IMPROVING STREAM CROSSINGS FOR FISH PASSAGE

FINAL REPORT

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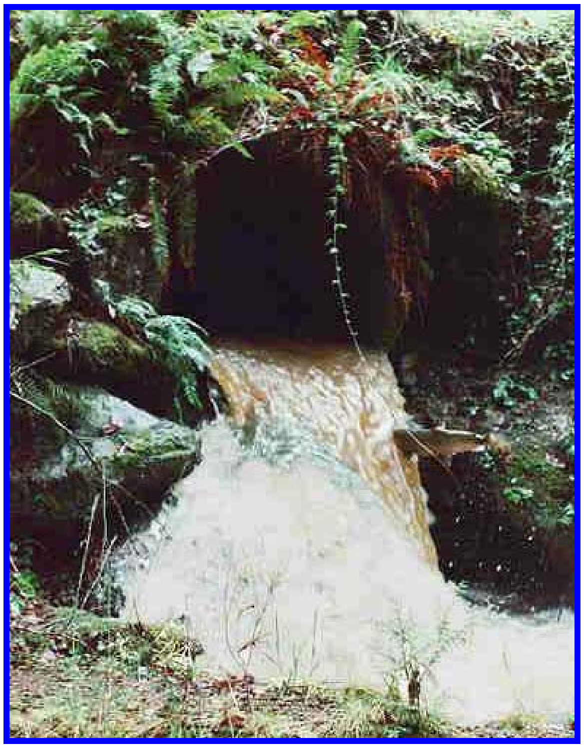

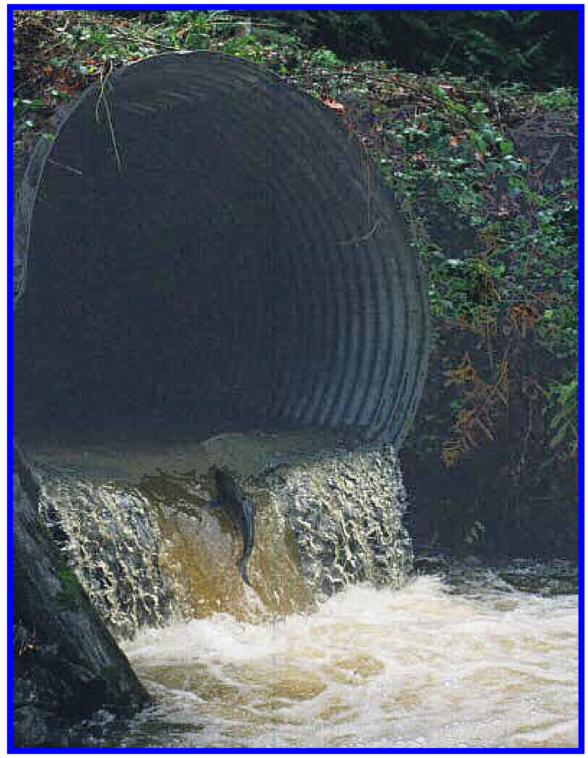

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EXECUTIVE SUMMARY

As anadromous fish swim to headwater streams to spawn, they often encounter stream crossing structures (culverts, fords, bridges, etc.) at roads. How fish pass—or fail to pass—through existing culverts is the focus of this study. Culvert designs capable of passing fish are well understood and readily available, yet culverts continue to be fish barriers because:

- Some culverts are installed incorrectly or improperly maintained,
- After a culvert is installed, stream geomorphology changes, so the culvert design no longer allows fish passage, and
- Opportunities for improving fish passage are lost due to the "emergency" status of culvert replacements following a flood or other culvert failure.

This project was initiated to "improve criteria for fish passage at…culverts by field verification and analysis" and to implement "a quality assurance process from design to field installation of culverts…in California" (NMFS, 1998). Specifically, this study examines: 1) culverts designed to current fish passage standards and their effectiveness, 2) causes of unsuccessful fish passage through culverts, and 3) new standards for culvert design, construction, maintenance, and monitoring. Culverts at twenty-two sites, throughout Humboldt, Del Norte, and Mendocino Counties, California, were considered. Ten of those sites were selected for detailed study because they were known to support several species and age classes of fish. These ten sites were monitored by continuous stage recorders; by observers counting, identifying, and describing fish passage success; and by remote sensing of tagged fish.

In this study, we attempted to characterize each site's watershed hydrology, fisheries biology, and culvert hydraulics. We then synthesized and integrated these factors to evaluate how well fish pass through culverts. Our synthesis and subsequent recommendations are the focus of this Executive Summary. Our findings include:

Juvenile and adult salmonids generally attempt to pass through culverts after the peak flow, on the falling limb of the hydrograph. On a per storm basis, adult attempts to pass through culverts generally occur before (at higher flows) the juveniles' attempts.

On a seasonal basis, juvenile attempts occur earlier in the water year (late November to early January) than adult attempts (mid-December through March).

Whether a water year is "wet" or "dry" affects the length of time fish spend in the mainstem, before migrating through culverts and up the tributaries. Storm distribution plays an important role in the rate of upstream migration. Monitoring tagged fish showed that they enter the mainstem during increased flows, and that the fish proceed up the tributaries during and after subsequent storms.

Juvenile fish attempt to pass culverts over a wide range of flows. A regional flow duration curve (FDC) was constructed; high exceedence flows on the FDC indicate low stream discharges, and vice versa. By overlaying fish passage attempts on the FDC curve, we documented that most (85%) of juvenile attempts occur between the 70% and 5% migration period exceedance flows (40% and 2.5% annual exceedance flows, respectively). Peak juvenile movement occurs between the 30% and 21% exceedance flows (15% and 11% annual exceedance flows).

Adults attempt passage at higher flows. At the higher end of the FDC (that is, at low stream discharge), no adults were observed attempting to pass through culverts at exceedances higher than 80% (47% annual exceedance flows). In fact, only 2% of adults attempted to pass at flows less than the 50% migration period exceedance flow (27% annual exceedance flow). Over one-third of the adults' attempts occurred between 5% and 2% migration period exceedances (2.5% and 1% annual exceedances). Of the adult attempts, a significant fraction (7%) occurred at discharges greater than the 2% migration period exceedance flow.

Drainage basin size can magnify the effects of high flows on fish passage. During extreme high flows, when water velocities become too high, fish can seek shelter along channel margins or within side channels. Because bank complexity provides shelter, and the relative percent of complexity increases as stream size decreases, fish migrate up smaller streams (in smaller drainages) at lower exceedances (that is, at higher relative flows) than larger streams. As drainage basin size decreases, fish migrate at exceedance flows that are lower than anticipated.

Drainage basin size also affects low flows and fish passage. As streams become smaller (with smaller drainage areas), more low flow barriers become apparent, so fish would need lower exceedance flows (higher flows) to pass.

Fish can be delayed in their upstream migration by flows that are too high (stream velocity is too fast) or by flows that are too low (insufficient water depth). The number of consecutive days that a flow was too high or low, in exceedance flows, was plotted against exceedance flows. The average delay due to high flows (the 2% migration period exceedence) was about 1 day. Delays due to low flows (85% migration period exceedence) could exceed 20 days.

However, delay times are also affected by whether a water year is "wet" or "dry." Because an FDC represents averages, it does not account for annual variation in flows. For example, during WY99 (a "wet" year), the low flow of 90% migration period exceedence caused a one-day delay. Yet during WY2001 (a "dry" year), the same 90% exceedance flow caused a 10-day delay.

Fish leaping performance and culvert outlet hydraulics were examined; the success or failure of the leap, the required leap height, the residual pool depth, and discharge (and hence, velocity) at the time of the leap were documented. However, because the relationship between leap height and discharge is a function of the pool's tailwater control and the culvert outlet's cross section, this relationship is unique for each site.

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1 INTRODUCTION

The need for fish to move within streams--and in and out of particular streams--is well established. Anadromous salmon and steelhead, the species of interest in this project, begin life in fresh water, spend one to several years in salt water, eventually returning to fresh water to spawn. Unimpeded movement within stream systems is crucial to these fish in all of their fresh water life stages. For example, juvenile salmonids need access to rearing habitat--typically pools--that provide food, shelter and cool water temperatures. Out migrating smolts need a continuous water "pathway" to travel from their fresh water origins to estuaries, and eventually to the ocean. Adults require access to spawning grounds when returning from the ocean. Both natural and man-made barriers to migration influence the ease and extent to which these fish can reach appropriate habitat. Road-stream crossings (culverts, fords, etc.), dams, and water diversions are all common types of man-made migration barriers. This report summarizes the findings of a three-year study of fish passage at culvert stream crossings in the coastal northern California counties of Del Norte, Humboldt, and Mendocino.

1.1 EFFECTS OF STREAM CROSSING BARRIERS ON MIGRATING SALMONIDS

Numerous passage problems can exist at a stream crossing to affect the ability of fish and other aquatic species to migrate. Briefly, these characteristics include:

- Perched culvert outlets,
- Shallow jump pools or outflow that cascades over riprap,
- Insufficient water depth within the culvert barrel,
- Excessive water velocities,
- Debris accumulation at the inlet or within the culvert barrel, and
- Steep channel bed just upstream of the culvert inlet due to deposition upstream of an undersized culvert.

The effects of these stream crossing conditions can be temporal (impassable to fish some of the time depending on the flow condition), partial (impassable to a particular species or life stage at all times); or total (impassable to all fish at all times). For adult salmonids, passage problems may:

- Disrupt spawning migrations,
- Cause under-utilization of tributary habitat,
- Create over-crowding of available spawning habitat.
- Increase the likelihood of stress, injury, or predation/poaching, and
- Limit the spatial separation of competing species.

The effects of stream crossing barriers on juvenile salmonids include limiting fish to downstream stream reaches, thus, increasing competition for food and shelter; excluding them from upstream over-wintering habitat in tributaries; increasing predation in culvert outlet pools; and preventing summer migration from thermally-stressed mainstem channels to cool-water refugia in smaller tributaries.

1.2 CAUSES OF STREAM CROSSING BARRIERS

Improving fish passage at stream crossings has recently become a key component of many salmon and steelhead restoration efforts. A United States Government Accounting Office report states that recent inventories identified over 2,600 culverts that block migrating fish on Federal Lands in Oregon and Washington, and inventories are not yet complete (GAO, 2001). Surveys conducted in Oregon and northern California have identified thousands of stream crossings that act as total or partial barriers to fish passage (Mirati, 1999; Taylor, 2000, 2001a & b). The Oregon Department of Fish and Wildlife survey estimates that more than half of 4,370 state and county culverts pose fish passage problems (Mirati, 1999).

Culvert designs that are intended to provide fish passage have been presented in several detailed design manuals developed by various government agencies that oversee fisheries and road construction and maintenance (e.g., WDFW, 1999; Poulin, 1998; Baker and Votapka, 1990). However, culverts continue to act as barriers to fish passage because:

- Earlier designs tended to target passage of only adult anadromous salmonids, failing to address needs of migrating juvenile salmonids,
- Culverts designed to provide fish passage have frequently been incorrectly installed and improperly maintained,
- Changes in stream morphology often create conditions that hinder fish passage at culverts, and
- Opportunities for improving fish passage are lost due to the "emergency" status of culvert replacements following flood events.

Culverts installed in fish-bearing streams rarely receive post-construction evaluation. As a result, our understanding of the hydraulic behavior, resulting channel adjustments, and fish passage effectiveness for different culvert designs is lacking. The common practice of retrofitting existing culverts to improve fish passage has also failed to receive adequate post-project evaluation.

Another component of fish passage design that has received insufficient review is the selection of fish passage design flows. The lower and upper fish passage design flows define the range of flows that a culvert should accommodate fish passage. Within this range of flows, hydraulic conditions throughout the culvert should be within the swimming abilities of the fish. Ideally, this range of flow should encompass the actual flows used by upstream migrating fish.

Several State and Federal agencies have published guidelines for determining lower and upper design flows for passage of adult salmon and steelhead at stream crossings. One of the earliest published guidelines for selecting fish passage design flows is found in a California Department of Transportation Research Report (Kay and Lewis, 1970). During the same period Washington State Department of Fish and Wildlife prescribed a similar design flow guideline. Scientists from the Six Rivers National Forest and the Humboldt State University Institute of River Ecosystems researched the origins of these flow guidelines and found their selection was made independent of supporting biological evidence, and no follow-up evaluation has occurred since implementation (Per. Com., Kay, 1997; Per. Com, Bates, 1997).

Prior to the draft stream crossing guidelines released by the California Department of Fish and Game in October 2001, none of the guidelines addressed fish passage flows for juvenile salmonids.

2 PROJECT PURPOSE AND OBJECTIVES

This project was initiated to "improve criteria for fish passage at stream crossings (primarily culverts) by field verification and analysis and implementing a quality assurance process from design to field installation of culverts and other stream crossings in California" (NMFS, 1998).

The overall project goal was to better understand the influence of culvert design, installation, retrofit, and maintenance on fish passage, and to make informed recommendations for stream crossing standards. Specific project objectives were to:

- Evaluate culverts designed to current fish passage standards, and assess the culverts' abilities to pass adult and juvenile anadromous salmonids upstream and downstream,
- Document causes of unsuccessful fish passage (such as design flaws, lack of quality control during installation, poor maintenance, or changed geomorphic conditions), and
- Propose new standards for stream crossing evaluation, design, construction, maintenance, and monitoring in conjunction with existing standards (NMFS, 1998).

To fulfill the project purpose and objectives, data collection focused on (1) characterizing hydraulic conditions within a variety of culvert types and installations, (2) documenting passage success and failure of adult and juvenile fish, and (3) obtaining continuous stream flow measurements for small, coastal streams. These data allowed us to address the following questions:

- Over what range of flows do adult and juvenile salmonids migrate up smaller streams within coastal northern California? "Smaller streams" is defined here as a stream that conveys a discharge that can feasibly flow through a culvert, rather than a larger structure such as a bridge.
- How long are the delays in upstream migration caused by culverts acting as temporal barriers?
- How precise are methods for calculating fish passage design flows in small, ungaged streams?
- Is the use of velocity reduction factors appropriate when designing culverts for juvenile fish passage?
- Can channel morphology be used to define a low passage design flow?

2.1 REPORT ORGANIZATION

This report is organized into eight sections. Sections 1 through 3 provide a project introduction and important background information. Section 4 presents the hydrologic data collected at continuously monitored sites over the three-year study period, describes and evaluates a method for estimating fish passage design flows in ungaged coastal California streams, and reviews a method for placing confidence intervals on flow duration curves. Section 5 presents analyses of hydraulic measurements collected at the studied culverts, compares model predictions against values measured in the field, and examines the implications of using model parameters from the literature versus parameters determined in the field. Section 6 summarizes fish passage observations, which were obtained visually and by passive integrated transponder (PIT) tags. Section 7 synthesizes the information of the preceding six sections describing how fish pass (or fail to pass) through culvert stream crossings. Combining our field observations and findings, we present recommendations pertaining to culvert design, monitoring, and maintenance in Section 8.

3 PROJECT DESCRIPTION

Twenty-one culverted stream crossing sites in three counties (Humboldt, Mendocino, and Del Norte) were selected. This section describes the site selection process, and lists the attributes of each site. These include site location, culvert shape, size, and material; its length, slope, and placement relative to the adjacent stream channel; and inlet and outlet conditions.

3.1 SITE SELECTION

Twenty-one stream crossing sites in three counties (Humboldt, Mendocino, and Del Norte) were studied. This allowed us to include a broad range of culvert types and installations, but not all streams supported high populations of fish. Therefore, ten *Tier 1* sites believed to have healthy populations of salmon and steelhead were selected for detailed study of fish migration timing, swimming ability, and behavior. The remaining 11 stream crossings were categorized as *Tier 2* sites, with study of these culverts limited to characterizing their hydraulic behavior. The two levels of effort allow detailed study of fish passage at *Tier 1* sites, and characterization of culvert hydraulics encountered by migrating fish through combining findings from both *Tier 1* and *2* sites.

At *Tier 1* sites, we conducted extensive monitoring of culvert hydraulics, stream flow characteristics, and fish movement. Continuous stage recorders were installed to obtain a flow record on all *Tier 1* streams. Fish observation and tagging were used to document fish passage success. For each site, transverse and longitudinal velocity distributions and water surface profiles were measured at different flow rates to characterize culvert hydraulics.

All *Tier 1* sites had recently documented anadromous salmonid populations within the stream reach in which the culvert was located. Additionally, to ensure visual observations of passage attempts would be possible, seven of the ten selected *Tier 1* sites had perched outlets that required the fish to leap to enter the culvert. Because of the extreme timeliness and large effort required for performing fish observations and tagging, all selected *Tier 1* sites were clustered relatively close together and within a 45 mile drive from Humboldt State University.

At the 11 *Tier 2* sites, we conducted hydraulic analyses similar to the *Tier 1* sites. However, little or no monitoring of fish migration or stream flow was performed. The *Tier 2* sites represented a variety of culvert types and installations, and included sites referenced in an earlier study, *Passage of Anadromous Salmonids Through Highway Drainage Structures* (Kay and Lewis, 1970).

3.2 SITE CHARACTERIZATION

The baseline information collected at *Tier 1* and *2* study sites are listed below.

1. Stream crossing location, ownership, and upstream land use.

2. Culvert type, installation, and alignment with the upstream channel.

3. Land survey of each site which includes (1) a longitudinal profile upstream and downstream of the culvert; (2) plan view mapping of the crossing and stream channel, including the outlet pool tailout and active channel margins; (3) a channel cross-section at the point functioning as the tailwater elevational control; and (4) a cross-section above the influence of the culvert at a location having well-expressed channel morphology.

4. Photographs of study sites.

In an attempt to match the diversity of culvert types found within the road systems of coastal California, the study sites included a wide variety of culvert shapes and sizes (Tables 3-1, 3-2, 3-3). Baseline data for each site (longitudinal profiles, channel cross-sections, plan maps, and photographs) are included in Appendix A.

Table 3-1. Culvert shapes and materials found at study sites and associated acronyms.

CSP	– Corrugated Steel Pipe (circular)
CSPA	– Corrugated Steel Pipe, Arch
CSPE	– Corrugated Steel Pipe, Elliptical
CSPH	– Corrugated Steel Pipe, Helical
SSPA	– Structural Steel Plate Arch
SSPP	– Structural Steel Plate Pipe (circular)
SSPPA	– Structural Steel Plate Pipe, Arch
RCA	– Reinforced Concrete Arch
RCP	– Reinforced Concrete Pipe (circular)
WSP	– Welded Steel Pipe (smooth, circular)

Table 3-2. Description of culverts at *Tier 1* sites (additional site information is included in Appendix A).

Road, Post Mile (Stream Name)	Tributary to (Basin)	Drainage Area	No. of Culverts	Culvert Type	Culvert Size Dia. or H x W	Length	Slope	Inlet Type	Culvert Bottom	Outlet Type (Residual Drop)
HW 101, PM 126.13 (May Creek)	Prairie Creek (Redwood Creek)	1.75 mi^2	1	RCA	9.8 ft x 10 ft	400 ft	2.2%	Wingwalls	Concrete w/notched concrete weirs; height = 2 ft, spacing =25 ft.	Perched outlet apron w/notched weir (0.7 ft).
Streeloh Ck Road (N. Fork Streeloh Creek)	Streeloh Creek/ Prairie Creek (Redwood Creek)	1.18 mi^2	3	CSP	4.0 ft	28 ft	0.7%	Projecting	Corrugated steel, rusted through near outlet.	Perched outlet at confluence w/ Streeloh Creek (1.8 ft).
Warren Creek Road [1] (Warren Creek)	Mad River (Mad River)	1.60 mi^2	1	RCP/ WSP	6.0 ft/ 5.5 ft	60 ft/ 20 ft	0.8%/ 5.8%	Projecting	Concrete lined (0.5 ft thick) and wooden offset baffles; height = 0.5 ft, spacing = 4 ft	Perched outlet and 3 downstream boulder jump-pool weirs (1.5 ft).
Riverside Road (Sullivan Gulch)	N. Fork Mad River (Mad River)	2.35 mi^2	1	SSPP	9.5 ft	60 ft	1.6%	Projecting	Concrete lined (1 to 1.5 ft thick) and steel ramp baffles; height = 1 ft, spacing = 12 ft.	Perched outlet w/ v-notched weir. Downstream jump-pool weir (2.1 ft).
Camp Bower Road (Hatchery Creek)	N. Fork Mad River (Mad River)	0.83 mi^2	1	CSP	4.5 ft	40 ft	0.8%	Projecting	Corrugated steel, lower half embedded w/sand and gravel; outlet depth = 1.1 ft.	Backwatered by downstream control consisting of sand and gravel (-0.5 ft).
South Quarry Road (Morrison Gulch)	Jacoby Creek (Humboldt Bay)	0.99 mi^2	1	CSP	5.0 ft	50 ft	1.0%	Projecting	Corrugated steel, rusted through near outlet.	Perched outlet above large pool (5.2 ft).
Freshwater Road (McCready Gulch)	Freshwater Creek (Humboldt Bay)	1.98 mi^2	1	RCB	10 ft x 10 ft	102 ft	1.2%	Wingwalls	Embedded throughout w/sand and gravel; inlet depth = 0.5 ft outlet depth = 1.8 ft	At stream grade w/ no outlet pool.
Old Freshwater Road (McCready Gulch)	Freshwater Creek (Humboldt Bay)	1.95 mi^2	1	RCB	8.4 ft x 10 ft	61 ft	0.6%	Headwall	Concrete w/ wooden offset baffles along right side; height = 1 ft, spacing = 6.5 ft	Perched outlet w/ v-noched weir. Large outlet pool (3.1 ft)
Freshwater Road (Cloney Gulch)	Freshwater Creek (Humboldt Bay)	4.67 mi^2	1	SSPA	9.3 ft x 16 ft	60 ft	0.9%	Headwall	Reinforced concrete floor w/ notch wooden weirs along left side; height = 0.4 ft, spacing = 10 ft.	Perched outlet w/ wooden weir. Two downstream boulder jump-pool weirs (2.9 ft).
HW 254, PM 40.83 (Chadd Creek)	Eel River (Eel River)	3.56 mi^2	1	SSPP	9.0 ft	92	2.0%	Projecting	Corrugated steel invert.	Grouted outlet apron at grade with large outlet pool.

[1] The Warren Creek culvert has an RCP added to the inlet and outlet of the original WSP and has a slope break approximately 60 ft downstream of the inlet.

Table 3-3. Description of culverts at *Tier 2* sites (additional site information is included in Appendix A).

Road, Post Mile (Stream Name)	Tributary to (Basin)	Drainage Area	No. of Culverts	Culvert Type	Culvert Size Dia. or H x W	Length	Slope	Inlet Type	Culvert Bottom	Outlet Type (Residual Drop)
Tan Oak Drive (Peacock Creek)	Smith River (Smith River)	2.10 mi^2	1	CSP	7.5 ft	55 ft	4.3%	Headwall	Corrugated steel with steel ramp baffles in lower portion; height = 0.9 ft, spacing = 13 ft.	Perched outlet apron w/concrete weir, small shallow pool downstream. (1.5 ft).
HW 197, MP 2.12 (Peacock Creek)	Smith River (Smith River)	2.06 mi^2	1	SSPA	8.6 ft x 13 ft	70 ft	2.3%	Wingwalls	Reinforced concrete floor w/notched wooden weirs; height = 1.5 ft, spacing = 10 ft.	Perched outlet apron w/concrete weir, small pool downstream. (1.4 ft).
HW199, PM 2.56 (Clarks Creek)	Smith River (Smith River)	1.77 mi^2	2	RCB	8 ft x 8 ft	75.5 ft	1.3%	Wingwalls	Concrete w/wooden offset baffles; height = 1.5 ft, spacing = 9 ft.	Perched outlet w/ v-notch weir and large outlet pool (2.1 ft).
Honeydew Road (Cow Creek)	Bull Creek (S. Fork Eel River)	2.38 mi^2	1	CSPE	8 ft x 7.5 ft	42 ft	4.4%	Projecting	Corrugated steel and lower half embedded w/sand and gravel; outlet depth = 2.1 ft.	Backwatered by downstream control consisting of gravel (-2.2 ft).
HW 254, PM 7.69 (Dry Creek)	S. Fork Eel River (S. Fork Eel River)	1.28 mi^2	1	RCB	8 ft x 6 ft	36.5 ft	0.8%	Wingwalls	Smooth concrete floor.	Perched outlet above small pool (2.0 ft).
Lower Road, Richardson Grove State Park (Durphy Creek)	S. Fork Eel River (S. Fork Eel River)	2.49 mi^2	1	SSPPA	6.3 ft x 9.3 ft	50 ft	1.4%	Mitered	Embedded with gravel; inlet depth = 0.5 ft, outlet depth = 1.2 ft	At stream grade w/ no outlet pool.
HW 101, PM 1.61 (Durphy Creek)	S. Fork Eel River (S. Fork Eel River)	2.49 mi^2	1	RCB	8 ft x 12 ft	91 ft	4.3%	Wingwalls	Concrete floor w/exposed rebar, lower 15 ft embedded w/sand and gravel.	At stream grade w/ no outlet pool.
Upper Road, Richardson Grove State Park (Durphy Creek)	S. Fork Eel River (S. Fork Eel River)	2.42 mi^2	1	SSPP	10.0 ft	50 ft	0.6%	Wingwalls	Corrugated steel, lower 20 ft embedded w/cobble	Backwatered by downstream control consisting of gravel and cobble (-0.7 ft).
Road 300 Jackson State Forest (Boundary Creek)	N. Fork Noyo River (Noyo River)	0.36 mi^2	1	CSPH	7.0 ft	80 ft	3.3%	Projecting	Corrugated steel invert.	Cascade over riprap armoring (3.0 ft).
Road 120 Jackson State Forest (N. Fork James Creek)	James Creek (Big River)	1.78 mi^2	1	SSPP	12.0 ft	46 ft	4.6%	Headwall	Corrugated steel invert	Perched outlet apron w/offset baffle and notched weir (2.0 ft).
Road 440, Jackson State Forest (Walton Creek)	Hare Creek (Hare Creek)	0.50 mi^2	1	CSP	4.0 ft	60 ft	2.2%	Projecting	Corrugated steel invert, rusted through near outlet	Perched outlet w/ three partially failed log jump-pool weirs (3.6 ft).

4 STREAM FLOW CHARACTERISTICS

For adult and juvenile salmonids, the interaction between upstream migration timing and stream flow has not been adequately studied. Migration timing for adult salmon and steelhead in small, coastal California rivers and streams is highly dependent on flow magnitude and timing. The relationship between stream flow and migration timing should guide the selection of appropriate design flows for fish passage to ensure stream crossings provide acceptable water depth and velocity conditions for migrating fish.

To study this relationship, a continuous hydrologic record for the study period was obtained by installing gaging stations adjacent to each *Tier 1* site. Each gaging station consisted of a pressure transducer, data logger, and staff plate. The data were used to:

- Compare flow magnitudes and durations between *Tier 1* sites and between water years.
- Assess scaling methods for predicting stream flow on small ungaged streams using historic gaging records, and
- Identify the flows during which fish were observed attempting to pass through culverts at *Tier 1* sites.

The first two topics are discussed in this section and the hydrologic conditions present when fish were observed moving are discussed in Section 7.

4.1 MONITORING METHODS

Adjacent to all *Tier 1* culverts staff plates and continuous stage recorders (Global Water WL14 pressure transducer/data loggers) were installed. Discharge was routinely measured to develop and maintain stage-discharge rating curves for each gaging station. The discharge measurements were collected according to USDA Forest Service protocol (Harrelson et al., 1994) using Pygmy current meters. At *Tier 2* culverts, stage was not continuously recorded but discharge was measured whenever other hydraulic measurements were collected.

4.2 OBSERVED SMALL STREAM HYDROLOGY

Stream gages were operated between November 1 and April 30 to monitor flows during the migrational period of adult and juvenile salmonids. Data discontinuities are inevitable in studies of significant duration; this study was no exception (Table 4-1). The data gaps were filled by correlating stream flows between adjacent study sites and nearby gaged streams.

The study period, November 1998 through May 2001, spanned three complete salmonid migration cycles, and captured a wide range of hydrologic variation. This hydrologic variation is evident in hydrographs from the Sullivan Gulch site for each project year (Figure 4-1). Axes scales are consistent to emphasize the differences in flow magnitudes between years. Hydrographs for the other streams in the project show very similar patterns (Appendix B).

Rainfall from the National Weather Service rainfall gaging station in Eureka, California was analyzed to compare rainfall amounts between different years of the study and put them into a historical context. The Eureka gaging station is centrally located relative to the study sites and began recording in 1905. Rainfall patterns observed in Eureka are generally representative of those found throughout the study area. During the first year of the study, water year 1999, the annual rainfall total for Eureka was 50.13 inches, or 139% of the average (38.98 inches). The 1999 water year was the 10th wettest year on record and included a high intensity rainfall event in November 1998. This November 1998 rainfall event produced peak flows with recurrence intervals ranging from five to twenty years. The higher return intervals occurred at the northernmost study sites.

Table 4-1. Hydrologic data discontinuities at each *Tier 1* site.

Site	Water Year and Dates	Notes
Chadd Creek	None	The first stage recorder installed at this site was vandalized and the second failed.
Cloney Gulch	WY1999: 12/8/98 – 4/30/99	Synthetically generated from McCready Gulch.
	WY2000: 10/1/99 – 9/30/00	Data gap 9/7/00 to 9/9/00.
	WY2001: 10/1/00 – 5/8/01	Data gap 2/28/01 to 3/5/01.
Hatchery Creek	WY 1999:12/27/98 – 4/30/99	Data gap 3/21/99 to 4/1/99.
	WY 2000: 11/1/99 – 4/30/00	Data gap 11/26/99 to 12/7/99 and 1/15/00 to 2/6/00.
	WY 2001: 11/1/00 – 4/30/01	No data gaps.
May Creek	WY1999: 12/11/98 – 9/30/99	Start date 12/11/98. Data gap 4/1/99 to 6/1/99.
	WY2000: 10/1/99 – 9/30/00	Data gaps 11/21/99 to 11/27/99 and 3/17/00 to 3/22/00.
	WY2001: None	Stage recorder failure.
McCready Gulch	WY1999: 12/8/98 – 4/30/99	Downstream migrant trap installation prevented spring operation. Data gap 1/5/99 to 1/11/99.
	WY2000: 10/1/99 – 3/30/00	Trap installed on 3/30/00. No data gaps.
	WY2001: 10/1/00 – 3/10/01	Stage recorder failure on 3/10/01. Data gaps 11/14/00 to 11/21/00, 12/5/00 to 12/9/00, and 2/28/01 to 3/5/01.
Morrison Gulch	WY1999: 11/23/98 – 5/1/99	No data gaps.
	WY2000: 11/19/99 – 5/25/00	Transducer removed in May because of possible culvert replacement. No data gaps.
	WY2001: 10/1/00 – 5/8/01	Data gap 3/1/00 to 3/5/00.
Streeloh Creek	WY1999: 3/2/99 – 9/30/99	Data gap 5/5/99 to 6/1/99.
	WY2000: 10/1/99 – 9/30/00	Data gaps 3/16/00 to 3/22/00, 4/7/00 to 4/12/00, and 5/25/00 to 9/15/00.
	WY2001: 10/1/00 – 2/16/01	Stage recorder failure on 2/16/01. No data gaps before 2/16/01.
Sullivan Gulch	WY1999: 11/20/98 – 9/30/99	Data gaps 5/4/99 to 5/17/99 and 9/22/99 to 9/23/99.
	WY2000: 10/1/99 – 9/30/00	Data gap 5/2/00 to 5/9/00.
	WY20001: 10/1/00 – 5/8/01	No data gaps.
Warren Creek	WY 1999: 1/16/99 – 5/1/99	No data gaps.
	WY2000: 10/1/99 – 1/6/00	Stage recorder failure on 1/6/00.
	WY2001: None	

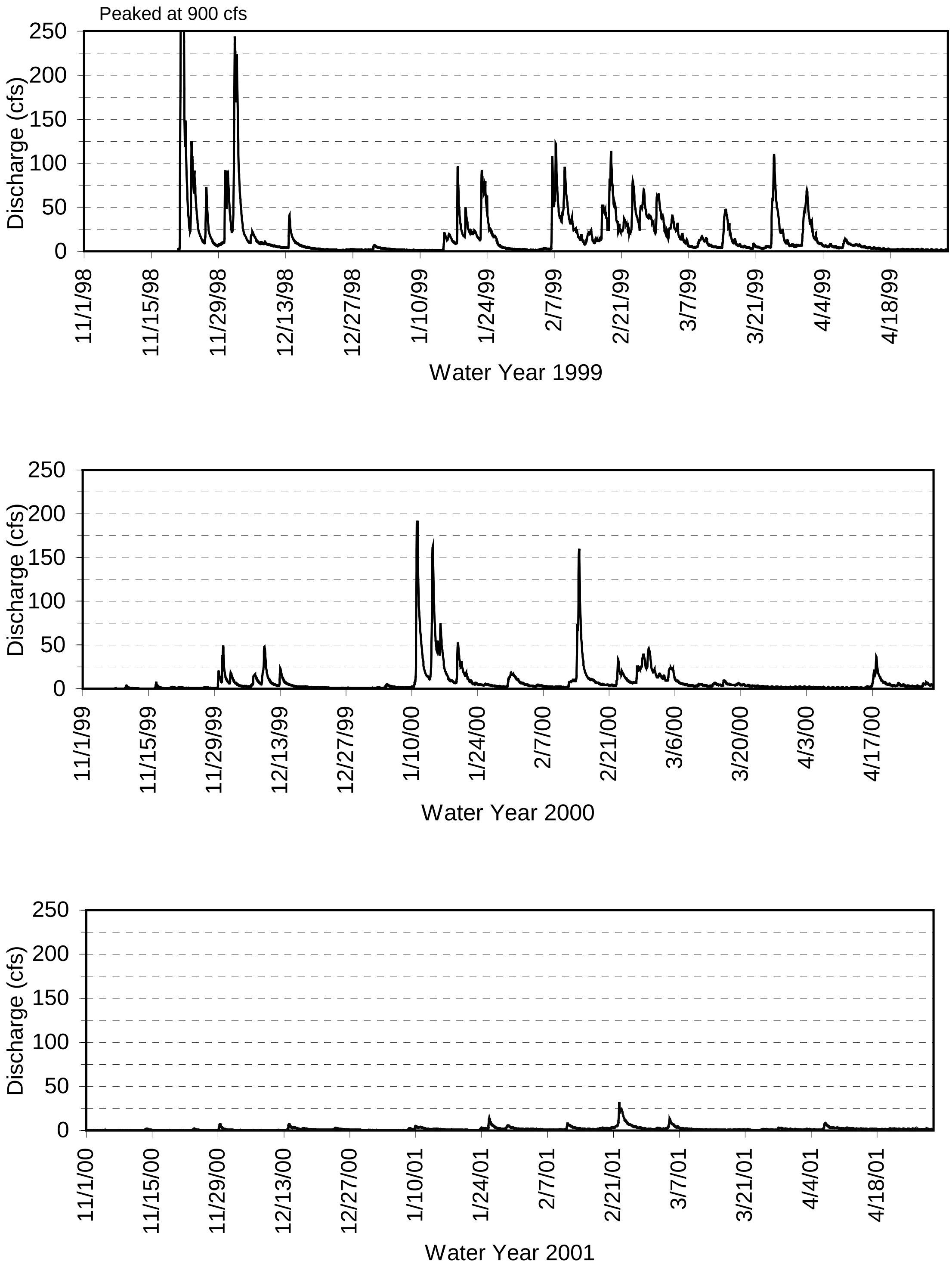

Figure 4-1. Sullivan Gulch hydrographs for all three years of the study.

During the study's second year, water year 2000, Eureka experienced 36.64 inches of precipitation, or 94% of average. The initial storms occurred about one week later than in water year 1999 and the storms' magnitudes were much lower. Most of the coastal streams experienced their largest storms in January and February of 2000, with annual peak flows slightly greater than bankfull discharge. Storms in water year 2000 were more discrete than in water year 1999, and streams generally returned to base flow between storm events.

In water year 2001, Eureka experienced the seventh driest year on record. Total rainfall was only 22.26 inches (57% of average). In many streams throughout the study area, base flow conditions persisted throughout much of the migration period.

All three water years experienced very low rainfall for about a three-week period in late December through early January (see Figure 4-1).

4.3 A PREDICTIVE METHOD FOR GENERATING FLOW DURATION CURVES FOR UNGAGED STREAMS

To accommodate fish passage at stream crossings, guidelines prescribe a lower and upper passage design flow for each targeted fish species and lifestage. The design flows are intended to encompass the range of flows expected to occur during periods when the target fish migrates upstream. At flows below an upper fish passage design flow, the water velocities must not exceed the fish's swimming ability. At flows above a lower fish passage design flow, water depths within the stream crossing must be adequate for the fish to swim through. These design flows are commonly defined in terms of exceedance flows and are derived from flow duration curves (e.g. Vogel and Fennessey, 1994). An exceedance flow defines the average percent of time the stream flow exceeds a specified flow. For example, in 1970 the California Department of Transportation, in conjunction with California Department of Fish and Game, defined an upper fish passage design flow for adult salmon and steelhead as that flow which was equaled or exceeded 10% of the time during the period of upstream migration (Kay and Lewis, 1970).

Reporting stream flow in terms of an exceedance flow allows comparison between watersheds of various sizes and hydrologic characteristics. To place this study's hydrologic and fisheries observations into a larger regional context, and to compare our observations and results to existing flow guidelines, we constructed daily average flow duration curves spanning the migration period (November through April) for the five *Tier 1* sites where fish were observed attempting to pass through the culverts.

Similar to most small streams, no long-term stream flow records exist for any of the *Tier 1* study sites. To estimate the exceedance values associated with flows occurring at the study sites, we used two predictive methods. In the most widely employed method, one generates a daily average flow duration curve (FDC) using flows from a stream with an extensive data set. Then, the exceedance flows are scaled by the difference in contributing drainage areas between the gaged and ungaged streams. Although this approach is relatively easy to apply, it has several obvious shortcomings. Adjusting only by drainage area fails to account for differences in precipitation, evapotranspiration, geology, drainage patterns, and potential scale effects between watersheds.

An alternative technique attempts to account for differences in mean annual rainfall and evapotranspiration between the gaged and ungaged basins. Using the flow duration curve from the gaged stream, exceedance flows are multiplied by a ratio of the estimated mean annual discharge (Q_{ave}) of the gaged and ungaged streams. Although this method attempts to account for hydrologic variation between basins, it relies on accurate estimates of basin wide mean annual precipitation and evapotranspiration to calculate Q_{ave}. Precipitation patterns can vary widely between and within basins due to orographic effects common to California's Coastal Range, making accurate estimates of mean annual precipitation difficult.

4.3.1 Normalizing Flow Duration Curves

Historic stream flow data were used to determine which method worked best for normalizing FDCs of gaged streams within the study area: scaling by drainage area or scaling by Q_{ave}. Four data sets were identified, each having at least 9 years of daily average discharge records, all possessing drainage areas less than 50 mi^2, and all located within close proximity to the *Tier 1* sites (Table 4-2).

The mean annual discharge for each of the four gaged streams was estimated using a regional runoff regression equation developed by Rantz (1968) for the coastal streams in northern California:

$$R = MAP - 0.4(PET) - 9.1 \quad (1)$$

$$Q_{ave} = 0.07362[\mathrm{ft^3\text{-}yr/(s\text{-}in\text{-}mi^2)}]*R*A \quad (2)$$

Where:

Q_{ave}	=	mean annual discharge [ft^3/s]
MAP	=	mean annual precipitation [in/yr]
PET	=	potential evapotranspiration [in/yr]
R	=	mean annual runoff [in/yr]
A	=	drainage area [mi^2]

For the four gaged streams, the basin wide mean annual precipitation (MAP) and potential evapotranspiration (PET) were obtained from isohyetal maps and tables produced by Rantz (1964). For three of the four streams, the mean annual discharges calculated using Equations 1 and 2 were only slightly higher than that calculated using the historic stream flow records (Table 4.2). For unknown reasons, Elk River produced the largest difference between predicted and historical values of Q_{ave}.

Next, FDCs were constructed for each stream using only flows occurring during the period of migration (November through April). To compare the two methods of normalizing the FDCs, exceedance flows were divided by drainage area and predicted Q_{ave}, respectively (Figures 4-2 and 4-3). If the data were perfectly normalized, the flow duration curves for all four streams would converge to a single curve.

Table 4-2. Long-term stream flow gaging stations within the Humboldt Bay region.

USGS Gaging Station		Coverage	Drainage Area	MAP	PET	Q_{ave} (cfs)	
Name	**Number**	**(WY)**	**(sq. miles)**	**(in/yr)**	**(in/yr)**	**Predicted[1]**	**Historic[2]**
Jacoby C Nr Freshwater	11480000	1958-67	5.80	55	33	15.7	15.1
NF Mad R. Nr Korbel	11480800	1958-64 1973-74	40.40	68	36	144.2	141.6
Little River Nr Trinidad	11481200	1956-01	40.50	70	34	153.0	140.5
Elk R. Nr Falk	11479700	1958-67	44.20	55	33	119.4	83.8

[1] Q_{ave} estimated using equations (1) and (2)

[2] Q_{ave} calculated from historic stream flow record.

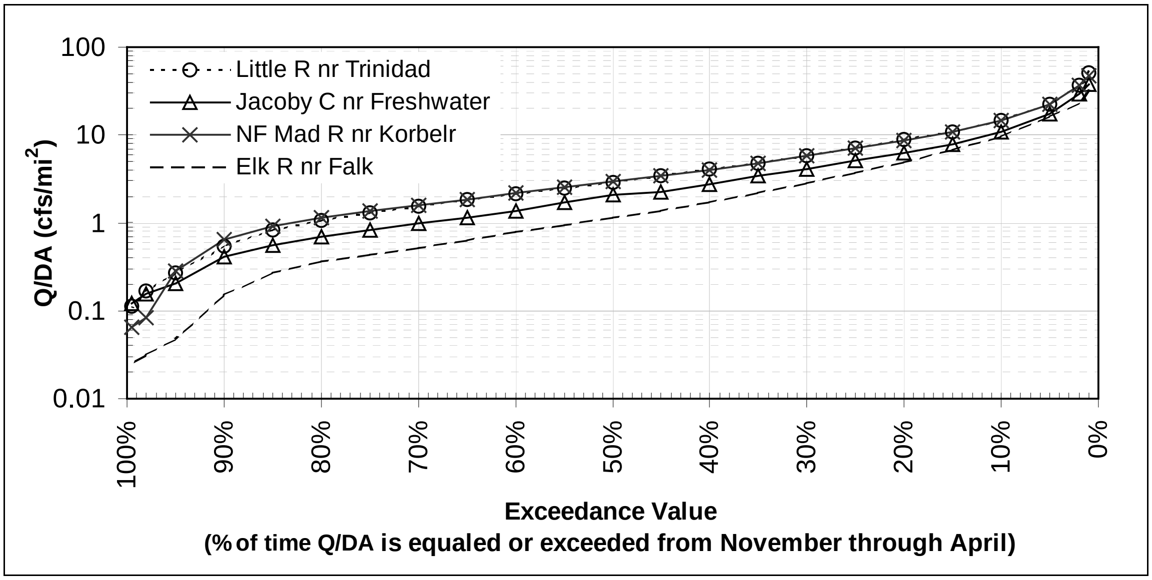

Figure 4-2. Flow duration curves for the migration period, scaled by drainage area (DA).

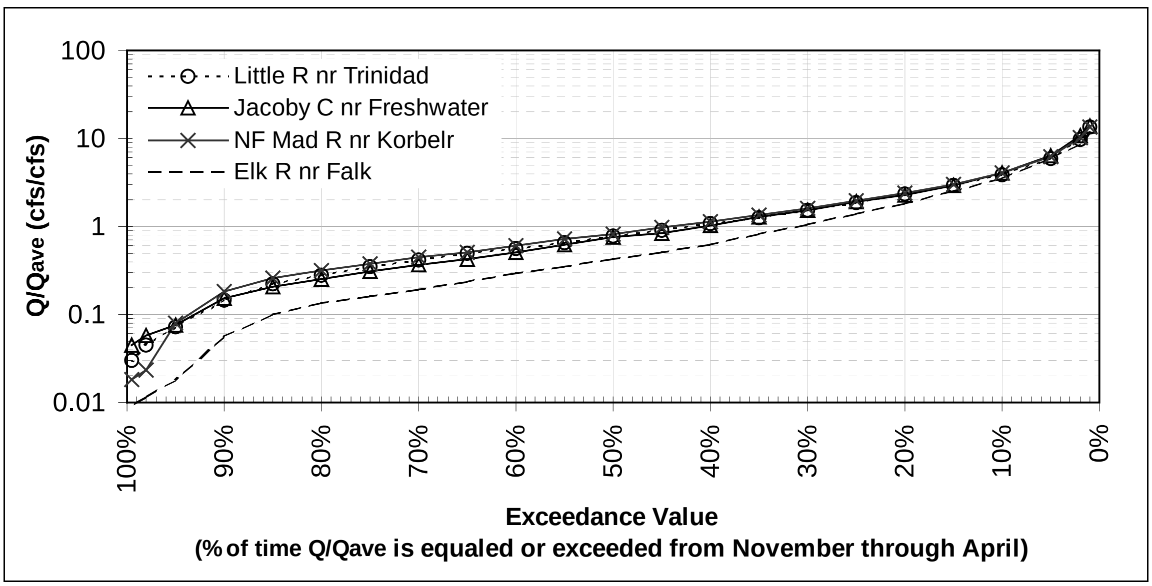

Figure 4-3. Flow duration curves for the migration period, scaled by mean annual discharge, (Q_{ave}).

Visual comparisons show that normalizing the exceedance flows by Q_{ave} is the more effective method. However, in both cases the FDC for Elk River failed to normalize. Unlike the other three streams, Elk River also showed a substantial difference between the historical and predicted mean annual discharge (Table 4-2). Efforts to explain these differences were unsuccessful.

At exceedance flows above 95%, both methods failed to normalize the flow duration curves. This result is not surprising given that low flows are generally associated with base flow conditions, which are typically controlled by basin geology and groundwater storage capacity rather than mean annual precipitation.

4.3.2 Constructing a Regional Flow Duration Curve

Although flows at the *Tier* 1 streams were gaged throughout the study period, flow duration curves created using this three-year record is likely not representative of the streams' average long-term flow characteristics. To create FDCs for the *Tier* 1 sites that represent average long-term flow characteristics, we constructed a regional flow duration curve by taking the median of the normalized exceedance flows from the four gaged streams (Figure 4-4). The median was used instead of the average to avoid biasing the regional FDC towards the outliers. Since there were only four exceedance flows for each corresponding exceedance value, the median was obtained by discarding the smallest and largest flows and then calculating the midpoint between the two remaining flows.

To convert the normalized regional flow duration curve into individual FDCs, Q_{ave} was calculated for each of the study sites using equations (1) and (2) and then multiplied by the normalized exceedance flows. The FDCs for the *Tier 1* study sites are presented in Appendix C.

While preparing this report, the California Department of Fish and Game was deciding whether to define fish passage design flows using annual FDCs or migration period FDCs (CDFG, 2002). To allow comparison between the two approaches, we also constructed a normalized regional flow duration curve that encompasses the entire water year (Figure 4-5). In addition, tabular and graphical comparisons between the annual and migration period FDCs, both regional and site specific, are included in Appendix B.

The FDC created using the migration period spans six months, or roughly half of the entire water year. Average monthly precipitation values for each month from November through April are greater than the May through October average monthly precipitation values. Through comparing the annual and migrational FDCs, we see that a year's upper 25% of flow occurs almost exclusively between November and April. For this reason, exceedance flows associated with the six-month migrational FDC (Figure 4-4) that are between zero and 50% can be converted to annual exceedance flows by dividing by two. For example, the 10% exceedance flow from the migration period FDC is equivalent to the 5% exceedance flow for the annual FDC.

4.4 FLOW DURATION CURVES AND ANNUAL VARIABILITY

Generally, flow duration curves are empirically derived from historic stream flow data and are devoid of measures of statistical significance. Thus, the traditional FDCs do not describe the degree of annual variability common to the stream flow. Vogel and Fennessey (1994) describe a non-parametric technique for constructing FDCs that statistically demonstrate the annual flow variability using confidence intervals. This approach requires constructing individual flow duration curves for each year of record. Using all of the yearly FDCs, the median exceedance flow is calculated for each exceedance value, thus constructing the median annual flow duration curve. This median annual flow duration curve represents the entire period of record. On this non-parametric FDC, for example, if the 10% exceedance flow is 15 cfs, half of the years within the period of record would have experienced a 10% exceedance flow less than 15 cfs and the other half would have experienced a 10% exceedance flow greater or equal to 15 cfs.

Using the individual year FDCs allows for estimating confidence bounds on the median annual FDC. For example, to construct an upper 95% confidence bound for a specific exceedance flow, one identifies the flow that was exceeded 5% of the years corresponding to that exceedance value. Conversely, a lower 95% confidence bound can be calculated by identifying the flow that was exceeded 95% of the time at a particular exceedance flow. Calculating the upper and lower 95% confidence bounds for each exceedance flow creates a two-sided confidence interval around the median annual FDC.

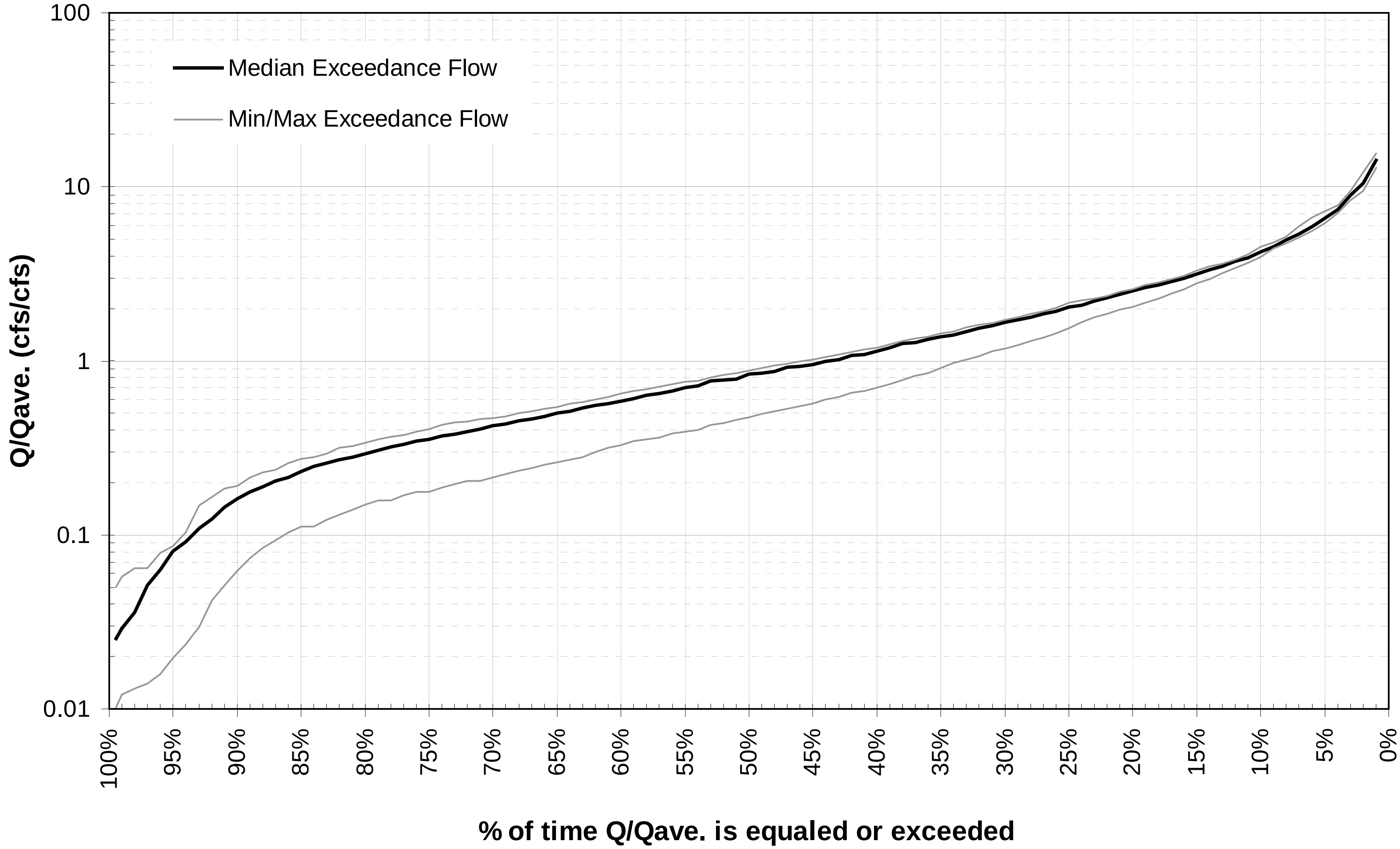

Figure 4-4. The Humboldt Bay region normalized flow duration curve for the migration period (November to April), constructed using the median exceedance flows from the Little River, Jacoby Creek, North Fork Mad River, and Elk River flow duration curves.

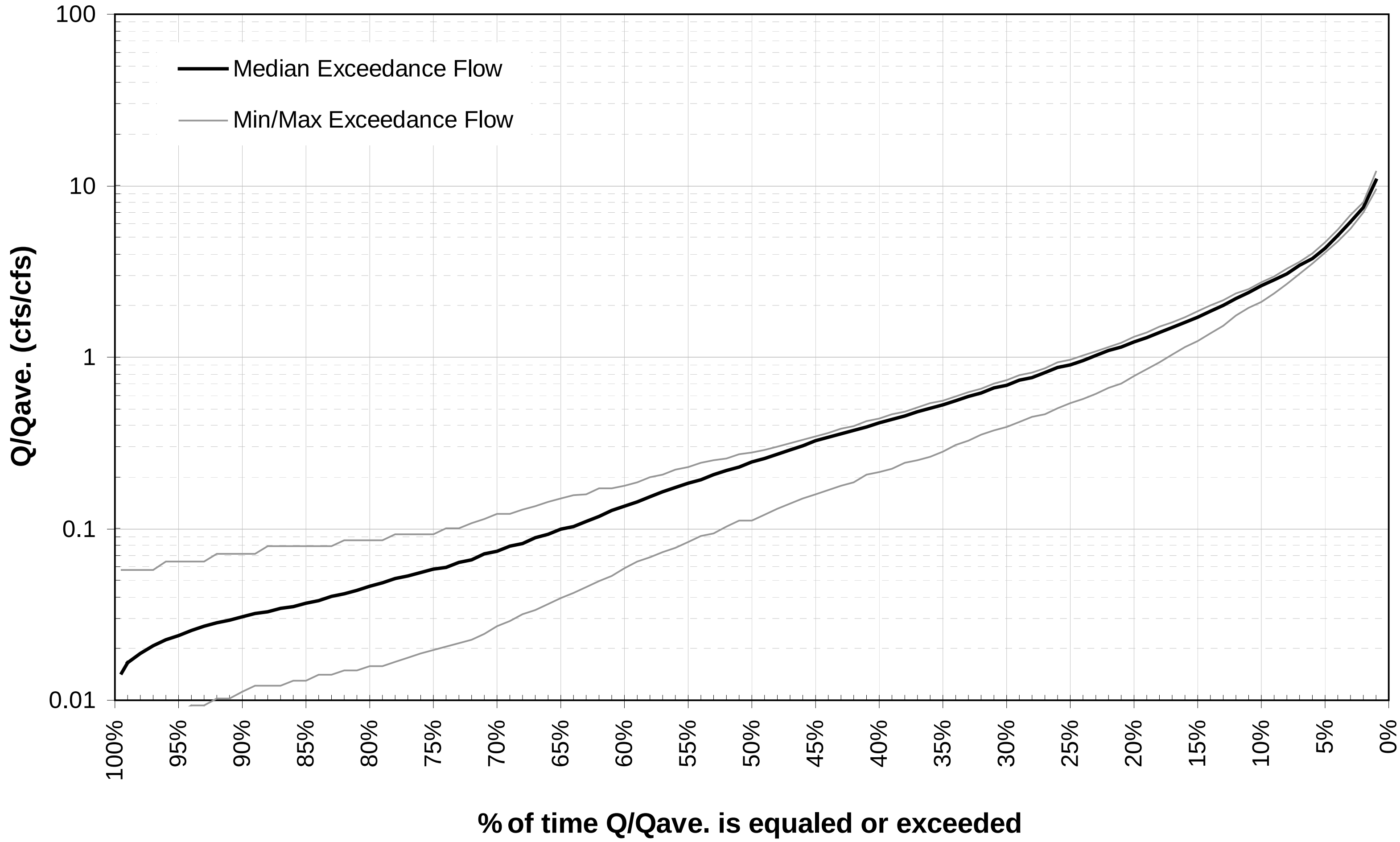

Figure 4-5. The Humboldt Bay region normalized annual flow duration curve for the entire water year, constructed using the median exceedance flows from the Little River, Jacoby Creek, North Fork Mad River, and Elk River annual flow duration curves.

Of the four long-term gaged streams used to create the regional flow duration curve, the Little River has the longest record (46 years) and was the only gage in operation throughout the three-year study. Using Little River data, we applied the non-parametric technique to construct a median annual FDC with a 95% confidence interval, normalized by Q_{ave} (Figure 4-6). The upper confidence interval represents the wettest 5% of years. The FDC is shifted upward because higher relative flows occur more frequently in wet years. The converse interpretation explains the lower confidence interval.

Using this approach to construct flow duration curves can assist in quantifying the potential delays imposed by a selected fish passage design flow during wet or dry years. As an example, one question of interest may be during years of low rainfall in the Little River Watershed what are the potential implications of selecting the 50% annual exceedance flow ($Q_{50\%}$) as the lower fish passage design flow? Using Figure 4-6, we observe that the lower 95% confidence limit for the $Q_{50\%}$ corresponds to the 29% exceedance value. This indicates that during 5% of the years flows will be below the lower fish passage design flow for more than 71% of the time, in contrast to the desired 50%.

Flow duration curves for each year of the study were also plotted on Figure 4-6 to compare the annual variation experienced between water years 1999 through 2001. Exceedance flows during WY1999 were generally greater than the median annual exceedance flows, but did not surpass the upper 95% confidence interval. The FDC for WY2000 was approximately equal to the median annual FDC. The WY2001, a very dry year, FDC almost coincides with the lower 95% confidence interval.

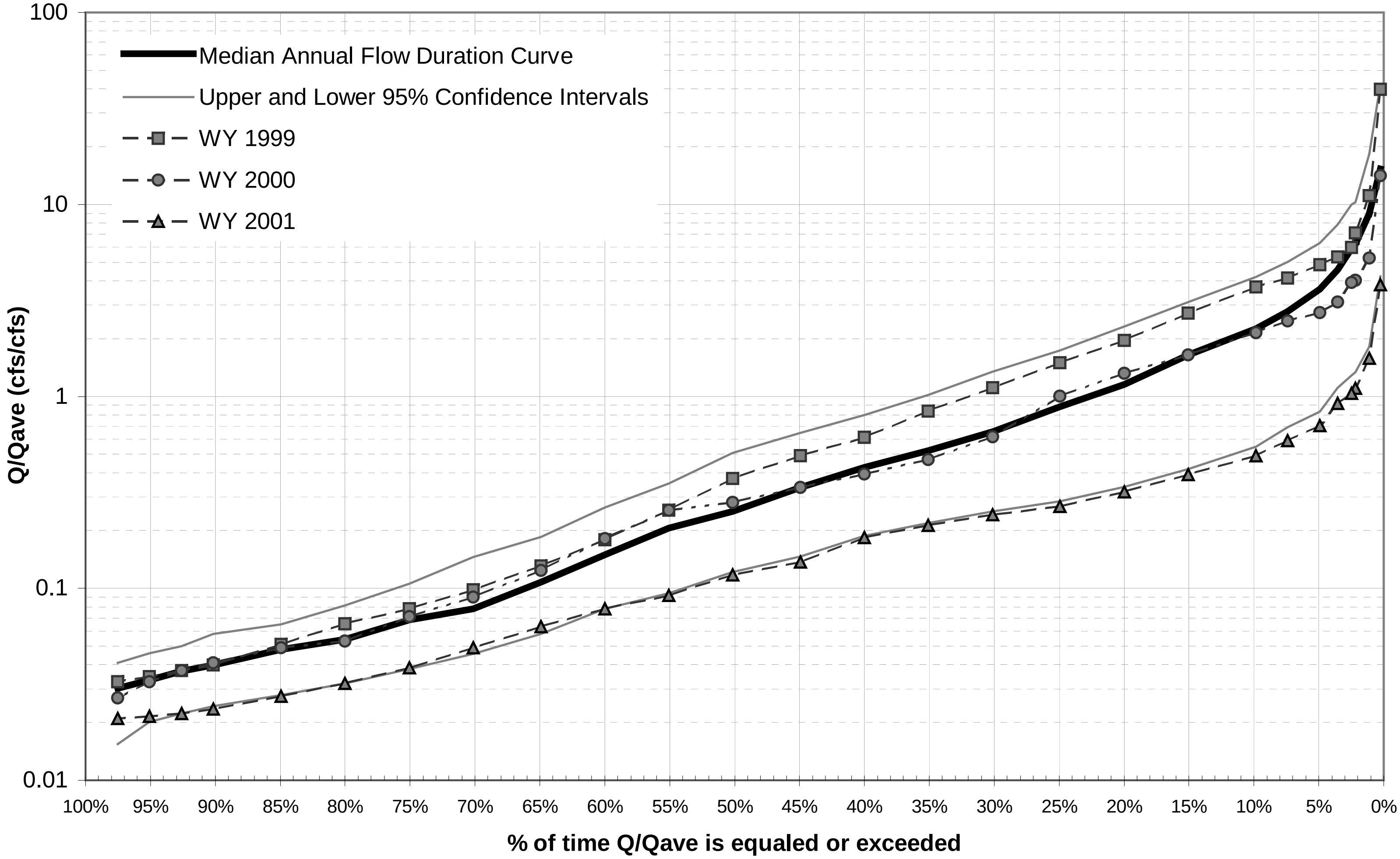

Figure 4-6. The median annual FDC for the Little River, normalized by average annual discharge (Q_{ave}). The curves were constructed using non-parametric techniques outlined by Vogel and Fennessey (1994). Exceedance flows fall inside the confidence intervals 90% of the years. To demonstrate the annual variability in flow conditions, the flow duration curve for each of the three project years are also plotted.

4.5 SUMMARY AND DISCUSSION

The three-year study period captured a range of hydrologic conditions representative of the variation expected within the coastal mountains of Northern California. The first year of the study, water year 1999, was a wetter than average season; the peak flow event had a return period ranging from five to twenty years, depending on the site location. Water year 2000 produced close to average flow conditions within the project area, while the third year of the study was characterized by drought.

To accommodate fish passage at stream crossings, guidelines prescribe a lower and upper passage design flow for each targeted fish species and lifestage. These design flows are commonly defined in terms of exceedance flows and are derived from flow duration curves. Reporting stream flow in terms of an exceedance flow allows comparison between watersheds of various sizes and hydrologic characteristics.

To place this study's stream flow and fisheries observations into a larger regional context, and to compare our observations and results to existing flow guidelines, we constructed daily average flow duration curves for four historically gaged streams within the Humboldt Bay region. Two methods of normalizing the curves were compared; adjusting by the ratios of drainage area and Q_{ave}. Normalizing by Q_{ave}, which accounts for differences in mean annual precipitation and evapotranspiration between basins, better normalized the gaged streams' flow duration curves.

Both methods fail to normalize the low flow portion of the FDC. The variability between stream flow at lower flows is more likely due to differences in underlying geology than precipitation. With a limited number of streams having sufficient flow records within the region and due to the complex nature of the geology within the California Coastal Range, it is unlikely that a method can be developed to normalize the low flow portion of flow duration curves for streams within the region.

Two regionalized flow duration curves, normalized by Q_{ave}. were constructed. One curve represents regional flow conditions during the period of upstream fish migration, considered to occur from November through April. The other curve describes regional flow conditions occurring throughout the entire year.

Using a non-parametric technique, a normalized median annual FDC with upper and lower 95% confidence intervals was constructed for the Little River. Where extensive gaging records are available, this method for constructing FDCs, allows quantifying the potential impacts of a selected fish passage design flow on fish migration due to annual variability in flow conditions.

5 HYDRAULICS

When fish attempt to pass through culverts, the culverts' hydraulic conditions strongly influence passage success. Culvert hydraulic conditions were evaluated by measuring water surface profiles and velocity distributions perpendicular and parallel to the flow direction. The water surface profiles (WSPs) were used to (1) determine the Manning's roughness coefficient for different culvert types under varying flow conditions, and (2) verify and compare predictions from the FishXing hydraulic model against actual field conditions. Field velocity data allowed us to generate velocity contour (isovel) plots and calculate average cross-sectional velocities. We then compared average velocity against occupied velocity, which is the velocity that a swimming fish may actually encounter.

5.1 DATA COLLECTION METHODS

Water surface profiles were measured using a Sokkisha model B2A automatic level (Appendix D). Spacing of longitudinal measurements depended on how quickly the water surface slope changed and the length of the culvert. Closely spaced measurements (typically within 1 ft) were collected near the culvert inlet and outlet, and at all other locations with rapidly varying slopes. Where water surface slopes were relatively gentle, measurement intervals ranged from 5 to 10 feet. Generally, measurements were made along the culvert's centerline; if the culvert was baffled on one side or other unique conditions were encountered, water surface profiles were measured at multiple longitudinal locations. For culverts baffled only on one side, water surface profiles were measured down the center of each side. A discharge measurement was collected every time a WSP was measured (Appendix A).

Within a culvert cross-section, velocity contour plots can show areas of relative high and low velocity. Using a digital pygmy meter, velocity distributions perpendicular to the flow (velocity cross sections) were generated from point velocities measured on a "tight" grid at the culvert inlet, midpoint, and outlet. For example, in a 6 ft x 8 ft (H x W) box culvert with a 1-ft water depth, velocities were measured every 0.5 ft in the horizontal (width) direction and at 0.2, 0.5, and 0.8 ft in the vertical (depth) direction. For this case, 45 velocity measurements were collected at each cross section.

5.2 ROUGHNESS COEFFICIENTS

Roughness of the culvert material or embedded substrate greatly influences flow conditions within a culvert. We calculated roughness coefficients from field measurements for standard, baffled, and embedded culverts and compared field roughness coefficients to those in the literature (Tables 5-1 through 5-3) (field data in Appendix A). Under field conditions, roughness coefficients may be influenced by many factors, such as deposition of bedload along the culvert invert, or by differential settling that warps the culvert. To determine whether roughness coefficients vary with discharge, many culvert's hydraulic conditions were measured at multiple flow rates.

Manning's roughness coefficients were calculated from the water surface profiles in standard culverts (no embedded substrate or modifications for fish passage) assuming uniform flow in the culvert barrel. Those sites meeting the following requirements were included: (1) a significant length of flow inside the culvert was not affected by inlet or outlet conditions, and (2) culvert slope and water surface slope were sufficiently similar to assume uniform flow (Table 5-1). Both culvert slope and water surface slope through the culvert barrel are presented in the table for comparison; roughness coefficients were calculated using the culvert slopes.

Table 5-1. Manning's roughness coefficients (n) for standard CMP and concrete culverts. Manning's n-values are calculated using the culvert slope, water depth, and measured flow within the culvert barrel. Water surface slope is included to assess the suitability of assuming uniform flow in the culvert barrel.

Culvert	Description	Discharge (cfs)	Depth (ft)	Water Surface Slope	Culvert Slope	n
Walton	Circular CMP, D = 4 ft, 2 2/3"x 1/2" corrugation	1.6	0.44	2.3%	2.3%	0.044
		6.6	0.90	1.7%	2.4%	0.049
Morrison Creek	Circular CMP, D = 5 ft, 2 2/3"x 1/2" corrugation	17.3	1.20	1.1%	1.0%	0.025
		11.9	1.13	1.1%	1.0%	0.032
		6.7	0.79	0.8%	1.0%	0.028
Boundary Creek	Circular CMP, D = 7 ft, 2 2/3"x 1/2" corrugation	5.5	0.52	2.8%	3.3%	0.030
Chadd Creek	Circular SSPP, D = 9 ft, 6"x2" corrugation	24.2	1.56	1.7%	2.0%	0.061
		30.4	1.52	1.6%	2.0%	0.046
		44.3	2.00	1.9%	2.0%	0.055
James Creek	Circular SSPP, D = 12 ft, 6"x2" corrugation	10.5	0.77	4.7%	4.6%	0.058
Dry Creek	Concrete box, 6' H x 8' W	15.9	0.64	0.7%	0.5%	0.027
Durphy Cr (Middle)	Concrete box, 8' H x 12' W	16.6	0.45	3.9%	4.7%	0.041

Table 5-2. Manning's roughness coefficients (n) for embedded culverts calculated from water surface profiles. Roughness coefficients are calculated using FishXing to identify the roughness coefficient that matches the water surface profile through the culvert at each flow rate.

Culvert	Description	Discharge (cfs)	Depth (ft)	Water Surface Slope	Culvert Slope	n
Durphy Cr (Lower)	Pipe Arch 6.25' H x9.33' W, CMP 5"x1", embedded throughout	16.6	1.12	0.8%	1.4%	0.059
Durphy Cr (Upper)	Circular CMP, D = 10 ft, 6"x2" corrugation. Partially embedded.	34.9	2.00	0.3%	0.3%	0.030
Lower McCready	Concrete Box, 10' Hx10' W, embedded throughout	39.6	2.02	0.1%	0.2%	0.050
		10.3	0.72	0.4%	0.1%	0.032
		7.5	0.59	0.7%	0.6%	0.061

Table 5-3. Manning's roughness coefficients (n) for baffle retrofits calculated from water surface profiles.

Roughness coefficients are calculated assuming uniform flow in the culvert barrel for those culverts with standard shapes (Clarks Ck, Upper McCready Gulch, Lower Peacock and Warren Gulch). The roughness coefficients for Upper Peacock Creek and Sullivan Gulch were determined using FishXing to identify the roughness coefficient that best matched the water surface profile through the culvert at each flow rate. Roughness coefficients were only calculated for flow conditions that resulted in completely submerged baffles. These values are composite roughness coefficients accounting for the sum effects of the culvert materials, modifications and retrofits and are highly dependent on flow rate.

Culvert	Description		Discharge (cfs)	Depth (ft)	Water Surface Slope	Culvert Slope	n
Clarks Creek	Concrete box 8' H x 8' W, retrofit with offset baffles		29.7	2.38	1.5%	1.3%	0.142
			4.8	1.50	1.2%	1.3%	0.448
Upper McCready	Concrete Box, 8' H x 10' W, Right side retrofit with offset baffles		19.8[A]	1.95	1.2%	0.6%	0.062
			5.2[A]	1.27	1.0%	0.8%	0.107
			7.5[A]	1.17	0.6%	0.6%	0.076
	Left side retrofit with corner blocks		19.8[A]	1.91	1.0%	0.6%	0.059
			5.2[A]	0.66	0.8%	0.7%	0.082
			0[A]	Insignificant flow in left side of cuvlert at 7.5 cfs.			
Warren	Circular, D = 6 ft. Retrofit with offset baffles. Culvert has two distinct segments with very different slopes.	US segment	5.2	1.07	0.7%	0.8%	0.063
			15.1	1.45	0.8%	0.7%	0.039
		DS segment	5.2	0.60	5.7%	5.8%	0.054
			15.1	1.09	5.4%	5.8%	0.063
Lower Peacock	Circular CMP, D = 7.5 ft, 6"x 2" corrugation w/only three remaining ramp baffles		10.6	0.77	2.9%	3.1%	0.036
Sullivan Gulch	Modified Circular SSPP, D=9.5 ft, 6"x2" corrugation, retrotfit with ramp baffles.		43.1	1.31	0.7%	1.7%	0.042
			17.6	0.98	1.0%	1.7%	0.063
			15.1	0.96	1.0%	1.7%	0.072
Upper Peacock	Pipe Arch, H=8.5 ft, W=13 ft, retrofit with alternating notched weir baffles		33.4	1.84	3.3%	3.6%	0.163

[A] - The flow through the left and right sides of the McCready Gulch culvert was assumed to be evenly split above approximately 10 cfs.
Below 10 cfs, a board across the left-side of the culvert inlet effectively blocked inflow to the left, maintaining higher water depths on the culvert's right side.
The flows reported in the table are the flows through each side of the culvert; the total flow is the sum of the right and left side flows.

A composite roughness coefficient was used for baffled and embedded culverts. A composite roughness is a function of the wetted perimeter for each of the different materials; the culvert wall material and the embedded substrate or bottom modification. Thus, these coefficients depend strongly on flow rate. For baffled culverts and those embedded with large substrate, as flow increases the relative percent of the wetted perimeter contacting the smoother culvert walls increases, resulting in a lower composite roughness. Composite roughness coefficients for these culverts were calculated using FishXing's one-dimensional, gradually varied flow solution. Roughness coefficients were varied until the observed water surface profile for each flow rate was matched. In baffled culverts, roughness coefficients were calculated only if the baffles were completely submerged. Roughness coefficients were not calculated for embedded culverts with discontinuous substrate or highly variable substrate depths.

For embedded culverts, roughness coefficients varied from 0.030 to 0.061 (Table 5-2). The two culverts that have embedded substrate throughout have very different substrate sizes: the d_{50} of the Durphy Creek (lower culvert) substrate was 28 mm, and Lower McCready's d_{50} was <4 mm.

Offset baffles and ramp baffles were examined as part of this study, and both are presented in the *California Salmonid Habitat Restoration Manual* (CDFG, 1998). Baffled culverts' roughness coefficients varied from 0.036 to 0.448 (Table 5-3). At Clarks Creek, the offset baffles significantly increase roughness at low flow (n=0.142 at 30 cfs; n=0.448 at 4.8 cfs). A similar relationship was observed for the ramp baffles at Sullivan Gulch, but to a lesser degree (n=0.043 at 43 cfs; n=0.072 at 15 cfs). Clarks Creek's 1.5 ft high offset baffles increased roughness more effectively than Sullivan Gulch's alternating 1 ft x 2 ft x 3 ft (H x W x L) ramp baffles with 12 ft spacing. Lower Peacock also has ramp baffles with dimensions 0.9 ft x 2.0 ft x 2.6 ft (H x W x L) placed along the right side of the culvert with 12 ft spacing. However, all but three of the baffles have been dislodged which explains the lower roughness values.

When designing culverts for fish passage, engineers typically use standard roughness coefficients listed in the Federal Highways Administration's publication, *Hydraulic Design of Highway Culverts* (Normann et al., 2001). However, these roughness coefficients were intended for use in modeling culvert hydraulics at very high flows (approximately ¾ full), well above the typical fish migration flow. Comparing measured Manning's roughness coefficients against these accepted literature values; the measured n-values were generally much greater (Table 5-4). These differences in roughness coefficients will impact hydraulic model predictions for fish passage. These potential impacts are investigated in Section 5.3.

Table 5-4. Comparison of observed and literature roughness coefficients for standard culvert materials.

Material	**Range of Measured n**	**Literature n (Normann *et al.*, 2001)**
Concrete box	0.023 – 0.053	0.012 – 0.015
2 2/3 x ½-inch corrugated metal	0.024 – 0.049	0.022 – 0.027
6 x 2-inch corrugated metal	0.054 – 0.061	0.033 – 0.035

5.3 Comparison of Field Measurements and Model Results

Culvert hydraulics software programs are commonly used in designing and assessing stream crossings for fish passage. Generally, when calculating hydraulic conditions within the culvert barrel, these models assume one-dimensional and steady-state, gradually varying flow [HydroCulv v1.2 (HydroTools, 2000); FishPass (Behlke et al., 1991); FishXing v2.2 (Love et al., 1999)]. Because fish passage designs are based on these models, it is critical to determine if the models adequately describe real, field-verified conditions.

For evaluating fish passage through culverts, a widely used software program is FishXing Version 2.2 (Flanders and Cariello, 2000; Taylor and Love, 2003; Taylor, 2001a,b). We evaluated FishXing's ability to accurately predict measured water depths in standard culverts (culverts not embedded or modified for fish passage), using roughness coefficients calculated from our field measurements (Table 5-1). Embedded and modified culverts were not evaluated because FishXing was used to calculate the roughness coefficients that best simulated the observed culverts hydraulics for these types of sites. We also predicted water depths and velocities using the standard roughness coefficients (Normann et. al, 2001). These standard roughness coefficients are widely used and offered as the default values in FishXing and other hydraulic analysis software (Table 5-4).

Using the field derived roughness coefficients, the predicted water surface profiles correspond reasonably well with those profiles measured in the field (Figures 5-1 through 5-5). Most of the discrepancies can be explained by slope breaks within the corrugated metal culverts. Most culvert software, including FishXing, assumes a constant culvert slope. However, within nearly all corrugated metal culverts the invert sags and the slope fluctuates throughout. Frequently, the cross sectional shape will gradually vary throughout the culvert due to deformation caused by loading. Although these variations in slope and shape are typically inadvertent, they occur during installation or through aging and can lead to unintended hydraulic conditions.

At Dry Creek's concrete box culvert, the modeled and field measured water surface profiles closely agreed. Like most concrete stream crossings, this site had a constant slope and cross-sectional shape, which are characteristics that match the model assumptions.

Predicted fish passage conditions—primarily water depth and velocity—can be greatly affected by which roughness coefficient, field-measured or literature, is used. In all cases, the field measured roughness coefficients were greater than the literature coefficients. Comparing the predicted water surface profiles generated using the two roughness coefficients, the field-based n-values generally produced substantially greater water depths and lower velocities. Using the field-based n-value instead of the literature n-values decreased predicted average velocity within the barrel of each culvert (Table 5-5), which could produce a significant change in predicted passage conditions.

If literature n-values tend to overestimate velocities, and underestimate water depths, then using literature n-values for hydraulic design of fish passage culvert design introduces a substantial element of conservatism. This degree of conservatism can be considered a factor-of-safety for fish passage design, guarding against installation uncertainties and changes due to aging that may create undesirable hydraulic conditions for fish passage.

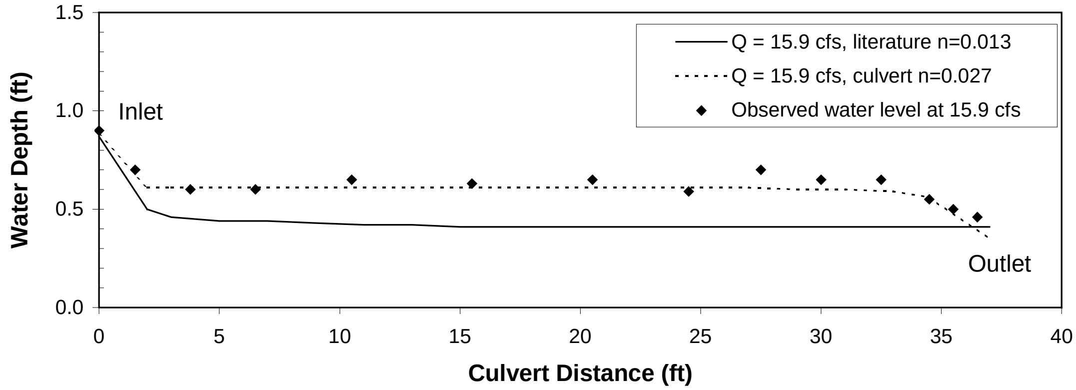

Figure 5-1. Dry Creek culvert longitudinal profile of water depths at Q = 15.9 cfs, modeled with FishXing, using culvert n =0.027 and literature n =0.013.

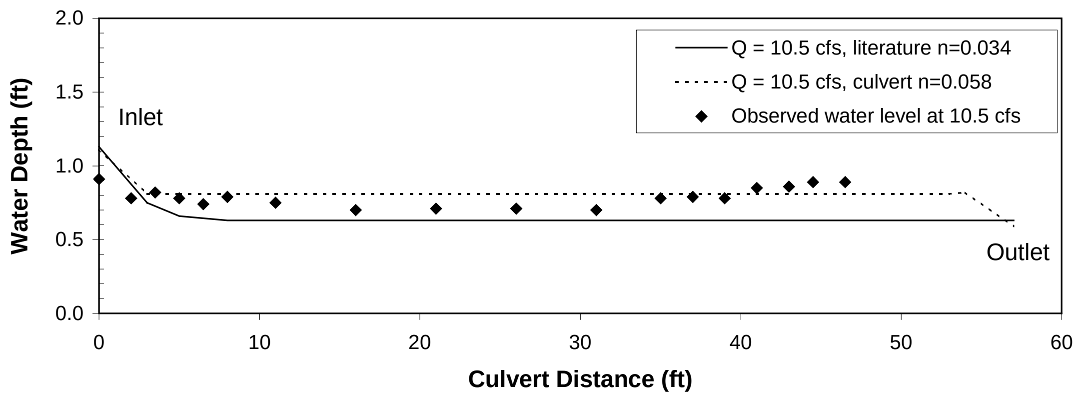

Figure 5-2. James Creek culvert water depths at Q = 10.5 cfs, modeled with FishXing, using culvert n=0.058 and literature n=0.034.

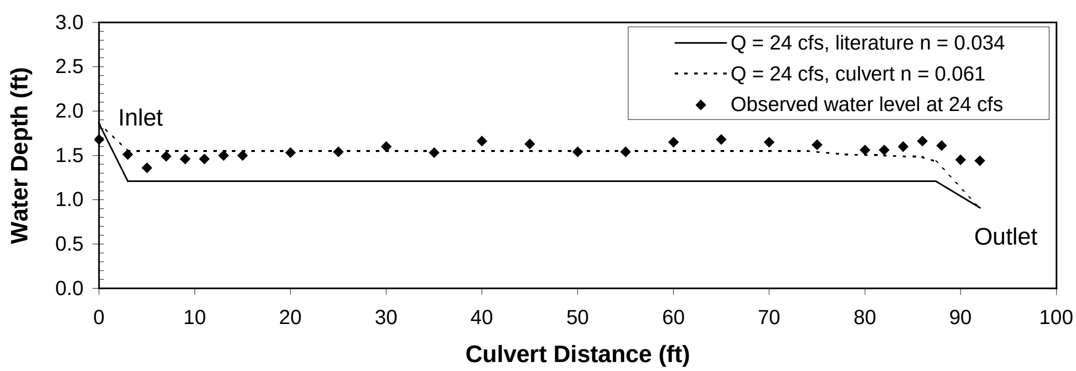

Figure 5-3. Chadd Creek culvert water depths at Q = 24 cfs, modeled with FishXing, using culvert n=0.061 and literature n=0.034.

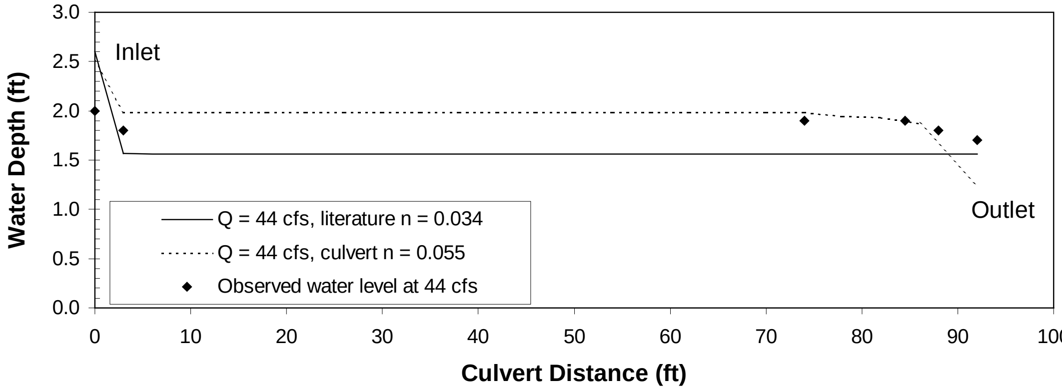

Figure 5-4. Chadd Creek culvert water depths at Q = 44 cfs, modeled with FishXing, using culvert n=0.055 and literature n=0.034.

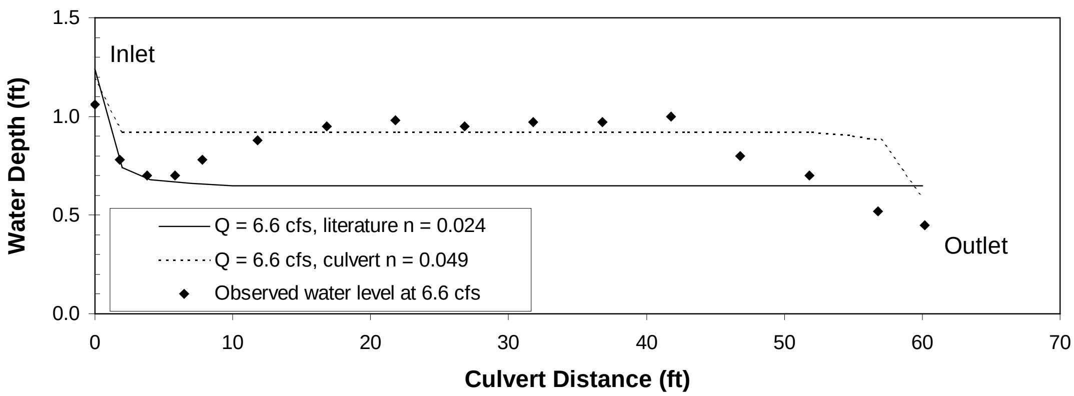

Figure 5-5. Walton Creek culvert water depths at Q = 6.6 cfs, modeled with FishXing, using culvert n=0.049 and literature n=0.024.

Table 5-5. Average water velocities in the culvert barrel calculated using both culvert and literature n-values. Culvert roughness coefficients were always greater than those reported in the literature.

Culvert Location	Modeled Average Water Velocity (ft/s)		Decrease in Velocity
	Using literature n-value	Using culvert n-value	
Dry Creek (15.9 cfs)	4.9	3.3	33%
James Creek (10.5 cfs)	5.2	3.6	31%
Chadd Creek (24.2 cfs)	4.7	3.6	23%
Chadd Creek (44.3 cfs)	6.0	4.3	28%
Walton Creek (6.6 cfs)	5.0	3.5	30%

5.4 VELOCITIES IN CULVERT CROSS SECTIONS

Plots of culvert cross sections containing contours of equal water velocity were created using the point velocities measured along cross sectional grids (Appendix A). These plots verify that velocities along the culvert walls were generally far lower than those velocities in the center of the flow.

The James and Dry Creek culverts are not embedded and, as expected, their culvert cross sections show smooth transitions in velocity contours (Figures 5-6 and 5-7). Even at a relatively low discharge of 10.5 cfs, the James Creek culvert causes high velocities, primarily due to its steep slope (4.6%). The maximum velocity measured was 9.9 ft/s (3.0 m/s). Cow Creek, an embedded culvert, demonstrates how downstream backwater effects can substantially reduce the peak velocities (Figure 5-8).

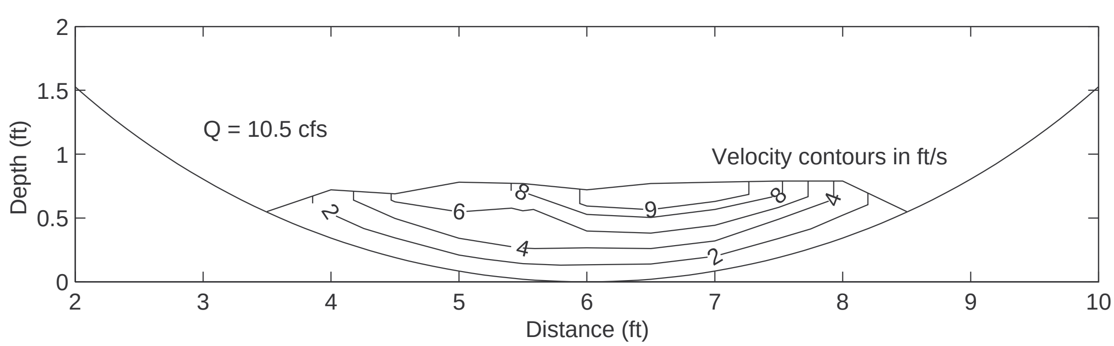

Figure 5-6. Velocity contours in the James Creek culvert barrel cross section at Q = 10.5 cfs (0.30 cms). This culvert is a 12-ft (3.6-m) diameter circular metal pipe with 6x2-inch corrugations installed on a 4.6% slope.

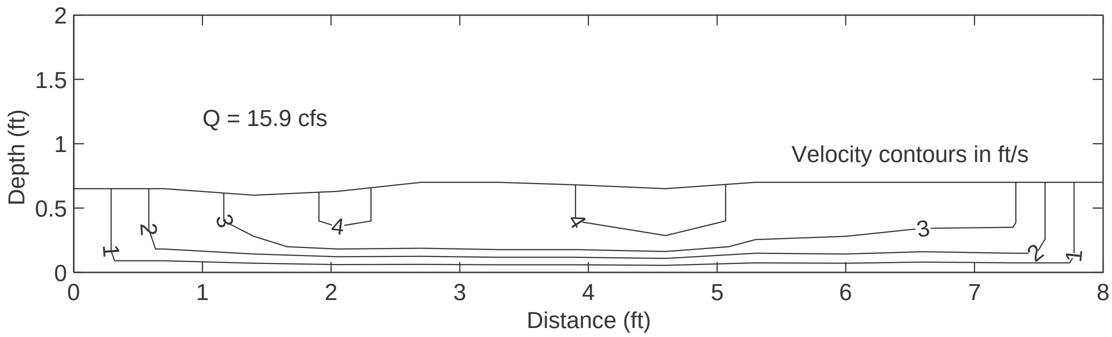

Figure 5-7. Velocity contours for the Dry Creek culvert barrel cross section at Q = 15.9 cfs (0.45 cms). This culvert is a 6-ft high by 8-ft wide (1.8 m x 2.4 m) concrete box culvert installed on a 0.8% slope.

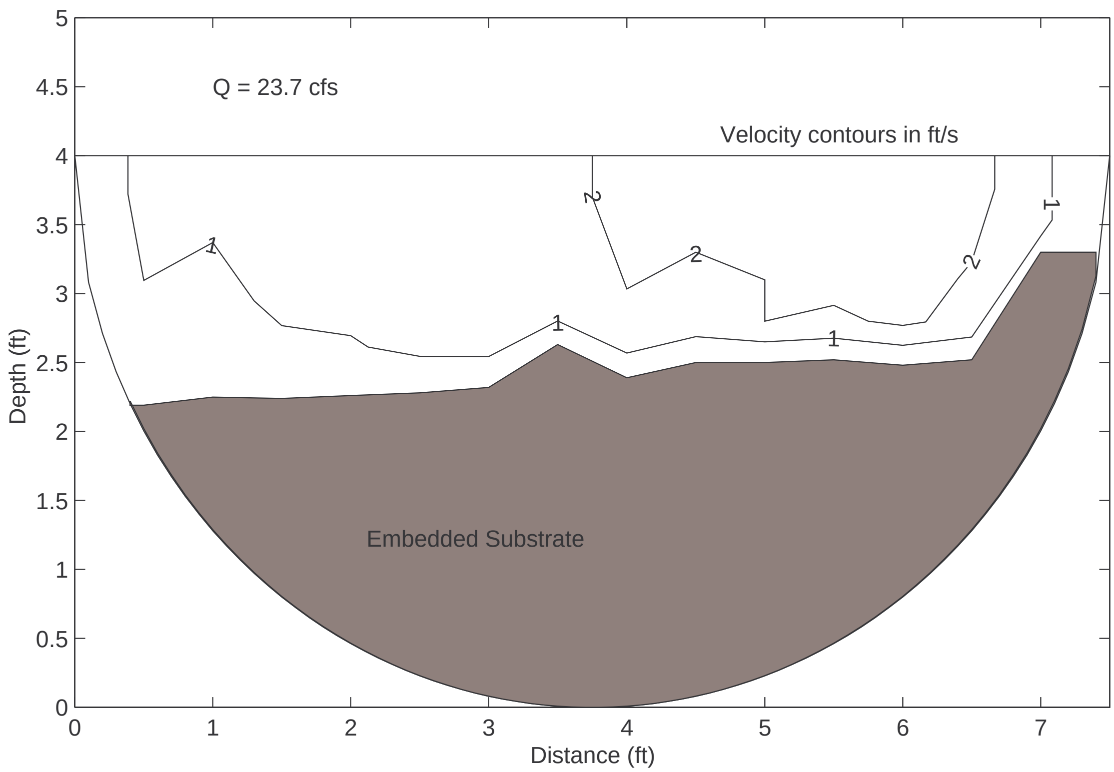

Figure 5-8. Velocity contours for the Cow Creek culvert barrel cross section at Q = 23.7 cfs (0.67 cms), which is almost twice the discharge of the non-embedded culverts shown in Figures 5-6 and 5-7. This culvert is an embedded, elliptical metal culvert 7.5-ft high by 8-ft wide (2.3 m x 2.4 m), with 2-2/3x1/2-inch corrugations installed on a 4.4% slope. The culvert is backwatered by a downstream control with an elevation greater than the inlet invert elevation.

5.5 OCCUPIED VELOCITY

Fish observations in natural channels and culverts confirm that fish often swim along channel and culvert margins, utilizing regions of lower water velocity. Juvenile salmonids have even been observed using the corrugations of metal culverts as resting areas (Powers, 1996; Behlke, 1998). The velocities a fish encounters when it takes advantage of lower velocities near the culvert walls or bottom is commonly referred to as the occupied velocity.

Most current guidelines for fish passage at stream crossings specify average water velocities. To determine whether accounting for occupied velocity is warranted, and if occupied velocities can be correlated to average water velocity, we computed average and occupied velocities. The difference between the average and occupied velocities in a culvert is sometimes accounted for by multiplying the average velocity by some fraction (a reduction factor) to obtain the occupied velocity. Reduction factors have been reported to range between 0.4 and 0.8 for juvenile salmonids (Behlke et al., 1991).

To calculate the occupied velocity, a tenth of a foot uniformly spaced water velocity grid was generated, assuming linear interpolation between the measured point velocities. A representational cross section of each fish species and life stage was assumed and overlain onto this uniform velocity grid (Figure 5-9). The fish's cross-section area was assumed to be square, to simplify calculations. The assumption of a square cross section area overestimates the actual cross section of a swimming fish, so occupied velocity should be slightly overestimated by this simplification.

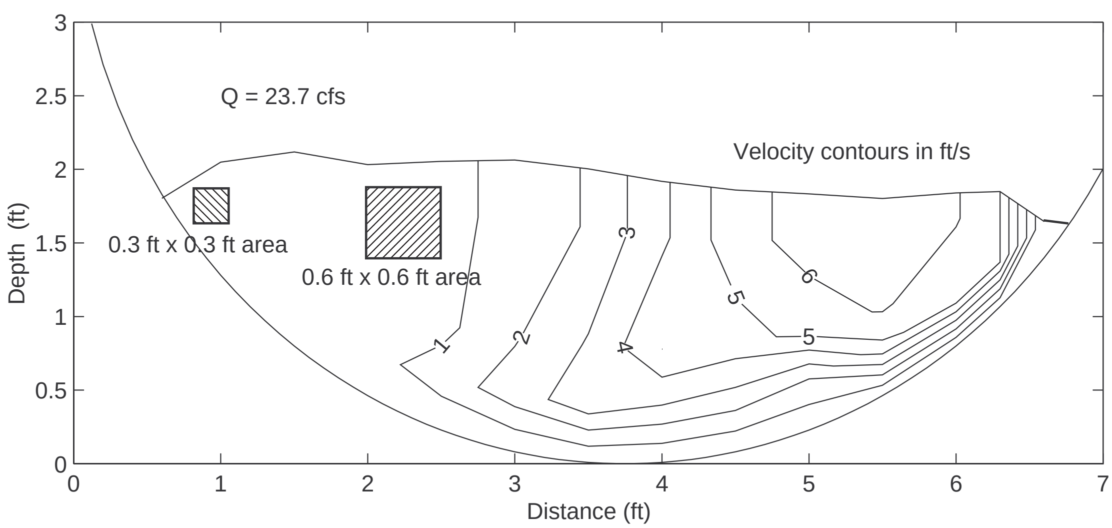

Figure 5-9. Velocity distribution within a circular culvert. The square boxes represent the assumed fish cross sections when fish are swimming upstream.

A juvenile salmonid was assumed to occupy a cross-sectional area of 0.3 ft x 0.3 ft (0.09 sq. ft) while swimming upstream. For adult trout, salmon, and steelhead, a 0.6-ft square (0.36 sq. ft) and a 0.8-ft square (0.64 sq. ft) were used, respectively. By overlying these fish cross-section areas throughout the velocity grid, the average velocity in the fish cross section could be calculated. By noting the minimum average velocity calculated for each fish cross section, the occupied velocity for that fish species or life stage is found. The minimum average velocity encountered for each fish size class is then compared to the average velocity in the culvert cross section to determine the reduction factor.

As water depth decreases, the relative difference between the occupied and average velocities should decrease (that is, reduction factors should become closer to 1.0). In non-embedded culverts, a linear fit reasonably describes the relationship between water depth and the reduction factor for a 0.3 x 0.3 ft^2 fish body area, but not for a 0.6 x 0.6 ft^2 fish body area (Figure 5-10). The 0.8 x 0.8 ft^2 area representing adult salmon and steelhead is not included here due to insufficient data. It is evident that as the size of the occupied area increases the correlation between water depth and reduction factors decreases. This observation is expected because the larger occupied areas sample greater variations in point velocities.

Embedded culverts also exhibit a good relationship between reduction factors and water depth for the smallest fish size class (Figure 5-11). However, no relationship was observed for either of the larger fish size classes, 0.6-ft x0.6-ft and 0.8-ft x0.8-ft. In both the embedded and the non-embedded circular culverts, the reduction factor regression lines for the smallest fish size class are very similar. At a water depth of 1 foot, the reduction factors for juvenile fish are approximately 0.4 for both embedded and non-embedded circular culverts. This suggests that the embedded substrate at these measured sites had little effect on the velocity reduction factors for juvenile fish.

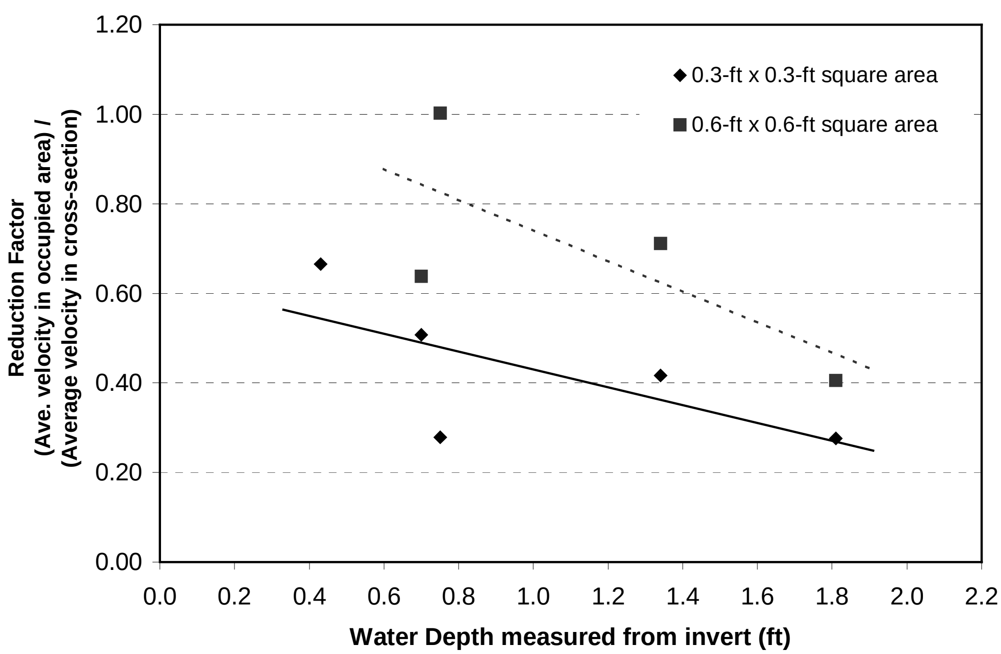

Figure 5-10. Velocity reduction factors for a circular culvert barrel with 2-2/3x1/2-inch corrugations. The 0.3x0.3-ft area represents the swimming cross-section of a juvenile salmonid, and the 0.6x0.6-ft area represents the swimming cross-section of an adult resident trout.

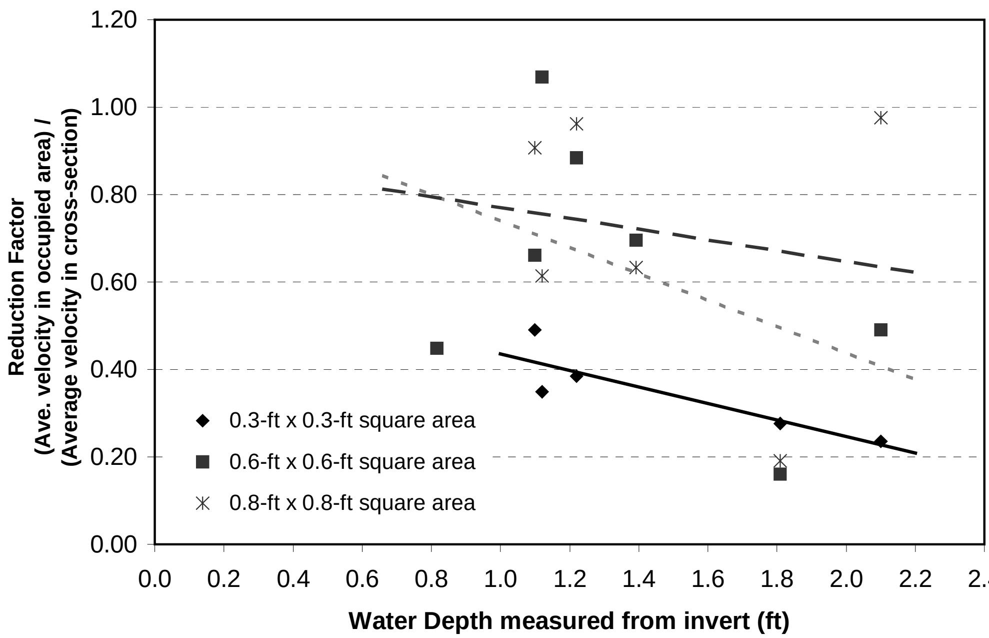

Figure 5-11. Velocity reduction factors for an embedded culvert barrel. The 0.3x0.3-ft area represents the swimming cross-section of a juvenile salmonid; the 0.6x0.6-ft area represents the swimming cross-section of an adult resident trout, and the 0.8x0.8-ft area represents the swimming cross section of adult salmon and steelhead.

When considering the use of the lower edge or boundary velocities by smaller fish, a common concern is the potential for this boundary zone to be discontinuous. The use of velocity reduction factors assumes that velocity distributions are relatively uniform throughout the entire length of the culvert. However, if the zone of lower velocity along the culvert walls is not continuous throughout the entire culvert length, the fish may encounter velocities that are too fast as it swims upstream along the culvert wall. In this situation, the fish may be forced to swim across the swift moving current to the opposite side of the culvert in order to find slower water, which would likely by physically and behaviorally impossible. If boundary layer velocities are not continuous, the use of velocity reduction factors may be inappropriate.

In an effort to investigate the distribution of velocities throughout the length of a particular culvert and develop field methods that may be useful as part of further research on the subject, we measured velocities longitudinally from the outlet to inlet. The selected site was Chadd Creek at Highway 254, which has a skewed culvert alignment relative to the upstream channel (APPENDIX A, p.A5-A6). Velocities were measured at multiple depths along three separate longitudinal sections. One located along the culvert centerline and the others located one foot from the left and right edge of water.

The longitudinal velocity distributions showed that the inlet skew greatly affected the edge velocities throughout most of the culvert length. It also shows that both the centerline and edge velocities at the inlet and outlet are substantially higher than those measured within the culvert barrel. Although the use of velocity reduction factors may be appropriate in many situations, these measurements and other observations indicate that there are numerous circumstances in which they should not be applied.

5.6 EMBEDDED CULVERTS AND SUBSTRATE RETENTION

Embedding, or countersinking, culverts to retain streambed substrate has recently become a widely employed fish passage design strategy throughout the Pacific Northwest (Paul et al., 2002; WDFW, 1999). To ensure that the culvert will be able to retain substrate, guidelines for design and installation of embedded culverts generally prescribe the:

1. Degree to which the culvert should be embedded,
2. Minimum required width of the culvert,
3. Culvert slope, and
4. Substrate placement during installation.

However, the prescribed specifications for each of these four criteria often vary substantially between guidelines. For example, the Washington Department of Fish and Wildlife design manual prescribes culvert width for stream simulation culverts as $W_{Culvert} = 1.2\ W_{Channel}$ (ft) + 2 ft (Bates et al., 2003) while Oregon's design guidelines (Robison et al., 1999) state that "the culvert should be wider than the active width of the stream to prevent inlet drop and possible bed scour. Active width is the stream width that occurs when larger streamflow events occur. The recurrence of these larger streamflow events associated with active flow is about once every one or two years."

Although it is unknown whether any of the *Tier 1* or *Tier 2* culverts were designed to be embedded, five of them retained substrate throughout at least half of their length. From these sites several important qualitative observations were made pertaining to the culvert width, embedded depth, and ability to retain substrate.

To determine the extent to which each culvert was constricting the channel, the ratio of the culvert width to bankfull channel width was calculated. The depth embedded is typically reported as a percentage of the overall culvert height that is placed below the original stream grade. Since we were unable to obtain any information about the stream channels prior to the culverts being installed, connecting the existing upstream and downstream channel profile estimated the location of the unaltered streambed. From this, we determined the degree to which the culvert was embedded by taking the difference between the approximate elevation of the unaltered streambed and the culvert invert elevation.

All five sites had difficulty retaining substrate near the inlet, likely due to scour caused by contracting flow. The only culvert that retained substrate throughout its entire length was Lower McCready Gulch. This box culvert was as wide as the bankfull channel and roughly 20% of the overall culvert height was embedded (Table 5-6). Even though it matched the bankfull channel, much of the substrate had been scoured out of the inlet.

Table 5-6. Size and placement of the five embedded culverts relative to the stream channel.

Site	Width Culvert / Bankfull	% Culvert Height Embedded	Length of Culvert without Substrate
Lower McCready Gulch	10 ft / 10 ft (1.00)	18%	0
Lower Durphy Creek	9.3 ft / 28 ft (0.33)	50%	2 ft
Hatchery Creek	4.5 ft / 18 ft (0.25)	33%	12 ft
Cow Creek	7.5 ft / 21 ft (0.36)	30%	13 ft
Upper Durphy Creek	10 ft / 28 ft (0.36)	20%	25 ft

The Hatchery and Cow Creek sites are good examples of the difficulties culverts have in retaining substrate near the inlet when sized less than the bankfull channel width (Figure 5-12a, 5-12b). The Lower Durphy Creek culvert was only a third as wide as the bankfull channel but appeared to be embedded nearly 50% of the culvert height (Figure 5-12c). As a result, it retained substrate throughout almost the entire culvert, but a steep drop was created immediately upstream and a scour hole formed at the inlet. These conditions suggest that even if culverts are sufficiently embedded, if they are not sized to the width of the channel adverse fish passage conditions can form.

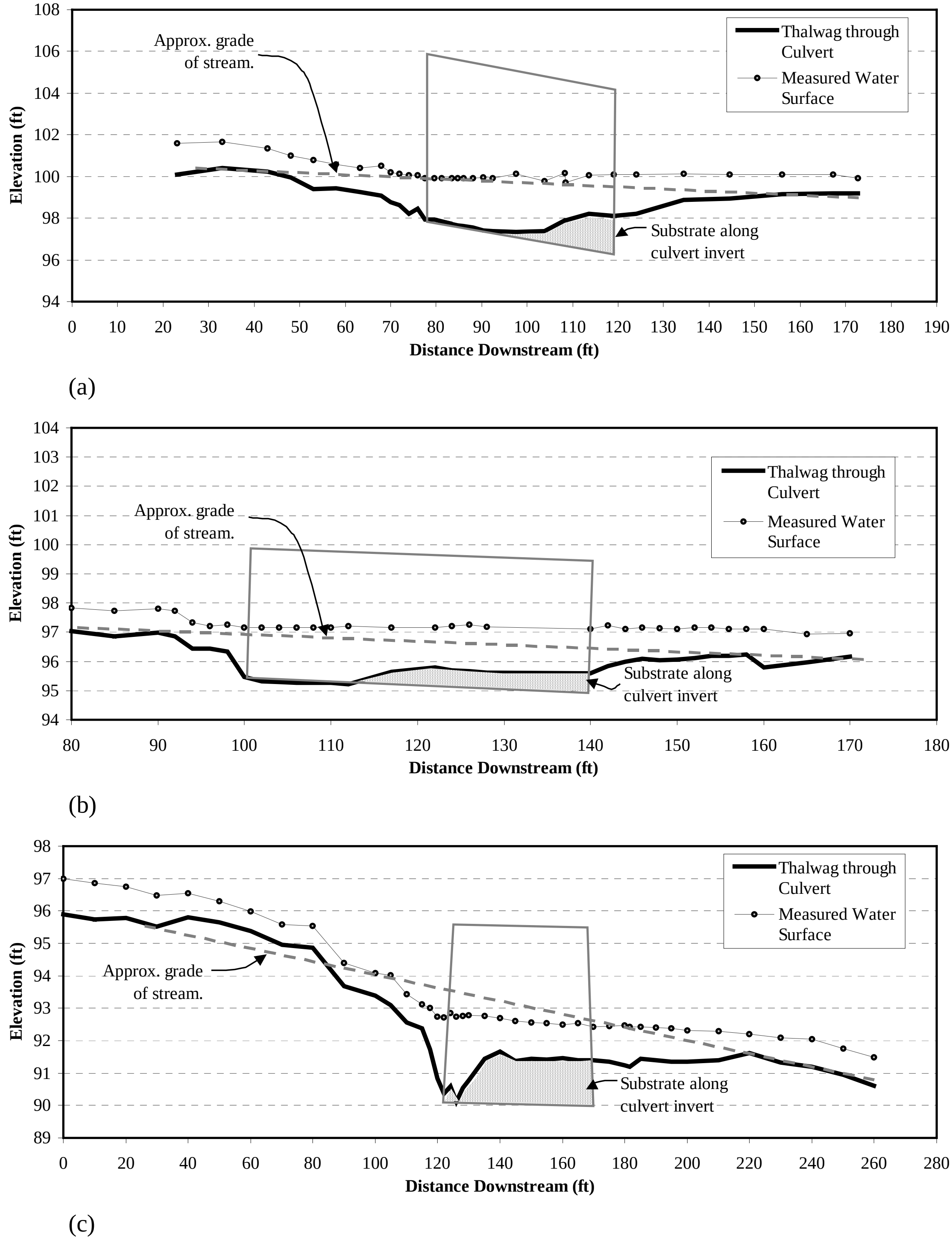

Figure 5-12. Profiles showing substrate coverage through three embedded culverts: (a) Cow Creek, (b) Hatchery Creek, and (c) Lower Durphy Creek. All three fail to retain substrate near the inlet due to scour caused by flow constriction as it enters the culvert.

5.7 SUMMARY AND DISCUSSION

Manning's roughness coefficients presented in documents published by the Federal Highways Administration are widely used in the design of culverts for fish passage. For culverts constructed of standard materials (such as concrete and corrugated metal), recommended "literature" Manning's n-values were consistently less than n-values measured in the field. These discrepancies arise because literature n-values were empirically determined for modeling peak flow capacity, and are not intended for use in modeling hydraulics of culverts flowing less than approximately three quarters full.

The two commonly installed baffle types, offset baffles and ramp baffles, effectively increased water depth and decrease average velocities, as evident by the large measured roughness values. However, measured roughness varied strongly with flow rate, decreasing as flows increased. When baffles are completely submerged at high flows, it may be possible to predict water depths using roughness coefficients. At low flows, baffles define a channel through the culvert and use of constant roughness coefficients is not recommended.

A hydraulic model of gradually varying flow through culverts (FishXing, V2.2) accurately predicted water surface profiles and average velocities when using the field-measured roughness coefficients. Model runs using the literature n-values underestimated predicted water depth and overestimated predicted average velocity. Actual average velocities were at least 30% lower than those predicted using "literature" n-values. Therefore, when modeling fish passage, the use of roughness coefficients presented in literature introduces a factor-of-safety into the design. This factor of safety may counter differences between a culvert's design and its as-built conditions, such as differences in culvert slope.

For small fish size classes, represented as 0.3-ft square projected area, occupied velocities were well correlated to water depth. Recommended reduction factors (the ratio occupied velocity to average velocity) of 0.4 to 0.8 (Behlke et al., 1991), were supported by our analyses. However, the continuity of the lower velocity zones along the culvert walls is not well understood. Our observations suggest these layers were close to continuous within the culvert barrels but were often disrupted at the culvert inlet and outlet. Additional research on the effect of inlet and outlet conditions on the continuity and occupied velocity magnitude is needed.

Qualitative observations of embedded culverts suggest that the most difficult location to retain substrate within a culvert is near the inlet. The scour and loss of substrate immediately below the culvert inlet is a result of the complex hydraulics created when culverts constrict the approaching flow. Based on our observations, the best means of preventing scour and loss of substrate near the inlet of embedded culverts is to size them to be at least as wide as the upstream channel.

6 FISH OBSERVATION METHODS AT STREAM CROSSINGS

In coastal northern California, upstream migration timing of adult anadromous salmonids is fairly predictable. In coastal streams, upstream adult fish migration starts when the first fall rains provide adequate runoff, allowing unimpeded upstream movement. Within smaller coastal streams, flows high enough for passage generally occur between mid-November through April. The actual migration season varies among species. Chinook salmon are generally the first to arrive, followed by coho, then steelhead. However, migration seasons are also dictated by the annual timing and distribution of rainfall and much overlap between species migration timing is observed.

Instream movements of juvenile and resident salmonids are highly variable and still poorly understood. Juvenile coho salmon spend approximately one year in freshwater before migrating to the ocean, and juvenile steelhead may rear in freshwater for up to four years before out-migration; one to two years is common in California. Because much of their life history is spent in freshwater, juveniles of both species are highly dependent on instream habitat. For over-wintering juvenile coho, a common strategy is to migrate out of larger river systems into smaller streams, during late-fall and early-winter storms. Although reasons for this behavior are not certain, juvenile coho may migrate upstream to find more suitable overwintering habitat, away from higher flows and potentially higher turbidity levels found in mainstem channels (Skeesick 1970; Cederholm and Scarlett 1981; Tripp and McCart 1983; Tschaplinski and Hartman 1983; Scarlett and Cederholm 1984; Sandercock 1991; Nickelson et al. 1992). During summer months in western Washington State, juvenile salmonids that moved upstream grew faster than both non-moving and downstream moving juveniles, demonstrating that this behavior may play an important role in the overall heath of the population (Kahler et al. 2001).

In small coastal streams, an understanding of migrational behavior in adult and juvenile salmonids is essential in developing guidelines for fish passage at stream crossings. For adult anadromous fish, resident trout, and juvenile salmonids, the primary questions are:

1) How do culverts influence behavior,
2) When is the migration season, and
3) At what flows do they migrate upstream within the migration period?

To assist in answering these questions, we combined visual fish observations and fish tagging at the *Tier 1* sites.

6.1 VISUAL OBSERVATIONS METHODS

Visual observations were attempted at all ten *Tier 1* sites, but fish attempting to pass through were seen at only five of the culvert sites. All five were perched culverts that allowed direct visual observations of fish leaping. At the remaining five *Tier 1* sites, two were perched outlets where leaping fish could be easily observed, if any were present. The other three *Tier 1* culverts had outlets that were at stream grade, so fish could swim directly into the culvert. Although observers monitored these three sites, no fish were observed swimming into these culverts, possibly due to high turbidity limiting fish visibility.

Over the project's three-year duration, between October and April, approximately 300 hours of visual observations were logged at all *Tier 1* sites. Most observations occurred during and shortly after storm events, but some observations occurred during base flow periods. Visual observation periods were 20 minutes long. After each 20-minute observation period, changes in the stage height were noted and the numbers of adult and juvenile leaping attempts were tabulated. The visual observation protocol used for recording adult and juvenile upstream passage attempts is included in Appendix D. In addition to recording visual observations using a repeatable protocol, video recordings were collected for post-observation analysis.

Many fish made multiple leap attempts. However, numerous successful leaps ended with the fish failing to make it all the way through the culvert, washing it back out. To track multiple attempts by the same fish, each distinguishable adult was given an individual identification number. For each adult fish observed attempting to pass through the culvert, field personnel recorded quantitative parameters (such as leap height or leap angle) and any necessary qualitative descriptions (Table 6-1).

Visual observations of juvenile passage followed the same protocol as the adult passage; however, only the size class of the fish (3-5 inches, 5-8 inches, or >8 inches) and whether the attempt succeeded or failed was recorded. These size classifications are approximations because fish were not caught and identified; classification was determined from a “split second” observation. The largest size class, > 8 inches, had an upper limit of approximately 15 inches and was intended to include resident rainbow and cut-throat trout, but exclude returning coho, chinook, and steelhead.

Table 6-1. Parameters recorded for each adult salmonid observed attempting to pass through a culvert.

General Information	If Fish Attempted to Leap into Culvert	If Fish Entered Culvert Successfully
Culvert Name	Was Leap successful?	Whether fish swam through culvert or was flushed out?
Fish species/ Identification number[1]	Location of attempt[2]	Total time spent in culvert
Approx. fish length	Leap height	Location and cause of difficulty/failure
Time of attempt	Horizontal distance traveled	Time spent swimming at burst speed through inlet
Pool stage/discharge	Leap angle	

[1] - When distinguishable, individual adults are identified to account for multiple passage attempts.
[2] - Location attempt is described with respect to the culvert outlet orientation and characteristics of the culvert outlet hydraulics (e.g., flow through notches, over weirs).

6.2 ADULT TAGGING METHODS

Culverts on Cloney Gulch and McCready Gulch, two tributaries of Freshwater Creek, were equipped with antennas that remotely detect and record passive integrated transponder (PIT) tags inserted into adult coho and steelhead. The purpose of the tagging was to evaluate remote methods for assessing fish passage through culverts, and to compare our visual observations with the PIT tag results. The antenna systems use Texas Instruments TIRIS technology adapted to fish passage analysis and monitoring by Dr. Alex Haro of the Conte Anadromous Fisheries Research Center (Castro-Santos et al., 1996). The systems record the date, time, and ID number of tagged fish passing through the culvert. From this information we determined the time of arrival at a culvert, the time spent negotiating the culvert, whether the passage attempt was successful, and the length of time each fish remained upstream of the culvert.

Freshwater Creek was selected as the trial watershed for the tagging system for two reasons: (1) it contains three *Tier 1* culverts, one on Cloney Gulch and two on McCready Gulch, and (2) the Humboldt Fish Action Council (HFAC) operates an upstream migrant trap near the mouth of Freshwater Creek. The HFAC cooperated with this research by inserting the PIT tags into adult steelhead and coho passing through their trap; they also recorded the date, time, fork length, species, and sex of all tagged fish. The HFAC trap is located within the tidally backwatered portion of lower Freshwater Creek. The culverts on McCready Gulch are 3.0 miles (4.8 km) upstream of the HFAC trap, and the Cloney Gulch culvert is 4.4 miles (7.0 km) upstream (Figure 6-1).

Antennas were installed on the inlet and outlet of the Cloney Gulch culvert and became operational in January 2000. This culvert is a 60-foot long corrugated metal arch with a concrete floor. The arch is 16 feet wide by 9.3 feet high and the floor has been retrofitted with wooden baffles. At most flows, the outlet is perched approximately two feet above the downstream pool, requiring fish to leap into the culvert. At flows greater than approximately 100 cfs (2% exceedance flow for migration period), the culvert becomes backwatered by Freshwater Creek, eliminating the perched outlet.

Three antenna systems were installed on McCready Gulch’s culverts in October 2000. Two consecutive roads cross McCready Gulch in the lower portion of the stream. The lower stream crossing is a newer concrete box culvert, dimensions 10 feet by 10 feet by 100 feet (W x H x L). The entire culvert floor is embedded approximately between 1 and 2 feet deep with sands and gravels.

The second culvert lies 50 feet upstream and is a concrete box culvert, dimensions 10 feet by 8 feet by 61 feet (WxHxL), that has been modified on its right side with standard offset baffles. The outlet is perched approximately three feet above the downstream pool, requiring fish to leap into the culvert.

PIT tag antennas were installed on the inlet and outlet of the upper culvert. Since earlier measurements of water depths and velocities within the lower box culvert were well within the swimming abilities of adult coho and steelhead over a wide range of flows, an antenna was installed only at the culvert inlet. This inlet antenna was placed to: (1) assist in determining when fish entered the pool between the two culverts, (2) estimate the length of time spent in the pool before making a first attempt at passage through the upper culvert, and (3) document whether fish prefer certain ambient lighting conditions before attempting to leap at perched culverts.

At Cloney Gulch, tagging and antenna operations began in January 2000. During water year (WY) 2000, HFAC tagged 21 adult coho and 36 adult steelhead. However, the Cloney Gulch antennas detected only four coho and no steelhead. Antenna performance was verified with a test PIT tag every 2 to 3 days during battery changes. Visual observations continued at the Cloney Gulch culvert throughout this period and one coho attempting passage through the Cloney Gulch culvert was both visually observed and detected by the PIT tag antenna system. No steelhead were observed or detected. Visual observations and spawning surveys conducted by HFAC also failed to detect steelhead in Cloney Gulch (A. Dunlap, pers. comm. 2001).

In WY 2001, antenna systems operated at both Cloney and McCready Gulch throughout the migration season. HFAC tagged a total of 52 adult coho (42 male and 10 female) and 45 adult steelhead (12 male, 30 female, 3 unknown). Seven coho and no steelhead were detected at Cloney Gulch; three coho and one steelhead were detected at McCready Gulch. Antenna performance was again verified every 2 to 3 days when the batteries were changed, and visual observations were also conducted during this period.

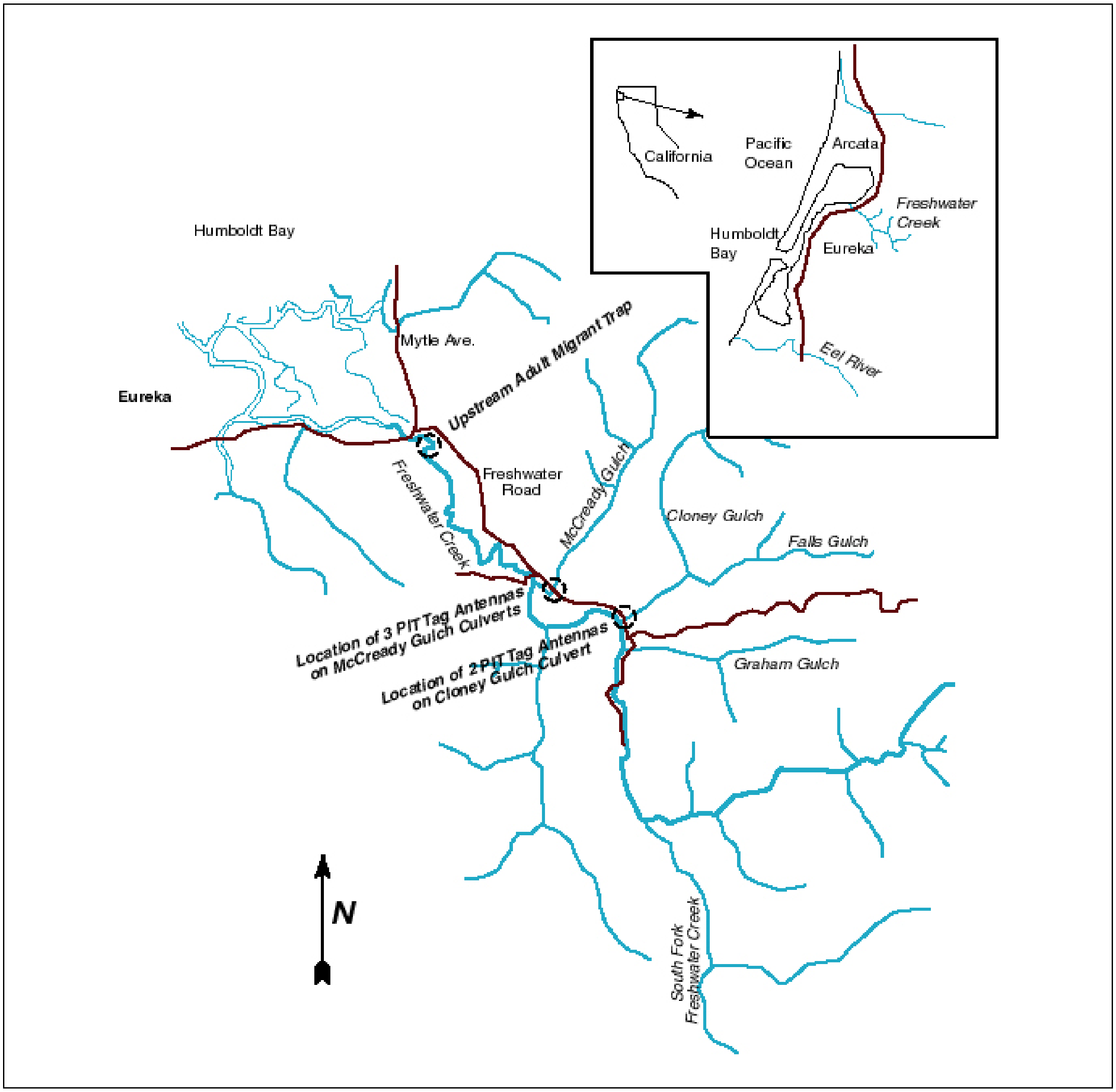

Figure 6-1. Map of Freshwater Creek watershed showing the Humboldt Fish Action Council's upstream migrant trap and the location of PIT tag antennas on McCready and Cloney Gulches.

Discrepancies between the numbers of fish scanned, and those visually observed, were initially disconcerting. However, discussion with HFAC personnel revealed that substantial numbers of adult fish passed through their trap untagged due to poor physical condition, small size (smaller fish were less likely to be tagged), or because personnel trained in tagging were not available. In WY 2001, a total of 177 adult coho passed through HFAC's trap but only 52 of these fish were tagged. Similarly, 86 steelhead were caught but only 45 were tagged. The HFAC trap is also believed to allow a significant percentage of escapement. It becomes submerged during high flows and during moderate flows coupled with spring tides. Consequently, the number of fish scanned entering each tributary is not a reliable estimate of the populations using each tributary.

7 SYNTHESIS—HYDROLOGY, HYDRAULICS, AND FISH OBSERVATIONS

Migration of adult and juvenile salmonids is highly seasonal; access to small coastal streams depends largely on stream flow. By comparing visual observations, PIT tag detections, and stream hydrographs, hydrologic conditions needed for passage can be identified. To identify these conditions, we first compared measured stream flow at four *Tier 1* sites against fish observation data. This comparison documents the time of year at which different size classes of fish attempt to move upstream through culverts, and the hydrologic conditions they require to do so. Second, we combined fish observations from multiple sites and related the timing of passage attempts to the flow duration curves. This second analysis allowed us to define the exceedance flows at which migration occurs on a regional basis. Hydraulic conditions at the culverts were also quantified, and their effects were noted where relevant.

Assuming that observations of adult and juvenile salmonids leaping at, or attempting to swim into, culvert outlets indicate an immediate biological desire to migrate upstream, we defined the range of flows that fish prefer for passage at stream crossings. For adult anadromous salmonids, upstream movement is assumed to be associated with the desire to reach upstream spawning grounds.

For juvenile salmonids, leaping at culverts indicates a biological need to migrate to upstream habitat. Although the exact reason why juvenile fish migrate upstream is uncertain, this movement is likely an important component in their overall life history. All of the outlet pools below the observed culverts contained year-round populations of juvenile and resident salmonids. Therefore, we assumed that when we observed no leaping juvenile fish, the juveniles had no motivation to move upstream.

Other factors exist, both physical and behavioral, that may influence our observations and assumptions about fish leaping. As stream flow increases conditions within the outlet pools become more turbulent. This turbulence may affect both adult and juvenile's ability and desire to leap. Also, it is unclear what conditions initiate leaping by juveniles. It has been suggested that changes in flow may trigger juvenile fish to leap rather than swim. In this case the lack of juvenile leaping may not indicate a lack of motivation to move upstream.

7.1 FISH MIGRATION TIMING

During the three-year study period, over 1,900 observations of leaping adult and juvenile fish were recorded at five of the *Tier 1* sites: Sullivan Gulch, Morrison Gulch, Upper McCready Gulch, Cloney Gulch, and Warren Creek. By superimposing the juvenile and adult fish observations onto the hydrographs for Sullivan Gulch, we can determine the flows during which fish move (Figures 7-1 through 7-6). All 20-minute observation periods were plotted. The open circles represent 20-minute observation periods when no fish were detected; the filled circles indicate that one or more leaps were observed during the period. Plots summarizing this data for Morrison Gulch, Upper McCready Gulch, and Cloney Gulch are included in Appendix C. At Warren Creek, reliability problems with the automated stream gaging equipment compromised the flow record; no similar plots are available for that location.

During WY 1999, the wettest year of the study, two distinct peak flows exceeded bankfull; numerous smaller, but significant storms (those resulting in flows above the 1% exceedance flow for the migration period) also occurred. Overlaying the fish observations on to the hydrographs show that few fish migrate during base-flow conditions. Instead, passage attempts generally began during either the rising or falling limb of the storm flows and would often continue throughout much of the recession limb. Observed juvenile attempts occurred during smaller storm events and at lower flows than adult attempts.

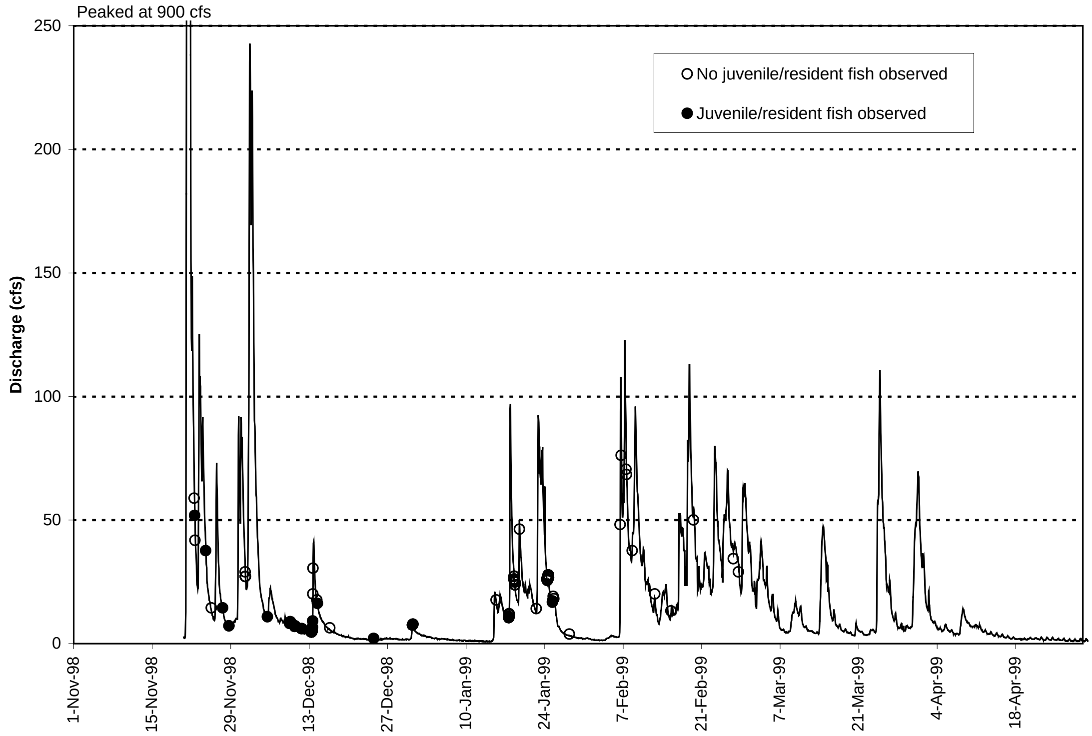

Figure 7-1. Juvenile fish observations during water year 1999 at Sullivan Gulch at Riverside Road. Hydrograph was constructed using hourly average flows.

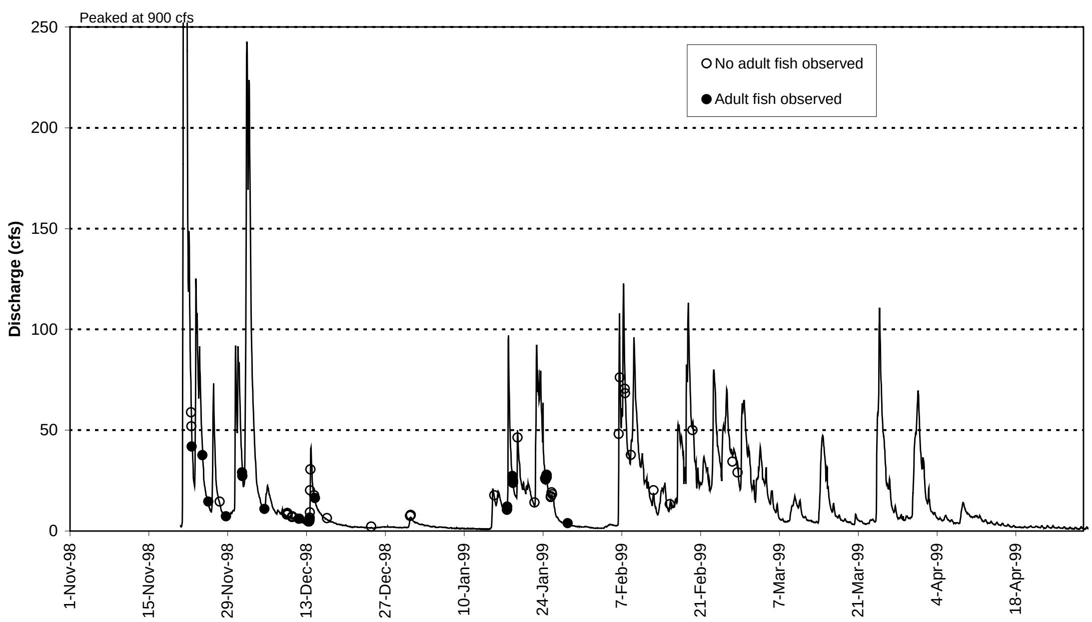

Figure 7-2. Adult fish observations during water year 1999 at Sullivan Gulch at Riverside Road. Hydrograph was constructed using hourly average flows.

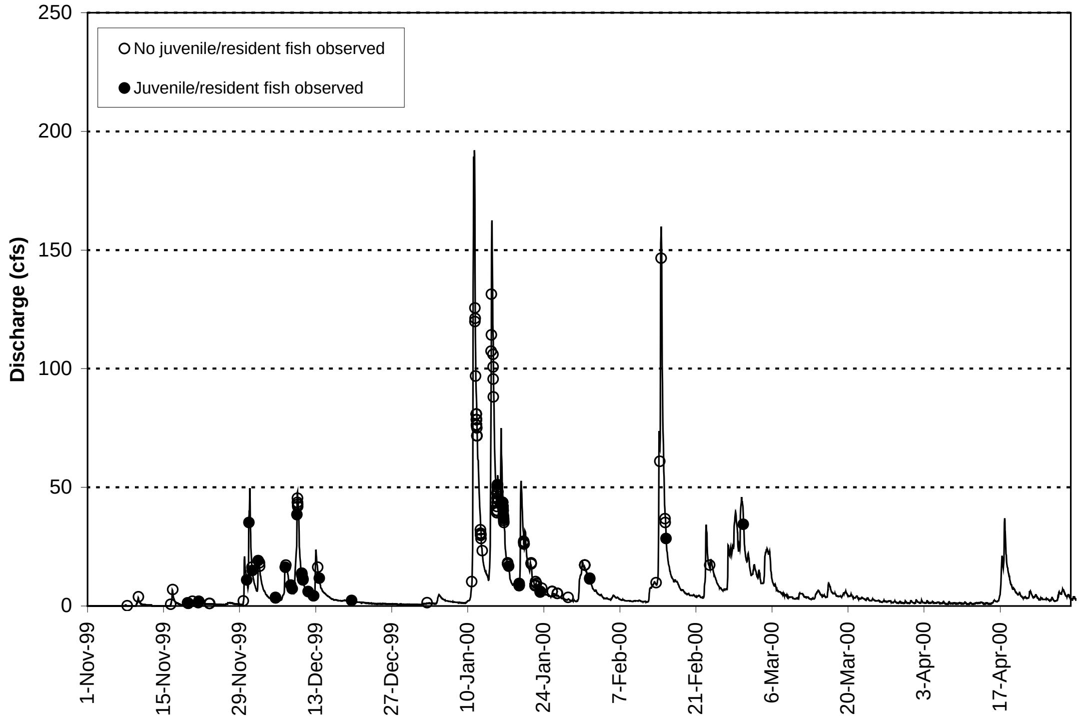

Figure 7-3. Juvenile fish observations during water year 2000 at Sullivan Gulch at Riverside Road. Hydrograph was constructed using hourly average flows.

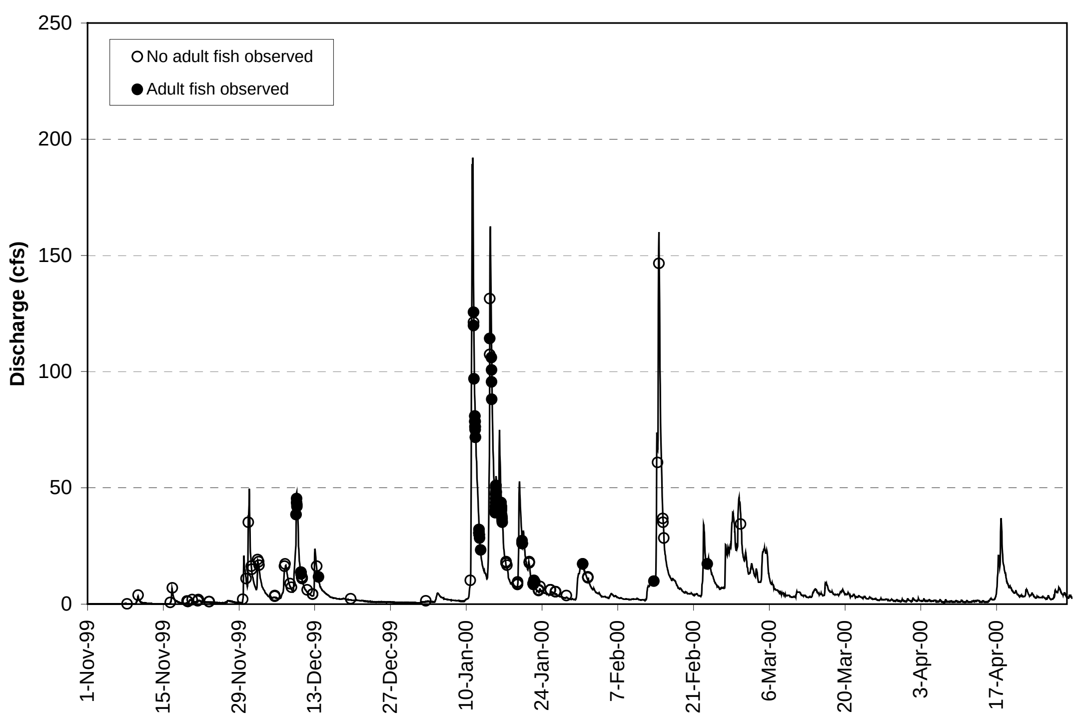

Figure 7-4. Adult fish observations during water year 2000 at Sullivan Gulch at Riverside Road. Hydrograph was constructed using hourly average flows.

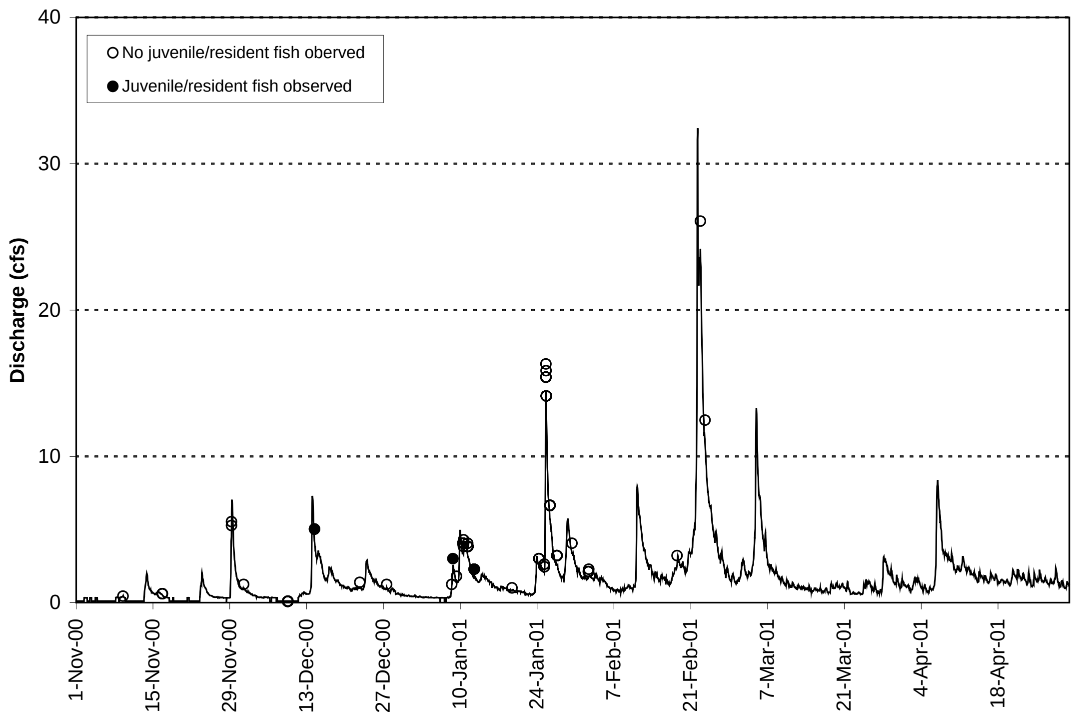

Figure 7-5. Juvenile fish observations during water year 2001 at Sullivan Gulch at Riverside Road. Hydrograph was constructed using hourly average flows.

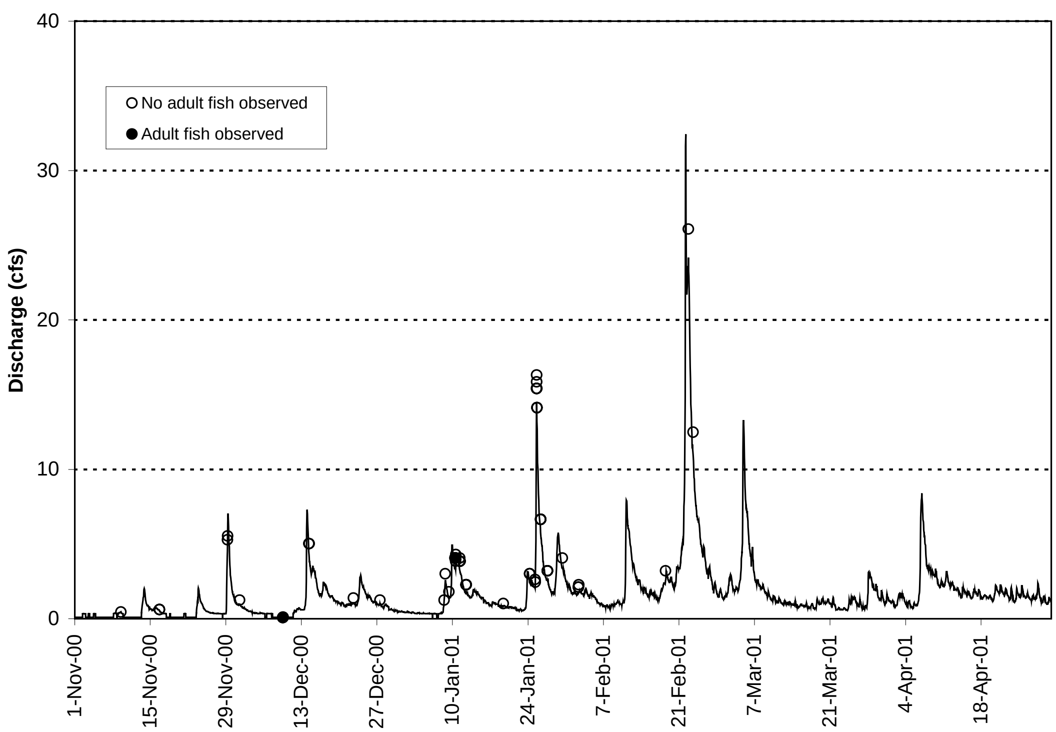

Figure 7-6. Adult fish observations during water year 2001at Sullivan Gulch at Riverside Road. Hydrograph was constructed using hourly average flows.

Water year 2000 experienced a gradual onset of winter rains, with initial storms providing relatively low precipitation in the first two weeks of November. Juveniles were observed on the third low rainfall event. The storms on November 30 to December 1, and on December 9 to 10, were approximately equal in magnitude. Adult and juvenile fish migration was observed at all five sites. Adults were observed at Cloney Gulch on the first storm and at Sullivan Gulch on the second storm. Four distinct storms occurred in January and early February, including a peak flow event that was slightly greater than bankfull throughout the region. During these storm events, adult fish migrated at higher flows than juveniles. Adult coho salmon were even observed leaping at Morrison Gulch at flows above bankfull.

Few fish were seen during WY 2001, which was an extremely dry year. Juveniles were first observed on December 14, nearly one month later than first observed in water years 1999 and 2000. At Sullivan Gulch, adult fish were observed leaping at the culvert outlet on only one day, January 10, 2001, when flows reached 4 cfs. This flow was the second lowest flow during which adults were observed at Sullivan Gulch over the three-year study period.

At all sites, observation indicated that juvenile fish begin migrating upstream earlier in the season than adult salmon and steelhead, with over 70% of the juvenile movement observed between mid-November and mid-December (Table 7-1, Figure 7-7). The lack of adult and juvenile activity in the latter half of December coincides with approximately three weeks of dry weather that occurred in all three years (see hydrographs in Appendix B).

On stream hydrographs, more fish—juveniles and adults—moved during the falling limb of storm-flows than the rising limb. However, this observation may be biased because rising limbs periods were much shorter than falling limb periods. Also, the majority of storms began during nighttime hours. A strong effort was made to conduct observations during evening and early morning periods, but safety concerns and access issues prevented extensive nighttime observations.

Table 7-1. Date and stream flow of the first observed passage attempts by juvenile and adult anadromous salmonids at culvert outlets for each water year (WY). At both Morrison Gulch and Sullivan Gulch, the first observed leap by a juvenile occurred much earlier than the first adult attempt for all three water years.

	WY 1999 (Wet)		WY 2000 (Average)		WY 2001 (Dry)	
Culvert Site	**Juveniles**	**Adults**	**Juveniles**	**Adults**	**Juveniles**	**Adults**
Sullivan Gulch	Nov-08 (N/A)	Nov-25 (N/A)	Nov-19 (1.1 cfs)	Dec-09 (45.4 cfs)	Dec-14 (5.0 cfs)	Jan-10 (4.1 cfs)
Morrison Gulch	Nov-22 (N/A)	Dec-03 (19.2 cfs)	Nov-19 (1.2 cfs)	Jan-11 (25.2 cfs)	Dec-15 (0.6 cfs)	Jan-11 (2.2 cfs)
Cloney Gulch	Nov-18 (N/A)	Nov-17 (N/A)	Dec-07 (36.8 cfs)	Dec-1 (41.9 cfs)	Dec-21 (1.9 cfs)	Jan-10 (10.4 cfs)
McCready Gulch	-	-	Nov-30 (11.0 cfs)	Jan-11 (26.5 cfs)	Jan-11 (3.7 cfs)	Jan-10 (4.1 cfs)

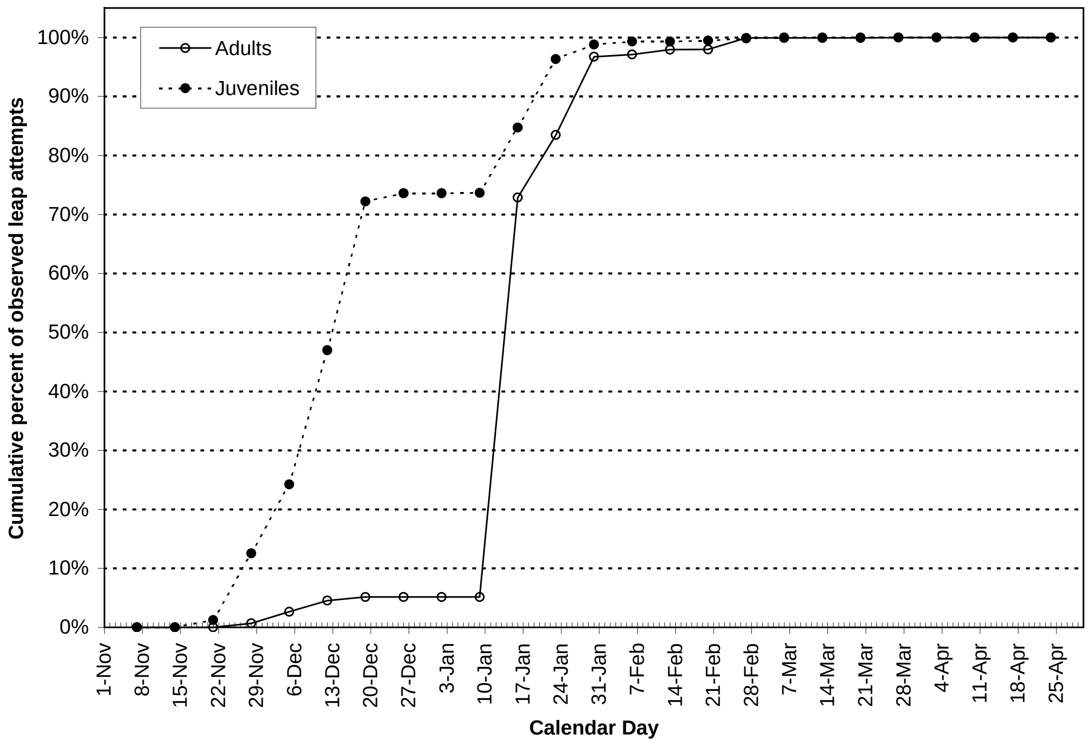

Figure 7-7. Timing of observed leap attempts by adult and juvenile salmonids at culvert outlets during water years 1999 through 2001. Most juvenile activity occurred earlier in the season than adult activity.

7.2 INDIVIDUAL FISH MIGRATION AND HYDROLOGY

Using upstream adult migrant trapping data collected by the Humboldt Fish Action Council, the timing and distribution of fish entering Freshwater Creek from Humboldt Bay were analyzed. Fish attempting to migrate through culverts on McCready Gulch and Cloney Gulch, two tributaries of Freshwater Creek, were monitored using PIT tagging and visual observations. Chinook typically begin their upstream migration first, peaking in December, followed by coho and steelhead. However, species migration overlaps considerably, with chinook, coho, and steelhead generally present from December through February (Table 7-2).

Table 7-2. Timing and distribution of adult fish entering Freshwater Creek during WY 2001 (HFAC, 2002).

Month	Chinook	Coho	Steelhead
November 2000	54	9	1
December 2000	84	58	4
January 2001	13	94	26
February 2001	4	16	27
March 2001	0	0	17
April 2001	0	0	11
Total 2000-2001	**155**	**177**	**86**

At Cloney Gulch, tagged fish attempted to enter the culvert at flows ranging from 3.3 to 117 cfs (Figure 7-8 and 7-9). These flows correspond to the 74% and 1% exceedance flows on the six-month migration period FDC, respectively (42% and greater than the 1% exceedance flow on the annual FDC). Two of the 11 fish were detected only at the outlet and we assume they failed to pass through the culvert. Of these two fish, one attempted to pass at 3.3 cfs, but never successfully leaped into the culvert. The other fish attempted to pass at 37 cfs. Multiple scans at the outlet suggest that it succeeded in entering the culvert but did not proceed upstream; it was scanned by the outlet antenna, presumably leaving the culvert, shortly after entering. This particular fish was also scanned entering and leaving the McCready Gulch tributary earlier the same day.

In WY 2001, tagged fish successfully entered and passed through the McCready Gulch culverts at flows ranging from 6.3 to 26 cfs. These flows correspond to the 30% and 5% exceedance flows on the migration period FDC (15% and 1% annual exceedance flows) (Figure 7-10).

The magnitude and timing of flows during the migration season affected the length of time fish spent in Freshwater Creek before migrating into its tributaries. Peak flows during WY 2001 were much lower than in WY 2000. By examining the duration between when fish were tagged at the HFAC trap and when their tags were first detected at tributary culverts, we found fish spent much more time in the mainstem during the drier year. In WY 2000, fish remained in Freshwater Creek an average of 11.0 days (range 0.7 to 32.7 days) before being detected at Cloney Gulch. In WY 2001, the average time spent in Freshwater Creek before detection at Cloney Gulch was almost three times longer, 31.1 days (range 17.6 to 54.9 days).

Most fish entered Freshwater Creek from Humboldt Bay during either storm flows or high tide, and were detected at an upstream culvert during the next high flow. This timing suggests that passage conditions in the mainstem of Freshwater Creek initially limit upstream migration. During the dryer year (WY 2001), fish remained in the mainstem of Freshwater Creek for over a month before the tributaries became accessible. During the wetter year (WY 2000) the fastest travel time was 16.8 hrs, recorded between the trap and Cloney Gulch, a distance of 4.4 miles (7.1 km); this correlates to an average upstream migration velocity of 0.4 ft/s. This particular tagged fish was the only one detected entering the system and traveling to the Cloney Gulch culvert within the same storm event (Fish No. 4, Figure 7-8).

Swimming performance of salmon and steelhead has often been related to the physical condition of the fish (Powers and Orsborn, 1985). Our findings suggest that fish spawning in coastal streams should not be presumed to be in good condition merely because of their short migration distance. Depending on flow conditions, some of these coastal salmon and steelhead spend as much time holding in freshwater as those migrating up larger inland rivers. As a result, these fish can be in fairly poor physical condition when attempting to pass through culverts. Design criteria for maximum water velocities and leap heights should accommodate passage of weaker swimming adult fish regardless of the stream crossing’s distance from the ocean.

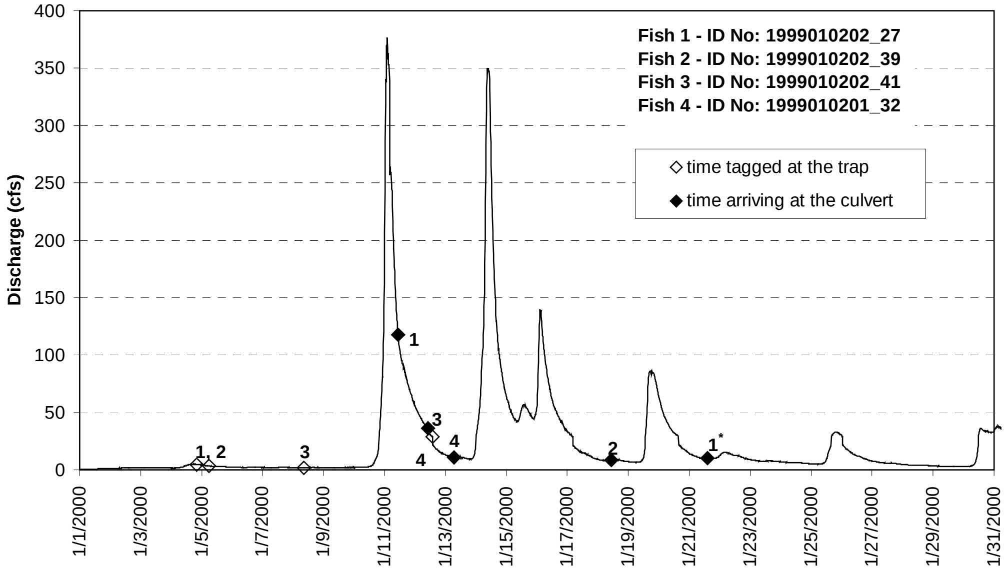

Figure 7-8. PIT tagging detection at Cloney Gulch, superimposed on the Cloney Gulch hydrograph, during WY 2000. All four fish were detected at the culvert on the falling limb of the storm hydrograph, and during a flow after the initial peak flow in which they entered the system. Fish 1 was detected entering and exiting Cloney Gulch; the second arrival time is noted as 1^*.

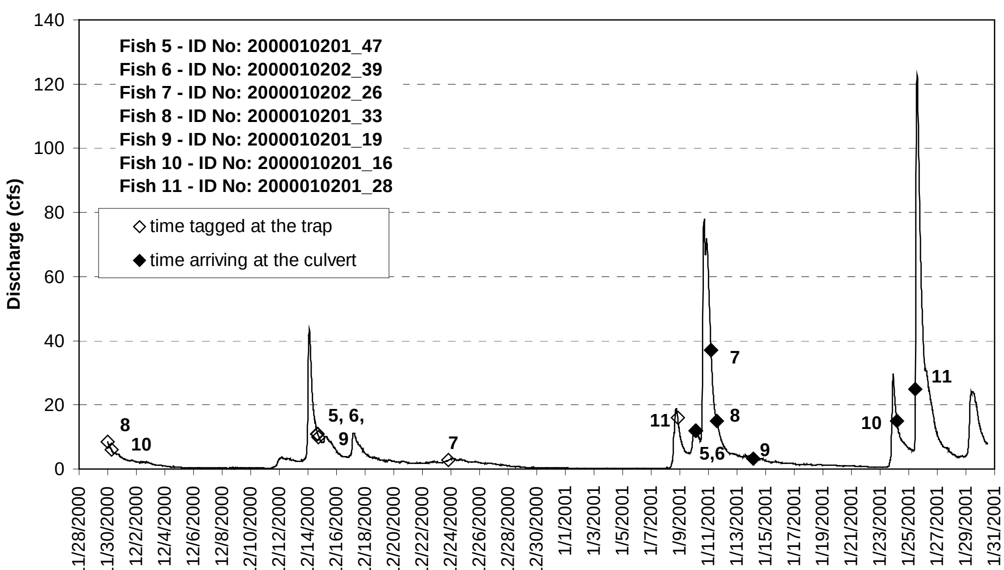

Figure 7-9. PIT tagging detection at Cloney Gulch, superimposed on the Cloney Gulch hydrograph, during WY 2001. Again all seven fish were detected at the culvert on the falling limb of the storm hydrograph, and all were detected at the upstream culvert during peak flows that occurred during the next storm which allowed access into Cloney Gulch.

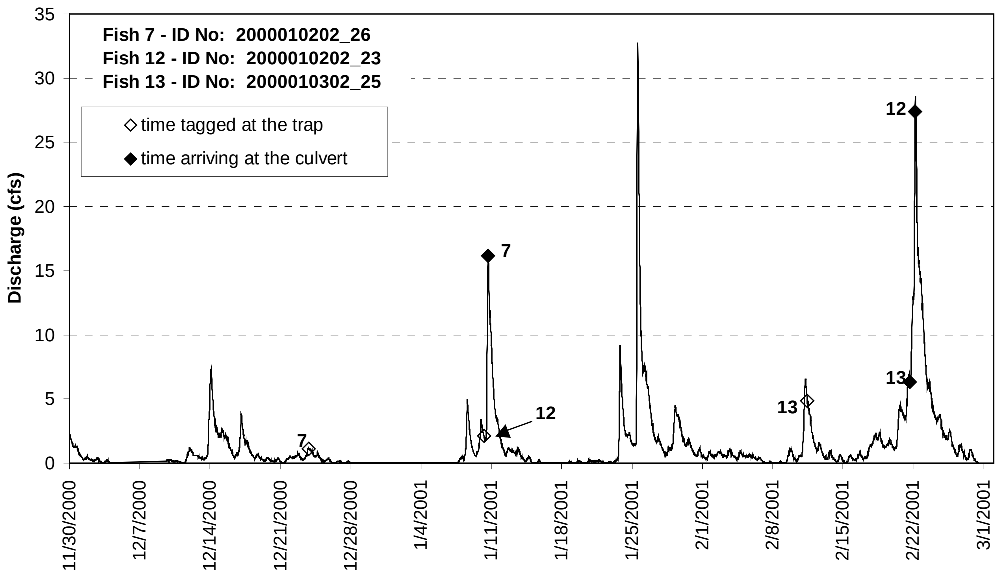

Figure 7-10. PIT tag detection at McCready Gulch, superimposed on to the McCready Gulch hydrograph, during WY 2001. Unlike fish observed at Cloney Gulch, two of three fish attempted to pass on the rising limb of the hydrograph. Fish 7 was also detected entering Cloney Gulch.

7.3 Relationship between Flow Duration and Observed Migration

For design and assessment of stream crossings, guidelines typically specify fish passage criteria within a prescribed range of flows. This range is defined by an upper and a lower fish passage flow. Assuming fish do not migrate at extreme low flows (water too shallow) or extreme high flows (water too fast and turbulent), this prescribed range of flows aims to encompass those flows used by the target fish to migrate upstream.

Upper and lower fish passage design flows are often specified in terms of the average amount of time these flows will be exceeded during a specified period. This period can be annual (CDFG, 2002), for the migration period of a specific fish run (WDFW, 1999), or for a period that encompasses the migration of all the fish runs (Kay and Lewis, 1970). For example, an upper fish passage flow may be defined as that flow which is equaled or exceeded 2% of the time during the migration period of salmon and steelhead in Northern California. This flow has an exceedance value of 2% and is referred to as the 2% exceedance flow. If adult salmon and steelhead migrate from November through April (a total of 181 days), then stream flow would exceed the upper fish passage design flow an average of 3.6 days (2% of the time) during the migration period.

Conversely, if we define the lower fish passage design flow as the 80% exceedance flow during the migration period, stream flows would, on average, be less than the lower fish passage flow during 20% of the migration period, or approximately 32 days. In total, from November through April, stream flow would lie between the lower and upper fish passage flows (between the 80% and 2% exceedance flows) an average of 78% of the time, or approximately 140 days.

Flow duration curves (FDCs) express the relationship between stream flow and the percent of time the flows are equaled or exceeded for a specific stream. Flow duration curves were synthesized for each *Tier 1* site, using the techniques presented in Section 4 for ungaged streams. Using these FDCs, flows can be expressed in terms of exceedance values, which allows comparison of migration timing and passage attempts and success between *Tier 1* sites.

By combining the FDCs, stream flow gaging records, fish observation records, and tagging data from the *Tier 1* sites, the following questions are addressed:

1. What range of exceedance flows do juvenile and adult salmon and steelhead migrate within Northern California's coastal streams?

2. How does the selection of fish passage design flows (lower and upper) affect migration delay created by culverts?

3. Does drainage basin size affect the timing of upstream migration, and how?

7.3.1 Upstream Migration Flows

For each 20-minute fish observation, an average stream flow was calculated using a combination of 15-minute stage recorder data and observed stage heights. Then, using the Regional Migration-Period FDC (Figure 4-4), we determined the exceedance value associated with the flow for each fish observation period. This allowed us to combine fish observations from all sites, and explore the relationship between upstream migration timing and exceedance values. Exceedance values presented in this section are for the migration period of November through April. A table to convert migration period to annual exceedance values, and vice versa, is included in Appendix B.

From the fish observations, we confirmed that different fish size classes attempted to leap at different exceedance flows (Figures 7-11 and 7-12). For size classes of 3 to 5-inch, 5 to 8-inch, and greater than 8-inch, most (over 85%) observed passage attempts occurred between the 70% and 5% exceedance flows. Using the 3 to 5-inch and 5 to 8-inch size classes, peak juvenile movement was observed between the 30% and 21% exceedance flows (Figure 7-11). Fish in the greater than 8-inch size class were not frequently observed, but appeared to move at slightly higher flows than the smaller size classes.

As expected, smaller exceedance flows were associated with observations of adult migration rather than with juveniles. Over one-third of the adult attempts occurred between the 5% and 2% exceedance flows (Figures 7-11, 7-12). An additional 7% of the observed adult fish attempted to migrate at flows greater than the 2% exceedance flow. At the Morrison Gulch culvert, several adults were observed leaping at approximately bankfull flow, which is well above the 0.5% exceedance flow.

No adult salmon or steelhead were observed attempting to pass through culverts at flows lower than the 80% exceedance flow (Figure 7-12). In fact, only 17 (less than 2% of the total adult observations) adult passage attempts were observed, either visually or by the PIT tag antennas, at flows lower than the 50% exceedance flow. Most observations of these low flow passage attempts (13 of 17 observations) by adult salmonids occurred in the dry year of the study, water year 2001.

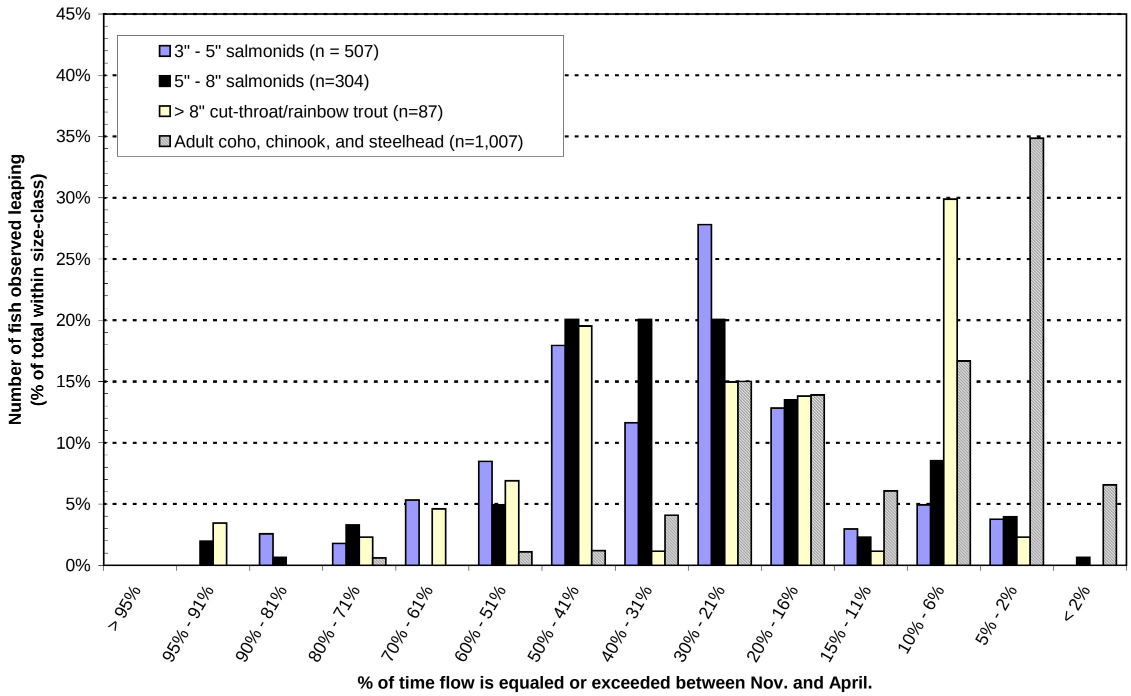

Figure 7-11. Observed fish passage attempts at culvert outlets for WY 1999-2001. More juveniles than adults attempt to pass at flow between the 50% and 20% exceedance flows; over a third of adult attempts occurred at flows between the 5% and 2% exceedance flows.

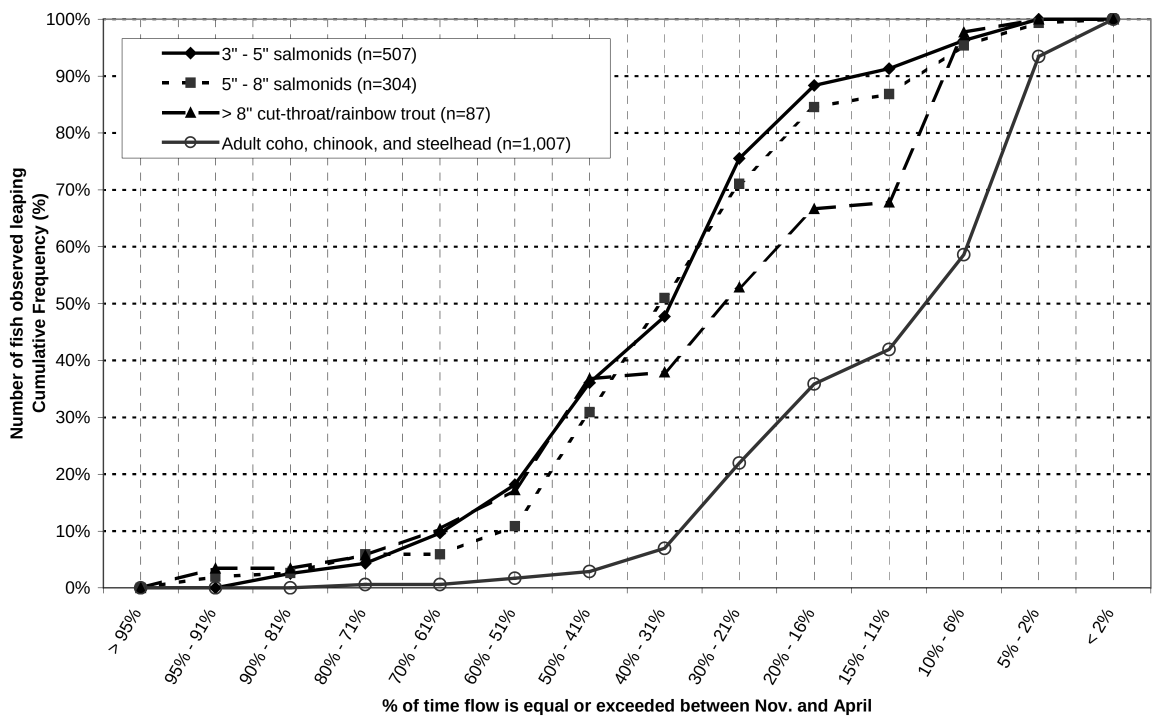

Figure 7-12. Cumulative frequency of fish observations (WY 1999-2001) and corresponding flows, expressed as migration period exceedance flows. Upstream passage attempts by juvenile and resident salmonids occurred at higher exceedance values (lower flows) than adult salmon and steelhead.

7.3.2 Flow Duration and Migration Delay

For design and assessment of stream crossings, choosing appropriate lower and upper fish passage flows for numerous species and life stages can be challenging. Considerations should include understanding the length of the migration delay that may be imposed by flows lower or higher than the passable flow range, and the potential impacts delays may cause. Figure 7-13 shows the maximum consecutive days during which stream flow at the four gaged sites surpassed the indicated exceedance flow in water year 2000 (the "average" year). The curves summarize the relative impact a specific upper passage design flow may have on migration delay in these streams. As an example, if a 1-day delay is considered acceptable, then in water year 2000 an upper fish passage design flow defined as the 3% exceedance flow would result in a 1-day or less delay at all four sites.

Exceedance values taken from flow duration curves represent long-term averages, and fail to account for inter-annual variation. During most years, adult salmon and steelhead migrate within a specific range of flows, but during extremely wet or dry years, they may be forced to migrate outside of that flow range. At Sullivan Gulch, the maximum migration delay that a fish might encounter during high flows varies dramatically between years (Figure 7-14). Assuming an upper fish passage design flow equal to the 2% exceedance flow was used for a culvert installed on Sullivan Gulch, fish could have been delayed due to high flows for 36 consecutive hours in WY 1999. The following year the maximum delay due to high flows would have been 21 hours. During water year 2001 peak flows never surpassed the 2% exceedance flow, the largest flow was equivalent to the 7% exceedance flow.

In coastal Northern California, low-flow periods typically occur at the beginning of the migration period, prior to the onset of rains, and during dry intervals between storm events. If the lower fish passage flow is set above the flow where the downstream channel becomes impassable due to lack of depth, fish could arrive at a stream crossing but be unable to move further upstream until adequate flows become available. For example, if the lower fish passage flow was the 80% exceedance flow, in 1999—a relatively wet year—fish could have experienced a 9-day delay due to insufficient depth in the culvert (Figure 7-15). But in 2001, a relatively dry year, the maximum delay increases to 18 days at the same 80% exceedance flow.

Assuming lower and upper fish passage flows corresponding to the 95% and 2% exceedance flows, respectively, low flow and high flow delays to fish passage can be estimated. Low-flow periods at all four sites persist for much longer than high-flow periods. During WY2001, stream flows were less than the 95% exceedance flow from 10 to 21 consecutive days, depending on the site. The dates over which these periods occurred varied between sites. The Freshwater Creek sites, Cloney and McCready Gulches, experienced their driest conditions in late December and early January, which is the peak migration season. Sullivan Gulch's lowest flows during the migration period occurred in early November, and Morrison Gulch's occurred towards the end of the migration period.

High flow periods persisted for a much shorter period than lower flows. At Sullivan Gulch, the maximum consecutive time above the 2% exceedance flow was 38 hours and occurred during the largest storm of the study, November 20-22, 1998. This storm was approximately a 15-year return period event. The other sites experienced delay durations slightly less than 24 hours at the 2% exceedance flows, but these sites were not yet gaged during the November 20-22, 1998 storm. The storm on February 14, 2000 was approximately a bankfull event in the Freshwater Creek watershed; for both Cloney and McCready Gulch, delay periods of 22 and 21 hours, respectively, occurred during this storm.

Because peak flows often rise and fall abruptly on smaller, coastal streams, migration delay created by flows greater than the upper passage flow are generally brief. However, low flow conditions often persist for extended periods of time. As a result, migration delays arising from flows lower than the lower passage flow often persist for prolonged periods.

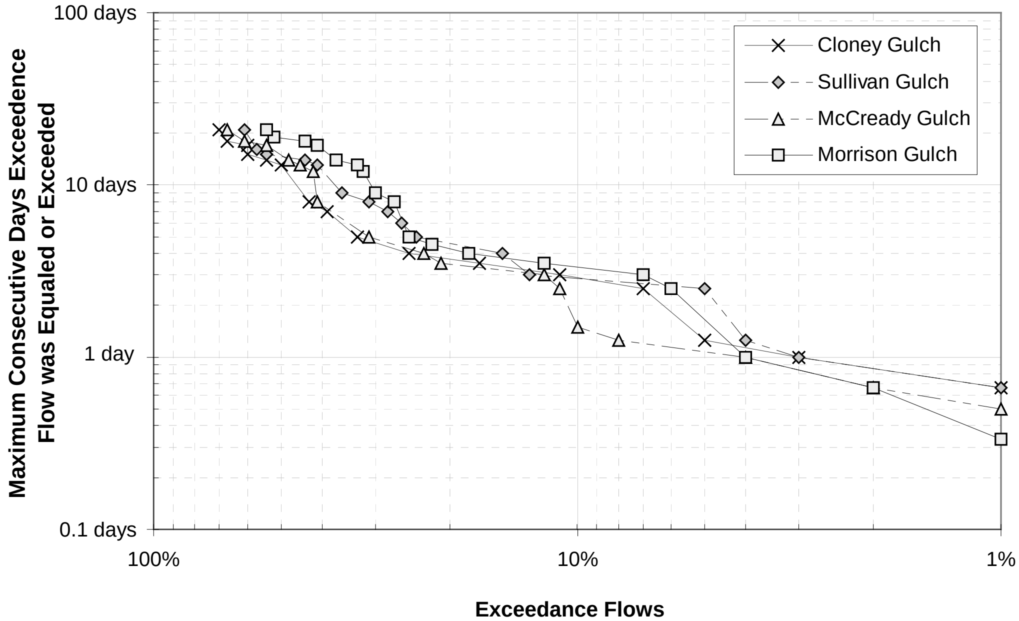

Figure 7-13. Maximum consecutive days stream flow remained at, or above, the indicated migration exceedance flow in water year 2000.

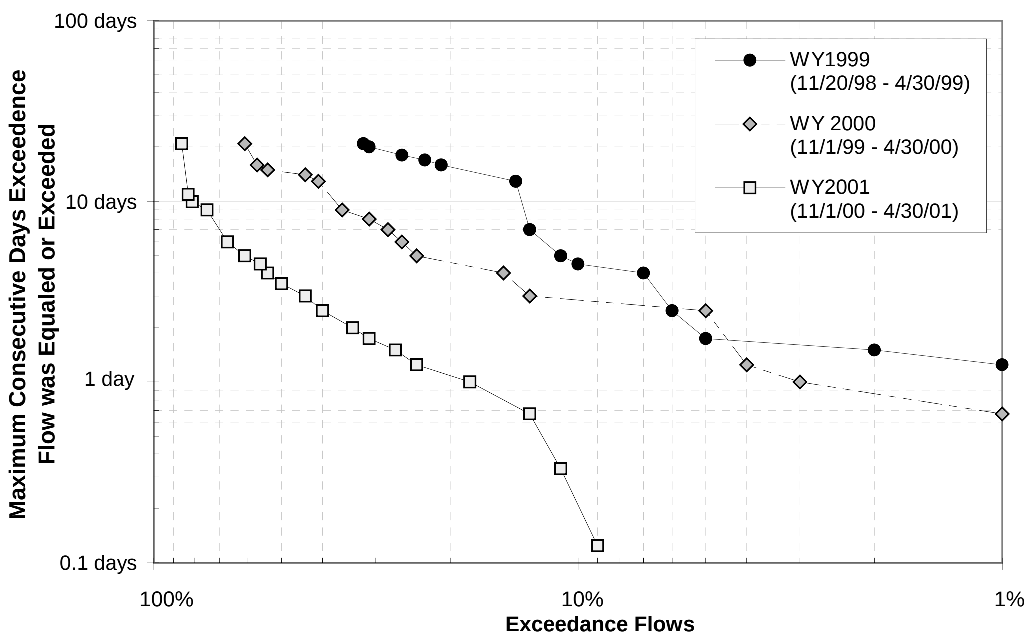

Figure 7-14. Maximum consecutive days stream flow remained at, or above, the indicated migration exceedance flow at Sullivan Gulch, Riverside Road. In water year 1999, stream gaging began November 20th, prior to the onset of high flows. The highest flow occurring in water year 2001 was less than the 6% exceedance flow.

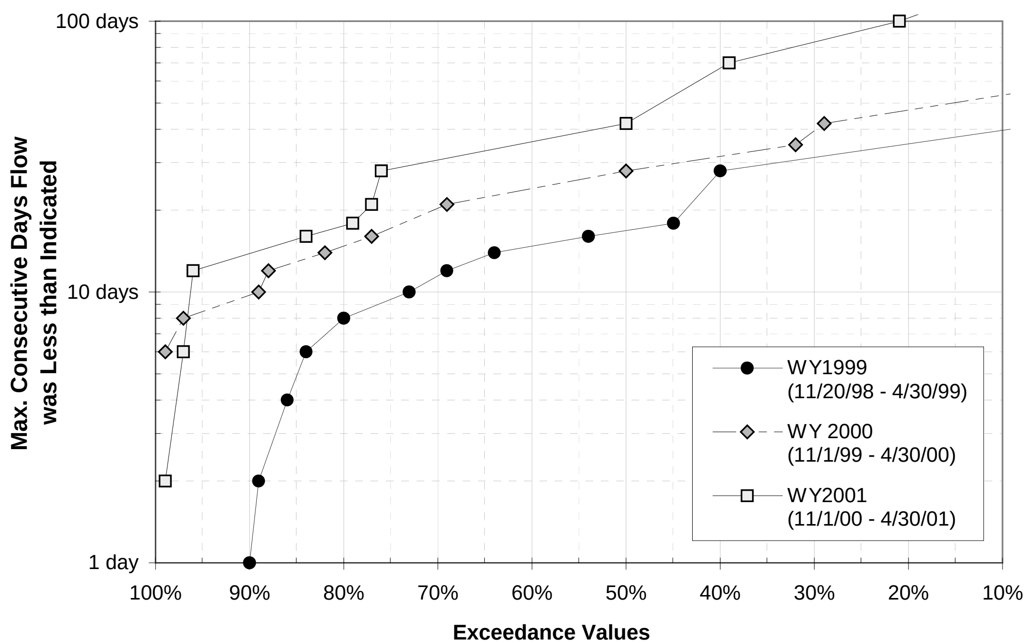

Figure 7-15. Maximum consecutive days stream flow remained below, the indicated exceedance flow at Sullivan Gulch, Riverside Road. In water year 1999, stream gaging began November 20th, prior to the onset of high flows.

7.3.3 Minimum Riffle Depths and Observed Migration

Because low flow migration delays are likely to persist for much longer periods than high flow delays, identifying the low flow at which the stream channel itself becomes a migration barrier due to insufficient water depths is necessary for defining a reasonable lower fish passage design flow for culverts and other crossings. If, at a given low flow, fish are unable to pass through a stream riffle, a culvert above that riffle should not be required to accommodate fish passage at that flow. Therefore, a stream's minimum passable riffle depth may be an important factor for determining culvert design criteria for water depth requirements and selection of a lower fish passage design flow.

To define a minimum riffle passage depth, stream depths were measured in eleven creeks (Table 7-4) within each stream, at least eight riffles were visually surveyed; the deepest route through a riffle was plotted, and depths within that route were measured. (The deepest route is assumed to be the preferred route of a migrating adult fish.) The shallowest depth within the route is then assigned to be the minimum passage depth (MPD) for that riffle. Finally, the MPDs associated with individual riffles were averaged, yielding an average MPD for each stream at a particular flow.

The eleven streams at which MPDs were measured are located within Humboldt and northern Mendocino Counties. Drainage areas varied from 0.1 square miles to 6.5 square miles, with the exception of the South Fork Eel drainage, which is 42.5 square miles. Generalizations that apply to these eleven creeks should also apply to the four study sites, whose drainage areas varied from 1.00 to 4.67 square miles.

Table 7-4. Average MPD is a strong function of discharge, within twelve streams in Humboldt County and northern Mendocino County. Each average MPD resulted from at least 8 riffles within each stream, at that particular discharge.

Stream	Drainage Area (mi^2)	Flow (cfs)	Average Minimum Passage Depth (MPD) (ft)
Sugar Creek	0.11	1.1	0.28
Fox Creek	1.07	1.1	0.30
Skunk Creek	0.21	2.1	0.34
Sullivan Gulch	2.34	2.3	0.45
Rock Creek	3.0	3.0	0.47
Redwood Creek	3.15	3.8	0.39
Jack of Hearts Cr.	3.95	4.0	0.45
Deer Creek	1.2	4.2	0.23
Redwood Creek	3.15	8.3	0.61
Fox Creek	1.07	10.7	0.72
Elder Creek	6.5	17.0	0.82
Rock Creek	3.0	20.5	0.95
Sullivan Gulch	2.34	23.4	0.82
Cow Creek	2.38	23.8	0.77
Sullivan Gulch	2.34	30.0	1.00
Rock Creek	3.0	30.0	1.05
Redwood Creek	3.15	31.5	1.01
Jack of Hearts Cr.	3.95	35.4	1.42
SF Eel River	42.5	36.5	1.20

NMFS recommends a minimum flow for adult fish of 3 cfs (NMFS 2001). In Humboldt County and northern Mendocino County watersheds, a 3 cfs discharge correlates to an average MPD of 0.4 ft., a realistic expectation based on fish migration observations (Figure 7-16). This MPD-discharge relationship appears to hold for drainages up to 40 square miles (see the South Fork Eel river MPD of 1.2 feet at 42.5 mi^2), but the majority of these data represent watersheds ranging in size from two to four square miles. Limiting the application of this relationship to smaller watersheds is reasonable given that culverted stream crossings draining much larger watersheds are not likely to be found within the study area (northwest, coastal California).

A variance is associated with any average number. In the MPD averages, meaningful variances could not be calculated because the number of data points was too few. However, a MPD variance of ±0.1 ft is estimated, based on field observations of fish behavior in riffles and included on Figure 7-16. For example, assuming this ±0.1 ft variance at a discharge of 5 cfs, one could expect to see adult fish attempting to swim through depths ranging from 0.34 to 0.54 feet.

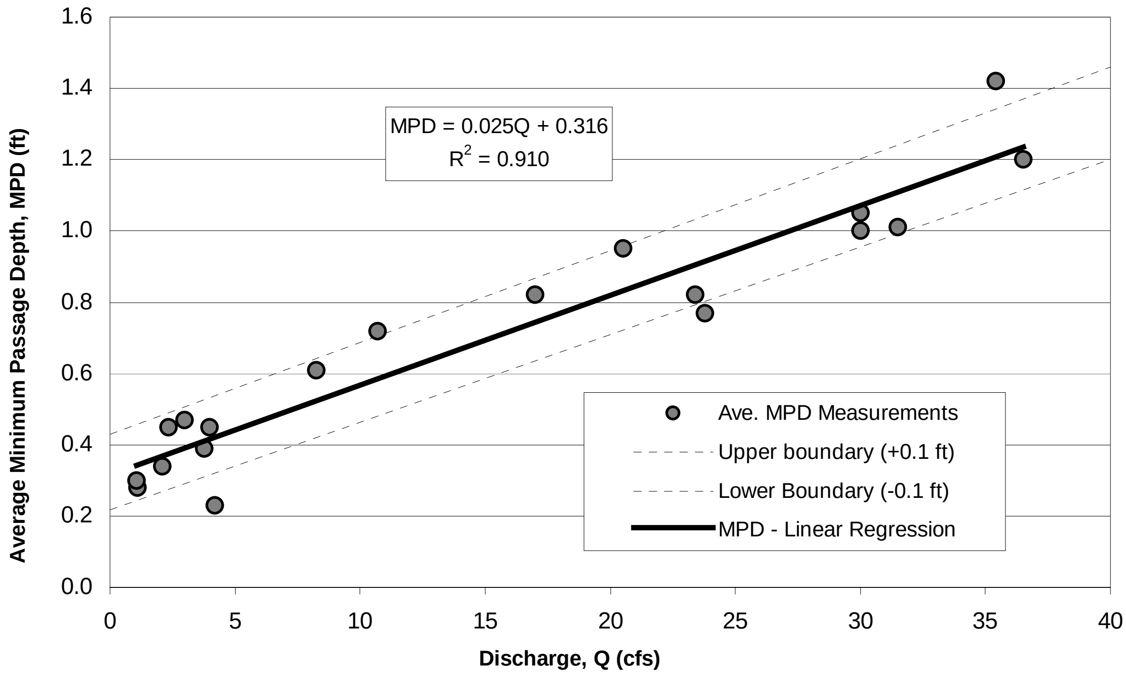

Figure 7-16. Average Minimum Passage Depth (MPD) is a strong function of discharge. The data points represent measurements within eleven streams (& rivers) in Humboldt County and northern Mendocino County.

7.3.4 Effect of Drainage Basin Size on Migration Flows

At flows having identical exceedance values, the flow in a smaller drainage basin may be too shallow for fish passage, while the flow in a larger basin may be sufficient. Shallow riffles, drops over large wood in the channel, and discontinuous flow, are likely to become significant barriers at lower exceedance values (higher relative flows) in small streams compared to larger streams. As flows decrease, low flow fish barriers reemerge, limiting adult and juvenile migration upstream. At flows equal in exceedance value, a smaller stream may be more likely to contain low flow barriers that inhibit upstream migration than a larger stream. During dry periods, small streams can even become discontinuous, stranding juvenile and resident fish in perennial pools.

Drainage basin size can also magnify the effects of high flows on fish passage. During extreme high flows, water velocities within stream channels may become too high for fish, forcing them to seek shelter along channel margins or within side-channels, until flows recede and velocity decreases. As channel size and drainage area decrease, stream bank complexity generally increases. Complex banks provide more extensive regions of lower velocity, allowing adults and juveniles to migrate up small channels at relatively higher exceedance flows (lower exceedance values) than within larger streams and rivers.

Spawning grounds suitable for coho, and especially steelhead, are typically inaccessible in many small streams because low flow barriers inhibit movement. Only during extreme high flows do these small streams become accessible to spawning salmon and steelhead. If these factors hold true, then as a stream’s drainage area decrease the exceedance values that encompass the range of migration flows would decrease. For example, in a larger stream adult fish may be observed migrating between the 60% and 5% exceedance flows compare to the 20% and 1% exceedance flows in a small watershed.

To assess whether smaller streams need larger flows for fish passage, the observed adult migration in Cloney, McCready, Sullivan and Morrison Gulches was compared as a function of exceedance values (Table 7-3, Figure 7-17). This analysis suggests that the range of exceedance values associated with the flows used by migrating adults do decrease as basin and stream size decrease. At Cloney Gulch, the site with the largest drainage area, over a third of adult observations occurred at stream flows below the 30% migration period exceedance flow. As the drainage area decreases, the distribution of adult observations shifts towards the higher exceedance flows

For juvenile fish, no relationship between fish observations, exceedance flows, and drainage area was readily apparent. All culvert outlet pools contained year-round populations of juvenile and resident fish, so neither low-flow barriers nor high-flow water velocities would limit juvenile presence at a stream crossing. The influence of drainage size would, therefore, have much less influence over observed juvenile passage attempts.

Table 7-3. Percent of adult salmon and steelhead observed at each site attempting to pass flows below the 30% exceedance flow ($Q_{30\%}$) and above the 2% exceedance flow ($Q_{2\%}$). Exceedance flows are for the migration period, November through April.

		Percentage of All Observed Adult Passage Attempts	
Culvert Site	**Drainage Area**	**Observed at flows < $Q_{30\%}$**	**Observed at flows > $Q_{2\%}$**
Cloney Gulch	4.67 mi^2	36%	**a**
Sullivan Gulch	2.35 mi^2	6.6%	16%
McCready Gulch	1.98 mi^2	0	20%
Morrison Gulch	1.00 mi^2	1.7%	23%

a. At Cloney Gulch, the outlet pool is often backwatered by Freshwater Creek when flow is greater than the 2% exceedance flow. Once the perched outlet is eliminated, visual observations of leaping fish are ineffective.

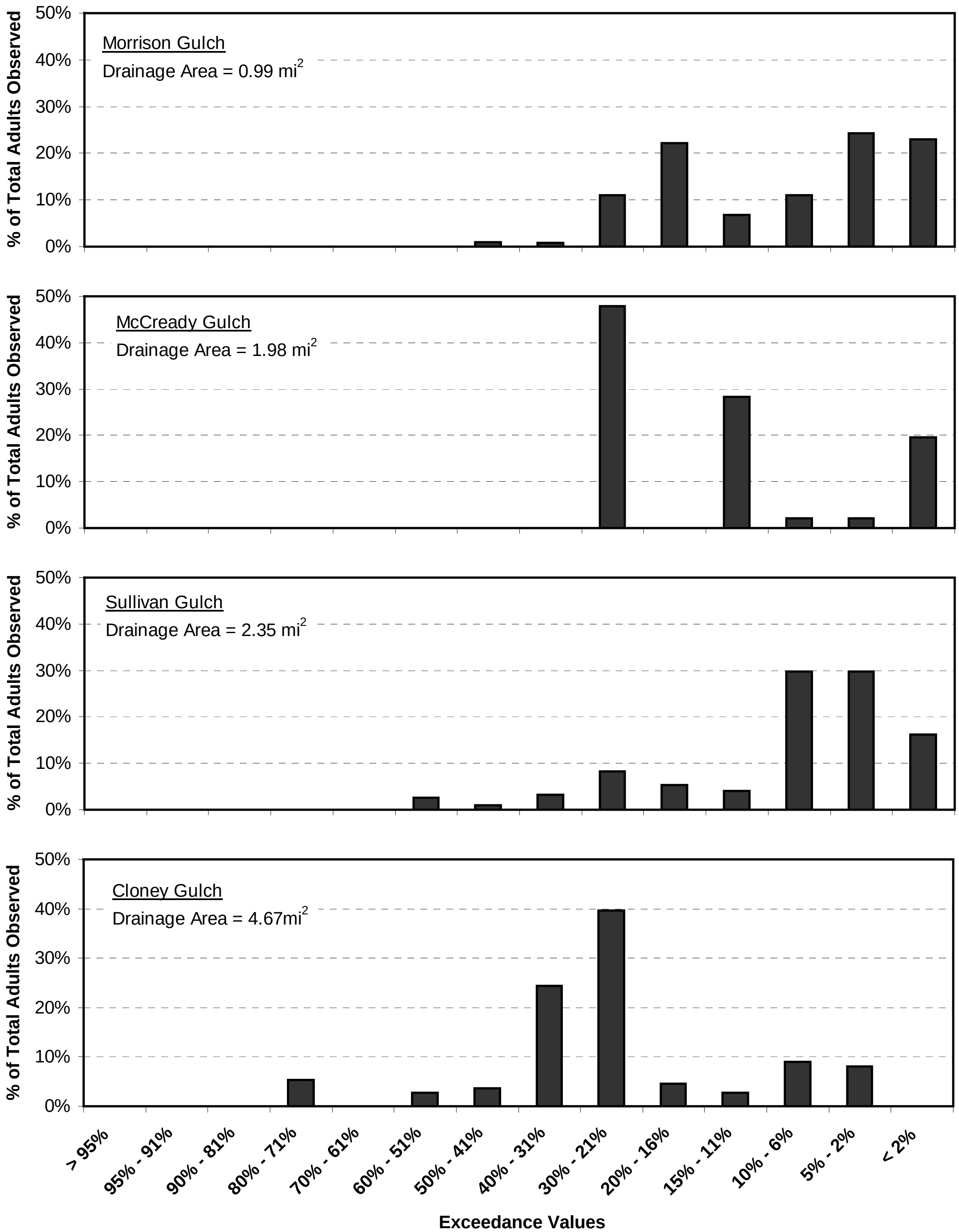

Figure 7-17. The relationships between drainage area, exceedance value, and adult fish observations. In general, as drainage area decreases, more fish were observed at higher exceedance flows (lower exceedance values). This effect is evident as a shift to the right in the distribution of adult observations as drainage area decreases.

7.4 FISH PASSAGE AND CULVERT HYDRAULICS

Swimming and leaping performance were evaluated visually and through PIT tag detection. Swimming and leaping ability could then be quantified by comparing fish performance to the hydraulic conditions that they encountered.

7.4.1 Leaping Performance and Outlet Hydraulics

Leaping performance of adult and juvenile salmonids was quantified from visual observations and PIT tag results. Leaping is a natural ability of salmonids, which enables them to access the upper reaches of stream channels by negotiating instream obstacles. In the small, coastal streams that this study focused on, fish routinely encounter leaping opportunities, such as log and debris jams and small waterfalls. However, leaping requires a large energy expenditure, which can deplete a fish's energy reserves and reduce survival or spawning success.

Ideally, stream crossings are installed such that no leaps are required for fish to pass. However, stream channels are dynamic landscape features, continuously changing in response to the influences of climate, geology, and channel and upslope activities. Installation of culverts, grade control, and other structures in or near stream channels can increase channel erosion downstream, creating situations, such as a perched culvert outlet, that require leaping. Thus, many existing culverts require fish to leap to gain access. Leaping ability was assessed at four perched culverts to quantify the migration delay, and compare leaping success under different situations.

Understanding the conditions that lead to successful leaps and the migration delay caused by failed attempts should assist in setting priorities for addressing stream crossing barriers. Retrofitting or replacing culverts that no longer pass fish due to perched outlets often requires grade control structures that backwater the culvert and eliminate or minimize the drop. In some situations, complete elimination of a drop or perch at the outlet may not be possible, so understanding which fish species can or cannot easily negotiate perched outlets is important. Another requirement for successful leaps is proper take-off conditions. Stuart (1962) concluded that a pool depth of at least 1.25 times the leap height is needed to reach swim speeds fast enough to make a successful leap. Powers and Orsborn (1985) summarize the findings of Aaserude (1984) relating requirements for the pool depth to the penetration depth of the plunging water (plunge depth < pool depth) and to the fish length (fish length > pool depth) needed for a successful leap.

Significant leaps were required at the Sullivan Gulch, Cloney Gulch, McCready Gulch, and Morrison Gulch culvert outlets. Low flow leap heights and residual pool depths for all sites were determined from site surveys conducted at low flows (Table 7-5). Leap heights are measured from the pool water surface to the water surface in the culvert outlet, and typically vary with stream flow. Most of these leap heights decrease at higher flows, but the Sullivan Gulch leap height increases with increasing flow. At Sullivan Gulch, the leap height varied from 1.9 to 3.1 ft when adult salmonids were present, but when juvenile attempts were observed, leap height varied from 2.3 to 3.4 ft. The leap height at Morrison Gulch ranged from 3.3 to 4.5 ft when fish were attempting to move upstream. The leap height at Cloney Gulch disappears completely at the estimated migration 2% exceedance flow, because Freshwater Creek backwaters the culvert outlet.

The outlet configurations for the four culverts vary. Morrison Gulch's outlet is a standard CMP; Sullivan Gulch is a structural steel plate modified with a concrete slurry bottom and a wooden v-notch outlet weir; Cloney Gulch is a 16-ft wide arch with a concrete floor and a wooden outlet weir with a small rectangular notch; and the upper concrete box culvert on McCready Gulch has a wooden v-notch weir at the outlet. Site photographs are included in Appendix A.

Table 7-5. Height of culvert outlet above the downstream tailwater control, which closely matches the maximum required leap height at each site.

Culvert Site	Residual Outlet Drop (ft)	Residual Pool Depth (ft)
Sullivan Gulch	2.1	4.5
McCready Gulch	3.1	2.6
Cloney Gulch	2.9	3.0
Morrison Gulch	5.2	5.1

We observed leaps at these four culverts and recorded successful ("S") and failed leap attempts ("F") for three size classes of juveniles and for adult salmon and steelhead (Table 7-6). These numbers do not represent the number of fish present, only the number of leaps observed and whether those leaps were successful. The Morrison Gulch culvert presented the greatest outlet drop, and had the fewest number of successful leaps.

The smallest juvenile size class, 3- to 5-inches, had little success negotiating the leap heights present at these four culverts. The 5- to 8-inch size class performed slightly better, with some successes recorded during higher flows at all sites except Morrison Gulch. Comparing the relative number of failed attempts, the greater than 8-inch size fish, representing rainbow and coastal cutthroat trout, were fairly successful at Cloney Gulch and McCready Gulch, but not at Sullivan or Morrison Gulch.

Adult fish were most successful at the Cloney Gulch culvert. At flows where adult fish were generally moving upstream, the water at the Cloney Gulch culvert flowed over the full length of the 16-ft wood weir. The leap height under these conditions is approximately 2 feet. Adult fish successfully passed through the Sullivan Gulch culvert but required many attempts. McCready Gulch had fewer observation hours, but some fish were observed successfully negotiating the leap. Only the most athletic fish succeeded at Morrison Gulch.

Table 7-6. Summary of fish leaping performance at perched outlets. S indicates the number of successful leaps; F indicates the number of failed leaps.

	Water	3 to 5-inch		5 to 8 inch		>8 inch		Adult		Observation
Site	Year	S	F	S	F	S	F	S	F	Hours
Sullivan Gulch	1999	0	419	5	189	0	5	6	119	42
	2000	7	211	2	32	0	10	18	212	54
	2001	0	6	0	9	0	2	2	6	19
McCready Gulch	1999	0	2	5	11	0	0	1	21	4
	2000	0	0	1	2	1	1	1	4	20
	2001	1	9	6	25	3	21	3	14	11
Cloney Gulch	1999	1	5	5	41	4	3	6	31	7
	2000	1	37	3	28	1	3	4	11	33
	2001	0	4	0	5	0	20	16	35	17
Morrison Gulch	1999	0	32	0	16	0	18	5	593	26
	2000	0	19	0	11	0	3	0	224	37
	2001	0	0	0	9	0	8	0	163	12

Leaping performance was evaluated as a function of the leap height (water surface elevation in the culvert outlet – water surface elevation in the outlet pool) and flow. These two factors interact to control the turbulence within the pool, the horizontal and vertical distance a fish needs to leap, and the water velocity encountered when the fish lands in the culvert outlet. Leap height may either increase or decrease with increasing flow depending on the relative rate of change between the pool depth and outlet water depth. Thus, how the leap height varies with flow rate is a function of the cross-sectional areas of the tailwater control on the outlet pool and the culvert outlet. This relationship will be unique to each site. At Sullivan Gulch, the leap height ranged from 1.9 to 3.75 feet, and increased with increasing discharge. The success or failure of leaps at Sullivan Gulch is shown below as a function of discharge; the measured leap heights are also included (Figures 7-18, 7-19 and 7-20).

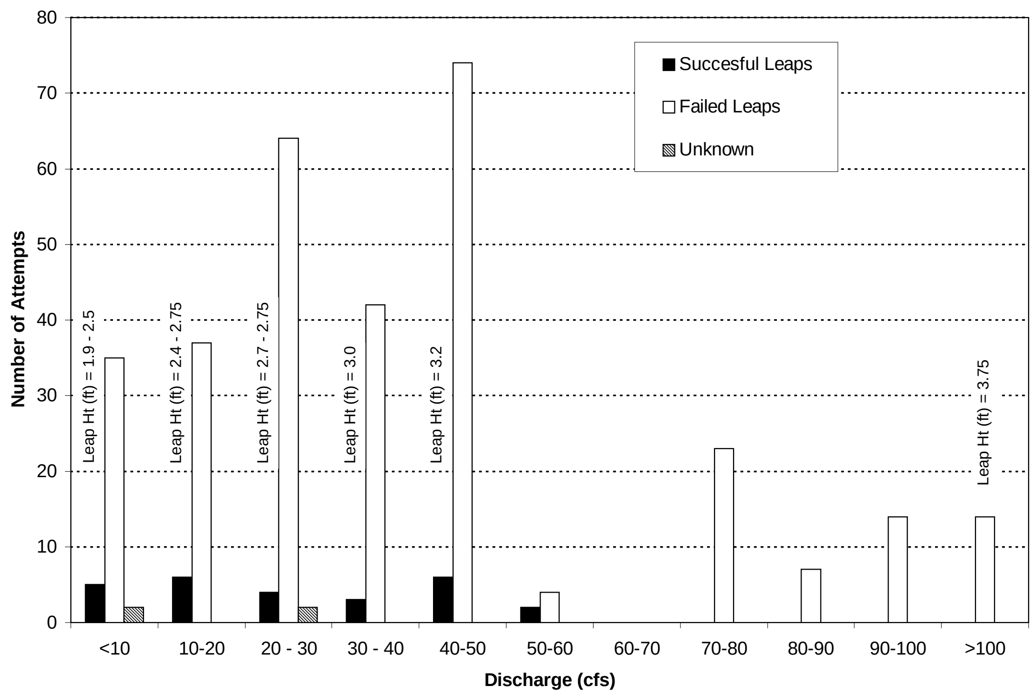

Figure 7-18. Leaping performance of adult salmon and steelhead at Sullivan Gulch as a function of discharge. The leap heights for each flow range are also shown. Successful leaps were observed at flow rates between 8 and 51 cfs. These flows correspond to the 35% and 3% migration period exceedance flows (18% and ~1.5% annual), respectively.

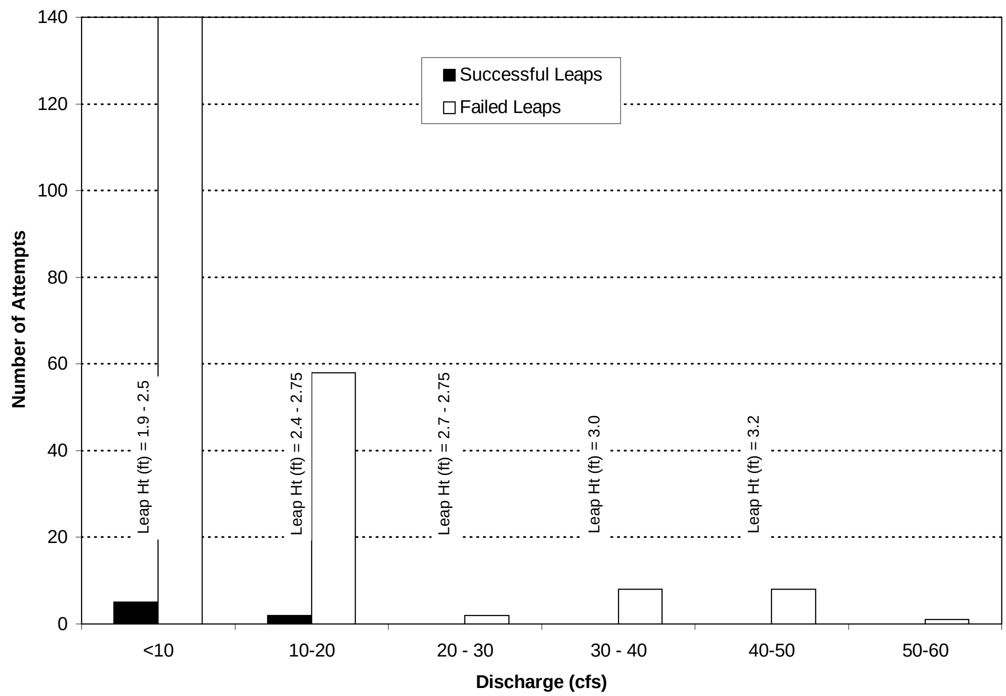

Figure 7-19. Leaping performance of 3- to 5-inch size class juvenile fish as a function of discharge at Sullivan Gulch. The leap heights for each flow range are also shown. Successful leaps were observed at flow rates between 3 and 17 cfs. These flows correspond to the 64% and 17% migration period exceedance flows (35% and 9% annual), respectively.

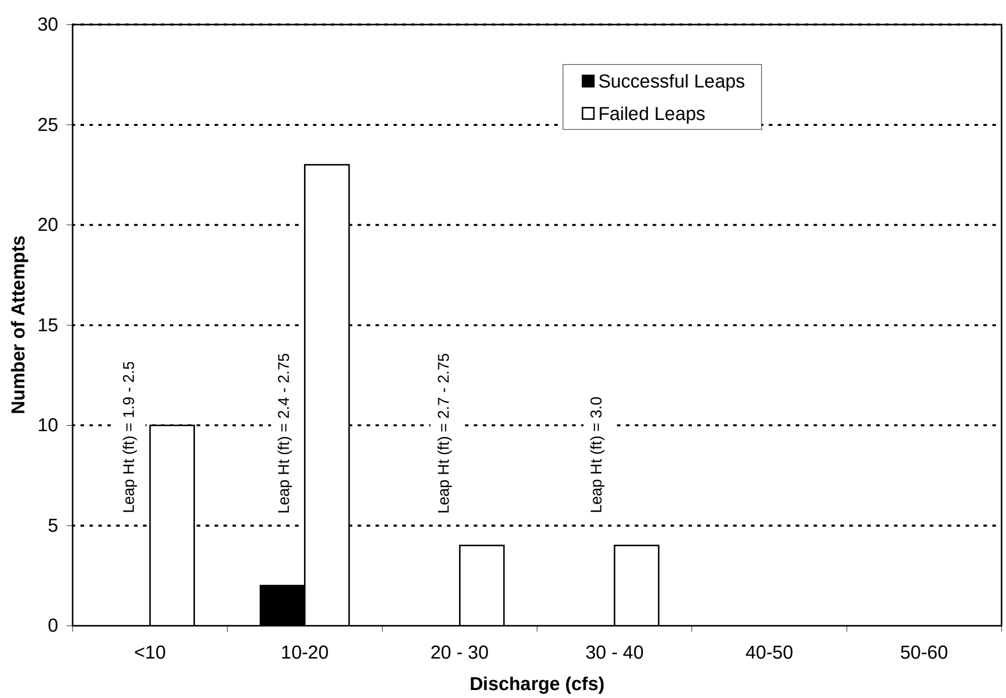

Figure 7-20. Leaping performance of 5- to 8-inch size class juvenile fish as a function of discharge at Sullivan Gulch. The leap heights for each flow range are also shown. Successful leaps were observed at flow rates between 11 and 15 cfs. These flows correspond to the 27% and 19% migration period exceedance flows (14% and 10% annual), respectively.

Leaping performance and the effects of culvert outlet hydraulics on migration was also evaluated from the PIT tag results (Table 7-7). A failed leap attempt into the culvert outlet was assumed when a single PIT tag scan was detected by the outlet antenna, but not followed by detection at the culvert inlet. For Cloney Gulch, the culvert delay was estimated from the time between the first detection at the culvert outlet and the first detection at the culvert inlet. All fish detected passing through the Cloney Gulch culvert had at least one failed attempt detected (range was 1 to 6 attempts). The PIT tag detections underestimate both of these measures since attempts to enter the culvert outlet are only detected if the fish come within 1-2 ft of the antenna.

The McCready Gulch study site has two consecutive culverts separated by approximately 75 ft. The downstream culvert has a natural stream bottom and excellent passage conditions, while the upstream culvert has a significant perch. PIT tag detection antennas were operated on the inlet of the downstream culvert and on both the outlet and inlet of the upstream culvert. The culvert delay (Table 7-7) was calculated as the time between the first detection at the downstream antenna and the first detection at the inlet antenna on the upstream culvert. The leap height at McCready Gulch is greater than that at Cloney Gulch so failed jumps are less likely to come within antenna range and be detected at McCready Gulch. Only the fish attempting the culvert at 6.3 cfs was detected making multiple leap attempts to enter the upstream McCready Gulch culvert.

Table 7-7. Leaping performance and delay caused by the culvert outlet estimated from PIT tag scans at Cloney and McCready Gulch. These results are primarily for coho but one steelhead (fish number 13) was also detected.

Fish Number (PIT tag ID number)	Sex	Fork Length (cm)	Number of Leap Attempts	Culvert Delay (mins)	Discharge (cfs)
1999-2000 Cloney					
1 (1999010202_27)	M	71	3*	Unknown	117 & 10
2 (1999010202_39)	M	49	1	6	10
3 (1999010202_41)	F	67	3	8	39
4 (1999010201_32)	M	68	5	17	13
2000-2001 Cloney					
5 (2000010201_47)	F	70	4	18.5	12
6 (2000010202_39)	M	70	5	7.5	12
7 (2000010202_26)	M	43	1	27	37
8 (2000010202_33)	M	43.5	1	6.5	15
9 (2000010202_19)	M	50	6	29	3.3
10 (2000010202_16)	M	44	3	11	15
11 (2000010202_28)	M	42	2	70	25
2000-2001 McCready					
7 (2000010202_26)	M	43	None Detected	114	16
12 (2000010202_23)	M	68	None Detected	288	27
13 (2000010202_25)	M	41	2	24	6.3

* This fish entered and exited the Cloney Gulch culvert two times over the course of two weeks. The failed leap attempts were detected at the lower flow rate, 10 cfs.

7.4.2 Swimming Performance and Culvert Hydraulics

Swimming performance could not be quantitatively analyzed from the visual observations. Most sites that allowed accurate visual observation had inlet conditions, such as deep pools or channels combined with high turbidity, which precluded continued observation of fish after fish passed through the culvert.

Swimming performance was evaluated using the PIT tag data to determine the travel time through the culvert. These times are the difference between the last detection at the culvert outlet and the first detection at the culvert inlet as the fish travels upstream.

Fish appear to utilize the low velocity regions near inlet and outlet weirs for resting. Travel times through the Cloney Gulch culvert varied from 23 to 985 seconds (approximately 16 minutes). The 23-second travel time occurred at 39 cfs, which corresponds to an average water velocity (determined from hydraulic modeling) through the culvert of approximately 2.1 ft/s. The fish's ground speed was 2.6 ft/s for a relative swimming speed of 4.7 ft/s, assuming it experienced the average water velocity. This swim speed is well within the prolonged swim speed for adult coho (Bell, 19XX).

Visual observations, and the 5 to 10 minute periods between "in and out" PIT tag scans, confirmed that fish must use the low velocity regions near the inlet and outlet weirs and behind baffles for resting. These retrofits were present in both the Cloney and McCready Gulch culverts.

The long travel times for most fish negotiating the culverts suggest that when water velocities are well below the swimming abilities of the fish, the travel time is primarily influenced by behavior.

7.5 SUMMARY

Assuming observations of salmonids leaping at culverts indicated a motivation to migrate upstream, juveniles began upstream movement earlier in the fall and at lower flows than adults. However, movement of both juveniles and adults appeared to be triggered by flow; no attempts at upstream migration were observed until after the first fall rains and very few attempts were observed during prolonged dry periods.

The flow occurring during each passage attempt was expressed as an exceedance flow to allow comparison of migration flows between sites and to permit extrapolating findings across the region. Over one-third of the adults' attempts to enter culverts occurred between the 5% and 2% migration period exceedance flows. An additional 7% of adult attempts occurred at flows greater than the 2% migration period exceedance flow. At the Morrison Gulch culvert, several adults were observed leaping at approximately bankfull flow, which is well above the 0.5% exceedance flow.

No adult salmon or steelhead were observed attempting to pass through culverts at flows lower than the 80% exceedance flow (Figure 7-12). In fact, only 17 (less than 2% of the total adult observations) adult passage attempts were observed, either visually or by the PIT tag antennas, at flows lower than the 50% migration period exceedance flow. Most observations of these low flow passage attempts (13 of 17 observations) by adult salmonids occurred in the dry year of the study, water year 2001.

Timing of juvenile migration was also evaluated in terms of exceedance. For size classes of 3- to 5-inch, 5- to 8-inch, and greater than 8-inch, most (over 85%) observed passage attempts occurred between the 70% and 5% migration period exceedance flows. Considering only the 3- to 5-inch and 5- to 8-inch size classes, peak juvenile movement was observed between the 30% and 21% migration period exceedance flows. Fish in the greater than 8-inch size class were not frequently observed, but appeared to move at slightly higher flows than the smaller size classes.

The consecutive days in which stream flow remained above specific exceedance flows were quantified for the three years of study. During water year 1999, discharge remained above the 2% migration period exceedance flow at Sullivan Gulch for 36 consecutive hours. If a stream crossing was required to be designed to provide adult fish passage up to the 2% exceedance flow, then a fish swimming up Sullivan Gulch may have been delayed at the culvert outlet for up to 36 hours due to high flows during WY 1999. In WY 2000 this delay would have dropped to 21 hours, and have been nonexistent in WY 2001 since the peak flow never reached the 2% migration period exceedance flow.

The minimum water depth within a stream is a factor in determining the lowest flow that adult salmon and steelhead are able to migrate upstream. Culverts should not need to provide fish passage when there is insufficient depth within the stream for fish to migrate. Most often this minimum depth occurs within a riffle. By measuring the water depth over the riffles, a minimum passage depth (MPD) was obtained as a function of flow. A strong relationship was found between stream flow and the average MPD, regardless of basin size. At a flow of approximately 3 cfs the MPD is approximately 0.4 ft, a fairly shallow flow for most migrating adults.

Observations suggest that adult migration occurs at flows having smaller exceedance values as the watershed size decreases. Using fish observations from the four sites, the distribution of fish movement shifts towards higher exceedance flows as drainage area decreases. In smaller watersheds, conditions may be such that low flow barriers persist until higher relative flows allow passage, compared to large watersheds. The number of watersheds studied during this three-year project was too low to significantly quantify this observation. Additional study of the relationship between drainage basin size and exceedance flows is needed because it implies that a single exceedance flow guideline may not be appropriate over a wide range in watershed sizes.

At perched outlets, the effects of culvert hydraulic conditions were quantified by leaping performance. Adult fish successfully negotiated most leaps but at every perched culvert requiring a leap from 1 to 4+ feet, multiple leap attempts were observed before fish successfully continued upstream. Juveniles had very little success negotiating the range of leap heights observed.

Swim speeds through the culverts studied appeared to be controlled by fish behavior, rather than ability or in-culvert water velocity. The PIT tag data collected at Cloney and McCready Gulch provided measurements of travel time through these culverts, but at both sites fish took advantage of culvert baffles and weirs for resting. Therefore, in-culvert velocities did not appear to be a limiting factor. In most cases visual observation data could not provide quantitative evidence that in-culvert velocities were a factor in fish passage because inlet conditions did not allow observation due to high turbidity and water depth.

8 Conclusions and Recommendations

These conclusions and recommendations summarize and synthesize quantitative findings, qualitative observations at study sites, and other lessons learned during monitoring of fish passage at stream crossings on coastal streams in Del Norte, Humboldt and Mendocino counties since 1998.

8.1 Hydrologic Criteria

8.1.1 Annual Hydrologic Variability and Limited Migration Window

Conclusions

This study demonstrated the effects of high annual variability in precipitation and runoff on fish migration throughout coastal Northern California. Coastal basins receive most of their precipitation as rainfall due to their low elevation and close proximity to the ocean. Coastal streams examined as part of this study showed a quick response to precipitation events, with stream flows both rising and falling rapidly. These flashy runoff characteristics greatly limit the window of opportunity for migrating fish. The entire window available for upstream migration and spawning in these streams may be limited to only several hours each storm event.

Extended dry periods were common during the peak migration period. Fish encountering a stream crossing with unfavorable low-flow passage conditions during the falling limb of a storm hydrograph may be unable to negotiate the crossing until the next storm increases flow. During an extended dry period, fish may have to hold for months before the next opportunity to migrate upstream occurs. Migration delays approaching 30 days were observed through our PIT tag results in Freshwater Creek during WY2001, suggesting that it is a common situation in dry years.

Migration delay of adult salmon and steelhead due to unfavorable high-flow hydraulic conditions at a stream crossing (excessive velocity or turbulence) often forces the fish to wait for flows to drop. Once the fish successfully negotiates the stream crossing at some lower flow, the upstream conditions may have become marginal or insufficient for spawning. Since many small streams provide inadequate habitat for large fish to hold until the next flow event, which may not occur for many weeks, the fish are forced to either spawn in poor locations and conditions or migrate back downstream to find suitable holding or spawning habitat.

Recommendations

To prevent these undesirable effects on migrating adult anadromous salmonids as they attempt to complete their lifecycle, stream crossings within coastal California need to provide conditions favorable to fish passage over a wide range of flows. The lower extent of this flow range should be the low flow that fish can reasonably be expected to move within the stream channel. The upper extent of this flow range should be selected to minimize high flow delays. Our observations indicate that for adult anadromous salmonids a low flow corresponding to the 50% annual exceedance flow [adult salmonids were never observed trying to pass culverts below 3 cfs (0.085 cms)] and a high flow at the 1% annual exceedance flow, minimized migration delay at stream crossings.

When selecting an upper fish passage design flow for a specific site, one factor to consider is the responsiveness of the stream to rainfall events. The more rapidly a stream hydrograph drops to base flow following a rain event (flashier systems), the more important it is to provide passage over a wide range of flows.

The climate and rainfall patterns along California's coastline transition from a temperate rainforest in the north to the dry Mediterranean climate found at the southern extent of steelhead range. Due to this variation in hydrologic characteristics, it is inappropriate to apply fish passage design flow criteria developed for salmon and steelhead in other regions. In fact, due to the vast differences in rainfall patterns and quantities throughout the state, it may be necessary to develop multiple fish passage design flow guidelines, each aimed at a specific region of California.

8.1.2 Hydrology and Retrofits

Recommendations

Various constraints can lead to stream crossing designs that fail to satisfy passage criteria over the desired range of fish passage design flows. In these situations, it is important to quantify the benefit gained by only partially improving passage conditions through the installation of retrofits such as fish ladders, baffles, or weirs. Flow duration curves with confidence intervals, as outlined in Section 4.4, can help evaluate the benefit of incrementally improving fish passage by quantifying the effects of annual variability in flow conditions.

8.1.3 Juvenile Migration – Thermal Refugia

Conclusion

When selecting a design flow for a stream crossing, site-specific issues relating to upstream migration needs should be identified. Thermal stress induced by high water temperatures may require fish to migrate upstream or into tributaries seeking cooler waters. Roads following river valleys generally cross streams immediately upstream of their confluence with the larger watercourse. Blocked or reduced passage through these stream crossings may prevent access to cool waters in summer months.

Recommendation

Fisheries biologists should determine if the habitat upstream of crossings provides thermal refugia or other water quality benefits compared to the downstream reaches or water bodies. In situations where the upstream habitat is vital thermal refugia, the fisheries biologist should identify the species and age classes using the refugia. In many smaller coastal systems, only juvenile and resident salmonids need thermal refugia since most coastal runs of adult salmon and steelhead do not enter freshwater until late fall or winter when cooler water conditions prevail.

8.1.4 Design Flows for Stream Simulation

Recommendation

Fish passage design flows should not apply to embedded and open-bottom culverts, because they are designed to retain natural streambed substrate. Instead, guidelines for these crossing types should recommend that water depths and velocities within the crossing mimic those found within the adjacent stream channel at all flows below the bankfull flow. This will ensure the crossing provides adequate passage conditions whenever the stream channel has water depths and velocities that allow fish to migrate upstream.

8.2 STREAM CROSSING DESIGN AND ASSESSMENT

8.2.1 Leaping Criteria

Conclusions

Although the literature often cites the impressive leaping abilities of salmon and steelhead, our observations repeatedly documented the extreme difficulty a majority of the fish had negotiating even slightly perched culvert outlets. In addition, even after a successful leap, fish were often washed back out of the culvert. The difficulty encountered by the fish appeared to be compounded when water exited as sheeting flow. This was plainly evident at the Cloney Gulch culvert outlet, which consists of 16-foot wooden weir with a small rectangular notch. At fish migration flows, water flows as a sheet across the entire weir, drowning out the notch and providing no discernable region of concentrated flow. Even when the outlet drop was one foot or less the hydraulics created by the weir appeared to confuse the fish, resulting in extremely poor aim when leaping.

On the other hand, adult and juvenile fish seem to have little trouble negotiating boulder jump pool weirs located downstream of this and other culverts. Adults were typically observed swimming up the nappe, rather than leaping over these weirs. Generally these weirs concentrate flows into the channel center and create complex velocity distributions, allowing fish to swim through areas of lower velocity. Juveniles were observed leaping from the side, at the edge of the nappe as water flowed over the weirs. In most cases, a resting pool upstream of each weir prevented the fish from washing back downstream.

Recommendations

Given the great difficulty all fish demonstrated negotiating even the smallest culvert outlet perch, all new designs and retrofits should attempt to eliminate perched outlets. Since boulder jump pool weirs that fully span the channel appear to be much more negotiable for both adult and juvenile salmonids, they can be used to raise the stream grade (hydraulic grade line) below the culvert outlet in many situations. Qualitative observations of boulder jump pool weirs indicate that water surface drops over the weirs can be as much as a one-foot drop while still providing juvenile passage. The acceptable drop for juveniles may be less for more uniform weir constructions (e.g. log or concrete weirs). A maximum drop of 0.5 feet appears reasonable, even for juvenile salmonids.

All weirs, whether they are placed within the culvert or the channel, should be tapered and point upstream to concentrate the flow towards the channel center and prevent sheeting flow.

8.2.2 Physical Fish Condition versus Prescribed Water Velocities

Conclusions

Powers and Osborn (1985) used a fish condition factor to estimate the swimming ability of salmon and steelhead. Typically, a fish is in top physical condition when it first leaves the ocean environment and enters fresh water. Therefore, it has been assumed that fish migrating up short coastal streams would be in better physical condition when spawning than fish that swim many miles inland to reach their spawning grounds. Our observations indicate that this is not a valid assumption.

Low flows can persist for extended periods during adult migration, as occurred during WY2001. Several coho were PIT tagged in early and mid-December 2000 as they entered Freshwater Creek from Humboldt Bay. Even though the spawning grounds are only a few miles upstream of tidewater, where they were tagged, an extended low flow period prevented these fish from successfully swimming up tributaries to spawn for almost two months. As a result, these fish were in fairly poor physical condition by the time flows were sufficient for them to reach their spawning grounds. In addition, returning anadromous adult fish face a gauntlet of predators such as sea lions and otters. It is common for adult fish to have recently inflicted wounds before they enter small, coastal streams (HFAC, personal communication).

Recommendation

Given these observations of fish condition and the potentially sporadic nature of precipitation along coastal California, the maximum allowable water velocities at stream crossing should accommodate passage of weaker swimming individuals regardless of the crossing's proximity to tidewater.

8.2.3 Conservative Design Criteria

Conclusions

Design guidelines and criteria for providing fish passage at new stream crossings are typically divided into two categories: stream simulation design and hydraulic design. Stream simulation guidelines aim to simulate the stream channel's form and function through the crossing using culvert sizing and placement techniques based on the stream's morphology. Properly functioning stream simulation culverts retain substrate, maintain stream channel hydraulic conditions, and provide unimpeded transport of bedload and debris. Thus, design criteria for stream simulation culverts should be based on matching the local stream geomorphology to provide process continuity.

Hydraulic culvert design requires that suitable passage conditions for the target species and lifestage exist at flows bounded by the lower and upper fish passage design flows. The hydraulic design criteria typically prescribe a minimum water depth, maximum average velocity, and maximum outlet drop for each target fish. To ensure passage of even the weakest swimming individuals within the targeted species, the design criteria are selected to be far from challenging for the average fish. For most species and lifestages, the criteria below appear to be extremely conservative:

1. Lower fish passage design flow.
2. Minimum depth requirements for relatively short culverts.
3. Average cross-sectional water velocity criteria for smaller fish.
4. Roughness values for culverts at fish migration flows.

Although the intent is to provide passage of the weakest individuals, the conservatism built into each criterion is generally compounded. Cumulatively, this conservatism may result in overly conservative design criteria that offer no additional benefit but force an unnecessary increase in project complexity and cost, and may invalidate the credibility of the responsible agency.

Recommendation

Existing design criteria should be reviewed on a regular basis and updated as new data emerges from both research and monitoring of recently completed stream crossing projects.

8.2.4 Differentiating between Inventory and Design Criteria

Conclusions

With the recently renewed interest in eliminating fish migration barriers, inventory and assessment of existing stream crossings to identify migration barriers have become widespread. The objectives of most inventories include (1) identifying all stream crossings on anadromous stream reaches, (2) assessing the extent to which each crossing hinders upstream passage of target fish species and life stages, and (3) rank sites for treatment based on factors that include extent of barrier, quantity and quality of upstream habitat, and species diversity.

To determine the degree to which the crossing is a barrier, it is necessary to define passage criteria (i.e. maximum average velocities and outlet drops, and minimum water depths). These criteria should be met between the lower and upper fish passage design flows for all target species and lifestages for the crossing to be considered providing unimpeded passage. As discussed above, design criteria are generally extremely conservative and aimed at providing passage for the weakest individuals of a species and age class over a broad range of flows. Inventory results show that when comparing the performance of existing stream crossings to current design criteria most sites fail to meet the criteria at all flows within the required flow ranges. However, field observations indicate that many of these sites are only partial barriers, providing passage for some, if not all, fish under certain flow conditions.

Recommendation

For assessment of existing culverts it is preferable to use passage criteria that are less conservative than those used for design. The development of assessment criteria will allow for finer resolution of site rankings by presenting a clearer picture of the extent to which each crossing is a barrier.

8.2.5 Design versus Constructed Elevations

Conclusions

The difficulty of installing corrugated metal (CMPs) and structural steel plate (SSPs) culverts at the design slope has become obvious through implementation monitoring of newly designed and constructed culverted stream crossings and through experience gained during large-scale inventories. In addition, study results show that installed metal pipes are highly susceptible to slumping and bowing, which cause changes in slope within the culvert. These two factors, associated primarily with metal pipes, greatly increase the likelihood of a properly designed culvert becoming a migration barrier.

Recommendation

To account for the difficulty in installing metal pipes at the design slope and the likelihood of culvert settling with age, sensitivity analysis should be incorporated into the hydraulic design process to determine the degree to which the inlet and outlet elevations can vary while still satisfying passage criteria. In addition, construction plans should clearly indicate tolerances associated with finished inlet and outlet invert elevations and culvert slope.

The same problem was encountered with boulder grade control structures, such as jump pool weirs. It is difficult to place boulders at a specified elevation with a high level of precision.

Imprecision in construction and the potential for changes in site configuration over time supports the use of conservative design criteria.

8.2.6 Spacing of Jump Pool Weirs

Conclusions

During the course of this study, it became evident that placement of weirs and adequate sizing of pools for energy dissipation should be part of any design. In several locations pools created by weirs within and below the outlet of culverts appeared to function adequately for fish passage at lower flows. However, due to their inadequate effective volume, the pools become extremely turbulent at moderate and higher flows when adult fish were present. Turbulence in several cases appeared to prevent the adult salmonids from even attempting to leap into the culvert. Instead, the fish observed in the turbulent pools waited for flows to drop before proceeding upstream.

Recommendation

Determination of height and spacing of weirs should attempt to minimize turbulence at fish migration flows. Weir height and placement should be designed using similar energy dissipation criteria currently used in design of pool and weir fishways.

8.2.7 Velocity Reduction Factors

Conclusions

The study examined velocity distributions within culverts and the appropriateness of using velocity reduction factors to account for regions of lower velocity along culvert walls. Both field and laboratory observations have documented fish using these edge velocities with great success. However, our results indicate the area, magnitude, and continuity of this low velocity region is inconsistent; influenced by a myriad of factors, including flow rate and adjacent stream dynamics. In addition, velocity distributions fail to quantify the turbulence that is often found along the culvert walls. Field observations show that turbulence can create an effective barrier to upstream swimming juvenile salmonids.

In regions that use reduction factors during culvert design and assessment, such as Alaska, it is only applied to juvenile and resident fish passage. Practitioners in these regions generally consider the velocity reduction factor to be a means for compensating for the overly conservative nature of the existing design criteria (Gubernick, Pers. Com., 1999).

Recommendation

Due to the variability of velocity distributions within culverts, we recommend that velocity reduction factors not be used in the design or assessment of stream crossings

8.3 DATA GAPS AND ADDITIONAL RESEARCH NEEDS

8.3.1 Migration Flows and Scale Effects

Consistently, we observe that the smaller the contributing drainage area the relatively higher flow (i.e. smaller exceedance value) that adult fish migrate upstream. At Morrison Gulch, the smallest stream among our intensively monitored sites, we observed fish migrating at flows exceeding bankfull. Also, experience with streams located in more southerly coastal regions has found fish spawning in extremely small tributaries (less than 0.35 mi^2), but only during extreme events (greater than 1.5-year return interval) (Taylor, 2003). All evidence points to a scale effect relative to a stream's drainage area. In general, we suspect that as a stream's drainage area decreases the window of flows utilized by adult anadromous fish shifts upward. In a hypothetical example, a stream with a drainage area of 2 mi^2 may see adult salmon and steelhead migration between the 30% and 2% exceedance flows. However, further upstream the drainage area decreases to 0.5 mi^2. Within this reach, fish migration occurs at flows falling between the 5% and 0.1% exceedance flows. Although there are no large datasets available to test this supposition, it is highly probable given stream dynamics.

The initial findings associated with the minimum passage depths (MPD) lend validity to the theory. Results suggest that in fluvial and semi-fluvial controlled channels the minimum water depth within a channel is independent of drainage area or stream size. It is also commonly accepted that many low flow barriers, such as debris jams, become passable to upstream migrating fish during high flows. As channels become smaller, the frequency of low flow barriers associated with large woody debris appears to increase. Therefore, as stream size decreases the flow required to provide enough depth for passage within the stream channel and to allow for negotiating debris-related low flow barriers increases relative to the frequency of the flows occurrence.

To better refine the selection of appropriate fish passage design flows, further research is needed to verify and quantify the existence of any scale effect related to migration flows and watershed area.

8.3.2 Low Passage Flow and the Minimum Passage Depth (MPD)

As part of this study, minimum passage depths (MPD) were measured at various flows in numerous streams. The measurements were collected at riffles within alluvial channel reaches. Preliminary results suggest that the MPD is independent, or not strongly dependent, on either drainage area or channel slope. This observation implies that smaller streams become accessible to migrating adult salmon and steelhead at flows associated with a smaller exceedance value (relatively higher flows) than larger streams. Additional data collection comparing MPD and flow over a range of watershed sizes is needed to confirm this relationship.

8.3.3 Roughness Coefficients

Currently, Manning's roughness coefficients for existing culvert materials apply to culverts flowing at least half full (Normann et al., 2001). Study results indicate that these roughness values change with depth and are typically much higher during typical migration flows than those commonly reported for estimating hydraulic capacities. A need exists for developing roughness coefficients for various culvert materials at flows common to fish passage.

8.3.4 Rapid Biological Assessment Techniques

Most stream crossing inventory and assessment techniques rely on comparing the physical and hydraulic attributes of the existing crossing to a selected set of fish passage criteria. Additionally, newly installed stream crossings designed to provide fish passage have been subject to a similar type of compliance monitoring, which deems the project a success if it meets all of the stated fish passage design criteria. However, these approaches are susceptible to many uncertainties, including the appropriate passage criteria for each lifestage and species, the difficulty in predicting how fish behavior influences passage success at a site, and the uncertainty in the range of flows that fish migrate within a given stream reach.

The primary objective of all of these assessment and monitoring techniques is to determine if a crossing hinders fish passage and if so, to what degree. With this in mind, an alternative or complementary method that utilizes rapid biological assessment techniques should be developed. The techniques should attempt to have the following attributes:

- Field measurements that are relatively quick to execute, although revisiting sites at various times throughout the year may be necessary.
- The ability to assess passage conditions for both adult and juvenile salmonids.
- Guidance on how to incorporate monitoring results into existing assessment techniques.

Developers of this technique should examine techniques that compare fish populations above and below the crossing or monitor activities of individual fish. Methods could consist of examining population densities or using a mark-recapture method at specific times throughout the year. The use of a rapid biological assessment technique should supplement existing physically based methods of assessment, and only be used on an appropriate subset of inventoried crossings. Given the uncertainty associated with existing techniques for estimating fish passage performance, the level of confidence associated with any rapid biological assessment technique would only need to meet or exceed that which currently exists.

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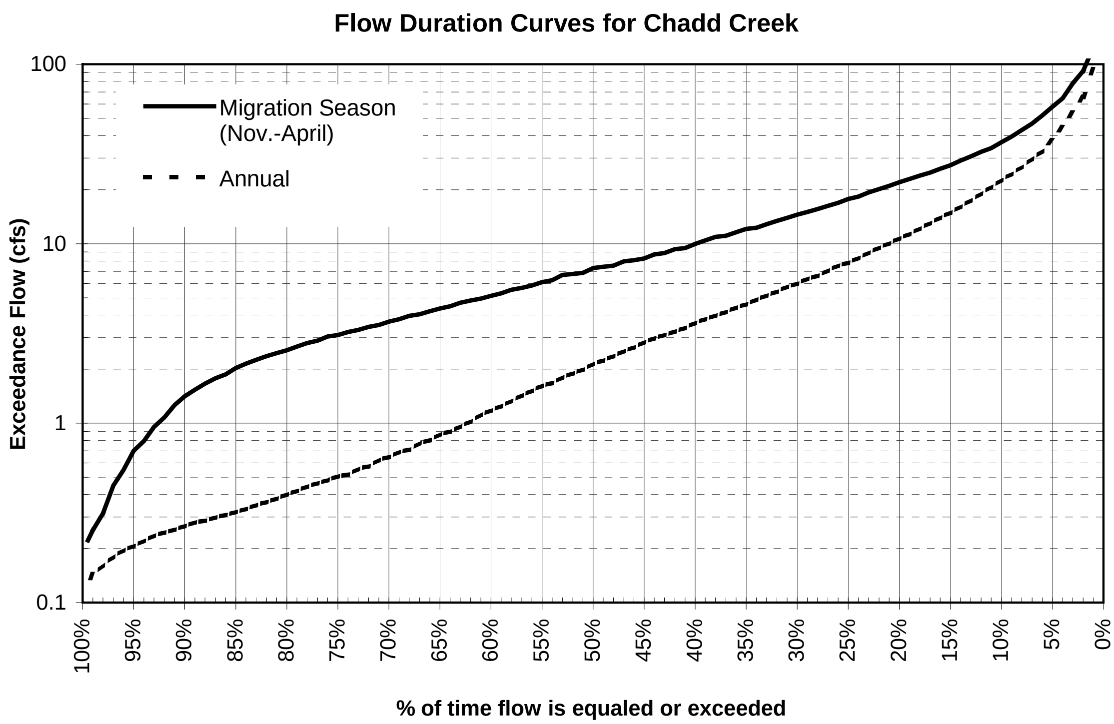
Appendix B – Hydrology

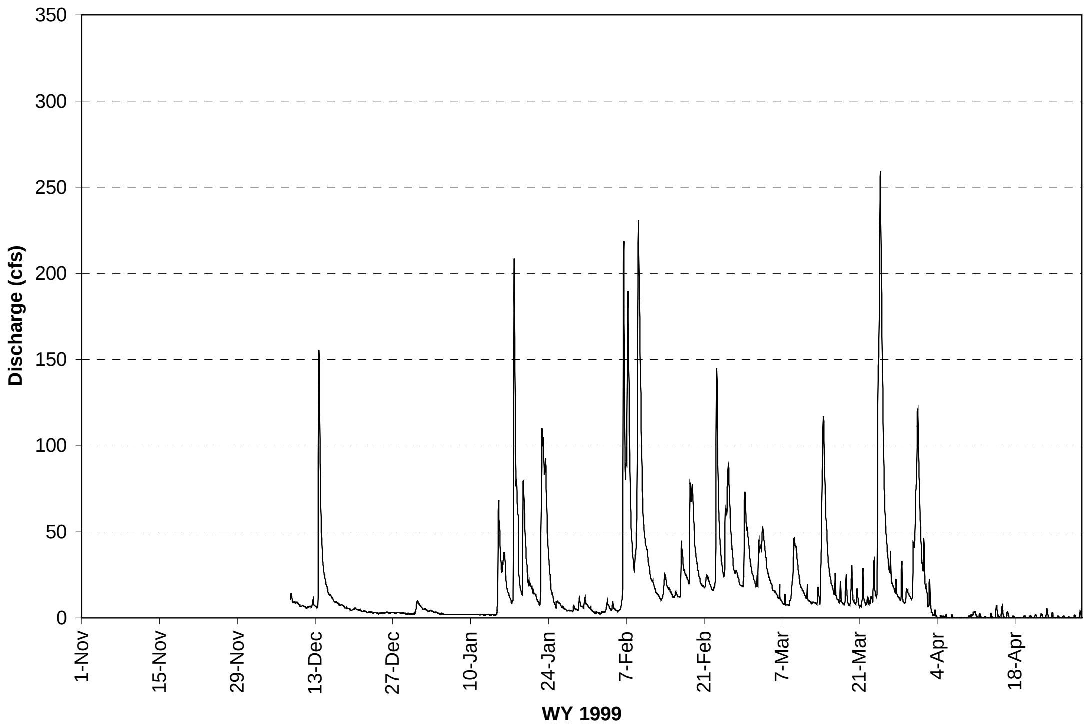
Chadd Creek

Hydrographs are not available for Chadd Creek. Two separate stage recorders were installed at this site. The first was stolen and the second failed. No reliable stage data was collected.

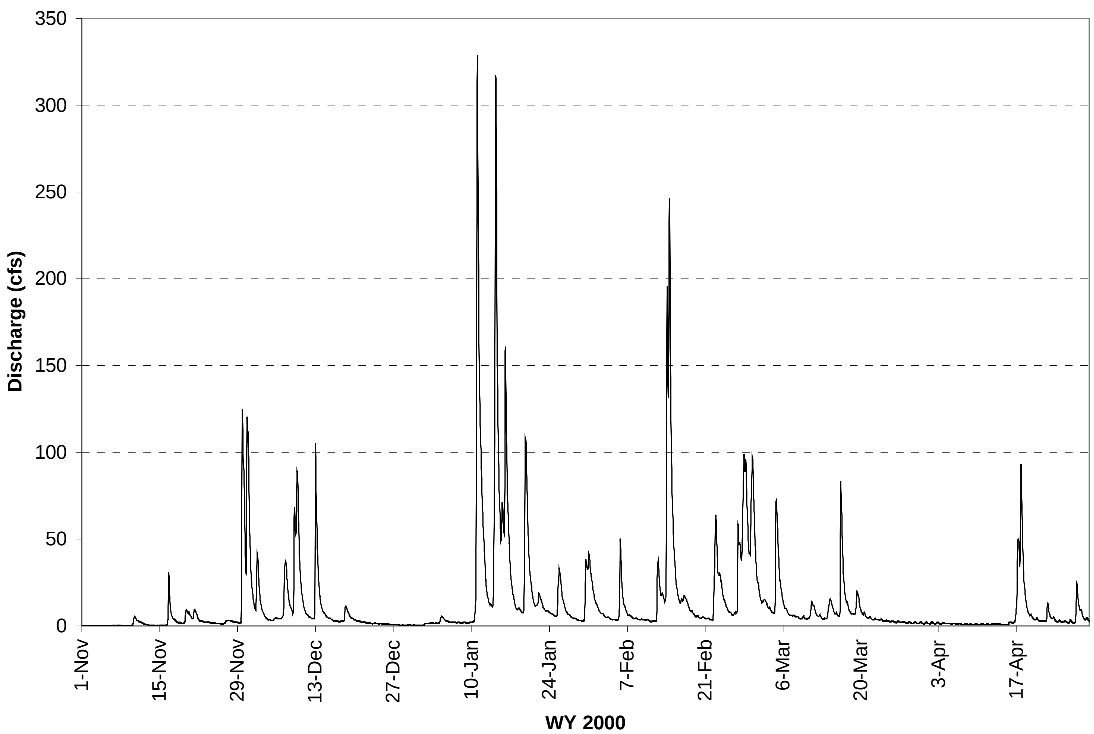


Synthetic flow duration curves for Chadd Creek, based on flows occurring from November through April (Migration Season) and October through September (Annual). Curves were created using the regional flow duration curve. The average annual flow (Qave) for Chadd Creek was estimated to be 8.7 cfs.

Cloney Gulch

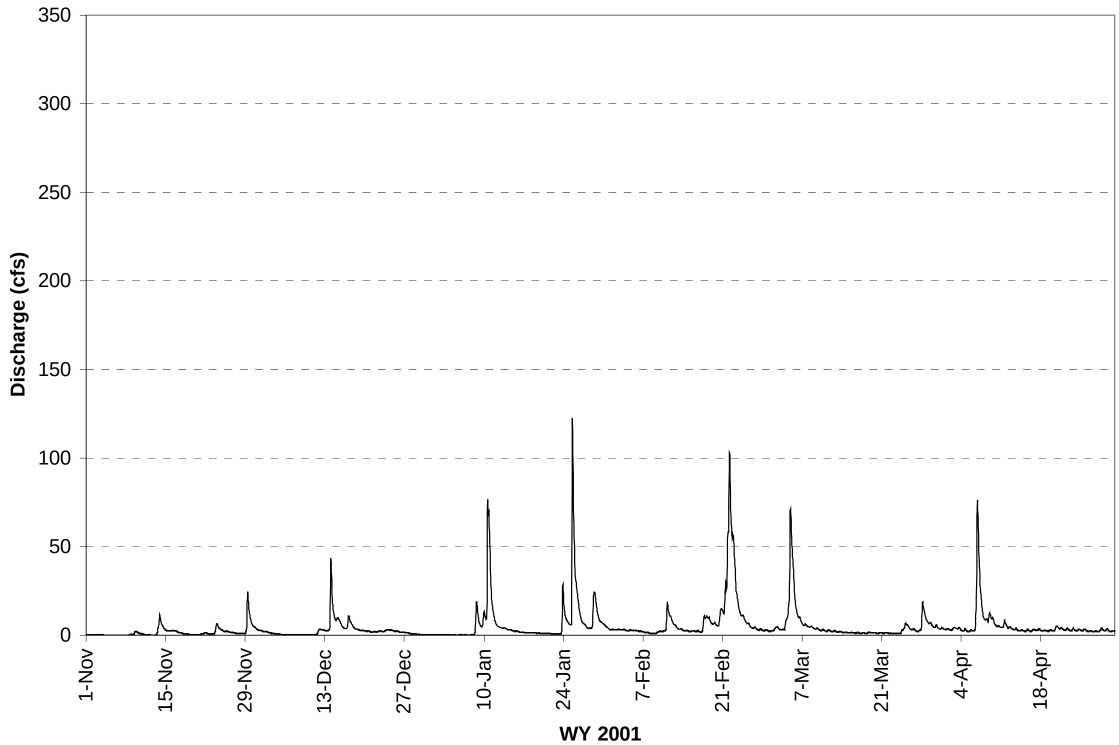


Synthesized hourly average flow at Cloney Gulch from November 1998 through April 1999. The gage at Cloney Gulch was not installed until WY 2000. These flows were synthesized using the McCready Gulch data and a nearby gage on Freshwater Creek.

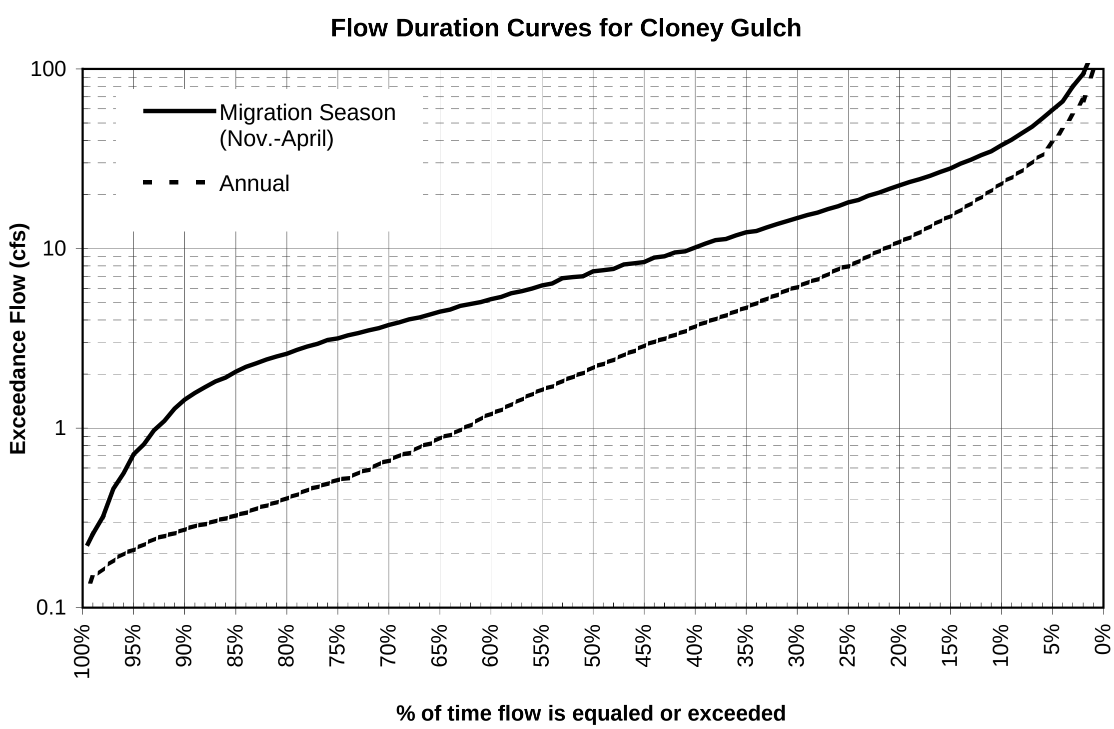


Hourly average flow at Cloney Gulch from November 1999 through April 2000. The Cloney Gulch stage recorder was installed in October 1999.

Cloney Gulch

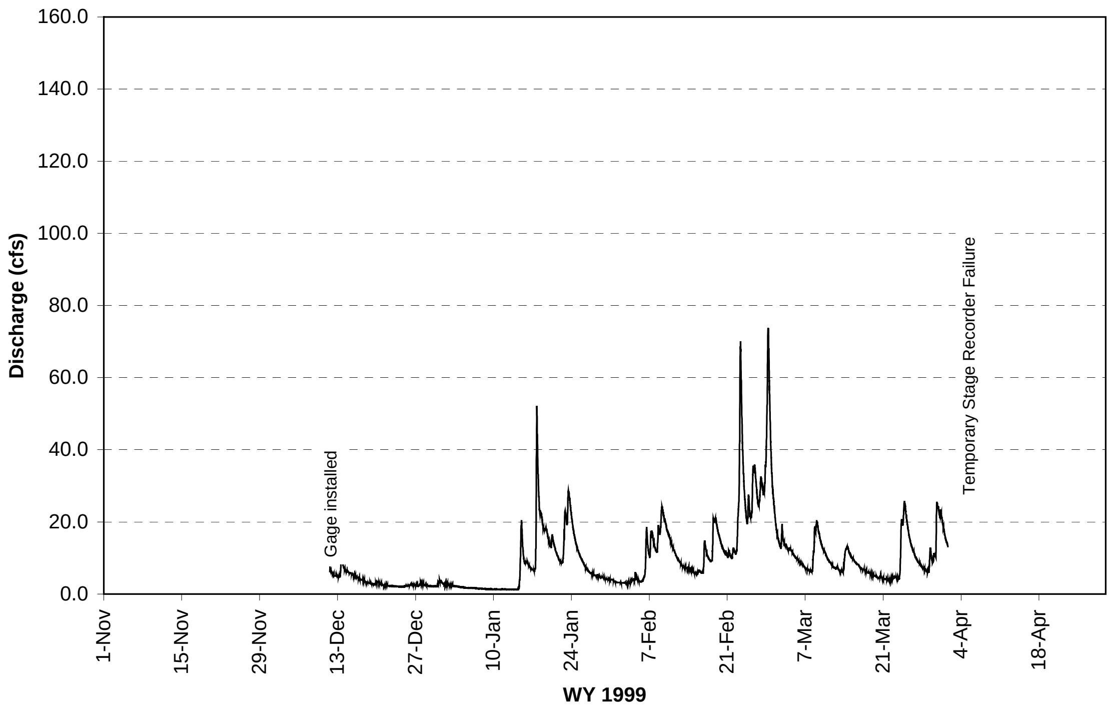


Hourly average flow at Cloney Gulch from November 2000 through April 2001.

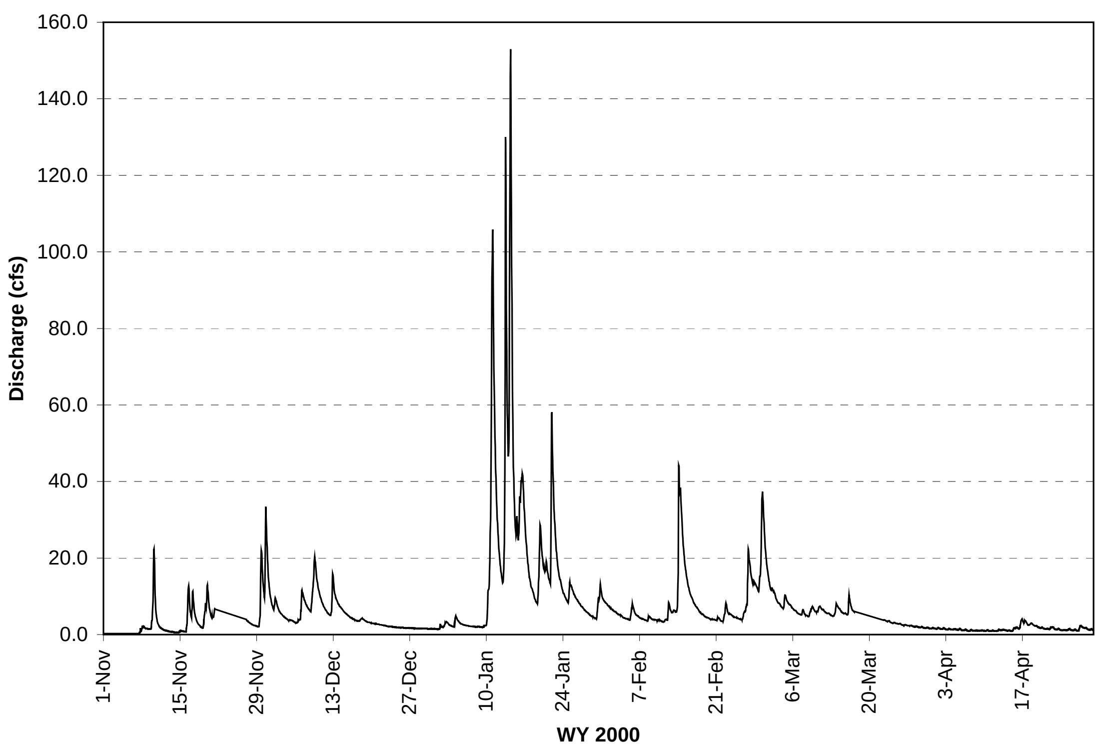


Synthetic flow duration curves for Cloney Gulch, based on flows occurring from November through April (Migration Season) and October through September (Annual). Curves were created using the regional flow duration curve. The average annual flow (Qave) for Cloney Gulch was estimated to be 8.9 cfs.

May Creek



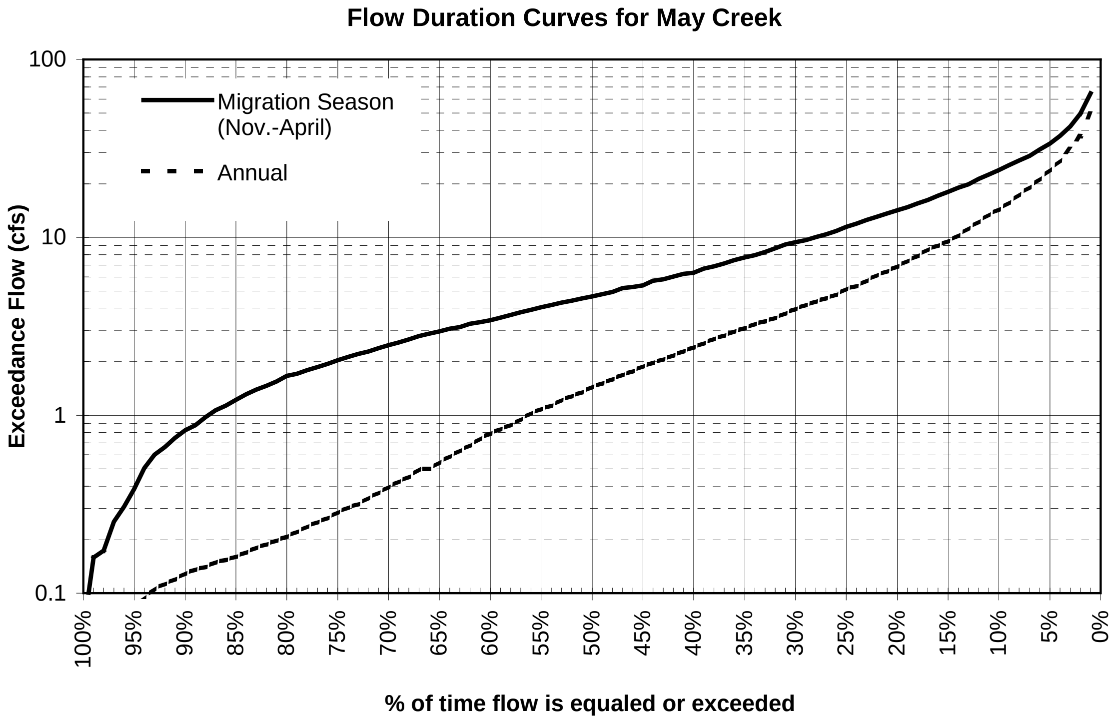
Hourly average flow at May Creek from November 1998 through April 1999. The gage at May Creek was installed on December 11, 1998.



Hourly average flow at May Creek from November 1999 through April 2000.

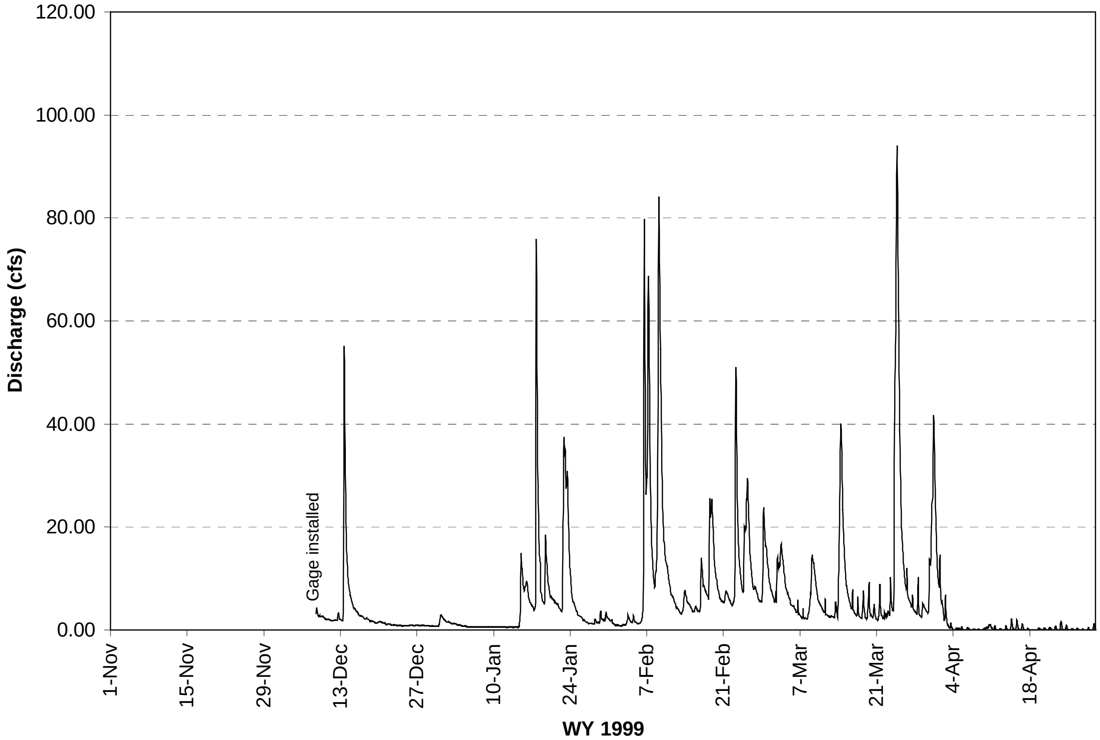
May Creek

Hourly average flow at May Creek from November 2000 through April 2001 is not available. The May Creek stage recorder failed in July 2000.

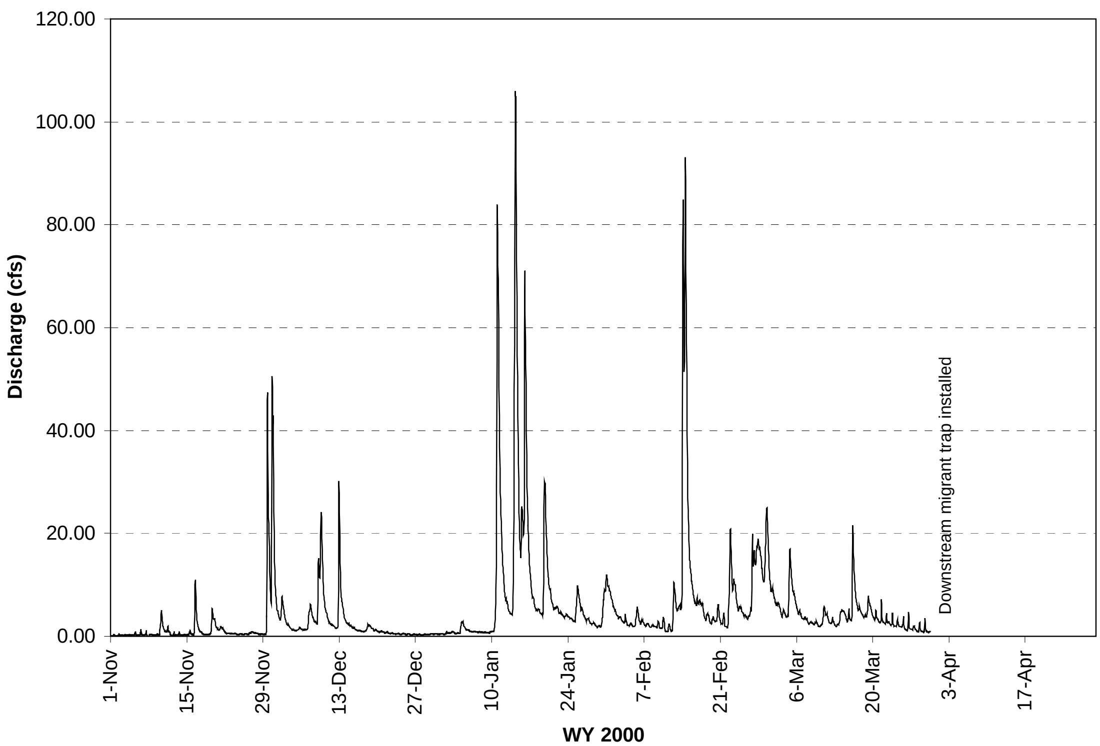


Synthetic flow duration curves for May Creek, based on flows occurring from November through April (Migration Season) and October through September (Annual). Curves were created using the regional flow duration curve. The average annual flow (Qave) for May Creek was estimated to be 5.9 cfs.

McCready Gulch

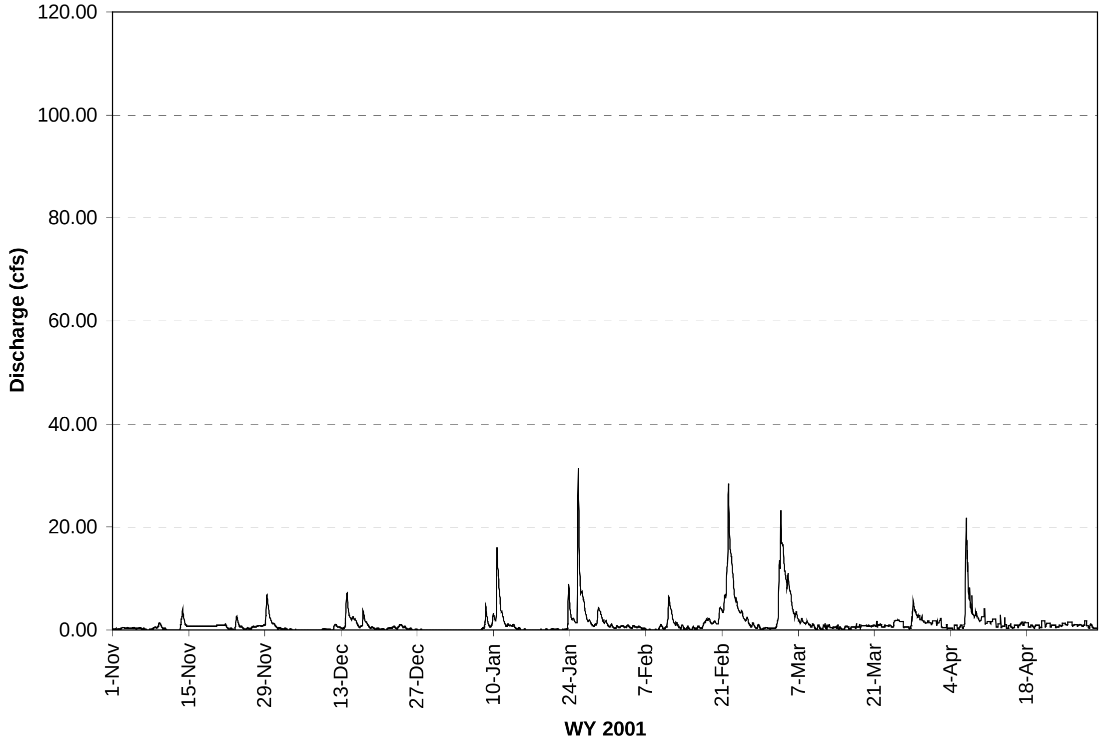


Hourly average flow at McCready Creek from November 1998 through April 1999. The gage at McCready Creek was installed on December 8, 1998.

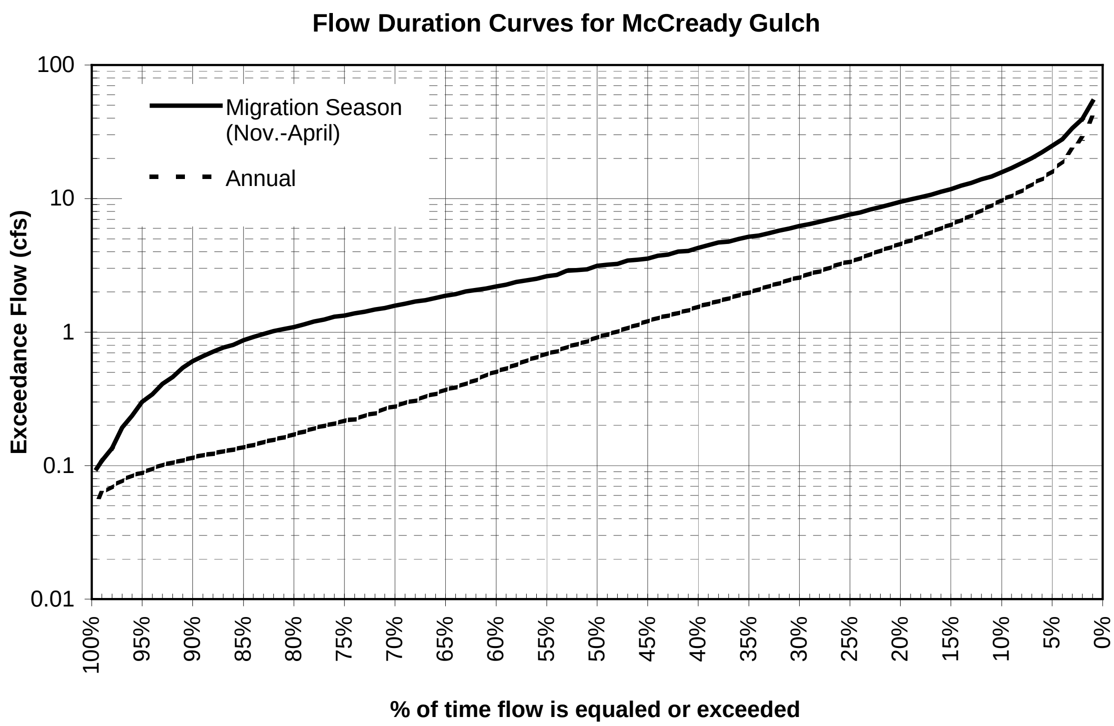


Hourly average flow at McCready Creek from November 1999 through April 2000.

McCready Gulch

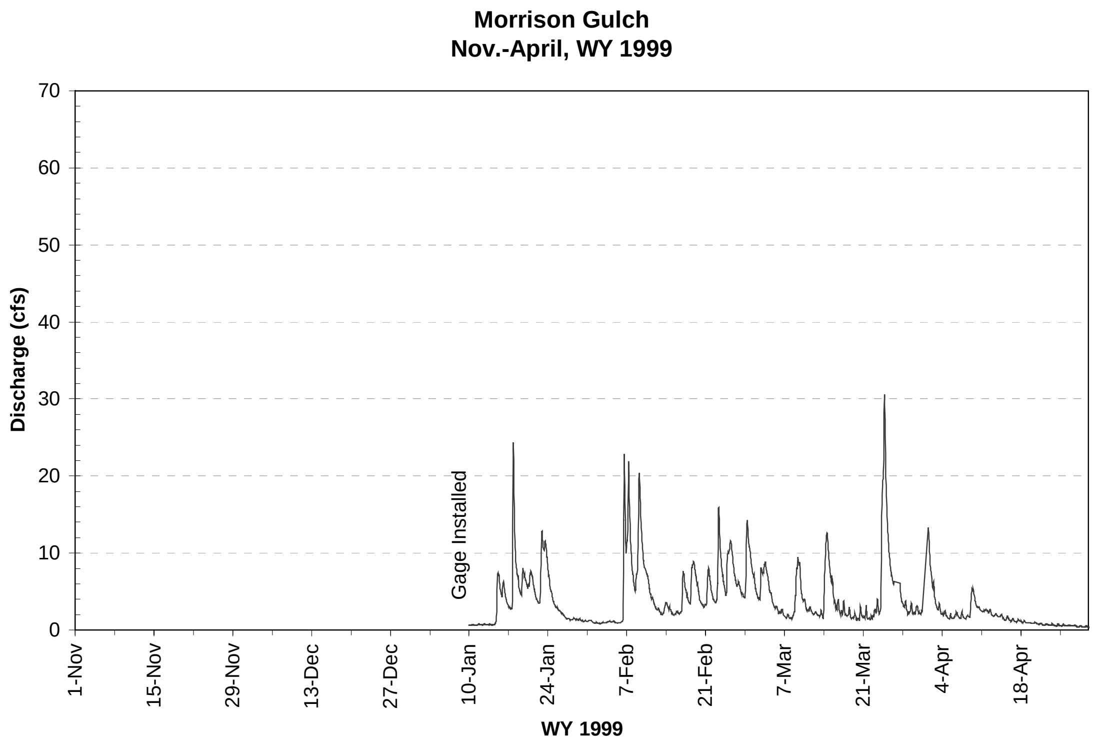


Hourly average flow at May Creek from November 2000 through April 2001.

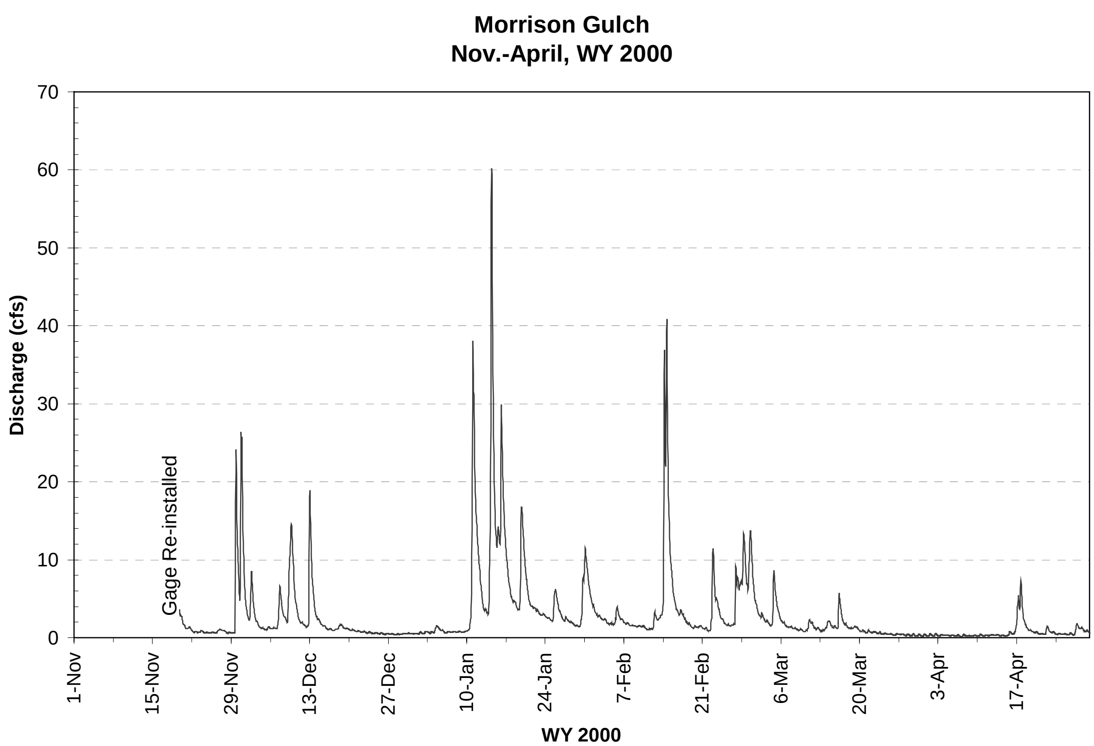


Synthetic flow duration curves for McCready Creek, based on flows occurring from November through April (Migration Season) and October through September (Annual). Curves were created using the regional flow duration curve. The average annual flow (Qave) for McCready Creek was estimated to be 3.7 cfs.

Morrison Gulch

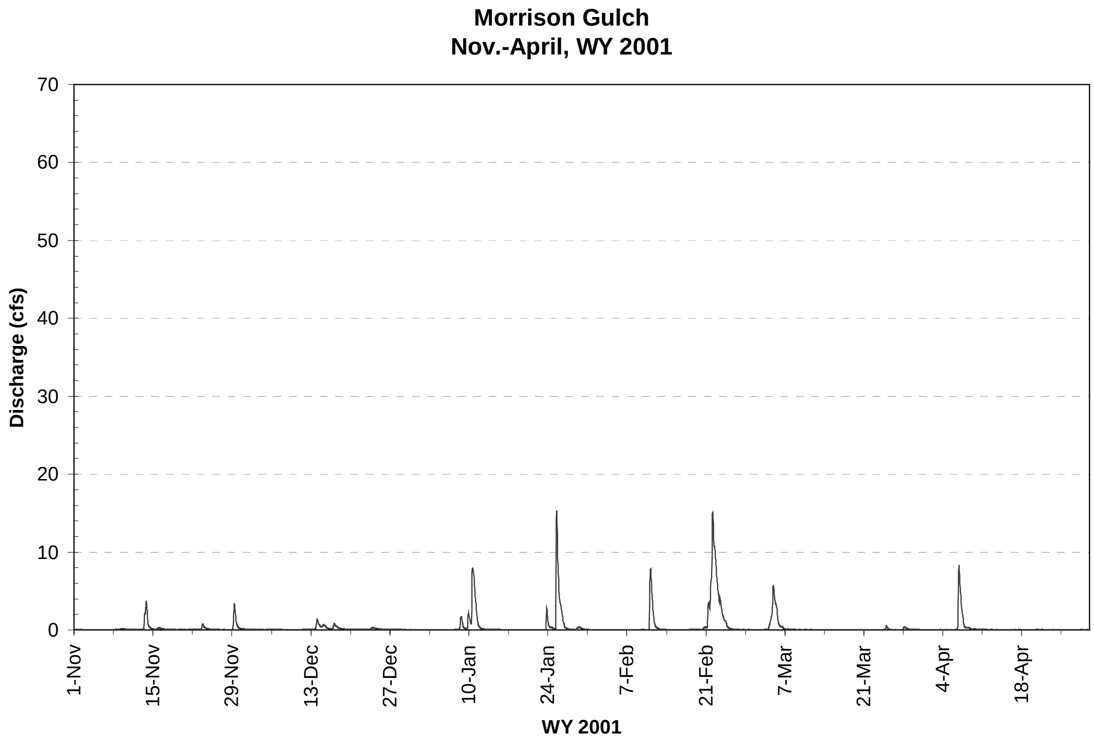


Hourly average flow at Morrison Gulch from November 1998 through April 1999. Stream gage began recording in January 1999.

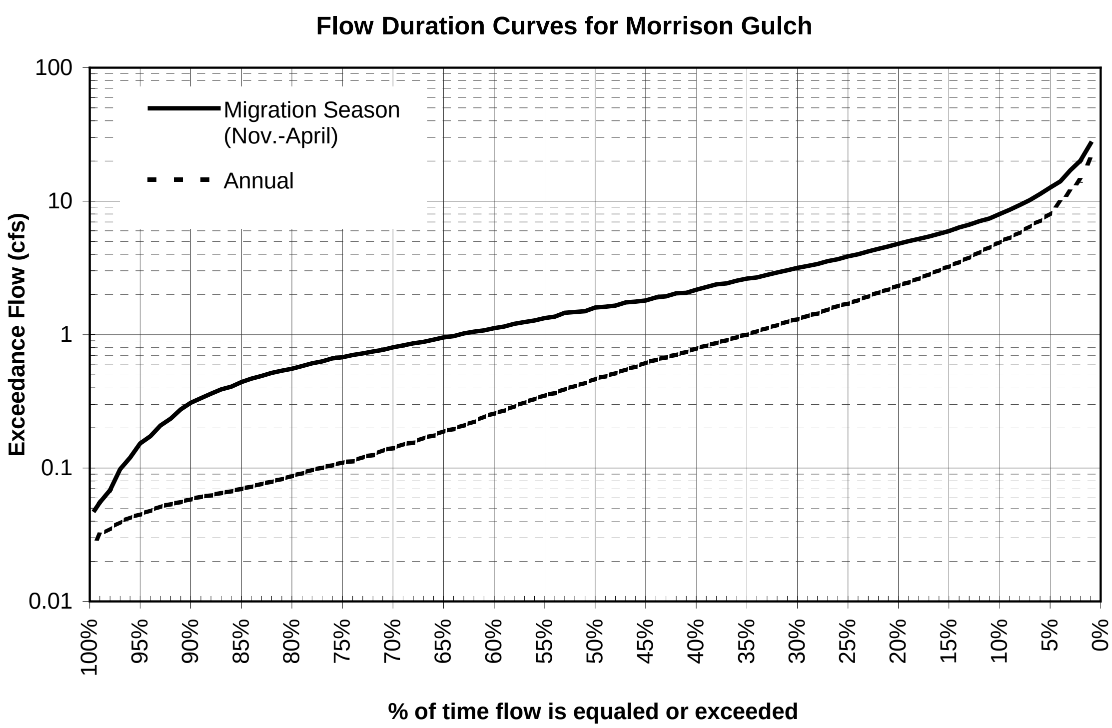


Hourly average flow at Morrison Gulch from November 1999 through April 2000. Stream gage was non-operational prior to November 19th.

Morrison Gulch

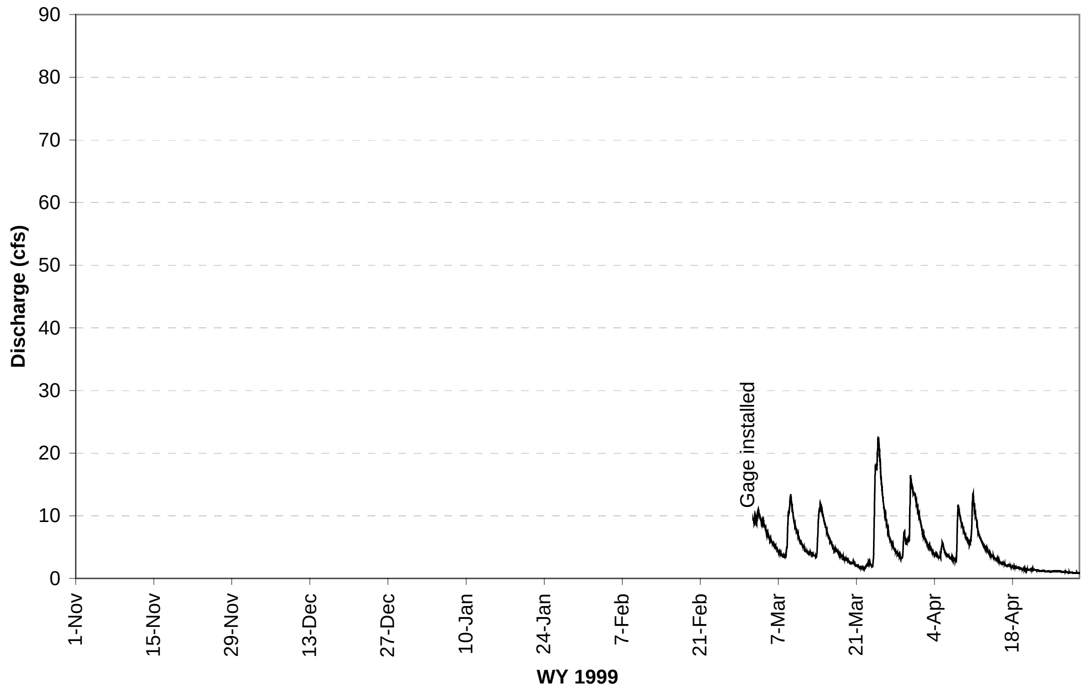


Hourly average flow at Morrison Gulch from November 2000 through April 2001.

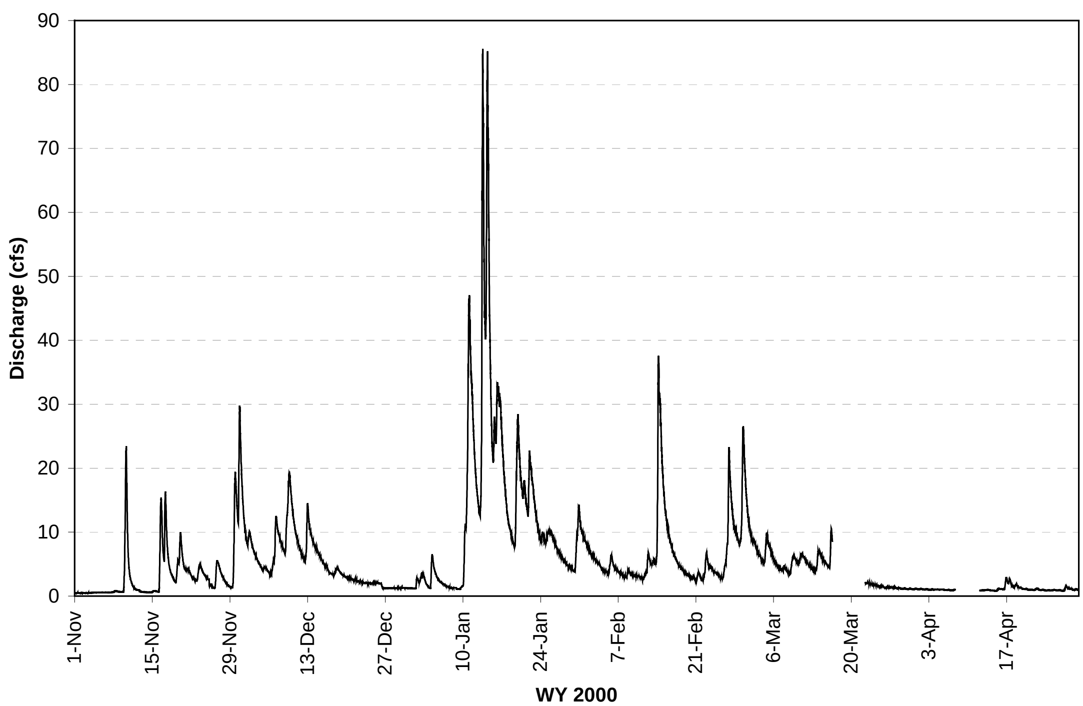


Synthetic flow duration curves for Morrison Gulch, based on flows occurring from November through April (Migration Season) and October through September (Annual). Curves were created using the regional flow duration curve. The average annual flow (Qave) for Morrison Gulch was estimated to be 1.9 cfs.

North Fork Streeloh Creek

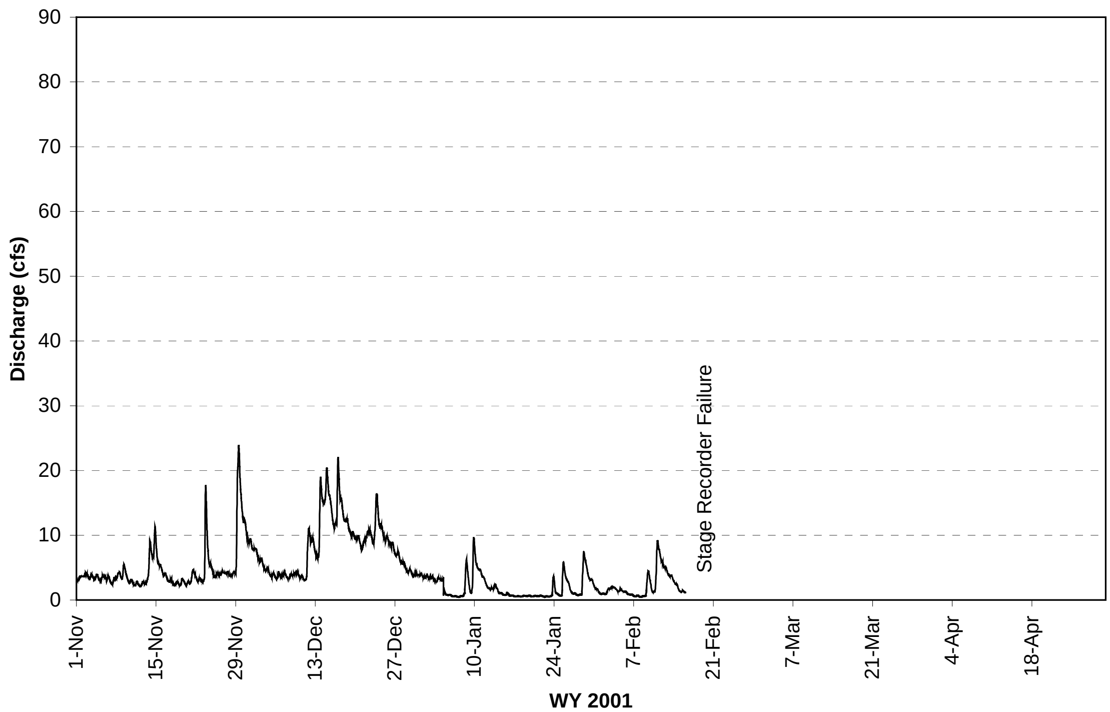


Fifteen-minute flow at NF Streeloh Creek from November 1998 through April 1999. The gage at NF Streeloh Creek was installed on March 2, 1999.

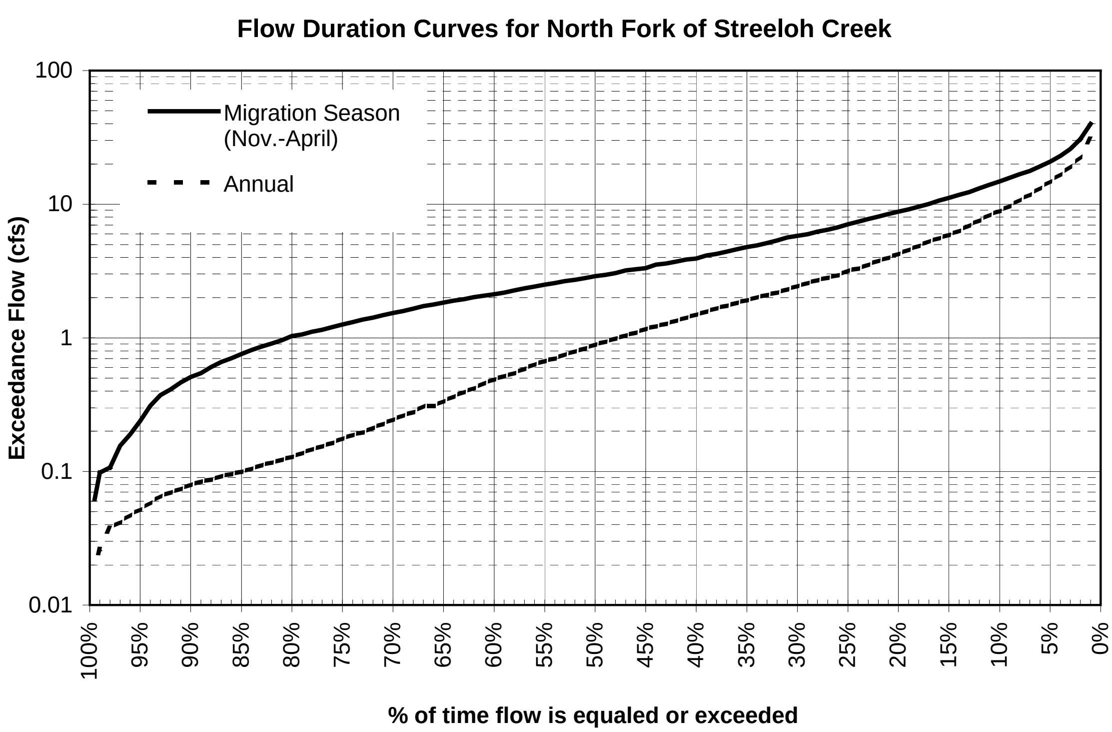


Fifteen-minute average flow at NF Streeloh Creek from November 1999 through April 2000.

North Fork Streeloh Creek

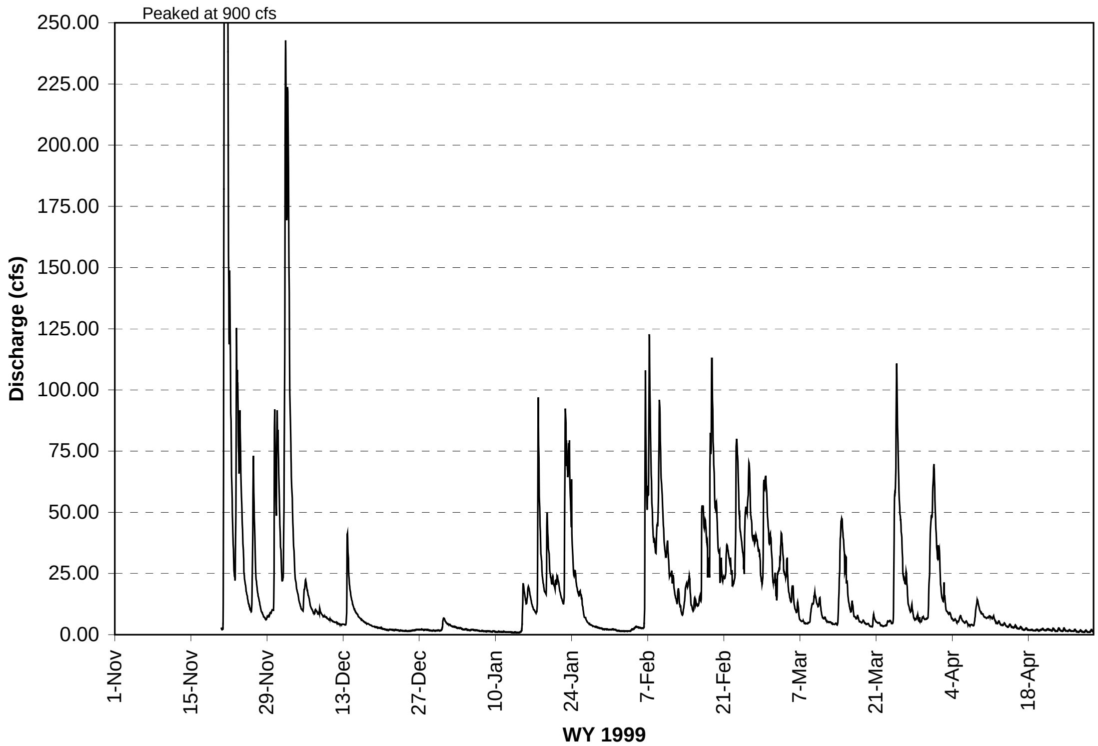


Fifteen-minute flow at NF Streeloh Creek from November 2000 through April 2001.

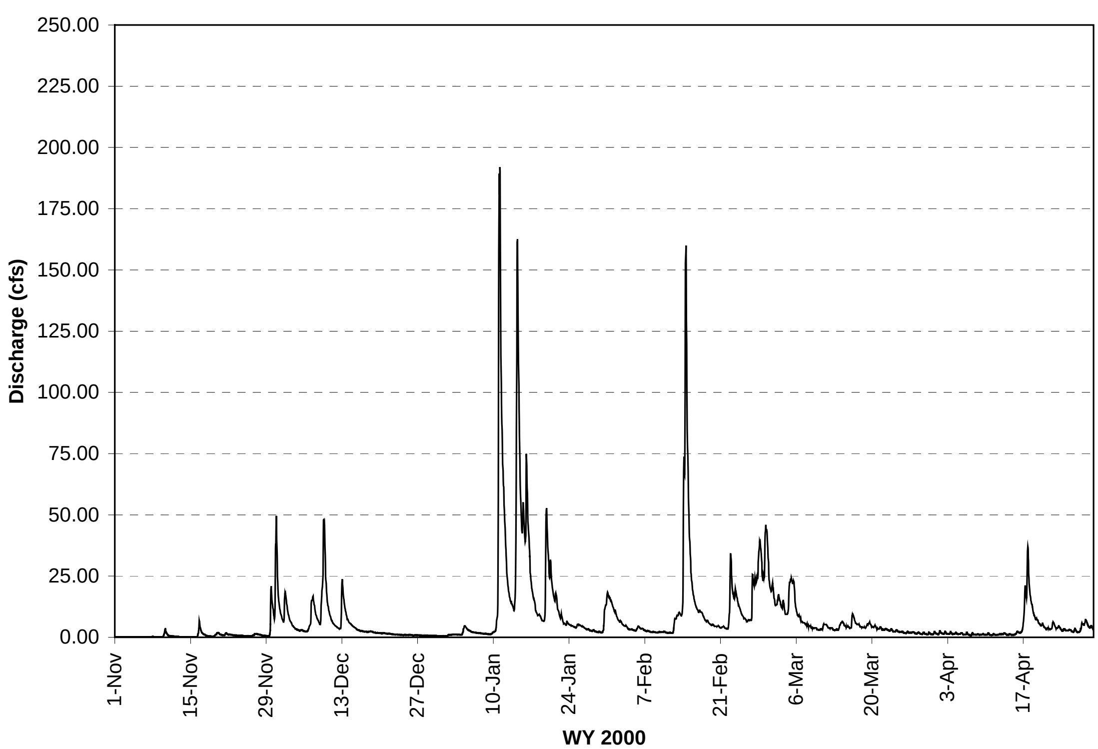


Synthetic flow duration curves for NF Streeloh Creek, based on flows occurring from November through April (Migration Season) and October through September (Annual). Curves were created using the regional flow duration curve. The average annual flow (Qave) for NF STreeloh Creek was estimated to be 3.7 cfs.

Sullivan Gulch

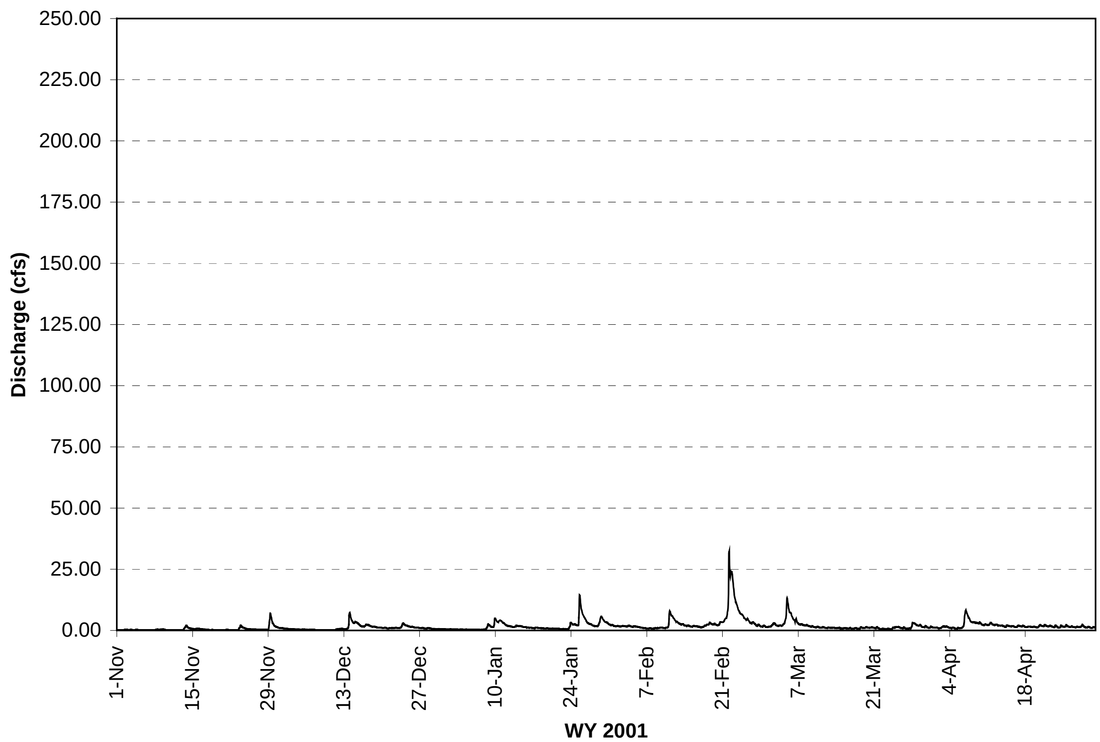


Hourly average flow at Sullivan Gulch from November 1998 through April 1999. The gage at Sullivan Gulch was installed on November 20, 1998.

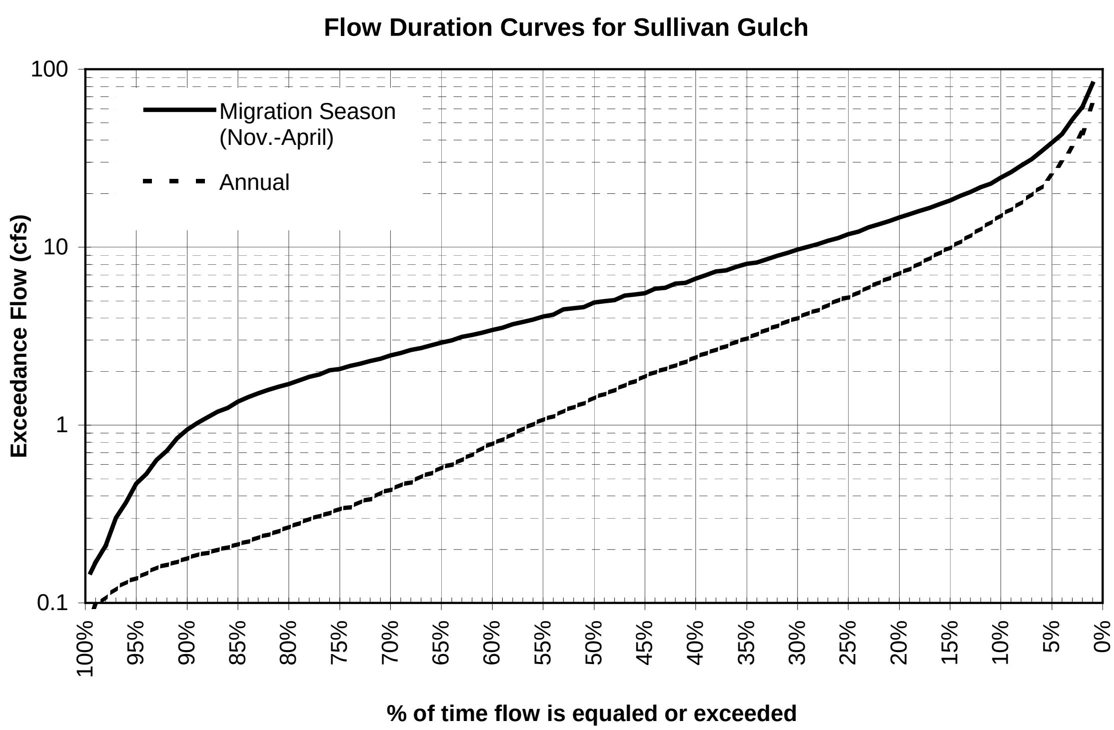


Hourly average flow at Sullivan Gulch from November 1999 through April 2000.

Sullivan Gulch

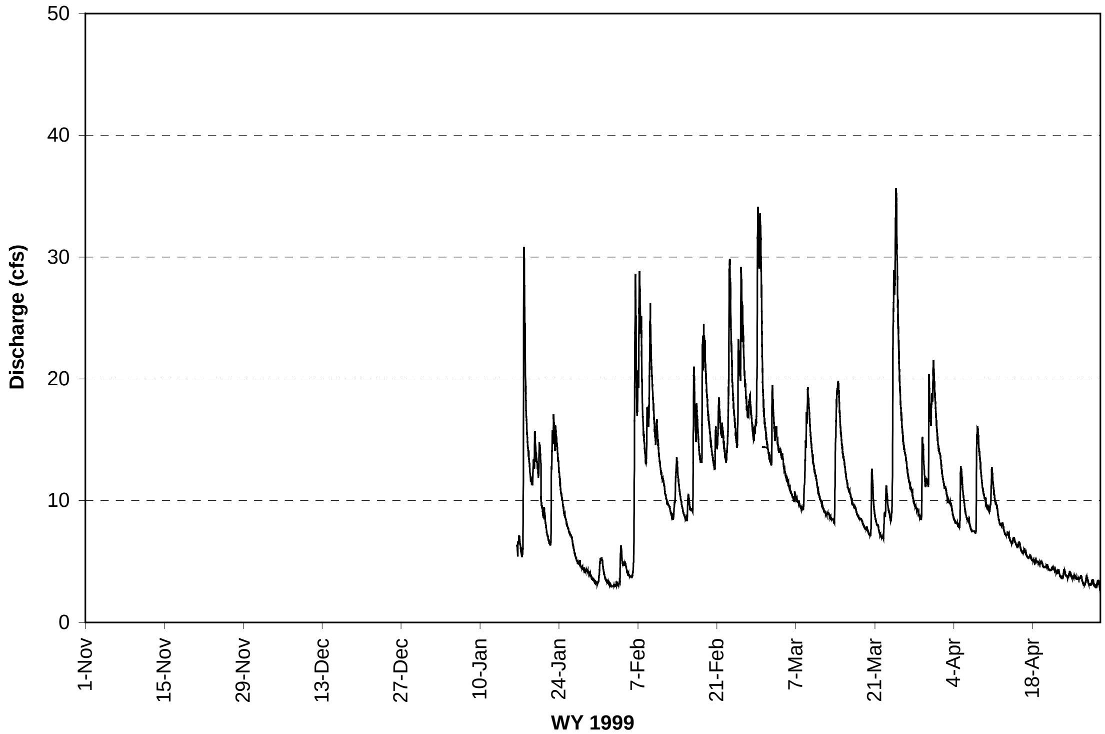


Hourly average flow at Sullivan Gulch from November 2000 through April 2001.

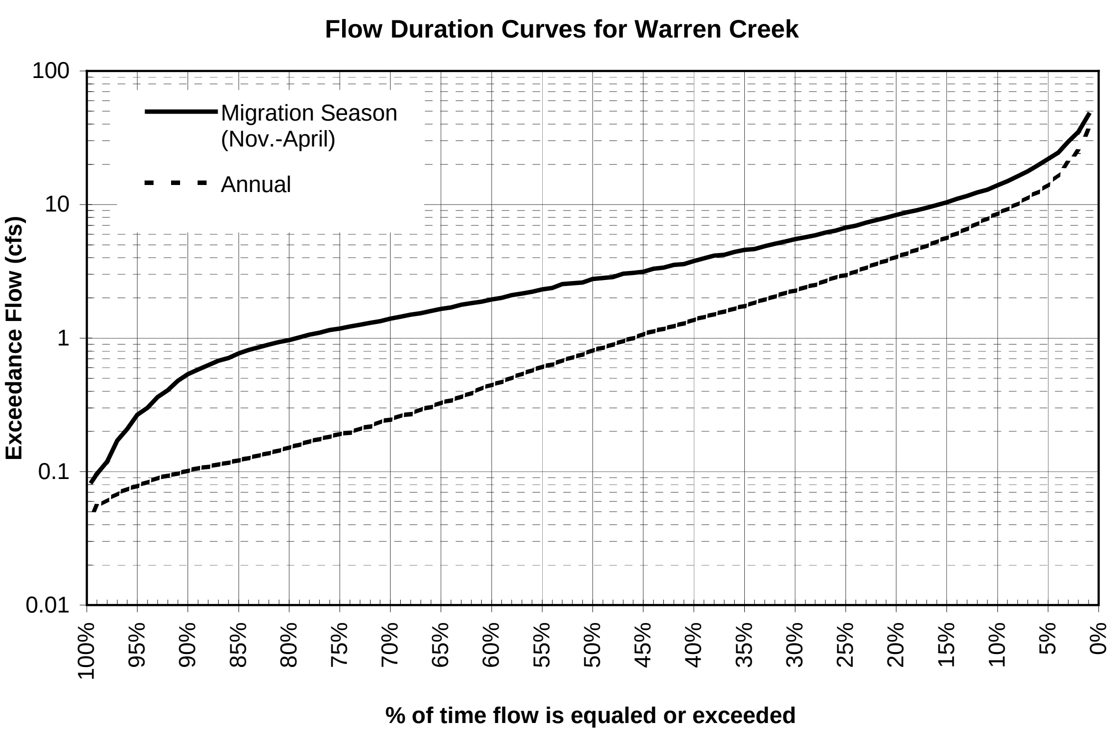


Synthetic flow duration curves for Sullivan Gulch, based on flows occurring from November through April (Migration Season) and October through September (Annual). Curves were created using the regional flow duration curve. The average annual flow (Qave) for Sullivan Gulch was estimated to be 5.8 cfs.

Warren Creek



Fifteen minute, raw discharge at Warren Creek from January 1999 through April 1999. The gage at Warren Creek was installed on January 16, 1999. Discharge from Warren Creek is not available after WY 1999 because the recorder was damaged by debris.



Synthetic flow duration curves for Warren Creek, based on flows occurring from November through April (Migration Season) and October through September (Annual). Curves were created using the regional flow duration curve. The average annual flow (Qave) for Warren Creek was estimated to be 3.3 cfs.

	Humboldt Bay Region					
	Migration Season			**Annual**		
Exceedance Values (Nov.-April)	Regionalized (cfs/cfs)	Min (cfs/cfs)	Max (cfs/cfs)	Regionalized (cfs/cfs)	Min (cfs/cfs)	Max (cfs/cfs)
1%	14.17	12.78	15.58	10.76	9.48	12.10
2%	10.51	9.51	12.10	7.51	7.01	7.97
3%	8.89	8.35	9.46	6.15	5.60	6.73
4%	7.42	6.98	7.88	5.10	4.74	5.55
5%	6.64	6.16	7.23	4.30	4.09	4.70
6%	5.95	5.53	6.67	3.78	3.52	4.01
7%	5.36	5.05	5.93	3.44	3.07	3.60
8%	4.92	4.67	5.19	3.08	2.68	3.29
9%	4.53	4.36	4.80	2.82	2.37	2.96
10%	4.18	3.93	4.50	2.61	2.11	2.72
11%	3.88	3.64	4.08	2.38	1.94	2.51
12%	3.70	3.41	3.83	2.19	1.76	2.36
13%	3.48	3.19	3.61	2.01	1.53	2.15
14%	3.31	2.95	3.51	1.85	1.37	2.01
15%	3.11	2.78	3.29	1.71	1.25	1.86
16%	2.98	2.59	3.08	1.61	1.15	1.72
17%	2.84	2.43	2.94	1.50	1.03	1.59
18%	2.72	2.28	2.84	1.39	0.93	1.50
19%	2.61	2.15	2.72	1.30	0.85	1.39
20%	2.49	2.04	2.58	1.23	0.78	1.32
21%	2.38	1.96	2.51	1.15	0.70	1.22
22%	2.28	1.87	2.37	1.09	0.66	1.15
23%	2.19	1.77	2.29	1.02	0.61	1.08
24%	2.07	1.66	2.22	0.96	0.57	1.02
25%	2.01	1.53	2.15	0.90	0.54	0.96
26%	1.92	1.44	2.01	0.87	0.50	0.93
27%	1.84	1.36	1.93	0.81	0.47	0.86
28%	1.76	1.31	1.86	0.76	0.45	0.82
29%	1.70	1.23	1.79	0.73	0.42	0.79
30%	1.65	1.18	1.72	0.69	0.39	0.74
31%	1.58	1.14	1.65	0.66	0.37	0.70
32%	1.52	1.06	1.61	0.62	0.35	0.66
33%	1.45	1.01	1.55	0.59	0.33	0.63
34%	1.39	0.97	1.47	0.56	0.31	0.59
35%	1.37	0.91	1.43	0.53	0.28	0.56
36%	1.31	0.85	1.38	0.51	0.26	0.54
37%	1.26	0.82	1.35	0.48	0.25	0.51
38%	1.24	0.78	1.30	0.46	0.24	0.48
39%	1.18	0.74	1.24	0.44	0.22	0.46
40%	1.12	0.70	1.19	0.42	0.21	0.44
41%	1.07	0.67	1.16	0.39	0.21	0.43
42%	1.06	0.65	1.13	0.37	0.19	0.40
43%	1.00	0.62	1.09	0.36	0.18	0.38
44%	0.99	0.60	1.05	0.34	0.17	0.36
45%	0.93	0.57	1.02	0.32	0.16	0.34
46%	0.92	0.55	0.99	0.30	0.15	0.33
47%	0.90	0.53	0.96	0.29	0.14	0.32
48%	0.85	0.51	0.94	0.27	0.13	0.30
49%	0.84	0.50	0.90	0.26	0.12	0.29
50%	0.83	0.47	0.88	0.25	0.11	0.28

	Humboldt Bay Region					
	Migration Season			**Annual**		
Exceedance Values (Nov.-April)	Regionalized (cfs/cfs)	Min (cfs/cfs)	Max (cfs/cfs)	Regionalized (cfs/cfs)	Min (cfs/cfs)	Max (cfs/cfs)
51%	0.78	0.46	0.85	0.23	0.11	0.27
52%	0.77	0.44	0.83	0.22	0.10	0.26
53%	0.76	0.43	0.80	0.21	0.09	0.25
54%	0.71	0.40	0.77	0.19	0.09	0.24
55%	0.69	0.39	0.76	0.19	0.08	0.23
56%	0.66	0.38	0.74	0.17	0.08	0.22
57%	0.64	0.36	0.71	0.16	0.07	0.21
58%	0.62	0.35	0.68	0.15	0.07	0.20
59%	0.59	0.35	0.67	0.14	0.06	0.19
60%	0.58	0.33	0.65	0.14	0.06	0.18
61%	0.56	0.32	0.62	0.13	0.05	0.17
62%	0.55	0.30	0.60	0.12	0.05	0.17
63%	0.53	0.28	0.58	0.11	0.05	0.16
64%	0.51	0.27	0.57	0.10	0.04	0.16
65%	0.49	0.26	0.54	0.10	0.04	0.15
66%	0.47	0.25	0.53	0.09	0.04	0.14
67%	0.46	0.24	0.52	0.09	0.03	0.14
68%	0.45	0.23	0.50	0.08	0.03	0.13
69%	0.43	0.22	0.48	0.08	0.03	0.12
70%	0.42	0.21	0.47	0.07	0.03	0.12
71%	0.40	0.21	0.46	0.07	0.02	0.11
72%	0.39	0.21	0.45	0.07	0.02	0.11
73%	0.37	0.20	0.44	0.06	0.02	0.10
74%	0.36	0.19	0.43	0.06	0.02	0.10
75%	0.35	0.18	0.40	0.06	0.02	0.09
76%	0.34	0.18	0.39	0.06	0.02	0.09
77%	0.32	0.17	0.38	0.05	0.02	0.09
78%	0.31	0.16	0.37	0.05	0.02	0.09
79%	0.30	0.16	0.35	0.05	0.02	0.09
80%	0.29	0.15	0.34	0.05	0.02	0.09
81%	0.28	0.14	0.32	0.04	0.01	0.09
82%	0.27	0.13	0.32	0.04	0.01	0.09
83%	0.25	0.12	0.29	0.04	0.01	0.08
84%	0.24	0.11	0.28	0.04	0.01	0.08
85%	0.23	0.11	0.27	0.04	0.01	0.08
86%	0.21	0.10	0.26	0.04	0.01	0.08
87%	0.20	0.09	0.24	0.03	0.01	0.08
88%	0.19	0.08	0.23	0.03	0.01	0.08
89%	0.17	0.07	0.21	0.03	0.01	0.07
90%	0.16	0.06	0.19	0.03	0.01	0.07
91%	0.14	0.05	0.18	0.03	0.01	0.07
92%	0.12	0.04	0.16	0.03	0.01	0.07
93%	0.11	0.03	0.15	0.03	0.01	0.06
94%	0.09	0.02	0.10	0.03	0.01	0.06
95%	0.08	0.02	0.09	0.02	0.01	0.06
96%	0.06	0.02	0.08	0.02	0.01	0.06
97%	0.05	0.01	0.06	0.02	0.01	0.06
98%	0.04	0.01	0.06	0.02	0.01	0.06
99%	0.03	0.01	0.06	0.02	0.01	0.06
99.5%	0.03	0.01	0.05	0.01	0.00	0.06

	Redwood Creek Region					
	Migration Season			**Annual**		
Exceedance Values (Nov.-April)	Regionalized (cfs/cfs)	Min (cfs/cfs)	Max (cfs/cfs)	Regionalized (cfs/cfs)	Min (cfs/cfs)	Max (cfs/cfs)
1%	10.91	7.86	14.26	8.41	6.17	11.35
2%	8.40	6.20	10.84	6.25	4.83	7.67
3%	7.10	5.47	9.42	5.28	4.05	6.30
4%	6.30	4.85	7.50	4.61	3.58	5.30
5%	5.70	4.45	6.68	4.08	3.07	4.52
6%	5.27	4.08	5.93	3.64	2.80	3.92
7%	4.85	3.83	5.37	3.25	2.63	3.60
8%	4.58	3.59	4.97	2.96	2.46	3.22
9%	4.31	3.29	4.64	2.67	2.29	2.96
10%	4.05	3.10	4.35	2.44	2.15	2.72
11%	3.82	2.94	3.99	2.28	1.98	2.50
12%	3.61	2.80	3.83	2.08	1.88	2.31
13%	3.36	2.73	3.61	1.91	1.78	2.10
14%	3.22	2.63	3.40	1.74	1.67	1.93
15%	3.05	2.53	3.21	1.62	1.59	1.79
16%	2.91	2.46	3.08	1.53	1.47	1.69
17%	2.74	2.39	2.92	1.45	1.38	1.59
18%	2.63	2.29	2.84	1.34	1.29	1.47
19%	2.50	2.19	2.67	1.25	1.20	1.39
20%	2.41	2.15	2.57	1.17	1.11	1.32
21%	2.31	2.05	2.46	1.09	1.02	1.21
22%	2.21	2.02	2.37	1.04	0.94	1.16
23%	2.12	1.91	2.27	0.97	0.88	1.09
24%	2.02	1.88	2.13	0.90	0.82	1.06
25%	1.94	1.84	2.09	0.87	0.77	1.02
26%	1.84	1.76	1.96	0.81	0.72	0.99
27%	1.76	1.68	1.91	0.77	0.68	0.92
28%	1.70	1.60	1.82	0.74	0.63	0.89
29%	1.64	1.59	1.76	0.71	0.59	0.85
30%	1.59	1.52	1.71	0.67	0.55	0.85
31%	1.54	1.46	1.64	0.64	0.51	0.79
32%	1.47	1.42	1.61	0.60	0.49	0.79
33%	1.40	1.36	1.55	0.57	0.45	0.75
34%	1.34	1.33	1.47	0.55	0.42	0.72
35%	1.31	1.28	1.43	0.52	0.40	0.68
36%	1.26	1.22	1.38	0.50	0.37	0.65
37%	1.21	1.17	1.37	0.48	0.35	0.61
38%	1.16	1.12	1.33	0.46	0.32	0.58
39%	1.13	1.08	1.30	0.43	0.31	0.55
40%	1.07	1.02	1.24	0.41	0.30	0.51
41%	1.06	0.98	1.22	0.39	0.27	0.51
42%	1.02	0.94	1.20	0.37	0.25	0.48
43%	0.98	0.90	1.16	0.35	0.24	0.44
44%	0.96	0.87	1.13	0.33	0.23	0.41
45%	0.91	0.84	1.09	0.32	0.21	0.41
46%	0.89	0.80	1.09	0.30	0.20	0.38
47%	0.88	0.77	1.06	0.29	0.19	0.38
48%	0.83	0.74	1.02	0.27	0.18	0.34
49%	0.81	0.72	0.99	0.26	0.17	0.33
50%	0.79	0.69	0.99	0.25	0.16	0.31

	Redwood Creek Region					
	Migration Season			**Annual**		
Exceedance Values (Nov.-April)	Regionalized (cfs/cfs)	Min (cfs/cfs)	Max (cfs/cfs)	Regionalized (cfs/cfs)	Min (cfs/cfs)	Max (cfs/cfs)
51%	0.77	0.65	0.96	0.23	0.15	0.30
52%	0.75	0.64	0.92	0.22	0.14	0.28
53%	0.73	0.62	0.89	0.21	0.14	0.27
54%	0.70	0.59	0.89	0.19	0.13	0.26
55%	0.68	0.57	0.89	0.18	0.12	0.25
56%	0.66	0.54	0.85	0.17	0.11	0.23
57%	0.64	0.51	0.85	0.16	0.11	0.23
58%	0.62	0.50	0.82	0.15	0.10	0.21
59%	0.60	0.48	0.79	0.14	0.09	0.21
60%	0.58	0.46	0.79	0.13	0.09	0.20
61%	0.57	0.45	0.75	0.13	0.08	0.19
62%	0.55	0.42	0.75	0.12	0.08	0.18
63%	0.53	0.41	0.72	0.11	0.07	0.17
64%	0.52	0.40	0.68	0.10	0.07	0.16
65%	0.50	0.37	0.68	0.09	0.06	0.15
66%	0.49	0.35	0.65	0.08	0.06	0.15
67%	0.47	0.35	0.65	0.08	0.05	0.14
68%	0.45	0.33	0.61	0.08	0.05	0.13
69%	0.43	0.32	0.58	0.07	0.04	0.13
70%	0.42	0.31	0.58	0.07	0.04	0.12
71%	0.40	0.30	0.55	0.06	0.03	0.12
72%	0.39	0.28	0.55	0.06	0.03	0.11
73%	0.37	0.26	0.51	0.05	0.03	0.10
74%	0.36	0.25	0.48	0.05	0.03	0.10
75%	0.34	0.24	0.48	0.05	0.03	0.09
76%	0.33	0.24	0.44	0.04	0.03	0.09
77%	0.32	0.23	0.44	0.04	0.03	0.09
78%	0.30	0.21	0.41	0.04	0.03	0.08
79%	0.29	0.20	0.38	0.04	0.02	0.08
80%	0.28	0.19	0.38	0.04	0.02	0.07
81%	0.26	0.19	0.34	0.03	0.02	0.07
82%	0.25	0.18	0.33	0.03	0.02	0.07
83%	0.24	0.16	0.31	0.03	0.02	0.06
84%	0.22	0.15	0.30	0.03	0.02	0.06
85%	0.21	0.15	0.28	0.03	0.02	0.05
86%	0.19	0.14	0.26	0.03	0.01	0.05
87%	0.18	0.13	0.24	0.03	0.01	0.04
88%	0.17	0.12	0.23	0.02	0.01	0.04
89%	0.15	0.11	0.21	0.02	0.01	0.04
90%	0.14	0.10	0.19	0.02	0.01	0.04
91%	0.13	0.09	0.18	0.02	0.01	0.04
92%	0.11	0.08	0.16	0.02	0.01	0.04
93%	0.10	0.06	0.15	0.02	0.01	0.04
94%	0.09	0.04	0.11	0.02	0.01	0.03
95%	0.07	0.03	0.10	0.01	0.01	0.03
96%	0.05	0.02	0.09	0.01	0.01	0.03
97%	0.04	0.01	0.07	0.01	0.00	0.03
98%	0.03	0.01	0.07	0.01	0.00	0.03
99%	0.03	0.01	0.05	0.01	0.00	0.02
99.5%	0.02	0.00	0.03	0.01	0.00	0.02

Site Specific Migration Period and Annual Exceedance Flows.

Exceedance Flows:	May Creek		N.F. Streeloh Creek		Sullivan Gulch		Warren Creek	
% of time flow is equaled or exceeded	Migration Season	Annual	Migration Season	Annual	Migration Season	Annual	Migration Season	Annual
1%	64.51	49.75	39.90	30.77	82.63	62.72	46.91	35.61
2%	49.68	36.94	30.72	22.84	61.25	43.77	34.77	24.85
3%	41.99	31.25	25.97	19.33	51.84	35.85	29.43	20.35
4%	37.23	27.28	23.02	16.87	43.23	29.76	24.54	16.89
5%	33.71	24.15	20.85	14.93	38.71	25.09	21.98	14.24
6%	31.15	21.52	19.27	13.31	34.69	22.01	19.69	12.50
7%	28.71	19.23	17.75	11.90	31.23	20.03	17.73	11.37
8%	27.08	17.53	16.75	10.84	28.70	17.95	16.29	10.19
9%	25.49	15.77	15.76	9.75	26.40	16.42	14.99	9.32
10%	23.93	14.44	14.80	8.93	24.37	15.19	13.83	8.62
11%	22.61	13.50	13.98	8.35	22.61	13.89	12.84	7.89
12%	21.35	12.28	13.21	7.60	21.55	12.76	12.23	7.24
13%	19.90	11.28	12.31	6.98	20.32	11.70	11.53	6.64
14%	19.01	10.30	11.76	6.37	19.30	10.78	10.95	6.12
15%	18.04	9.57	11.16	5.92	18.16	9.97	10.31	5.66
16%	17.19	9.05	10.63	5.60	17.40	9.37	9.88	5.32
17%	16.23	8.58	10.04	5.31	16.57	8.73	9.41	4.95
18%	15.53	7.93	9.61	4.91	15.88	8.13	9.02	4.62
19%	14.79	7.41	9.15	4.58	15.19	7.58	8.62	4.30
20%	14.25	6.90	8.81	4.27	14.54	7.16	8.25	4.07
21%	13.65	6.46	8.44	4.00	13.90	6.72	7.89	3.82
22%	13.07	6.15	8.09	3.80	13.32	6.36	7.56	3.61
23%	12.51	5.73	7.74	3.54	12.76	5.97	7.24	3.39
24%	11.95	5.34	7.39	3.30	12.08	5.58	6.86	3.17
25%	11.44	5.16	7.08	3.19	11.74	5.23	6.66	2.97
26%	10.87	4.78	6.72	2.96	11.17	5.06	6.34	2.87
27%	10.42	4.57	6.45	2.83	10.76	4.74	6.11	2.69
28%	10.06	4.38	6.22	2.71	10.28	4.43	5.83	2.52
29%	9.67	4.18	5.98	2.58	9.91	4.27	5.63	2.42
30%	9.39	3.97	5.81	2.46	9.59	4.00	5.45	2.27
31%	9.11	3.76	5.64	2.32	9.20	3.86	5.22	2.19
32%	8.68	3.54	5.37	2.19	8.85	3.62	5.02	2.06
33%	8.30	3.39	5.14	2.09	8.48	3.45	4.81	1.96
34%	7.94	3.27	4.91	2.02	8.13	3.26	4.61	1.85
35%	7.72	3.10	4.78	1.92	7.97	3.08	4.53	1.75
36%	7.44	2.97	4.60	1.84	7.66	2.95	4.35	1.67
37%	7.15	2.82	4.42	1.74	7.33	2.79	4.16	1.59
38%	6.86	2.70	4.25	1.67	7.21	2.66	4.09	1.51
39%	6.69	2.55	4.14	1.58	6.90	2.55	3.91	1.45
40%	6.34	2.42	3.92	1.50	6.55	2.42	3.72	1.38
41%	6.25	2.30	3.86	1.42	6.26	2.28	3.55	1.29
42%	6.02	2.18	3.72	1.35	6.16	2.18	3.49	1.24
43%	5.81	2.07	3.59	1.28	5.85	2.07	3.32	1.18
44%	5.71	1.98	3.53	1.22	5.75	1.99	3.26	1.13
45%	5.38	1.89	3.33	1.17	5.44	1.89	3.09	1.08
46%	5.26	1.77	3.26	1.10	5.33	1.77	3.03	1.00
47%	5.18	1.69	3.20	1.05	5.25	1.69	2.98	0.96
48%	4.94	1.60	3.05	0.99	4.97	1.58	2.82	0.90
49%	4.80	1.52	2.97	0.94	4.90	1.50	2.78	0.85
50%	4.67	1.45	2.89	0.90	4.82	1.43	2.74	0.81

Site Specific Migration Period and Annual Exceedance Flows.

Exceedance Flows:	May Creek		N.F. Streeloh Creek		Sullivan Gulch		Warren Creek	
% of time flow is equaled or exceeded	Migration Season	Annual	Migration Season	Annual	Migration Season	Annual	Migration Season	Annual
51%	4.54	1.35	2.81	0.84	4.53	1.33	2.57	0.76
52%	4.41	1.28	2.73	0.79	4.47	1.27	2.54	0.72
53%	4.30	1.22	2.66	0.76	4.41	1.21	2.51	0.68
54%	4.16	1.13	2.57	0.70	4.12	1.12	2.34	0.64
55%	4.04	1.09	2.50	0.67	4.02	1.08	2.28	0.61
56%	3.91	1.03	2.42	0.64	3.88	1.02	2.20	0.58
57%	3.80	0.95	2.35	0.59	3.75	0.96	2.13	0.54
58%	3.66	0.89	2.27	0.55	3.63	0.89	2.06	0.51
59%	3.53	0.84	2.18	0.52	3.47	0.83	1.97	0.47
60%	3.42	0.79	2.12	0.49	3.36	0.79	1.91	0.45
61%	3.34	0.74	2.07	0.46	3.26	0.75	1.85	0.42
62%	3.27	0.68	2.02	0.42	3.18	0.68	1.80	0.39
63%	3.14	0.64	1.94	0.39	3.08	0.64	1.75	0.37
64%	3.07	0.59	1.90	0.37	2.95	0.60	1.68	0.34
65%	2.96	0.55	1.83	0.34	2.85	0.58	1.62	0.33
66%	2.88	0.50	1.78	0.31	2.77	0.54	1.57	0.31
67%	2.79	0.50	1.72	0.31	2.67	0.52	1.51	0.29
68%	2.67	0.45	1.65	0.28	2.60	0.48	1.48	0.27
69%	2.57	0.43	1.59	0.26	2.48	0.46	1.41	0.26
70%	2.48	0.40	1.53	0.25	2.42	0.43	1.37	0.25
71%	2.39	0.37	1.48	0.23	2.32	0.42	1.32	0.24
72%	2.29	0.34	1.41	0.21	2.26	0.38	1.28	0.22
73%	2.21	0.32	1.37	0.20	2.17	0.37	1.23	0.21
74%	2.13	0.30	1.31	0.19	2.11	0.35	1.20	0.20
75%	2.04	0.29	1.26	0.18	2.03	0.34	1.15	0.19
76%	1.95	0.27	1.21	0.16	1.99	0.32	1.13	0.18
77%	1.86	0.25	1.15	0.16	1.89	0.31	1.07	0.18
78%	1.80	0.24	1.11	0.15	1.83	0.30	1.04	0.17
79%	1.71	0.22	1.06	0.14	1.74	0.28	0.99	0.16
80%	1.66	0.21	1.03	0.13	1.68	0.27	0.95	0.15
81%	1.55	0.20	0.96	0.12	1.62	0.25	0.92	0.14
82%	1.46	0.19	0.91	0.12	1.56	0.24	0.89	0.14
83%	1.39	0.18	0.86	0.11	1.48	0.23	0.84	0.13
84%	1.31	0.17	0.81	0.11	1.42	0.22	0.80	0.13
85%	1.22	0.16	0.76	0.10	1.33	0.21	0.76	0.12
86%	1.13	0.15	0.70	0.10	1.25	0.21	0.71	0.12
87%	1.07	0.15	0.66	0.09	1.17	0.20	0.66	0.11
88%	0.98	0.14	0.61	0.09	1.09	0.19	0.62	0.11
89%	0.88	0.14	0.54	0.08	1.01	0.19	0.57	0.11
90%	0.82	0.13	0.51	0.08	0.94	0.18	0.54	0.10
91%	0.75	0.12	0.46	0.07	0.82	0.17	0.47	0.10
92%	0.67	0.11	0.41	0.07	0.70	0.16	0.40	0.09
93%	0.60	0.11	0.37	0.07	0.62	0.16	0.35	0.09
94%	0.50	0.10	0.31	0.06	0.53	0.15	0.30	0.08
95%	0.39	0.08	0.24	0.05	0.47	0.14	0.27	0.08
96%	0.31	0.08	0.19	0.05	0.37	0.13	0.21	0.07
97%	0.25	0.07	0.16	0.04	0.30	0.12	0.17	0.07
98%	0.17	0.06	0.11	0.04	0.21	0.11	0.12	0.06
99%	0.16	0.04	0.10	0.03	0.17	0.10	0.10	0.05
100%	0.10	0.03	0.06	0.02	0.15	0.08	0.09	0.05

Site Specific Migration Period and Annual Exceedance Flows.

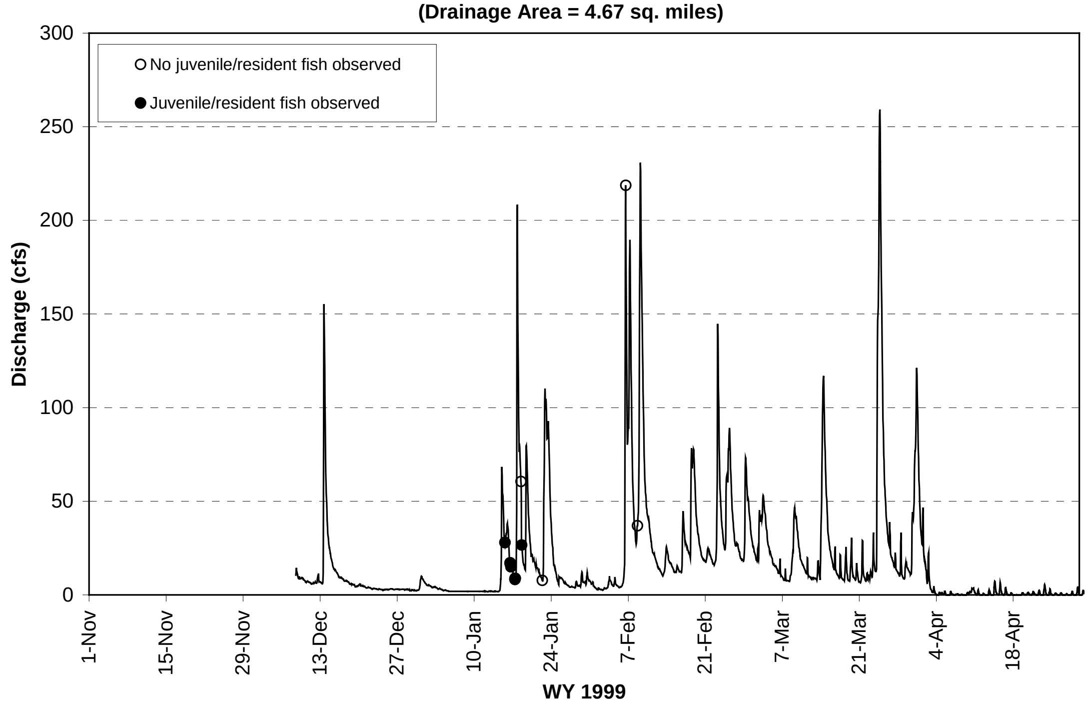
Exceedance Flows:	Morrison Gulch		McCready Gulch		Cloney Gulch		Chadd Creek	
% of time flow is equaled or exceeded	Migration Season	Annual	Migration Season	Annual	Migration Season	Annual	Migration Season	Annual
1%	26.96	20.46	53.10	40.31	126.20	95.79	123.70	93.89
2%	19.98	14.28	39.36	28.13	93.54	66.84	91.68	65.51
3%	16.92	11.70	33.32	23.04	79.18	54.75	77.61	53.66
4%	14.11	9.71	27.78	19.12	66.03	45.45	64.71	44.54
5%	12.63	8.19	24.88	16.12	59.12	38.31	57.95	37.55
6%	11.32	7.18	22.29	14.15	52.98	33.62	51.92	32.95
7%	10.19	6.54	20.07	12.87	47.70	30.59	46.75	29.98
8%	9.36	5.86	18.44	11.53	43.83	27.41	42.96	26.87
9%	8.62	5.36	16.97	10.55	40.33	25.08	39.53	24.58
10%	7.95	4.96	15.66	9.76	37.22	23.20	36.48	22.74
11%	7.38	4.53	14.53	8.93	34.54	21.22	33.85	20.80
12%	7.03	4.16	13.85	8.20	32.91	19.49	32.25	19.10
13%	6.63	3.82	13.06	7.52	31.03	17.86	30.41	17.51
14%	6.30	3.52	12.40	6.93	29.47	16.47	28.88	16.14
15%	5.93	3.25	11.67	6.41	27.74	15.23	27.18	14.92
16%	5.68	3.06	11.18	6.02	26.57	14.30	26.04	14.02
17%	5.41	2.85	10.65	5.61	25.31	13.33	24.81	13.06
18%	5.18	2.65	10.21	5.22	24.26	12.42	23.78	12.17
19%	4.96	2.47	9.76	4.87	23.20	11.57	22.74	11.34
20%	4.74	2.34	9.34	4.60	22.21	10.94	21.77	10.73
21%	4.53	2.19	8.93	4.32	21.23	10.27	20.80	10.07
22%	4.35	2.08	8.56	4.09	20.34	9.72	19.94	9.53
23%	4.16	1.95	8.20	3.84	19.48	9.12	19.10	8.94
24%	3.94	1.82	7.76	3.59	18.45	8.53	18.09	8.36
25%	3.83	1.71	7.54	3.36	17.93	7.99	17.57	7.83
26%	3.64	1.65	7.18	3.25	17.06	7.73	16.72	7.57
27%	3.51	1.55	6.91	3.05	16.43	7.24	16.10	7.10
28%	3.35	1.45	6.60	2.85	15.70	6.77	15.38	6.64
29%	3.23	1.39	6.37	2.74	15.14	6.52	14.83	6.39
30%	3.13	1.31	6.17	2.57	14.65	6.11	14.36	5.99
31%	3.00	1.26	5.91	2.48	14.05	5.89	13.77	5.77
32%	2.89	1.18	5.69	2.33	13.51	5.53	13.24	5.42
33%	2.77	1.13	5.45	2.22	12.95	5.27	12.69	5.16
34%	2.65	1.06	5.22	2.10	12.41	4.98	12.17	4.89
35%	2.60	1.00	5.12	1.98	12.17	4.70	11.93	4.61
36%	2.50	0.96	4.92	1.90	11.69	4.50	11.46	4.42
37%	2.39	0.91	4.71	1.79	11.19	4.26	10.97	4.18
38%	2.35	0.87	4.63	1.71	11.00	4.07	10.79	3.99
39%	2.25	0.83	4.43	1.64	10.53	3.89	10.32	3.81
40%	2.14	0.79	4.21	1.56	10.00	3.70	9.80	3.63
41%	2.04	0.74	4.02	1.46	9.56	3.48	9.37	3.41
42%	2.01	0.71	3.96	1.40	9.40	3.32	9.21	3.26
43%	1.91	0.68	3.76	1.33	8.93	3.17	8.75	3.10
44%	1.87	0.65	3.69	1.28	8.77	3.04	8.60	2.98
45%	1.77	0.62	3.49	1.22	8.30	2.89	8.14	2.83
46%	1.74	0.58	3.43	1.14	8.15	2.70	7.99	2.65
47%	1.71	0.55	3.38	1.08	8.02	2.57	7.87	2.52
48%	1.62	0.52	3.19	1.02	7.59	2.41	7.44	2.37
49%	1.60	0.49	3.15	0.96	7.49	2.29	7.34	2.24
50%	1.57	0.47	3.10	0.92	7.37	2.19	7.22	2.15

Site Specific Migration Period and Annual Exceedance Flows.

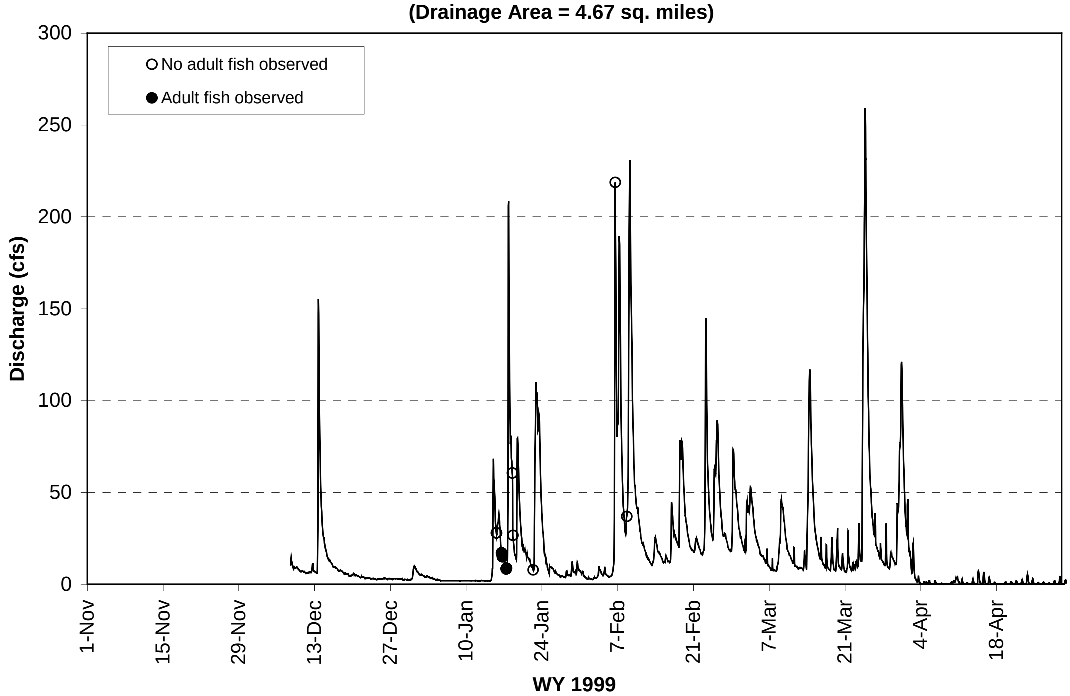
Exceedance Flows:	Morrison Gulch		McCready Gulch		Cloney Gulch		Chadd Creek	
% of time flow is equaled or exceeded	Migration Season	Annual	Migration Season	Annual	Migration Season	Annual	Migration Season	Annual
51%	1.48	0.43	2.91	0.86	6.93	2.04	6.79	2.00
52%	1.46	0.41	2.88	0.82	6.83	1.94	6.70	1.90
53%	1.44	0.39	2.84	0.77	6.74	1.84	6.61	1.80
54%	1.35	0.37	2.65	0.72	6.30	1.71	6.17	1.68
55%	1.31	0.35	2.58	0.69	6.14	1.65	6.02	1.62
56%	1.26	0.33	2.49	0.65	5.92	1.55	5.80	1.52
57%	1.22	0.31	2.41	0.61	5.73	1.46	5.62	1.43
58%	1.18	0.29	2.33	0.57	5.55	1.36	5.43	1.34
59%	1.13	0.27	2.23	0.54	5.29	1.27	5.19	1.25
60%	1.10	0.26	2.16	0.51	5.14	1.21	5.04	1.18
61%	1.06	0.24	2.10	0.48	4.98	1.14	4.88	1.12
62%	1.04	0.22	2.04	0.44	4.85	1.05	4.76	1.02
63%	1.00	0.21	1.98	0.41	4.70	0.98	4.61	0.96
64%	0.96	0.20	1.90	0.39	4.51	0.92	4.42	0.90
65%	0.93	0.19	1.83	0.37	4.35	0.89	4.27	0.87
66%	0.90	0.18	1.78	0.35	4.23	0.82	4.14	0.81
67%	0.87	0.17	1.71	0.33	4.07	0.79	3.99	0.78
68%	0.85	0.16	1.67	0.31	3.97	0.73	3.90	0.71
69%	0.81	0.15	1.59	0.30	3.79	0.71	3.71	0.69
70%	0.79	0.14	1.56	0.28	3.70	0.66	3.62	0.65
71%	0.76	0.14	1.49	0.27	3.54	0.64	3.47	0.63
72%	0.74	0.13	1.45	0.25	3.44	0.59	3.38	0.58
73%	0.71	0.12	1.40	0.24	3.32	0.57	3.25	0.56
74%	0.69	0.11	1.36	0.22	3.23	0.53	3.16	0.52
75%	0.66	0.11	1.30	0.22	3.10	0.52	3.04	0.51
76%	0.65	0.11	1.28	0.21	3.04	0.49	2.98	0.48
77%	0.62	0.10	1.21	0.20	2.88	0.47	2.82	0.46
78%	0.60	0.10	1.17	0.19	2.79	0.45	2.73	0.44
79%	0.57	0.09	1.12	0.18	2.66	0.43	2.61	0.42
80%	0.55	0.09	1.08	0.17	2.57	0.41	2.52	0.40
81%	0.53	0.08	1.04	0.16	2.48	0.39	2.43	0.38
82%	0.51	0.08	1.00	0.16	2.38	0.37	2.33	0.36
83%	0.48	0.08	0.95	0.15	2.26	0.36	2.21	0.35
84%	0.46	0.07	0.91	0.14	2.16	0.34	2.12	0.33
85%	0.44	0.07	0.86	0.14	2.04	0.33	2.00	0.32
86%	0.41	0.07	0.80	0.13	1.91	0.31	1.87	0.31
87%	0.38	0.07	0.75	0.13	1.79	0.31	1.75	0.30
88%	0.35	0.06	0.70	0.12	1.66	0.29	1.63	0.29
89%	0.33	0.06	0.65	0.12	1.54	0.29	1.51	0.28
90%	0.31	0.06	0.61	0.12	1.44	0.27	1.41	0.27
91%	0.27	0.06	0.53	0.11	1.25	0.26	1.23	0.26
92%	0.23	0.05	0.45	0.11	1.07	0.25	1.05	0.25
93%	0.20	0.05	0.40	0.10	0.94	0.24	0.92	0.24
94%	0.17	0.05	0.34	0.10	0.81	0.23	0.80	0.22
95%	0.15	0.05	0.30	0.09	0.72	0.21	0.70	0.21
96%	0.12	0.04	0.24	0.08	0.56	0.20	0.55	0.20
97%	0.10	0.04	0.19	0.08	0.46	0.18	0.45	0.18
98%	0.07	0.04	0.13	0.07	0.32	0.17	0.31	0.16
99%	0.06	0.03	0.11	0.06	0.26	0.15	0.25	0.14
100%	0.05	0.03	0.10	0.05	0.23	0.13	0.22	0.13

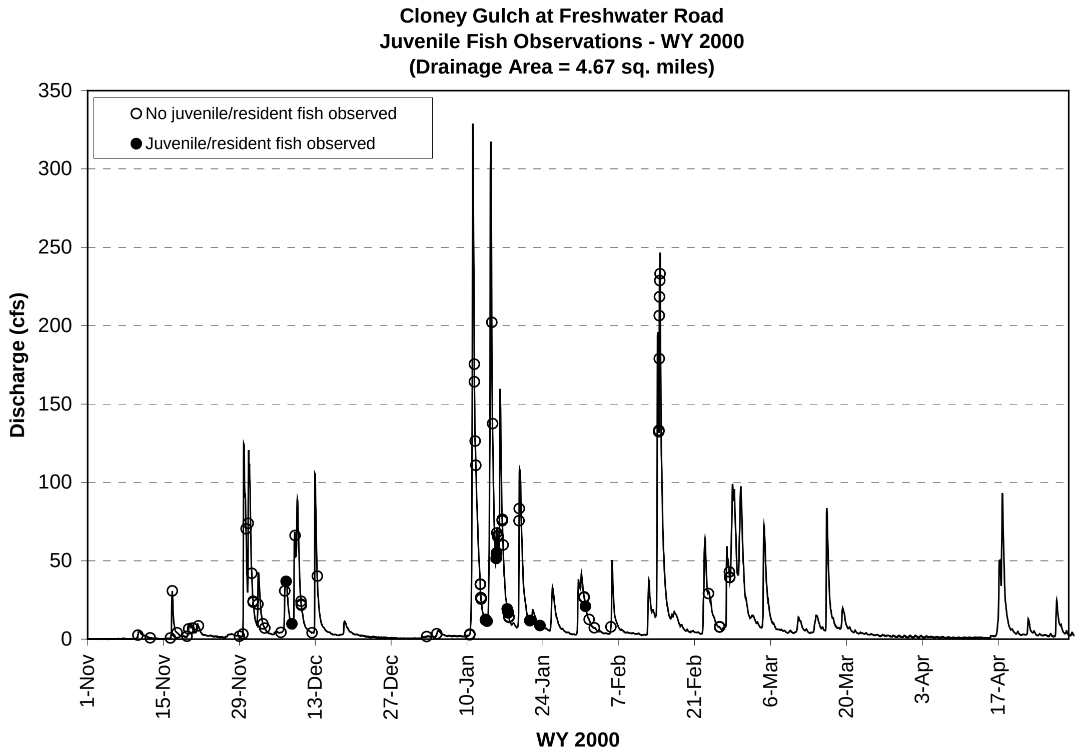
Appendix C – Fish Observations

Cloney Gulch at Freshwater Road
Juvenile Fish Observations - WY 1999
(Drainage Area = 4.67 sq. miles)

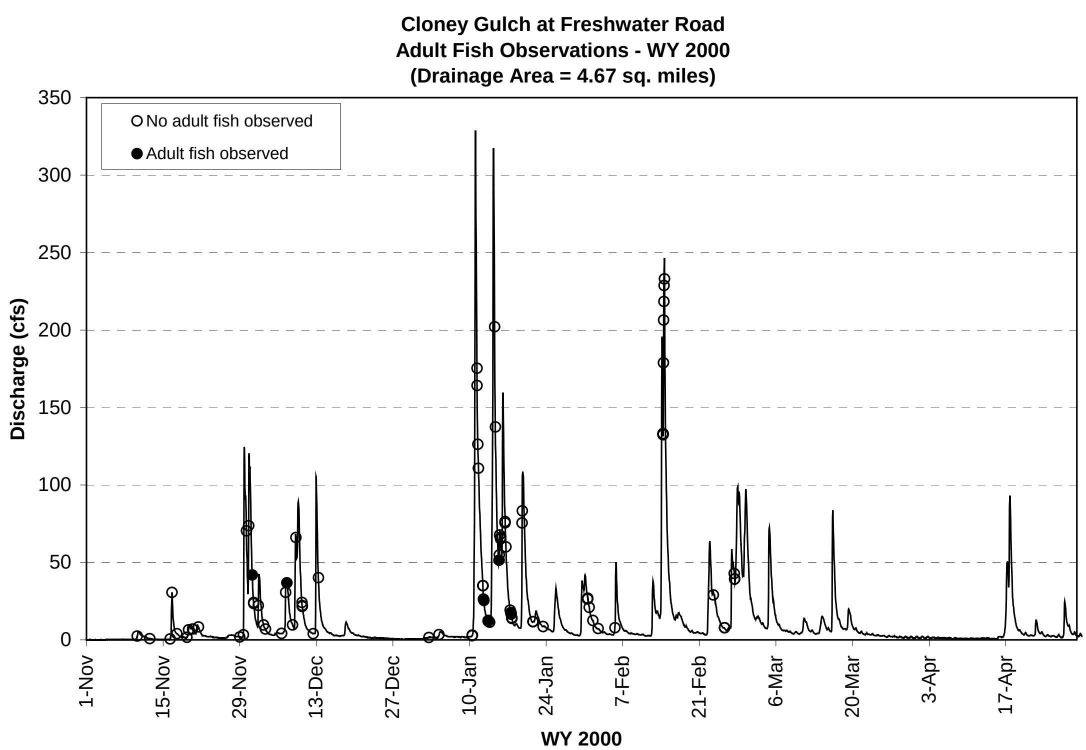


Cloney Gulch at Freshwater Road
Adult Fish Observations - WY 1999
(Drainage Area = 4.67 sq. miles)

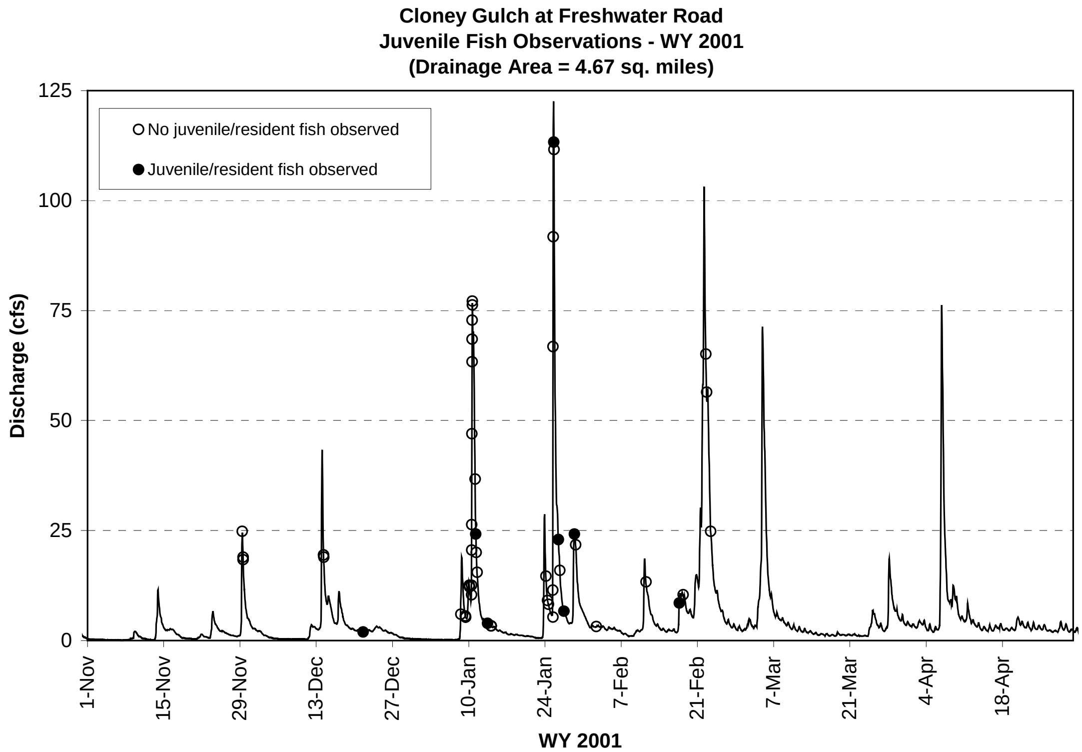


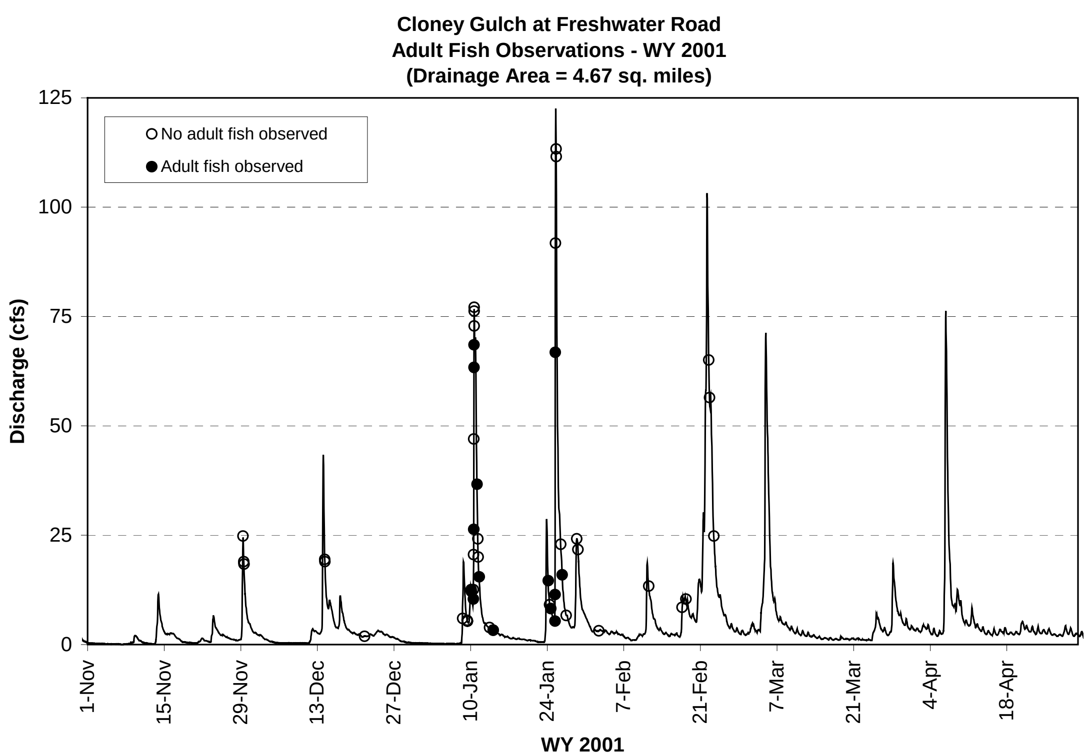


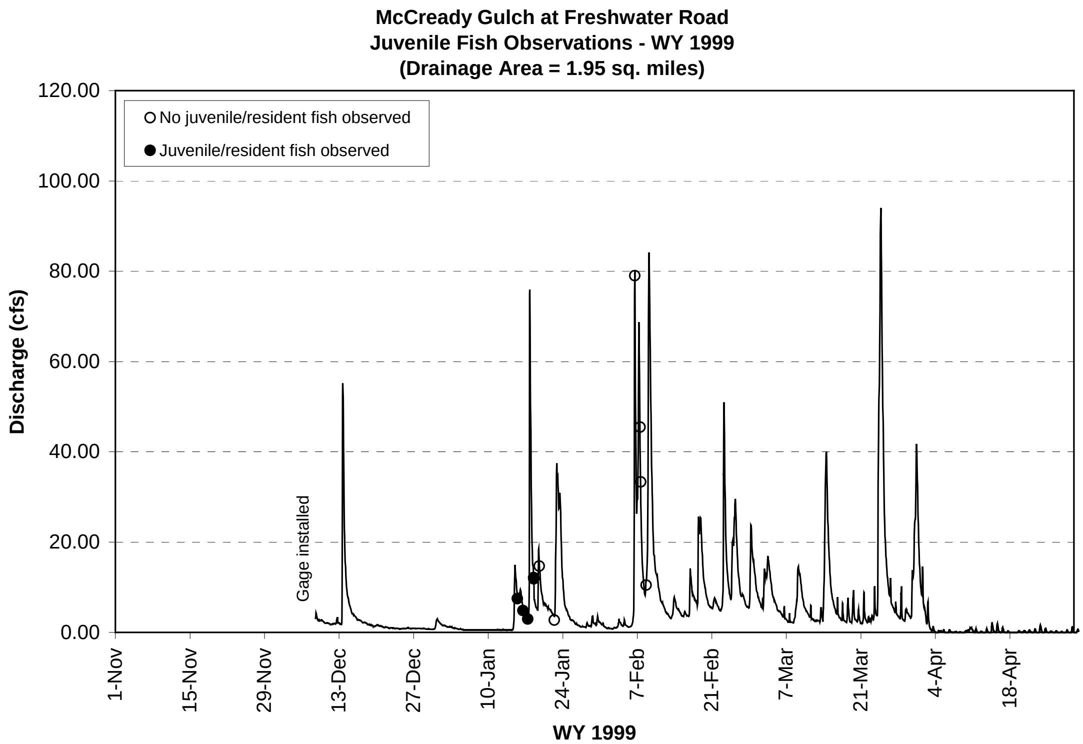
Cloney Gulch at Freshwater Road
Juvenile Fish Observations - WY 2000
(Drainage Area = 4.67 sq. miles)
No juvenile/resident fish observed
Juvenile/resident fish observed
Discharge (cfs)
0
50
100
150
200
250
300
350
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
6-Mar
20-Mar
3-Apr
17-Apr
WY 2000

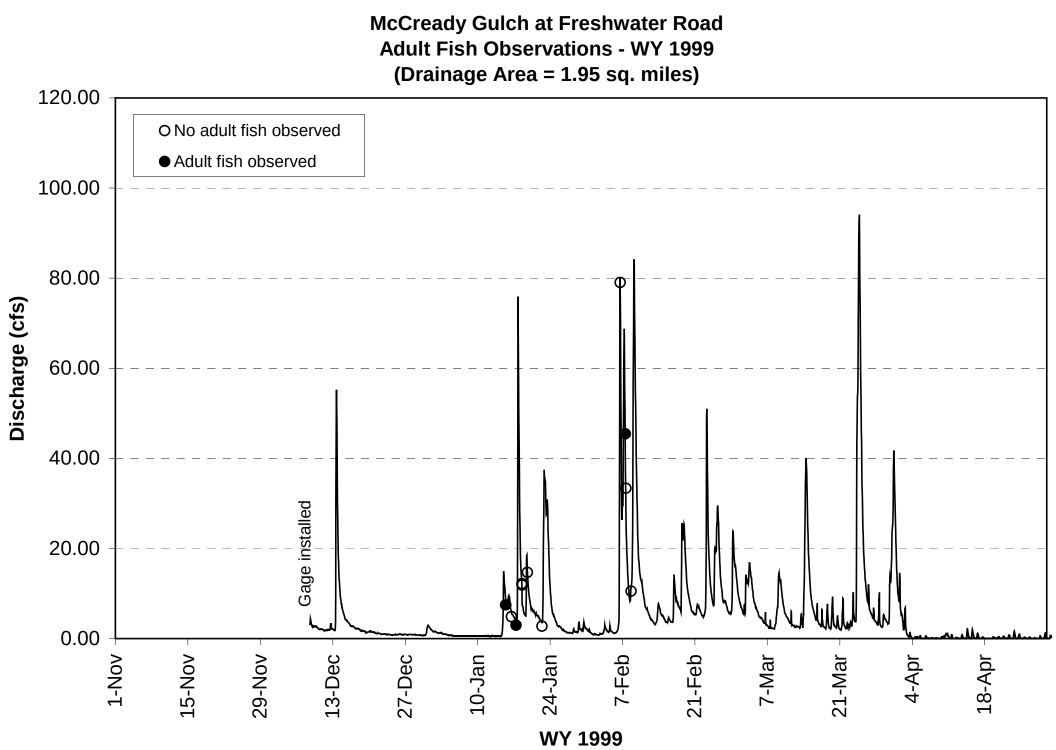


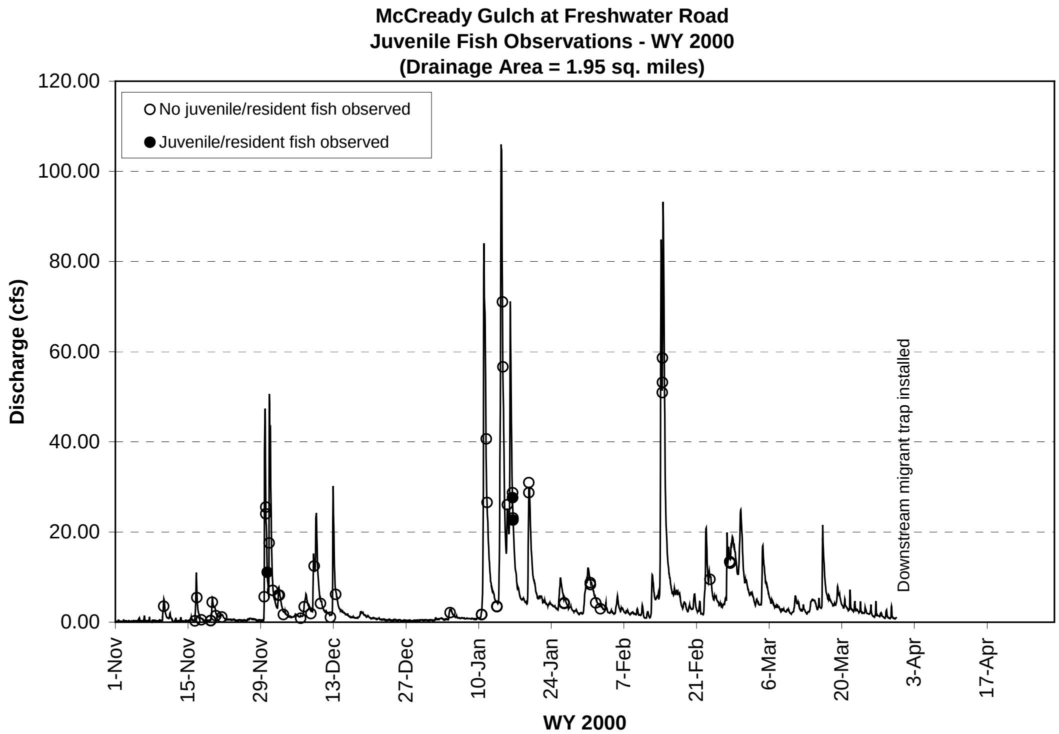
Cloney Gulch at Freshwater Road
Adult Fish Observations - WY 2000
(Drainage Area = 4.67 sq. miles)
No adult fish observed
Adult fish observed
Discharge (cfs)
0
50
100
150
200
250
300
350
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
6-Mar
20-Mar
3-Apr
17-Apr
WY 2000

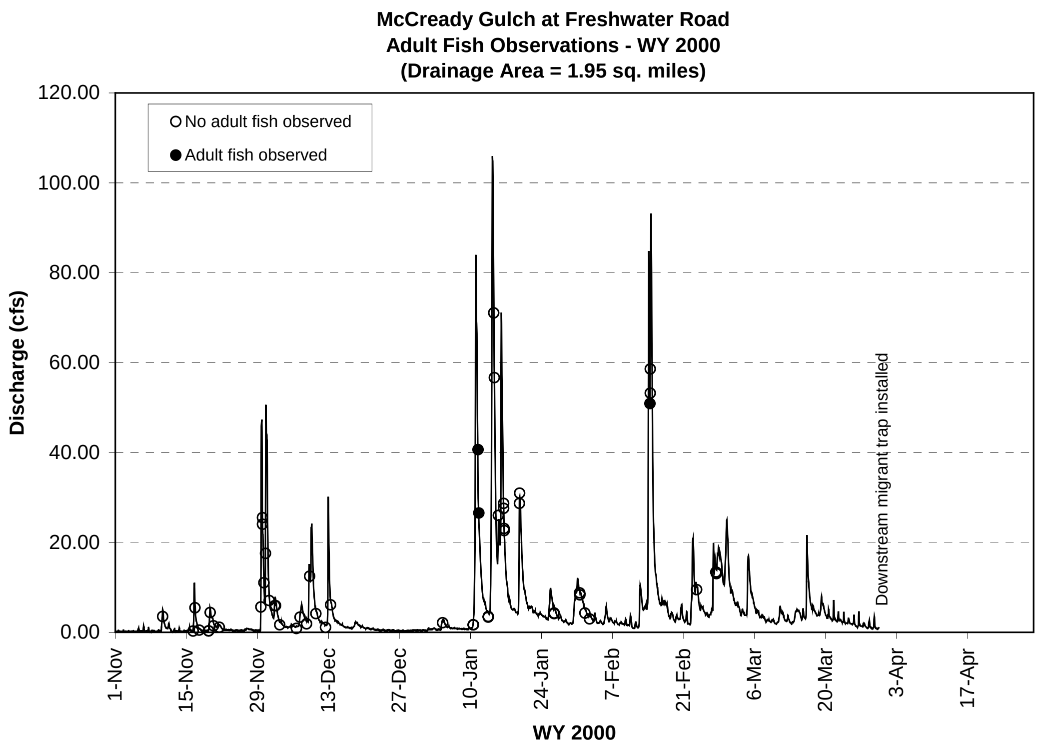

Cloney Gulch at Freshwater Road
Juvenile Fish Observations - WY 2001
(Drainage Area = 4.67 sq. miles)
No juvenile/resident fish observed
Juvenile/resident fish observed
Discharge (cfs)
0
25
50
75
100
125
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
7-Mar
21-Mar
4-Apr
18-Apr
WY 2001

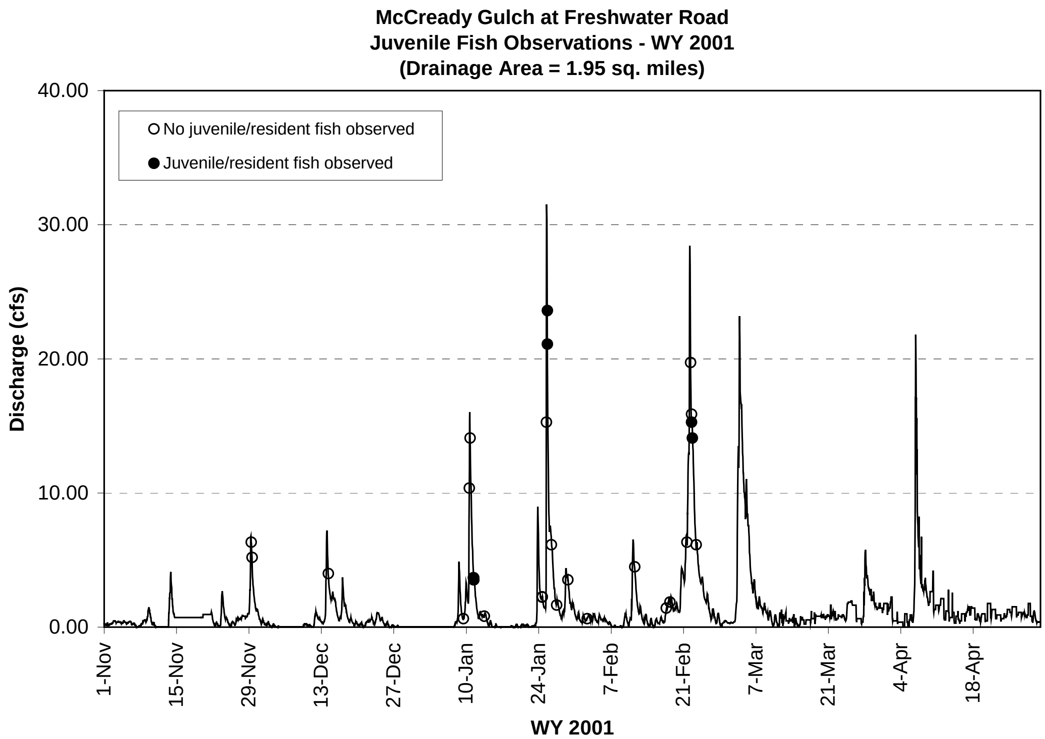

Cloney Gulch at Freshwater Road
Adult Fish Observations - WY 2001
(Drainage Area = 4.67 sq. miles)
No adult fish observed
Adult fish observed
Discharge (cfs)
0
25
50
75
100
125
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
7-Mar
21-Mar
4-Apr
18-Apr
WY 2001

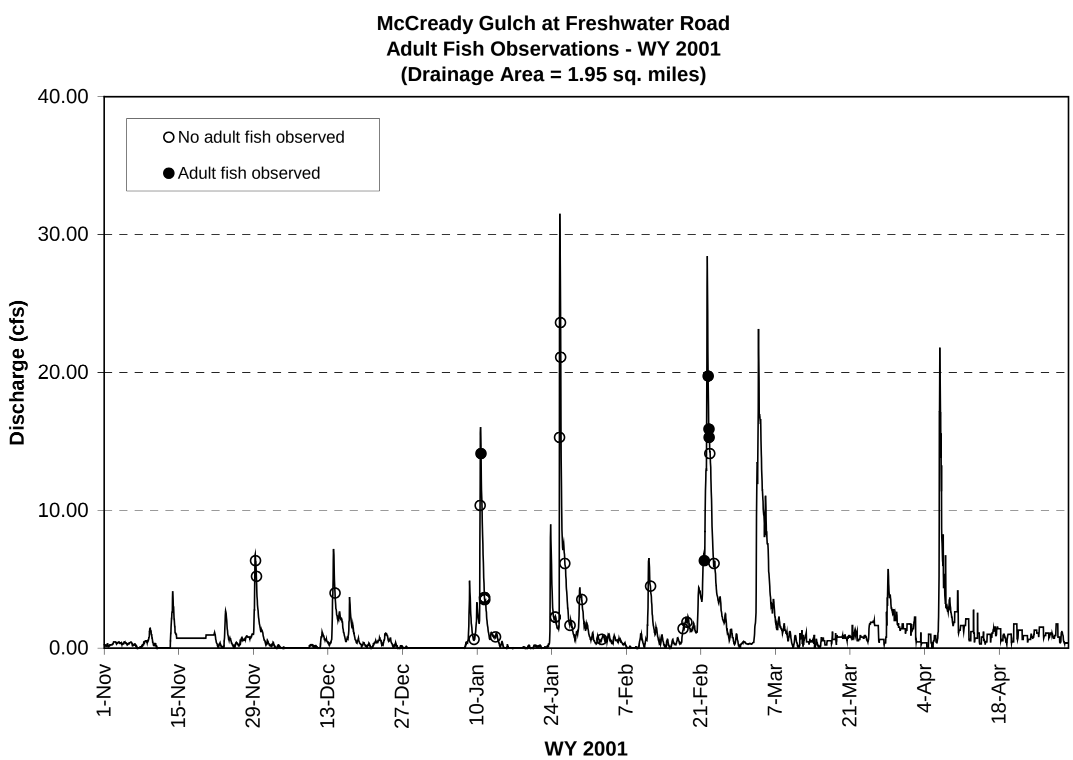

McCready Gulch at Freshwater Road
Juvenile Fish Observations - WY 1999
(Drainage Area = 1.95 sq. miles)
No juvenile/resident fish observed
Juvenile/resident fish observed
Gage installed
Discharge (cfs)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
7-Mar
21-Mar
4-Apr
18-Apr
WY 1999


McCready Gulch at Freshwater Road
Adult Fish Observations - WY 1999
(Drainage Area = 1.95 sq. miles)
No adult fish observed
Adult fish observed
Gage installed
Discharge (cfs)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
7-Mar
21-Mar
4-Apr
18-Apr
WY 1999

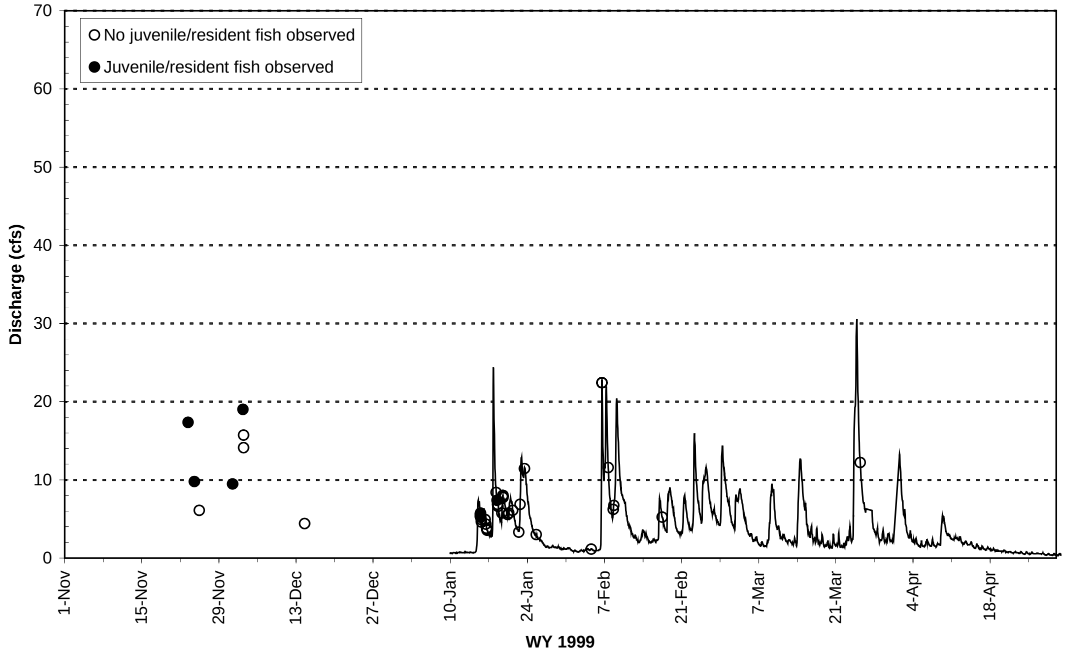

McCready Gulch at Freshwater Road
Juvenile Fish Observations - WY 2000
(Drainage Area = 1.95 sq. miles)
No juvenile/resident fish observed
Juvenile/resident fish observed
Discharge (cfs)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Downstream migrant trap installed
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
6-Mar
20-Mar
3-Apr
17-Apr
WY 2000


McCready Gulch at Freshwater Road
Adult Fish Observations - WY 2000
(Drainage Area = 1.95 sq. miles)
No adult fish observed
Adult fish observed
Discharge (cfs)
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Downstream migrant trap installed
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
6-Mar
20-Mar
3-Apr
17-Apr
WY 2000

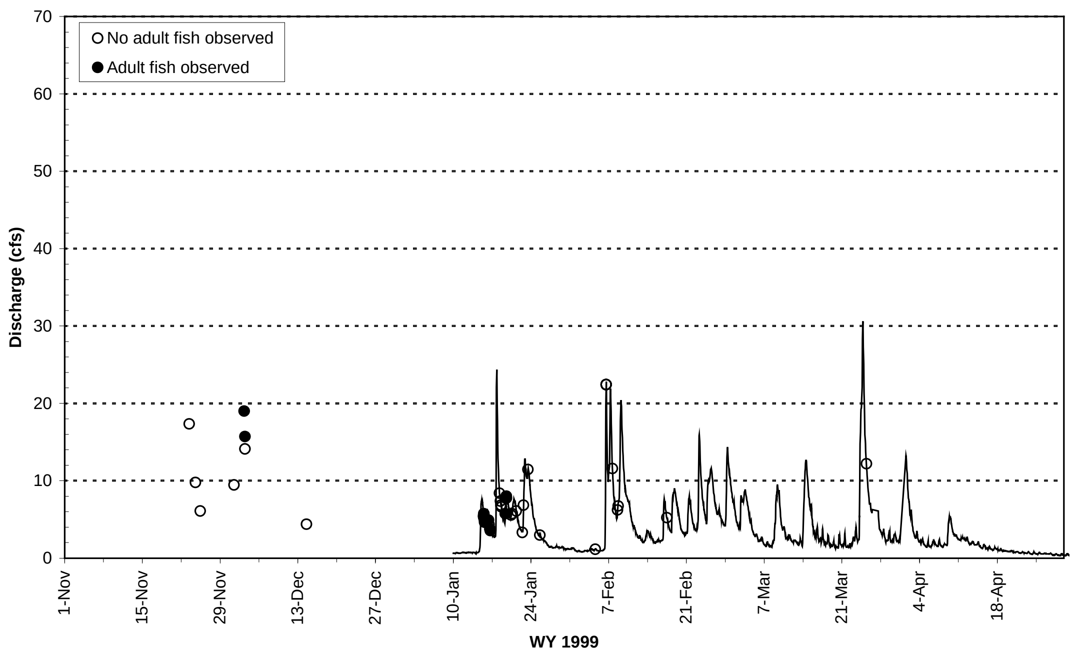

McCready Gulch at Freshwater Road
Juvenile Fish Observations - WY 2001
(Drainage Area = 1.95 sq. miles)
No juvenile/resident fish observed
Juvenile/resident fish observed
Discharge (cfs)
40.00
30.00
20.00
10.00
0.00
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
7-Mar
21-Mar
4-Apr
18-Apr
WY 2001

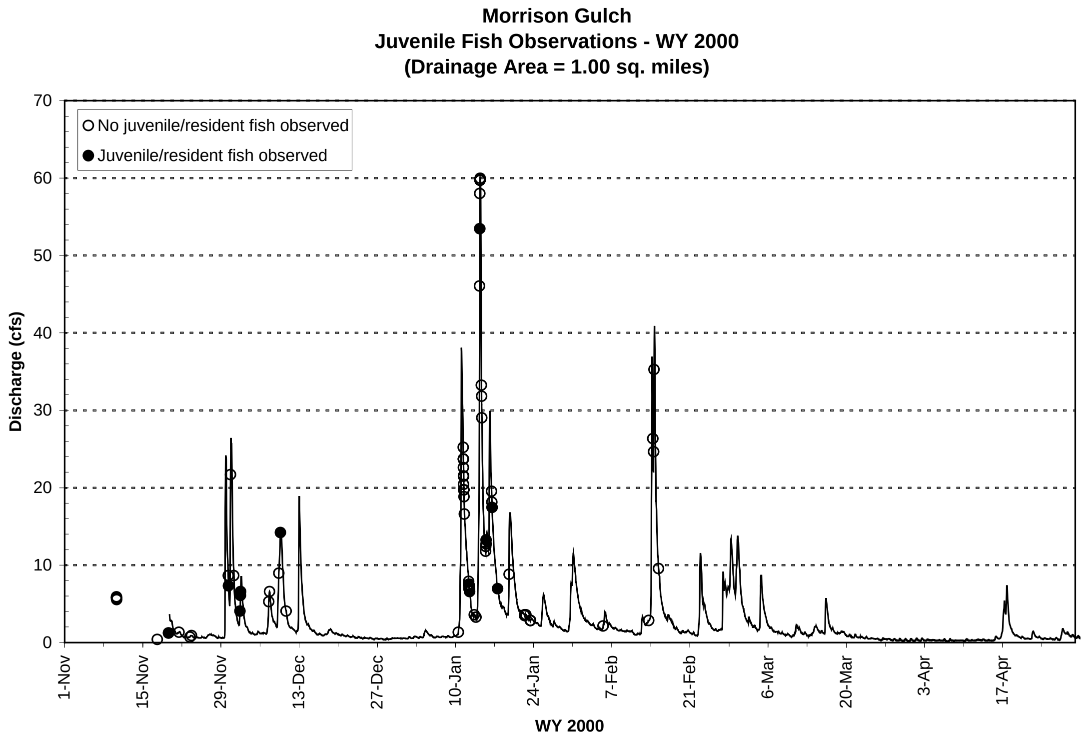

McCready Gulch at Freshwater Road
Adult Fish Observations - WY 2001
(Drainage Area = 1.95 sq. miles)
No adult fish observed
Adult fish observed
Discharge (cfs)
40.00
30.00
20.00
10.00
0.00
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
7-Mar
21-Mar
4-Apr
18-Apr
WY 2001

Morrison Gulch
Juvenile Fish Observations - WY 1999
(Drainage Area = 1.00 sq. miles)

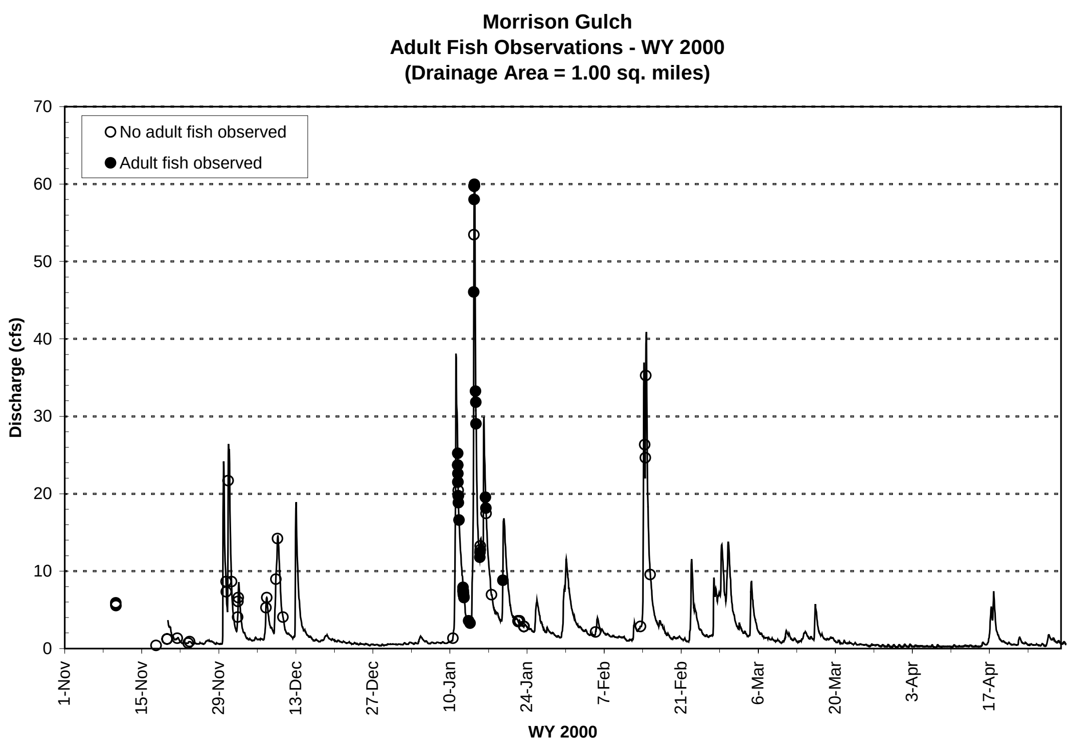


Morrison Gulch
Adult Fish Observations - WY 1999
(Drainage Area = 1.00 sq. miles)

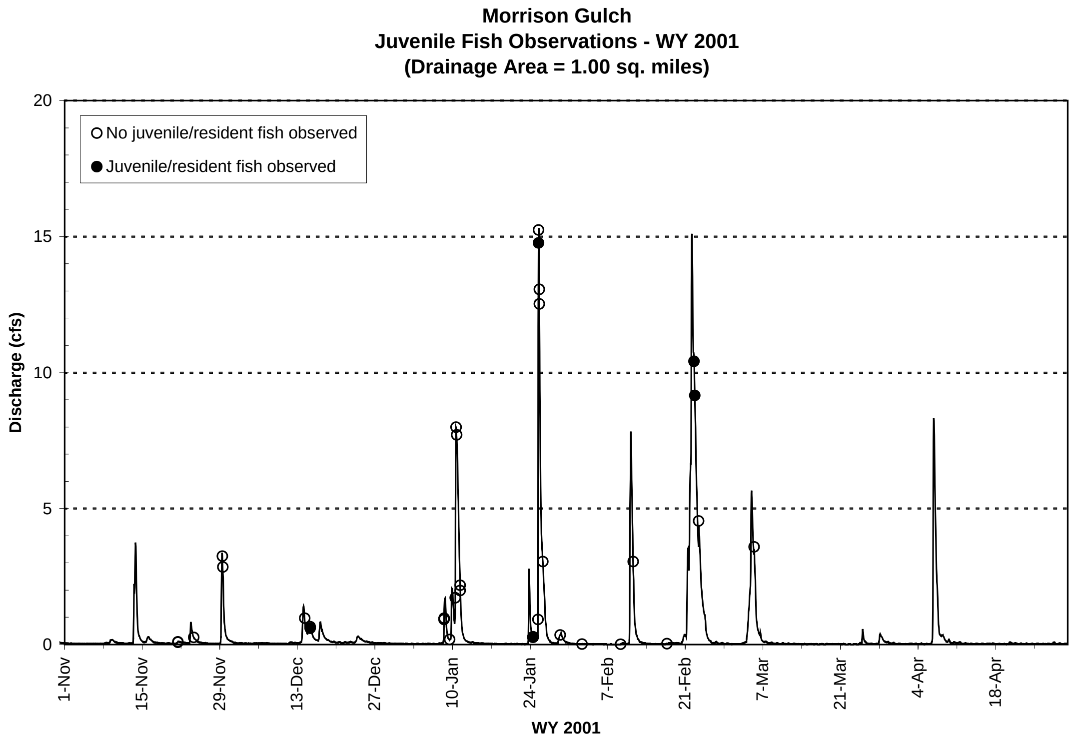


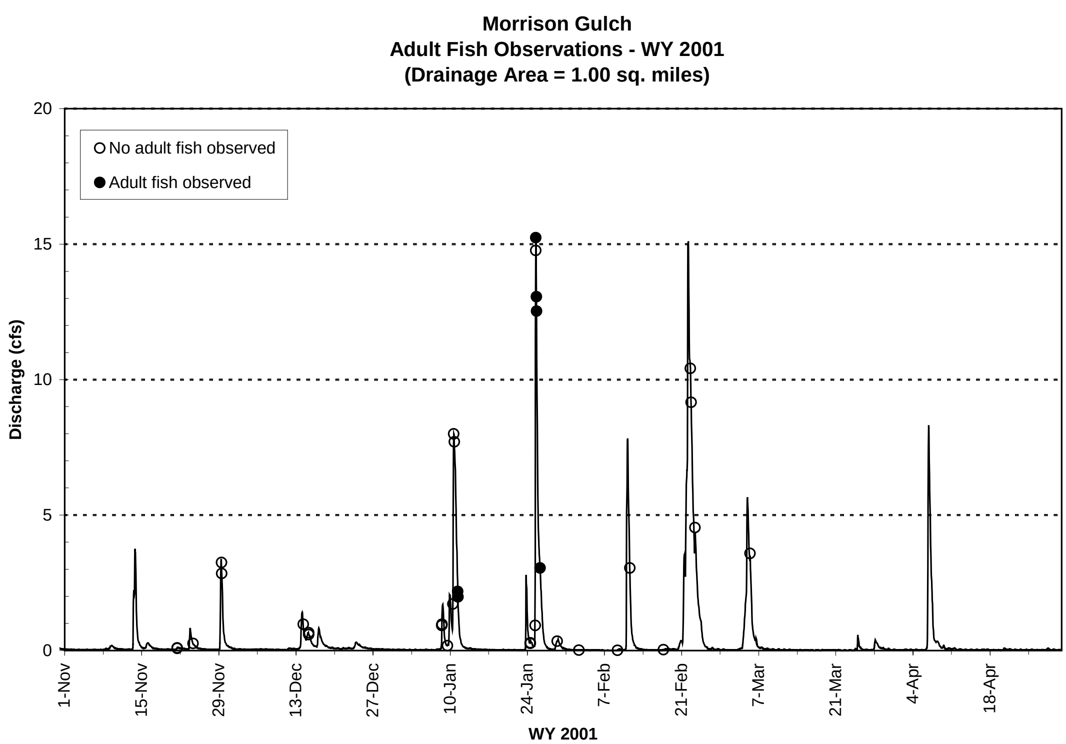


Morrison Gulch
Juvenile Fish Observations - WY 2000
(Drainage Area = 1.00 sq. miles)
No juvenile/resident fish observed
Juvenile/resident fish observed
Discharge (cfs)
0
10
20
30
40
50
60
70
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
6-Mar
20-Mar
3-Apr
17-Apr
WY 2000

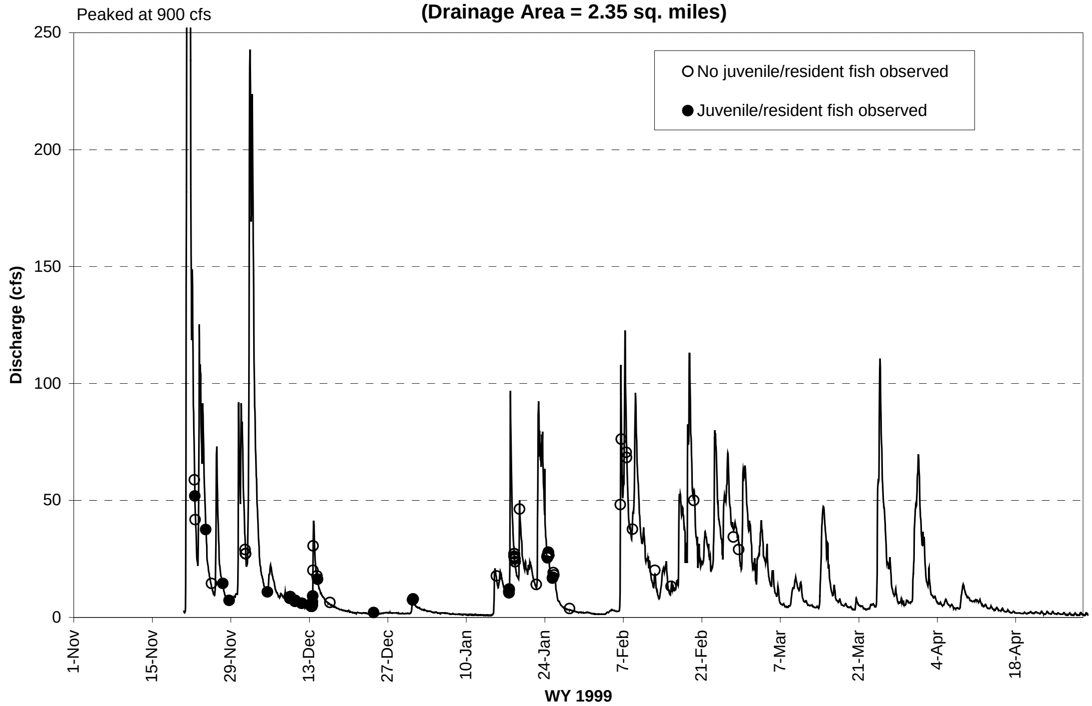


Morrison Gulch
Adult Fish Observations - WY 2000
(Drainage Area = 1.00 sq. miles)
No adult fish observed
Adult fish observed
Discharge (cfs)
0
10
20
30
40
50
60
70
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
6-Mar
20-Mar
3-Apr
17-Apr
WY 2000

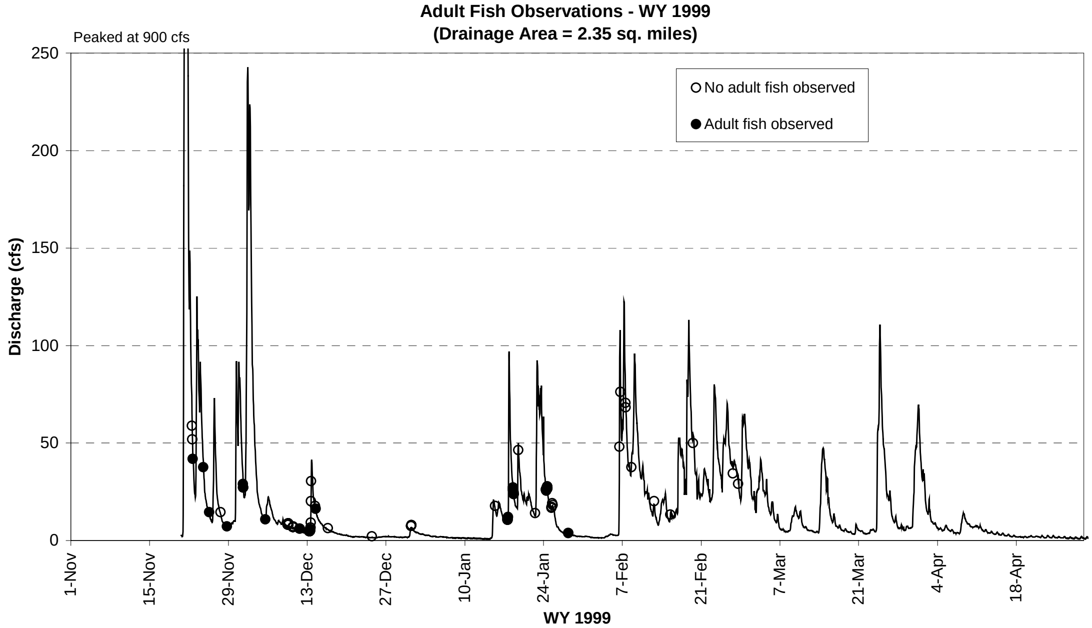

Morrison Gulch
Juvenile Fish Observations - WY 2001
(Drainage Area = 1.00 sq. miles)
No juvenile/resident fish observed
Juvenile/resident fish observed
Discharge (cfs)
0
5
10
15
20
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
7-Mar
21-Mar
4-Apr
18-Apr
WY 2001

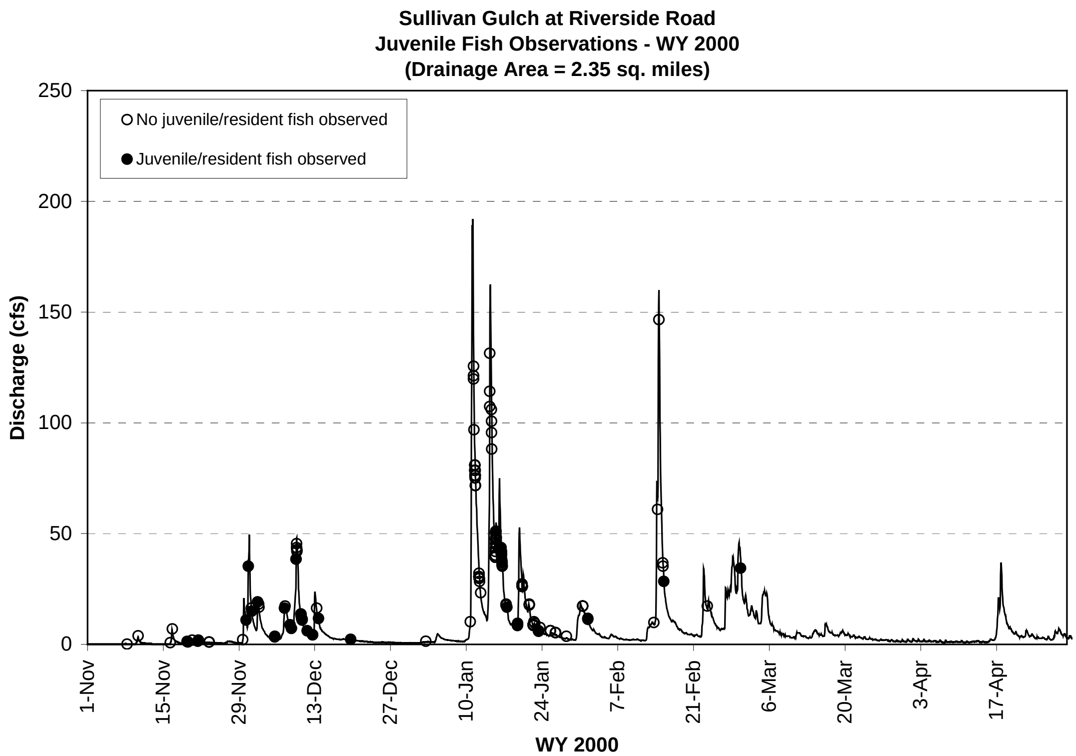

Morrison Gulch
Adult Fish Observations - WY 2001
(Drainage Area = 1.00 sq. miles)
No adult fish observed
Adult fish observed
Discharge (cfs)
0
5
10
15
20
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
7-Mar
21-Mar
4-Apr
18-Apr
WY 2001

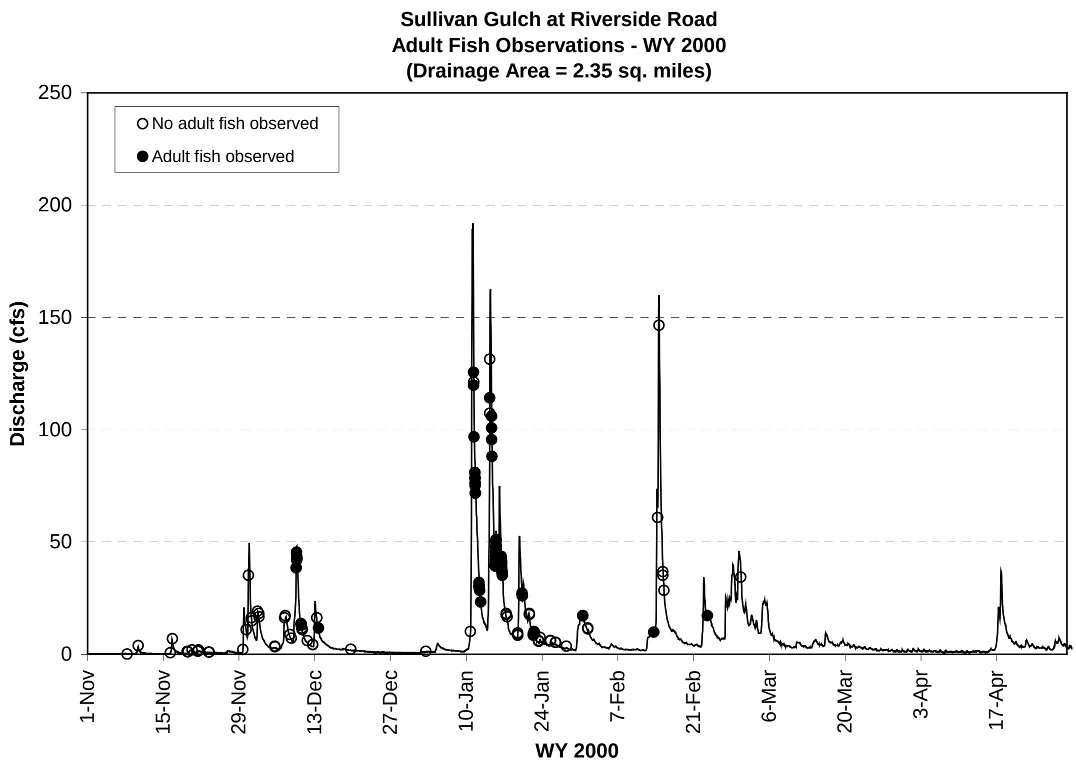
Sullivan Gulch at Riverside Road
Juvenile Fish Observations - WY 1999
(Drainage Area = 2.35 sq. miles)

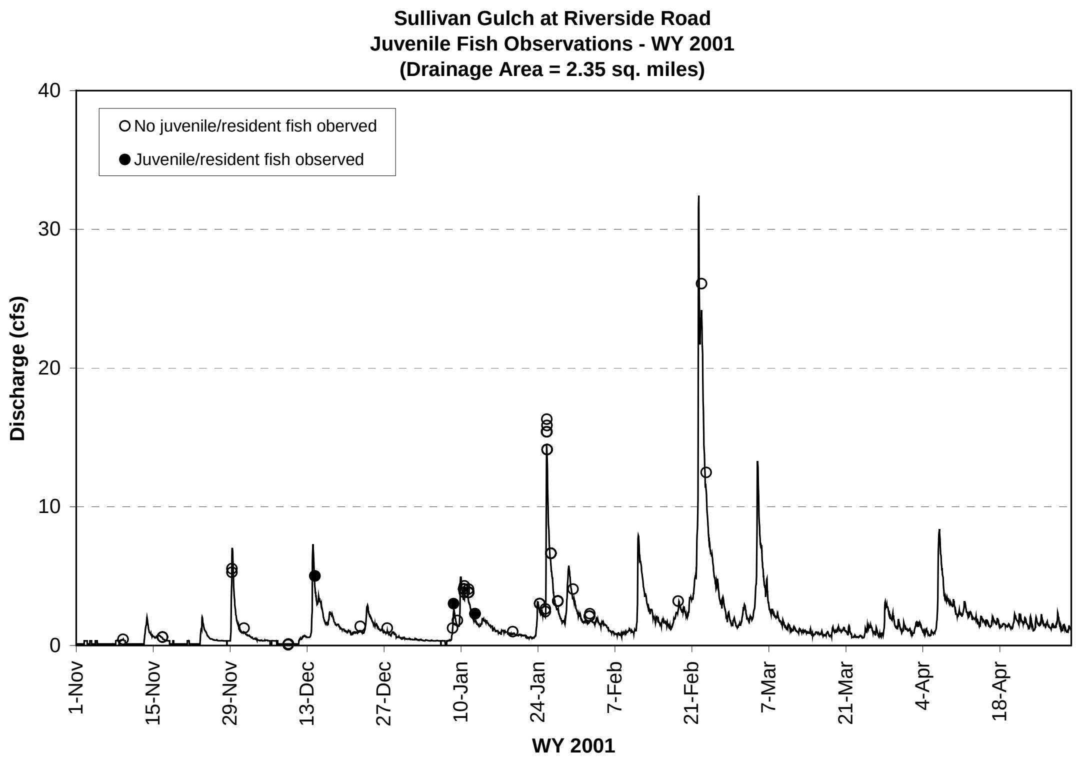


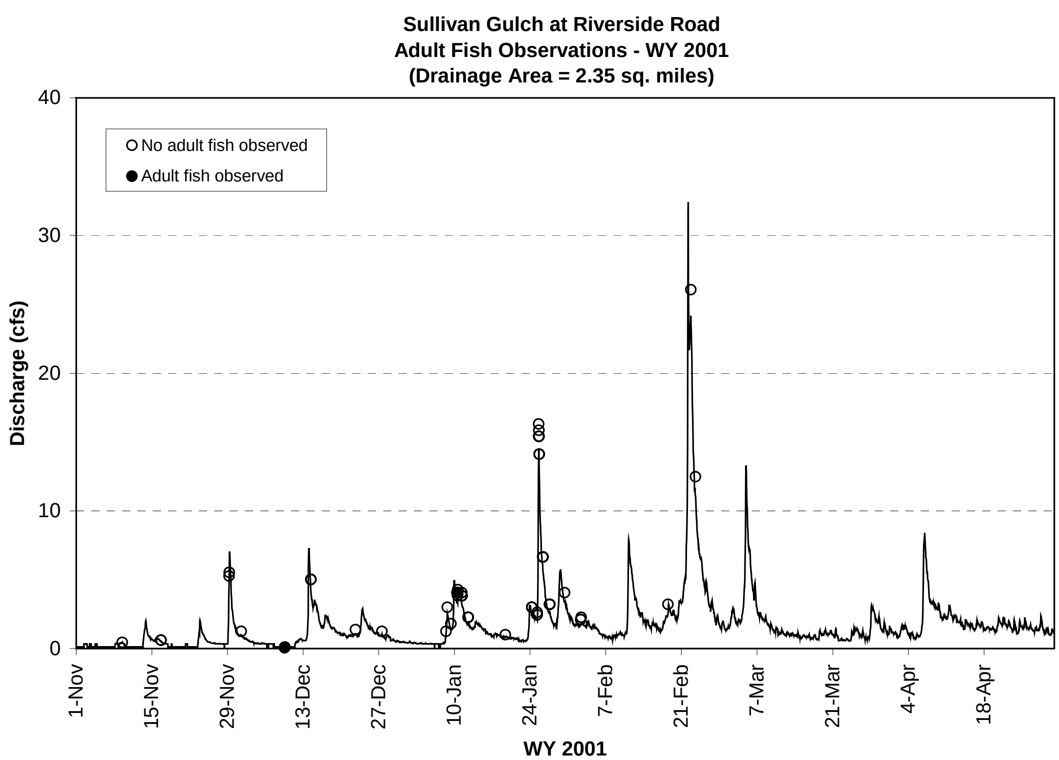
Sullivan Gulch at Riverside Road
Adult Fish Observations - WY 1999
(Drainage Area = 2.35 sq. miles)




Sullivan Gulch at Riverside Road
Juvenile Fish Observations - WY 2000
(Drainage Area = 2.35 sq. miles)
No juvenile/resident fish observed
Juvenile/resident fish observed
Discharge (cfs)
250
200
150
100
50
0
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
6-Mar
20-Mar
3-Apr
17-Apr
WY 2000


Sullivan Gulch at Riverside Road
Adult Fish Observations - WY 2000
(Drainage Area = 2.35 sq. miles)
No adult fish observed
Adult fish observed
Discharge (cfs)
250
200
150
100
50
0
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
6-Mar
20-Mar
3-Apr
17-Apr
WY 2000


Sullivan Gulch at Riverside Road
Juvenile Fish Observations - WY 2001
(Drainage Area = 2.35 sq. miles)
No juvenile/resident fish oberved
Juvenile/resident fish observed
Discharge (cfs)
0
10
20
30
40
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
7-Mar
21-Mar
4-Apr
18-Apr
WY 2001


Sullivan Gulch at Riverside Road
Adult Fish Observations - WY 2001
(Drainage Area = 2.35 sq. miles)
No adult fish observed
Adult fish observed
Discharge (cfs)
0
10
20
30
40
1-Nov
15-Nov
29-Nov
13-Dec
27-Dec
10-Jan
24-Jan
7-Feb
21-Feb
7-Mar
21-Mar
4-Apr
18-Apr
WY 2001

Appendix D – Field Measurement Protocols

Protocol for Surveying Water Surface Elevations

1. String tape from upstream of the culvert inlet to ~10 ft downstream of the downstream control.

- Start the tape several feet upstream of the inlet region. The inlet region is a channel reach that is directly or indirectly influenced by the culvert and is characterized by: a change in the water surface profile as it approaches the inlet, a steep drop in channel profile (riffle), or a change in the channel alignment near the inlet (channel makes sharp turn as it heads upstream). The tape should start AT LEAST 20 FEET UPSTREAM of the inlet.

  - The survey must proceed through the point controlling the downstream water surface elevation. The riffle crest at the downstream end of the outlet pool often defines the downstream control. Make sure the survey continues at LEAST 10 FEET PASS THE CONTROL POINT. All control points should be within the natural stream channel (CONCRETE OUTLET APRONS WITH NOTCHED SILLS ARE NOT CONSIDERED DOWNSTREAM CONTROLS FOR THE PURPOSE OF THIS SURVEY)

2. Setup tripod and auto-level in a location which allows a clear path of sight through the entire culvert, and if possible, from upstream of the inlet region to the downstream control. If the entire survey reach can not be visible from a single station, a turning point will be required. When setting up the tripod, attempt to find a stable location. Saturated soils, such as sand and mud are unstable and may cause the tripod to shift during the survey.

3. BEFORE STARTING THE SURVEY, take a point at a temporary benchmark that can be reoccupied. This will allow you to check if the auto-level has shifted during the survey. ALSO, record the stage height from the staff plate (if there is one), and the time.

4. **UPSTREAM -** START THE SURVEY AT THE UPSTREAM END. Take a survey point approximately every 5 FEET. AT EACH SURVEY POINT, ALSO RECORD THE WATER DEPTH AT THAT LOCATION. When you begin to enter the region immediately upstream of the inlet (approximately 10 feet upstream), begin taking points every 2 FEET. Note when there are changes in the bottom substrate, directional changes within the channel, or any other influencing feature.

5. **INLET and CULVERT BARREL -** NOTE when you reach the culvert inlet, and make sure a point is taken **exactly** at the inlet. Once in the culvert, continue to take MEASURMENTS EVERY 2 FEET for the first 10 – 20 feet (until the slope of the water surface appears relatively constant). Once the water surface becomes relatively uniform, return to taking points every 5 FEET. Meaurements should be taken in the center of the culvert.

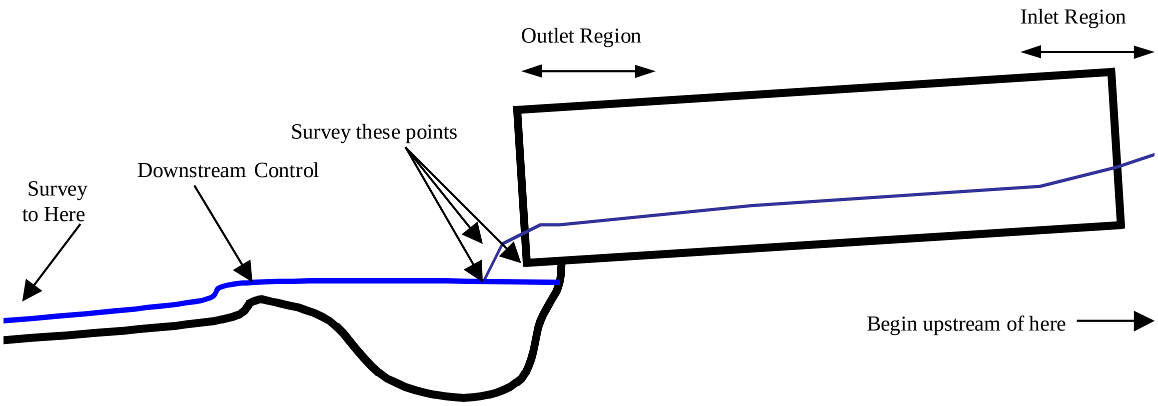
   For each point within the culvert, note whether the stadia rod was on the culvert bottom, stream substrate, or other.

6. **OUTLET** – When the water surface slope begins to change as you approach the outlet, return to taking measurements every 2 FEET. This will typically occur approximately 20 feet upstream of the outlet.

   Make sure to take a point exactly at the outlet and make note of it. If there is a notched weir at the outlet, take one or more survey points and water depth measurements on the upstream side of the weir where the water surface elevation (WSE) is highest in addition to a point in the center of the notch. Often the WSE in the notch is lower than the WSE that is spilling over the weir.

7. **DOWNSTREAM**

Perched Outlets – If the water plunges into a downstream pool, attempt to take several survey points along the water surface of the nape. Then, make sure to take a survey point of either the pool bottom, or the water surface at the point where the nape makes contact with the pool. The goal is to be able to plot the water surface as it plunges into the pool.



Outlet at stream grade – If the water at the outlet does not plunge, than continue taking survey points and water depths EVERY 2 feet until the water surface levels out.

Ending Survey – Once you've reach the downstream channel or pool and the water surface slope is relatively constant, take points every 5 – 10 FEET through the downstream control till you reach the end of the survey reach. NOTE the location of the downstream control.

8. **Ending The Survey** – When all the points have been taken through the survey reach, revisit the temporary benchmark and take a FINAL SURVEY POINT.

   RECORD the ENDING stage height (if applicable) and ending TIME.

REMEMBER - A discharge measurement should be taken immediately after finishing the survey!

Field Procedures for Measuring Water Velocities within Culverts

Fish often choose the path of least resistance when faced with challenging situations. Several fish passage researchers have reported observing numerous fish of various sizes skirting along the culvert wall when attempting to swim upstream. This region often contains the lowest water velocities, sometimes being far less than the average water velocity. To determine what water velocities a fish may encounter when swimming through a culvert we need to understand how velocities vary spatially.

This document explains the procedures for mapping point and cross-sectional water velocities in different culvert types.

Field Procedures

All velocity measurements should be accompanied by a water surface profile. At tier 2 sites (sites without gages) an accompanying discharge measurement is also essential (and is highly recommended for tier 1 sites). Since the flow often changes while at the site, **discharge should be measured in-between surveying the water surface profile and mapping water velocities**, not at the beginning or end of the fieldwork. This attempts to assure the *average* discharge over the period is measured.

The velocity information collected at each site varies depending on the culvert type.

For all sites record the header information listed below and measure one velocity cross-section across the culvert inlet.

> **For unmodified culverts** (no weirs or baffles), collect one additional velocity cross-section near the middle of the culvert. Look for grease pen markings along the culvert wall to show where to take this measurement.
>
> **For weir/baffled culverts**, measure a point velocity in the middle of each notch or constriction. Include the distance from the inlet for each point measurement. Additionally, collect one velocity cross-section between the baffles at a location near the culvert middle**. Consult with others before going into the field for details particular to each site.**

Header Information

- Date
- Field Personnel
- Time started and stopped for each velocity cross-section
- *Starting* and *stopping* stage (if stage plate exists) and plate location (i.e. At Pool or At Gage). Give the stage at both plates if possible.
- Location of cross-section, reported as distance from inlet

Cross-sectional Velocity Measurements

Water velocities will be measured at regular intervals **from left to right** (looking downstream). The procedure is similar to taking a discharge measurement, with multiple velocity measurements being made at each station. One person should hold the wading rod while the other holds the electronic display and records the numbers into the notebook

Required equipment: Digital pygmy meter, measuring tape, grease pen, notebook.

1. Begin by stringing a tape from left to right across the widest point in the culvert at the appropriate location (inlet, middle, or outlet of culvert). For concrete box culverts, you may use a grease pen to mark the measurement intervals on the culvert ceiling. If others have already done so, use the same intervals.
2. Construct a table within your notebook formatted as shown below. Begin taking your measurement as close to the LEW as possible. This is important since juvenile salmonids have been observed swimming in this zone, and even holding between corrugations.

LEW = 0.34 ft		REW = 7.23 ft	
Station (ft)	Water Surface (ft)	Depth of Meas. (ft)	Velocity (ft/s)

3. Record the station distance at the left and right water's edge (LEW and REW). Use a **maximum measurement interval of 0.50 feet between stations**.
4. In most situations multiple velocity measurements at differing depths will be made at each station. Take velocity measurements at **depth intervals of 0.30 feet**, with the first measurement being at 0.30 feet from the bottom. These sample intervals are not rigid, but only meant to serve as maximums. You may always use smaller intervals or take points between intervals if its appropriate for the situation (such as taking additional points along the culvert walls or near the water surface).
5. Use the digital pygmy meter set for instantaneous velocity measurements (gives a velocity every 4 seconds). Take 2 to 3 readings and record the average into your notebook.

Processing Data

Each culvert has a specific Excel form for entering velocity cross-sections. Use a blank form and enter the data into the appropriate cells. After entering the data, e-mail it to Margaret and Mike and it will be added to the database. Instructions for point velocity data collected at baffled/weir culverts will be given at a later date.

Protocol for Fish Observations

Field Equipment
Required

- Waterproof notebook and pencils
- Stopwatch
- Calibrated rod (measure heights, distances, water depths)

Recommended

- 2-Way radios
- Video camera and still camera
- Binoculars (staff plate readings)

Fish Observations
Use the following protocol as a guide for making fish observations:

1. Upon arriving on-site record the following information in a field book: location, date, time, staff plate reading in outlet pool, and weather conditions (SPECIFICALLY STATE WHAT STAFF PLATE YOU ARE USING).

2. If the outlet is perched and water is cascading into an outlet pool, sketch in the field book the trajectory of the cascading water. Measure with a tape the horizontal distance the water is traveling from the culvert outlet to the surface of the outlet pool. Also measure the vertical distance from the pool surface to the water surface at the culvert outlet. Include a sketch of the culvert outlet cross-section with description of the water level within the outlet.

3. **Observations will be made in 20-minute increments**. Position yourself at the culvert outlet. Select a location relatively close to the outlet where the entire outlet area is within view. If you have a video camera, set it on a tripod focused on the outlet. The field of view should encompass the water surface below the culvert invert to the top of the water within the culvert. If possible, start the taping with a shot of the outlet pool staff plate.

4. For juvenile attempts at perched culvert outlets, record each jump attempt as “success” or “fail” on a tally sheet within your notebook. Record attempts based on estimated size classes. Juvenile sizes will be broken down by 3”-5”, 5”-8”, and >8”. Below is an example table for tallying attempts. **CONSTRUCT A NEW TABLE FOR EACH 20-MINUTE OBSERVATION PERIOD.**

Juvenile Jump Attempts		
Location		Date
Begin time:	Begin stage:	
End time:	End stage:	
	Stage Location:	
Size Class	**Success**	**Fail**
3” – 5”		
5” – 8”		
> 8”		

5. **Each passage attempt by an adult** will be recorded as a separate event within the notebook. Record the time and pool stage height after each attempt. For all adult passage attempts, try to determine the species and estimated length of the fish. For observations of coho, note if it is a jack (a 2-year-old coho typically less than 22” length). Also, note the condition of the fish (does the tail look white with fungus or have gashes?).

6. If multiple adult fish are attempting to pass through a culvert, attempt to distinguish between them and give each individual fish a number based on order of initial observation (e.g., Fish#1). For subsequent attempts, record the fish's identification number if able to distinguish.

7. For culverts with perched outlets, after **each attempt of an ADULT fish** record the following information:

- **Note if the fish attempted to swim up or jump into the culvert outlet**. If the fish jumped, estimate and record the height, horizontal distance, and location and angle the fish exited the water. Also, note the location of the landing (e.g., outlet pool, 1.5 feet from top of falls, riprap on right bank).

- **Record whether the fish successfully entered the culvert barre**l. For failed attempts, describe the probable cause: poor jump projectery, insufficient height, confusion caused by outlet flow conditions such as turbulence or sheeting flow over outlet weir, fish likely scouting jump conditions, excessive velocity at outlet immediately swept out fish.

- Note whether fish are being injured at culvert or jumping to exhaustion and moving back downstream.

8. **When the adult fish successfully enters the culvert barrel**, regardless whether it is a perched or a swim-through culvert, begin your stopwatch. If you have a field partner notify them that a fish is in the culvert. They should then rush to the culvert inlet. Use 2-way radios or hand signals to communicate. The person stationed at the inlet will attempt to observe the fish passing out of the culvert. The person at the outlet must remain in position to observe if the fish is swept back out **(if you do not have a field partner remain at the outlet)**. If conditions permit, the observer at the outlet may move into the culvert to observe and record swimming behavior. Caution must be given to remain undetected by the fish. When the fish exists either end of the culvert, halt the stopwatch.

   After the attempt, record whether the fish successfully passed through the culvert, the fish's identification, the total time the fish remained in the culvert, and the outlet pool staff height. Describe any observations of the fish's swimming behavior (e.g., used burst swimming only at the inlet) and difficulties it encountered (e.g., regions of high velocity, shallow water, attempted to swim through unbaffled portion of culvert).

Processing Observational Data

Two databases exist for entering observations. The first is an Excel spreadsheet that is used to enter the number of juvenile and adult fish observed, including times when no fish were observed. If you recorded the observations in your notebook you are responsible for entering them into the Excel database on a regular basis and sending it to Margaret and Mike by e-mail so it can be combined with the rest of the data.

The second database is in MS Access and is on one of the Engineering Department computers in Sci D. You may also use it on your personal computer if you have MS Access. This database is for entering details about passage attempts by adult fish only.

Sample Field Notes

(16)

CLONEY 12-JAN-99 CONTINUED

• FISH #1 – 15:20:45 (SUCCESS)
LEAPED AT NOTCH AND
SWAM LAST FOOT

LANG AT INLET/LOVE AT OUTLET

• FISH #1 – 15:43:18 (PASS THRU INLET)
LANG OBSERVED FISH SWIM
THRU U/S NOTCH AT CULVERT
INLET AND GO TO POOL ALONG
LEFT STREAM BANK.

WATCHED INLET UNTIL 15:55
BUT FISH #1 DID NOT APPEAR
AGAIN

CLONEY GULCH
OBSERVATION #3 (17)

	TIME	POOL	GAGE
BEGIN	15:24	0.32	1.03
END	15:44	0.30	1.00

RAIN HAS STOPPED, WAITING FOR
ADULT TO APPEAR (STOP WATCH RUNNING)

SIZE	SUCCESS	FAIL
3"5"	—	11
5"8"	1	—
78	—	—
ADULT	—	1

• FISH #2 – 15:40 (FAILED)
SMALL LEAP ON RIGHT SIDE

FISH #2 DESCRIPTION: APPERS TO
BE A COHO JACK ~14" LENGTH
GRAY COLOR

LEFT CLONEY AT 16:00. DIDN'T
SEE FISH #2 AGAIN.