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CHAPTER 6. FISH PASSAGE DESIGN

6.1 INTRODUCTION

This chapter is intended to provide design criteria and procedures for fish passage improvement structures. The types of obstructions encountered in Santa Clara County are discussed. The species of fish present and their migration needs are covered. Design considerations such as design flows and energy dissipation are discussed. Typical methods for providing improved fish passage in open channels and culverts are covered. The references at the end of the chapter are provided for further information and detail.

6.2 TYPES OF OBSTRUCTIONS

This chapter will address physical obstructions to fish passage. Other obstructions such as temperature barriers and barriers caused by human interference (illegal fishing, etc.) are not going to be addressed in this chapter. Physical obstructions to fish passage are typically caused by three factors: excessive drop, excessive flow velocity, and inadequate flow depth. Excessive drop refers to an abrupt change in the invert elevation of a channel (waterfall, man-made drop structure, etc.) which creates a situation where fish have to jump upstream in order to have access to upstream habitat areas (see Figure 6-1). Excessive velocity situations usually involve man-made structures such as culverts where high flow velocities generated by steep slope exceed fish swimming capabilities and impede upstream fish passage (see Figure 6-2). Situations of inadequate flow depth are also prevalent in man-made structures. When the channel bottom width is too wide, shallow flow conditions result during low flows and prevent fish movement upstream or downstream (see Figure 6-3).

Figure 6-1. Excessive Elevation Drop (Alamitos Drop Structure, Guadalupe River)

Figure 6-2. Excessive Flow Velocity Downstream of a Culvert (From US Dept of Agriculture Forestry Dept.)

Figure 6-3. Shallow Depth of Supercritical Flow in Culvert (From Road Engineering Journal, Transafety, Inc.)

6.3 TYPES OF FISH

For fish-passage purposes, the main division of fish for Santa Clara County creeks is between anadramous fish and resident fish species. Anadramous fish are those species that spend a portion of their life cycle in the ocean and return to the creeks in order to spawn. These include Steelhead Trout, Chinook Salmon, and Pacific Lamprey. Resident fish are those species that spend their entire life cycle in freshwater. These include resident Rainbow Trout (as opposed to the ocean-going Steelhead), other native creek fish, and various non-native fish species. A partial list of the fish potentially encountered in Santa Clara County creeks is provided below:

Natives:	Introduced:	
Steelhead/Rainbow Trout	Black Crappie	Bluegill
Sculpin (Prickly, Riffle)	Bullhead	Channel Catfish
California Roach	Carp	Chinook Salmon
Sacramento Sucker	Fathead Minnow	Goldfish
Three Spine Stickleback	Green Sunfish	Golden Shiner
Pacific Lamprey	Hitch	Largemouth Bass
	Mosquitofish	Pumpkinseed
	Pacific Staghorn	Red Shiner
	Threadfin Shad	Yellowfin Goby

Fish have widely varying swimming capabilities. It is important to know the types of fish for which a particular fish passage improvement is being designed, as it will affect the design considerations significantly. For example, a fish passage structure that works well for Steelhead may not work at all for less athletic fish like carp or sunfish.

Anadramous fish have very specific requirements for freshwater rearing, the juvenile's voyage downstream to the Bay, and the adult upstream spawning migration. As Steelhead trout are threatened in the SCVWD jurisdictional area, they tend to be the "design" species for fish passage improvements (see Figure 6-4).

Figure 6-4. Steelhead Trout

It should be noted, however, that the community at large may have a larger goal in mind in terms of fish passage than just one species. Therefore, more conservative design considerations which allow most species to thrive may be more appropriate at times.

6.4 DESIGN CONSIDERATIONS

The main design considerations for fish passage have to do with design flow, step height, pool depth, and energy dissipation. Design flows are determined based on watershed hydrology and target species needs. The step height refers to the maximum allowable drop in bed elevation, which depends on the target fish species' leaping capabilities and the stage of life, i.e., juveniles are less capable than returning adults. Energy dissipation refers to the capability of the fish passage structure in dissipating energy such that it remains passable through the design flow range.

6.4.1 Design Flows

This parameter has often been one of the hardest ones to quantify. Watersheds vary greatly in terms of hydrology. While it is tempting to develop the widest possible design flow range to promote the best possible fish passage opportunities, feasibility criteria should be considered also. The idea is to find the balance: a wide enough design flow range to cover a sufficient spectrum of actual fish passage flow conditions balanced against a needlessly large and expensive structure.

There are two flows that need to be determined: the lower fish passage flow (Q_l) and the upper fish passage flow (Q_u). Q_l is typically set at the lowest flow rate at which fish movement is expected to be successful in the creek environment. This flow sets the minimum flow depth limit. Q_u is the highest flow at which fish movement through the creek is expected. This flow sets the maximum velocity and energy dissipation requirements.

Recently, California Department of Fish and Game [California 2002b] developed guidelines on the determination of Q_u and Q_l. The procedure requires developing a flow duration curve for the project location using stream gauge records from nearby stations. If these are not available, either another creek in the region with similar characteristics, i.e., drainage area, rainfall intensity, etc., and gage data may be used or a temporary gage should be installed and monitored. Since the flows sought are high-recurrence flows, not, for example the one-percent flood, a period of record as short as two years is sufficient. The flow duration analysis is counting the percentage of time in an average year a flow rate is exceeded. It uses the raw gauge flow record and counts the duration of each data point to calculate statistically the flow-duration relationship. An example of this application using gauge data from Station #35 of the Stevens Creek is shown in Table 6-1 and plotted in Figure 6-5.

Table 6-1. Flow Statistics for Streamflow Gage Station 35 at Stevens Creek*

Water Year	Total Hours of Record (Total Time)	Total Hours of Record (Migration Season**)	Number of Hours in Year When Flow Exceeded "x" CFS																							
			5		10		25		50		100		150		200		250		300		350		400		500	
1950	8760	6192	24.0	0.0	24.0	24.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1951	8760	6192	6600.0	5088.0	1512.0	960.0	552.0	336.0	216.0	168.0	48.0	24.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	24.0
1952	8784	6192	7056.0	4248.0	2808.0	528.0	2280.0	1200.0	1088.0	480.0	600.0	240.0	360.0	144.0	216.0	48.0	168.0	24.0	144.0	0.0	144.0	48.0	96.0	0.0	96.0	96.0
1953	8760	6192	5952.0	5064.0	888.0	672.0	216.0	120.0	96.0	72.0	24.0	24.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1954	8760	6192	3600.0	3600.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1955	8760	6192	6528.0	6312.0	216.0	168.0	48.0	48.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1956	8784	6192	5136.0	3072.0	2064.0	528.0	1536.0	240.0	1296.0	696.0	600.0	384.0	216.0	48.0	168.0	0.0	168.0	24.0	144.0	0.0	144.0	0.0	144.0	72.0	72.0	72.0
1957	8760	6192	2592.0	1920.0	672.0	168.0	504.0	24.0	480.0	360.0	120.0	48.0	72.0	72.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1958	8760	6192	4680.0	1896.0	2784.0	600.0	2184.0	744.0	1440.0	528.0	912.0	336.0	576.0	96.0	480.0	192.0	288.0	0.0	288.0	24.0	264.0	0.0	264.0	0.0	264.0	264.0
1959	8760	6192	3408.0	2832.0	576.0	336.0	240.0	96.0	144.0	48.0	96.0	24.0	72.0	48.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	24.0
1960	8784	6192	1896.0	1512.0	384.0	120.0	264.0	120.0	144.0	96.0	48.0	24.0	24.0	0.0	24.0	24.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1961	8760	6192	1824.0	1080.0	744.0	168.0	576.0	96.0	480.0	264.0	216.0	96.0	120.0	24.0	96.0	24.0	72.0	48.0	24.0	24.0	0.0	0.0	0.0	0.0	0.0	0.0
1962	8760	6192	4512.0	3912.0	600.0	288.0	312.0	144.0	168.0	48.0	120.0	24.0	96.0	24.0	72.0	24.0	48.0	48.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1963	8760	6192	4704.0	2112.0	2592.0	936.0	1656.0	576.0	1080.0	552.0	528.0	240.0	288.0	96.0	192.0	72.0	120.0	24.0	96.0	24.0	72.0	24.0	48.0	0.0	48.0	48.0
1964	8784	6192	2736.0	2472.0	264.0	120.0	144.0	72.0	72.0	24.0	48.0	24.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	24.0
1965	8760	6192	4560.0	2160.0	2400.0	840.0	1560.0	672.0	888.0	504.0	384.0	96.0	288.0	144.0	144.0	48.0	96.0	24.0	72.0	0.0	72.0	0.0	72.0	24.0	48.0	48.0
1966	8760	6192	3456.0	2904.0	552.0	216.0	336.0	168.0	168.0	96.0	72.0	24.0	48.0	24.0	24.0	0.0	24.0	0.0	24.0	24.0	0.0	0.0	0.0	0.0	0.0	0.0
1967	8760	6192	6072.0	3192.0	2880.0	960.0	1920.0	528.0	1392.0	624.0	768.0	312.0	456.0	168.0	288.0	72.0	216.0	0.0	216.0	48.0	168.0	48.0	120.0	0.0	120.0	120.0
1968	8784	6192	5832.0	5208.0	624.0	96.0	528.0	144.0	384.0	216.0	168.0	24.0	144.0	48.0	96.0	48.0	48.0	24.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	24.0
1969	8760	6192	4872.0	2520.0	2352.0	456.0	1896.0	240.0	1656.0	576.0	1080.0	312.0	768.0	288.0	480.0	96.0	384.0	144.0	240.0	72.0	168.0	0.0	168.0	24.0	144.0	144.0
1970	8760	6192	2952.0	1824.0	1128.0	288.0	840.0	240.0	600.0	336.0	264.0	120.0	144.0	24.0	120.0	24.0	96.0	48.0	48.0	0.0	48.0	0.0	48.0	24.0	24.0	24.0
1971	8760	6192	7392.0	5736.0	1656.0	744.0	912.0	504.0	408.0	216.0	192.0	24.0	168.0	72.0	96.0	0.0	96.0	0.0	96.0	24.0	72.0	0.0	72.0	24.0	48.0	48.0
1972	8784	6192	4032.0	3504.0	528.0	48.0	480.0	240.0	240.0	96.0	144.0	144.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1973	8760	6192	8328.0	4416.0	3912.0	960.0	2952.0	792.0	2160.0	1080.0	1080.0	264.0	816.0	144.0	672.0	192.0	480.0	48.0	432.0	72.0	360.0	72.0	288.0	72.0	216.0	216.0
1974	8760	6192	6792.0	4080.0	2712.0	792.0	1920.0	768.0	1152.0	480.0	672.0	168.0	504.0	192.0	312.0	96.0	216.0	24.0	192.0	24.0	168.0	72.0	96.0	24.0	72.0	72.0
1975	8760	6192	8376.0	6552.0	1824.0	408.0	1416.0	504.0	912.0	456.0	456.0	96.0	360.0	48.0	312.0	72.0	240.0	120.0	120.0	72.0	48.0	0.0	48.0	48.0	0.0	0.0
1976	8784	6192	5856.0	5352.0	504.0	288.0	216.0	120.0	96.0	72.0	24.0	24.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1977	8760	6192	576.0	216.0	360.0	72.0	288.0	72.0	216.0	72.0	144.0	72.0	72.0	48.0	24.0	0.0	24.0	0.0	24.0	24.0	0.0	0.0	0.0	0.0	0.0	0.0
1978	8760	6192	2688.0	240.0	2448.0	432.0	2016.0	504.0	1512.0	528.0	984.0	48.0	936.0	120.0	816.0	216.0	600.0	240.0	360.0	120.0	240.0	72.0	168.0	48.0	120.0	120.0
1979	8760	6192	3816.0	2376.0	1440.0	360.0	1088.0	384.0	696.0	192.0	504.0	168.0	336.0	96.0	240.0	24.0	216.0	72.0	144.0	48.0	96.0	24.0	72.0	24.0	48.0	48.0
1980	8784	6192	5256.0	2568.0	2688.0	912.0	1776.0	336.0	1440.0	384.0	1056.0	240.0	816.0	144.0	672.0	96.0	576.0	96.0	480.0	72.0	408.0	72.0	336.0	168.0	168.0	168.0
1981	8760	6192	3264.0	2136.0	1128.0	432.0	696.0	216.0	480.0	264.0	216.0	96.0	120.0	24.0	96.0	0.0	96.0	24.0	72.0	0.0	72.0	72.0	0.0	0.0	0.0	0.0
1982	8760	6192	7248.0	3096.0	4152.0	792.0	3360.0	1032.0	2328.0	768.0	1560.0	336.0	1224.0	408.0	816.0	168.0	648.0	120.0	528.0	72.0	456.0	96.0	360.0	192.0	168.0	168.0
1983	8760	6192	8712.0	2808.0	5904.0	1560.0	4344.0	936.0	3408.0	984.0	2424.0	504.0	1920.0	264.0	1656.	216.0	1440.	144.0	1296.	168.0	1128.	216.0	912.0	408.0	504.0	504.0
1984	8784	6192	5928.0	3096.0	2832.0	912.0	1920.0	696.0	1224.0	480.0	744.0	264.0	480.0	120.0	360.0	96.0	264.0	72.0	192.0	0.0	192.0	144.0	48.0	0.0	48.0	48.0
1987	8760	6192	1704.0	1224.0	480.0	72.0	408.0	192.0	216.0	120.0	96.0	24.0	72.0	0.0	72.0	24.0	48.0	0.0	48.0	24.0	24.0	0.0	24.0	0.0	24.0	24.0
1988	8784	6192	1224.0	744.0	480.0	144.0	336.0	96.0	240.0	96.0	144.0	72.0	72.0	24.0	48.0	24.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	24.0
1989	8760	6192	480.0	144.0	336.0	48.0	288.0	72.0	216.0	96.0	120.0	72.0	48.0	48.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1990	8760	6192	816.0	408.0	408.0	48.0	360.0	120.0	240.0	24.0	216.0	24.0	192.0	72.0	120.0	72.0	48.0	24.0	24.0	0.0	24.0	0.0	24.0	0.0	24.0	24.0
1991	8760	6192	768.0	240.0	528.0	72.0	456.0	120.0	336.0	120.0	216.0	72.0	144.0	48.0	96.0	48.0	48.0	0.0	48.0	24.0	24.0	24.0	0.0	0.0	0.0	0.0
1992	8784	6192	1920.0	696.0	1224.0	600.0	624.0	120.0	504.0	96.0	408.0	168.0	240.0	96.0	144.0	0.0	144.0	24.0	120.0	48.0	72.0	0.0	72.0	24.0	48.0	48.0
Totals:	**359424.0**	**253872.0**	**174168.0**		**61608.0**		**43448.0**		**29816.0**		**17496.**		**12240.**		**9024.**		**7008.**		**5592.**		**4584.**		**3600.**		**2424.**	
% total Time	**100.0**	**-**	**48.5**		**17.1**		**12.1**		**8.3**		**4.9**		**3.4**		**2.5**		**1.9**		**1.6**		**1.3**		**1.0**		**0.7**	
% Migration Season		**100.0**	**68.6**		**24.3**		**17.1**		**11.7**		**6.9**		**4.8**		**3.6**		**2.8**		**2.2**		**1.8**		**1.4**		**1.0**	

Migration season is from September 16 through May 31 of each year

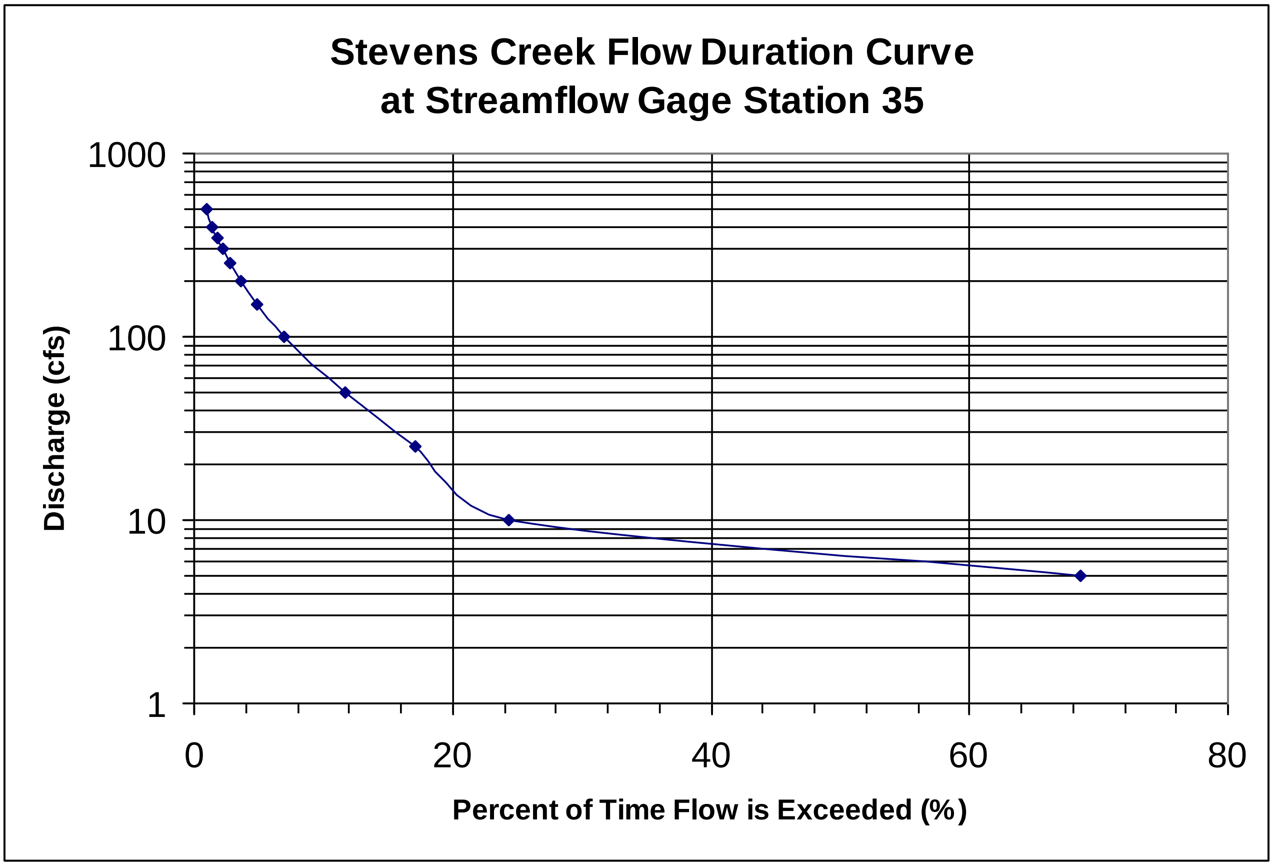


Figure 6-5. Flow Duration Curve for Stevens Creek at Gauge Station 35

After the flow data is analyzed, the design flows are determined according to the following table:

Table 6-2
High and Low Design Flows for Fish Passage

Species and Life Stage	Q_u		Q_l	
	% annual exceedance flow	Alternatively, % of 2-yr recurrence flow	% annual exceedance flow	Alternate minimum flow (cfs)
Adult anadromous salmonids	1%	50%	50%	3
Adult non-anadromous salmonids	5%	30%	90%	2
Juvenile salmonids	10%	10%	95%	1
Native non-salmonids	5%	30%	90%	1
Non-native species	10%	10%	90%	1

As can be seen, the high design flow, Q_u, for adult anadromous salmonids is a flow that's only exceeded 1% of the time in the flow record, or alternatively if flow-duration data are not available, 50% of the 2-year flow. The Q_l for juvenile salmonids is a flow that's exceeded 95% of the time, or 1 cfs, whichever is greater. Hence, depending on which target species there are, the design flows for fish passage are determined.

It should be noted here that the 1% exceedance flow of a flow duration analysis is not the same as a 1% flow from a flood frequency analysis. The latter is determined from statistical analysis of annual peak flow rates, consisting of one peak flow from any year in the record, and the former is determined from statistical analysis of all data points in the record.

6.4.2 Step Height

This parameter refers to the allowable drop height between pools in pool-type fish passage systems. This parameter is dependent on the target fish species and life stage. For example, for many fish species the allowable drop height is near zero, since they don't jump. For these fish, swim-through fish passage structures are the only good option. Salmonids are typically good jumpers, though this varies by species and life stage. Adults typically can pass 1-foot jump heights (with sufficient downstream and upstream pool depth), while juveniles require smaller drops. Since District fish passage structures are typically expected to pass adult and juvenile fish, the recommended design approach is to avoid drops, and when drops are not avoidable, limit the step height to 6 inches. This is consistent with requirements of the Department of Fish and Game [California 2002b] and National Marine Fisheries Services [NOAA 2001]

6.4.3 Water Depth

The typical requirement for pool depth for salmonids is 1¼ to 1½ times the step height. However, a minimum pool depth of 1.5 feet is required, even for a 6-inch step height. The calculation for pool depth should also consider sediment accumulation. If there is bed-load sediment, the pool should be designed to keep sediment sluicing through the system or away from fish passage.

There is also consideration for minimum water depth required by fish. California [2002b] provides the following requirements:

Table 6-3
Minimum Water Depth in Fish Passage

Species and Life Stage	Minimum Water Depth (ft)
Adult anadromous salmonids	1.0
Adult non-anadromous salmonids	0.67
Juvenile salmonids	0.5
Native non-salmonids	Require species-specific swimming performance data
Non-native species	

6.4.4 Energy Dissipation

It is important for fish passage structures to be able to fully dissipate energy in each step, so that there's no carryover effect. Otherwise, velocity and turbulence can build up downstream such that they become a barrier to passage at the lower end of the fish passage structure. For example, step pool systems need to fully dissipate the drop energy in each step *through the full range of the design flow*, otherwise the pool flow pattern changes from stepping regime to streaming regime and fish passage is impeded. The minimum pool volume required for this purpose is defined in Eq. (6-1) later.

For long stretches of artificial channel, such as culverts, the continuous flow momentum may become critical impedance for fish migration. Hence, California [2002b] specifies the following channel length and velocity requirements:

Table 6-4
Channel Length vs. Maximum Average Velocity for Adult Salmonids

Channel Length (ft)	Max Velocity for Adult Non-Anadromous Salmonids (fps)	Max Velocity for Adult Anadromous Salmonids (fps)
<60	4	6
60-100	4	5
100-200	3	4
200-300	2	3
>300	2	2

More discussions on high velocity limits will be provided in Section 6.6 later.

6.5 OPEN CHANNEL FISH PASSAGE IMPROVEMENTS

Fish passage improvements in open channels can be classified as using either natural or structural techniques. Natural techniques use in-creek structures such as bypass channels, rock or log weirs, or simply invert re-grading to enhance fish passage. These techniques should always be preferred as fish passage improvement methods over structural techniques, because by mimicking natural flow conditions, they are much more likely to be successful in meeting fish passage goals. They also tend to actually improve the creek habitat and be less maintenance-intensive than structural techniques.

For example, in the case of a too-high vertical drop, the creek invert may be:

- re-graded to a steeper but stable slope from downstream, such that the vertical drop is eliminated,
- stepped-up to upstream grade using rock or log weirs, or
- modified to add a steeper but stabilized low-flow channel to bypass the drop structure during design flow conditions.

If these techniques are needed, refer to Chapter 2 for details of designing a stable channel and Chapter 3 for designing rock and log weirs to control grade. It should be noted that the design criteria (such as maximum drop height per step and design flows) should be developed first from the considerations provided above. Figure 6-6 shows an example of using rock weirs to improve fish passage by replacing a vertical passage barrier.

Figure 6-6. Hillsdale Rock Weir Fish Passage Improvement

There are many types of structural fish passage improvements, also called “fish ladders,” in use. Many of these are not appropriate for Santa Clara County creeks, since they work best in relatively high base-flow conditions. The following techniques have worked reasonably well in SCVWD settings.

6.5.1 Pool and Weir Fishways

Pool and weir fishways have distinct pools in which the energy of the vertical drop of each step is fully dissipated. An example of this structure on Alamitos Creek is shown in Figure 6-7. The hydraulic controls between the pools are overflow weirs that are sized for the design high and low flows. The weir structures can also incorporate orifices to increase pool flow and provide a non-leap passage path.

Figure 6-7. Pool and Weir Fishway at Alamitos Drop Structure

Fish Behavior

Fish behavior and swimming performance affect the design of pool and weir fishways. Different species and fish in different life stages move through fishways in different ways. Young Chinook salmon tend to swim through orifices, while returning adults prefer weirs. Steelhead patterns are the reverse of this, with the younger fish preferring to leap over weirs and the adults preferring to swim upstream. Therefore, it is extremely important to properly assess the target fish species and life stage to determine proper design.

Head Differential

This criterion depends entirely on the design fish species and the stage of life. To cover juveniles as well as returning adults, the recommendation is to allow no more than 6 inches head differential between pool steps.

Flow Regime

The design high and low flows (Q_u and Q_l) are determined using the procedure described in Section 6.4.1. Pool hydraulics should stay in “plunging”, rather than “streaming” flow regime (see Figure 6-8 for illustration). Plunging regime allows the weir overflow to plunge down into the downstream pool, flow along the bottom of the pool until it meets with the downstream weir, and come up the face of the downstream weir to plunge into the downstream pool. If the water level in the pool is too high to drown the weir overflow, streaming flow regime will develop. By designing the weir length properly to control the pool water level under Q_u the streaming flow condition may be avoided.

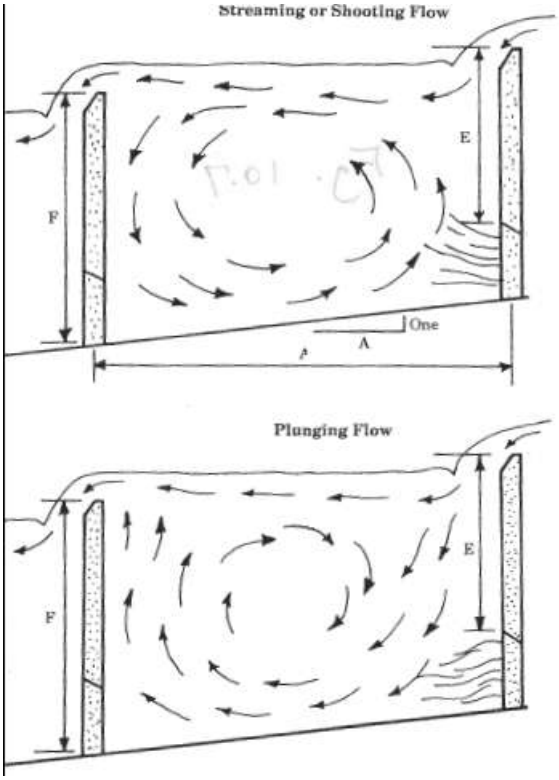


Figure 6-8. Plunging and Streaming Flow Regimes [USACE 1991]

Pool Volume and Depth

The pool volume must provide adequate energy dissipation and sufficient depth for fish movement. In Santa Clara County creeks, the energy dissipation requirement usually governs. Equation 6.1 is used to calculate the pool volume. It assumes a maximum energy dissipation of 4 foot-pounds of energy per second per cubic foot of volume.

$$\text{Volume} = (\gamma)(Q_u)(h) / 4 \qquad (6\text{-}1)$$

where: γ is the unit weight of water in pounds per ft^3 (approximately 62 at normal temperature)

Q_u is the upper design flow in cfs, and
h is the water depth above the weir in feet

For example, for a Q_u of 50 cfs and a 1 foot head over the weir, the pool volume required is:

$(62)(50)(1)/4 = \underline{775\ \text{ft}^3}$

It is not recommended that pool system steps be longer than 10 feet in the downstream flow direction. Past that point, the energy dissipation feature does not work efficiently. Thus, given the example above, for a 10-foot long by 10-foot wide pool, the required pool depth is approximately 8 feet.

Pool depth can be as little as 3 feet, though 5-7 feet are more common. Note that a portion of the pool depth should be set aside for sediment and debris accumulation, so that minimum pool volume is maintained between periodic maintenance cycles.

Weir Design

Studies on fish passage have shown that there is an optimum weir flow depth which promotes successful fish passage. The limits are a minimum of 6 inches of depth for the Q_l flow and a maximum of 1 foot depth for the Q_u flow. Fishway weirs must be designed so that they can accommodate both these requirements. This is typically done using a two-stage weir, with the low flow portion typically consisting of a v-notch in the middle, while the high flow is the weir spanning the entire pool. An example is shown in Figure 6-9.

Figure 6-9. Compound Weir Shape at Masson Dam on Guadalupe Creek

Eq. (6-2) and (6-3) are simplified equations used to calculate approximately the flow over sharp-crested weirs:

$$Q = 2.5\ H^{2.5} \text{ (for 90 degree triangular weir)} \qquad (6\text{-}2)$$

$$Q = 3.3\ b\ H^{3/2} \text{ (for rectangular weirs)} \qquad (6\text{-}3)$$

where b is the width (ft) of the weir and H is the head (ft) over the weir.

For example, calculate the effective flow range for a 10-foot wide weir with a 6-inch deep triangular notch in the middle:

@ 6-inches deep, the v-notch weir $Q = 2.5\ (.5^{2.5}) = 0.4$ cfs which is less than Q_l of 1 cfs, OK.

@ 1-foot deep over the entire weir (neglecting the notch), $Q = 3.3\ (10)\ (1^{3/2}) = 33$ cfs

Note that, because the actual flow differential between the pools is limited to 6 inches per the head differential requirement above, there is some submergence of the flow, which will reduce the overall high flowrate. Equation (6-4) is used for calculating submergence factor:

$$Q_{sub} = Q_{free}\,[1 - (H_{downstream} / H_{upstream})^{3/2}]^{.385} \qquad (6\text{-}4)$$

In the case of the example above, with $H_{downstream}$ being 6 inches and $H_{upstream}$ being 1 foot, the submerged flow is approximately 85% of the free flow. So, the effective flow range for the example weir is from a Q_l of 0.4 cfs to a Q_u of 28 cfs. If a higher Qu is desired, the weir width will need to be increased.

Fishway Bends and Layout

Long fishways are often set up such that they switch back on themselves, sometimes more than once, in order to save space. However, studies have shown significantly longer fish passage times through corner and bend pools, so these should be avoided, if possible. Bend details should be designed carefully to avoid upwelling in corners and other hydraulic irregularities that confuse fish from their intended passage direction.

The downstream outlet to a fishways needs to be very carefully designed to ensure maximum success. The fishway will simply not be effective if fish cannot find it. Fish are attracted to splash noise and strong current; and if there is a source of these away from the fishway entrance, fish will be distracted from the proper path. The key is to:

1. Attempt to raise the Q_u as high as possible in order to extend the period where the only flow from upstream in coming through the fishway, and thus there is no other current to distract the fish.

2. If there is a competing source of flow, make sure the outlet is in close proximity to the competition.

3. If considered necessary by fishery experts, there are artificial ways to attract fish to the fishway, such as attractant jets and currents.

4. Protect the outlet from predators, whether human or animal.

The upstream inlet of the fishway needs to be designed to be as self-maintaining as possible. The inlet needs to be protected from floating debris with a floating barrier and/or trash rack. Placing the inlet along the natural scouring side of the upstream channel (outside of a bend) will help prevent sediment accumulation.

Freeboard

There should be a minimum of three feet of freeboard between the Q_u flow elevation and the top of the structure. Fish can jump completely out of the pool system if this practice is not followed.

This often happens when fish try to jump up a weir at an angle and jump entirely out of the pool. Besides freeboard, other ways to minimize this problem are to place the dominant spill weir in the middle of the pools and to eliminate corner upwelling, which can confuse fish into jumping at the wrong location.

Orifices

Orifices can be used to increase the effective flow range of fishways and to provide a swimming (as opposed to jumping) flow path for the species that need it. A minimum size of 12 inches wide by 15 inches high can be used, though smaller orifices are more prone to debris blockage. The location of the orifice should be directly under the low-flow portion of the weir, so that the orifice flow contributes to the desired stepping flow pattern (see Figure 6.7). Orifices pass flows downstream efficiently. During low flow periods, they can pass all the flow and drain the fishway down to the orifice level. Therefore, for Santa Clara valley creeks, orifices should not be placed flush at the bottom of the fishway, so that even during low flows some pool volume is maintained. The recommendation is to design the bottom of the orifice opening to be no less than 3 feet from the bottom of the fishway. Also, to accommodate a design fish species or lifecycle stage that prefers a jumping flow path over a swimming path, the orifices should be designed so that they can be closed off during low flows.

Eq. (6-5) is used to calculate flow through orifices that are submerged on both sides (same as a fully submerged culvert):

$$Q = (C_d)\ (A)\ (2gh)^{1/2} \tag{6-5}$$

where C_d is the orifice coefficient (varies from 0.6 to near 1 depending on smoothness, and h is the difference in elevation between the upstream and downstream pools

Flexibility in Design

It is important to provide as flexible a fishway as possible. This is because it is impossible to foresee future changes in thinking in terms of fish species the fishway must accommodate, head differential, depth, and slope criteria, etc. One good method for maintaining flexibility is to design the weirs using frames and members that can be custom-fitted to changing circumstances. For example, the Alamitos fish ladder on Guadalupe River was designed using steel frames fitted with wooden flashboards to create the weirs as shown in Figure 6-7. The flashboards can be added to, removed, and their shapes can be changed as needed. Even the locations of the weirs are not set, as the steel frames simply slide into grooves cut in the concrete (at every 2.5 feet). Though the initial fishway was set up with weirs at every 10 feet, creating a 1 foot per pool head differential, it would be very easy to add weirs in between to decrease the head differential or to remove weirs in order to increase the head. Finally, maintenance is easy, since the entire weir frames can be removed for better access to the fishway invert.

6.5.2 Vertical Slot Fishways

A vertical slot fishway also has distinct steps between each pool area. In this case, however, the hydraulic control is provided by a narrow, full height vertical slot open at the top, as shown in Figure 6-10. The greatest advantage of these fishways is that they are entirely self-regulating, they operate over a wider range of flows than step pool fishways, are relatively low maintenance, and they do not require jumping. The disadvantages are that they do not operate as well as pool systems at very low flowrates.

Figure 6-10. Vertical Slot Fishway [From FAO Fisheries Department]

The vertical slot fishway operates without mechanical adjustment through a range of upstream and downstream water surface elevations. Any changes in the water surface upstream of downstream simply results in a corresponding lowering or rising of the water surface through the entire fishway. Energy is dissipated in each pool by the turbulence created by the specially designed baffles. As flowrate increases, depth increases, creating additional pool volume and maintaining energy dissipation.

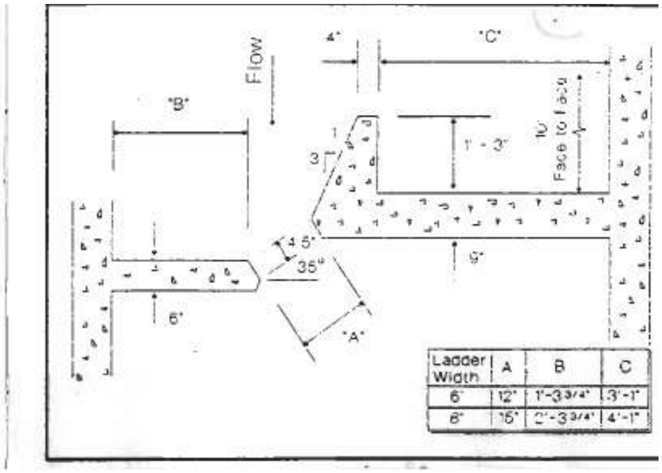
Flow

Flow through a vertical slot fishway is a function of the slot width, water depth in the slot, and head differential (see Figure 6-11) as per Equation 6.6:

$$Q = C\, w\, D\, (2gh)^{1/2} \tag{6-6}$$

where C is an orifice coefficient, usually taken as 0.75, and
w is the slot width (ft)
D is water depth upstream of the slot (ft)

g is the gravitational constant (ft/sec^2)
and h is the head differential between pools (ft)



Ladder Width	A	B	C
6"	12"	1'-3 3/4"	3'-1"
8"	15"	2'-3 3/4"	4'-1"

Figure 6-11. Typical Vertical Slot Fishway Layout [Bates 1997]

The drop between pools does sometimes vary slightly, based on response to downstream and upstream elevation changes. A corresponding change in the water depth compensates.

Dimensions

The dimensions of the slot are critical to the correct functioning of the fishway. The dimensions provided in Figure 6.11 should be used, unless a physical model is produced to verify other dimension designs or the new design based on a published field tested operational fishway. Sills across the bottom of the slots tend to stabilize the flow. They also prevent the situation where the entire fishway is drained during very low flows. However, the sill depth is not available for flow, so the D factor in Eq. (6-6) should be reduced appropriately. Normal slot widths are 12 and 15 inches; but smaller sizes (down to 6 inches) can be used for smaller fish or for lower flow situations.

Other Issues

Freeboard is not as much of an issue here, since jumping between pools is not the transport mode. However, a two foot freeboard should still be provided. Fish passage upstream and down occurs throughout the full vertical slot depth. Tests have confirmed that velocity over the slot depth is near constant. This fishway design is not appropriate for species or life stages that prefer leaping transport over swimming.

6.5.3 Denil Fishways

Denil fishways are used extensively around the world. They consist of a series of baffles built into a relatively narrow channel which create a turbulent flow pattern that allows upstream and downstream fish passage (see Figure 6-12). They are certainly not the most successful fishway design; however, ease of installation and low cost make them a practical choice for a temporary fishway until more permanent measures can be implemented. They operate over a rather limited flow range and can be readily impacted by sediment and debris. Blockage by woody debris is a very common problem; therefore, maintenance access during winter flow situations is crucial. It is not recommended to use Denil fishways as a permanent fish passage improvement.

Figure 6-12. Denil Fishway in Operation
(From Massachusetts Dept. of Marine Fisheries)

Dimensions and Design

The normal slope is one on six (or 17%), though steeper slopes can be used. The most commonly used size is the 4-foot width. A range of design flows is possible, depending on size, slope, and water depth as provided in Eq. (6-7):

$$Q = 5.73\ D^2\ (bS)^2 \qquad (6\text{-}7)$$

Where: D is flow depth above the V baffle (ft)
b is the open width of the fishway between the baffles (ft)
and S is the fishway slope

Denil fishways can be built of plywood, steel, or concrete with steel baffles.

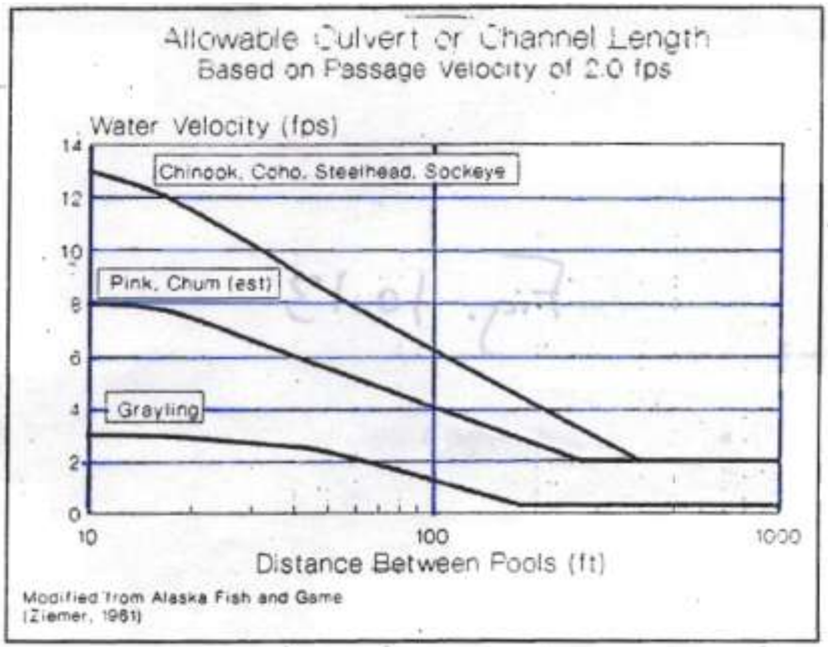
6.6 FISH PASSAGE IMPROVEMENTS FOR CULVERTS

Culverts are the second major class of fish passage improvements. There are various situations at culverts that create migration barriers for fish. These include:

- Excessive velocity
- Shallow flow depth at low flows
- Excess drop at outlet

Excessive Velocity

Maximum velocities in culverts (in the Q_u to Q_l flow range) should not exceed the design species' prolonged swimming speed. A good standard relating culvert length to allowable velocity is provided in Figure 6-13. As can be seen, shorter culverts can be designed with relatively liberal velocities; but as the culverts reach length of 100 feet or more, the allowable velocity drops to very low numbers.



Modified from Alaska Fish and Game (Ziemer, 1961)

Figure 6-13. Allowable Velocity Vs. Culvert Length [Bates, 1997]

Shallow Depth

Shallow depth through flat-bottom culverts is another migration barrier. The normal requirement is for a minimum depth of six inches at the Q_l flow. This can be accomplished by designing a fish passage low flow channel into the culvert invert; however, these channels tend to require significant maintenance for sediment. A better method for providing adequate depth through a culvert is the placement of a weir at the downstream end to back flood the culvert.

Excessive Outlet Drop

This is a condition that tends to occur over time, as high exit velocities from the culvert create erosion just downstream. The appropriate response is to fill in the eroded area and protect with erosion resistant lining, if necessary. See Chapter 3 of this manual for invert degradation protection techniques.

Burying Culverts

For new or re-designed culverts, the best way to provide fish passage is by either not lining the culvert invert (in other words, building a bridge rather than a culvert) or by burying the culvert by placing 1–2 feet of creek invert materials on the culvert bottom. The creek sediments allow the formation of a natural low flow channel, similar to normal creek bottom.

Culvert Baffles

Several different types of culvert invert baffle systems have been tried. Typically, these are installed in existing culverts. They are generally discouraged in new culverts. As these measures are very prone to sediment and vegetation debris blockage, they are not recommended.

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