fish passage condition in the new culverts compared to the old culverts both quantitatively and qualitatively. The extent to which the new culverts had improved the condition of fish passage at each stream crossing was quantified by the calculation of the average cross-sectional velocity before and after installation of the stream simulation culverts. The improvement over the old culverts is qualified through photographic documentation. The third objective of this study was to compare velocity measurements and channel characteristics between the natural stream and the culvert. The comparisons were used to define whether similarity was achieved between the culvert and the natural stream. Velocity and channel characteristic measurements were taken during one discharge condition of spring snowmelt, the migration period for spawning redband trout. The comparisons were further examined to determine which would be appropriate metrics in the determination of success or failure of the installation. The fourth objective was to quantify the channel stability at each culvert. The stability of the placed material within the stream simulation culverts was determined by using colored rocks, scour chains, and change in digital terrain models of each culvert site.

Literature Review

Fish movement

Fish move for several reasons, including spawning, refuge, and habitat. Impeding movement of fish may result in limited access to existing upstream habitat, decreased spawning of fish, increased predation, and the isolation of smaller or weaker fish may limit genetic diversity and result in metapopulation development. Culverts, where a pipe is placed under a road to convey water from one side to the other, are possible barriers to fish movement.

Several factors, including water velocity, water depth, fish swimming ability, and the height of the outlet drop influence the success or failure of fish movement through culverts. Fish use both red and white muscle tissue for swimming. Red muscle activity (aerobic) is used for prolonged and sustained action while white muscle activity (anaerobic) is limited to short, high intensity action (Behlke, 1991). Swimming capability is often divided into three categories of speed: cruising speed, sustained speed, and burst speed. Cruising speed is used during migration, sustained speed for passage through difficult areas, and burst speed for escape and feeding (Bell, 1986). Cruising speed, sustained speed, and burst speed are further defined as ranging from 2-4 body lengths per second, 4-7 body lengths per second, and 8-12 body lengths per second, respectively (Reiser and Bjornn, 1979). However, a study in Montana, which used trout of different lengths (total length of fish ranged from 161 mm to 470 mm) to explore passage ability in culverts that included bare pipes, pipes with baffles, and pipes with bed load accumulation, yielded no relationship between passage success and the length of trout studied (Belford and Gould, 1989).

The apparent contradiction between the existence of a relationship between swimming ability and body length is clarified if one considers fish location in the water column when they move. Lower velocity zones typically exist near the bottom and sides of a culvert and smaller fish have the opportunity to take advantage of these zones more than do larger fish. Typically, fish moving under strenuous conditions will swim very close to the culvert sides and bottom (Travis and Tilsworth, 1986; Belford and Gould, 1989; Behlke et al., 1991). Arctic grayling, tested for swimming performance, were observed "schooling together in the lower one-third" of the flume and most were near the bottom of the flume (MacPhee and Watts, 1976). Lower velocity zones are even larger, other factors remaining equal, with increased roughness from streambed substrate material.

Detailed hydraulic analysis of fish moving through water has also been explored. Behlke (1991) outlined equations and procedures in order to compare one design to another based on power and energy requirements for a fish to move through a given design scenario. This procedure necessitates a stronger database than currently exists for design engineers to confidently use the procedure. More specifically, there is a lack of information regarding where fish actually swim, water and fish velocities, and fish accelerations (Behlke, 1991).

Critical velocities or maximum sustainable velocities of several fish have been studied and are used to indicate maximum aerobic swimming performance. Rainbow trout, with an average fork length of 38 cm (1.2 ft), were found to have a critical velocity of 1.4 to 2.2 body lengths per second when measured in a test ramp (Jain et al., 1997). The critical velocity of wild-caught rainbow trout, with an average fork length of 31 cm (1.0 ft), was 67 cm/s (2.2 ft/s) (Jones et al., 1974). The variability among critical swimming speeds is substantial. For the wild-caught rainbow trout studied the range of critical velocity is from 47 to 83 cm/s (1.6 to 2.7 ft/s) (Jones et al., 1974). Due to the wide range of swimming performance data, designers of culverts are forced to design for passage by the weakest swimming fish of the species of interest (ODFW, 1997).

Redband trout movement

Great Basin redband trout (*Oncorhynchus mykiss)*, a resident species found in seven closed basins of Oregon and northern California, are the fish species of interest for the project area. Movement of these fish has not been studied in detail but more than likely occurs as upstream movement of spring spawning migrations of adults, downstream movement to over-wintering habitat for both adults and juveniles, and first year density redistribution (Bowers et al., 1999). Redband trout in southeastern Oregon streams were found to spawn in April and May (Kunkel, 1976). Little information is available on the life histories of the populations in the Fort Rock Basin, where the study sites are located (Bowers et al., 1999), and even less is known about the juveniles of this species. It is agreed, however, that redband trout spawn in the spring during snowmelt generated high flow and are similar to rainbow trout in several respects (size, spawning, etc). In Buck Creek, a drainage west of the study sites, it was found that redband trout become sexually mature at age three and reach six inches in size at age four (Bowers et al., 1999).

Based on capture and release research, it was concluded that the movement of resident stream fish was limited, but the use of more advanced methods may prove this theory untrue. Adult resident stream fishes likely move in search of resources and to optimize habitat conditions (Fausch and Young, 1995). One school of thought suggests that there is limited upstream and downstream movement (Behnke, 1992) and movement is restricted to finding suitable spawning habitat (Hesthagen, 1988). An older study of redband trout in a tributary of the Chewaucan River, using capture and release research, concludes that very few of the trout were found to have moved more than 300 feet (Osborn, 1968). Contrary to these findings, other researchers have found substantial movement of resident trout in streams via the incorporation of radio telemetry and two-way weirs (Gowan et al., 1994). Radio telemetry studies in the spring of 2000 and 2001 in the Chewaucan Basin quantified movement of several adult spawning redband trout. Average round trip, upstream and downstream, distances traveled by redband trout after tagging was 66 and 40 river kilometers in 2000 and 2001, respectively. The maximum upstream distance traveled in 2001 was 23 river kilometers while 44% of the radio-tagged fish moved upstream less than six river kilometers (Tenniswood, 2001).

The extent and reason behind resident redband trout movement at all life-stages is not clear. There is limited data on juvenile redband trout movement needs. However, there is clear evidence of upstream movement of spawning adults during the spring.

Limits to data

Data are available regarding fish movement and swimming ability. However, capabilities of fish in the wild must be further researched and defined before the data can be used for design purposes. Several inherent problems were highlighted regarding the determination of fish ability, including fish condition, translating laboratory findings to natural settings, temperature, salinity, and captivity effects (Blaxter, 1969). More than 20 years later, the tests of swimming performance are characterized as difficult and expensive to perform (Behlke et al., 1991). Moreover, knowing the swimming ability concluded from a laboratory test may not translate into how the fish will perform when confronted with specific obstacles. Behlke et al. (1991) speculates that although a fish may be physically capable of rapid progress through a culvert, it will minimize power output as it moves through a culvert of unknown length. The limits of the data regarding design specific information coupled with the possibility that the fish will not utilize its full swimming ability to get through a culvert barrel, leaves the culvert designer searching for a better solution.

Stream simulation culverts

One design that is not dictated by fish swimming ability is a design based on the physical conditions created by the natural stream. The creation of natural stream characteristics within the confines of a culvert may be accomplished in a stream simulation culvert and in a bottomless arch culvert. Both designs incorporate a natural substrate bottom and, if sized properly, aim to have conditions within the culvert be similar to those within the natural stream. However, with bottomless arch culverts, structural stability issues are critical and footings of the arches should be placed near surficial bedrock (Browning, 1990) or additional modification of the footings should be considered. At the same time, bedrock may impede the proper installation of a stream simulation culvert and the existence of bedrock should be investigated during the design phase (Robison et al., 1999). The design and installation of bottomless arches is typically more expensive and difficult than a stream simulation culvert (Robison et al., 1999). The stream simulation culvert, when properly sized, should be indistinguishable from a bottomless arch (Poulin and Argent, 1997).

Culverts with buried inlets or with the inlet and outlet buried (stream simulation culverts) have long been recommended as strategies for fish passage (USDA, 1978; Evans and Johnston, 1980; Morsell et al., 1981; USDOT, 1985; Jordan and Carlson, 1987; Browning, 1990). The addition of juvenile passage criteria has made the use of stream simulation designed culverts more common in the last decade.

The definition of what a stream simulation culvert is ranges from the simple to the specific. Stream simulation can be simply defined as a condition where "substrate and flow conditions in the crossing structure mimic the natural streambed above and below the structure" (ODFW, 1997). By maintaining natural stream characteristics, the culvert will not impose low flow conditions that are any worse than the natural stream (Pyles, 2000a). Another definition calls for the maintenance of natural stream properties, such as average cross-section, width, slope, and substrate, at the stream crossing for flows up to migration discharge, and concentration of low flow discharge (McKinnon and Hyntka, 1985).

Design recommendations

The design of stream simulation culverts must consider several essential factors including slope, pipe size, invert elevation, and substrate material. A clear consensus has not been reached with regard to most of the essential factors of the design of a stream simulation culvert. The design recommendations highlighted here are based on fish passage policy, field data, and experience.

The natural channel gradient should be maintained through the culvert. The recommended slope for the successful use of stream simulation culverts varies between 2%-8% (Table 1). Higher gradient streams, between 4%-8%, should be considered with caution.

Table 1. Pipe slope recommendations for stream simulation culverts.

Slope & Culvert Type	Source	Comments	Reference
< 4%	field data	economical choice range: 2%-4%	Robison et al., 1999
4%-8%	limited field data		Robison et al., 1999
≤ 5% pipe-arch	limited field data		Poulin and Argent, 1997
≤ 2%-3.5% circular	unknown	Not field examined	Poulin and Argent, 1997
<6%	unknown	Use conservatively	WDFW, 1999

The culvert and road fill material should be designed to maintain structural integrity to the 100-year event (ODFW, 1997). The width of the culvert must be similar to bankfull (1.5- to 2-year flood event) stream width (Robison et al., 1999). Another recommendation for the calculation of the width of the culvert is the active channel width times 1.2, plus 2 feet (WDFW, 1999). This formula stems from the need for a natural channel to go outside of the active channel during minor floods and to avoid very small culverts that would allow for just a 20 percent increase in the stream which may not achieve stream simulation (WDFW, 1999). The primary consideration for the determination of width is limiting contraction and expansion forces at the inlet and outlet, respectively and allowing for the maintenance of the natural stream channel width (Poulin and Argent, 1997).

Invert elevation of the pipe must be considered in order to keep bed material inside of the culvert. A longitudinal profile of the existing pipe and the stream above and below the culvert must be surveyed. This profile will allow the designer insight into the vertical extent of variation of the streambed, typically the bottom of existing pools. This vertical extent of the pools can be used as an indicator of where the pipe should be placed to allow the retention of bed material (Pyles, 2000a). At sites where local movement of bed material is deemed insufficient to backfill the culvert via natural sediment processes, substrate material backfilling is recommended. Substrate material backfilling is recommended to 20% - 40% (Robison et al., 1999; Poulin and Argent, 1997) or 30%-50% (WDFW, 1999) of the rise of the culvert. However, the invert elevation of the pipe, determined from both the longitudinal profile, and the backfill height are dependent upon each other and must be considered jointly.

The streambed material guidelines range from simulating natural streambed roughness characteristics to placing riprap material. Backfill material should be well graded with approximately a D_{100}/D_{50} of 3.0 and D_{100}/D_{16} of 15 (WDFW, 1999). This material size is recommended to allow for bed sealing and address bed stability at high flows (WDFW, 1999). Riprap sized to the D_{90} of the stream channel (Poulin and Argent, 1997) and cobble to boulder size material (Robison et al., 1999) are recommended for bed material inside of a stream simulation culvert for streambed stability. At the same time, it is recommended that the natural stream roughness characteristics be provided in the culvert (Pyles, 2000a). One recommendation based on the results of an inventory of countersunk culverts, where the invert is lower than the streambed, suggested that a layer of local streambed substrate be placed or allowed to naturally fill if the backfill is composed of larger than local streambed substrate (White, 1996). This strategy would allow for the same roughness characteristics inside of the culvert as in the natural stream and, at the same time, would also provide the recommended bed stability via underlying larger bed material.

The concentration of flow during low discharge periods of the year is also considered during the design and construction of a stream simulation culvert. WDFW (1999) suggests that the bed material be place so that a low flow channel meanders down the center of the culvert with mildly sloping channel sides.

More time and experience with the stream simulation culverts will allow for a clearer approach to their design and performance. A consensus regarding the specific elements of how a stream simulation culvert should be designed is not yet available. The design guidelines presented here are based in science, experience and policy. However, current minimum expectations for successful stream simulation designed culverts are available. Outlet jumps and the constriction and expansion of flow at all but larger flood flows should be avoided and natural fluctuations in the streambed level should not expose the culvert bottom (Pyles, 2000a). Improvements upon these current minimum expectations may be suggested through more research and study. The slope of the stream simulation culvert should be at or near natural stream gradient, the culvert width should be at or near bankfull width, and the bed material should exhibit the same roughness characteristics as the natural stream, yet provide for bed stability.

Performance evaluation

Evaluation of fish passage using stream simulation designed culverts is limited. Only two of the six culverts studied by Belford and Gould (1989) in Montana had bed material accumulated in the corrugated-metal pipe. Relationships between passage length and mean bottom velocity were generated when fish passage was measured with traps and electrofishing. Water velocity was measured at and between resting sites to determine conditions that provided or prevented passages of several trout species. Native spawning rainbow trout (total length of fish ranged from 161 mm to 470 mm) could swim 10 m with mean bottom velocities, measured approximately 0.16 ft (5 cm) above the culvert bottom, of 3.15 ft/s (0.96 m/s) (Belford and Gould, 1989).

Regions of low velocity exist near the boundary between the water and the sides of the culvert and with bed material. Stream simulation culverts studied on the Liard River appeared to have areas of sufficiently low velocity to allow for successful fish passage (McKinnon and Hyntka, 1985). Equations have been generated to determine the amount of low velocity regions that exist in a culvert in order to use the amount of low velocity regions as an indicator of juvenile fish passage (Barber and Downs, 1996; White, 1996). Based on field surveys of 39 culverts in Oregon, pipes with natural streambeds were found to provide better overall fish passage conditions (based on the condition of pipe, outlet scour, foundation condition, hydraulics, and passage capability) than pipes with or without features designed to aid fish passage, like baffles and fish ladders (Browning, 1990).

White (1996) completed an evaluation of 28 countersunk culverts in Oregon, where the invert was set lower than the streambed and material was placed or allowed to backfill the bottom of the culvert. However, the width of the culverts inventoried was considerably narrower than the natural channel width and in most cases would not satisfy the width criteria used today. The culverts were inventoried after one of the largest events on record (February, 1996) and the streambed material was found to be stable. Additional findings of this inventory were that round pipes tend to constrict the channel more so than pipe-arches, average relative fill depth of 20% with effective downstream control maintained streambed material within the culverts, and the culverts were found to be resistant to erosion and capable of moving high discharges (White, 1996). However, during the planning stages of this project some of the culverts in White's study were re-inspected. Despite having stable substrates during and immediately following the February 1996 flood event, some of the culverts in White's study have lost all of their substrate material.

Stream simulation culverts were studied to determine passage of local fish species on the Liard River (McKinnon and Hyntka, 1985). The study, conducted between 1979 and 1984, determined there were no passage delays or failures of Arctic grayling, northern pike, or longnose sucker during spring high water migration. The distribution of cross-sectional velocities in one cross-section of the natural stream was compared to those of three cross-sections in the culvert (at the inlet, outlet, and mid-point of the barrel). The study concludes that the stream simulation approach is a "valid concept" and velocities within the culvert were similar to those in the natural stream (McKinnon and Hyntka, 1985).

Guidelines

Currently in Oregon, fish passage accommodations are required on any stream that is used by fish during any significant period of the year (ODFW, 1997). Average water velocity at high flow design discharge varies by culvert length, species, and age. For example, an average water velocity at a high-flow design discharge is six ft/s for salmon and steelhead in a culvert less than 60 ft long and one ft/s for adult trout in a culvert over 300 ft in length. The values presented are typically the lowest maximum average water velocity for the weakest-swimming fish that requires passage. Design for juvenile salmonid passage must have an average water velocity of less than two ft/s in a culvert less than 100 ft long or utilize stream simulation design. Stream simulation design allows one to design without the constraint of satisfying the velocity criteria (ODFW, 1997).

A hierarchy of desirable road/stream crossing structures is as follows: bridge, stream simulation using a bottomless arch or embedded culvert, stream simulation using embedded round metal or concrete box culvert, non-embedded culvert at less than 0.5% slope, and baffled culvert at 0.5% to 12% slope or a structure with a fishway (ODFW, 1997). It should be noted that among structures properly designed to pass fish there are no data to suggest that one type of structure is any better than another. It is cautioned that open bottom arch footings should be placed on bedrock or with proper structural support below the expected scour depth (Browning, 1990). This hierarchy closely reflects the relative cost of various installations. The relative cost of installations begins with bridges, as typically the most expensive solution, followed by open bottom culverts, weir/baffle culverts, stream simulation culverts, and culverts with backwater (Robison et al., 1999; Corsi and Knoblock, 1997).

Methods

Study sites

The study sites for this analysis are all located in the southwestern portion of the Silver Lake Ranger District of the Fremont National Forest in south central Oregon (Figure 1). All three sites are located within the Silver Creek watershed, which drains into Paulina Marsh. Two sites, North Fork Silver Creek at the 3038 Road (T30S, R13E, Section 16, SW ¼ of NW ¼) and West Fork Silver Creek at the 2917 Road (T29S, R13E, Section 36, SW ¼ of NE ¼) are located within the West Fork Silver Creek sub-watershed and have drainage areas of 3.2 square miles and 22 square miles, respectively. The third site, Guyer Creek at the 3038 Road (T30S, R13E, Section 27, NE ¼ of SW ¼), is located within the Guyer Creek sub-watershed and has a drainage area of 7.9 square miles. Guyer Creek and North Fork Silver Creek are steeper, forested sites while West Fork Silver Creek is located at the lower end of a large meadow.

All three sites are located on perennial fish-bearing streams. The fish species of particular interest for this study was the spawning Great Basin redband trout (*Oncorhynchus mykiss*). The Great Basin redband trout occupies remnant streams in several Pleistocene lakebeds in southeastern Oregon, with small portions in northwestern Nevada and northeastern California. These basins are completely isolated from the ocean by natural geological features. In most basins, the redband trout established adfluvial life histories, migrating from productive lakes and/or marshes and spawning in adjacent streams. Study sites for this project were all located in the Fort Rock Basin. The Fort Rock Basin is one of seven basins in Oregon where Great Basin redband trout are found.

The general study area is located in the semiarid rain shadow region east of the Cascade Mountains. Typical climatic characteristics of the region are low precipitation totals and large temperature fluctuations. Average annual

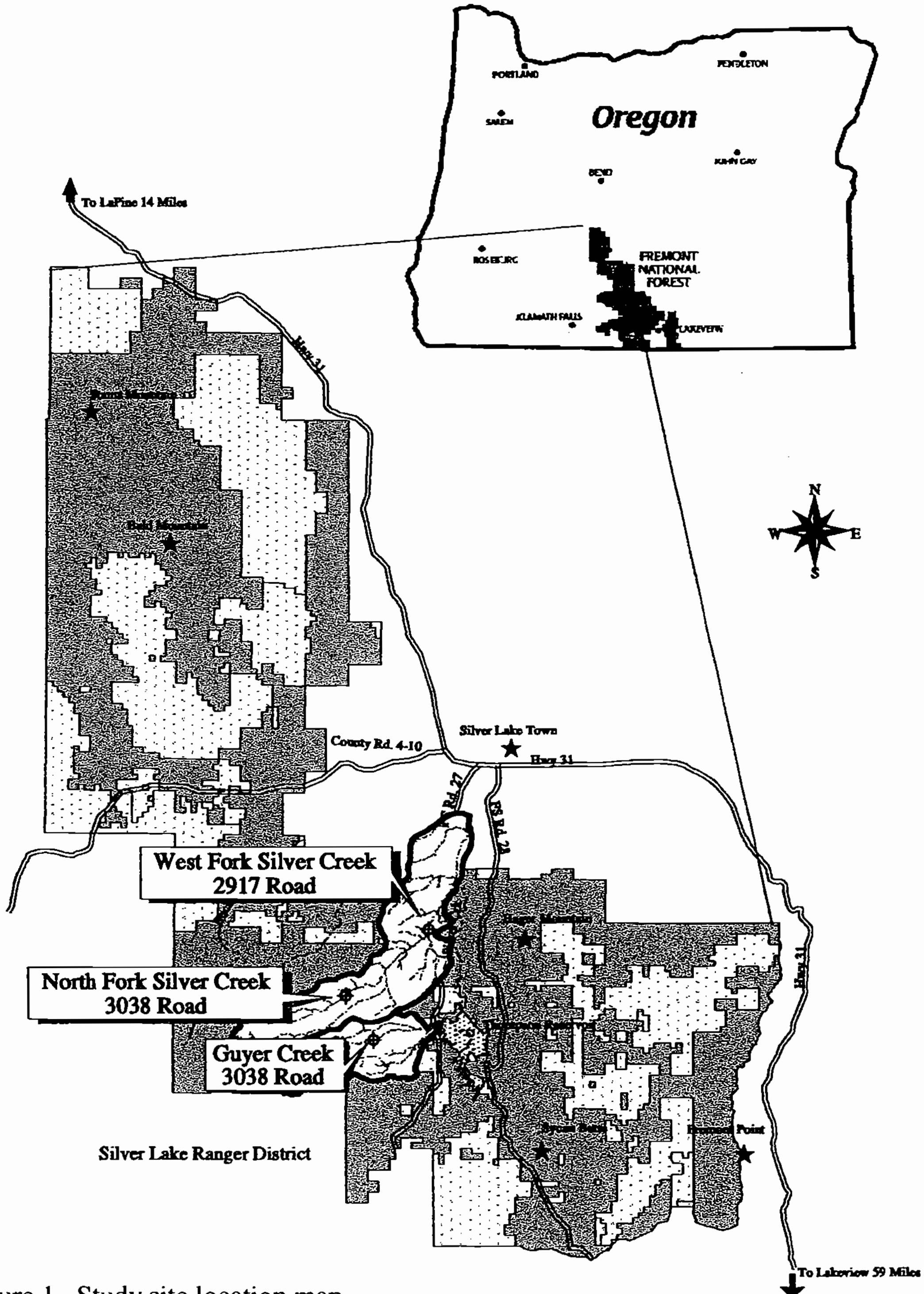


Figure 1. Study site location map.

precipitation varies from year to year and with increasing elevation, ranging from 10-15 inches in the valleys and to 20-30 inches in the mountains. Most of the precipitation occurs from October through March, with snow as the dominant precipitation type. Convective thunderstorms provide rain in spring and summer. Temperatures fluctuate widely both seasonally and with elevation. Summer months are characterized by warm days (70°F to mid 90°F) and cool nights (30°F to 50°F) while during winter months the average temperature is approximately 20°F. The general geology of the area consists of basalt and tuff flows. Soils in much of the West Fork Silver Creek subwatershed, which includes North Fork Silver Creek, are ash or pumice over buried basalt.

The dominant vegetation varies between pure *Pinus ponderosa* (ponderosa pine), pure *Pinus contorta* (lodgepole pine), and mixed conifer stands that include ponderosa pine, lodgepole pine, *Abies concolor* (white fir) and small amounts of *Pinus lambertiana* (sugar pine) and *Pinus monticola* (western white pine). The land management activities in the area include timber harvesting, livestock grazing, and recreational uses.

Stream simulation design

When the maximum velocity criteria for fish passage in culverts are applied to a natural stream, it is often found that those criteria are exceeded within some portion of the natural stream. Therefore, the design of culverts that satisfy the maximum velocity requirements must go beyond the conditions found in the adjacent natural stream. Nonetheless, fish move through the natural stream. If conditions in a culvert are made no worse than the conditions found in the adjacent natural stream a fish should be able to move through the culvert. The use of stream simulation culverts or culverts with a natural bed allows one to design without the constraint of satisfying the specific velocity requirements stipulated by the regulatory criteria (ODFW, 1997).

In a stream simulation approach, the major physical characteristics of the pipe are designed to hydraulically simulate the stream condition. The flood capacity, pipe size, pipe slope, invert elevation of culvert, and pipe backfill depth and material were considered for the design of the culvert replacements for this project. In addition, current and future channel changes must be considered during the design process.

Longitudinal profile

The longitudinal profile of the stream dictated both the pipe slope and the invert elevation of the pipe. The length of the profile used during the design process ranged from 1500 ft at the meadow site of West Fork Silver Creek to 1000 ft at Guyer Creek to 600 ft at North Fork Silver. The variation in length of the longitudinal profiles was a function of stream type and individual site characteristics. A reconnaissance of each site was completed prior to the survey to note changes in slope, stream shape, and floodplain shape. The longitudinal profiles captured the major changes in bed elevation and the corresponding water surface elevations. These major surveyed changes in streambed elevation were the deepest points in the pools, the pool tailout, and the beginning and the end of the riffles. The invert elevation of each culvert was set at the estimated lowest level that the bed may reach in the pipe. The extent of scour in the natural stream was estimated as the bottom of the pools surveyed in the longitudinal profile. As an example, the longitudinal profile for Guyer Creek is shown in Figure 2. A line connecting the bottom of the pools was used to determine the vertical location of the pipe. The longitudinal profile was used to infer the long-term equilibrium slope of the stream and was used as the design slope of each pipe.

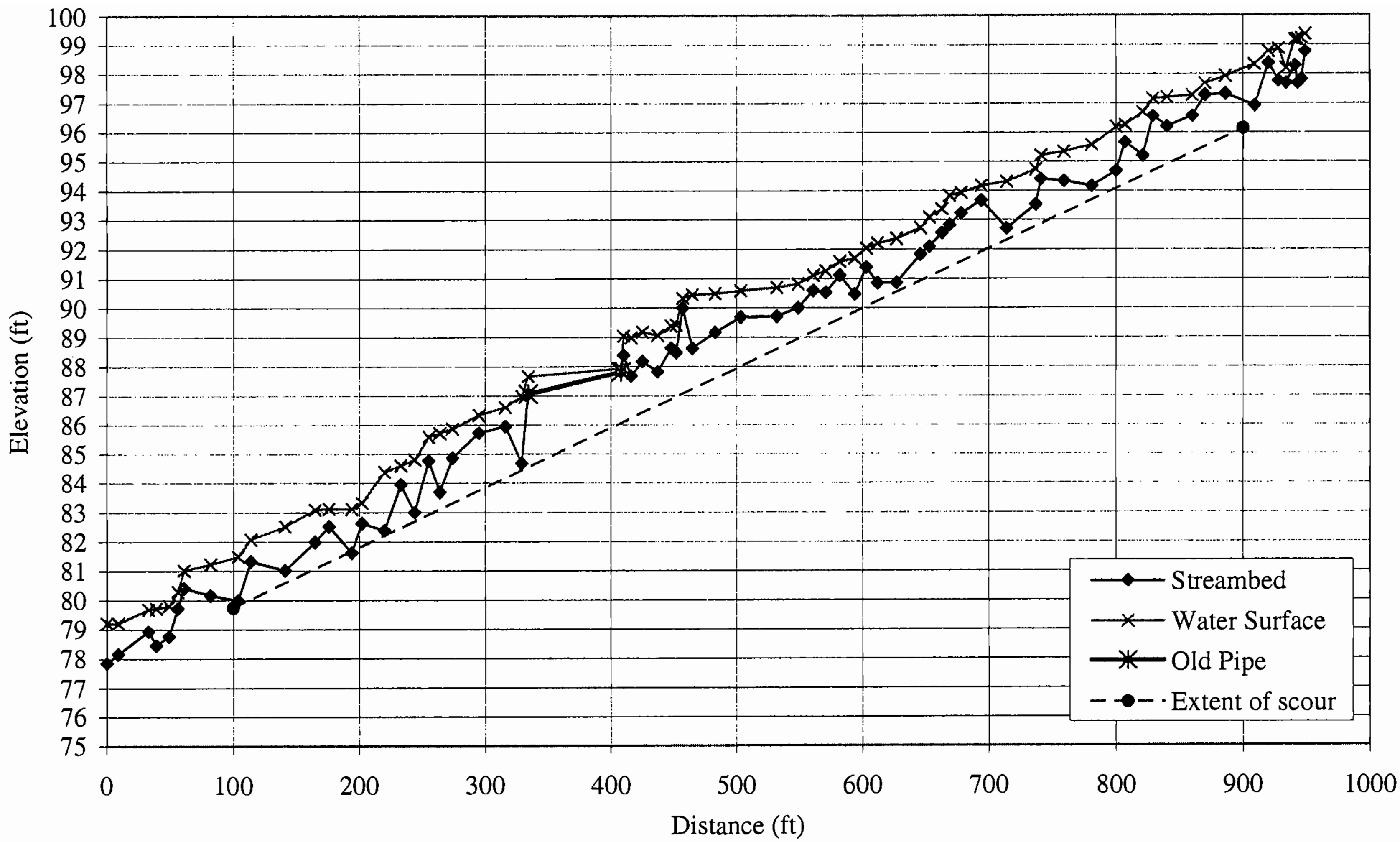


Figure 2. Guyer Creek: Longitudinal profile illustrating extent of pool scour.

Culvert size

The size of each culvert was designed to avoid channel constriction and expansion at the inlet and outlet, respectively. Each culvert was sized after careful review of the natural channel dimensions. The high flow wetted width, bankfull width (1.5- to 2-year flood event width), and an equation used to calculate culvert width (WDFW, 1999) were all considered to determine culvert width. During high flow of the design year, measurements of wetted width of the natural stream were first analyzed to determine culvert size. Ten measurements of bankfull width upstream and outside of the influence of the culvert were cross-referenced with the wetted width values. The spacing between each bankfull width measurement was an estimate of bankfull width. Taking the active channel width times 1.2 and adding 2 ft was also explored as a means to determine culvert size (WDFW, 1999). Culvert size was verified to have the capacity to pass the 100-year event with backfill material in place and a headwater depth equal to the height of the culvert.

Culvert backfill

Due to limited evidence of bedload movement at the study sites, it was deemed prudent to backfill the culverts with material during the construction phase. The invert elevation was determined for each culvert from the longitudinal profile and was backfilled with material to a minimum 20% of the height of the culvert or to a point that connected the material in the pipe to the natural stream.

The material was placed in each culvert with a low flow channel on the cross-section of the culvert to allow for concentrated movement of water during low flow periods of the year. This low flow channel was placed in each culvert with a meandering plan view through the barrel (Figure 3). The outlet and inlet of this low flow channel were placed in the center of the barrel. A low flow channel may avoid a splitting or dispersal of the discharge that may result in insufficient depth (Figure 4).

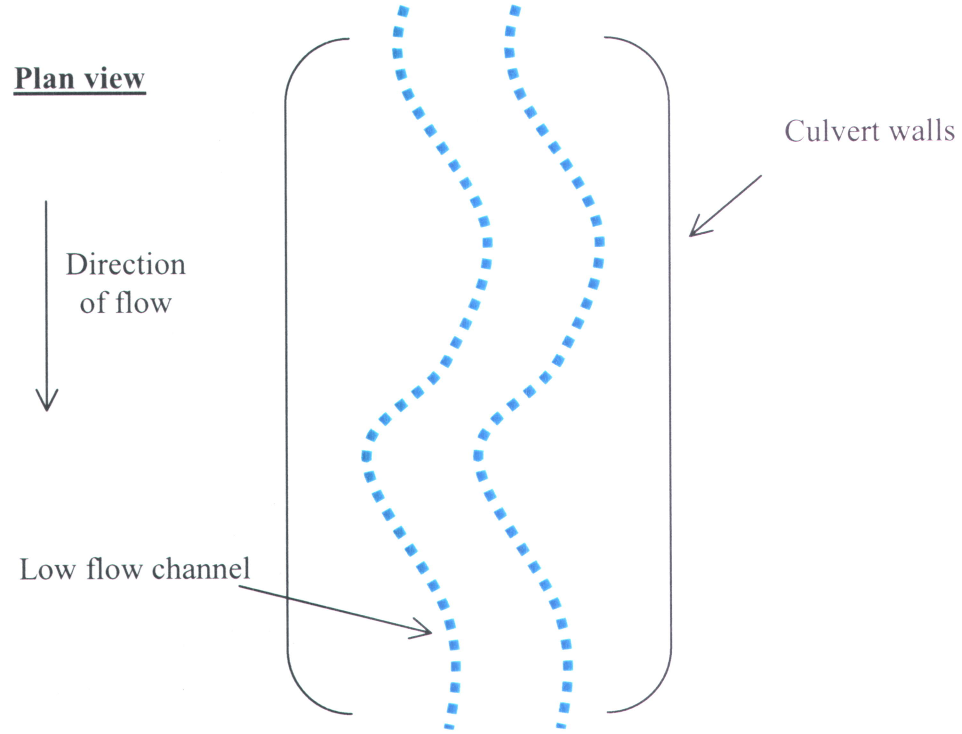


Figure 3. Low flow channel meandering through culvert.

Figure 4. Stream simulation culvert without a defined low flow channel. Inlet (top) and barrel (bottom).

The bed material used to backfill the pipes was larger than the bed material of the natural stream. The material was well-graded and ranged from fine material, which allowed for filling the bed voids, to gravel, which mimicked the natural bed material, to cobbles and large boulders, which provided stable material inside of the culvert. Smaller sized streambed material was concentrated in the bed of the low flow channel.

Field methods addressing research objectives

The season of interest for fish movement at these study sites is during the high flow months from April to June. Therefore, the majority of the data relating to hydraulic characteristics were collected during this time. The data were collected at each site before and after construction during the period of springtime snowmelt when the fish of interest were thought to be moving upstream. The interest with taking the data in this fashion was to look at a detailed snap shot of the culvert in order to compare it to the condition in the stream. However, the condition of the culvert may change over time with various flow conditions and with changes in the channel through the culvert. The one-year duration of the project study period did not allow for repeated measures during several high flow conditions.

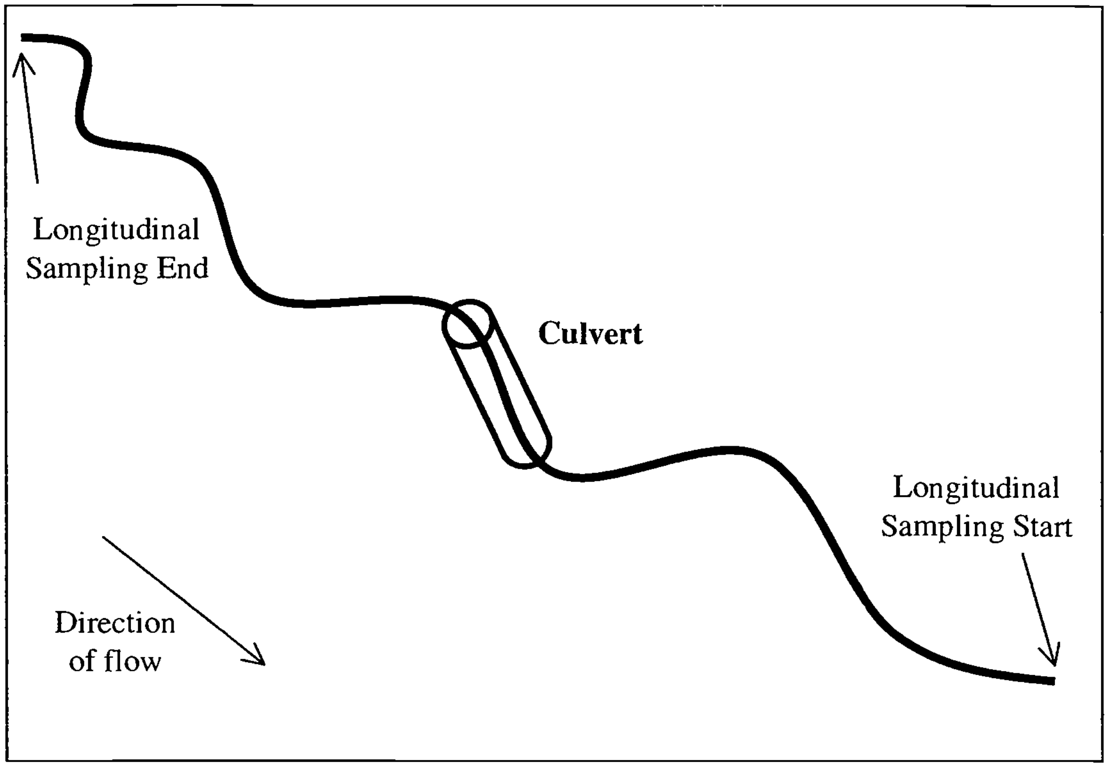
The design of stream simulation culverts in this study was standard and can be found in several design guidelines (Poulin and Argent, 1997; WDFW, 1999; Robison et al., 1999). However, the evaluation of stream simulation culverts has not been quantitatively addressed. The question of what metric to use in determining success or failure of these culverts is a difficult one. One approach is to determine how closely the hydraulic conditions in the culvert simulate the hydraulic conditions in the natural stream. One must first determine which hydraulic conditions can be measured accurately and efficiently and how those conditions relate to fish passage. The most common characteristic regarding fish passage is water velocity because it is used in passage criteria, is related to fish swimming ability, and is straightforward to measure. However, water velocity is difficult to characterize. The primary metric used in this study was measured point values of water velocity along the longitudinal profile of the stream and water velocity across several cross-sections of the stream. One must then turn to the factors that influence water velocity and explore those further. The water surface slope, cross-sectional area, habitat unit type, and streambed material were the secondary factors that were explored.

The stability of the streambed material was investigated using colored rocks, scour chains, and digital terrain models.

Sampling approaches

Two sampling approaches, a longitudinal profile based approach and a reach-based approach, were used to gather hydraulic condition information (Figure 5). The longitudinal profile approach was used in an effort to quantify the gradual variation in hydraulic condition along the length of the stream within the vicinity of the culvert and to measure hydraulic characteristics over a longer length of the stream. Under this sampling approach the start and end of each length sampled was determined in the field with the first measurement point randomly determined and the measurements thereafter systematically sampled every five feet. Approximately 1150, 1200, and 1600 ft of stream were sampled at Guyer Creek, North Fork Silver Creek, and West Fork Silver Creek, respectively. The culvert was typically located in the middle of the length sampled.

Under the reach-based approach, each site was broken into three reaches: (1) upstream, (2) culvert, and (3) downstream. Reach lengths were determined by the culvert length and size. Each reach was the length of the original pipe plus three times the culvert width upstream of the inlet, plus three times the culvert width downstream of the outlet. The other two reaches were called the upstream reach and downstream reach and were used to characterize the natural stream.



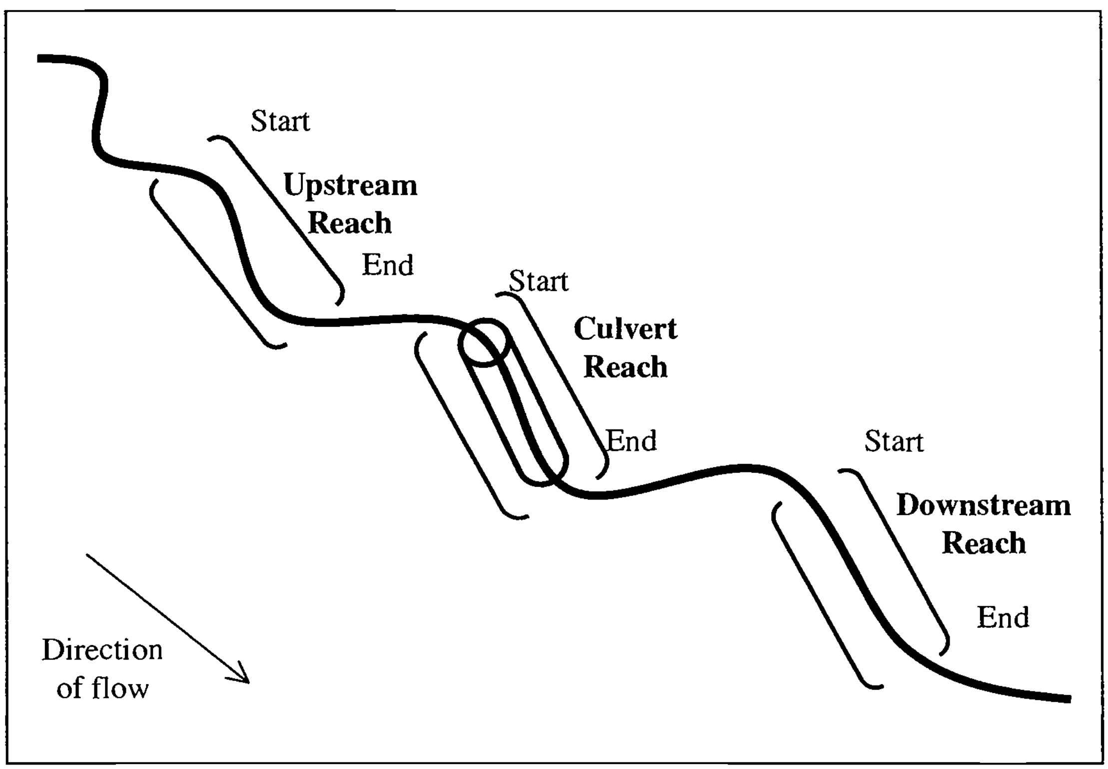


Figure 5. Plan view: Longitudinal profile sampling regime (top) and reach-based sampling regime (bottom).

Field reconnaissance and the elevation survey of the stream longitudinal profile helped locate the upstream and downstream reaches outside of the influence of the culvert. The reach lengths ranged from 102 ft to 128 ft. After culvert replacement, the culvert reach was modified due to the new pipe installation.

Velocity

Velocity was the primary metric that was used for this study. Assuming that the lateral velocity distributions were the same in the culvert as in the natural stream and the velocity measured in the thalweg was representative of the lateral velocity distribution, then the longitudinal velocity could be tracked via the measurement of the thalweg velocity over a substantial length of the stream and culvert. The longitudinal velocity was measured at the thalweg at five-foot intervals under the longitudinal profile sampling approach. In order to track the variation along the cross-section of the stream both in the culvert and the natural stream, the velocity was measured at several cross-sections in the culvert and in the upstream and downstream reaches of the reach-based sampling approach.

All velocity measurements were made using a Marsh-McBirney Model 2000 in order to determine point velocities. The instrument was set on the fixed point-averaging mode for 20 seconds. The Marsh-McBirney Model 2000 that was used for the study was calibrated in April 2000 prior to field use and was calibrated again in January 2001 prior to field use.

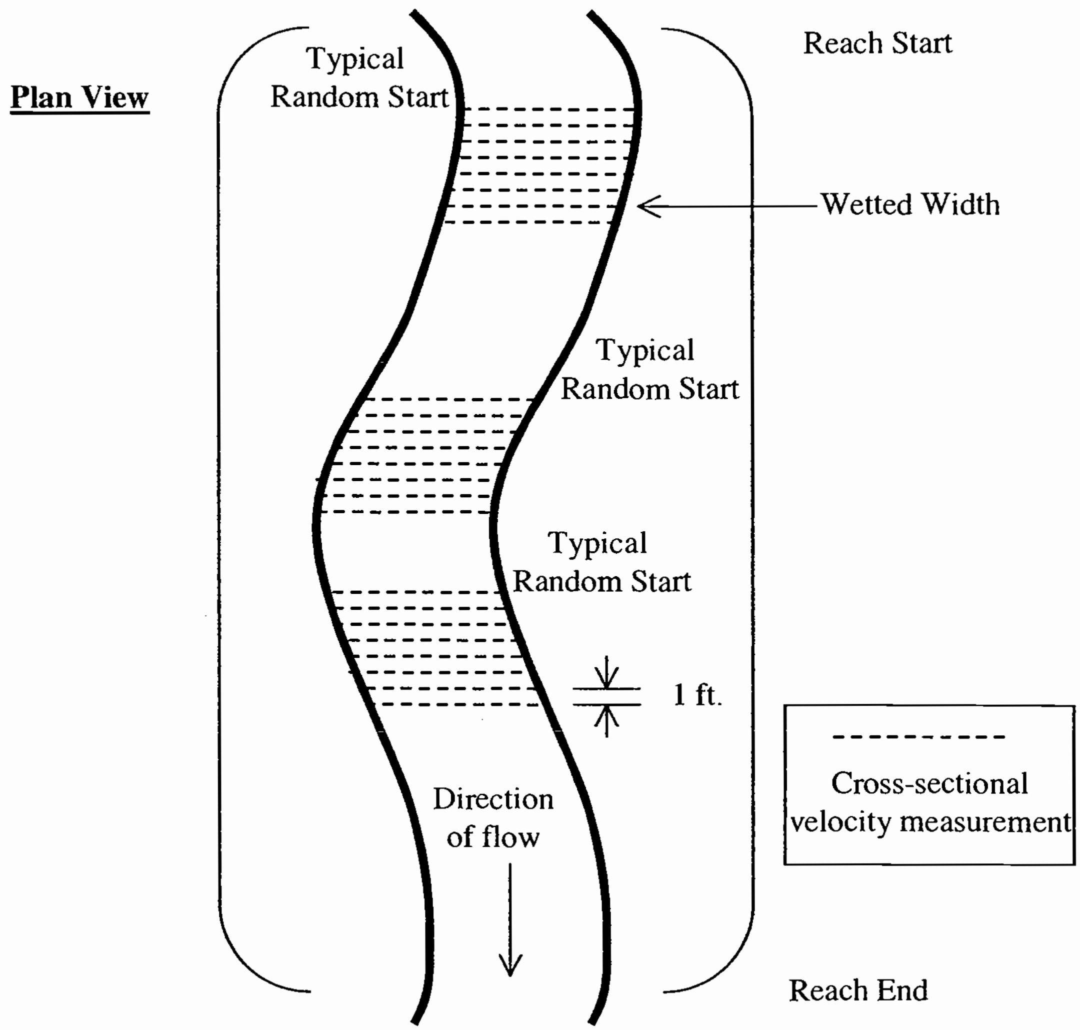
Thalweg velocity

Under the longitudinal profile sampling approach, thalweg measurements were taken every five feet longitudinally along the length of the stream. The starting point was determined randomly within 20 feet of the chosen starting location (determined in the field) and thereafter measurements were made systematically at five-foot intervals. A cross-section was placed perpendicular to the direction of flow and the deepest point along the cross-section was determined. Point velocity measurements were taken at this location at 0.2, 0.6, and 0.8 of the water depth, with the water surface as the zero datum.

Cross-sectional velocity

Under the reach-based sampling approach, the three reaches were sampled in the same manner. Twenty-four cross-sections within each reach were measured for velocity. These cross-sections were measured in three blocks of eight adjacent cross-sections (Figure 6). In the upstream and downstream reaches, the starting point of each block was randomly chosen. In the culvert reach the inlet, outlet, and midpoint of the culvert barrel were captured within the measured blocks. A block consisted of eight cross-sections spaced one foot apart longitudinally along the length of the stream. Each of the eight cross-sections was located perpendicular to the direction of flow.

At each cross-section, velocity measurements were taken laterally every foot. The edge measurements in each cross-section were taken where there was enough water to accurately measure velocity. Point velocity measurements were taken at 0.2, 0.6, and 0.8 of the water depth, with the water surface as the zero datum. An example of velocity measurement locations in a typical cross-section is shown at the bottom of Figure 6. Water depth was measured at each vertical measurement location; in addition, wetted width was measured at each cross-section.



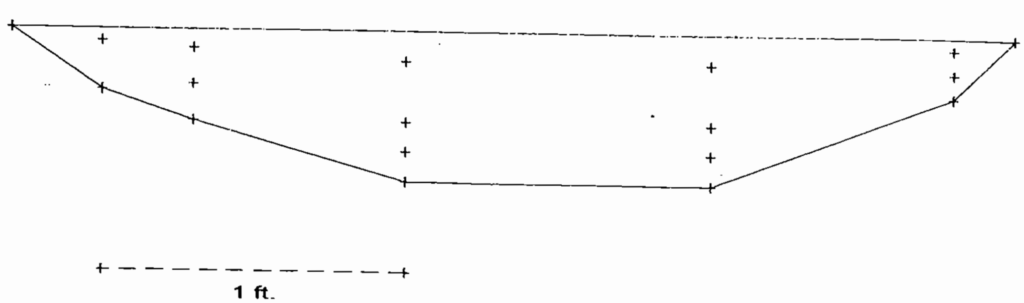


Figure 6. Cross-sectional velocity measurements scheme, plan view (top) and end view (bottom).

Slope

The longitudinal slope of the channel bed and water surface was determined by surveying major breaks in bed elevation. It was used to determine an equilibrium slope for the sites. This longitudinal slope was also used for the design of the culverts.

Under the longitudinal profile sampling approach, a measurement of bed and water surface elevation was made at the same point the thalweg velocity measurement was made. Therefore, the profile generated from the longitudinal profile sampling approach was determined systematically and not dictated by changes in bed form.

High flow channel characteristics

Regardless of sampling approach, wherever any velocity measurement was made, several channel geometry measurements were also made. At cross-sectional velocity measurement locations, the wetted width of the cross-section was measured and depth was measured at each point where velocity was measured. The wetted width and the maximum depth of the cross-section were measured where thalweg velocity was measured. The habitat unit type (pool or riffle) was also determined at every measurement location under the longitudinal profile sampling approach.

Streambed material

The bed material was characterized via two methods: a bulk method and pebble counts. The bulk method was used in order to evaluate the armor and sub-armor layer of the bed. The samples were taken in the upstream and downstream reaches in several locations. A sampling barrel was inserted into the bed of the stream at each sample location. The depth of the armor layer was determined by the depth of imbeddedness of the largest particle in the top layer. The material that was within this depth was taken as the armor layer. The sub-armor layer was determined in the same manner. The samples were sent to the soils laboratory in Lakeview, Oregon for sieving (ASTM D422, 2001).

Wolman pebble counts (Wolman, 1954) were also used to characterize the surface material. Pebble counts were performed before construction, after construction, and after spring flow of 2001. Samples of between 100 to 200 particles were taken using a step-toe procedure in a zigzag manner across the upstream and downstream reaches, the barrel of the culvert, and the low flow channel of the culvert.

Channel stability

The stability of the material placed inside of the culvert was of particular interest. The low flow channel inside of the culvert was constructed with a meandering plan view pattern (Figure 3). Monitoring the movement of the material was of interest to better understand how the placed material responded to the meandering plan view pattern and to determine variation between sediment transport in the stream and the culvert. Channel stability was monitored with scour chains, painted rocks, and a detailed survey of the culvert bed material.

Scour chains

Scour chains were inserted into the bed of the natural stream and the placed bed in the culvert to measure the aggradation or degradation of the streambed. Chains were installed in groups of two to four on five cross-sections in each culvert, and on several cross-sections in the approach to each culvert inlet, the upstream reach, and the downstream reach. The culvert scour chains were placed at the inlet, the outlet, and 25%, 50%, and 75% of the length of each culvert. Chains were installed vertically with their locations clearly marked to aid in retrieval. The number of links that were not buried was noted. The chains were excavated after peak spring flow and the depth of fill and/or scour were recorded.

Painted rocks

Approximately 20 painted and individually numbered rocks were placed in the culvert at each site. The painted rocks were placed outside of the low flow channel to monitor the stability of the meandering low flow channel. The location and intermediate axis of each of the rocks were noted and ranged from 24 mm to 395 mm. After spring flow 2001 the location of the painted rocks were again measured.

Digital terrain model

A digital terrain model (DTM) was created to show each culvert and its vicinity after construction in September 2000. This was repeated in September 2001 to monitor lateral and vertical changes in the bed material. A DTM is a digital representation of a surface designed to show topographic differences (Keim et al., 1999). The intent of using a DTM of the culvert and its vicinity was to track local scour and fill. A total-station theodolite was used to collect data electronically. Major breaks in slope were used to identify survey points. Triangular Irregular Network (TIN) is a continuous network of triangles that connect survey points. Elevations were interpolated along the axes of these triangles in order to create a topographic model of the area.

One model was created from the data collected in 2000 and another from the data collected in 2001. The models were then superimposed to calculate elevation changes. A third model was created from the overlay that shows the changes in vertical elevation of each site. The two models were also compared to look for lateral changes of the low flow channel within the culvert.

Results and Discussion

Site specific design

The culverts studied for this project were all deemed fish passage barriers for various reasons, such as excessive outlet drop and excessive barrel velocity. The three culverts chosen for replacement were bound by several criteria. The first was that the stream crossing was on a fish-bearing stream and did not meet fish passage guidelines. The economic constraint was on the culvert size and amount of fill material. The replacement culvert could be no wider than 11.8 feet wide, the widest pipe available before needing structural steel plated culverts. Structural steel plated culverts are relatively expensive and take longer to install. Sites with excessive amounts of fill material were also avoided due to the added cost of hauling and excavating material. In order to expedite the decision making process, the chosen culvert study sites were located on the same ranger district and therefore under the same decision making authority. Therefore, the sites that were chosen were large enough streams to support fish, were current barriers to fish passage, could be replaced by a pipe with a width of 11.8 ft or narrower, and were located on the Silver Lake Ranger District.

The mean annual flood discharge for each site was first calculated from a local peak flow equation (Lohrey, 1982). This equation was developed using a Log Pearson Type III frequency analysis from several gauged watersheds and is a function of drainage area. The design discharge was then calculated from the ratio between the mean annual flood and the flood at the 100-year return period (Lohrey, 1982) (Table 2). At West Fork Silver Creek, the calculation for the 100-year return period event was adjusted to standard procedure by the Fremont National Forest due to soil conditions in the drainage area. Culvert size was verified to have the capacity to pass the 100-year event, with backfill material in place and a headwater depth equal to the height of the culvert.

Table 2. Study site drainage area and discharge calculations for selected recurrence intervals (Lohrey, 1982).

Study Site	Drainage Area	$Q_{2.33}$	Q_{100}
	sq. mi.	cfs	cfs
Guyer Creek	7.9	57	225
North Fork Silver Creek	3.2	39	154
West Fork Silver Creek	22	178	400*

* Adjusted due to soil conditions.

Each of the culverts was replaced with a pipe-arch set at the slope determined from the longitudinal profile. The culvert size was determined from an analysis of wetted widths taken during high flow of the stream in the upstream and downstream reaches of the culvert. This analysis was also cross-referenced with an estimate of bankfull width at locations upstream of the existing culvert. The culvert sizes for each site were between 92% and 122% of the average of these bankfull width measurements.

The invert elevation was determined for each culvert from the longitudinal profile and was backfilled with material to a minimum 20% of the height of the culvert or to a point that connected the material in the pipe to the natural stream (Table 3). A drive probe was driven at each site as a preliminary test for bedrock depth to insure that bedrock would not interfere with the excavation during construction or with the invert elevation of the culvert. The bed material used for backfilling was larger than the bed material in the stream. The coarser material was used in an effort to avoid increased costs associated with the longer haul distances of smaller sized material. The less-than-ideal bed material size used to backfill the culverts was just one of several site specific challenges addressed during the design and construction phases.

Table 3. Old pipe and new pipe characteristics.

Study Site	Old pipe dimension	Old pipe slope	New pipe dimension	New pipe slope
	ft (Length x Span x Rise)	%	ft (Length x Span x Rise)	%
Guyer Creek	75' x 5' x 6' ovular	1.0%	78' x 11.4' x 7.3' pipe-arch	2.0%
North Fork Silver Creek	73' x 5' circular	2.9%	88' x 9.3' 6.3' pipe-arch	2.0%
West Fork Silver Creek	55' x 9' x 6' pipe-arch	1.0%	60' x 11.8' x 7.6' pipe-arch	0.5%

Guyer Creek

The design of this crossing was generally straightforward. The slope of the longitudinal profile of Guyer Creek near the culvert is constant at approximately 0.02 (Figure 7). This was the design and constructed slope of the culvert. One can easily follow the bottom of the pools in order to determine the extent of vertical scour and from that determine the vertical location of the pipe invert. The size of the culvert was determined from the average of over 100 wetted width

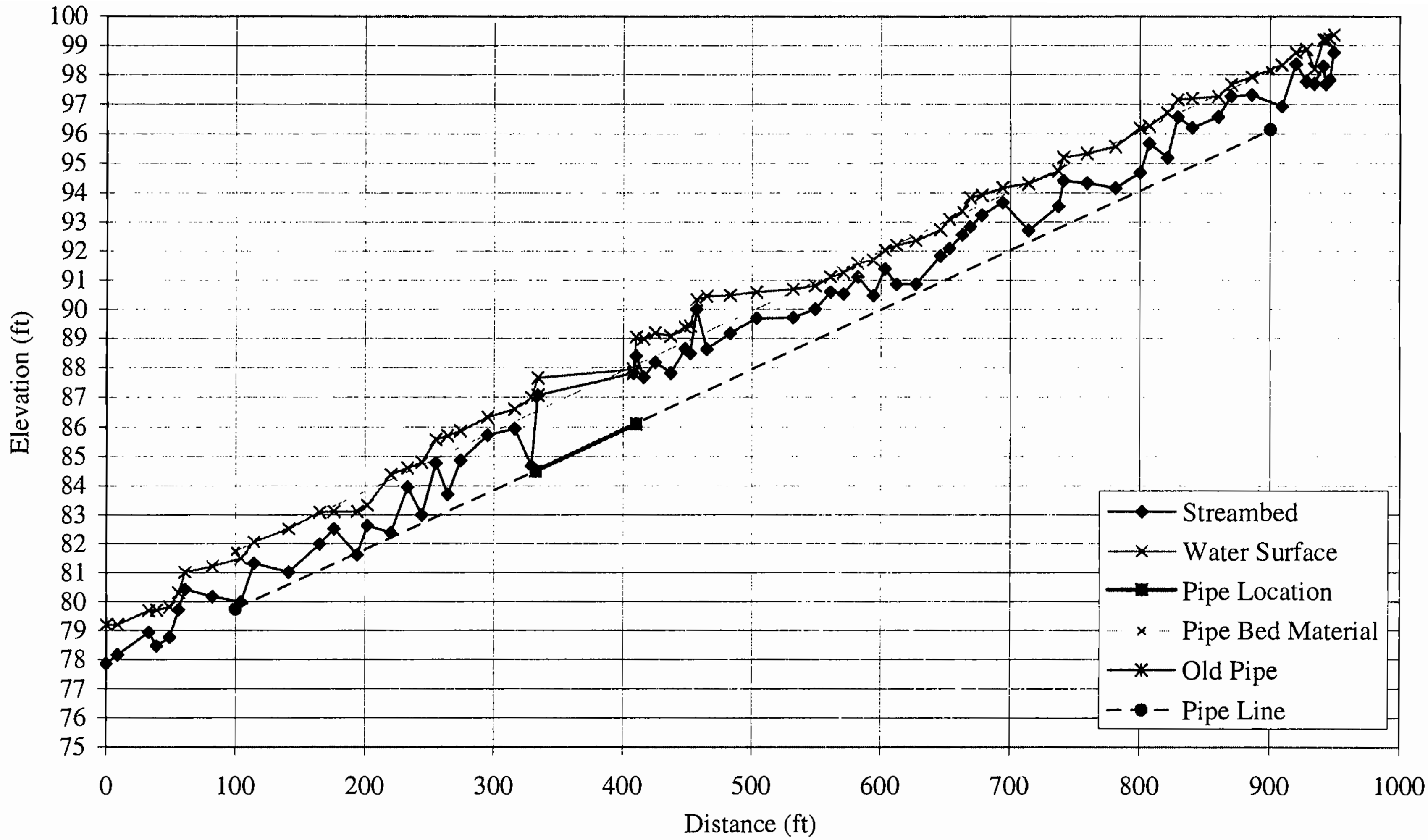


Figure 7. Guyer Creek: Longitudinal profile pre-construction.

measurements taken from the upstream and downstream reaches. The distribution of the wetted width measurements showed several points wider than the design pipe width (Figure 8). However, the wetted width values were taken at locations that were wider than the majority of the stream. The design pipe width was within 97% of the average bankfull width estimate of 11.8 ft. The equation to calculate the culvert width put forward by WDFW (1999) was explored and the culvert width from this equation, 16 ft, was determined to be extremely large. This site is located relatively high in the stream system and if the proper size at this site is 16 ft wide then the sites downstream will be enormous, very costly, and not feasible to replace. The old culvert was replaced with a pipe-arch 11.4 ft wide and 7.3 ft tall.

North Fork Silver Creek

This crossing posed a problem that is common in the design of replacement culverts: the slope of the longitudinal profile upstream and the slope downstream of the old culvert were different (Figure 9). The longitudinal profile at North Fork Silver Creek appeared to flatten out substantially at the approach to the inlet of the culvert. It was determined that the flattening was caused by the placement of the old culvert. The old culvert placement caused significant deposition upstream and altered the slope of the stream. This longitudinal profile is a classic example of why longitudinal profile measurements must be sufficiently long. A shorter measured longitudinal profile (Figure 10) would not allow the designer to have a complete understanding of the site and certainly not allow an accurate estimate of the slope of the stream. The design approach used at this site was to connect the slopes from the extreme upstream slope and the extreme downstream slope. The design assumed that the deposition above the old culvert inlet was artificial and that after culvert replacement the stream would downcut to the overall slope of the longitudinal profile of the stream.

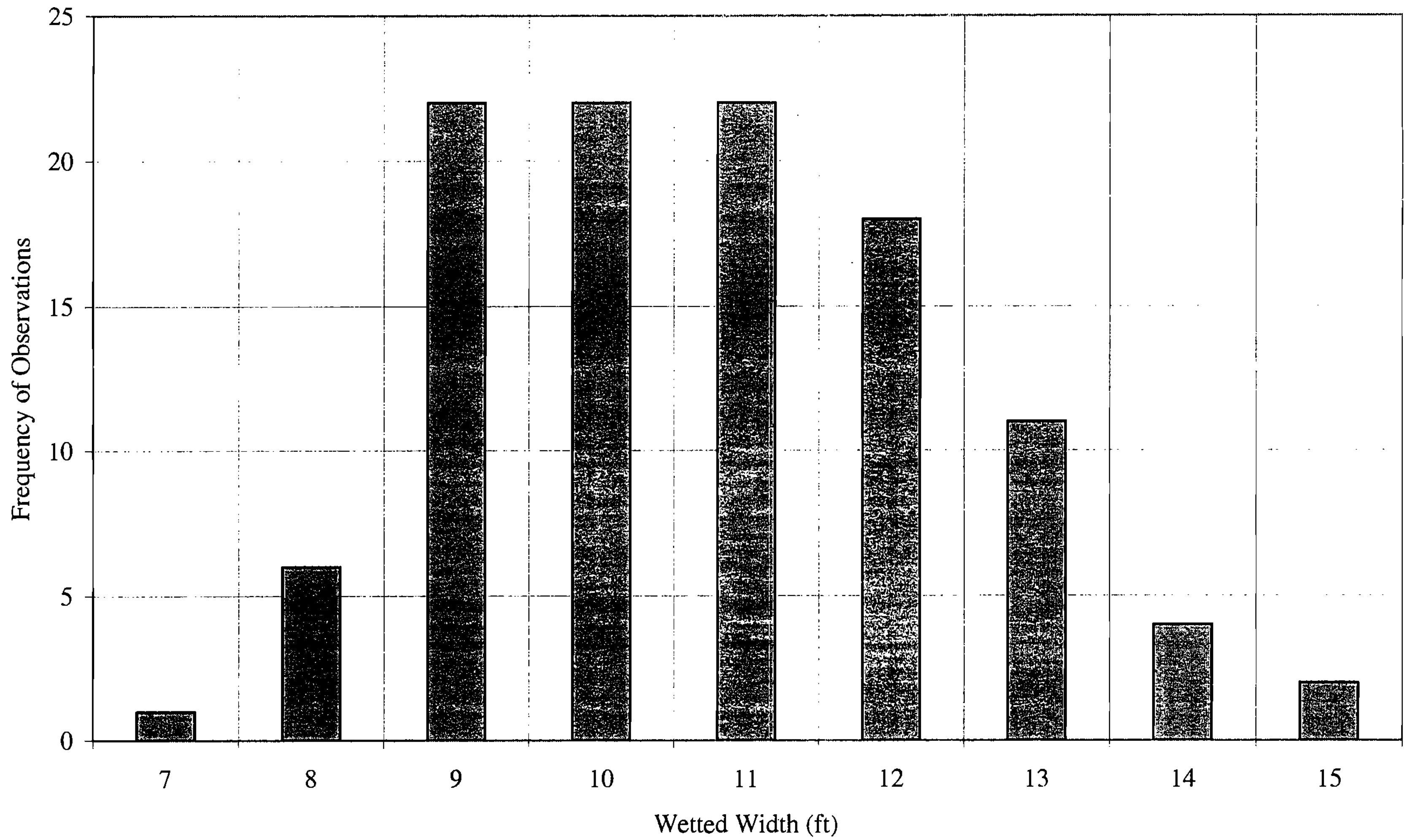


Figure 8. Guyer Creek: High flow wetted width distribution for culvert design.

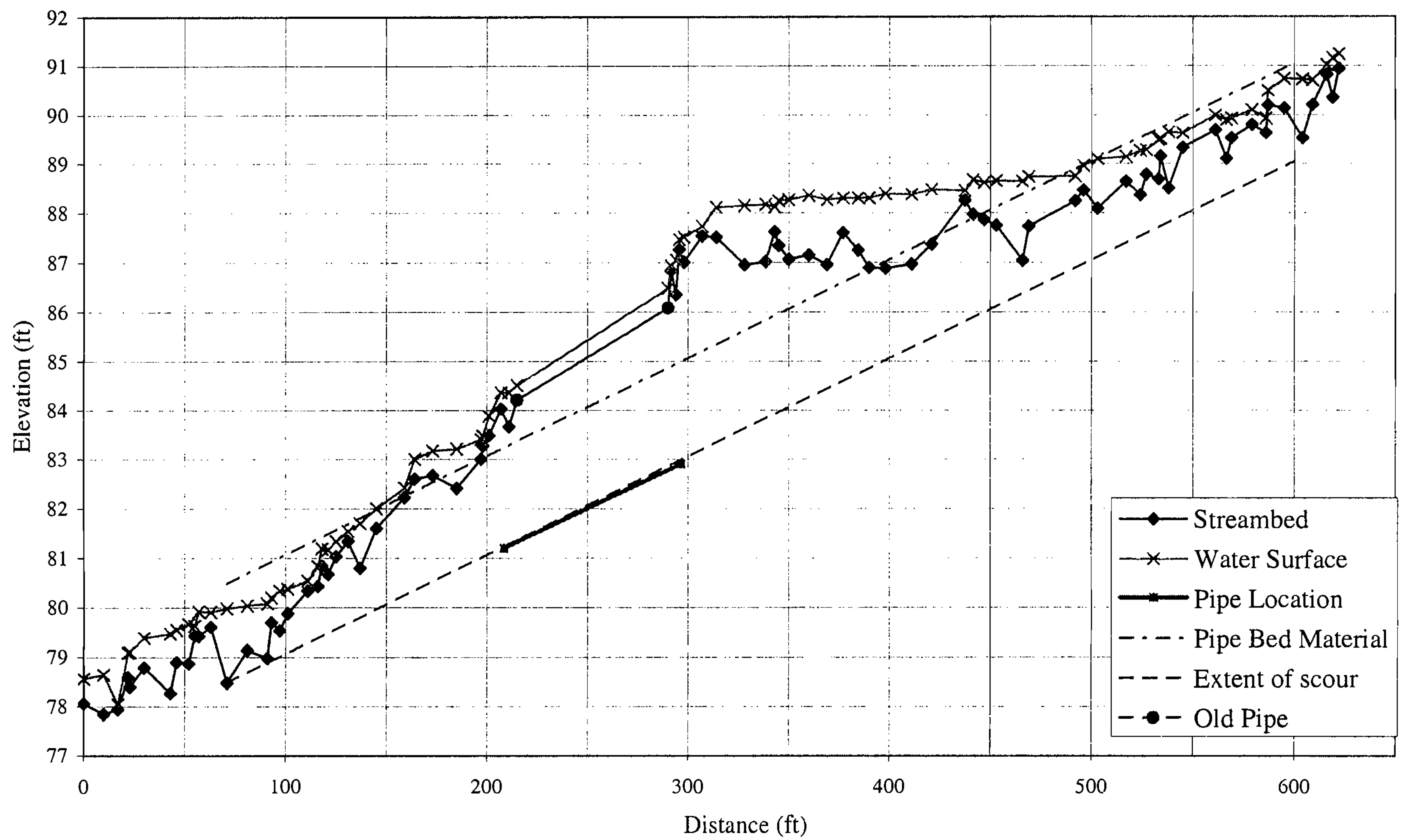


Figure 9. North Fork Silver Creek: Longitudinal profile pre-construction.

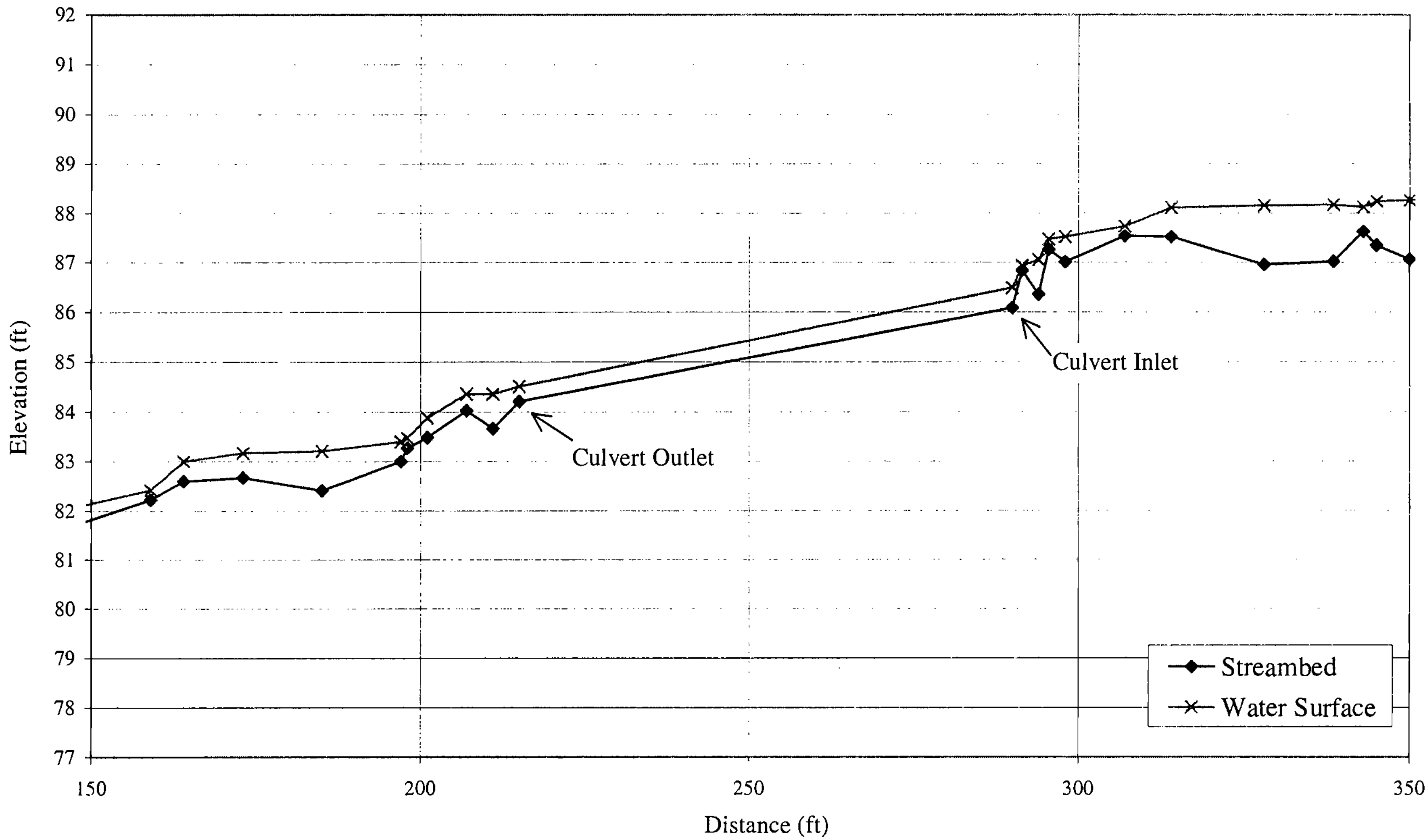


Figure 10. North Fork Silver Creek: Longitudinal profile of insufficient length.

The wetted width measurements in the upstream and downstream reaches were first examined to determine the pipe-arch size (Figure 11). The average value of the wetted width was 5.1 ft with a standard deviation of 1.4 ft. The average of the bankfull width measurements upstream of the old culvert was 9.9 ft. Multiplying 1.2 times the active channel width plus 2 feet gave a culvert width of 8.1 ft (WDFW, 1999). The culvert size used at this site was 9.3 ft wide by 6.3 ft tall and was 94% of the width of the estimated bankfull width. The estimate from just the wetted width was misleading and the equation from WDFW (1999) appeared prudent but narrower than the estimate of bankfull width.

There were two challenges associated with the construction of this replacement culvert. The first was connecting the backfill material near the inlet of the culvert to the natural streambed and the second was that the culvert was not tall enough to put a Bobcat front-end loader into the culvert to move backfill material. The deposition of material caused by the high placement of the old culvert made the connection between the newly placed culvert and the bed material substantially lower than the natural streambed level just upstream of the culvert. Some of this material was excavated so as to better connect the natural stream with the culvert. The remainder of the material was left in place with the expectation that the stream would downcut through the deposition material in order to find an equilibrium slope. Fill material was moved into the culvert with a six-wheeled all-terrain vehicle with a small dump on the back. The inability to get a more efficient piece of equipment into the culvert made this backfilling process more labor intensive than originally expected.

West Fork Silver Creek

This culvert is located at the downstream end of a large meadow and the scour at the outlet of the undersized old culvert had created a large pool that is used for recreational swimming during the summer months. The location of the culvert

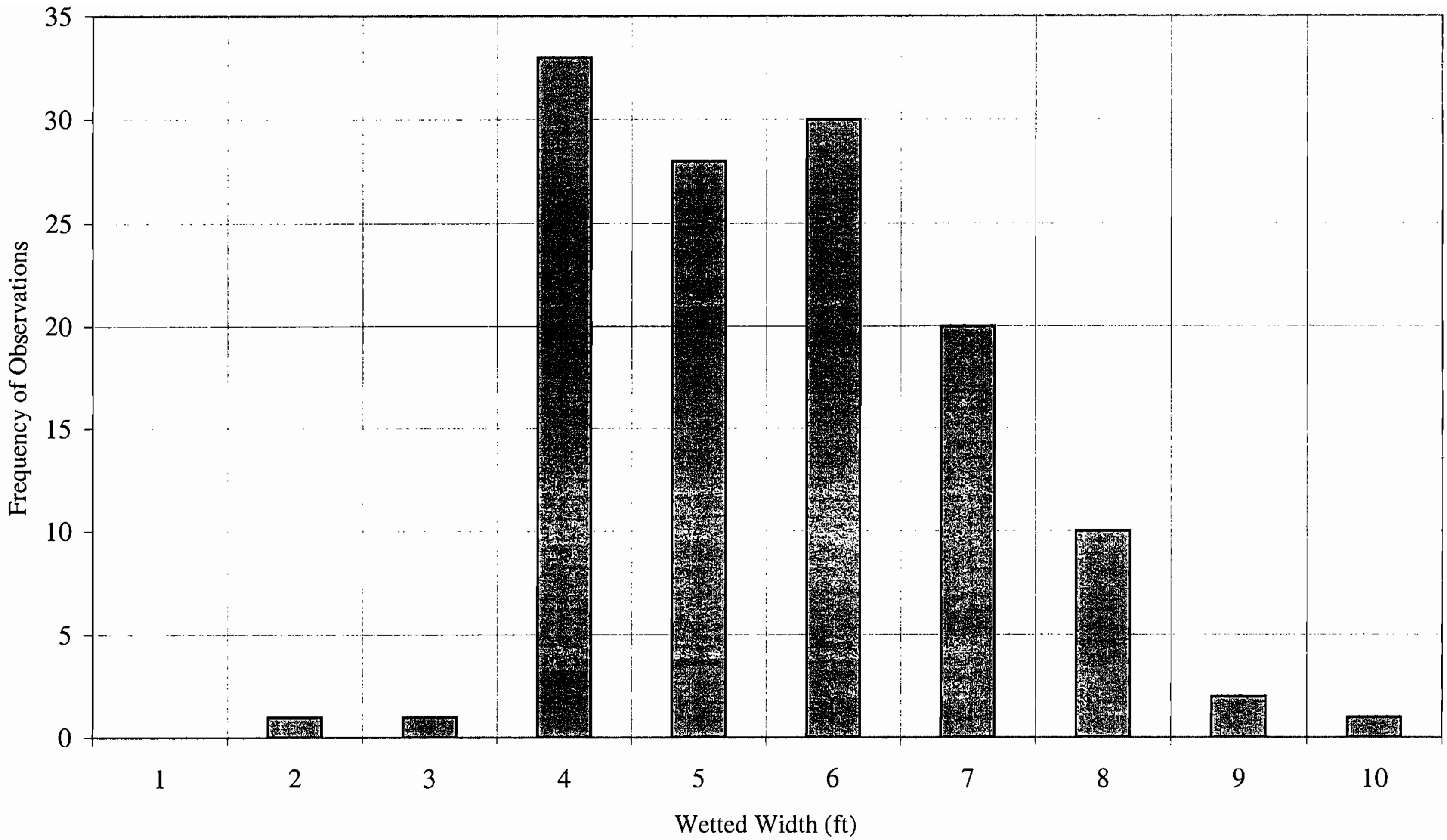


Figure 11. North Fork Silver Creek: High flow wetted width distribution for culvert design.

and public concern regarding the swimming hole were two challenges that had to be taken into consideration during the design and construction phases of the stream simulation culvert at this site.

There were three points in the longitudinal profile (Figure 12) of the West Fork site that were below the drawn line that connects the bottom of the pools in the longitudinal profile. These pools were field verified as anomalies to the typical scour of the remainder of the stream. The first and last deep scour pools, moving downstream along the longitudinal profile, were created by eddies shed by piles of brush or fallen sections of bank. The deep scour pool just downstream of the old pipe is a result of the old pipe size. It appeared that the old pipe was undersized, concentrated flow, scoured the material as the flow exited the old pipe, and created a deeply scoured pool. These three pools were disregarded for the exercise of determining the extent of scour in the natural stream.

The wetted width was measured upstream and downstream to investigate the pipe width of the replacement culvert. The average wetted width value was 8.3 ft and the distribution of the wetted width values dropped off at values greater than 10 ft. (Figure 13). Approximately 20 ft upstream of the culvert inlet is a livestock exclosure that extends upstream approximately 1000 ft. The stream appears to be narrowing and deepening near the downstream end of the exclosure and moving upstream the stream gets wider and shallow. Bankfull width was estimated at 10 points upstream of the old culvert, in the narrower section of the stream, and the average value was 9.3 ft wide. Bankfull width was also estimated further upstream where the width of the stream increased and the average value was 12 ft wide. Multiplying 1.2 times the active channel width plus 2 ft yielded a value of 11.9 ft and agreed with the wider estimate of the average bankfull width. It was determined that a culvert 11.8 ft wide and 7.6 ft tall would suffice under the assumption that the current management, maintenance of the exclosure, would continue. It was further assumed that under the current management the channel would continue to narrow and deepen with time, as it already appeared to be doing.

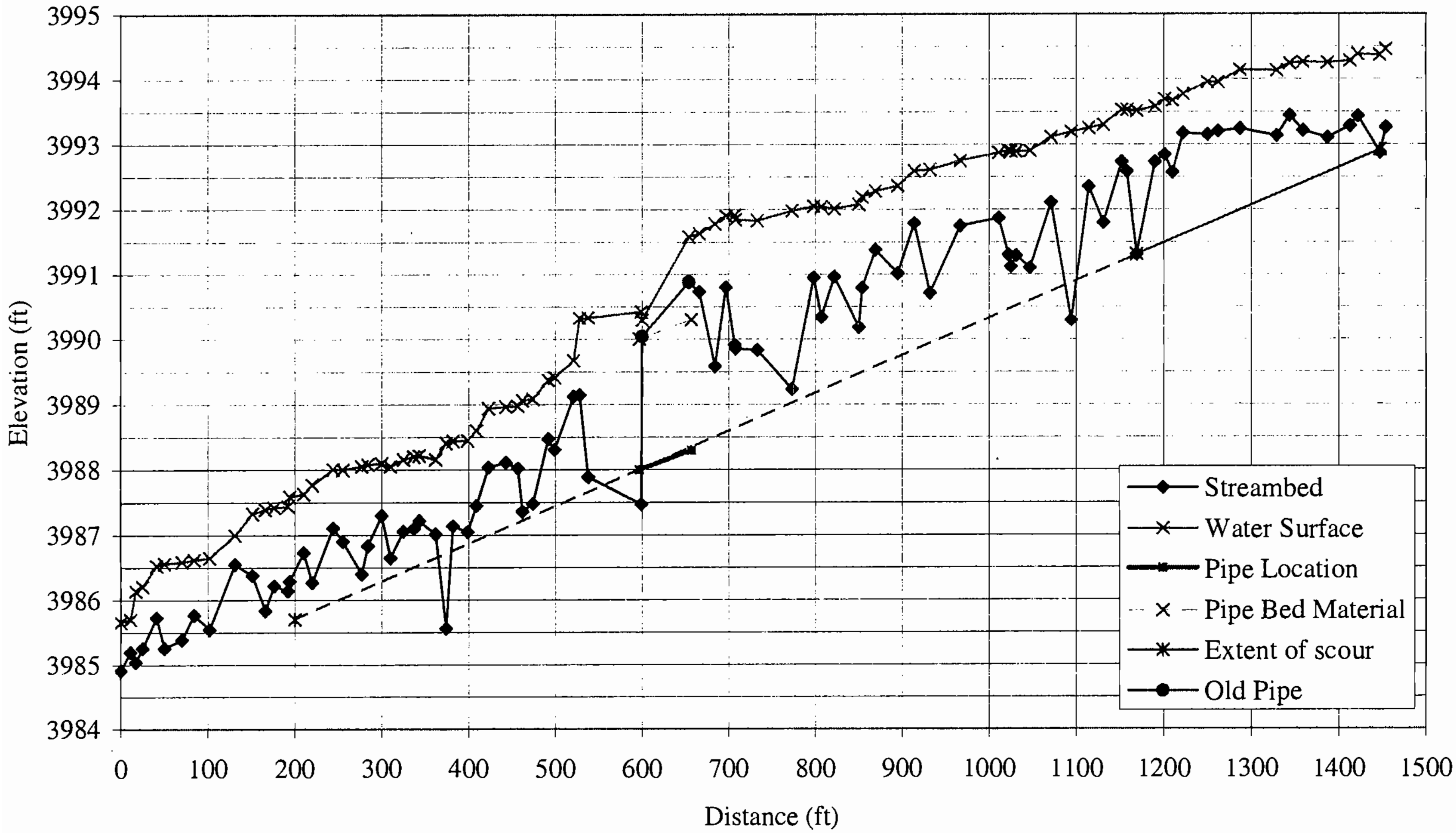


Figure 12. West Fork Silver Creek: Longitudinal profile pre-construction.

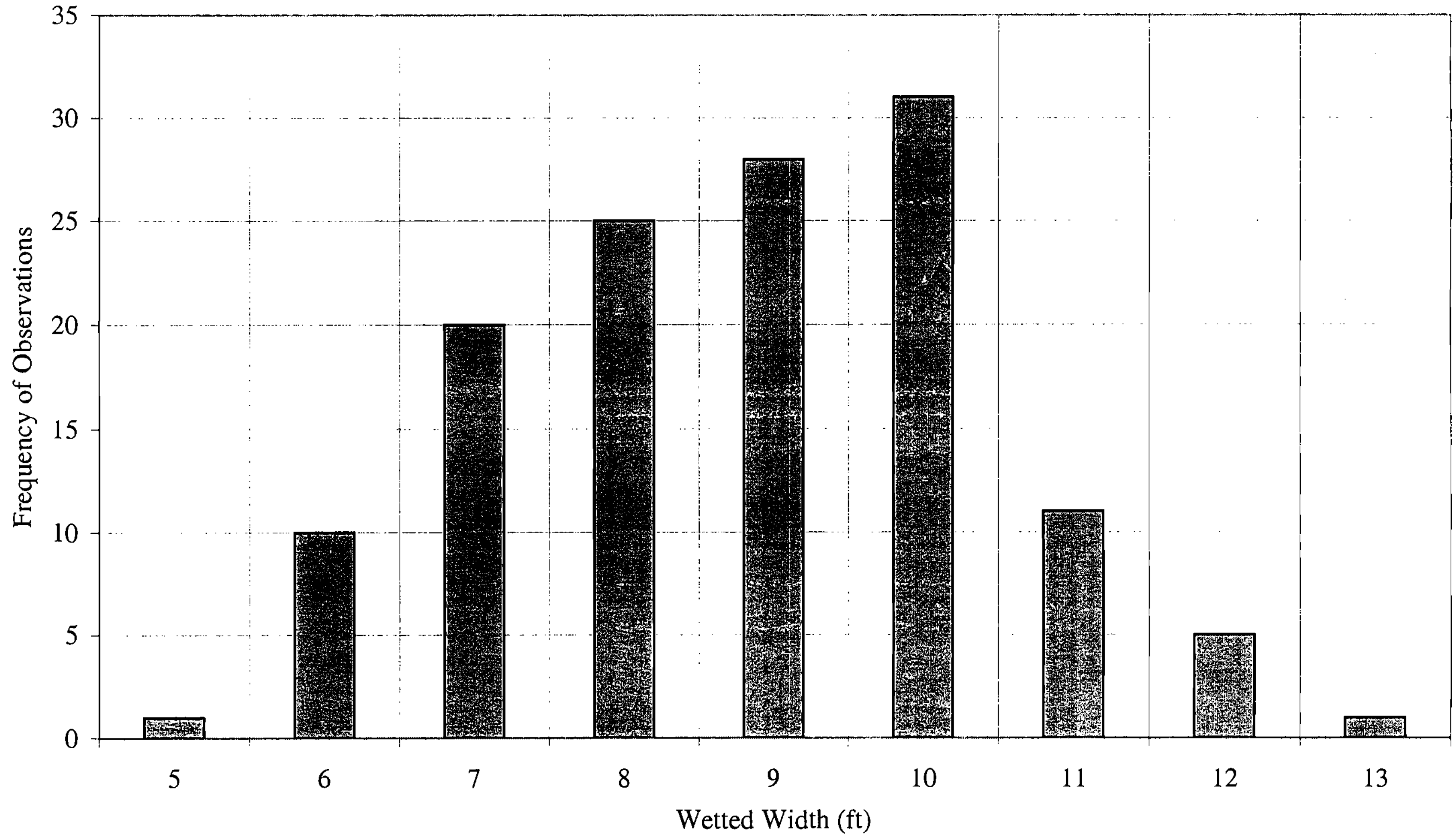


Figure 13. West Fork Silver Creek: High flow wetted width distribution for culvert design.

Typically, the scour hole at the outlet of an old culvert is filled with material at grade to allow connectivity of the streambed. The town swimming hole was of public concern and filling in the swimming hole was an undesirable option from both a safety standpoint and public opposition. The modification to the design, in order to accommodate the existence of the swimming hole and retain the material in the culvert, was a steel plate welded 1 foot upstream from the outlet of the culvert. The plate has a low flow notch cut into it and was placed in order to keep the material inside of the culvert. The plate spanned the entire width of the culvert, was 1.5 ft tall, and had a low flow notch shaped like a trapezoid, approximately 4 feet wide and 0.5 ft deep, in the center of the culvert to accommodate low flow. A weir of large boulders was also placed at approximately 65 ft downstream from the outlet of the culvert to create a backwater condition into the culvert.

Culvert 2000 to culvert 2001 comparisons

The measurements presented in the analyses of this study were taken during the spring of 2001. The discharge during which the measurements were made was 1.9 cfs, 0.9 cfs, and 5.4 cfs at Guyer Creek, North Fork Silver Creek, and West Fork Silver Creek, respectively. In order to put the discharge during measurement collection into perspective of the range of discharge conditions at a site, one could create a flow-duration curve for the site of interest. The discharge during measurement collection could then be associated with a probability of exceedance. A maintained, continuously recording stream gage record would be necessary for this analysis and was unavailable at or near the study sites.

In an effort to categorize where the discharge during measurement collection fell in a historical record, the unit area discharge-duration was calculated from a nearby stream gage record (Figure 14). The gage used was USGS 10384000 Chewaucan River near Paisley, Oregon (275 square mile drainage area) for daily mean streamflow data for 1960-1991. The unit area discharge was 0.25

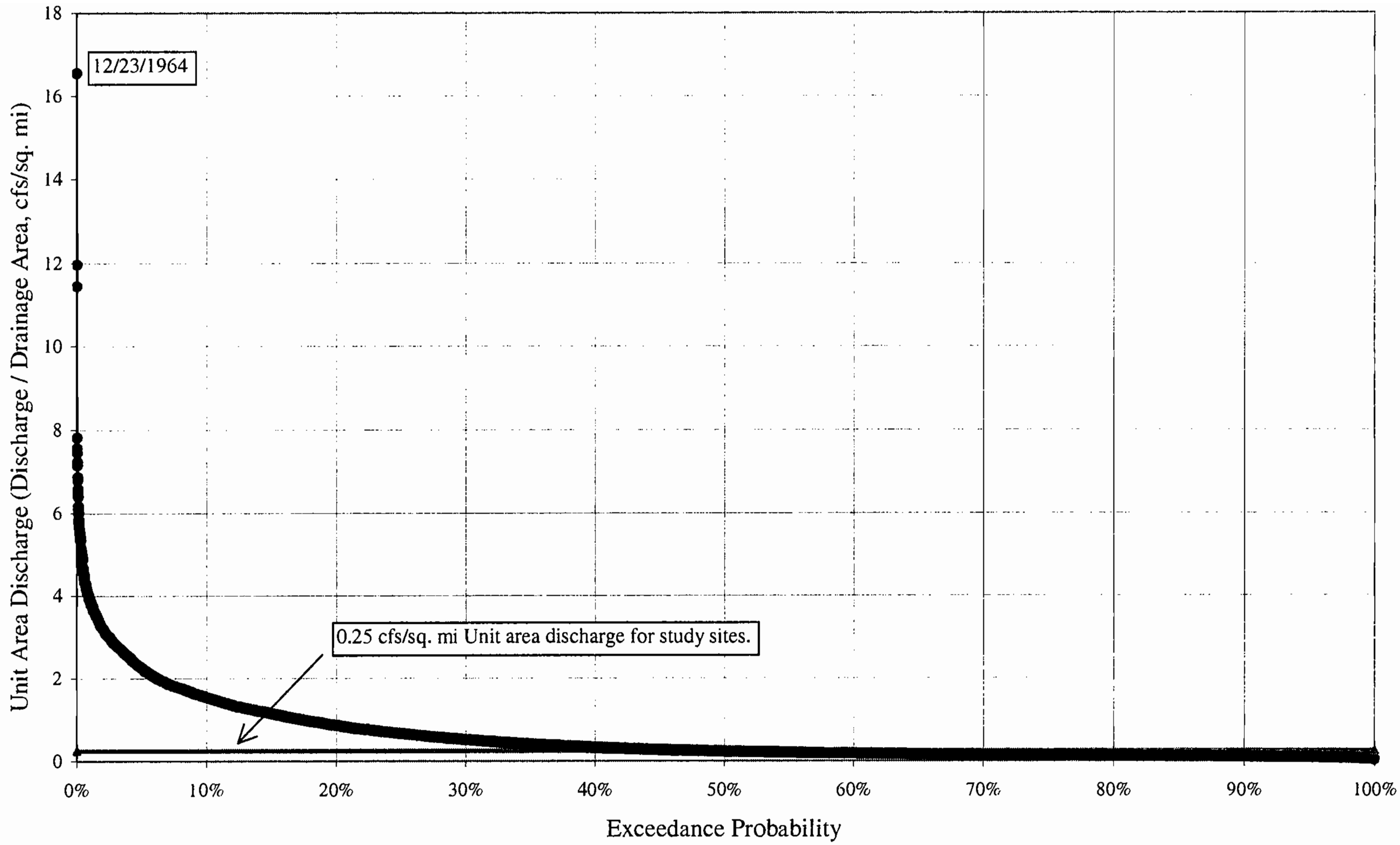


Figure 14. Chewaucan River near Paisley, Oregon: Daily mean stream flow, unit area discharge-exceedance probability.

cfs per square mile at Guyer Creek and West Fork Silver Creek and was 0.27 cfs per square miles at North Fork Silver Creek. The unit area discharges from the study sites were calculated as having a 47% exceedance probability from Figure 14.

The new culvert at each site showed qualitative improvement and decreased average cross-sectional velocities over the old culvert at equal discharges. Manning's equation was used in order to determine what the average velocity would have been if the old pipe would have remained during the measured spring flow of 2001. The slope and roughness were determined using cross-sectional measurements of channel dimensions and the discharge of spring flow of 2000. The values for slope and roughness were then used to determine what the cross-sectional characteristics would have been for the discharge measured in 2001. These cross-sectional characteristics were then used to determine the average cross-sectional velocity through the old culvert if the 2001 discharge was put through the old culvert. This average velocity was then compared to the average velocity calculated from the Manning's equation for the new culvert installation with the 2001 discharge (Table 4).

Table 4. Culvert 2000 to culvert 2001 average cross-section velocity for 2001 discharge.

Average Cross-Section Velocity for 2001 Discharge	**Guyer Creek** (Q = 1.9 cfs)	**North Fork Silver Creek** (Q = 0.9 cfs)	**West Fork Silver Creek** (Q = 5.4 cfs)
Old Culvert	1.77 ft/s	0.60 ft/s	1.95 ft/s
Stream Simulation Culvert	1.52 ft/s	0.39 ft/s	0.85 ft/s
% Change	-14%	-35%	-56%

The average cross-sectional velocity calculated at all three of the stream simulation culverts satisfied the maximum water velocity criteria set by the state for fish passage criteria (ODFW, 1997). In addition, all three culverts satisfied the water velocity criteria set for juvenile salmonids of 2.0 ft/s during high flow discharge.

The comparison of the hydraulic condition between 2000 and 2001 is difficult because the discharge during 2000 was between two and four times the discharge in 2001. The average cross-sectional velocity in the stream simulation culverts was 14%, 35%, and 56% slower than the average cross-sectional velocity in the old culvert for Guyer Creek, North Fork Silver Creek, and West Fork Silver Creek, respectively. Guyer Creek showed the least improvement with an average cross-sectional velocity at the new culvert of 1.52 ft/s and a calculated average cross-sectional velocity of 1.77 ft/s for the 2001 discharge through the old culvert.

Qualitative improvement from the old culvert to the stream simulation designed culvert was also evident. All of the culverts, when visually compared to the old culvert, allowed for increased opportunity for resting (Figures 15, 16, and 17), limited the constriction of flow at the inlet (Figures 18 and 19), limited expansion of flow at the outlet (Figure 20), and increased roughness in the bed of the culvert (Figures 21, 22, and 23). Guyer Creek no longer exhibited an outlet drop (Figure 24), the outlet crop at West Fork Silver Creek no longer exists (Figure 25) and North Fork Silver Creek no longer exhibited the abrupt inlet drop of the old culvert (Figure 26).

The quantification and qualification of improvement over the old culverts were numerous, which allows one to confidently suggest that the fish passage condition at each of the sites was improved. However, the new culverts were further tested to investigate how each compared to the natural stream they were designed to simulate and to investigate the stability of the channel within the culvert.

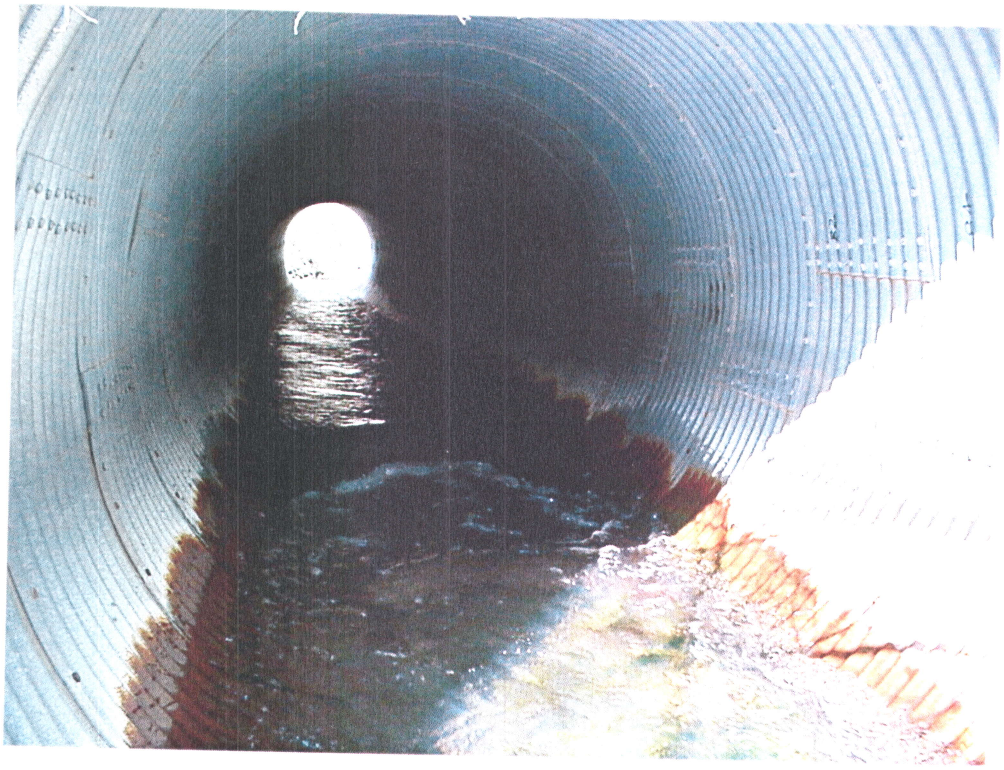


Figure 15. Guyer Creek: Culvert barrel 2000 (top) and 2001 (bottom).

Figure 16. North Fork Silver Creek: Culvert barrel 2000 (top) and 2001 (bottom).

Figure 17. West Fork Silver Creek: Culvert barrel 2000 (top) and 2001 (bottom).

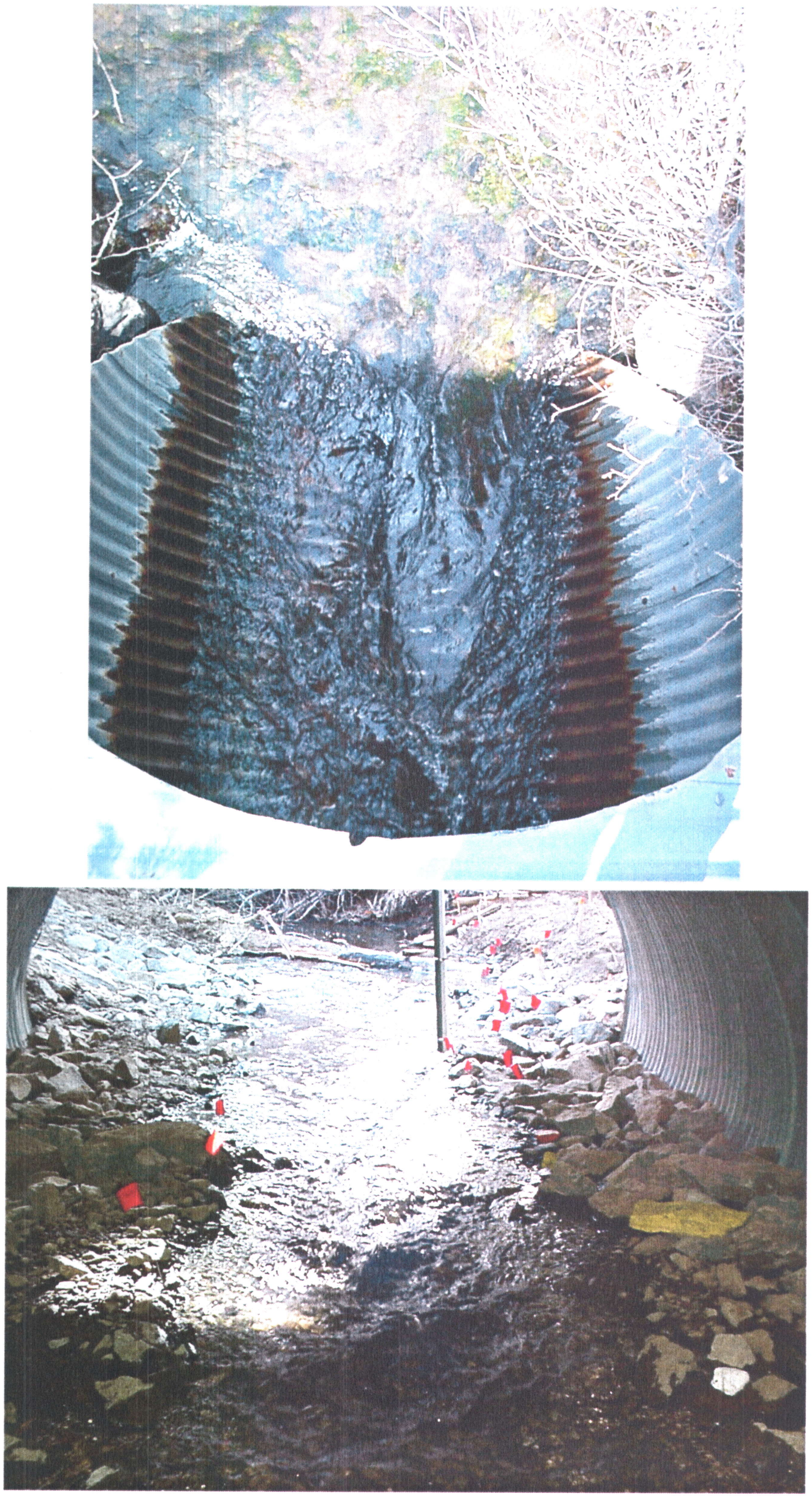


Figure 18. Guyer Creek: Culvert inlet 2000 (top) and 2001 (bottom).

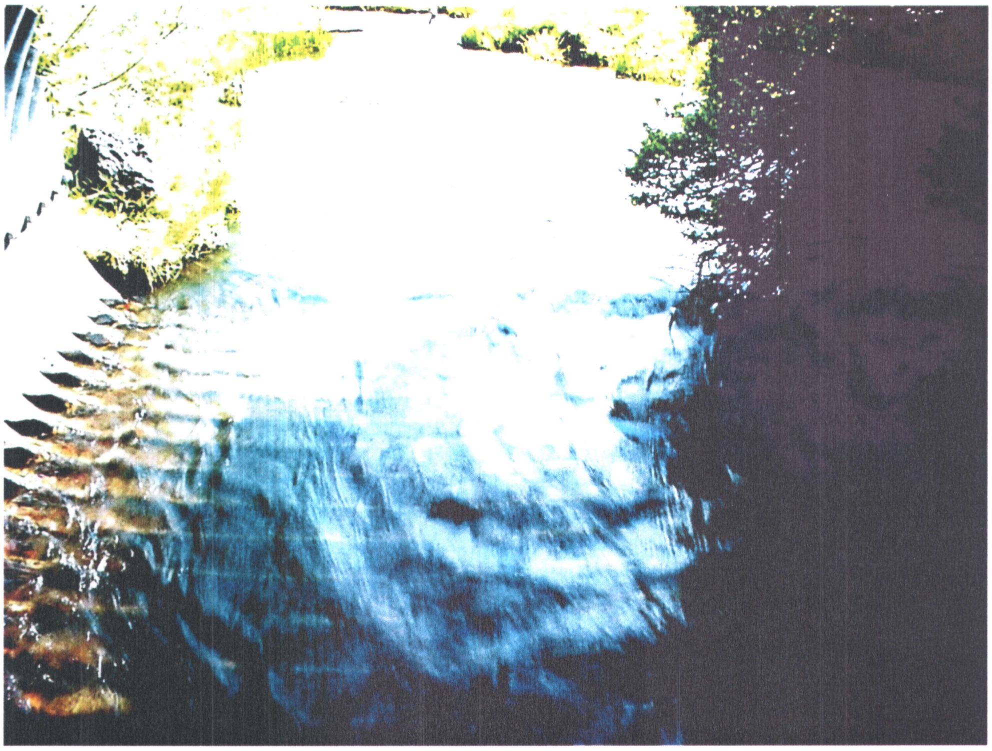


Figure 19. West Fork Silver Creek: Culvert inlet 2000 (top) and 2001 (bottom).

Figure 20. North Fork Silver Creek: Culvert outlet 2000 (top) and 2001 (bottom).

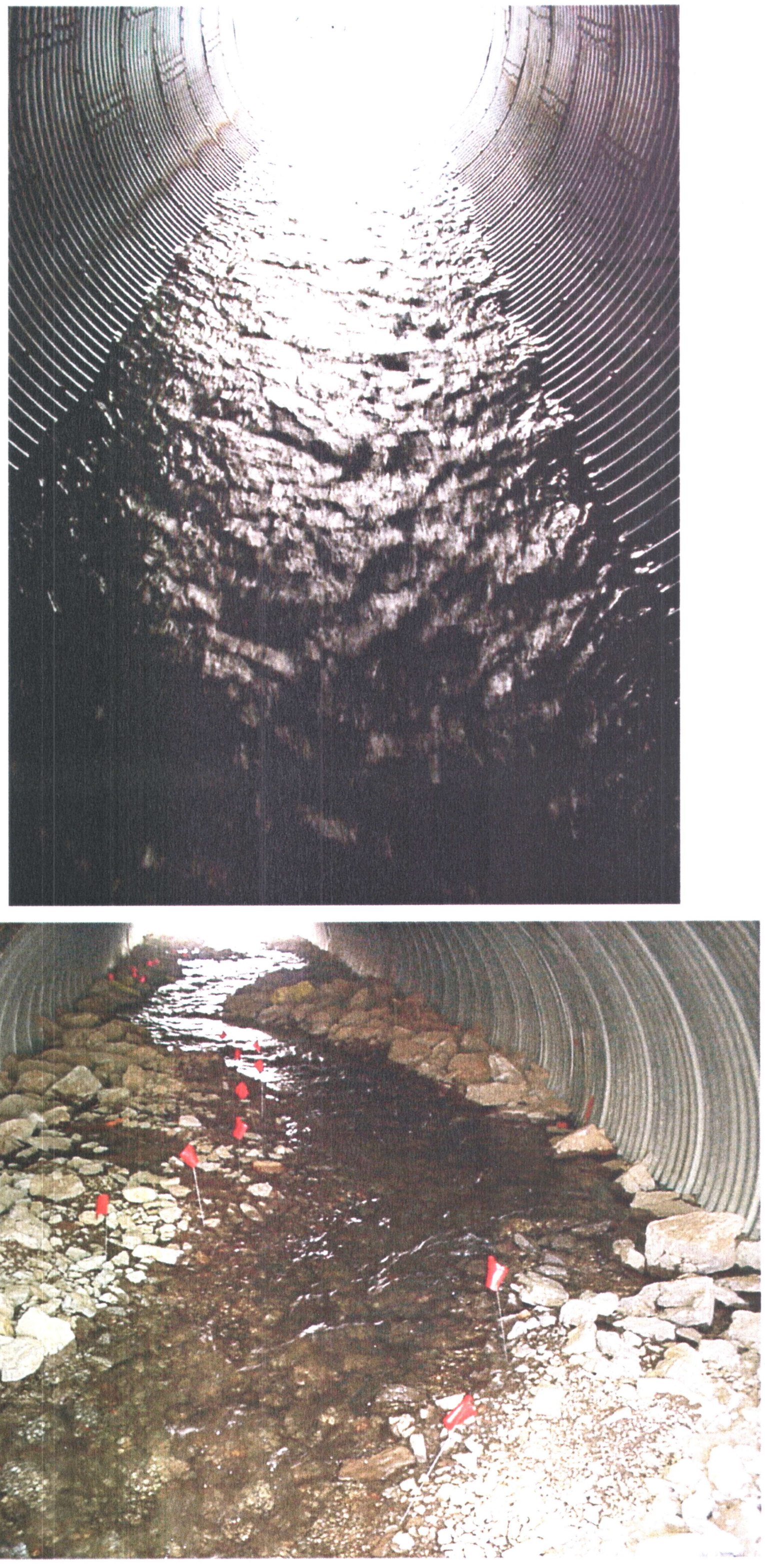


Figure 21. Guyer Creek: Culvert streambed material 2000 (top) and 2001 (bottom).

Figure 22. North Fork Silver Creek: Culvert streambed material 2000 (top) and 2001 (bottom).

Figure 23. West Fork Silver Creek: Culvert streambed material 2000 (top) and 2001 (bottom).

Figure 24. Guyer Creek: Culvert outlet 2000 (top) and 2001 (bottom).

Figure 25. West Fork Silver Creek: Culvert outlet 2000 (top) and 2001 (bottom).

Figure 26. North Fork Silver Creek: Culvert inlet 2000 (top) and 2001 (bottom).

Culvert to stream comparisons

The analysis of the three stream simulation designed culverts looked at a snapshot in time of each site and how the newly installed culvert compared to the natural stream. It must be remembered that the culverts are evolving and will change slowly or drastically depending on the magnitude of future discharge events. Unfortunately, the winter of 2000/2001 was mild with 60% of normal snow pack in the study area. The lack of snow pack resulted in limited high flows during spring snowmelt. As a result, it was expected that there would be little re-working of the bed material placed during the construction phase (2000).

Several metrics were explored to determine the success or failure of stream simulation culverts. Thalweg velocity, cross-sectional velocity, velocity distribution, substrate material, and habitat unit type were all investigated. Slope and channel dimensions were also included due to their effect on velocity. Each of the metrics in the natural stream was compared to the same metric in the culvert. Where statistical analysis was feasible, Wilcoxon rank sum tests were used to statistically compare the natural stream and the culvert measurements. The comparisons are statistical and do not consider the practical comparisons between the natural stream and culvert measurements. The Wilcoxon rank sum is a non-parametric, distribution-free statistical tool where no distribution assumptions are required (Ramsey and Schafer, 1997). S-Plus 2000, a statistical computer program, was used for the Wilcoxon rank sum calculations. The null hypothesis for the test is that the two populations have the same distribution. In this study a large p-value, greater than 0.10, does not give sufficient evidence to reject the null hypothesis and was referred to as statistically similar. Thus, a small p-value, less than 0.10, was suggestive evidence to reject the null hypothesis and was referred to as statistically different.

The term, "stream simulation" culvert, may be misleading for many reasons. Several of the stream processes and conditions that occur in the natural stream simply cannot occur at all or to the same degree within a culvert. Understanding the stream processes that can occur inside of a stream simulation culvert allows us better to determine the metric by which the success of stream simulation culverts could be judged. Several stream processes and conditions that are included in the design of a stream simulation culvert are natural lateral and longitudinal velocity distributions, natural stream substrate, formation of pools and riffles, and natural sediment transport (Pyles, 2000b). Stream processes and conditions that are not included in the design of stream simulation culverts are those having water velocities below fish passage design criteria, water velocities similar to the natural channel at large flood flows, meander bends, large wood roughness, and lateral channel migration within the flood plain (Pyles, 2000b). Therefore, comparisons between the natural stream and the stream simulation culvert must be modified to those stream processes included in stream simulation culvert design. In other words, channel form roughness (meander bends) and large wood roughness cannot be included in the comparisons between the culvert and the natural stream. Therefore, the pools created from meander bends and large wood roughness cannot be included in the comparisons between the culvert and the natural stream.

The culverts were first compared to the natural streams without consideration for the stream processes included in the design. Data collected under the longitudinal sampling approach, which measured water velocity in the thalweg of the stream, was used for this comparison. At all three sites, the velocity measurements in the natural stream were compared to those inside of the culvert. The comparison of the culvert velocity and the velocity of the stream indicated they were statistically different (two-sided p-values = <0.01 from Wilcoxon rank sum test) (Figures 27, 28, and 29). Negative values can be attributed to a back eddy in pools, debris, or bed material. The culverts were not designed to accommodate pools generated from large wood or channel form roughness. Moreover, pools generated from bed form structure had not yet formed in the culverts and the culverts were dominated by riffle habitat. The comparisons between the natural stream and culvert were more appropriate between the riffles of the stream to the riffle of the culvert. Therefore, the pools were taken out of the data set for the

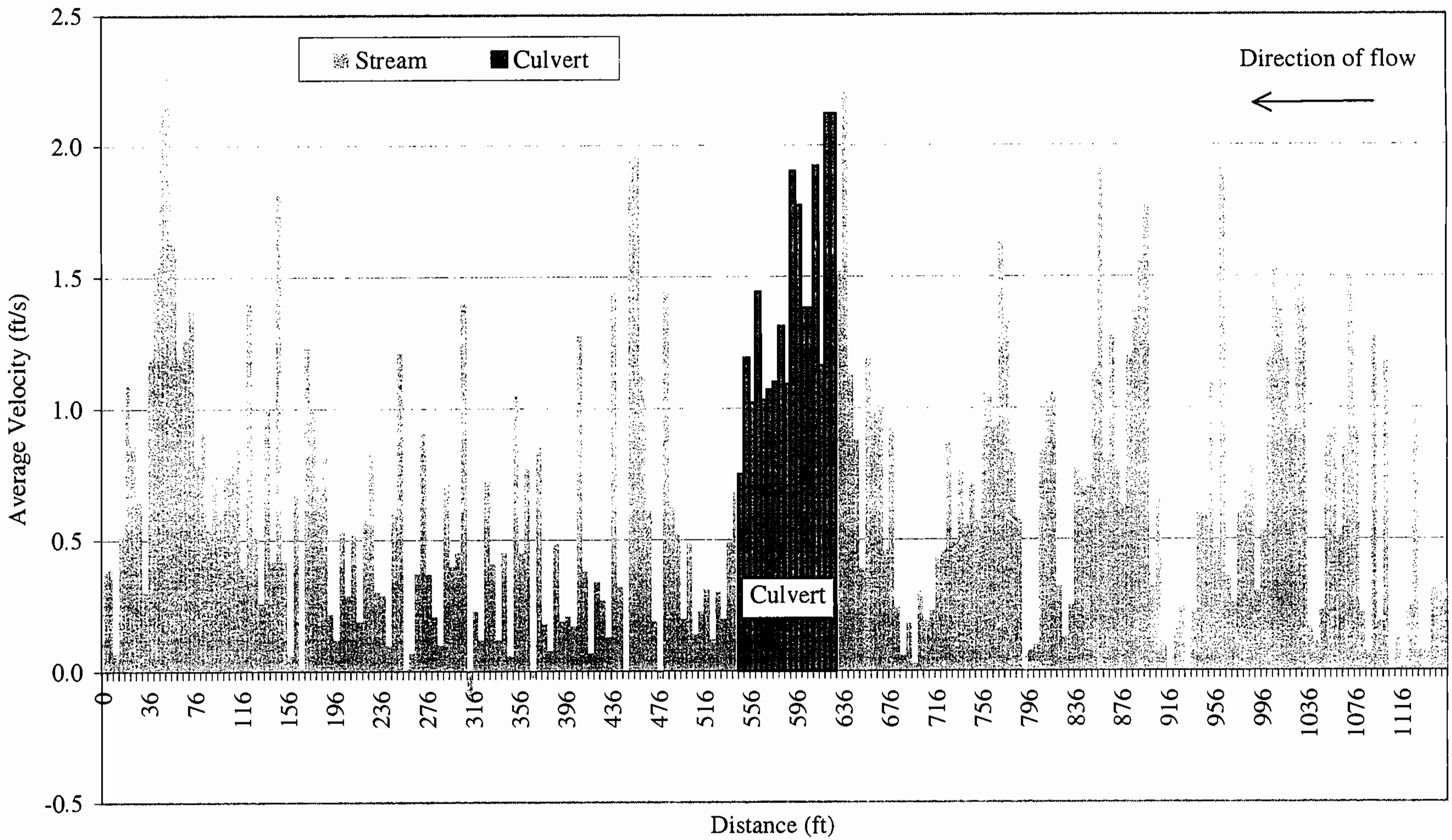


Figure 27. Guyer Creek: Thalweg average velocity (0.6 of depth) of all data.

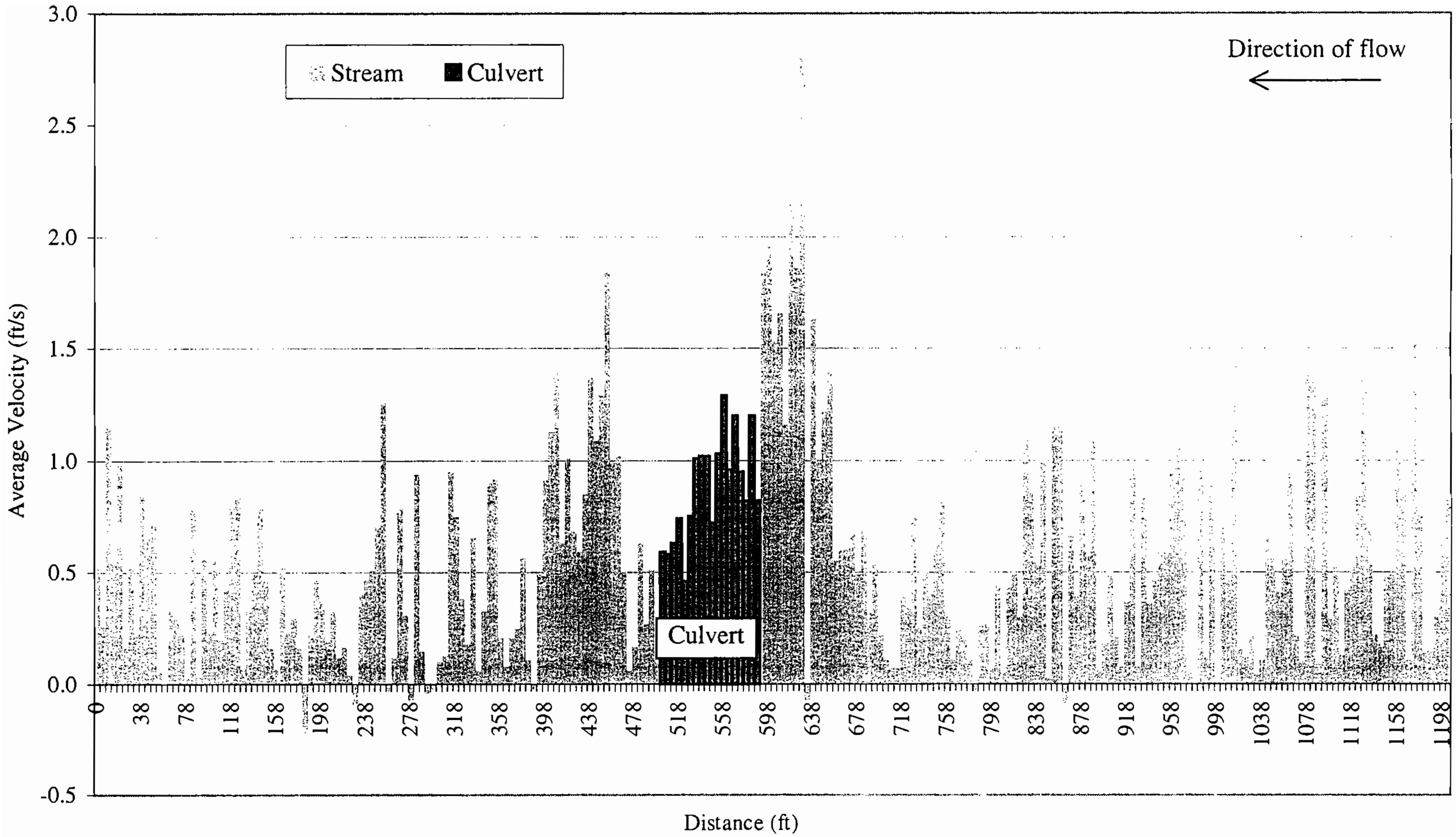


Figure 28. North Fork Silver Creek: Thalweg average velocity (0.6 of depth) of all data.

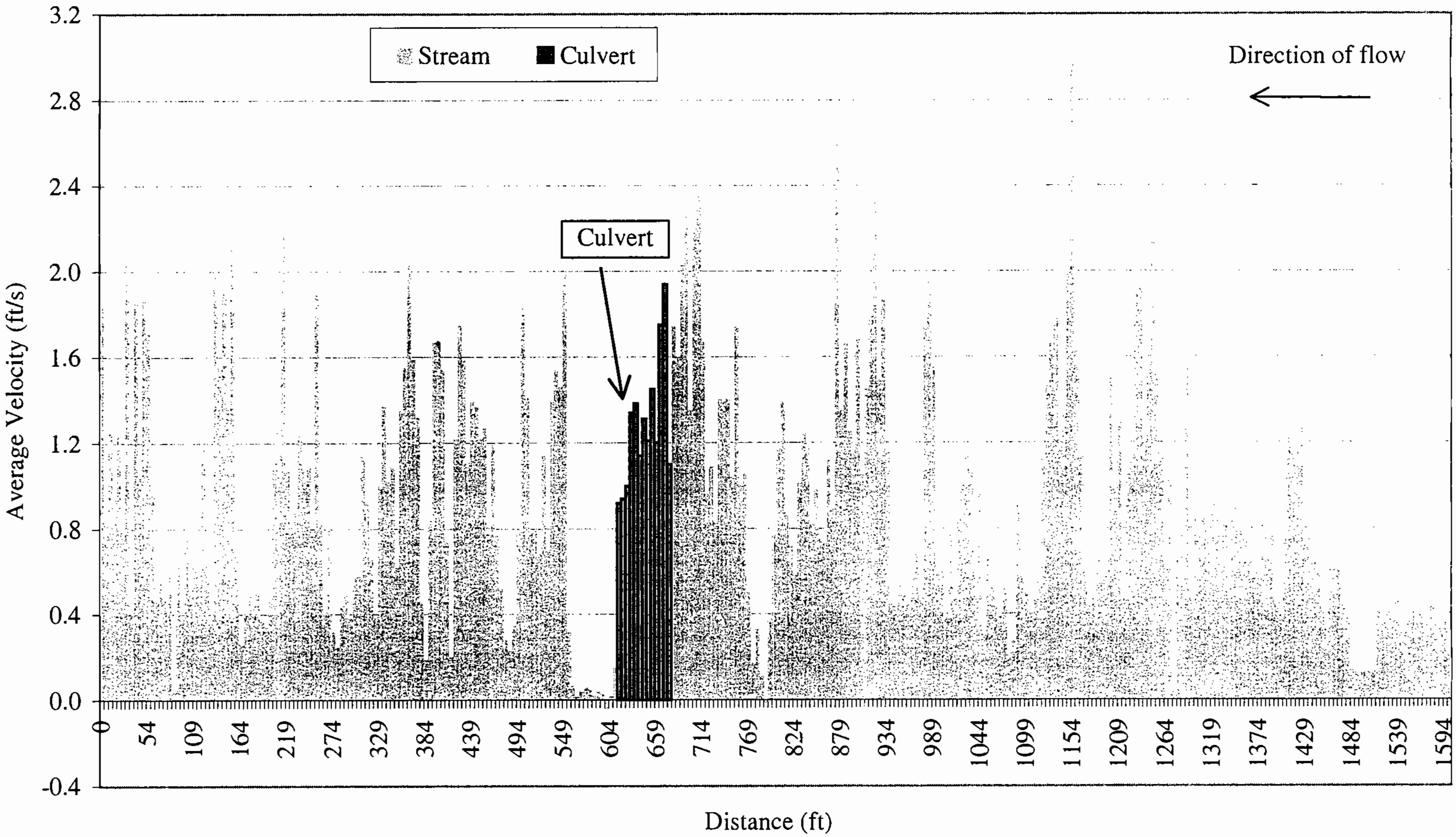


Figure 29. West Fork Silver Creek: Thalweg average velocity (0.6 of depth) of all data.

comparison exercises and the characteristics of the riffles of the stream were compared to the characteristics of the riffles inside of the culvert.

In addition to large wood roughness in the stream, heavy debris concentrations were found throughout the natural channel at Guyer Creek and North Fork Silver Creek. Again, the stream simulation culvert is not designed to accommodate excessive debris, such as branches, large wood, twigs, and organic debris. The locations where heavy debris concentrations occurred were taken out of the analysis in order to equalize the conditions in the culvert to those of the stream as much as possible (Figure 30). 8.2% and 9.2% of the points in Guyer Creek and North Fork Silver Creek, respectively, were taken out of the riffle analysis due to heavy debris concentrations at the measurement locations. West Fork Silver Creek has limited debris in the stream at this location and no points were removed due to heavy debris concentration.

Bottom velocity and average velocity

The water velocity measurement device used for this study was physically limited from taking velocity measurements any closer than 0.08 ft above the bed of the stream. For example, for a depth equal to 0.1 ft, only one velocity measurement could be made, which was measured at 0.08 ft above the bed of the stream (0.2 of the total depth). Furthermore, for a depth less than 0.4 ft, two velocity measurements could be made, which were measured at 0.2 and 0.6 of the total depth.

The relationship between the thalweg surface velocity (measured at 0.2 of the total depth) and the thalweg average velocity (measured at 0.6 of the total depth) for water depth less than or equal to 0.3 ft was determined using a linear least sum of squares regression (Figures 31 and 32). This relationship was used to determine velocities at the 0.6 of the depth location where the water velocity

Figure 30. Examples of heavy debris concentrations.

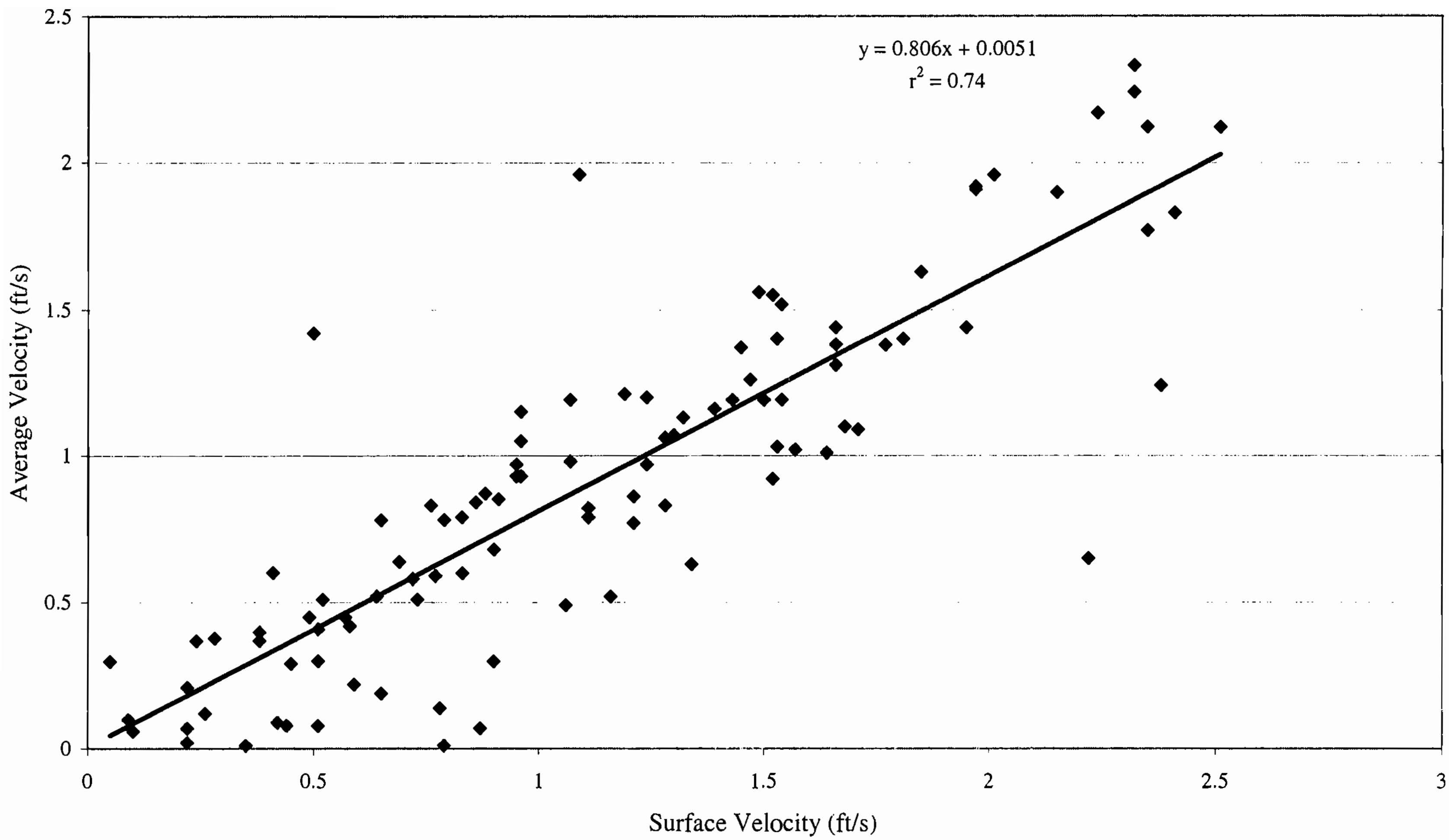


Figure 31. Guyer Creek: Thalweg average velocity (0.6 of depth) to surface velocity (0.2 of depth) for depth less than or equal to 0.3 ft.

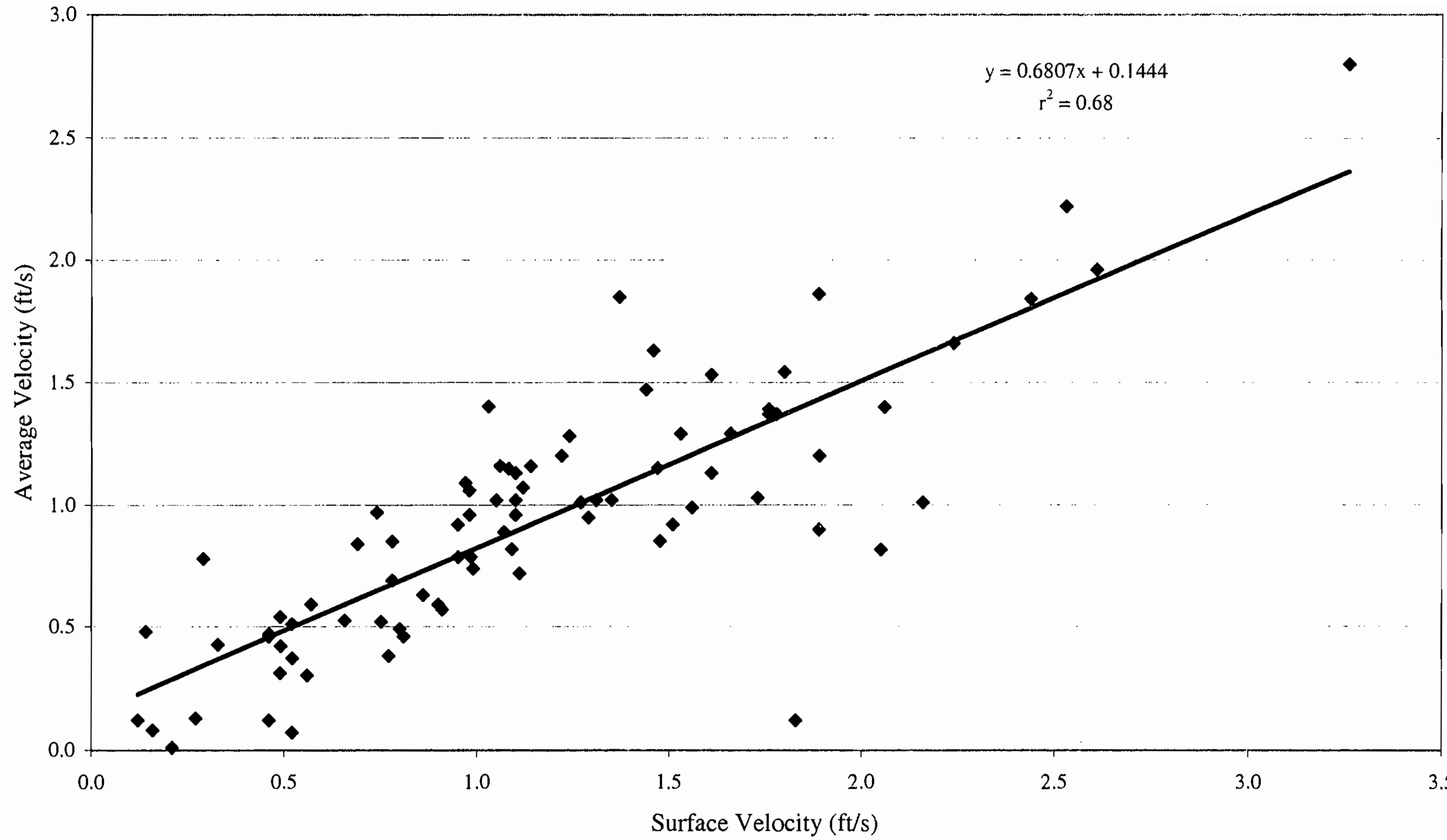


Figure 32. North Fork Silver Creek: Thalweg average velocity (0.6 of depth) to surface velocity (0.2 of depth) for depth less than or equal to 0.3 ft.

measurement device could not measure the velocity due to insufficient depth. In other words, the subset of values for depths less than or equal to 0.3 ft was used to create the relationship because the relationship was only used to generate velocities for shallow depths. In both North Fork Silver Creek and Guyer Creek, this relationship was used to determine a few (<1%) of the thalweg average velocities.

Velocity is generally assumed to decrease with depth and this was the case at all measurement locations but one. The relationships used here provided for a modest reduction of the bottom velocity compared to the measured average velocity. The relationship between the thalweg average velocity and the thalweg bottom velocity, measured at 0.8 of the total depth, was determined separately for water depth less than 0.4 ft at North Fork Silver Creek and Guyer Creek using a linear least sum of squares regression (Figure 33). These relationships were used to generate the calculated bottom velocity for 71% and 77% of the thalweg bottom velocity measurements for North Fork Silver Creek and Guyer Creek, respectively.

Thalweg velocity

The longitudinal variation in velocity was measured via the thalweg velocity. The thalweg velocity was measured at 0.2, 0.6, and 0.8 of the total depth at each stream crossing and will be referred to as thalweg surface velocity, thalweg average velocity, and thalweg bottom velocity, respectively. Unfortunately, at West Fork Silver Creek the measurements taken at 0.2, 0.6, and 0.8 of the total depth were taken during an extreme backwater condition, caused by build up of the downstream rock weir constructed to maintain the outlet pool, and should not be used for analysis (Figure 34). The average measurement was taken under normal conditions and was used for the comparison. The thalweg velocity measurements of interest with respect to fish movement were the thalweg average velocity because it is used in fish passage criteria and the thalweg bottom velocity because

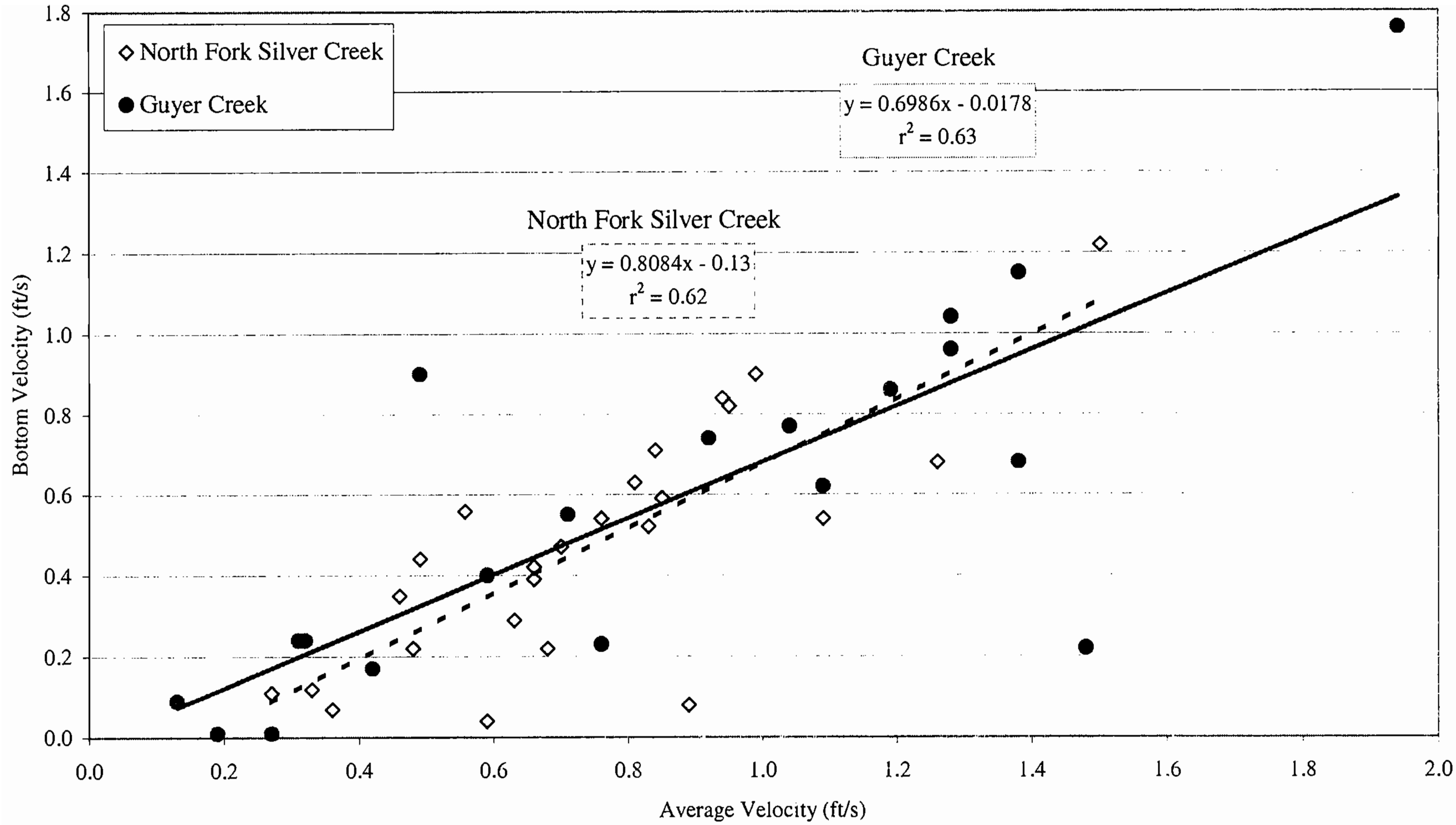


Figure 33. Guyer Creek and North Fork Silver Creek: Thalweg bottom velocity (0.8 of depth) to average velocity (0.6 of depth) for depth equal to 0.4 ft.

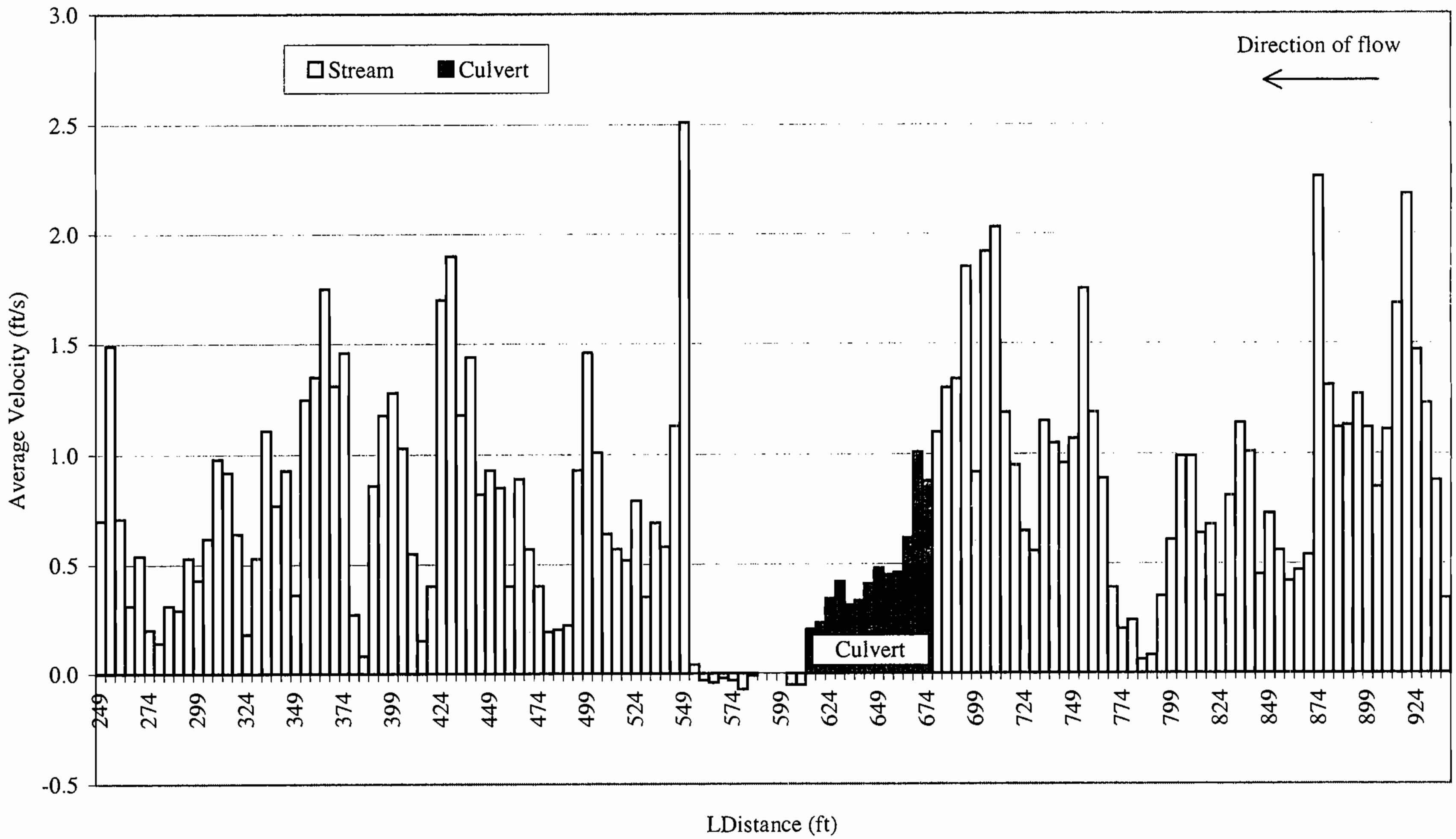


Figure 34. West Fork Silver Creek: Thalweg average velocity (0.6 of depth) extreme backwater effect.

of where fish are understood to move. Again, the comparison of thalweg velocities was analyzed for only riffle habitat types.

The comparison indicated that the culvert velocities and stream velocities of the riffles at West Fork Silver Creek and North Fork Silver Creek were statistically similar. The same comparison at Guyer Creek indicated that they were statistically different (Table 5). The comparison indicated that the thalweg average velocity measurement in the culvert and the natural stream was statistically similar at West Fork Silver Creek (two-sided p-value = 0.86 from Wilcoxon rank sum test) (Figure 35). At North Fork Silver Creek the comparison indicated that the thalweg average and thalweg bottom velocity of the culvert and the stream were statistically similar (two-sided p-value = 0.75 and 0.93, respectively, from Wilcoxon rank sum test) (Figures 36 and 37). Moreover, at North Fork Silver Creek the comparison indicated that the thalweg average velocity in the culvert and the natural stream without the removal of the heavy debris concentrations was statistically similar (two-sided p-value = 0.31 from Wilcoxon rank sum test). At Guyer Creek, the comparisons indicated that the thalweg average and thalweg bottom velocity of the culvert compared to the stream were statistically different (two-sided p-value < 0.01 and 0.01, respectively, from Wilcoxon rank sum test) (Figures 38 and 39).

The channel approach to the culvert inlet at North Fork Silver Creek was designed to reach an equilibrium slope that agrees with the longitudinal profile slope of the stream. The comparison between the culvert and the stream was also analyzed without the approach velocities as part of the stream data (Figure 40). The comparisons indicated that the thalweg average and bottom velocity of the culvert and of the stream were statistically similar (two-sided p-value = 0.28 and 0.38, respectively, from Wilcoxon rank sum test).

During the analyzed high flow state, the comparisons of the thalweg average and bottom velocities of the riffles in the culvert and the natural stream were statistically similar at West Fork Silver Creek and North Fork Silver Creek. However, the same comparisons were statistically different (two-sided p-value ≤ 0.10) at Guyer Creek. The conclusion of similarity or difference with respect to the

Table 5. Results of Wilcoxon rank sum test (two-sided p-value < 0.10) for comparison of natural stream vs. culvert of various stream conditions at each study site.

		Natural Stream			Culvert			Significance of natural stream vs culvert using **Wilcoxon Rank Sum Test** (two-sided p-value)
Stream Condition	Study Site	Average	Standard Deviation	n	Average	Standard Deviation	n	
Thalweg Average Velocity (0.6 of depth) of All Data	Guyer Creek	0.66	0.52	213	1.40	0.42	17	<0.01
	North Fork Silver Creek	0.55	0.48	224	0.88	0.24	18	<0.01
	West Fork Silver Creek	0.90	0.56	308	1.28	0.30	13	<0.01
Thalweg Average Velocity (0.6 of depth) of Riffles	Guyer Creek	0.94	0.52	113	1.40	0.42	17	<0.01
	North Fork Silver Creek	0.91	0.46	101	0.88	0.24	18	0.75
	West Fork Silver Creek	1.28	0.51	137	1.28	0.30	13	0.86
Thalweg Bottom Velocity (0.8 of depth) of Riffles	Guyer Creek	0.63	0.39	113	0.96	0.30	17	<0.01
	North Fork Silver Creek	0.61	0.39	101	0.57	0.20	18	0.38
	West Fork Silver Creek	NA	NA	NA	NA	NA	NA	NA
Thalweg Average Velocity (0.6 of depth) of Riffles without approach	North Fork Silver Creek	0.81	0.41	94	0.88	0.24	18	0.28

NA = Not Available

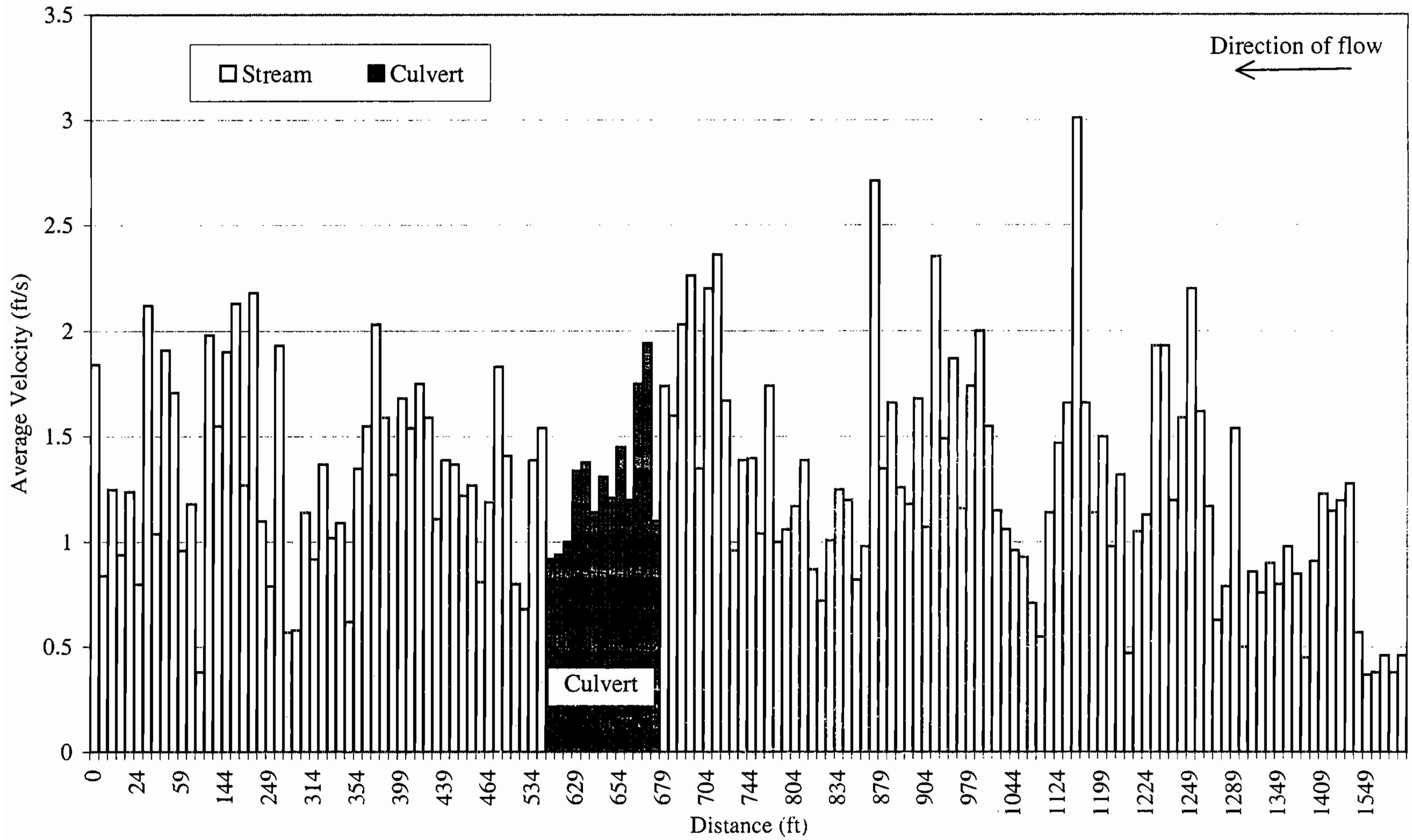


Figure 35. West Fork Silver Creek: Thalweg average velocity (0.6 of depth) of riffles.

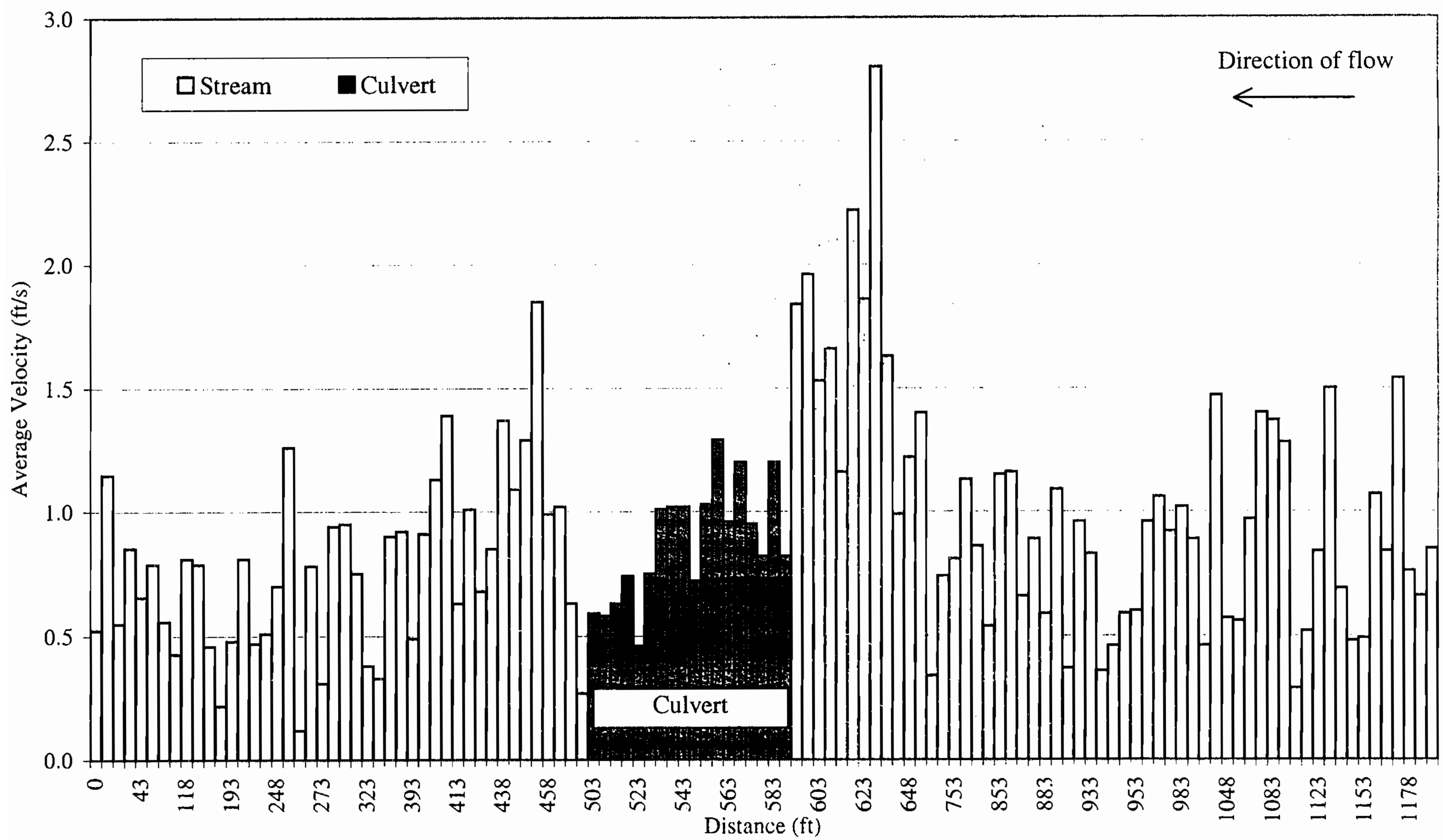


Figure 36. North Fork Silver Creek: Thalweg average velocity (0.6 of depth) of riffles.

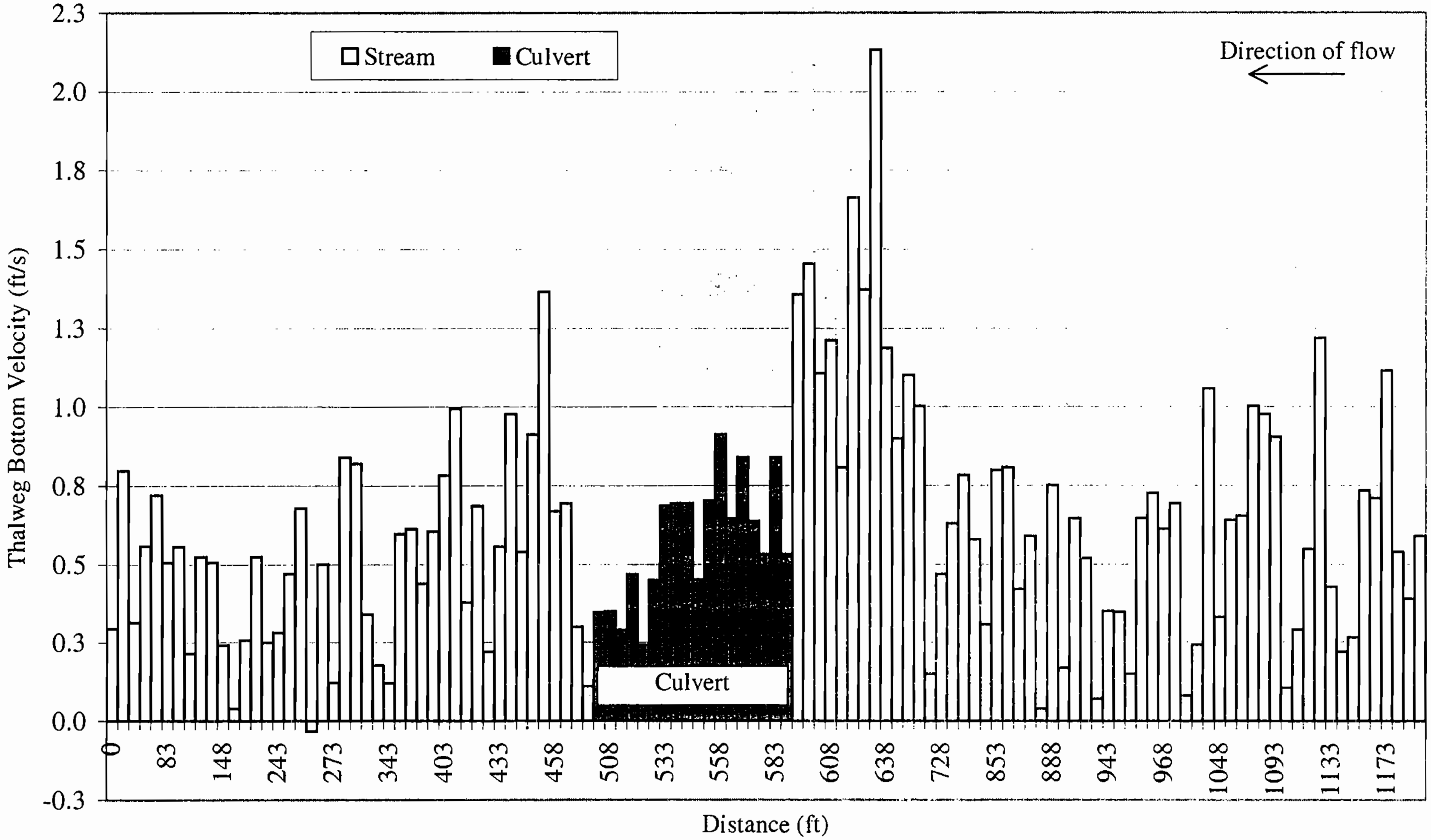


Figure 37. North Fork Silver Creek: Thalweg bottom velocity (0.8 of depth) of riffles.

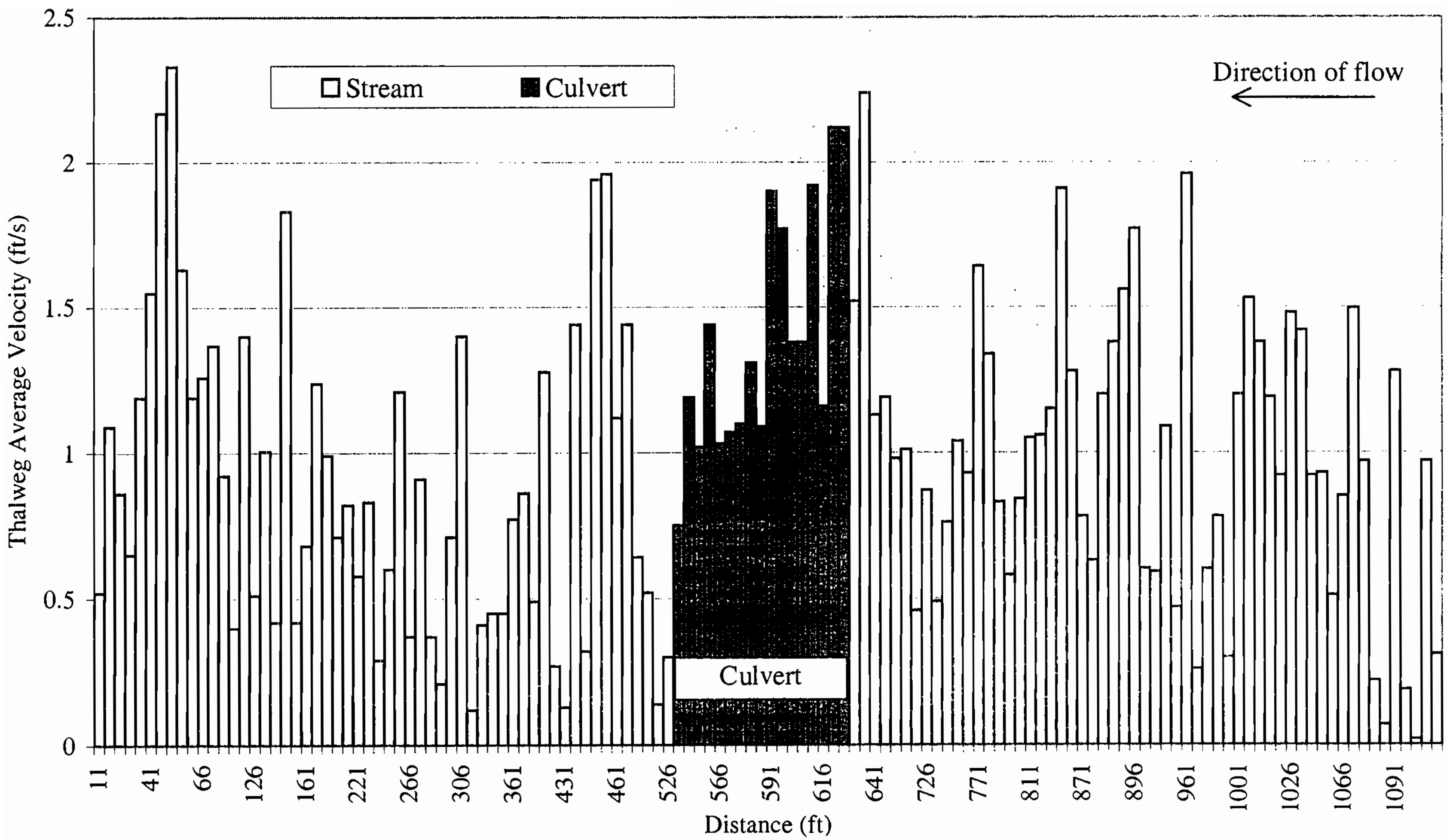


Figure 38. Guyer Creek: Thalweg average velocity (0.6 of depth) of riffles.

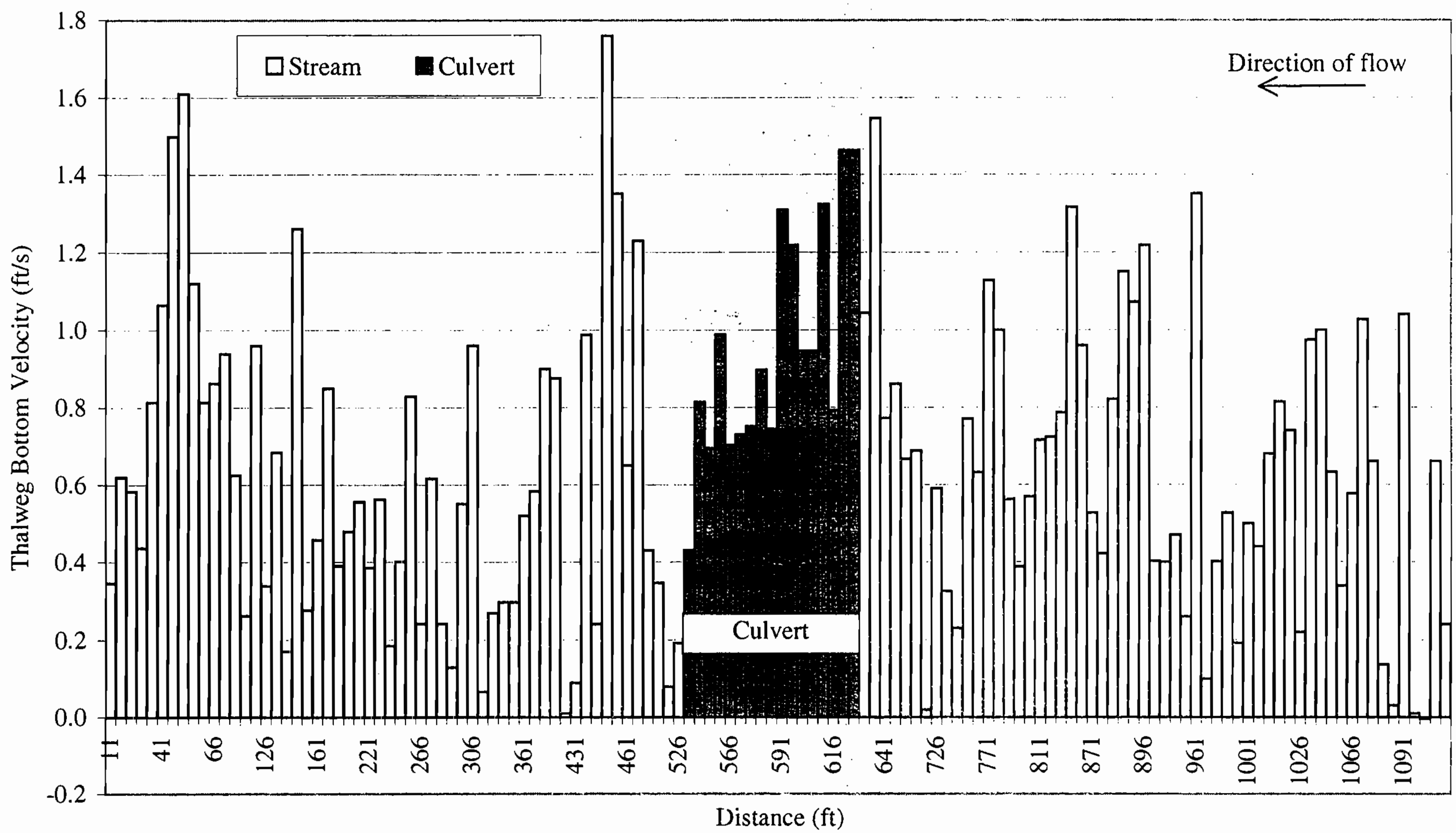


Figure 39. Guyer Creek: Thalweg bottom velocity (0.8 of depth) of riffles.

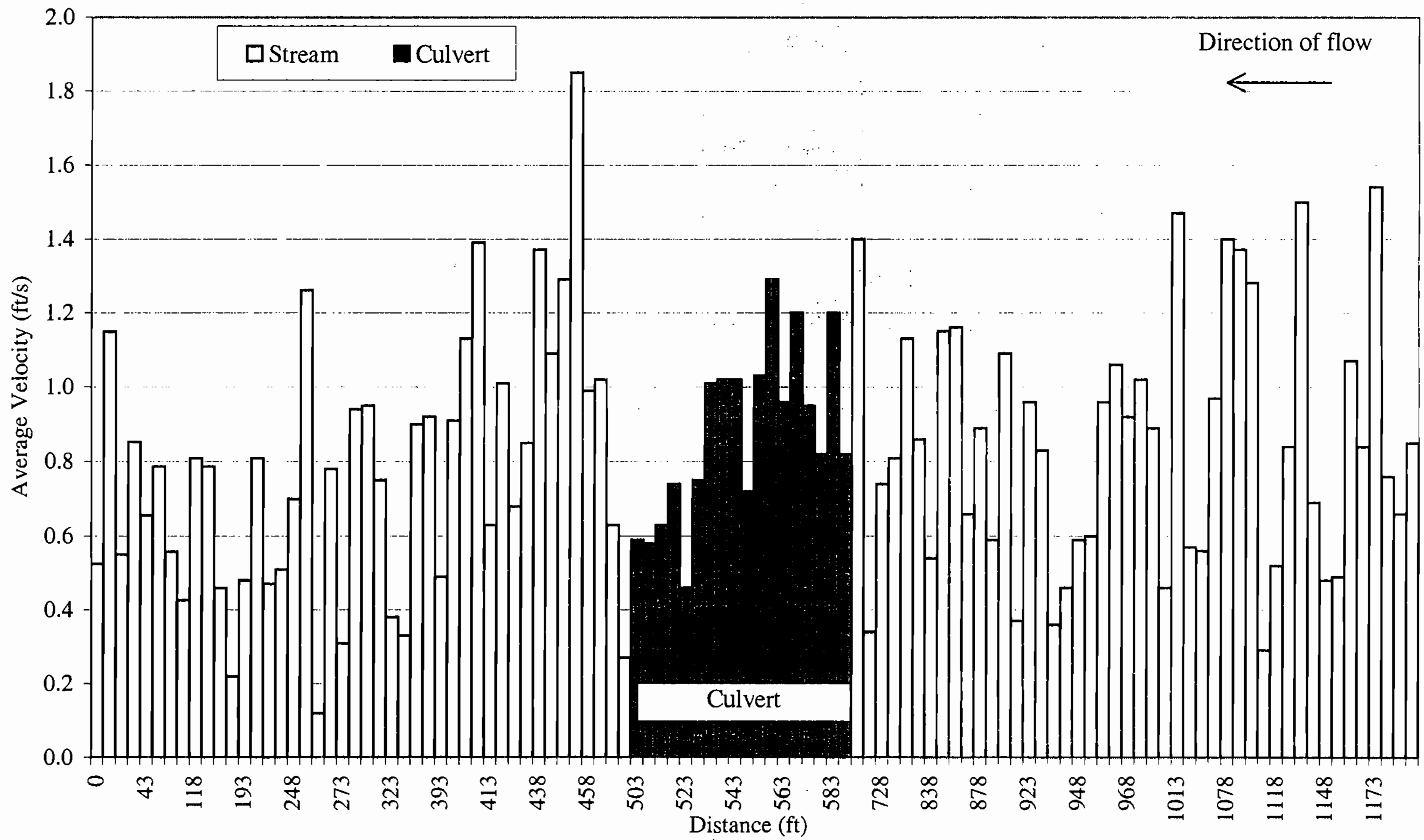


Figure 40. North Fork Silver Creek: Thalweg average velocity (0.6 of depth) of riffles without approach.

thalweg average and bottom velocities pertained to essentially the post-construction state of these sites. It is expected that the culverts will evolve with time and varying discharge rates. That is not to say that the culverts will only improve and become more like the stream hydraulically. The culverts were simply analyzed at one state in time and this state will change.

Typically, fish moving under strenuous conditions will swim very close to the culvert sides and bottom (Travis and Tilsworth, 1986; Belford and Gould, 1989; Behlke et al., 1991; Powers, 1997). At North Fork Silver Creek the comparisons between riffles in the culvert and the riffles in the stream with respect to thalweg average and thalweg bottom velocity were similar. Moreover, these measurements were applicable to the location in the water column of where fish move. West Fork Silver Creek, unfortunately, was not analyzed for the bottom and surface velocities. The analysis revealed that the velocities in the riffles of the stream were no worse than those created in the culvert through the strong similarity between stream and culvert thalweg average velocity. Guyer Creek responds differently than the other two study sites with respect to this analysis and clearly illustrates that thalweg velocities of the riffles in the culvert are much faster than those found in riffles of the natural stream.

Another comparison of the thalweg velocity measurements of the culvert and the natural stream was performed. This comparison allowed for a normalized view of the velocities regardless of depth of water by taking the measurement that was closest to the bed material. It is suggested that bottom velocities are a more accurate hydraulic characteristic of determining fish passage (Belford and Gould, 1989). The velocity measurement taken closest to the streambed was used in order to create another data set from the thalweg velocities of the riffles of North Fork Silver Creek and Guyer Creek (West Fork Silver Creek was not included in this analysis due to the lack of surface and bottom velocity measurements taken under normal backwater conditions). The comparison indicated that the velocity measured closest to the streambed of the culvert and the natural stream at North Fork Silver Creek was statistically similar (two-sided p-value = 0.6 from Wilcoxon rank sum test). At Guyer Creek, the same comparison was statistically different (two-sided p-value < 0.01 from Wilcoxon rank sum test). The conclusion that the culvert at North Fork Silver Creek was similar to the natural stream for riffle habitat types was made even stronger with this analysis.

The velocity was normalized by those variables that are generally assumed to affect velocity through Manning's equation. The average velocity was first normalized by the square root of the water surface slope and secondly by the hydraulic radius raised to the 2/3 power. The slope used in this analysis was not measured with stream habitat types as the dictating factor. The points used for the slope were taken at a fixed interval at the deepest point in the cross-section and were measured with a different intention. Therefore, they were not ideal for the slope calculation and added error into the slope calculation. Additional error is introduced into this calculation from the estimate of the cross-sectional area. The channel cross-sectional shape was assumed to be triangular and the wetted cross-sectional area was approximated by using the thalweg depth measurement as the height of the triangle and the wetted cross-sectional width as the base of the triangle (Robison and Beschta, 1989). This analysis did not remove the variation between the velocities in a discernible fashion.

The analysis of the thalweg velocity allows for longitudinal monitoring of the velocities through the natural stream and the culvert. It appears to be adequate, although labor intensive, metric in the determination of success or failure of stream simulation culverts. The velocity measurements could be minimized by the measurement of only the bottom and average velocities in the thalweg and by increased spacing of the measurements.

Cross-section velocity

Cross-sectional velocity measurements were entered into Liscad 5.0 and isovels of constant velocity were calculated using linear interpolation. Eight adjacent cross-sections were analyzed for both the culvert and for the stream. The analyzed culvert cross-sections were located at the mid-point of the culvert. Six contiguous cross-sections were measured in the natural stream reaches, each with randomly chosen starting points. One of the six contiguous cross-sections was chosen for analysis based on habitat type and compared to the culvert cross-sections. It is understood that fish take advantage of low velocity conditions when moving through a strenuous condition (Behlke et al., 1991) and low velocity conditions are found at or near the streambed across the entire stream. Therefore, the percent of the cross-sectional area that was less than 1.0 ft/s was measured for each cross-section in the stream and in the culvert and statistically compared.

The results from the percent of the area that was less than 1.0 ft/s, hereafter referred to as low velocity area, yielded mixed results. The comparison indicated that the culvert section and the stream section were statistically different at West Fork Silver Creek with more low velocity area in the culvert (two-sided p-value < 0.01, from Wilcoxon rank sum test). The same comparison at North Fork Silver Creek was statistically similar (two-sided p-value $= 0.40$, from Wilcoxon rank sum test). However, the same comparison at Guyer Creek was statistically different with less low velocity area in the culvert (two-sided p-value < 0.01, from Wilcoxon rank sum test). The minimum percent of the low velocity area of each culvert was 23%, 57%, and 41% at Guyer Creek, North Fork Silver Creek, and West Fork Silver Creek, respectively. The average of the percent of the low velocity area in each culvert compared to the percent in the natural stream was 31% compared to 72% at Guyer Creek, 69% compared to 74% at North Fork Silver Creek, and 54% compared to 26% at West Fork Silver Creek (Figures 41, 42, and 43).

The variation between the results of the analysis of the percent of the cross-sectional area that was less than 1.0 ft/s could be attributed to a few things. The measured discharge over-topped the low flow channel that ran through the culvert, backwater effect, and that the characteristics of the stream were similar or different to the stream characteristics of the culvert. The culvert at West Fork Silver Creek exhibited a greater percentage of the area as less than 1.0 ft/s than in the stream

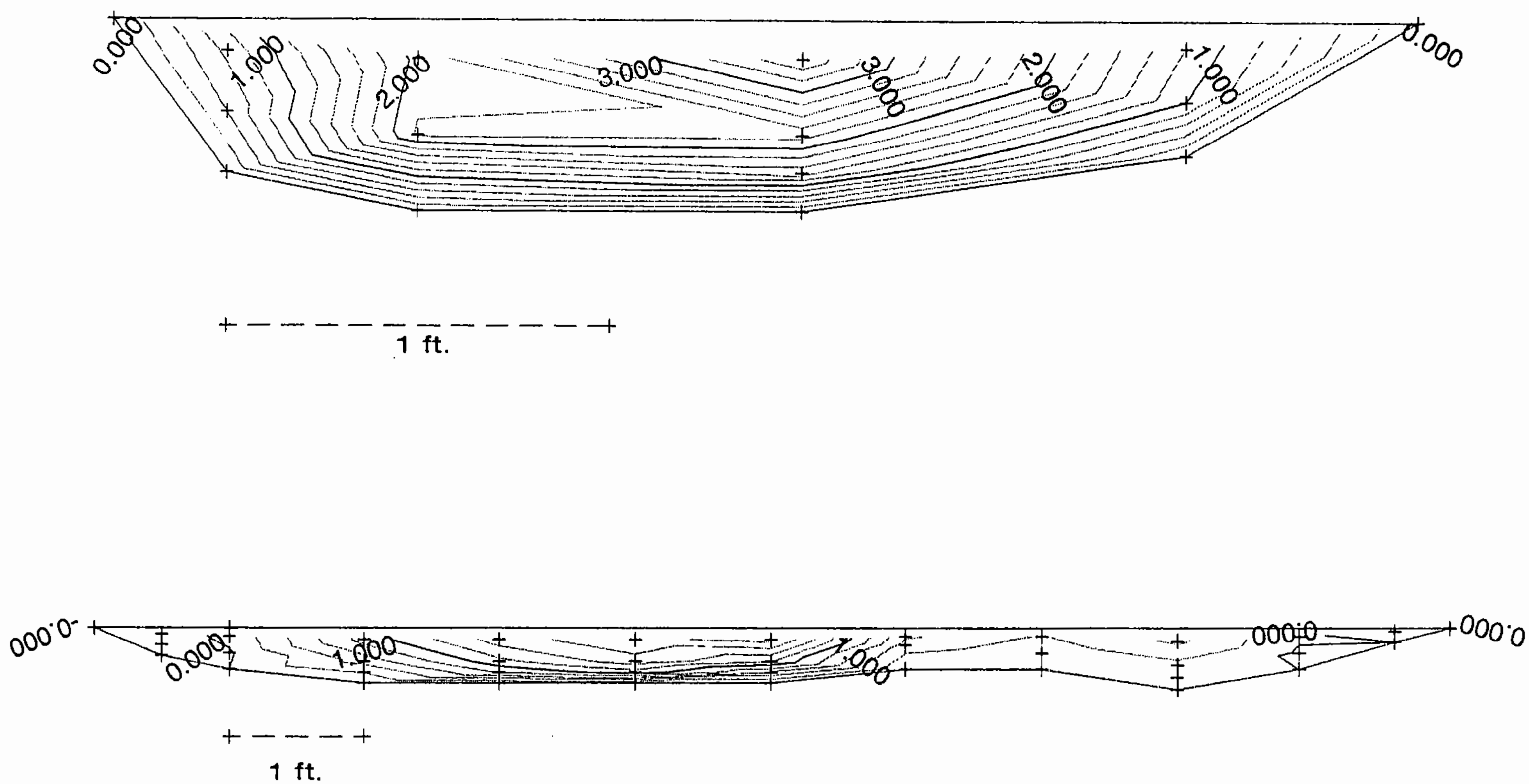


Figure 41. Guyer Creek: Cross-sectional velocity (ft/s) of the culvert (top) and natural stream (bottom) representing the average values of the percent of velocities less than 1 ft/s of the cross-sections analyzed.

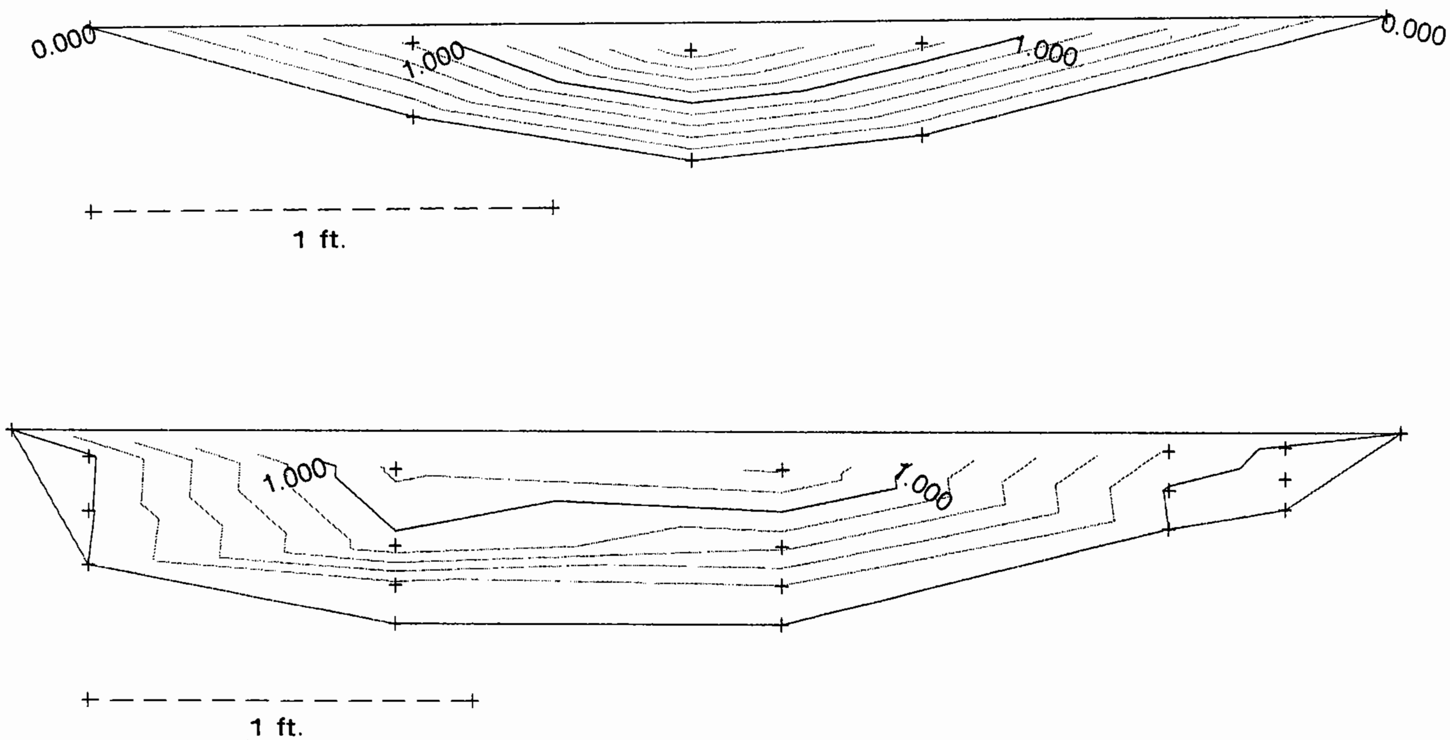


Figure 42. North Fork Silver Creek: Cross-sectional velocity (ft/s) of the culvert (top) and natural stream (bottom) representing the average values of the percent of velocities less than 1 ft/s of the cross-sections analyzed.

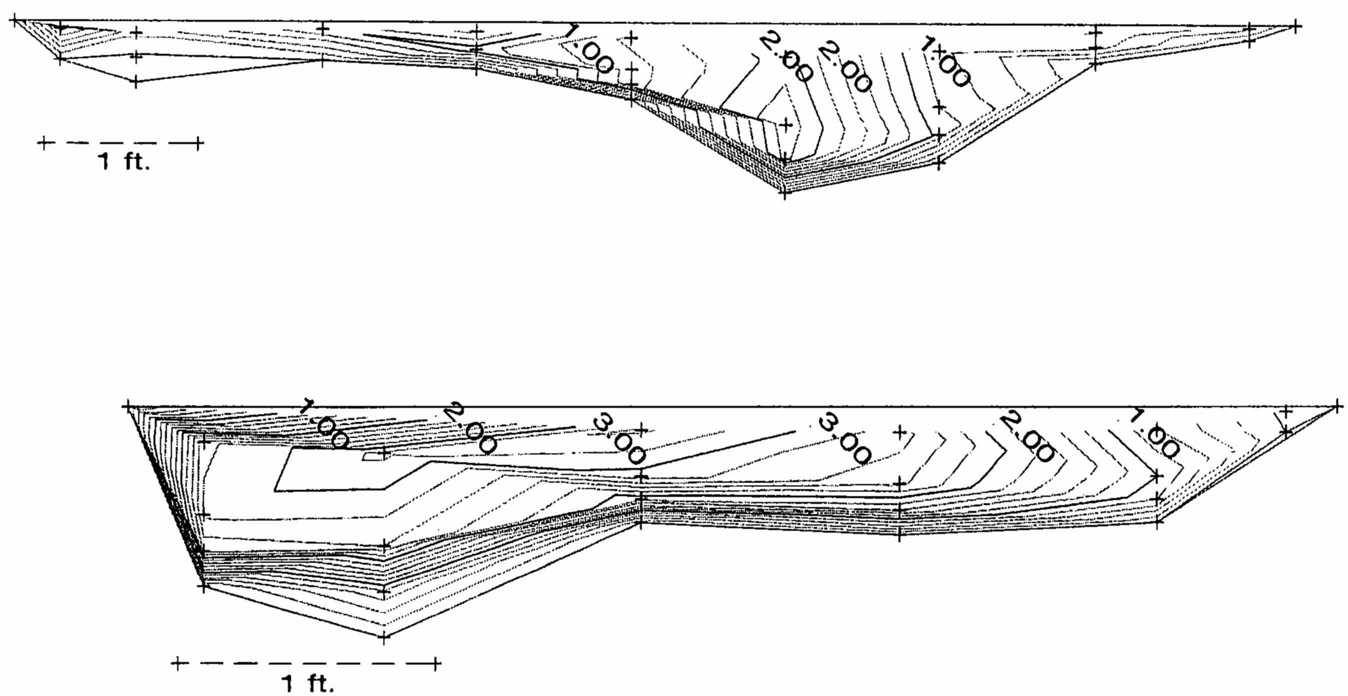


Figure 43. West Fork Silver Creek: Cross-sectional velocity (ft/s) of the culvert (top) and natural stream (bottom) representing the average values of the percent of velocities less than 1 ft/s of the cross-sections analyzed.

section analyzed. The backwater effect from the downstream rock weir also had a substantial effect. Each of the cross-sections analyzed in the culvert at West Fork Silver Creek there was a distinct low flow channel that was over-topped (Figure 44) and this region was the source of the majority of the area that was less than 1.0 ft/s. However, at the cross-sections analyzed in each of the culverts at Guyer Creek and North Fork Silver Creek (Figures 45 and 46) the flow was confined to the low flow channel and was unable to take advantage of the full width of the culvert. However, the areas of low velocity in the North Fork Silver Creek culvert were statistically similar to the stream. Therefore, the low flow channel in the culvert at North Fork Silver Creek was similar enough in channel shape to the natural stream that the overtopping of the low flow channel was not needed to create more low velocity zones.

The cross-sectional velocity analysis is the metric that best analyzed the condition a fish encounters. The comparison of the percent of low velocity zones in each cross-section was straightforward with the proper tools and the data collection was moderately labor intensive.

Velocity distribution

The thalweg velocity measurements of the riffle habitat unit types of the stream and of the culvert were separated into velocity categories in order to investigate the velocity distribution of the stream and culvert. The thalweg average and thalweg bottom velocity distributions were all plotted separately. The longitudinal distribution of velocity is one of the assumptions included in the design of stream simulation culverts. The thalweg velocity was measured to monitor the longitudinal velocity variation through the natural stream and the culvert.

The distribution of the culvert velocities at North Fork Silver Creek and West Fork Silver Creek did not have as wide a range of velocities and therefore

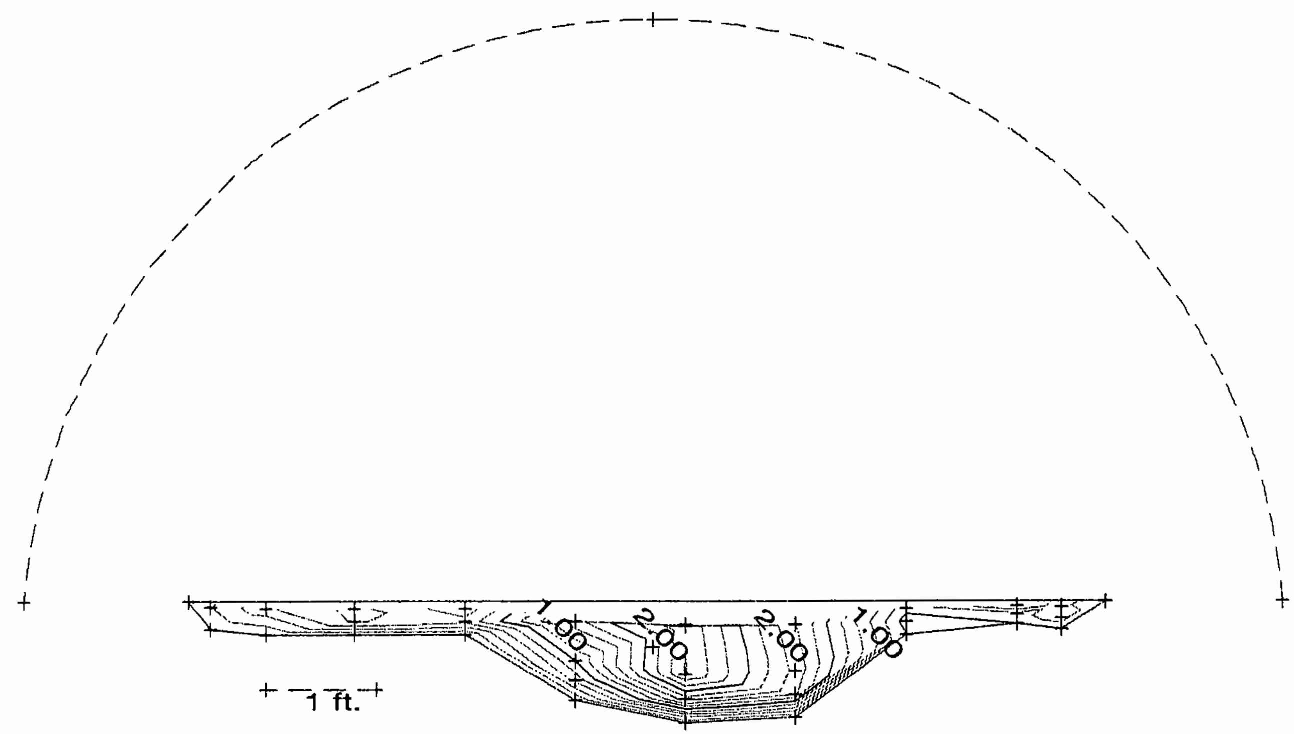


Figure 44. West Fork Silver Creek: Cross-sectional velocity (ft/s) of a representative culvert cross-section with culvert outline.

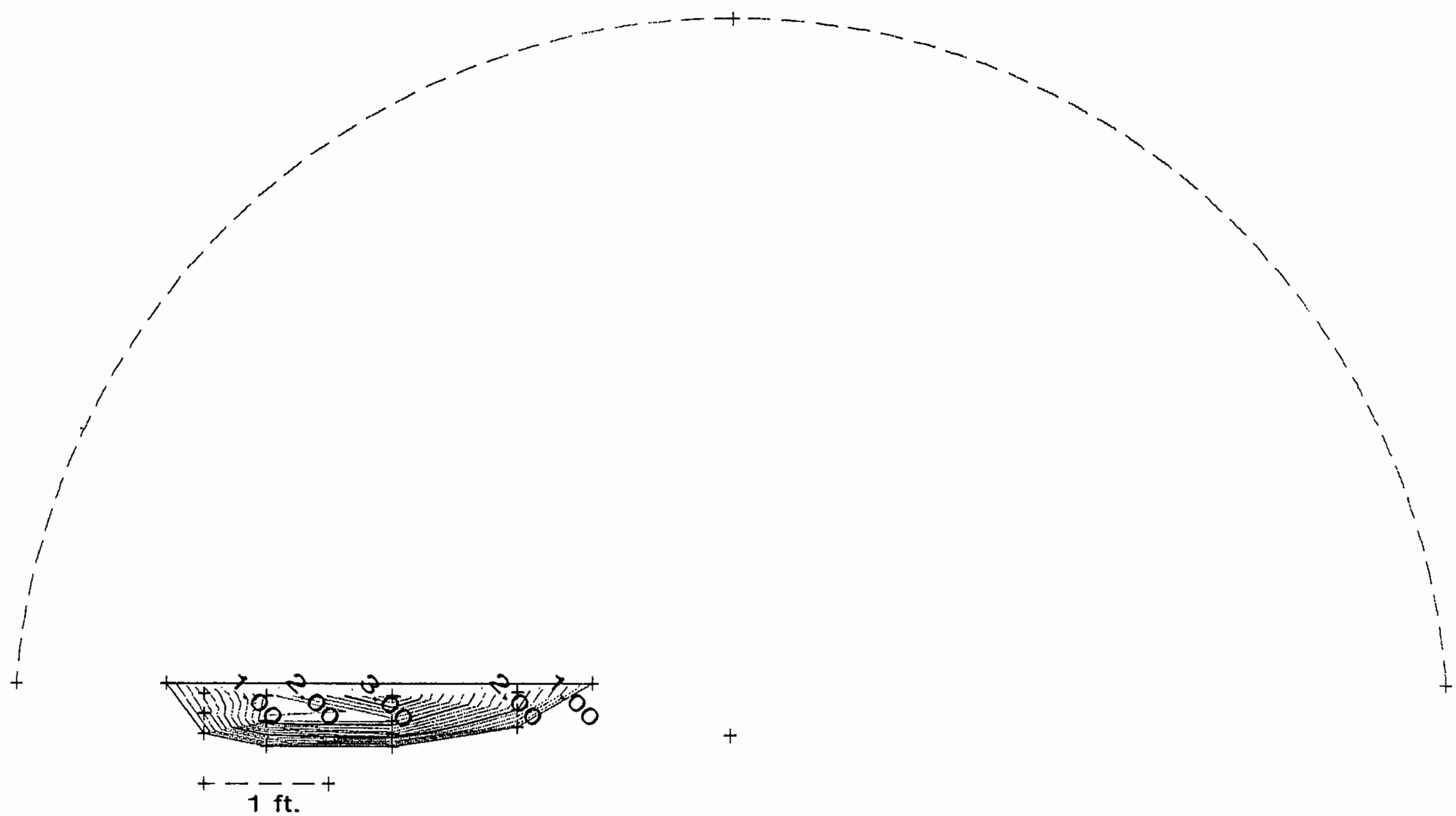


Figure 45. Guyer Creek: Cross-sectional velocity (ft/s) of a representative culvert cross-section with culvert outline.

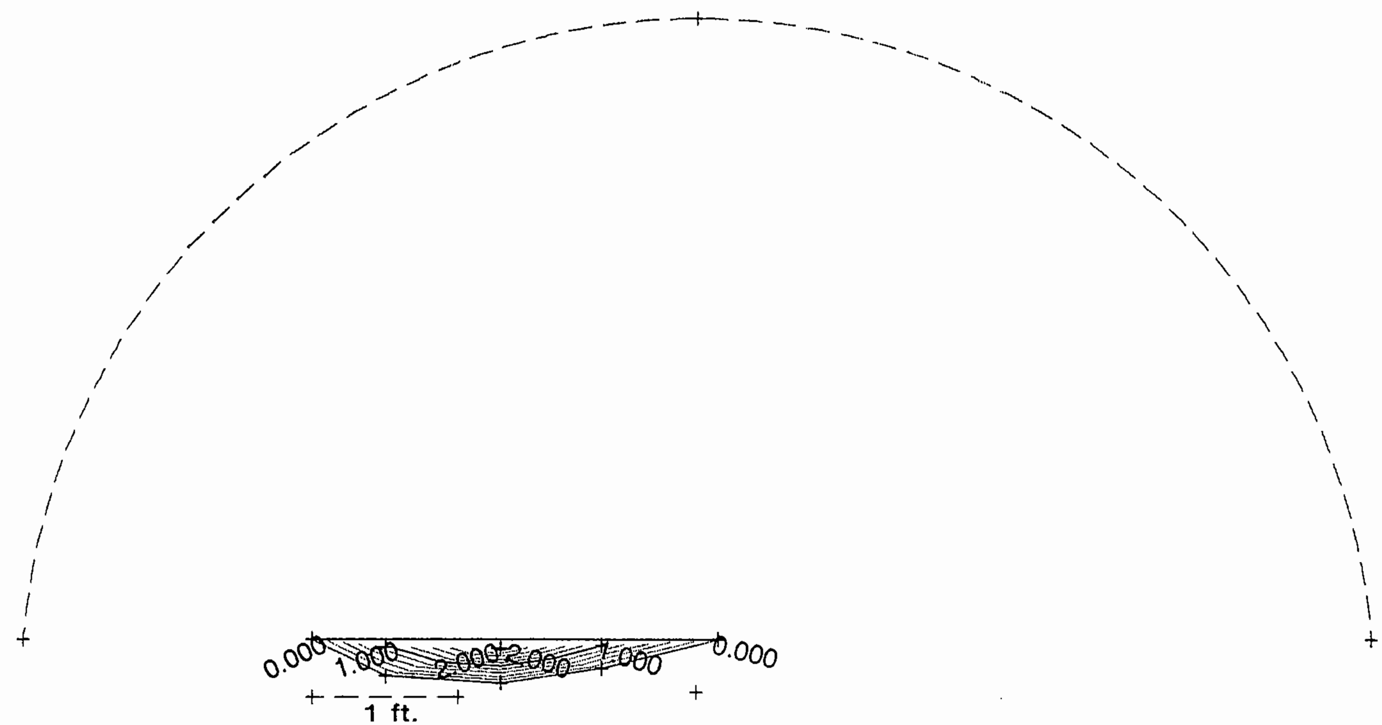


Figure 46. North Fork Silver Creek: Cross-sectional velocity (ft/s) of a representative culvert cross-section with culvert outline.

exhibited fewer extreme low velocities and fewer extreme high velocities (Figures 47 and 48). The distribution of the culvert velocities at Guyer Creek was in the upper 50-60% of the stream velocities in the thalweg average and thalweg bottom distributions (Figure 49) and the culvert does not exhibit velocity categories that are any faster than those found in the natural stream.

The velocity distribution of North Fork Silver Creek inside of the culvert were compared to the stream without the approach velocities. The culvert distribution for both the thalweg average and thalweg bottom velocities remain in the middle of the distribution of the stream velocities with the removal of the approach velocities (Figure 50).

At all three sites, the velocity distributions did not exhibit velocity categories that were any faster than those found in the natural stream. At the same time, the culverts did not exhibit the lower velocity categories found in the natural stream. One can conclude that the distributions of the velocities in the culverts were more uniform than those found in the streams.

The differences between the distributions between the culverts and the natural stream can be attributed to two factors. The first is that the lack of structure via bed form, plan form, and debris results in the absence of the lower velocity categories. There has not been enough time or high discharge events to create bed forms within the culverts. There are limited plan form features in the low flow channels of each culvert. This plan form structure is a direct result of the construction, not hydraulic shaping, and does not provide the degree of plan form that is available in the stream. Furthermore, it is not expected that dramatic increases in plan form structure will be introduced into the culvert by larger flows, due to the lateral limits imposed by the culvert upon the stream as it flows through the culvert. The natural stream sections at Guyer Creek and North Fork Silver Creek are characterized by debris in the form of large wood, small wood, branches, and twigs. The streams have some areas with heavy debris concentrations that alter the flow substantially, but they are more commonly characterized by long stretches having moderate to low amounts of debris that alter the flow. Currently, there is

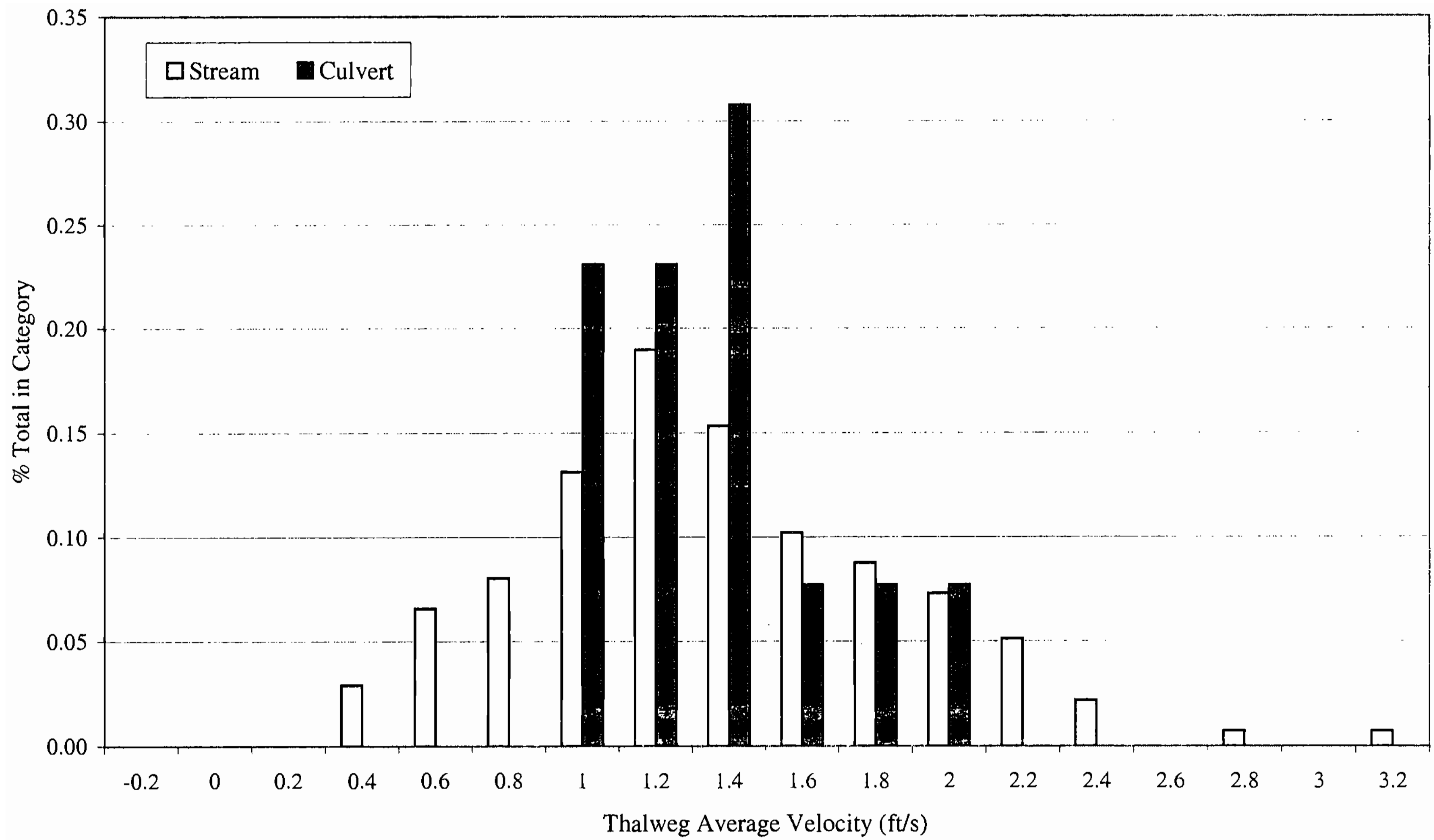


Figure 47. West Fork Silver Creek: Thalweg average velocity distribution of riffles of stream and culvert.

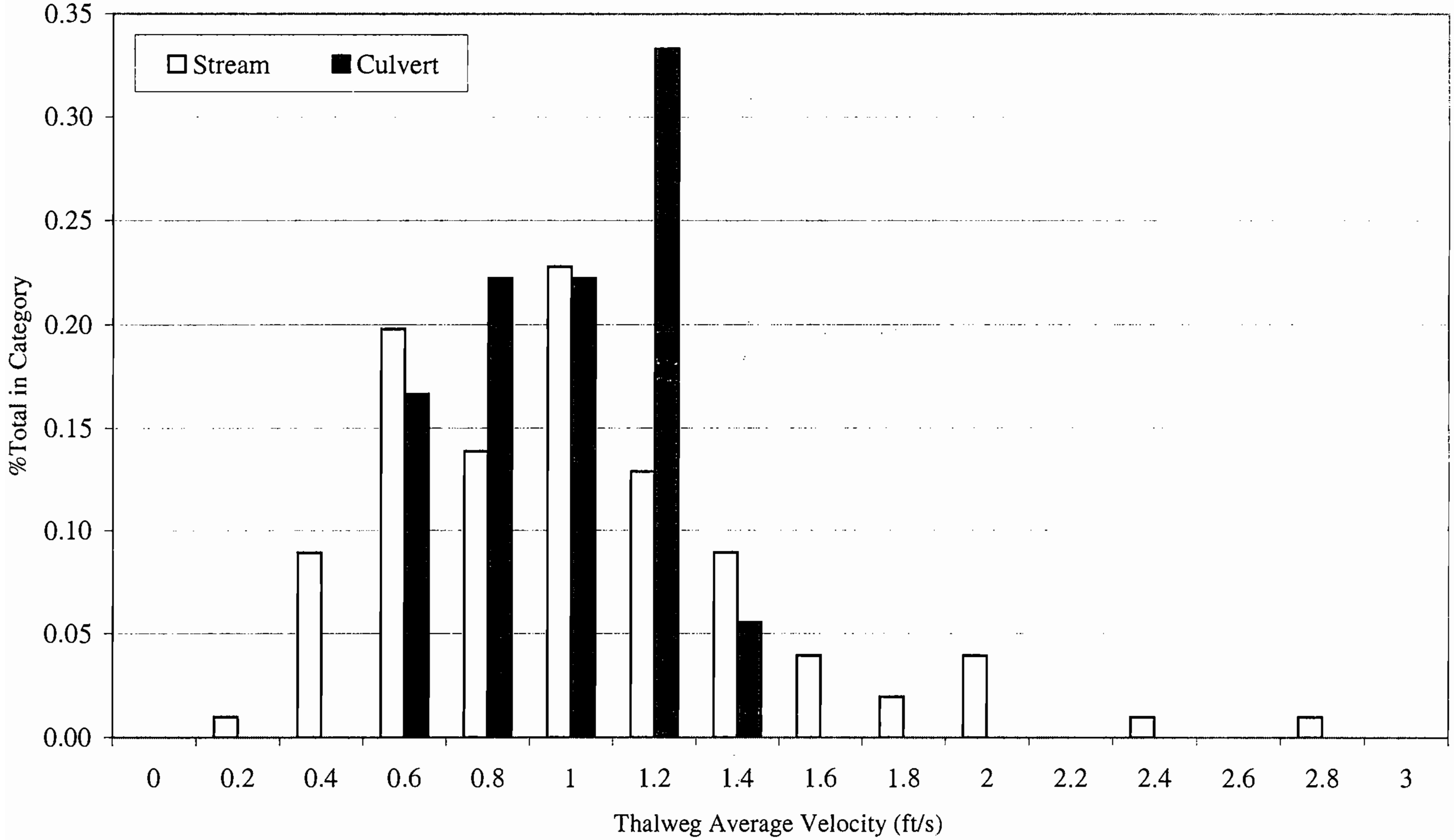


Figure 48. North Fork Silver Creek: Thalweg average velocity distribution of riffles of stream and culvert.

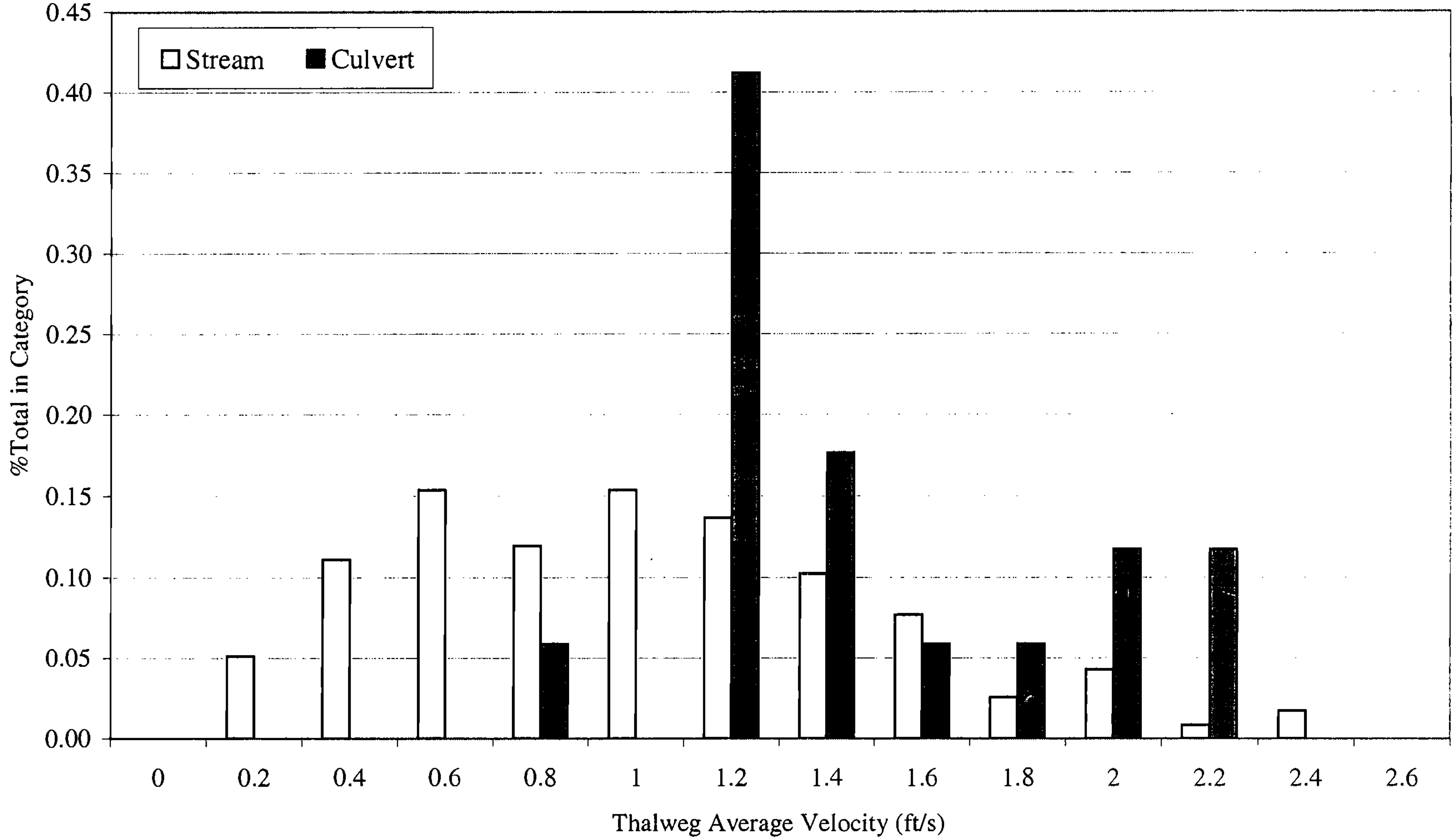


Figure 49. Guyer Creek: Thalweg average velocity distribution of riffles of stream and culvert.

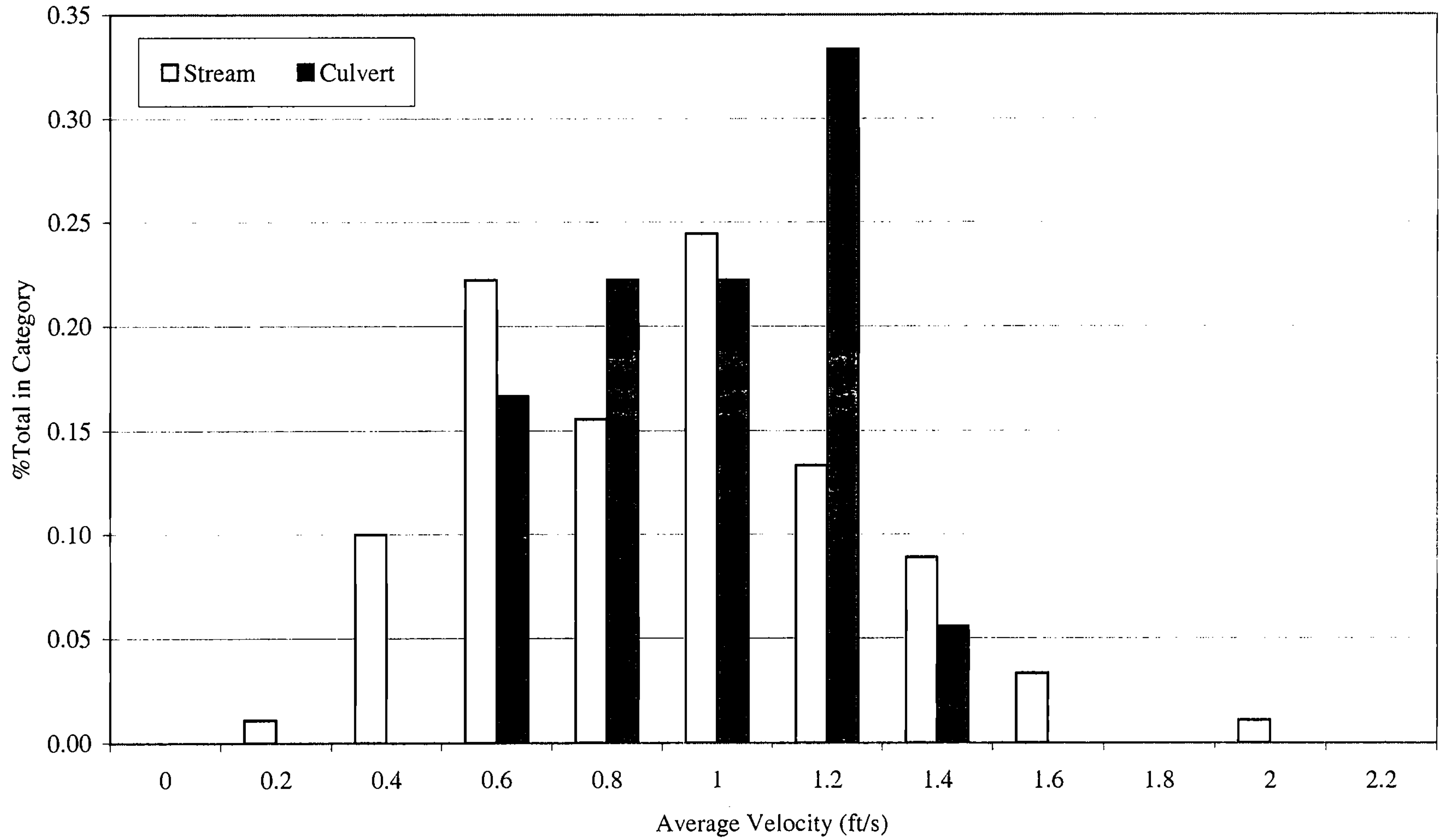


Figure 50. North Fork Silver Creek: Thalweg average velocity distribution of riffles of stream and culvert, without approach.

little or no debris in any of the culverts. Moreover, due to blockage concerns the culverts were not designed to include large wood or excessive debris in the barrel.

The differences in the longitudinal velocity distribution could be attributed to a second factor. The culvert may not have the capability to develop the full range of velocities, due to limitations in stream simulation culvert design. Lack of the degree of plan form found in the natural stream and the lack of large wood roughness may be enough to keep the average thalweg velocity in the culvert similar to that of the stream but may not allow for the same distributions in the culvert as in the natural stream.

The comparison of the longitudinal thalweg velocity distribution between the natural stream and the culvert would be an adequate metric to determine the success or failure of stream simulation culverts. The comparison of the velocity distribution allows one to evaluate the range of velocities a fish may experience in the natural stream and determine if the distribution of those velocities is similar or different in the culvert.

Slope

The slope of the culvert, after replacement, was the same as the slope from the longitudinal profile. The slope at which the culvert was set during construction and the slope of the bed material dictated the slope of the water surface inside of the culvert. The culvert at West Fork Silver Creek was set at the longitudinal profile slope of 0.005 and the water surface slope through the culvert was 0.007. The culvert and water surface slope inside of the culvert were the same, 0.02 at both Guyer Creek and North Fork Silver Creek.

At the culvert outlets of North Fork Silver Creek and at West Fork Silver Creek a milder slope was encountered when compared to the slope through the remainder of the culvert and was attributed to natural and artificial backwater structures, respectively. The slope through the culvert at Guyer Creek was constant throughout its length at 0.02. However, the outlet at Guyer Creek had very little water backing up into the culvert due to backwater effect.

The culverts had a relatively constant slope throughout their length and the slopes agreed with the longitudinal profile slope of the respective streams. However, the culvert effectively represented a long stretch of riffle habitat type at a constant slope, which was not found in the riffle habitat types of the natural stream (Figures 51, 52, and 53). Short lengths of riffles followed by flatter sloped pools characterized the natural stream. The lack of bed form structure within the culvert had not allowed for this type of variation but it is possible that bed form structure will be created within the culvert with sediment transporting spring flows. The introduction of bed form structure should allow for greater variation of the slope through the culvert.

The longitudinal slope alone would not be an accurate measure of the degree of similarity between the culvert and the natural stream. It is important to the overall success of the stream simulation culvert but is not a preferred metric to determine the success of the culvert.

High flow channel characteristics

Several channel shape measurements between the culvert and the natural stream were statistically compared (Table 6). Again, the measurements that were compared were those taken from riffle habitat types. The comparisons at North Fork Silver Creek and Guyer Creek indicated that the maximum depths in the culverts and the natural stream were statistically similar at the flow rates of the measurements (two-sided p-value = 0.53 and 0.23, respectively, from Wilcoxon rank sum test). The same comparison at West Fork Silver Creek was statistically different with deeper maximum depths found in the culvert than were in the stream. The artificial backwater at West Fork Silver Creek can be attributed to the reason for the deeper maximum depths in the culvert.

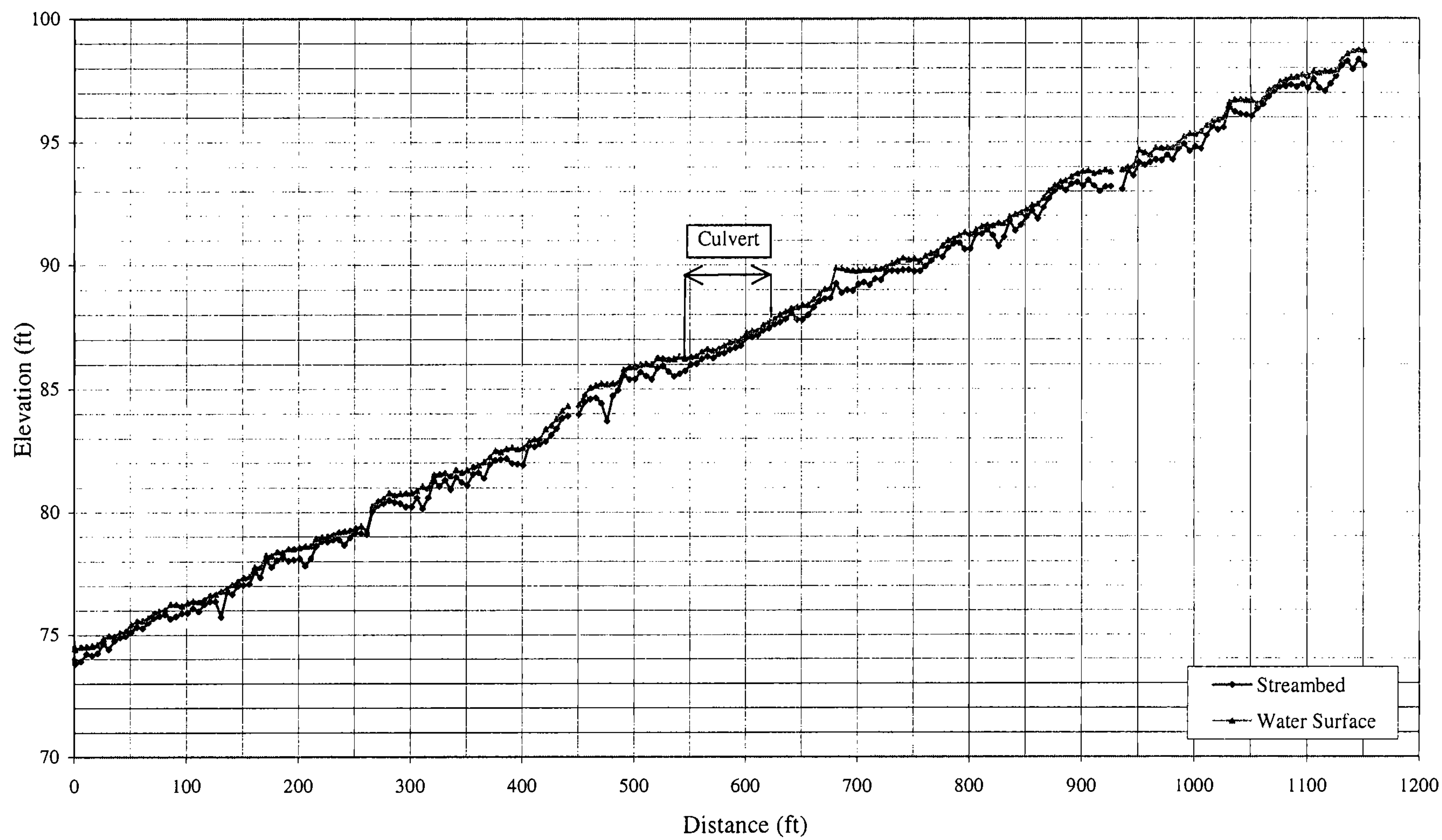


Figure 51. Guyer Creek: Stream bed and water surface elevations.

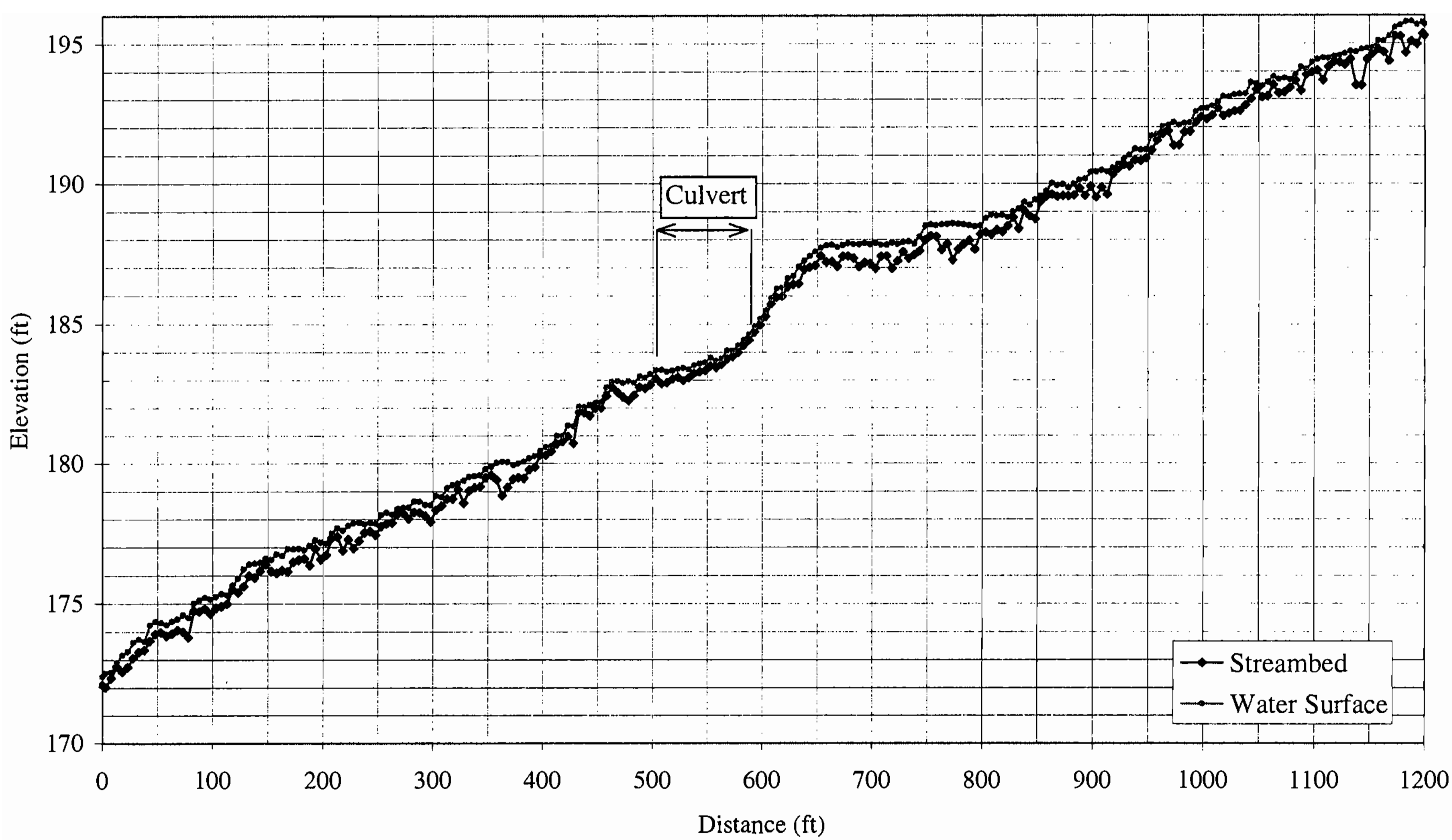


Figure 52. North Fork Silver Creek: Stream bed and water surface elevations.

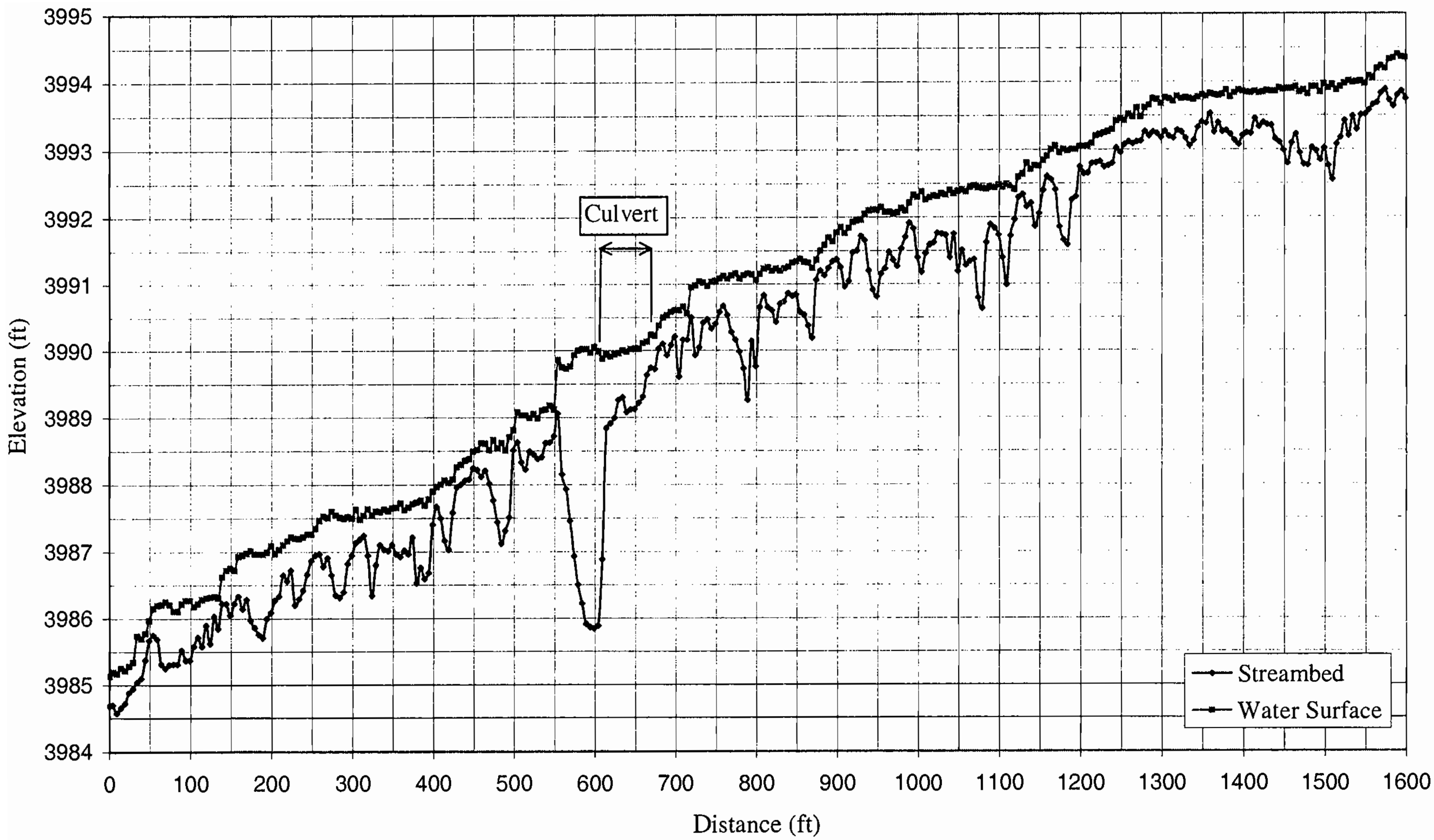


Figure 53. West Fork Silver Creek: Stream bed and water surface elevations.

Table 6. Results of Wilcoxon rank sum test (two-sided p-value < 0.10) for comparison of natural stream vs. culvert of various high flow physical channel measurements at each study site.

		Natural Stream			Culvert			Significance of natural stream vs culvert using **Wilcoxon Rank Sum Test** (two-sided p-value)
Measurement	Study Site	Average	Standard Deviation	n	Average	Standard Deviation	n	
High Flow Maximum Depth	Guyer Creek	0.30	0.11	113	0.27	0.07	17	0.29
	North Fork Silver Creek	0.32	0.11	101	0.30	0.08	18	0.53
	West Fork Silver Creek	0.47	0.13	137	0.79	0.20	13	<0.01
High Flow Wetted Width	Guyer Creek	6.2	2.1	113	3.4	0.9	17	<0.01
	North Fork Silver Creek	4.0	1.2	101	3.1	0.8	18	<0.01
	West Fork Silver Creek	7.4	2.5	137	8.3	2.1	13	0.12
High Flow Width-to-Depth	Guyer Creek	22.8	10.5	113	12.8	2.8	17	<0.01
	North Fork Silver Creek	14.3	8.0	101	11.2	3.6	18	0.12
	West Fork Silver Creek	17.2	8.5	137	10.7	2.4	13	<0.01

The wetted width and width-to-depth estimate of the stream were also compared to that of the culvert. The comparison indicated that the wetted width of the culvert and the stream at West Fork Silver Creek was statistically similar (two-sided p-value = 0.12 from Wilcoxon rank sum test). The same comparison at Guyer Creek and North Fork Silver Creek were statistically different (two-sided p-value = 0.0 and 0.0004, respectively, from Wilcoxon rank sum test). However, the difference between the average widths at Guyer Creek was nearly three feet less in the culvert than it was in the stream, while the difference at North Fork Silver Creek was 0.8 ft (Figures 54 and 55). The comparison indicated that the width-to-depth calculation of the culvert and the stream at North Fork Silver Creek was statistically similar (two-sided p-value = 0.12 from Wilcoxon rank sum test). The same comparisons at Guyer Creek and West Fork Silver Creek were statistically different (two-sided p-value = 0.0 and 0.001, respectively, from Wilcoxon rank sum test). The width in the culvert at North Fork Silver Creek was close enough to the width in the stream, that the comparison of the width-to-depth was statistically similar while at Guyer Creek the comparison was statistically different.

The low flow channel characteristics determined the channel characteristics used for the comparison at Guyer Creek and North Fork Silver Creek because high flow remained within the low flow channels during the measured discharge. The low flow channel at Guyer Creek was simply too narrow when compared to the natural stream channel and the channel sides of the low flow channel were too steep to allow for overtopping into the high flow channel with the available discharge.

The channel characteristics allow for insight into the similarity or difference between the culvert and the natural stream. The link between the channel characteristics and velocity is important to the overall success of the stream simulation culvert but is not a preferred metric to determine the success of the culvert.

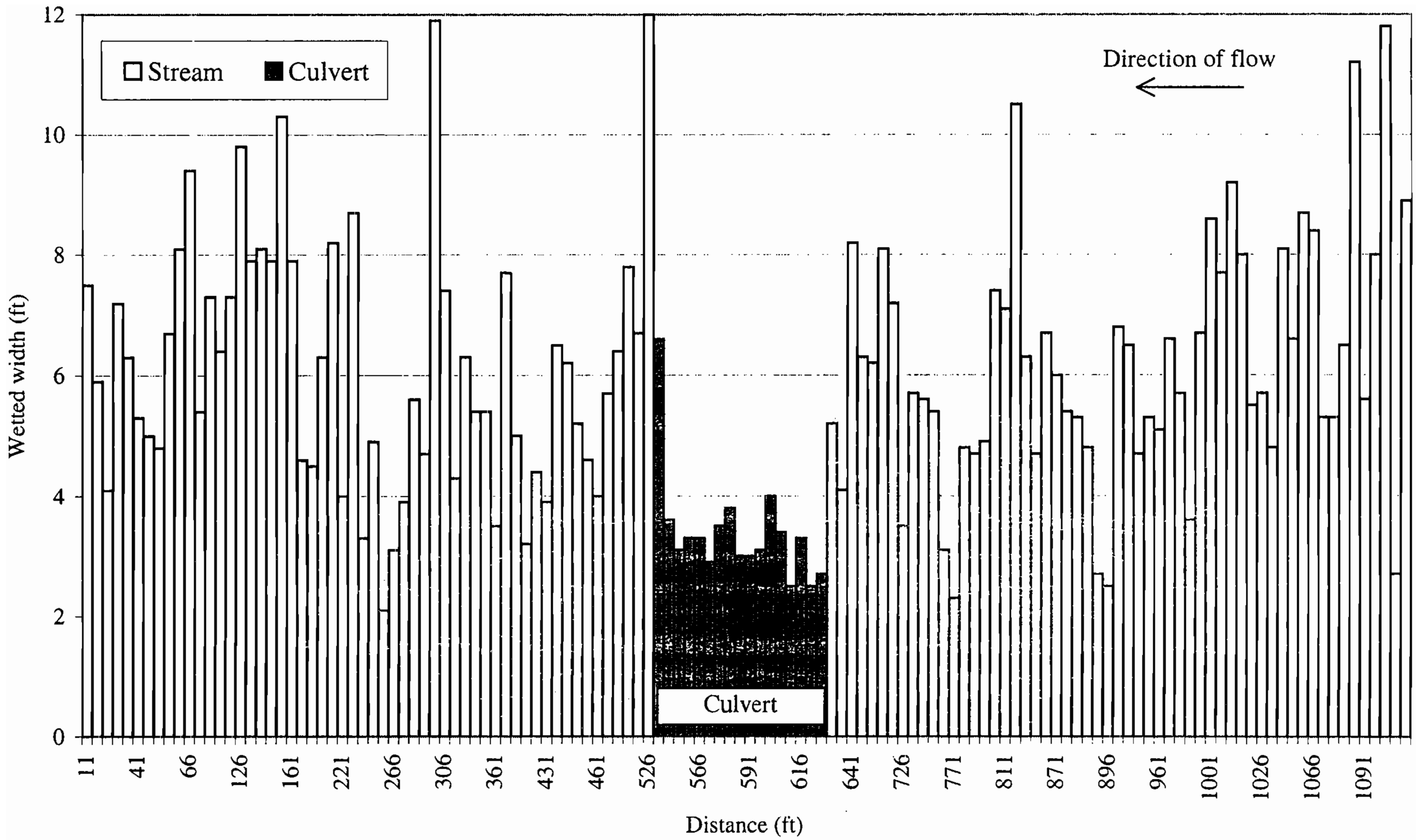


Figure 54. Guyer Creek: Wetted width of riffles.

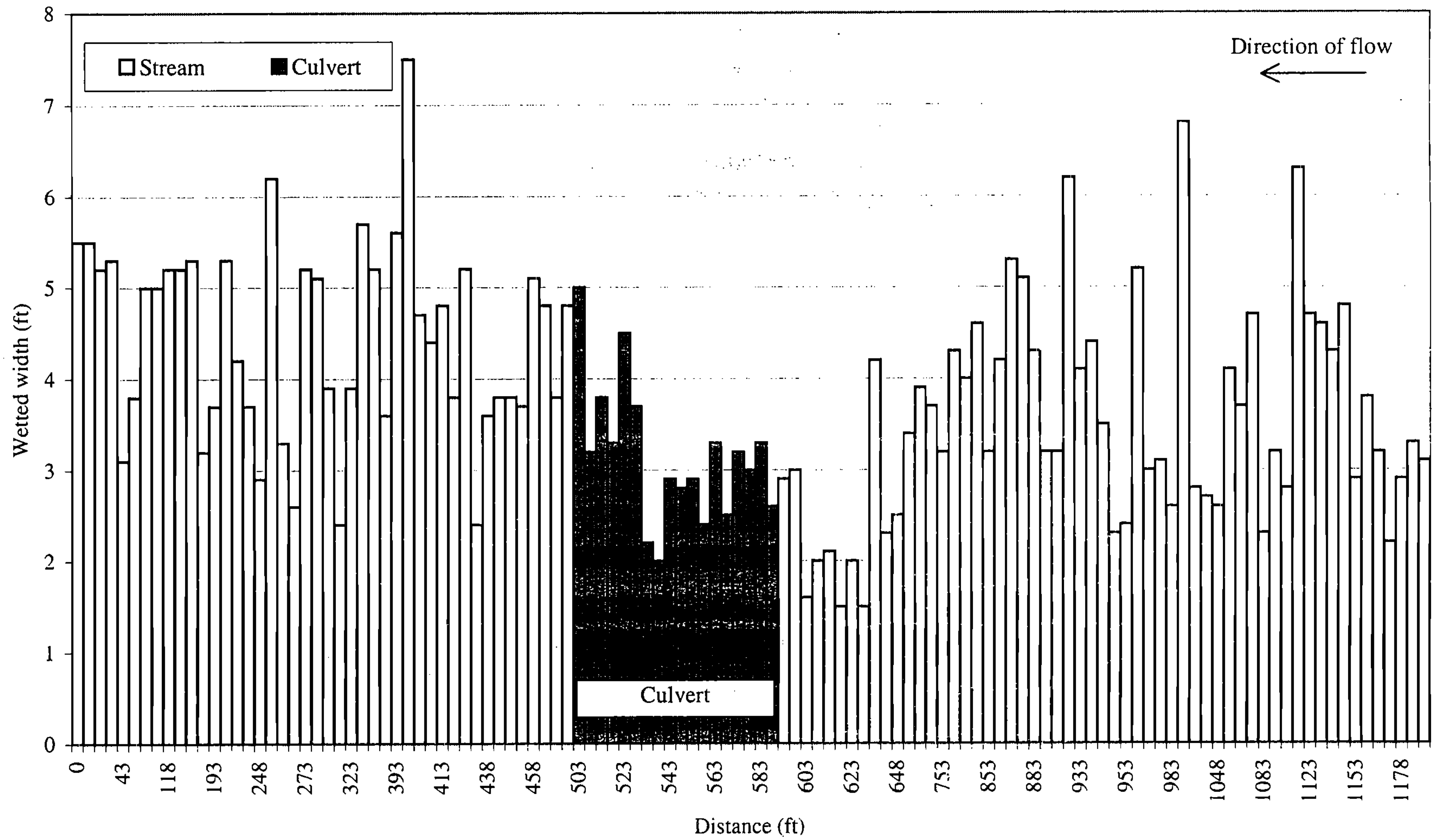


Figure 55. North Fork Silver Creek: Wetted width of riffles.

Streambed material

All pebble counts in the culverts, in 2001, were essentially unchanged from the summer 2000 pebble count with respect to bed material (Figures 56, 57, and 58). The percent finer plots in the upstream and downstream reaches were similar in 2000 and 2001. There was a minor shifting of the trend at all culverts and may be attributed to minor changes in the bed material. The culvert material was coarser than both the upstream and downstream surveyed reaches (Table 7). The streambed material changed midway through the downstream reach at North Fork Silver Creek and was plotted separately.

Table 7. Pebble count post 2001 spring discharge at each study site.

Pebble Count for 2001	**Guyer Creek**	**North Fork Silver Creek**	**West Fork Silver Creek**
D_{50} Culvert	64 mm	84 mm	130 mm
D_{50} Stream	19 mm	Upstream = 7 mm Downstream = 25 mm	25 mm
D_{90} Culvert	256 mm	230 mm	380 mm
D_{90} Stream	74 mm	Upstream = 18 mm Downstream = 175 mm	85 mm

Pebble counts were also taken in the low flow channel of North Fork Silver Creek and Guyer Creek. The distribution of the pebble counts showed that the low flow channel bed material was finer than the entire culvert but not as fine as the stream material. The D_{50} and D_{90} of the low flow channel at Guyer Creek were 30 mm and 55 mm, respectively. At North Fork Silver Creek, the D_{50} and D_{90} were 24 mm and 85 mm, respectively. The D_{90} value of the low flow channel was similar to the upstream reach of Guyer Creek. At the same time, the D_{90} value of the low flow channel was similar to the downstream reach at North Fork Silver Creek.

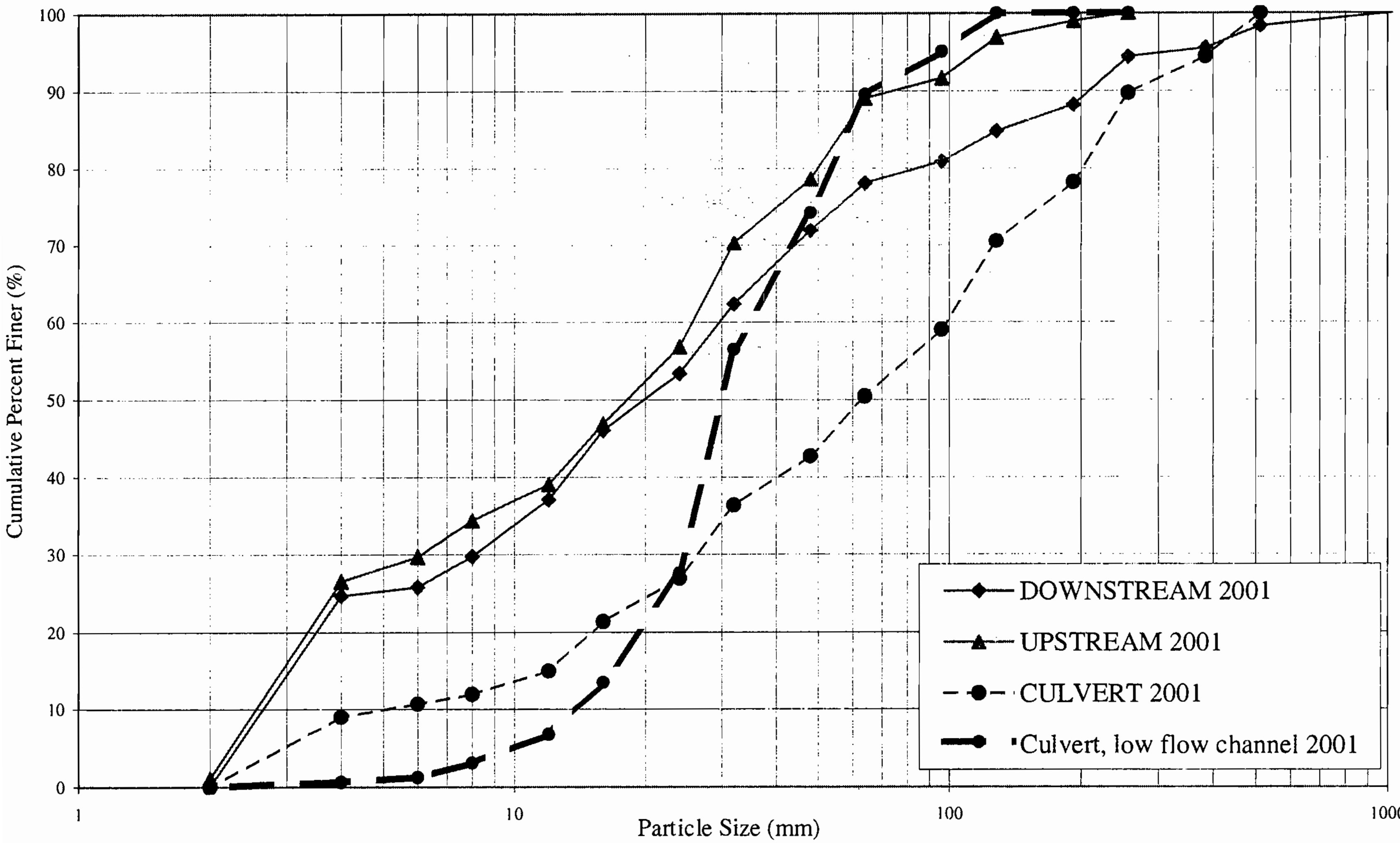


Figure 56. Guyer Creek: Pebble count 2001.

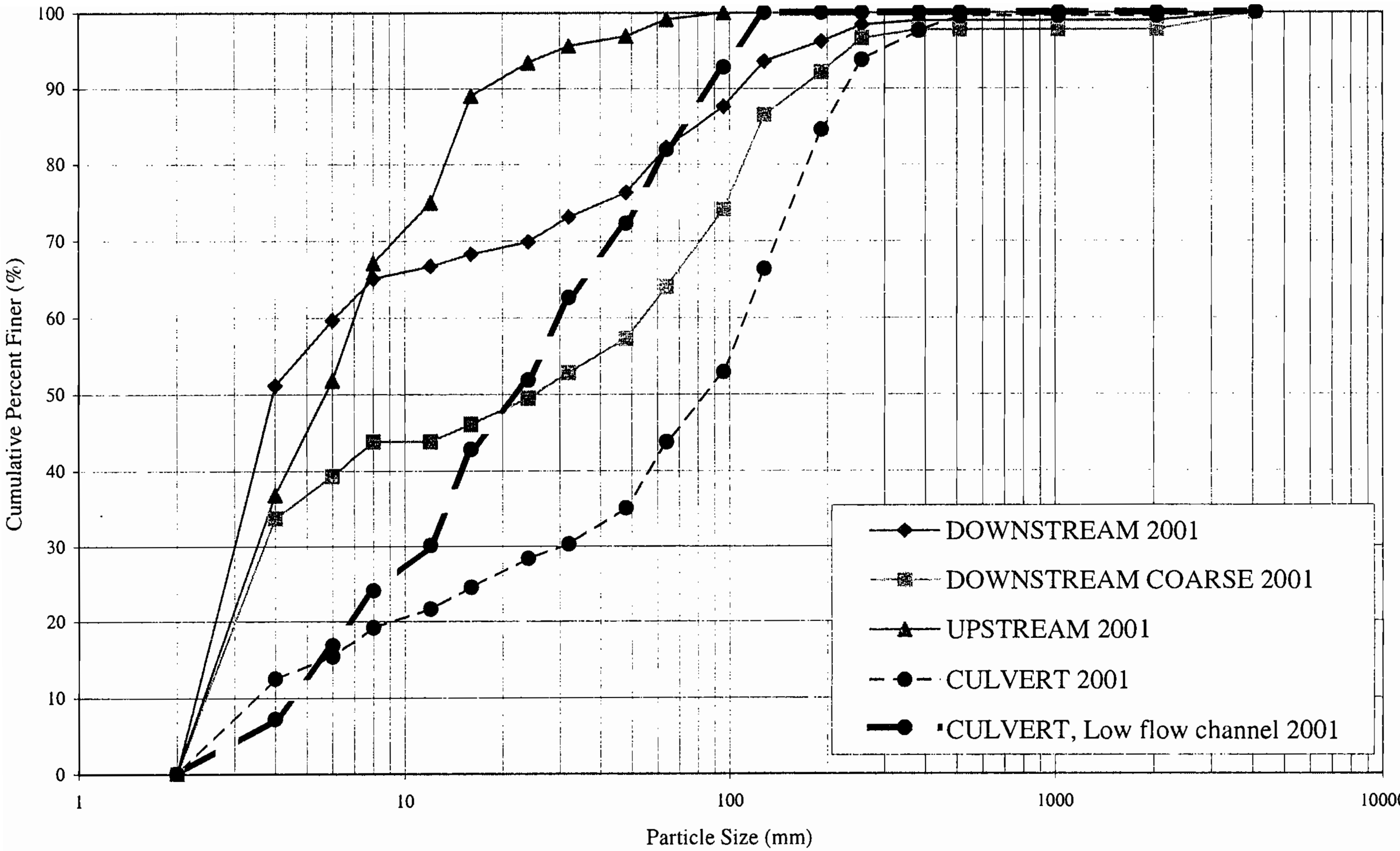


Figure 57. North Fork Silver Creek: Pebble count 2001.

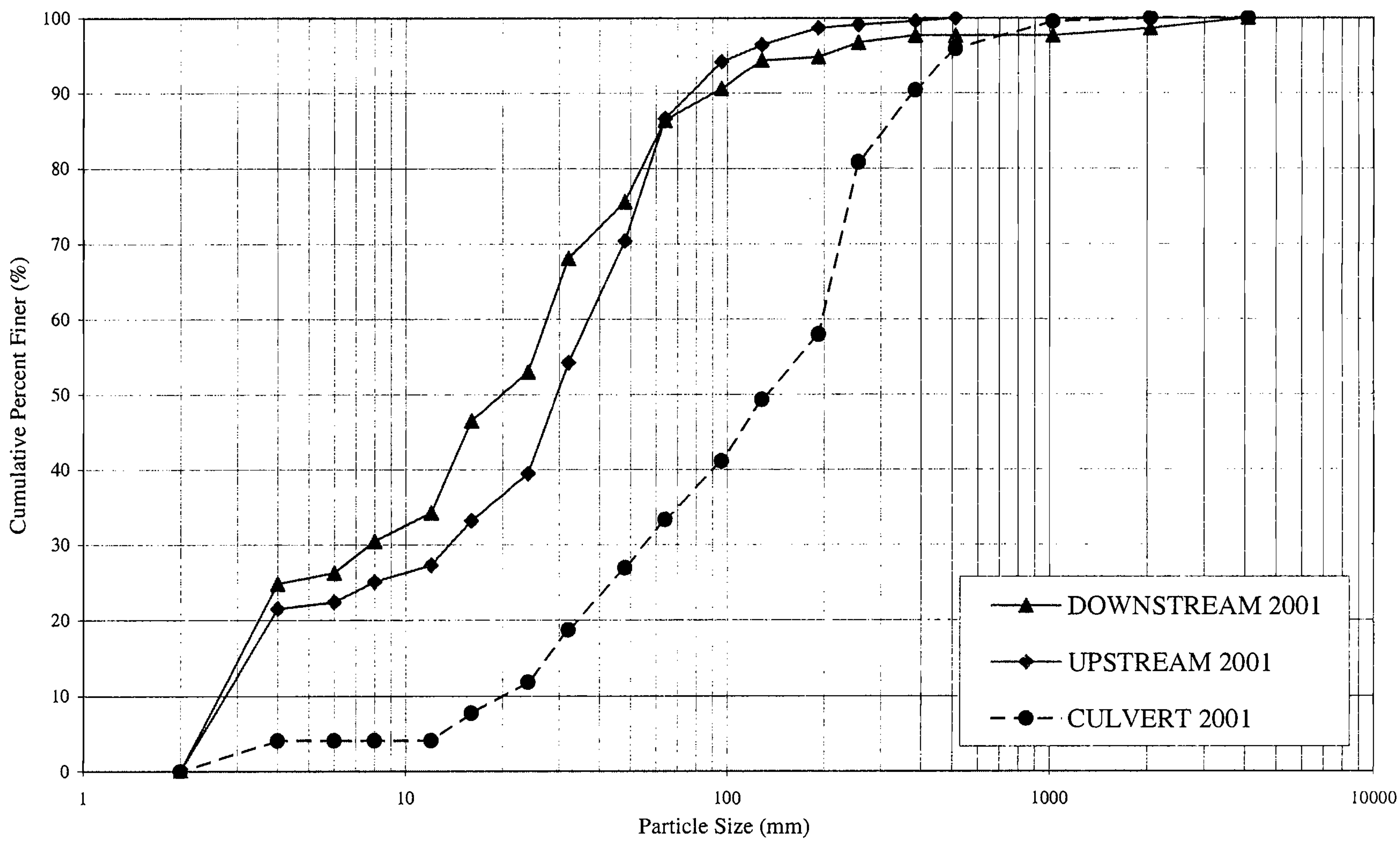


Figure 58. West Fork Silver Creek: Pebble count 2001.

Although the bed material in the culverts was larger than that of the respective streams, the bed material in the low flow channels of North Fork Silver Creek and Guyer Creek more closely reflected that of the stream. The coarser elements of both sites were more similar to the stream but the finer material that was available in the stream was not available in the culvert. At Guyer Creek the low flow channel exhibited the same distribution as the downstream reach at approximately D_{60} and continues along the same distribution of the upstream reach at approximately D_{80}. The North Fork Silver Creek distribution of the low flow channel exhibited the same distribution as the downstream reach at approximately D_{75}. The flow during spring snowmelt did not experience the roughness elements from the entire culvert, but rather, the roughness generated from the low flow channel.

The material in the culverts followed guideline recommendations of creating streambed stability through the use of coarse streambed material (WDFW, 1999) and reflecting the stream roughness characteristics of the natural stream with the material of the low flow channel (Pyles, 2000a). Cobble and boulder sized material characterize the large substrate of the high flow channel and should promote streambed stability within the culvert. The low flow channel lacked the very fine material of the natural stream but generally reflected the roughness found in the natural stream. However, the appropriateness of the streambed material was not sufficiently tested during a significant flood event. Analysis of the streambed material in the culverts of these study sites merits further review after one or several sediment transporting flood events.

The streambed material is an important factor in the success of stream simulation culverts due to the link streambed material has to velocity and refuge it creates for fish. A complete lack of streambed material would constitute the failure of a stream simulation culvert. However, the comparison between the material in the stream and in the culvert is difficult to quantify. Furthermore, the design guidelines suggest larger material to retain channel bed stability (WDFW, 1999; Robison et al., 1999; Poulin and Argent, 1997), but natural channel roughness is a stream condition we can simulate in stream simulation culverts (Pyles, 2000b). This study did not address this contradiction in design guidelines but the contradiction merits further research in this area. Due to the complications associated with what sized material is proper for these designs, the streambed material is not a preferred metric.

Riffle characteristics

The preceding analyses of stream and culvert comparisons have been largely confined to viewing the data as individual points. In an effort to evaluate the data by habitat unit types, contiguous riffle measurements were grouped together. The grouping was made up of two or more neighboring measured points that were classified as riffle habitat unit types. For each riffle, the average of the thalweg average velocities and the length were calculated. At all of the sites, the riffle habitat unit in the culvert was approximately double the length of the longest riffle habitat unit in the natural stream. A frequency distribution of the lengths of the riffles for all three study sites shows the lengths of the three culverts occur at the extreme right of the distribution (Figures 59).

Work done is a common calculation that considers a force exerted over a distance. Thus, a metric was generated to review both the length of an individual riffle unit and how fast the water was moving in that riffle. While Behlke et al. (1991) highlights various forces, such as profile drag, gradient force, and virtual mass force, which fish of various species and sizes must overcome to move through a culvert, a relatively simplified approach was used to calculate the work done. The profile drag was considered first and is defined by analytical methods for a fish

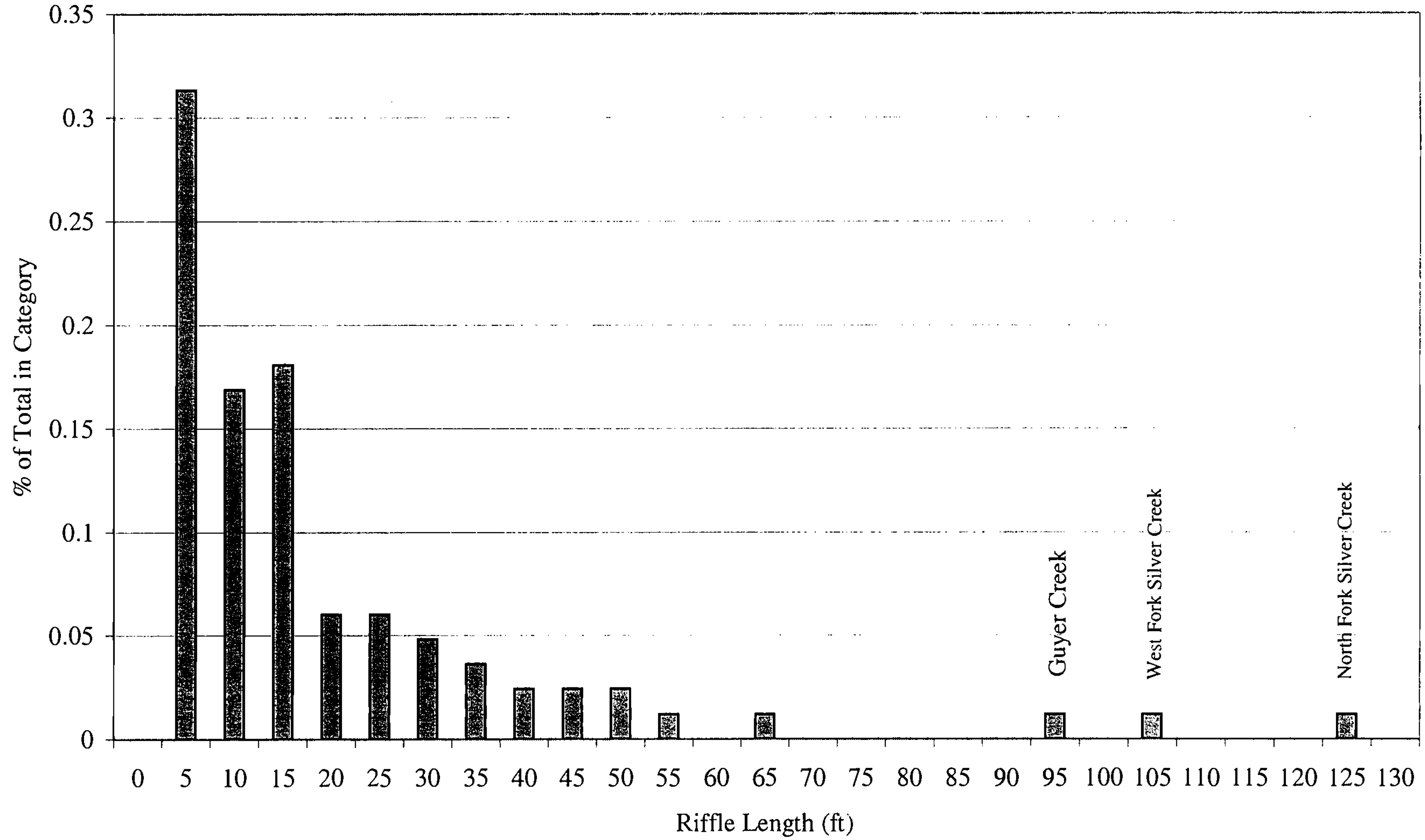


Figure 59. All sites: Distribution of riffle length.

that swims within a turbulent boundary layer (Behlke et al., 1991). The profile drag can be expressed as

$$F_D = \frac{C_D * \rho * S * V_{fw}^2}{2}$$

where C_d is a profile drag coefficient, ρ is the mass density of water, S is the surface area of the fish, and V_{fw} is the swimming velocity of the fish with respect to the surrounding water. The profile drag coefficient and surface area of the fish are functions of swimming condition and fish type, which would be relatively constant for this analysis. Therefore, the force calculated from profile drag can be considered proportional to velocity squared. Therefore, the square of the average of the thalweg average velocity multiplied by the length of the riffle was proportional to the work done for each riffle.

$$Proportional\ Work\ done = V_{avg}^2 * L$$

Where V_{avg} is the average of the thalweg average velocity of the riffle habitat unit and L is the total length of the riffle habitat unit. A frequency distribution of the work done calculations again exhibited relatively large values associated with the culverts (Figure 60). The riffle habitat unit in the culvert yields work done values that were generally twice as large as the next highest work done value associated with riffles in the natural streams at all three sites. This method of calculating work done assumed that the average of the thalweg average velocities was nearly equal to individual thalweg average velocity measurements.

Another way to calculate the work done without assuming the average was nearly equal to the individual measurements of velocity, would be to square each

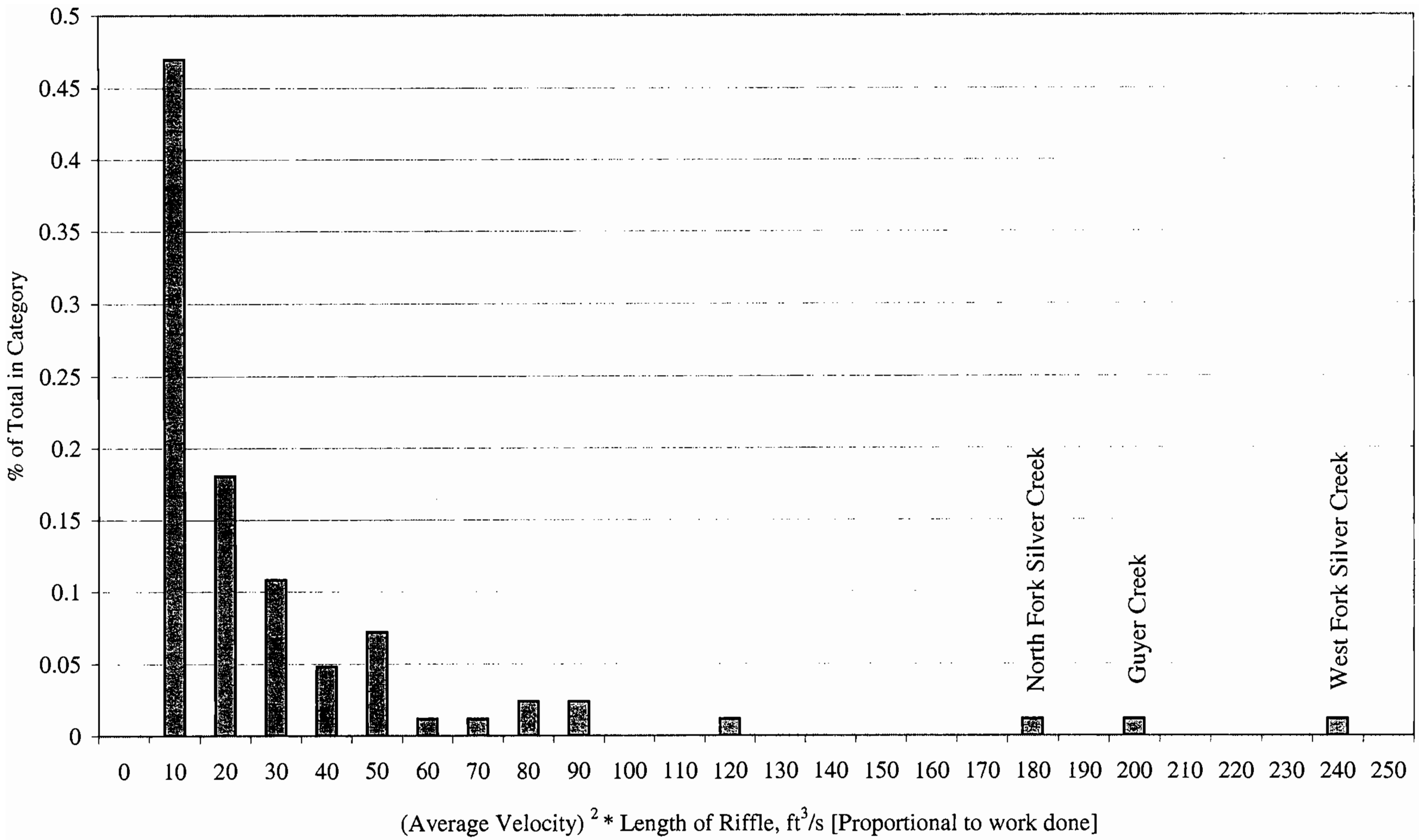


Figure 60. All data: Work done distribution

average thalweg velocity measured through the length of the riffle and multiply it by the length it represented.

$$\textit{Proportional Work done} = \sum_{i=1}^{n} V_i^2 * L_i$$

Where V_i is the velocity at riffle point measurement and L_i is the length of riffle the corresponding velocity represents. Each squared velocity multiplied by the length is then added up for each contiguous riffle and proportional to the work done.

The culvert riffles were on the order of twice as long as the next longest riffle in each of the studied streams. The length of the riffle dominated the work done to get through the riffle. Therefore, to more closely reflect the distribution of stream riffle lengths, the riffle length in the culvert would need to be shortened. While it is not expected that alternating riffles and pools will be generated from large wood inside of the culverts, overtime the bed form structure may adjust as sediment transporting flows occur. The addition of bed form structure within the culvert should allow for a breaking up of the extremely long riffle that currently exists inside of the culverts. The work done values between the culvert and the stream may become more similar with a shortened riffle length inside of the culvert.

The use of work done as a metric for the success or failure of a stream simulation culvert may be adequate with some modifications. The work done combines the length and the degree of difficulty of passage into one metric. To better reflect the condition a fish encounters, resting areas along the edges of the channel should be quantified within the riffles. For example, currently the culvert is a long riffle but there is refuge at the edges of the channel. This modification will complicate the calculation but may better reflect the situation.

Channel stability

Little movement of the bed material occurred during the study season due to limited high flow. Limit to the bed movement during one study season does not mean the sediment within the culvert lacks the conditions to move bed material, it simply lacked the discharge to move the material during this particular study season. The limited sediment transport that occurred during this study highlights the need for further review of these culverts after one or several sediment transporting discharge events occur.

Scour chains

The change detected in the bed material with the scour chains of both the newly installed culverts and the natural stream was limited. Overall, 8% (8 of 97) of the chains exhibited detectable scour, with only 2% (1 of 44) inside of the three culverts exhibited detectable scour. At the same time, the fill that was measured inside of the three culverts ranged from less than 0.1 ft to 0.4 ft.

The data gathered from the scour chains did not allow for meaningful comparisons between the sediment transport that occurred in the culvert and in the natural stream due to limited movement in both locations.

Painted rocks

The painted rocks that were placed into the high flow channel of barrel of the culverts did not exhibit detectable location changes.

The painted rocks showed no measurable movement from their original locations, nor did the digital terrain model (DTM) show evidence of lateral migration of the low flow channels. This was partly due to the lack of high flows but also due to the placement of the painted rocks. The majority of the rocks were placed outside of the low flow channel in an effort to monitor the changes in the form of the low flow channel during high flow. The discharge during the study season did not move the material in the high flow zone of the West Fork Silver Creek culvert and it did not inundate the high flow zones in North Fork Silver Creek and Guyer Creek.

Digital terrain model

The repeated elevation survey of the pipe and immediate vicinity exhibited some measurable changes in the bed material vertically but showed no detectable change laterally. The shape of the channel, based on an inspection of the survey data, did not appear to have been detectably altered at any of the culverts. However, vertical changes were most notable at the West Fork Silver Creek culvert where 90% of the points measured experienced scour to some extent. Where scour was measured, 86% of the surveyed points were scoured less than 0.6 ft in depth. The culverts at Guyer Creek and North Fork Silver Creek, on average show less than 0.1 ft change in elevation throughout the culvert. There was nearly equal distribution between points that exhibited measurable scour, fill, and no change at these two sites.

The approach into the North Fork Silver Creek culvert showed marked scour in the bed elevation but limited lateral movement. The comparison between the bed surface from 2000 to 2001 was completed for the approach into the North Fork Silver Creek culvert and showed that 92% of the points were scoured and approximately 66% of those points were between one and two feet of scour. The approach of the culvert is expected to downcut over time as the slope of the stream comes to equilibrium with the newly placed culvert. The material that the stream is downcutting through appears to be deposition due to the old culvert being placed high in the road fill.

Vertical change in the streambed occurred at the West Fork Silver Creek culvert and the approach to the inlet of the North Fork Silver Creek culvert. However, the scour chains did not exhibit the change that was captured in the digital terrain model (DTM) study. The scour chains were located at 14 to 16 locations in each culvert while the digital terrain modeling exercise generated over 1000 points at each site. The accuracy of the scour chains depends on the retrieval procedure, a lack of tampering with the chains between their implementation and retrieval, and size of chain links used. The retrieval procedure at each site was consistent and the links were 0.1 ft long. However, several of the chains were pulled out of the streambed by people prior to retrieval and were either replaced prior to winter 2000/2001 or they were lost if not discovered prior to winter 2000/2001. The accuracy of the DTM, on the other hand, was a function of consistency between each year as to how the points were collected and the pre-determined resolution of the survey, which in this case was 0.5 ft. The points were collected in as consistent a manner as possible between the two years. The change discovered via use of the DTM is not extreme and accurately reflected the limited changes that occurred at the culverts at Guyer Creek and North Fork Silver Creek. The scour chains appeared to reflect localized change while the DTM allowed for a generalized view of streambed change.

The painted rocks, scour chains and benchmarks related to the DTM survey remain at each study site. The long-term channel stability story and/or channel stability response to a large flood event at these study sites should be monitored and reported.

Individual sites

Continued monitoring of each of these sites is imperative to further understand the mechanisms behind their behavior. This detailed review of the installations after one minor spring flow while the culverts are essentially in their infancy allowed us some insight into their behavior and design but long-term review and analysis is crucial. Hopefully, the culverts will remain as fish passage structures for the duration of their design life, approximately four to five decades.

Guyer Creek

The comparisons indicated that the velocities of the culvert at Guyer Creek were significantly greater than the natural stream. If the longitudinal thalweg velocity and the cross-sectional velocity were used as metrics to determine success or failure at Guyer Creek, the site would be considered a failure. Each of the culverts was designed in essentially identical fashions, they were in the same watershed, and were characterized by the same land management, vegetation, and soil. The watershed area at this site was intermediate for the three sites studied. The slope of the longitudinal profile of Guyer Creek and the slope of the culvert were consistent with each other. Aside from the determination of the culvert width, the design posed no special challenges. As it turns out, the construction of the low flow channel was too narrow and the side slopes of the channel were too steep.

The best estimation of the reason behind the difference between the culvert and the stream at Guyer Creek was a combination of low flow channel design and backwater effect. The average wetted width was nearly three feet narrower and the maximum depth of the riffles was similar to that of the stream. In addition, the flow did not overtop the low flow channel during spring snowmelt of 2001 at Guyer Creek. The higher velocities in the Guyer Creek culvert were necessary in order to make up for the lack of wetted width when moving the same discharge through the culvert and the stream. The culvert at Guyer Creek had a minor backwater effect at the outlet of the culvert, which may contribute to limited lower velocities in the culvert. On the other hand, it is also possible that a difference between the culvert and the stream would have persisted even if the low flow channel widths were similar.

The culvert at Guyer Creek, like all of the study sites, was in a post-construction state. It is possible that the channel inside of the culvert will adjust with time or be manually modified and may become more similar to the natural stream with respect to thalweg velocities and channel characteristics.

North Fork Silver Creek

Overall, the culvert at North Fork Silver Creek was found to be statistically similar to the riffles in the stream for thalweg velocity comparisons and the majority of the channel shape comparisons. If the longitudinal thalweg velocity and the cross-sectional velocity were used as metrics to determine success or failure at North Fork Silver Creek, the site would be considered a success.

The flow did not overtop the low flow channel during spring snowmelt of 2001 at North Fork Silver Creek. However, the North Fork Silver Creek culvert wetted width was only 0.8 ft narrower than the stream. The comparison indicated that width-to-depth ratio of the culvert and the stream was significantly similar. The comparison of the thalweg average velocities of the culvert and the natural stream was statistically similar. The analysis of the cross-sectional area with velocity less than 1 ft/s in the middle section of the culvert was statistically similar to the selected section of the stream. The culvert velocity distribution was more uniform than that of the stream and did not exhibit the extreme high or extreme low velocities found in the stream.

A key element in the future success of this culvert is the stabilization of the slope through the culvert and its vicinity. This depends upon the downcutting of the approach to the inlet, which occurred on a limited basis this year. The further downcutting of the approach is expected to occur with time and sediment transporting discharge events.

West Fork Silver Creek

The similarities between the culvert and the stream in nearly all of the categories might be attributed to the low flow channel being inundated during high flow. The comparison indicated that the widths of the culvert and natural stream were similar. The artificial backwater structure created deeper maximum depths in the culvert than in the stream. If the longitudinal thalweg velocity and the cross-sectional velocity were used as metrics to determine success or failure at West Fork Silver Creek, the site would be considered a success with respect to fish passage.

Conclusions and Recommendations

Conclusions

Three culverts were replaced with stream simulation culverts in south central Oregon. This study reviewed the hydraulics, as they are understood to pertain to fish passage, of stream simulation culverts. Conclusions of this study can be drawn regarding the design of stream simulation culverts, the review of the study sites, and the use of several metrics in order to determine success or failure of culverts.

The current guidelines available for stream simulation culvert design were insufficient for the design of the culverts designed for this project. Local conditions forced the design beyond the recommendations of the guidelines with respect to the backfill material size and the design width of the culvert.

The analysis of the stream simulation designed culverts in this study looked at a snapshot in time of each site. All three of the culverts showed marked improvement over the old culverts both quantitatively, with respect to the average cross-sectional velocity and qualitatively. All three of the culverts satisfied the regulatory criteria for fish passage. The comparisons at two of the culvert sites were statistically similar to those physical features of a natural stream they were designed to simulate in the majority of comparison categories. However, one of these culverts was designed with an artificial backwater condition with a weir at the outlet. The comparisons of the physical features at the third culvert site were statistically different from the natural stream in the majority of comparison categories. The narrow width and steep side slopes of the low flow channel appeared to be the driving factor behind the differences between stream and culvert characteristics at this site.

Longitudinal thalweg velocity, cross-sectional velocity, and thalweg velocity distribution were the most appropriate metrics explored. The data for these metrics can be easily obtained, statistically compared, and the comparisons appear to be reasonable with respect to their affect on fish passage. The calculation of work done necessary to pass through the culvert would be a strong metric with modifications.

Unfortunately, the snapshot of each study site was taken after one of the driest winters on record, which resulted in limited spring snowmelt discharge. Little movement of the streambed material occurred during spring snowmelt to create bed form structure within the culverts and the culverts remained in essentially a post-construction state. The lack of change in the streambed structure and a need for more long-term testing of streambed stability calls for further review of these sites after one or several substantial high flow events.

Recommendations

Further research

The sizing of the bed material and the determination of the invert elevation of the culvert merits further research. The debate between whether streambed stability is at risk with material sized to the natural stream versus whether over-sized streambed material allows for natural fluctuation within the culvert to the extent necessary for streambed simulation. The details and answers to this debate remain and merit further investigated.

The vertical placement of the culvert should be an integral element in the design of stream simulation culverts. The use of the longitudinal profile and the extent of scour in pools of the natural stream as a method to determine the invert elevation should be investigated at stream simulation culverts.

Channel design within culvert

If the design calls for backfilling of the culvert, a low flow channel should be placed inside of the culvert to avoid a splitting or dispersal of the discharge that may result in insufficient depth or an increased opportunity for subsurface flow. The low flow channel should be easily inundated in order to over-top its banks during high flow and should not confine the flow to a width that is less than the natural stream. A low flow channel with shallow sloped sides will further promote the flow through a wider cross-section. By placing the meander bends into the culvert, a limited amount of form friction may be added to the flow that would not be present otherwise.

In order to more closely reflect the distributions of the stream riffle lengths, the riffle length in the culvert would need to be shortened. Additional bed form structure could be designed into the bed of the culvert in order to allow for a breaking up of the riffle length. The design of this type of feature is beyond the scope of this project and has not yet been explored.

Construction

The culverts should be large enough to safely and efficiently use small-mechanized equipment to move backfill bed material.

Channel stability

The use of the digital terrain model (DTM) lent insight into the bed material changes that was not gleaned from the use of the scour chains. The DTM offered a broad, but seemingly accurate, view of the changes at each site due to the chosen resolution. The use of the DTM appeared to be more appropriate than the scour chains for the limited amount of movement that occurred during spring snowmelt of 2001. Moreover, a light wire that easily bends may be more appropriate than chain links to more accurately measure localized change with the scour chains.

Monitoring

Channel stability and hydraulic characteristics are the items of primary interest for continued monitoring at these sites. The longitudinal profile should be monitored to track the long-term variation in slope and channel stability. After one or several sediment transporting events a digital terrain model (DTM) should be created and compared to the 2001 model to monitor lateral movement of the low flow channel and vertical changes throughout the culvert and thalweg and cross-sectional velocity measurements should be re-examined.

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APPENDICES

APPENDIX A.

Cross-sectional velocity.

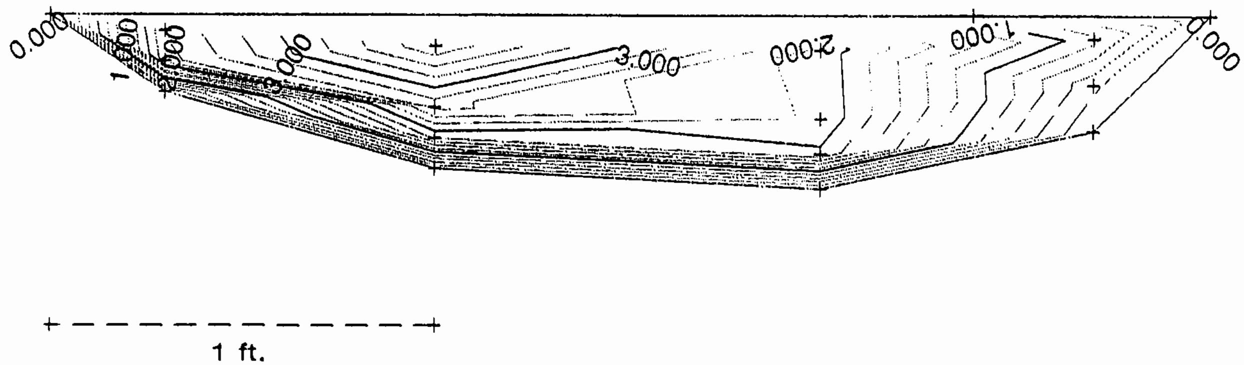


Figure A1. Guyer Creek: Culvert cross-section velocity (ft/s) (ft/s) at culvert reach 59.

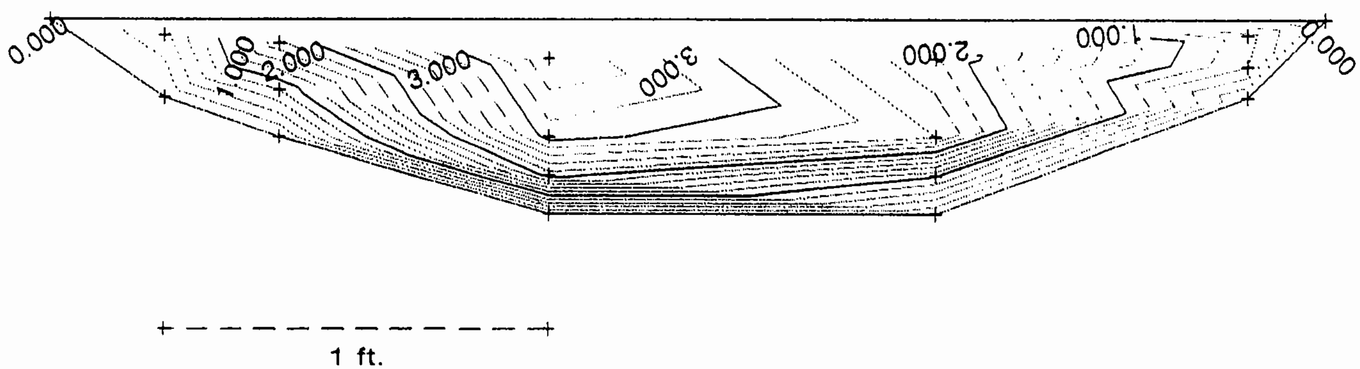


Figure A2. Guyer Creek: Culvert cross-section velocity (ft/s) at culvert reach 60.

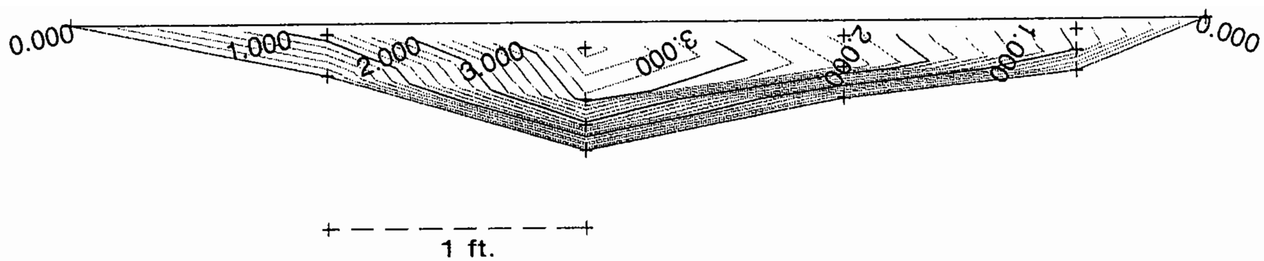


Figure A3. Guyer Creek: Culvert cross-section velocity (ft/s) at culvert reach 61.

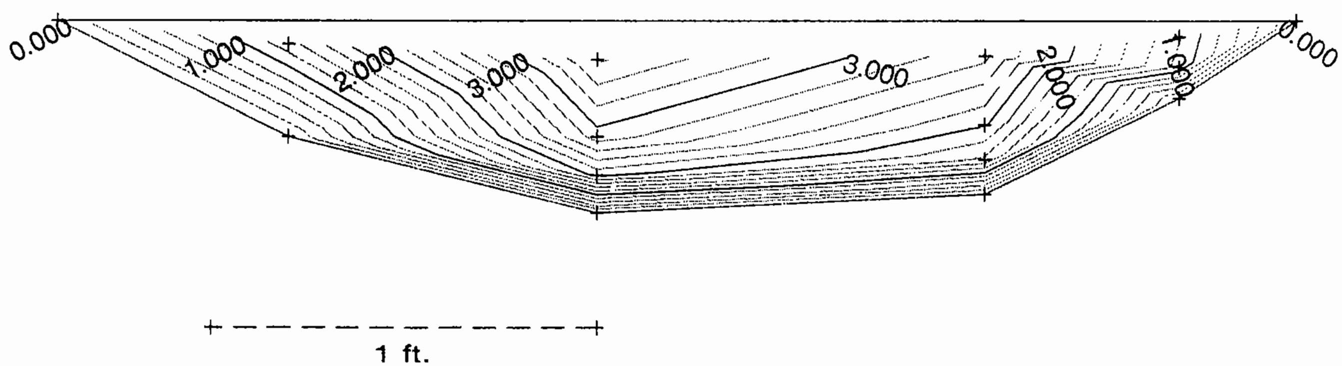


Figure A4. Guyer Creek: Culvert cross-section velocity (ft/s) at culvert reach 62.

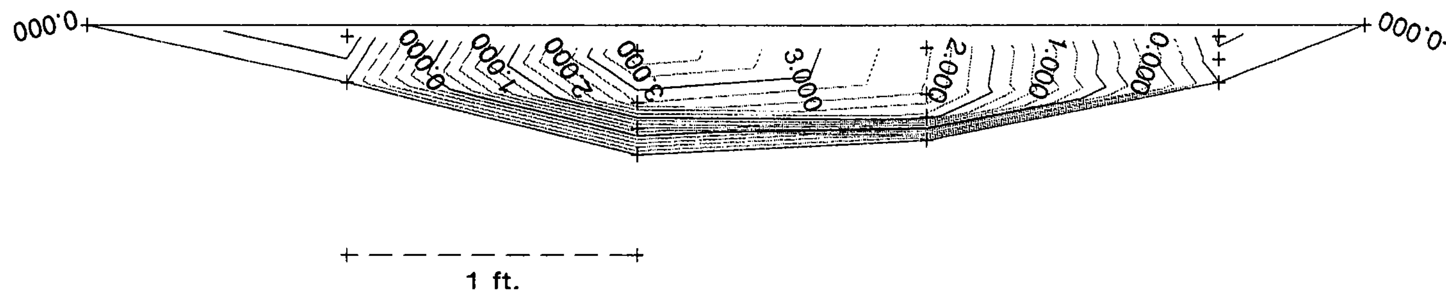


Figure A5. Guyer Creek: Culvert cross-section velocity (ft/s) at culvert reach 63.

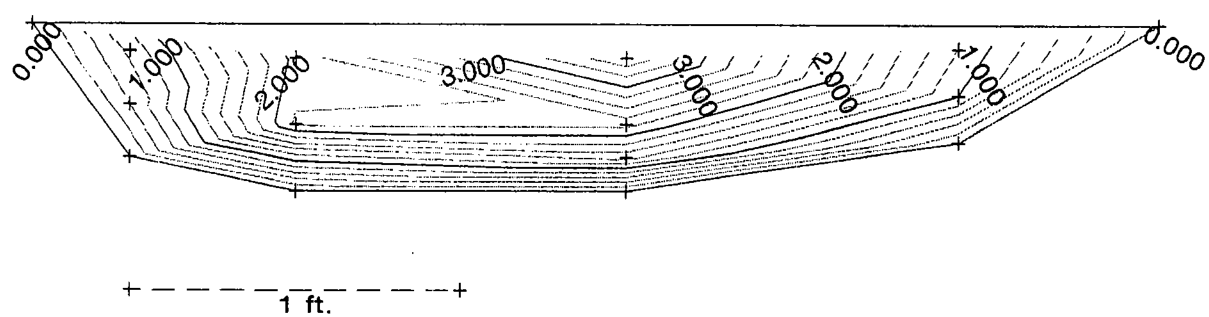


Figure A6. Guyer Creek: Culvert cross-section velocity (ft/s) at culvert reach 64.

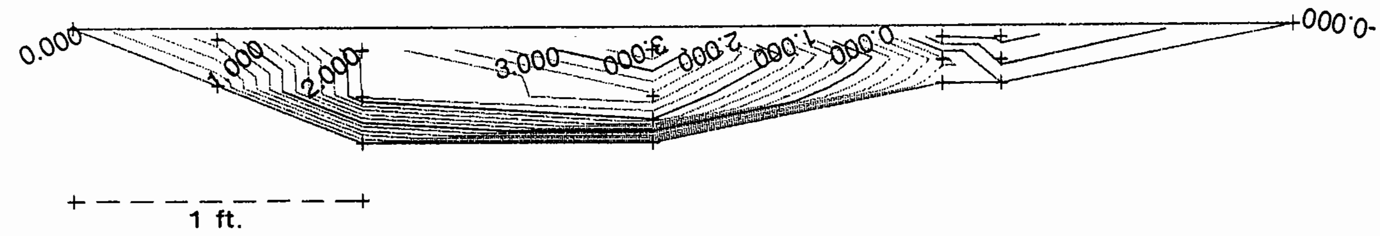


Figure A7. Guyer Creek: Culvert cross-section velocity (ft/s) at culvert reach 65.

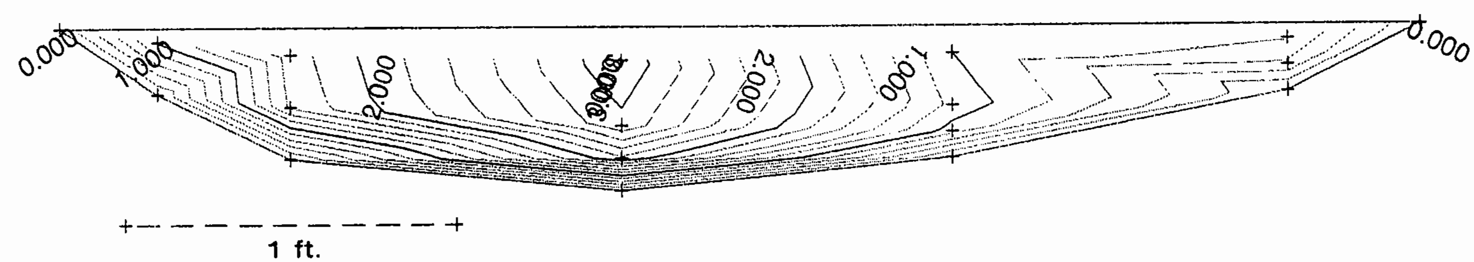


Figure A8. Guyer Creek: Culvert cross-section velocity (ft/s) at culvert reach 66.

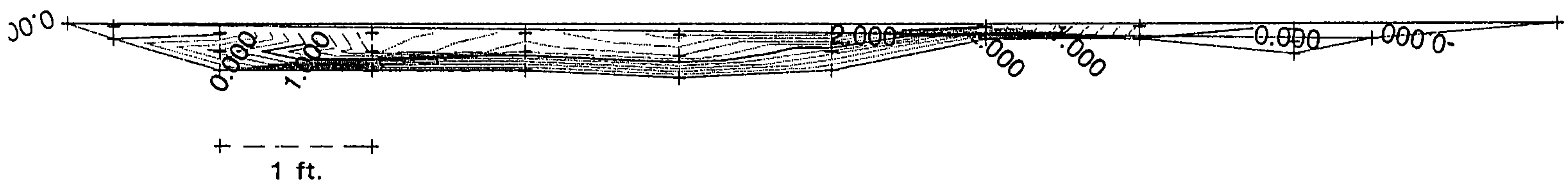


Figure A9. Guyer Creek: Natural stream cross-section velocity (ft/s) at upstream reach 78.

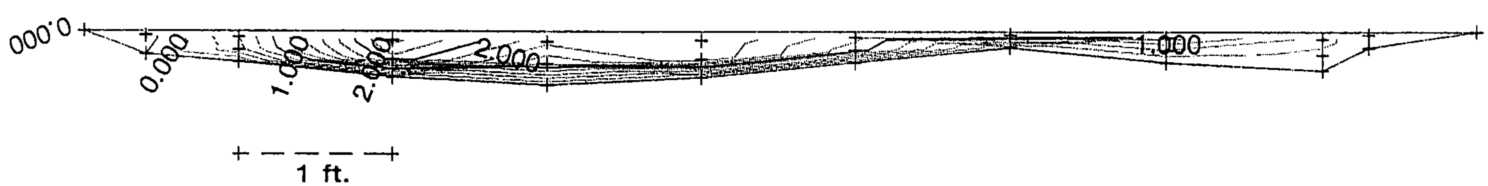


Figure A10. Guyer Creek: Natural stream cross-section velocity (ft/s) at upstream reach 79.

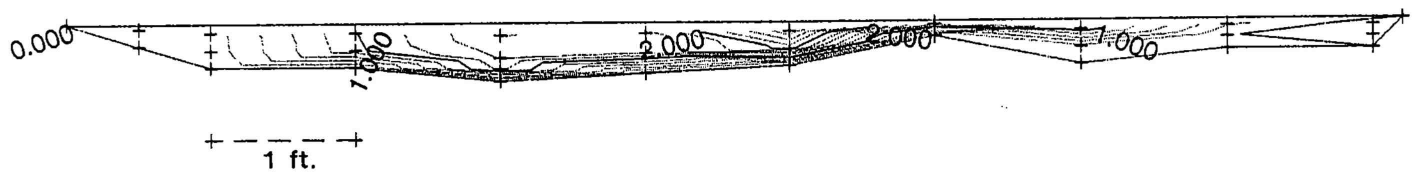


Figure A11. Guyer Creek: Natural stream cross-section velocity (ft/s) at upstream reach 80.

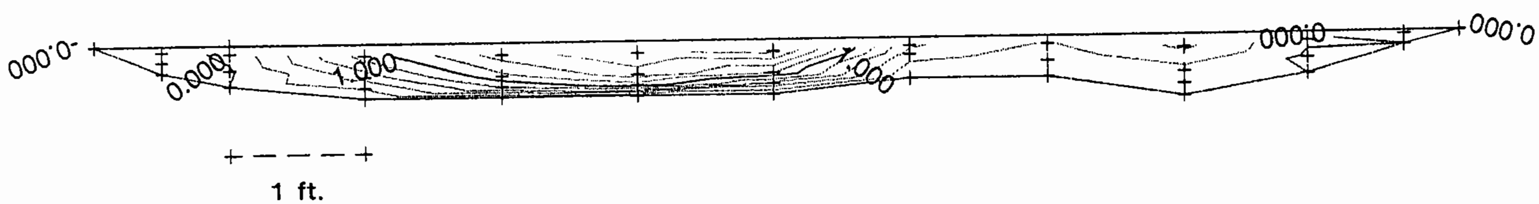


Figure A12. Guyer Creek: Natural stream cross-section velocity (ft/s) at upstream reach 81.

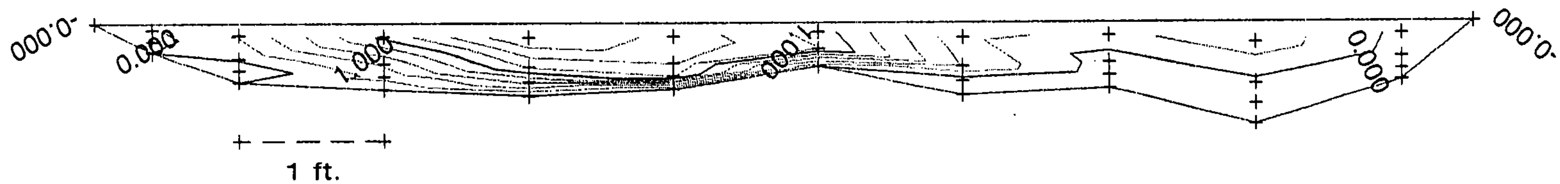


Figure A13. Guyer Creek: Natural stream cross-section velocity (ft/s) at upstream reach 82.

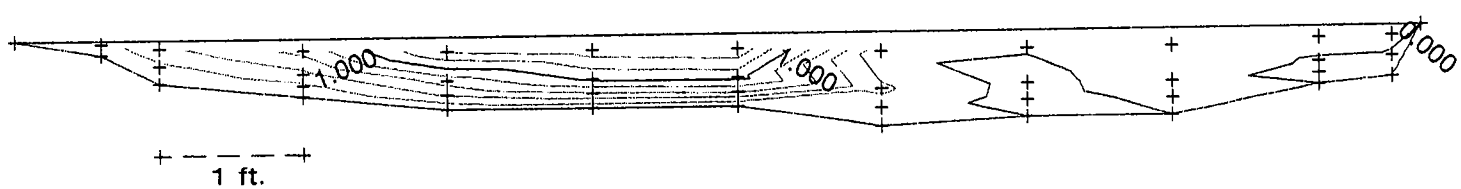


Figure A14. Guyer Creek: Natural stream cross-section velocity (ft/s) at upstream reach 83.

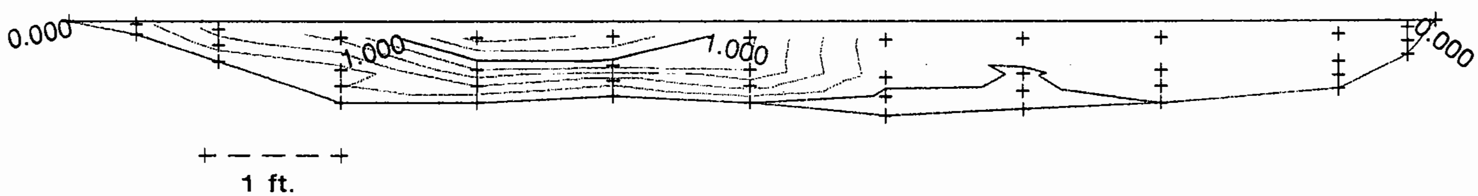


Figure A15. Guyer Creek: Natural stream cross-section velocity (ft/s) at upstream reach 84.

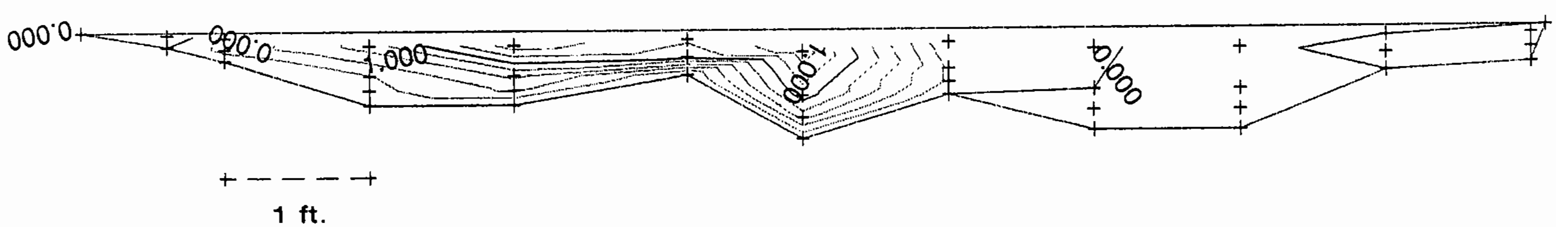


Figure A16. Guyer Creek: Natural stream cross-section velocity (ft/s) at upstream reach 85.

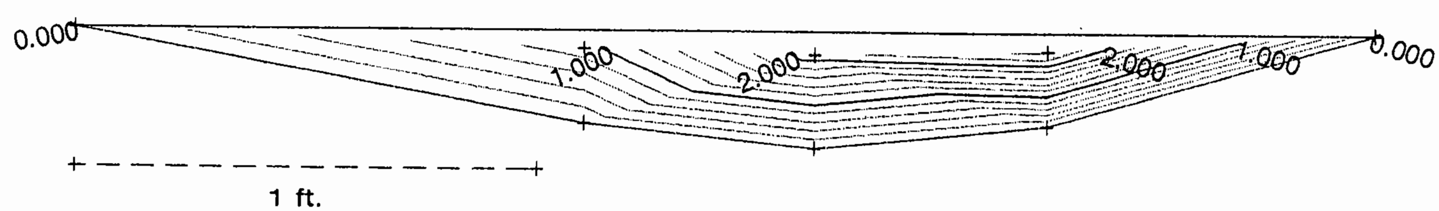


Figure A17. North Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 60.

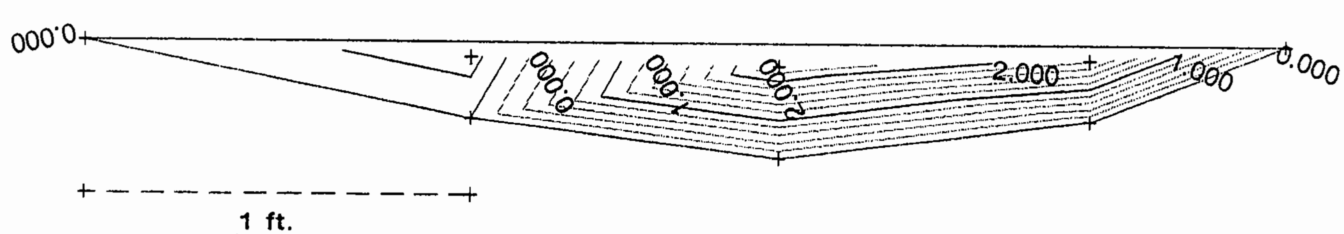


Figure A18. North Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 61.

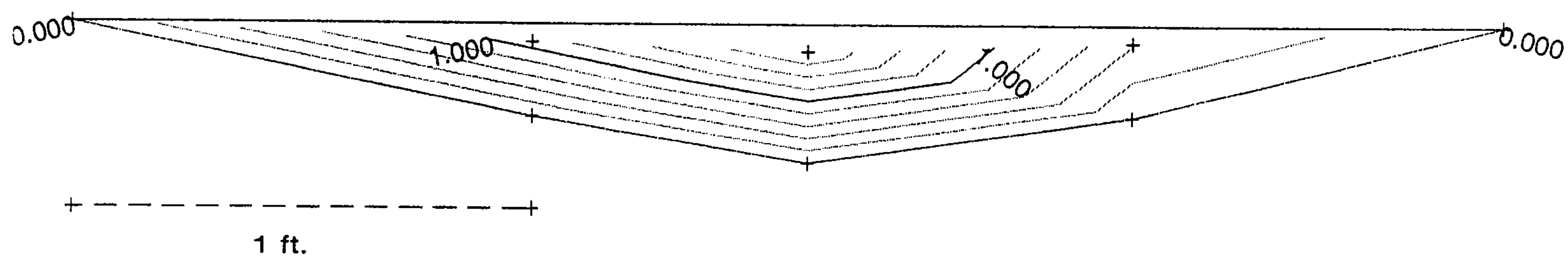


Figure A19. North Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 62.

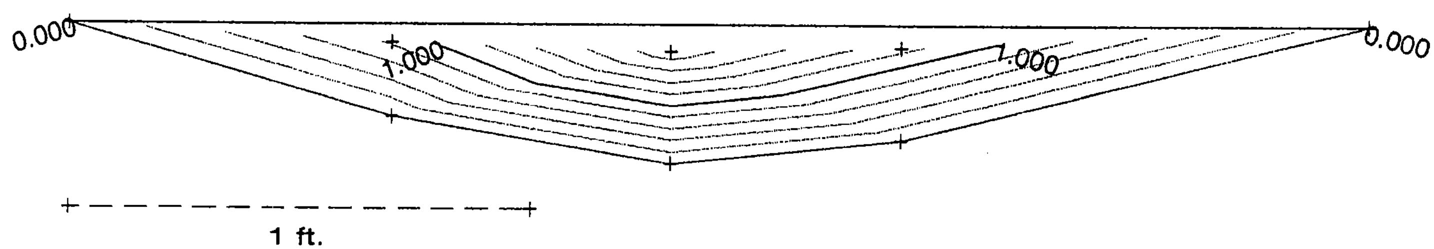


Figure A20. North Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 63.

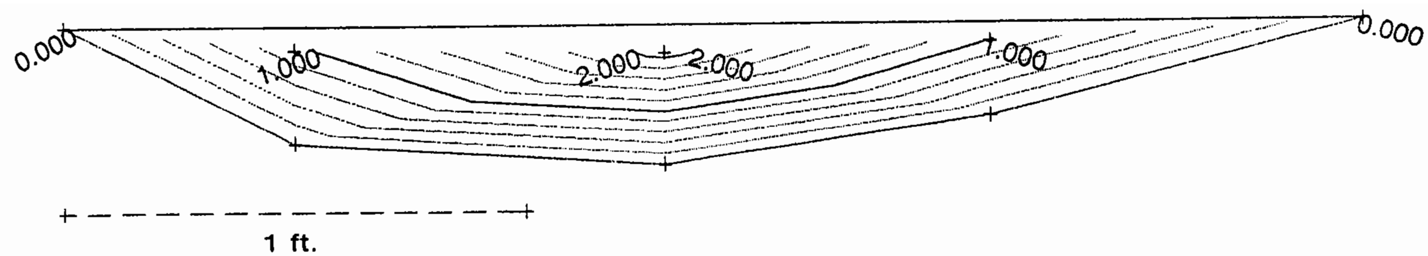


Figure A21. North Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 64.

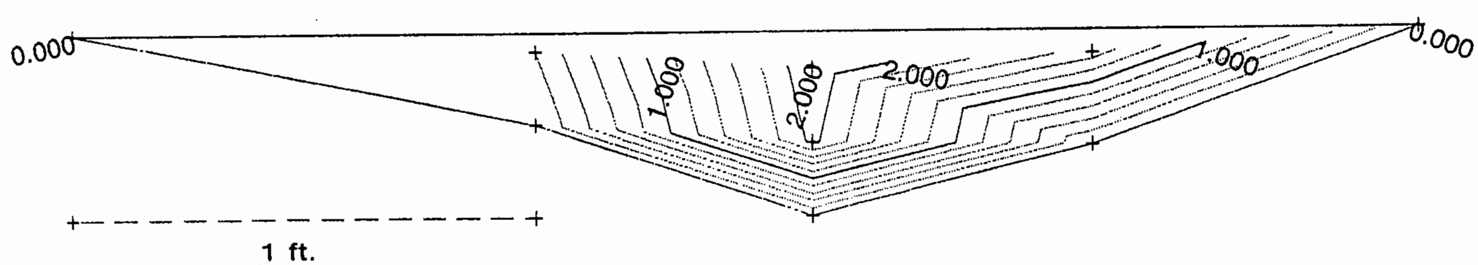


Figure A22. North Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 65.

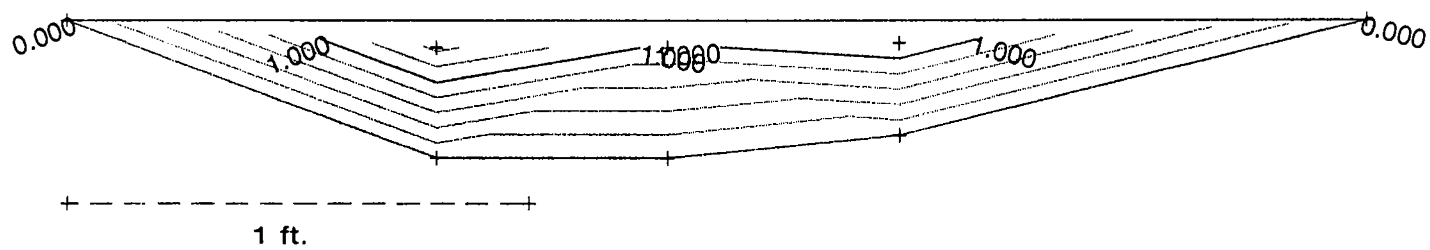


Figure A23. North Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 66.

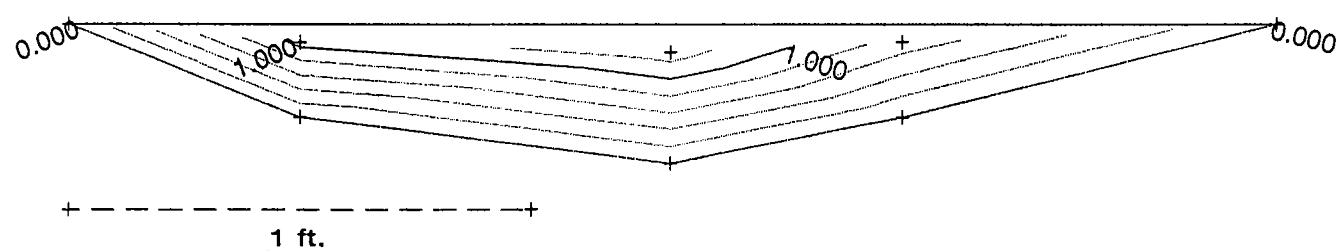


Figure A24. North Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 67.

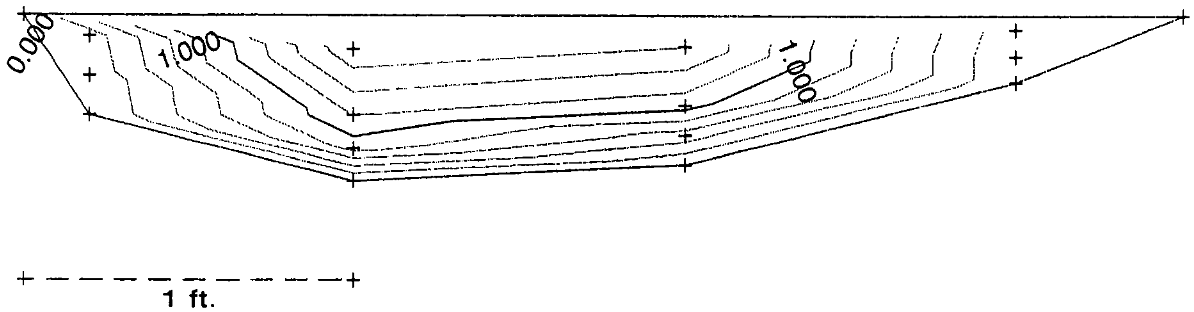
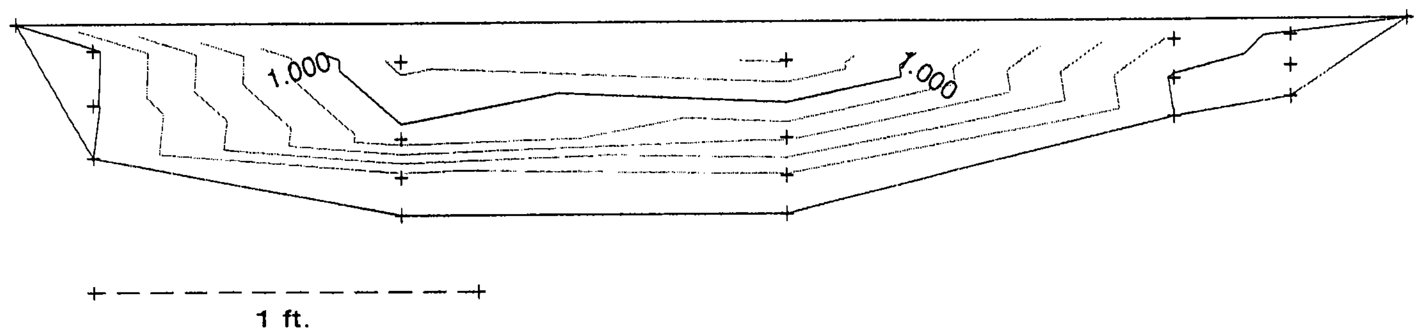


Figure A25. North Fork Silver Creek: Natural stream cross-section velocity (ft/s) at downstream reach 37.



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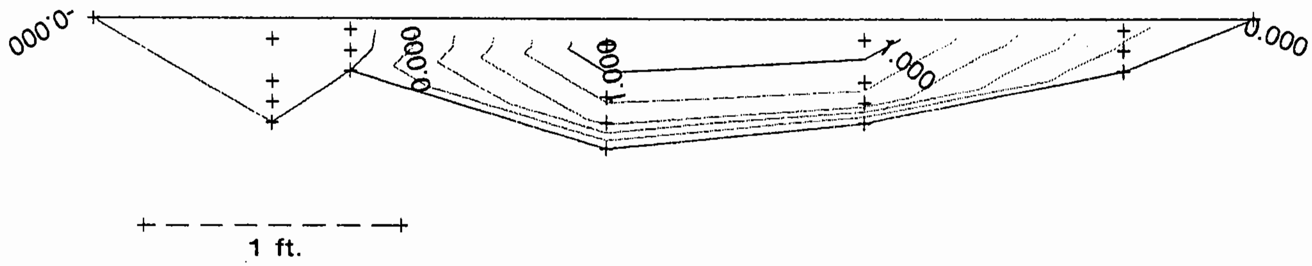

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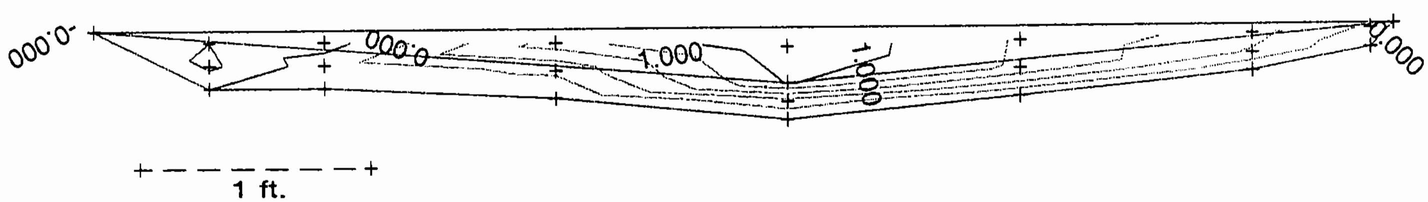
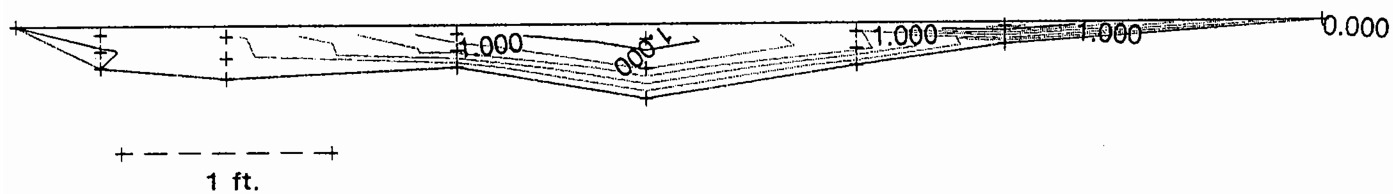


Figure A28. North Fork Silver Creek: Natural stream cross-section velocity (ft/s) at downstream reach 40.



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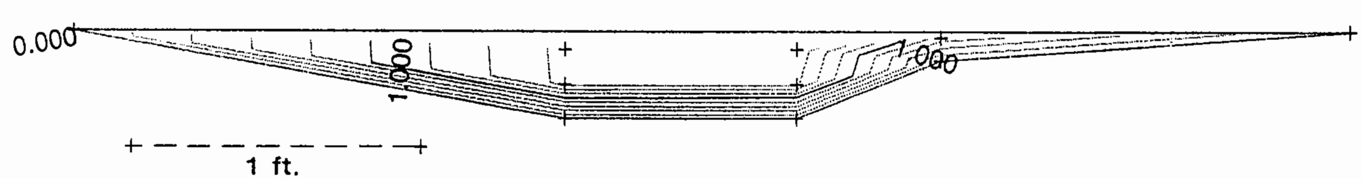

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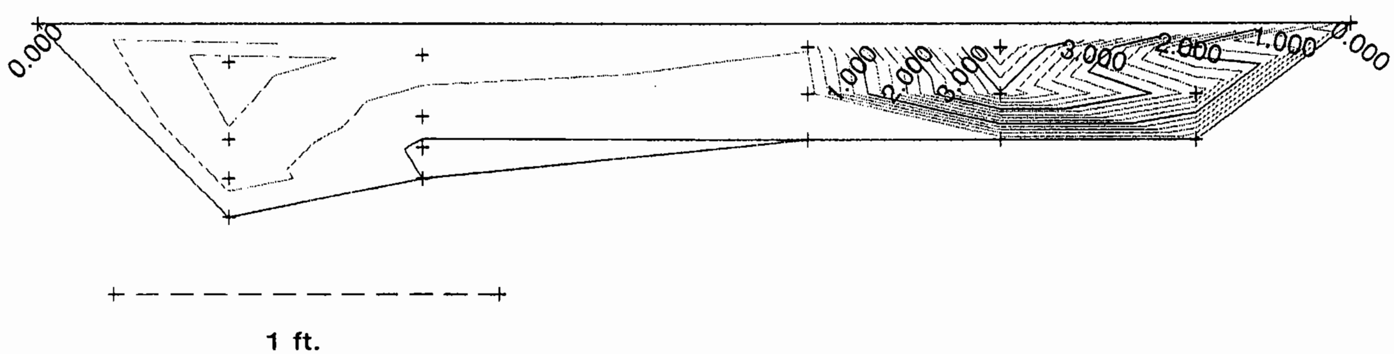

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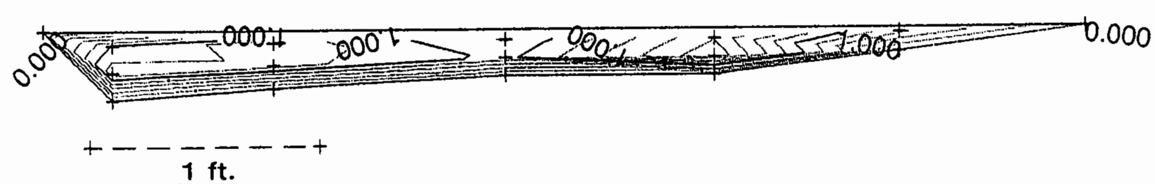

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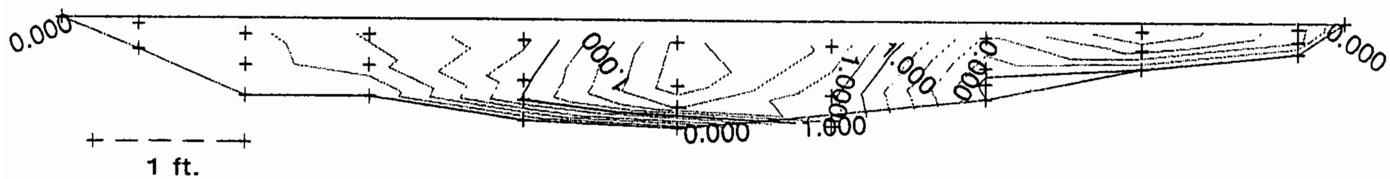

Figure A33. West Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 51.

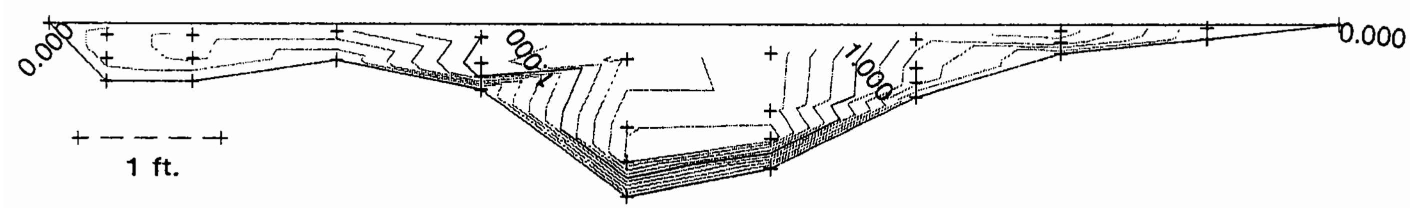

Figure A34. West Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 52.

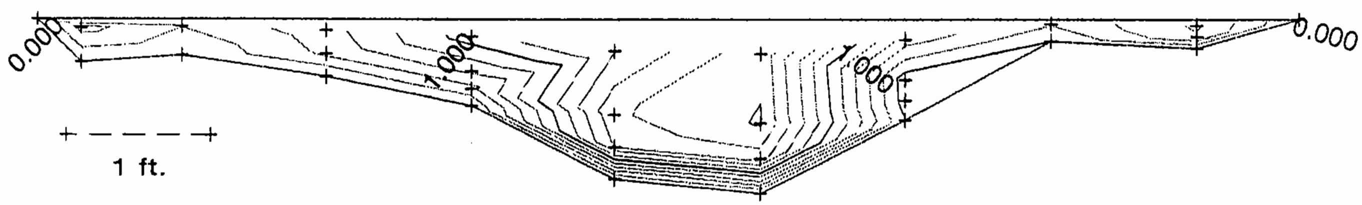

Figure A35. West Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 53.

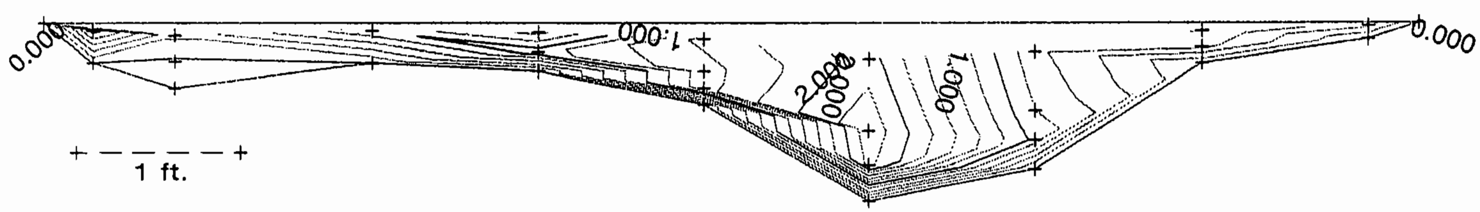

Figure A36. West Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 54.

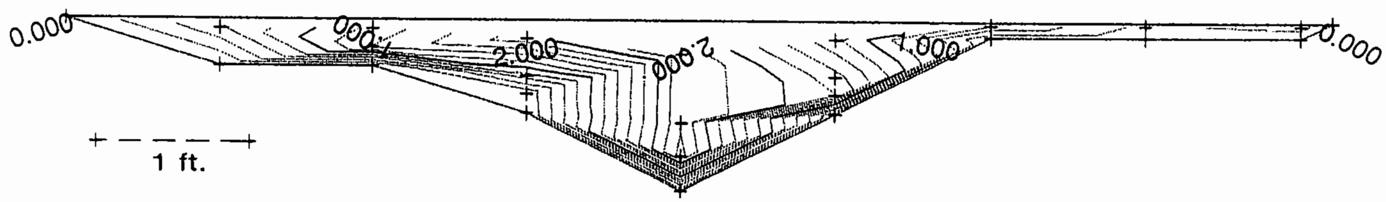

Figure A37. West Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 55.

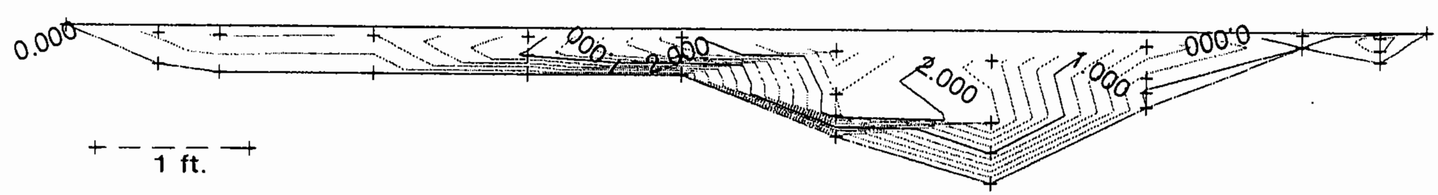

Figure A38. West Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 56.

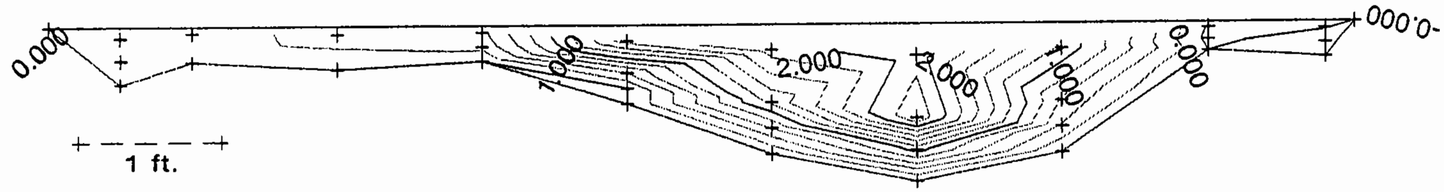

Figure A39. West Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 57.

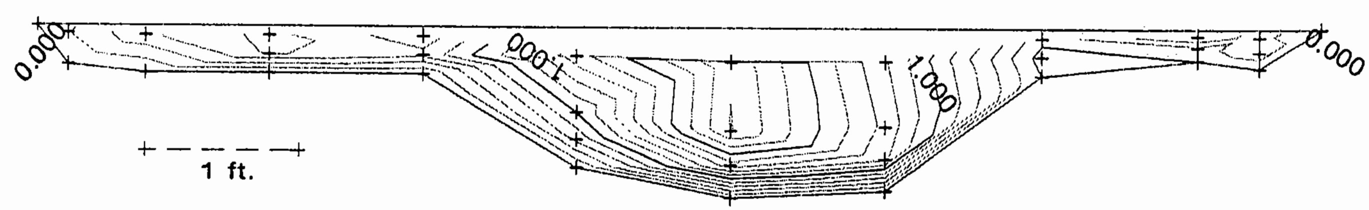

Figure A40. West Fork Silver Creek: Culvert cross-section velocity (ft/s) at culvert reach 58.

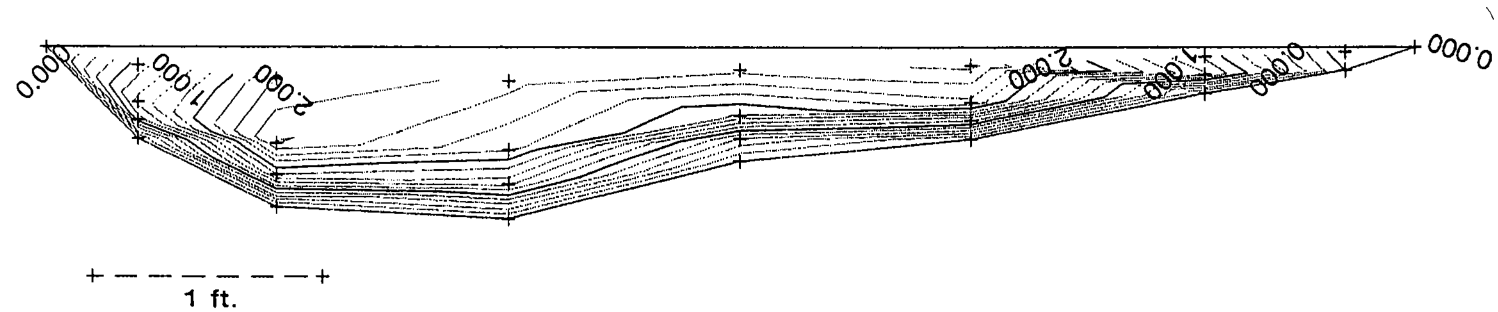

Figure A41. West Fork Silver Creek: Natural stream cross-section velocity (ft/s) at upstream reach 18.

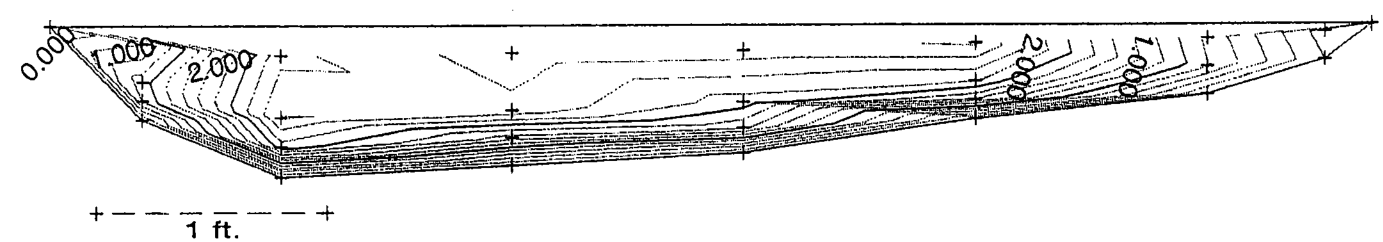

Figure A42. West Fork Silver Creek: Natural stream cross-section velocity (ft/s) at upstream reach 19.

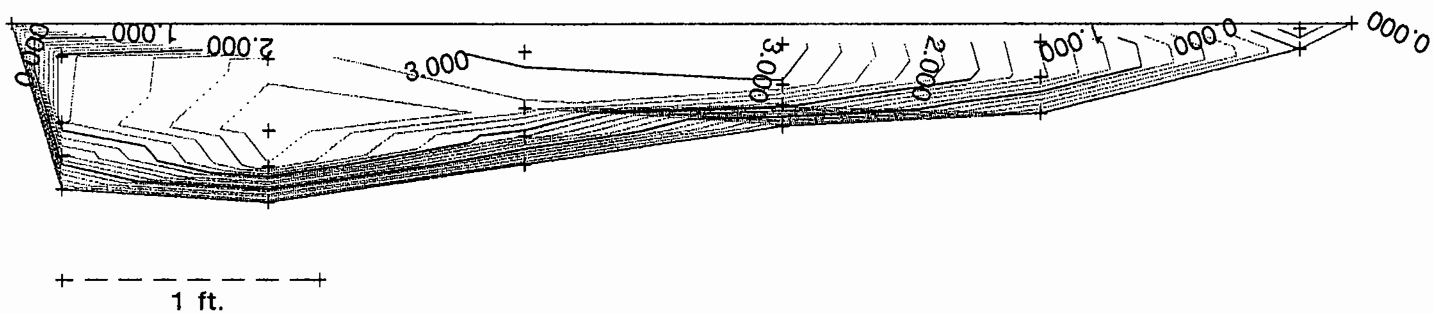

Figure A43. West Fork Silver Creek: Natural stream cross-section velocity (ft/s) at upstream reach 20.

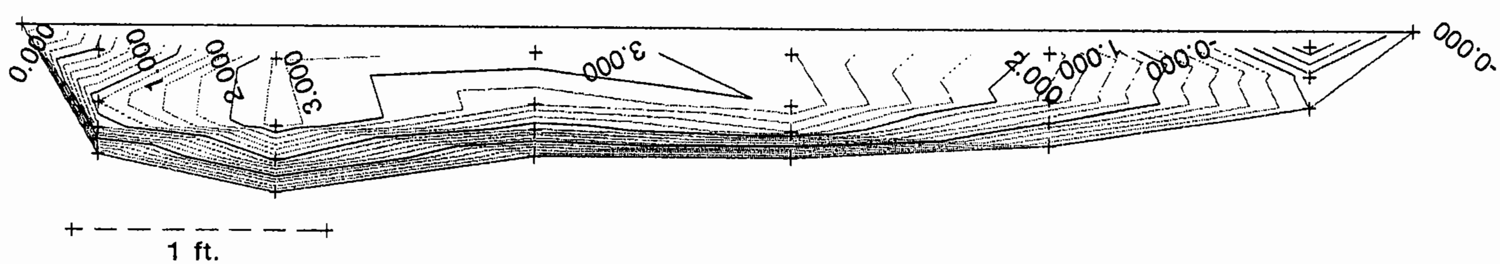

Figure A44. West Fork Silver Creek: Natural stream cross-section velocity (ft/s) at upstream reach 21.

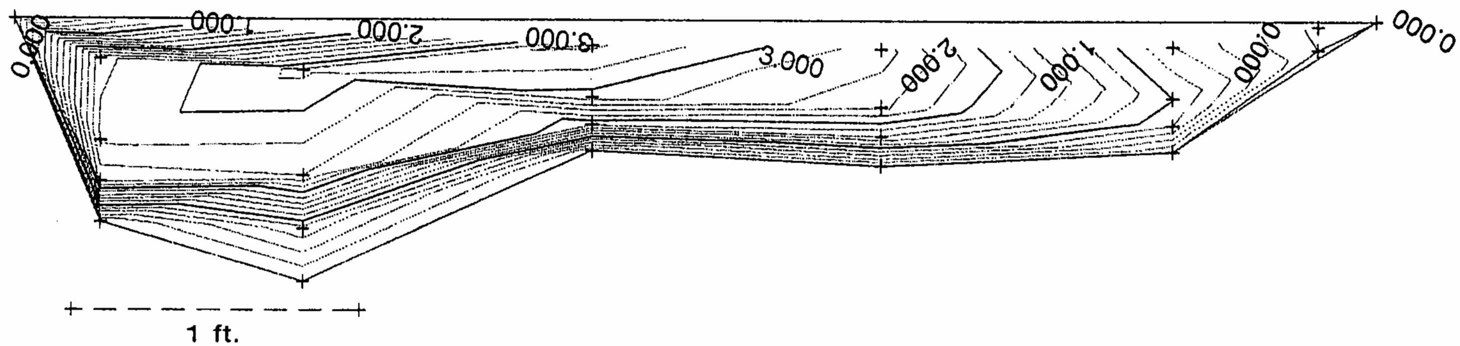

Figure A45. West Fork Silver Creek: Natural stream cross-section velocity (ft/s) at upstream reach 22.

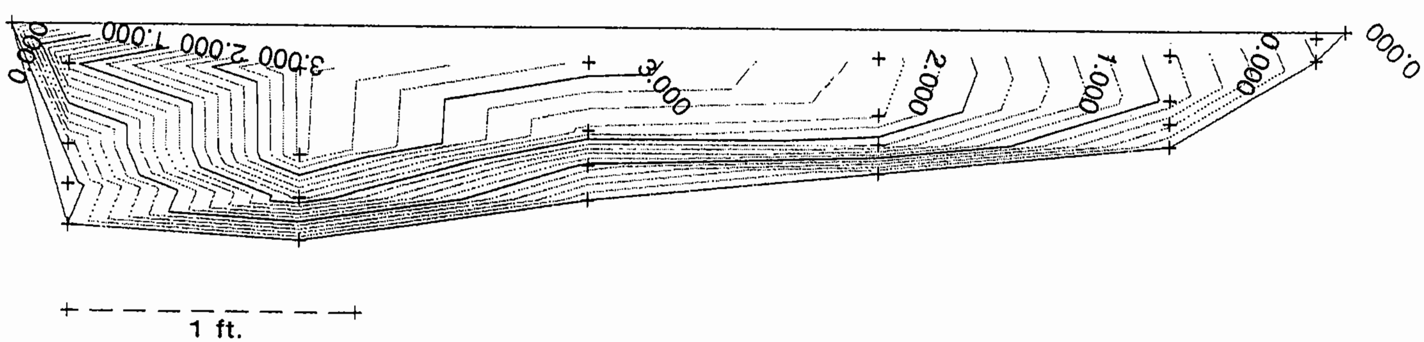

Figure A46. West Fork Silver Creek: Natural stream cross-section velocity (ft/s) at upstream reach 23.

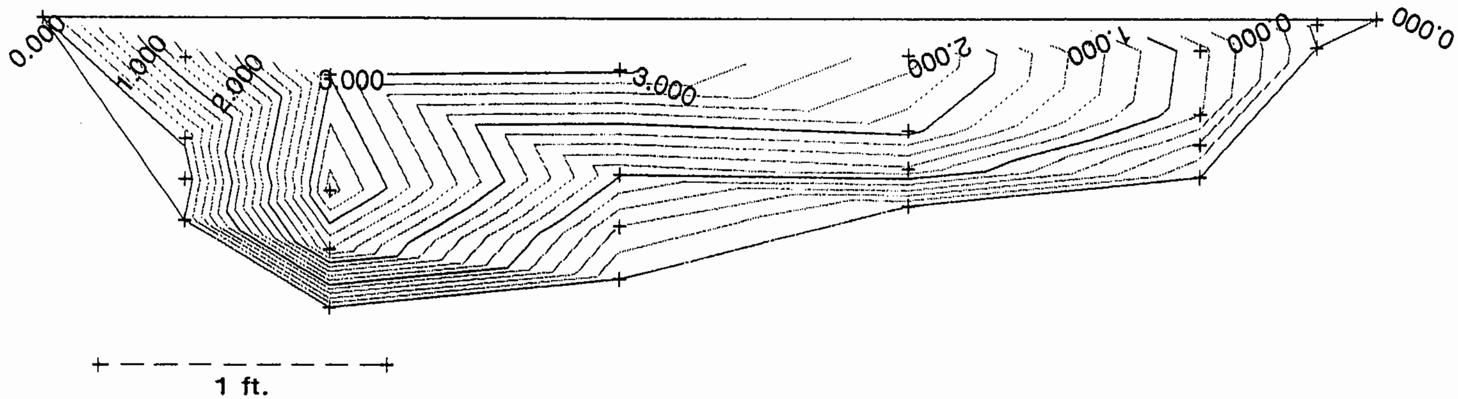

Figure A47. West Fork Silver Creek: Natural stream cross-section velocity (ft/s) at upstream reach 24.

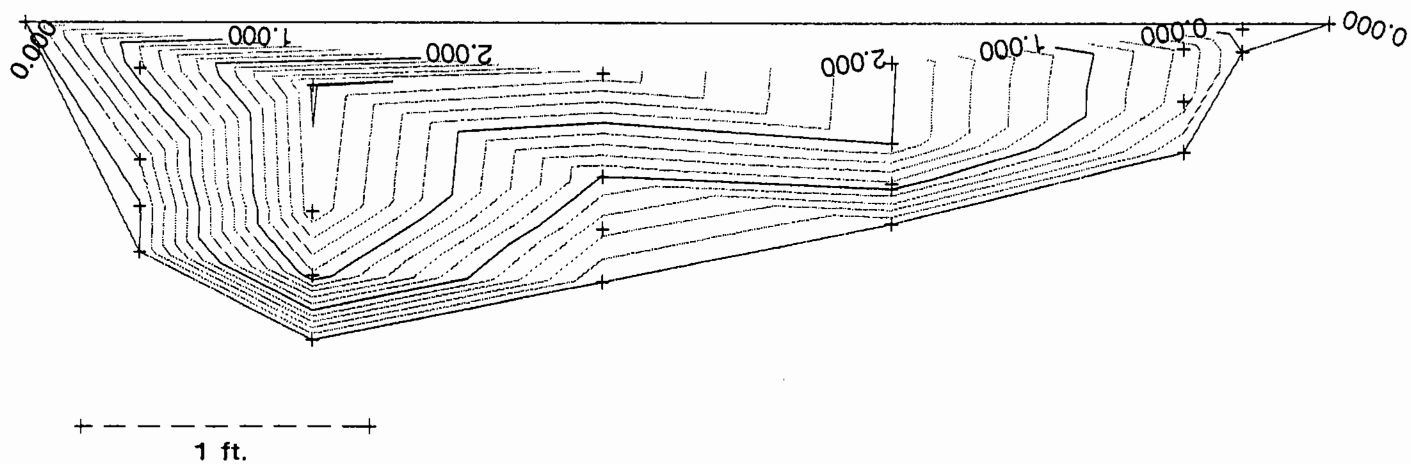

Figure A48. West Fork Silver Creek: Natural stream cross-section velocity (ft/s) at upstream reach 25.

APPENDIX B.

Digital terrain models.

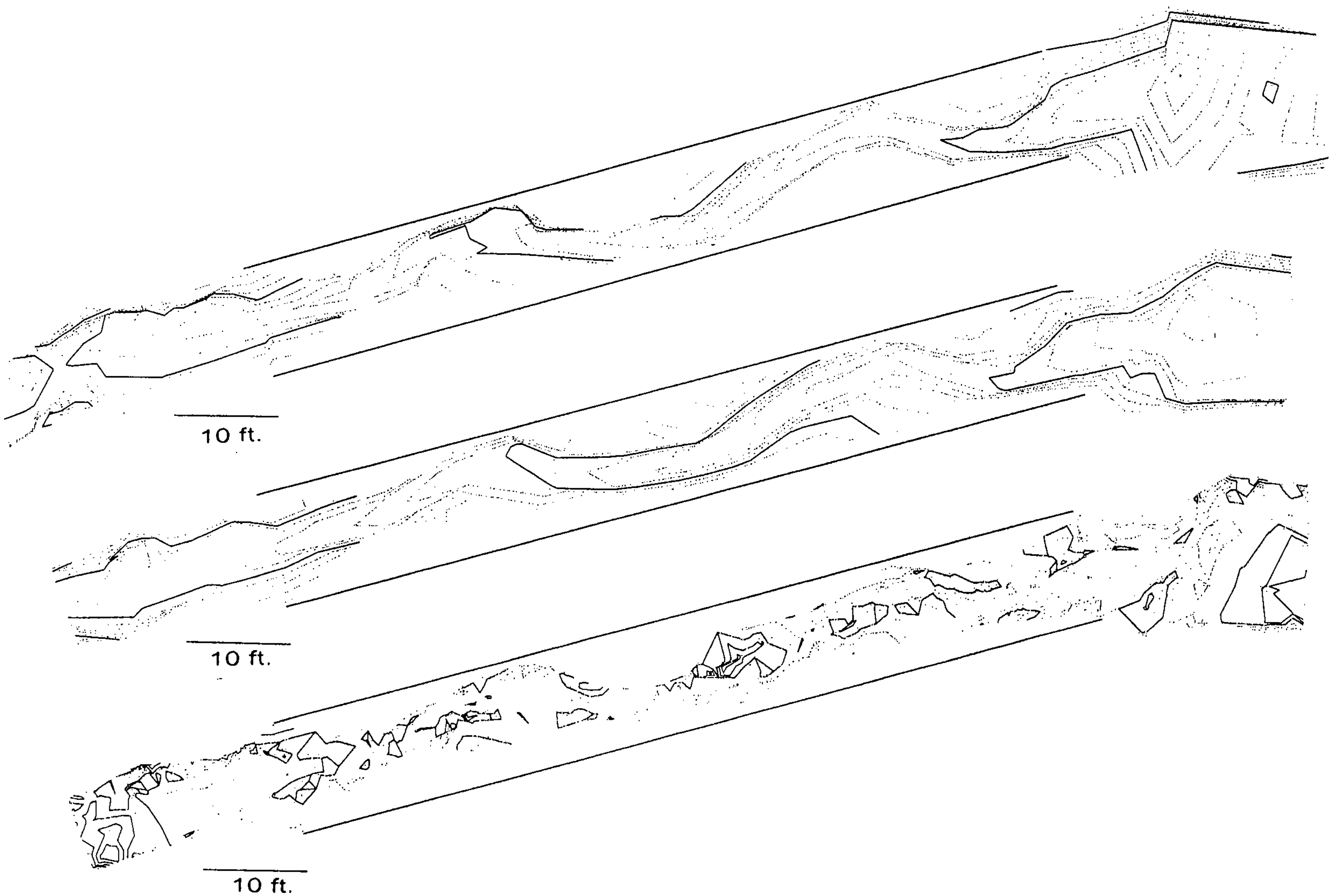

Figure B1. Guyer Creek: Digital terrain model 2000 (top), 2001 (middle), and the difference between 2000 and 2000 (bottom).

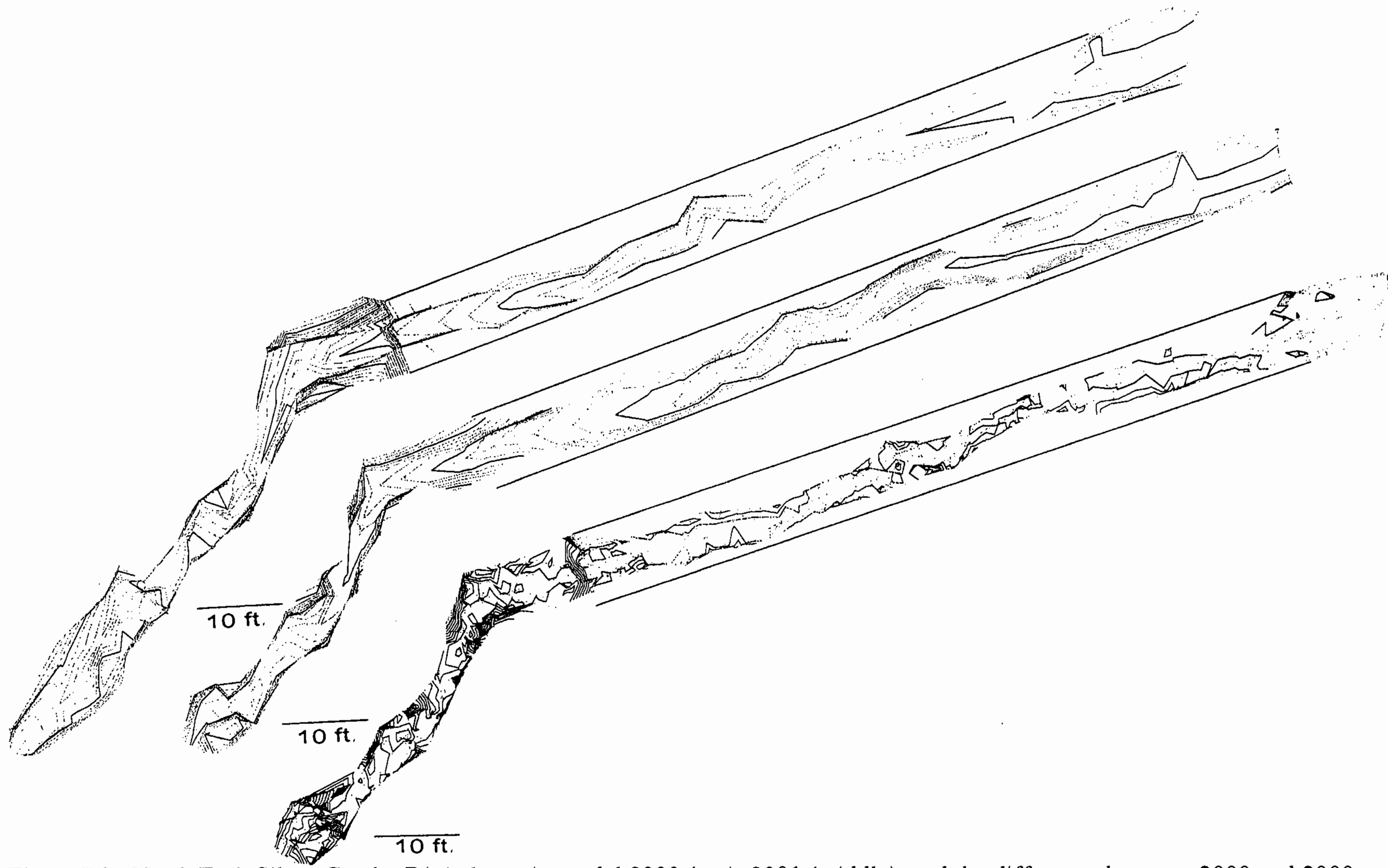

Figure B2. North Fork Silver Creek: Digital terrain model 2000 (top), 2001 (middle), and the difference between 2000 and 2000 (bottom).

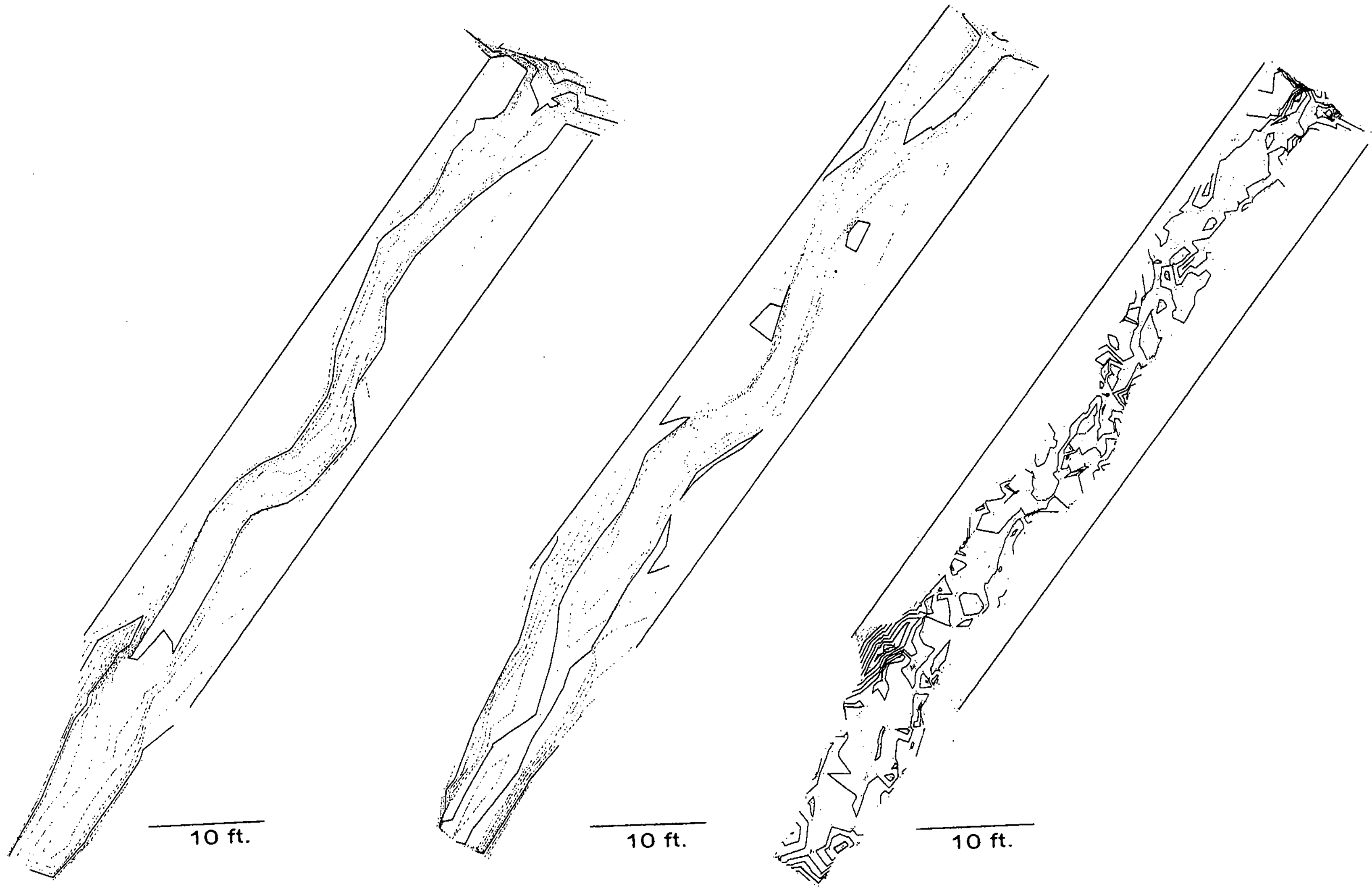

Figure B3. West Fork Silver Creek: Digital terrain model 2000 (left), 2001 (center), and the difference between 2000 and 2000 (right).