Design Report for a Fish Passage Improvement Project, San Anselmo Creek at Lansdale Avenue, San Anselmo, California

April, 2009

Prepared for:
Friends of Corte Madera Creek Watershed
PO Box 415
Larkspur, CA 94977

Through Funding from:
National Fish and Wildlife Foundation
Salmonid Habitat Restoration Fund
and
California Coastal Conservancy

Prepared by:

Michael Love & Associates
Hydrologic Solutions

PO Box 4477 • Arcata, CA 95518 • (707) 476-8938

DESIGN REPORT FOR A FISH PASSAGE IMPROVEMENT PROJECT, SAN ANSELMO CREEK AT LANSDALE AVENUE, SAN ANSELMO, CALIFORNIA

Prepared for:

Friends of Corte Madera Creek Watershed
PO Box 415
Larkspur, CA 94977

Through Funding From:

National Fish and Wildlife Foundation
California Coastal Conservancy

Prepared by:

Michael Love, P.E.
License No. C 71681, Exp. 12/31/2009

Michael Love & Assocaites
P.O. Box 4477
Arcata, CA 95518
(707) 476-8938

APRIL 2009

TABLE OF CONTENTS

Page

TABLES

FIGURES

APPENDIX

Project Description

San Anselmo Creek is the main tributary to Corte Madera Creek, which drains into San Francisco Bay in Marin County, California. San Anselmo Creek supports a population of anadromous steelhead trout, which are listed as threatened under the Federal Endangered Species Act. This project involves developing a concept design for improving upstream steelhead passage at the Lansdale Avenue culvert on San Anselmo Creek within the Town of San Anselmo.

Existing Site Conditions

Lansdale Avenue crosses San Anselmo Creek at the intersection with Center Boulevard and San Anselmo Avenue. The stream crossing consists of two different culvert shapes and makes a roughly 45 degree turn. The total length of the culvert crossing is nearly 320 feet. The upstream portion is a concrete double bay box culvert that has an overall width of 30.5 ft. The boxes are confluent with a 136 ft long single radius concrete arch with a span of 32 ft. At the outlet of the arch is a 33 ft long concrete apron. At the end of the apron is an approximately 3 ft drop to the downstream channel, which is lined with concrete rubble to protect the channel bed and banks from scour. The dimensions and slopes of the culvert and apron segments are provided in Table 1.

The channel is highly incised and characterized by steep banks that are heavily armored with riprap, concrete rubble, and retaining walls. Structures have encroached into the channel downstream of the crossing and construction access to the site is limited.

Table 1 – Dimensions of the different sections that comprise the Lansdale Avenue stream crossing. Due to the complexity of the crossing, it was divided into three sections: the double box upstream, arch mid-section and outlet apron.

Lansdale Avenue Existing Culvert Dimensions				
	Box Culvert		Arch	
Dimensions	Left Bay	Right Bay	Culvert	Outlet Apron
Height (ft)	10	10	16	n/a
Width (ft)	15.5	15.0	32	33
Length (ft)	154	145	136.2	32.6
Bottom Slope (ft/ft)	0.0046	0.0055	0.0067	0.0055

Existing Fish Passage Conditions

San Anselmo Creek, upstream and downstream of Lansdale Avenue maintains perennial flow and supports resident rainbow trout year-round. This reach of the creek provides spawning and rearing habitat for resident rainbow trout and anadromous steelhead. However, conditions at the Lansdale Avenue culvert makes it extremely difficult for the fish to move upstream.

Fish passage conditions at the culvert were assessed in 2006 as part of the Corte Madera Creek fish passage assessment conducted by Ross Taylor and Associates for the Friends of Corte Madera Creek Watershed (Taylor, 2006). The report refers to this crossing as #SA-03 and identified insufficient water depth and the 3 foot drop at the outlet as the limiting factors hindering upstream passage for adult steelhead, resident rainbow trout, and juvenile salmonids (Figure 1).

Figure 1 - Outlet of the Lansdale Avenue Crossing on San Anselmo Creek (2006). The outlet is a concrete single radius arch approximately 15-ft high and 30-ft wide with a 36 foot long concrete apron perched approximately 3 feet above the downstream channel.

Summary of Design Work to Date

In 2007 Michael Love & Associates (MLA) and Winzler & Kelly Consulting Engineers (W&K) were hired by the Center for Ecosystem Management and Restoration (CEMAR) to prepare a concept design for fish passage improvement for the Lansdale Avenue crossing. In 2008 Michael Love & Associates and Stetson Engineers Inc. were hired by the Friends of Corte Madera Creek

Watershed to develop the concept design to final construction drawings. Following recommendations presented in the previous stages of the project, Stetson Engineers subcontracted with Miller Pacific Engineering Group to conduct a geotechnical investigation of the downstream portion of the project site. Their findings and recommendations were documented in the geotechnical investigation report dated November 26, 2008 (Miller Pacific, 2008).

This report updates the conceptual design report previously completed by MLA and W&K.

Summary of Concept Design

The final fish passage design involves retrofitting the existing culvert with center-aligned angled baffles and constructing a pool-and-chute fishway at the outlet that would replace a portion of the outlet apron and extend several feet into the downstream channel. The engineering decisions, design details, and predicted hydraulic performance of the proposed fish passage retrofit are described in detail within this report. Refer to the attached drawings of the proposed modifications for additional detail.

Alternatives Considered

Prior to the selection of the proposed concept design, the design team investigated a series of alternatives. The crossing is in good structural condition and crosses under multiple lanes of traffic. Complete replacement of the 320 foot long culvert was considered cost prohibitive and generally infeasible.

Because of the nature of the barrier and length of the crossing, the retrofit alternatives investigation considered fish passage in two stages: (1) correcting the outlet drop and (2) increasing water depths through the culvert.

Outlet Drop

Providing access to the culvert requires addressing the 3 ft drop onto concrete rubble at the outlet of the concrete apron. Providing passage requires minimizing the water surface drop to a level that meets fish passage design criteria. This can be accomplished by raising the downstream channel bed gradually using a roughened channel or rock weirs, or over a shorter distance using a constructed concrete fishway.

Roughened Channel and Rock Weirs

Roughened channels are constructed by placing a large mass of rock that is sized to be immobile up to the design flow. This creates a channel that is steeper than the existing bed but provides fish passage by creating a wide variation in flow patterns. An alternative approach is to use a series of rock weirs constructed of large boulders. The maximum acceptable slope range for both a roughened channel and rock weirs is typically 4 to 5%. At a slope of 5%, the project would extend a minimum of 85 feet downstream of the culvert outlet apron. This would place a substantial portion of the roughened channel or rock weirs into an area which has an apartment building located along the right bank. The building foundation is within the active channel and the second floor is cantilevered over the channel. The foundation for the apartment building would make it extremely difficult to key in rock weirs, and the cantilevered second story would make it difficult to use heavy equipment around the building. Additionally, raising the channel bed in this area would potentially increase floodwater levels, which may impact flooding of the building.

Construction of a roughened channel or rock weirs would require a considerable amount of rock material. Based on stable rock sizing calculations, constructing a channel that remains stable at the design flow of 3,862 cfs and a slope of 5% requires using up to 3 ton rock. Because of the limited site access for heavy equipment and staging areas, the delivery and placement of the material would greatly increase the project costs and construction time.

Concrete Fishway

An alternative to constructing a roughened channel or rock weirs is a concrete fishway. Various types of fishways were looked at and a pool-and-chute fishway was selected as the best option for the site. This type of fishway can be operated at slopes up to 12.5%, greatly reducing the length of channel impacted by the project.

A pool-and-chute fishway is a hybrid type of fishway that operates simultaneously in two flow regimes, plunging and streaming. It can be categorized as a pool-and-weir at low flows (plunging flow only), and at higher flows as a combination of a chute (streaming flow) in the center portion of the ladder and weir (plunging flow) along the sides. By creating streaming flow in the center portion with plunging along the margins, the pool-and-chute fishway can provide fish passage through a much larger range of flows than a traditional pool-and-weir fishway. The increased operational range make it well suited for the site, which has very high fish passage design flows.

<u>Fish Passage through the Culvert</u>

Providing fish passage through a concrete structure, such as the Lansdale Ave crossing, usually requires increasing the depth of flow and reducing the water velocity. Because the crossing drops 1.5 feet from inlet to outlet apron, backwatering the entire culvert to the inlet was considered infeasible. An alternative approach to increasing depths in the culvert is to use baffles.

Baffles

Baffles can be cost effective method to improve fish passage in box culverts. They are designed to increase water depths and decrease water velocities. At low flows they function as weirs, with flow plunging over the baffle and into the pool between baffles. At higher flows the baffles create uniform hydraulic roughness. At the lower flows they can provide suitable passage conditions for both adult and juvenile salmonids and other fish within the stream. However, at moderate flows the turbulence can become excessive for juvenile salmonids. In some cases the turbulence can become extreme at higher flows, blocking passage of adult steelhead.

By design, baffles are obstructions to flow. This can lead to sedimentation between baffles and baffles clogging with debris. In some situations they can also reduce the culvert's hydraulic capacity. Therefore, the objective in the hydraulic design of baffles is to optimize between the competing objectives of increasing water depths and decreasing velocities at fish passage flows while promoting passage of water, sediment, and debris during flood flows.

Angled baffles are the preferred baffle type for low-sloping box culverts, such as at Lansdale Ave. (WDFW, 2003). They are simple to construct, provide adult and juvenile passage, and less prone to debris plugging than traditional offset (Washington) baffles. The angled type baffles were selected as the best approach for addressing fish passage conditions within the culvert. Although angled baffles have proven to be less susceptible to debris clogging than other baffle types, there is the risk of catching debris during large flow events. Therefore, inspection and occasional maintenance should be anticipated by the road department.

Hydrology

San Anselmo Creek at Lansdale Avenue has a drainage area of approximately 9.3 mi^2 and mean annual rainfall of roughly 40 inches/year. The channel maintains perennial flow, although during summer and early fall flows becomes very low. During a large flood event on December 31, 2005 the flow was fully contained within the channel at this location. The peak flow during this flood event is estimated to have roughly a 100-year return period (Stetson Engineers, 2007).

Peak Design Flow

The estimated peak flow having a 100-year return period was estimated by Stetson Engineers for San Anselmo Creek at Lansdale Avenue to be 3,862 cfs (Stetson Engineers, 2007). **For this project, 3,862 cfs was used to evaluate the proposed project's impact on upstream water levels.**

Fish Passage Design Flows

The low and high fish passage design flows define the flow range in which conditions at the crossing should be suitable for upstream passage for a specific species and life stage. Both NOAA Fisheries (2001) and California Department of Fish and Game (CDFG, 2002) have recommended fish passage design flow criteria for juvenile salmonids, resident rainbow trout, and adult steelhead. These are defined in terms of exceedance flows (Table 3), which are derived from an annual flow duration curve based on mean daily flows. Because flow in San Anselmo Creek at Lansdale Avenue is not gaged, exceedance flows from two nearby US Geological Service (USGS) stream gaging stations were utilized (Table 2):

Table 2 – US Geological Service (USGS) stream gaging stations utilized to develop site hydrology.

USGS Station No.:	11460100	11460000
Station Name:	Arroyo Corte Madera D Pres A Mill Valley	Corte Madera C A Ross
Drainage Area:	4.68 mi^2	18.1 mi^2
Years in Operation:	1965 -1986	1951 - 1993

The two gaged streams have very similar flow characteristics and their drainage areas bracket the 9.3 mi^2 drainage area of San Anselmo Creek at Lansdale Avenue. To develop a flow duration curve for the project site, exceedance flows for the two streams were scaled to the drainage area at Lansdale Avenue and then averaged (Figure 2). From the flow duration curve, fish passage design flows for San Anselmo Creek at Lansdale Ave. were obtained (Table 3).

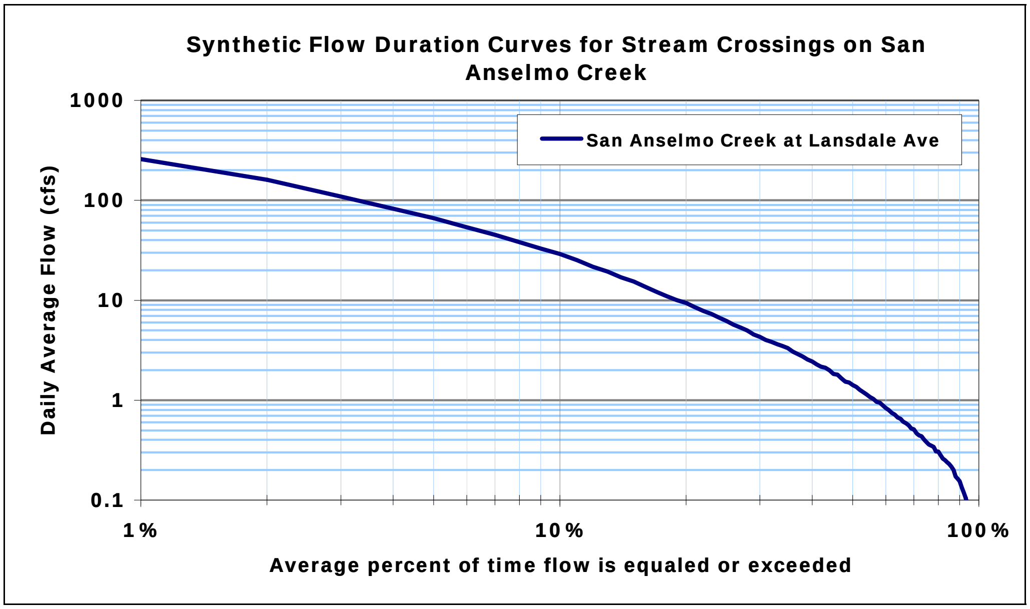

Figure 2 – Annual flow duration curve for Lansdale Avenue project site based on exceedance flows from two nearby gaged streams, scaled to drainage area of the project site.

Table 3 – Estimated fish passage design flows for San Anselmo Creek at Lansdale Ave., based on CDFG (2002) and NOAA Fisheries (2001) criteria. Exceedance flows calculated using flow duration curves from nearby stream gages, scaled by drainage area.

	Low Passage Design Flow		High Passage Design Flow	
Species & Lifestage	**Criteria**	**Flow**	**Criteria**	**Flow**
Juvenile Salmonids	Greater of 95% Exceedance Flow or 1 cfs	**1 cfs**	10% Exceedance Flow	**29 cfs**
Adult Rainbow Trout	Greater of 90% Exceedance Flow or 2 cfs	**2 cfs**	5% Exceedance Flow	**67 cfs**
Adult Steelhead	Greater of 50% Exceedance Flow or 3 cfs	**3 cfs**	1% Exceedance Flow	**260 cfs**

Fish Passage Design Criteria

Fish passage criteria used in designing the retrofit of the Lansdale Avenue culvert followed the CDFG and NOAA Fisheries guidelines, which establishes the desired minimum water depth, maximum water velocity, and maximum water surface drop. The design criteria are summarized in Table 4. The velocity criterion for adult resident and anadromous salmonids are dependent on the length of the culvert.

The CDFG and NOAA Fisheries fish passage design guidelines acknowledge that the hydraulic design criteria can be difficult to achieve when retrofitting an existing culvert, and should be viewed as a goal rather than a required design threshold.

Table 4 – CDFG and NOAA Fisheries fish passage criteria for culverts longer than 300 ft, used in the design of baffles for the Lansdale Avenue crossing.

Fish Passage Criteria	Juvenile Salmonids	Adult Resident Rainbow Trout	Adult Steelhead
Minimum Water Depth	0.5 ft	0.67 ft	1.0 ft
Maximum Water Velocity	1.0 ft/s	2.0 ft/s	2.0 ft/s
Maximum Water Surface Drop	0.5 ft	1.0 ft	1.0 ft

Turbulence

An additional consideration sometimes applied to baffles and fish ladders is turbulence, which can also create a fish passage barrier. One measure of turbulence is the energy dissipation factor (EDF), which is the rate which energy is dissipated within a volume of water. For baffles, Washington Department of Fish and Wildlife (WDFW) recommend EDF values for baffles not to exceed 5 ft-lb/s/ft^3 at the high passage design flow for adult steelhead (WDFW, 2003). For pool-and-weir and pool-and-chute fishways, Bates (2001) recommends a maximum EDF of 4 ft-lbs/s/ft^3 for adult salmon and steelhead and 3 ft-lbs/s/ft^3 for adult resident rainbow trout. There is no current guidance for EDF thresholds for juvenile salmonids or other similar sized fish.

Fish Attraction

Providing suitable attraction conditions for fish to find the entrance of the fishway is a key design parameter. For this project, fishway attraction depends on the percentage of the total streamflow that is contained within the pool-and-chute fishway, and the potential for distraction or confusion generated from flow exiting the unbaffled portion of the culvert. Attraction is important throughout the entire fish passage design flow range.

In larger rivers, fishways have proven to provide suitable attraction with less than 10% of the total streamflow contained within the fishway. However, the larger the proportion, the more likelihood the fish will find the fishway entrance with minimal delay. Given the rapid rate that streamflow declines following storm events in this region, it is important to avoid delaying upstream migrating steelhead. Therefore, for this conceptual design we conservatively used an attraction flow minimum criteria of 20% of the total flow.

Proposed Baffle Retrofit of Existing Culvert

Overview of Baffle Design Development

Angled baffles are the preferred baffle type for low-sloping box culverts, such as at Lansdale Ave. (WDFW, 2003). Standard angle baffles are skewed in plan-view and tapered along the crest, with the low-side of the baffle placed along one wall and the high-side along the other. Their configuration is designed to concentrate flow towards one side of the culvert and create slower water along the other side.

Due to the concave shape of the floor within the Lansdale Ave. box culverts, using the standard angle baffle would require a higher than typical profile to provide the needed minimum depth. To keep the height of the baffle to a minimum, a center-aligned angled baffle shape is recommended (Figure 3). This baffle shape conforms to the floor of the existing box culvert and will provide a smooth hydraulic transition into the fishway.

The baffles would be placed along the right bay of the box culvert (as looking downstream) and continue through the right side of the arch culvert section. The right bay provides the best alignment with the thalweg of the upstream channel.

A bypass weir, or sill, would be placed inside the left bay to concentrate lower flows into the baffled bay. The top of the sill would be positioned to split the streamflow between the baffled and unbaffled culverts with the objective of maximizing the range of flows that fish passage can be provided while maintaining sufficient attraction flow in the fishway. A sidewall would be constructed down the center of the arch culvert to contain the water within the baffled section at fish passage flows.

To avoid a reduction in hydraulic capacity of the culvert, the baffle size and placement is designed to maintain inlet control conditions during high flows and avoid causing an increase in the headwater depth at the 100-year peak flow. This is achieved by minimizing the profile of the baffle and avoiding placement of first baffle too close to the inlet.

Hydraulic Modeling Approach for Baffles

Baffles are designed to function as weirs at very low flows, with water plunging over each individual baffle. As flow increases, it transitions from *plunging* weir flow to *streaming* flow, and the baffles function as large roughness elements.

Low fish passage conditions

At low fish passage flows the baffles act as weirs. The hydraulics of low flow conditions were predicted using standard sharp crested V-notch weir equations. The shape and skew of the angled weir is accounted for by using the overall length of the weir crest in plan view.

Using equations developed by Ead (2004) the predicted transition from plunging to streaming flow in the baffled section of the culvert is calculated, which provides an estimate of when weir equations no longer were applicable.

Flows over the bypass sill in the other culvert were predicted using a rectangular weir equation at low flows.

High Fish Passage Conditions

At higher flows, baffles act as large-scale roughness elements and the resulting water depths and velocities can be estimated using the appropriate Manning's roughness coefficient. Flume studies of the hydraulics in box culverts with angled baffles were recently conducted by the Humboldt State University Engineering Department (Lang, 2008). Experiments were conducted on a variety of angled baffle arrangements and culvert slopes at flows representing fish passage flows up to culvert capacity flows. Results from these tests were used to provide estimates of Manning's roughness for the proposed baffles in the Lansdale Avenue culvert. Estimates of roughness are flow dependent and were used to evaluate the performance of the proposed baffles at fish passage flows. They were also used as a check when calculating capacity flows using published results from an earlier flume study by Shoemaker (1956).

At high fish passage flows the hydraulics of the sill in the left bay were calculated assuming critical depth over the sill. The resulting headwater depth was then estimated using a backwater calculation from the sill to the inlet. At fish passage flows the inlet headloss was considered negligible in both bays given the relatively low water velocities and width of the culverts.

Peak Flow Conditions

Headwater depths for each culvert were calculated for inlet control and outlet control conditions using procedures outlined in HDS-5 (FHWA, 1985). The control that resulted in the highest headwater was conservatively selected as the correct headwater.

To predict the effect of the baffles on culvert capacity, backwater calculations in the baffled box culvert were modeled with an increased hydraulic roughness. Roughness of the baffles was estimated using data and procedures described in a study of baffles in box culverts at full flow (Shoemaker, 1956). As a check, the Manning's roughness estimated by Shoemaker was compared to those from the Humboldt State University study.

At capacity flows the water depth inside the left bay inlet was calculated assuming critical depth over the sill and using a backwater calculation from the sill to the inlet.

Design and Analysis of Baffles

The design objective for the baffles was to identify the shape and spacing that best satisfies fish passage criteria listed in Table 4 while maintaining inlet controlled culvert hydraulics at the 100-year peak flow. This required an iterative process of modeling different baffle configurations at fish passage flows and then checking culvert capacity at the 100-year peak flow to see if the baffles increased the headwater depth. The following describes the resulting preferred baffle design.

Preferred Baffle Shape, Spacing and Dimensions

Several baffle shapes, dimensions and spacing were considered for meeting the required fish passage conditions. Based on physical modeling of standard angled baffles, the center angle in plan view is set at 120^{o} (60^{o} as measured from the wall), which results in an overall baffle length of 17.4 feet (Figure 3).

The baffle shape, height, and spacing combined with the culvert slope determine the minimum water depth between baffles at the low fish passage design flows. The criteria requires providing 1 foot of depth at the adult steelhead low passage flow of 3 cfs and at least 0.5 foot of depth at the juvenile low passage flow of 1 cfs. To meet these criteria the baffle spacing is 20 feet and the baffle crest height is a minimum of 0.6 feet at the center, rising to 1.2 feet at the walls (Figure 4). From crest to crest, the baffles maintain a constant slope of 0.005 ft/ft. However, since the slope of the culvert floor varies throughout, the height of each baffle from the floor varies to maintain the constant baffle slope.

The first baffle crest is placed 20 feet downstream of the inlet and the last baffle crest is placed 22 feet upstream of the pool-and-chute fishway exit. The flow transition equation from Ead (2004) predicts that the flow regime is fully streaming within the baffles at flows above 10.5 cfs.

Bypass Sill

The bypass sill is a horizontal curb designed to concentrate low flows into the baffled culvert and split higher flows between the baffled and unbaffled culverts. The cutoff sill in the unbaffled left bay is positioned 20 feet downstream of the inlet. To concentrate all of the flow into the baffled right bay of the culvert at flows up to the adult steelhead low passage design flow of 3 cfs, the bypass sill height is set 0.5 feet higher than the crest elevation of the first baffle. This provides a reasonable proportioning of flow between the baffled and unbaffled culverts at higher fish passage flows.

Baffle Sidewall

The baffles continue uninterrupted at the transition from the box culvert to arch culvert. To avoid a change in the baffle hydraulics, the slope, width, and dimensions of the baffles in the arch culvert are the same as in the box culvert. To maintain the same width as the box culvert, a sidewall is located 15 feet out from the right wall of the arch. The top of the sidewall is 2.6 feet above the crest of the baffles. This height is sufficient to contain 175 cfs within the baffled section, which corresponds to a total streamflow of 460 cfs (combined flow in left and right bays). Containing this amount of flow with the sidewall should provide adequate stream power to scour sediment between baffles and within the fishway, allowing them to function as designed.

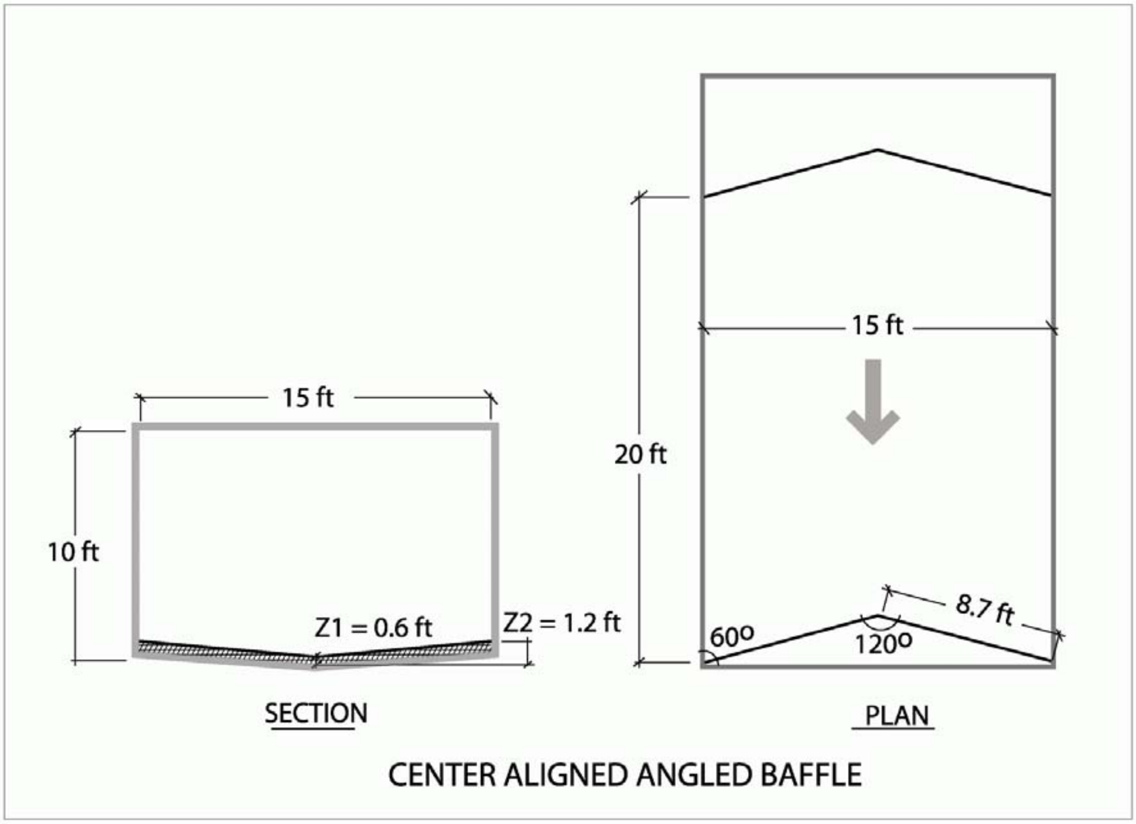

Figure 3 – Illustration of center-aligned angled baffles in the existing box culvert. The V-shape concentrates flow and debris down the center while providing slower water along the sides. The dimensions Z1 and Z2 are minimum baffle heights.

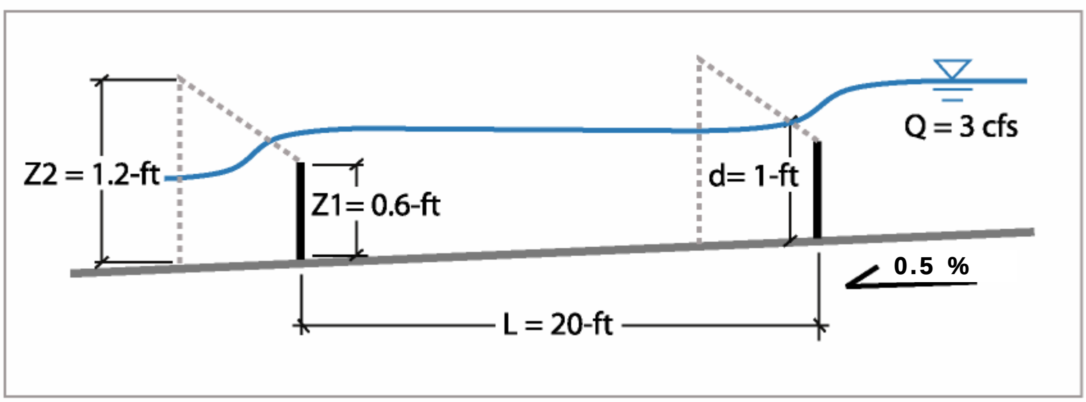

Figure 4 – Profile of baffle spacing and heights, which are design to provide a minimum water depth (d) of 1 foot at the adult steelhead low passage design flow of 3 cfs.

Fish Passage Performance of Baffles

The angle baffles improve fish passage throughout a wide range of flows. It provides the needed water depths at low flows while preventing excessive velocities and turbulence at higher flows (Table 5). Hydraulic conditions within the baffled section of the culvert are well within the requirements and recommendations for depth and turbulence (EDF) at all fish passage flows.

Velocity is adequate at all flows except the adult steelhead high passage design flow (260 cfs), which is 2.6 ft/s instead of the recommended 2.0 ft/s for culverts of this length. Velocity in the baffled section is 2.0 ft/s at a streamflow of 180 cfs, which is slightly higher than the 2% exceedance flow. This represents a significant improvement to existing conditions.

Table 5 – Hydraulic conditions predicted at fish passage flows for the proposed baffle arrangement for the Lansdale Avenue culvert.

	Baffled Section of Culvert			
Species/Lifestage	% of Total Flow in Baffles	Min Depth (ft)	Average Velocity (ft/s)	EDF (ft-lb/s/ft3)
Adult Steelhead				
Lower Passage Flow (3 cfs)	100%	1.0	0.2	0.08
Upper Passage Flow (260 cfs)	39%	2.5	2.6	0.90
Adult Resident Trout				
Lower Passage Flow (2 cfs)	100%	0.9	0.1	0.05
Upper Passage Flow (67 cfs)	32%	1.8	0.9	0.30
Juvenile Salmonids				
Lower Passage Flow (1 cfs)	100%	0.8	0.1	0.03
Upper Passage Flow (29 cfs)	36%	1.4	0.5	0.50

Proposed Pool-and-Chute Fishway

To reduce the drop at the outlet of the concrete apron, we propose building a concrete pool-and-chute fishway consisting of 6 pools with a 0.75 foot water surface drop over each weir. A pool-and-chute fishway is preferred because it provides passage over the largest range of flows and has the shortest overall length.

Project Alignment

During the preliminary design phase of the project an alignment for the fishway and baffles was examined for each bay of the culvert. Citing the steepness and potential instability of the right bank of the channel downstream of the outlet apron, the geotechnical report for the project recommended placing the fishway along the left bank. Alignment along the left bay was examined in detail but ultimately considered undesirable due to the resulting alignment of the fishway entrance with the downstream channel and the tight turn at the bend inside the culvert.

Pool-and-chute fishways produce a high velocity jet that must be dissipated in the receiving pool to prevent scour of the downstream channel bed and banks. The channel immediately downstream of the outlet apron bends slightly to the right (south). Placing the fishway on the left side of the channel would direct the flow jet towards the left bank, making undesirable hydraulic conditions for both fish passage and channel bank stability. Aligning the fishway to point the entrance towards the center of the channel would improve the alignment but reduce the channel width between the fishway and right bank. Because much of the high flow will be carried in the unbaffled side of the culvert, reducing flow conveyance in the downstream channel is undesirable. Additionally, realigning the fishway entrance would create a poor transition between the fishway and the baffled section of the culvert.

An additional consideration for placing the fishway and baffles along the right side was the turning radius of the baffled section inside the culvert. Midway through the arch culvert it turns roughly 45 degree towards the left (north). Placing the baffled section along the left side of the culvert rather than the right would result in a substantially tighter turning radius. Tight turns, such as this, can produce undesirable hydraulic conditions for fish passage, such as rapid or unsteady flow transitions that can create waves and turbulent sloshing between the baffles.

Hydraulic Modeling of Pool and Chute Fishway

The compound weir shape used in the pool-and-chute fishway allows both plunging and streaming flow to occur simultaneously (Figure 5). This allows for a large amount of the flow to stream down the center chute of the fishway while maintaining plunging flow along the sides. Fish are able to migrate upstream within the areas of plunging flow.

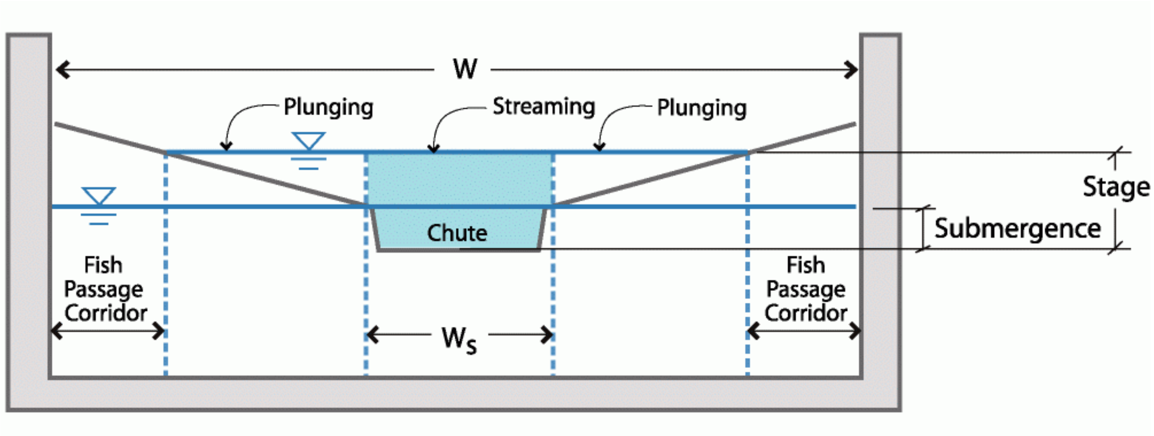

Figure 5 – Cross section of pool-and-chute fishway (looking upstream) with flow states and definition.

Identifying Transition from Plunging to Streaming Flow

Equations for predicting when flow transitions from plunging to streaming were developed empirically from flume studies of rectangular weirs (Rajartanam, 1988; Ead, 2004). The transition equation is used to size the chute and determine when flow is plunging rather than streaming in the chute.

Plunging Flow Calculations

At low fish passage flows water in the chute is plunging. Once flow in the chute begins to stream, water along the edges of the weir remains in plunging flow. Hydraulic conditions for the section with plunging flow are calculated using standard equations for horizontal and V-shaped weirs (King, 1939). For portions of the weir that are partially submerged by the downstream pool, the flow is adjusted using a submergence ratio (Villemonte, 1947).

Streaming (Chute) Flow Calculations

When flow is streaming in the chute the concrete weirs function as large roughness elements and the Chezy equation is used to predict the flow depth across the weirs. The slope used in the Chezy equation is the overall slope of the fish ladder. Bates (2001) and Powers (2004) provide a range of Chezy roughness coefficients for pool-and-chute fish ladders empirically derived from scale model tests and field monitoring. Based on the slope of the proposed fishway, we used a Chezy coefficient of 22 ft/s^2 for the analysis.

Entrance Conditions

The entrance of the fishway is the most downstream end of the structure and requires an additional hydraulic analysis. Having appropriate entrance conditions is critical to maintaining proper fish passage performance. The water level at the entrance of the fishway is controlled by the downstream channel shape and slope. As flow increases, the water depth over the weirs can rise faster than in the downstream channel, potentially creating an excessive drop over the lowest weir.

To analyze this transition and determine the drop over the lowest weir at the design flows, a tailwater rating curve was developed to predict water level in the channel downstream of the fishway entrance. Uniform flow conditions were assumed at the downstream tailwater control and a Manning's roughness coefficient of n = 0.05 and slope of 0.76% were used.

Proposed Dimensions for the Pool-and-Chute Fishway

General Guidance

The hydraulics and dimensions of pool-and-chute fishways have been studied in flumes and at several full-scale constructed ladders (Bates 2001, Powers 2004). Pool-and-chute fishways are applicable to situations with an overall drop of 6 feet or less. The drop over each weir usually varies between 0.5 and 1.0 feet and their overall slope ranges between 10% and 12.5%. The upstream two weirs should be lower relative to the overall gradient by 0.2 and 0.1 feet to account for the increased water depth over these two weirs because of lower chute velocities at the top of the structure.

Pool length should be 50% of the pool width. Studies have found that pool length less than 45% of pool width does not provide sufficient holding area and pool length greater than 55% of pool width does not develop streaming flow and may create excessive turbulence. To provide sufficient cover for fish while keeping the pools between weirs sufficiently clear of sediment, pool depth should be between 2.0 and 4.0 feet.

The recommended height of the chute section is 75% of the depth of flow that the water begins to stream in the chute. The side slope of the weirs should be 4:1 (h:v) to create sufficient depth in the center of the fishway for streaming flow while maintaining a fish passage corridor along both sides.

Proposed Fishway Geometry and Dimensions

Using the procedures and design parameters discussed above, a variety of different pool and chute configurations were analyzed, with the objectives of providing fish passage in the fishway through approximately the same flow range as in the baffled culvert, and fitting the fishway within the physical site conditions of the outlet apron and downstream channel.

The recommended maximum water surface drop for juvenile salmonids is 0.5 feet. However, to meet the minimum recommended fish ladder slope of 10% using 0.5 foot drops results in a maximum effective pool length (pool length between concrete weirs) of only 4.5 feet. Using these design criteria would result in a short pool length creating turbulent conditions that are excessive for adult steelhead at typical migration flows.

To meet all of the project criteria, a slightly higher drop height was examined. The proposed configuration for this pool-and-chute fishway is a drop height of 0.75 feet with spacing of 7 feet, and an overall slope of 10.7%. This drop height was selected as a compromise between the juvenile salmonid and adult steelhead drop height criteria. Young-of-the-year, 1-year and 2-year trout are often seen leaping at this height, and are therefore expected to be capable of ascending the proposed fishway. The proposed fishway would be constructed of concrete and have the following dimensions and characteristics:

Fishway width…………………………… 12.0 ft
Number of weirs……………………….…… 7
Weir spacing……………………………..…….. 7.0 ft
Total length ……………………………… 42.0 ft
Fishway slope……………………….…… 10.7%
Minimum Pool Depth…………….……... 2.0 ft
Water surface drop over weirs……….…. 0.75 ft
Chute bottom width……………….…....... 2.0 ft
Chute top width………………………….. 3.0 ft
Chute Depth……………………………… 0.60 ft
Weir Side Slope………………………….. 4(H):1(V)

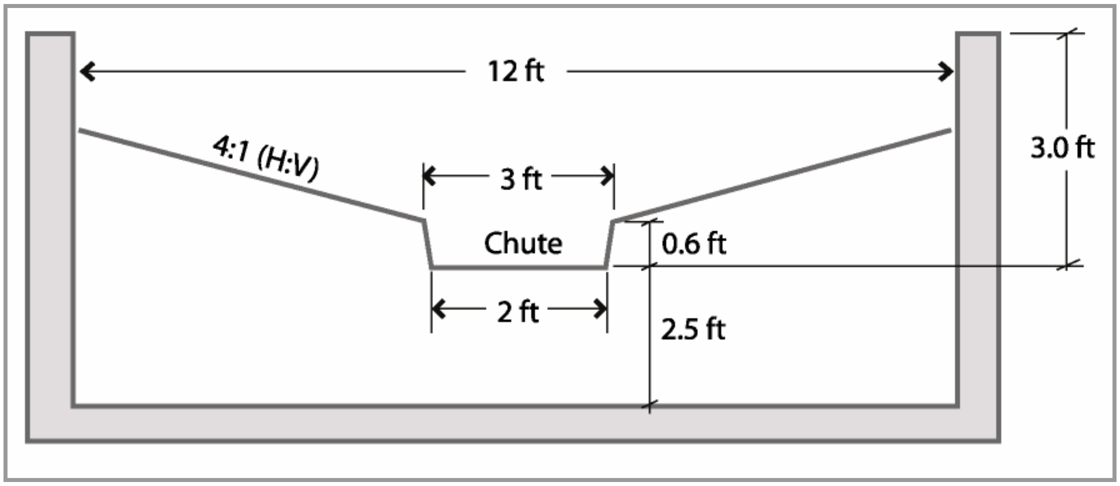

Figure 6 – Preferred geometry for pool and chute fishway for the outlet of the Lansdale Avenue crossing.

A fishway width of 12 feet was selected to (1) fit within the downstream channel, (2) provide the desired operational flow range, and (3) create an efficient hydraulic transition with the 15 foot wide upstream baffled fishway. The chute and tapered weir dimensions help to maximize the operational flow range of the fishway (Figure 6). The height of the side walls is designed to contain high flows that will provide sufficient scouring force as to avoid excessive sedimentation. They also provide 1.1 feet of freeboard at the upper end of the fish passage flow range (when EDF = 4 ft-lbs/s/ft^3) to help prevent adult steelhead from leaping out of the fishway.

Fish Passage Performance of Pool-and-Chute Fishway

The fishway was modeled as described above to evaluate hydraulic conditions for low and high fish passage design flows and to identify the upper end of operational flows. Results are summarized in Table 6.

The fishway provides desired passage conditions for adult steelhead (EDF < 4.0 ft-lb/s/ft^3) up to a total streamflow of 190 cfs, which is less than the upper fish passage design flow of 260 cfs. The passage range in the fishway is similar to that of the baffled section of the culvert, which exceeds the velocity criteria at 180 cfs. The upper operational range of the proposed pool-and-chute fishway, 183 cfs, corresponds to approximately the 2% exceedance flow for San Anselmo Creek at the Lansdale Avenue crossing.

Table 6 - Predicted hydraulic conditions for 12 ft wide pool-and-chute fishway with 0.75 ft drop between weir crests.

	Juvenile Trout Low Passage Design Low	Upper Operational Flow[1]	Adult Steelhead High Passage Design Low
Total Flow	**1 cfs**	**190 cfs**	**260 cfs**
Flow in Fishway	1 cfs	73 cfs	101 cfs
Depth over weir	0.3 ft	2.0 ft	2.4 ft
Energy dissipation factor (EDF)	0.3 ft-lb/s/ft^3	4.0 ft-lb/s/ft^3	6.5 ft-lb/s/ft^3
Wetted weir width	3.0 ft	12.0 ft	12.0 ft
Streaming flow velocity	n/a	7.7 ft/s	8.2 ft/s

[1] Maximum turbulence is when EDF reaches 4.0 ft-lb/s/ft^3. At higher flows fishway has excessive turbulence.

Culvert Hydraulic Capacity

In addition to providing fish passage, the retrofit design needs to maintain the existing hydraulic capacity of the culvert at the 100-year peak flow. This requires avoiding an increase in the culvert headwater depth at this flow.

For both existing and proposed conditions standard methods described in Hydraulic Design Series No. 5 (FHWA, 1985) were used to determine (1) the flow that produces a headwater depth (HW) equals the culvert height (D), referred to as HW/D = 1.0, and (2) the culvert headwater depth at the 100-year peak flow of 3,862 cfs, and. The headwater depth was calculated for both inlet and outlet controlled conditions, and the hydraulic control was conservatively defined as the greater of the two depths. Because each culvert inlet invert is at a slightly different elevation, an iterative approach was taken to split the flow between each culvert at a given headwater elevation.

Inlet Control Calculations

The culvert is considered inlet controlled if the headwater depth is higher than the headwater depth calculated assuming outlet control. For inlet controlled conditions the FHWA equations and coefficients for a box culvert with a headwall (Chart No. 8, Scale 2) were used to determine headwater depth. Under inlet control conditions the predicted headwater depth is a function of the culvert inlet geometry, and is not affected by conditions within the culvert. Therefore, the headwater depth under inlet controlled conditions would be the same for both existing and proposed conditions.

Outlet Control Calculations

Headwater depth for outlet control was determined using a backwater calculation beginning at the tailwater and proceeding through the culvert to the inlet. The culvert tailwater was predicted using the tailwater cross section and the average channel slope of 0.0076 ft/ft. The channel at the tailwater cross section consists of large concrete rubble mixed with cobbles, gravels and fines. A Manning's roughness of 0.050 was applied to the downstream channel cross section and a tailwater rating curve was generated assuming uniform flow through the cross section.

For the backwater analysis of the existing concrete culverts a Manning's roughness coefficient of 0.013 was used. For the proposed baffles in the right bay the roughness was estimated using procedures outlined in the previous section. For the proposed bypass sill in the left bay the backwater analysis was conducted assuming critical depth over the bypass sill and a Manning's roughness of 0.013.

The headwater depth was then determined using the standard headloss equation, which is a function of the depth and velocity within the culvert inlet and the type of inlet (i.e. headwall or wing-walls). The inlet type for the box culverts was described as a headwall, and a corresponding entrance loss coefficient of 0.5 was used.

Hydraulic Roughness of Baffles

The backwater analysis of the right culvert retrofitted with baffles required using an increased roughness coefficient to account for the increase in flow resistance. Physical model studies of hydraulics in box culverts with "weir baffles" were studied by Shoemaker (1956), and are discussed in WDFW (2003). Shoemaker tested full width, level baffles positioned perpendicular to the flow and calculated the resulting internal friction loss and entrance and exit losses associated with baffles having various heights and spacing. Tests where conducted for full flow conditions inside the culvert assuming that entrance, exit, and frictional losses are proportional to the velocity head. Among other things, he developed relationships between the Darcy-Weisbach friction factor, baffle height to culvert height, and baffle spacing to culvert height (Figure 7).

To use these relationships for analysis of the proposed angled baffles, the average height of the baffle was used. When the culvert is not flowing full, water depth was used as a substitute for culvert height to determine the appropriate friction factor. Since water depth and roughness are interrelated, an iterative approach was used to solve for each. After obtaining the appropriate Darcy-Weisbach friction factor, it was converted to a Manning's roughness coefficient. The resulting Manning's coefficient was applied to the entire baffled box culvert. A water surface profile was generated for the culvert using the FishXing 3.0 hydraulic model, which provided the depth and velocity within the inlet necessary to calculate the outlet controlled headwater depth.

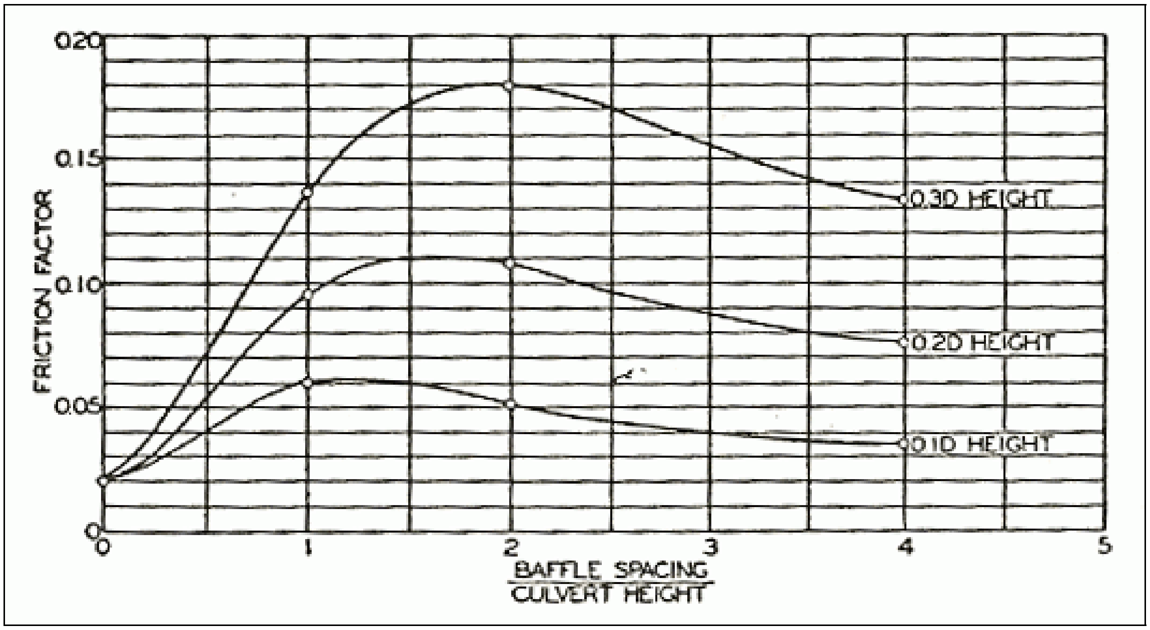

Figure 7 – Darcy Weisbach friction factor for a box culvert as a function of baffle spacing, baffle height and culvert height. Shoemaker developed curves for full width, level baffles, placed perpendicular to flow in a box culvert flowing full. Curves are shown for baffles with a height equal to 0.1, 0.2 and 0.3 times the culvert height (D). From Shoemaker, 1956.

Existing Culvert Capacity

Under current conditions the culvert is inlet controlled. The headwater depth at the culvert inlet (HW) is equal to the height of the box culvert (D) at approximately 2,450 cfs (HW/D = 1.0). At the 100-year return flow of 3,862 cfs the headwater depth in the left bay is 14.5 feet (HW/D = 1.45). The 2009 FEMA Flood Insurance Rate Map indicates flow is contained within the channel during the 100-year flood event, but does designate the lower terraces immediately upstream of the culvert inlet as falling within the 500-year floodplain (Zone B).

Culvert Capacity with Proposed Project

Using Figure 7, a Darcy Weisbach friction factor of 0.05 was estimated for the proposed baffles in the culvert during the 100-year return flow of 3,862 cfs (equivalent Manning's roughness of 0.025 at 100-year flow). This is nearly double the roughness of the existing unbaffled box culvert, and agrees closely with roughness values estimated in the Humboldt State University angled baffled flume study (Lang, 2008) . However, even with this increase in roughness the predicted headwater depth for inlet control is higher than predicted for outlet controlled. Therefore, the culvert remains inlet controlled with the proposed baffle retrofit, indicating that the project will not decrease the hydraulic capacity of the culvert.

Outlet Pool, Tailwater Control and Bank Stabilization

To maintain the water surface condition at the fishway entrance and maintain channel stability downstream of the culvert, an outlet pool, rock weir and bank stabilization are proposed.

Bed Stability Analysis

A rock stability analysis was used to determine the size of rock necessary to maintain a stable channel bed and banks at flows up to the 100-year peak flow of 3,862 cfs.

The stability analysis required an iterative process involving the interdependent variables of particle size, channel roughness, and channel geometry. For rock sizing, the water surface slope during the 100-year peak flow was assumed equal to the overall slope of the proposed channel.

The hydraulic roughness (Manning's n) of the channel was estimated using a depth dependent equation that predicts roughness as a function of particle size, water surface slope, and wetted channel geometry (Thorne and Zevenbergen, 1985). The results were combined with Manning's equation for uniform flow to predict hydraulic conditions in the channel at flood flows.

The US Army Corps of Engineers method for Steep Slope Riprap Design (ACOE, 1994) was used to predict the stable D_{30} particle size based on the channel slope and unit discharge in the channel during the 100 year flow. The predicated stable particle sizes forms the basis for developing design gradations for the material used in the channel bed and banks.

Entrance Pool

The pool immediately downstream of the new fishway and apron is susceptible to high velocities and scouring forces during high flow. To protect the downstream channel and prevent undermining of the apron and new fishway structure the entrance pool should be lined with a rock mixture sized to withstand these forces. This mixture, known as an engineered streambed material (ESM), was sized using methods outlined in CDFG (*in-press*) and WDFW (2003).

The ACOE riprap design method provided the basis for rock sizing. However, the ACOE riprap design generates a relatively uniform gradation of rock sizes that leads to problems with subsurface flow and fails to provide sufficient hydraulic roughness and diversity. Therefore, the engineered streambed material uses D_{84} particle size (84% of particles are smaller than D_{84}) is 1.5 times larger than the stable particle size predicted using the ACOE method. Also, the voids between the larger rocks are filled with a mixture of smaller material, including fine sands and silts. The resulting well-graded bed mixture is shown in Table 7.

Table 7 – Particle distribution for entrance pool downstream of the new fishway.

Percent Finer Than	100	84	50	32	20	10
Particle Size	2.8 ft	1.8 ft	0.7 ft	22 mm	8 mm	< 2 mm

Rock Weir

The downstream end of the entrance pool is stabilized with a rock weir that acts as the tailwater control for the fishway structure. The new rock weir will span the entire channel width and be keyed into the banks and bed as much as feasible to avoid flanking and undermining of the structure. Rock for the weir was sized using the NRCS method for sizing rock structures as described in CDFG (*in-press*). NRCS (2000) recommends sizing rock for rock weirs by computing the stable median rock size using the Far West States Lane Method for riprap sizing. These results are increased by scaling factors to obtain a rock size appropriate for rock weirs.

This yields a maximum rock size of 3.3 ft which is approximately equivalent to a 2-ton rock. The rock should be well graded between 1.6 and 3.3 ft, with the larger rock forming the surface of the weir and the smaller rock filling the voids between the larger rock. The rock weirs should be constructed of angular material and the larger rock placed in a minimum of two rows high.

Bank and Bed Stabilization

The banks and channel bed immediately downstream of the outlet are currently armored with concrete rubble and Rock Slope Protection (RSP). Areas of the bank and channel along the north side of the fishway will be armored with ¼ ton RSP, using Method A application, and 3 ft thickness, as indicated on the plan set. The ¼ ton rock size class was determined using ACOE (1994) riprap sizing method for steep sloped channels. Besides providing scour protection, this material is also intended to help guide fish into the fishway rather then attempting to swim through the unbaffled portion of the culvert.

Construction Considerations

Because access will be from the upstream side of the crossing construction should generally proceed from downstream to upstream, except for some work at the inlet of the box culverts. Six weeks are estimated for construction. The exact timing of the project is unknown until funding for construction is obtained, but it should occur during the low-water period between June 15 and October15.

The general steps for implementing the proposed project include the following:

- Traffic control, signage and notification
- Erosion and sediment control,
- Fish screening and relocation from project area,
- Water management plan, including stream bypass,
- Construction of inlet cut-off wall at upstream end of box culvert.
- Removal of *A. donax*.
- Reinforce existing retaining wall and piers of parking deck.
- Clearing, grubbing and saw cutting existing concrete apron.
- Temporary shoring of right bank retaining wall.
- Construction of boulder weir at tailwater control.
- Re-grading of channel in preparation of pool-and-chute fishway construction.
- Construction of pool-and- chute fishway and retaining wall extension.
- Rock slope protection (RSP) for bank armoring and pool facing.

- Construction of baffles and sidewall within right bay of box culvert and right side of arch culvert
- Construction of inlet sill within left bay of box culvert.
- Replanting of disturbed banks with native vegetation.

Construction Access

The downstream portion of the project reach is not accessible from the lower channel. All of the equipment will access the site from an existing upstream access road and if necessary lowered directly into the channel from the northern lane of Center Boulevard.

Access to the site will be from an unpaved route used by the City to perform maintenance on the existing crossing. Along the route and where it enters the channel, measures should be taken to reduce erosion and stabilize the access way for repeated heavy equipment access during delivery and end hauling of construction materials. Because the channel at the inlet of the crossing will be used to access the culvert, gravel or mats can be placed along the streambed to protect the existing channel and match the grade of the culvert floor. Material will be staged between the access route and the channel in a previously disturbed area with non-native vegetation or on a paved parking lot near Center Blvd.

The left bay of the box culvert will serve as the access way to the downstream portion of the project. Therefore all equipment will need to be sized to fit within the 15 foot wide by 10 foot high, structure. Consideration should be made for ventilation of exhaust fumes while equipment and labor are working within the structure. Additionally equipment with rubber tires or tracks may be required to protect the concrete of the existing floor of the culvert.

Apron Demolition and Retaining Wall Extension

An existing concrete retaining wall currently parallels the southern wall of the proposed fishway. To accommodate construction of the new fishway, the existing concrete apron below the existing concrete retaining wall will have to be demolished and removed. Temporary bracing of the existing retaining wall will likely be necessary during the construction process and until the new southern wall of the fishway has been constructed. Once constructed, the new fishway wall will provide support to the existing retaining wall. The southern channel bank extending approximately 15 ft downstream of the existing concrete retaining wall terminus appears to be unstable. The lower portion of the bank is veneered with concrete rubble and the upper portion of the bank supports a cantilevered parking lot on concrete piles. To protect the southern bank the design includes a new retaining wall extending approximately 15-feet downstream from the end of the new fishway. The new retaining wall will be an extension of the fishway wall and will buttress the channel bank while providing scour protection. The final design of the retaining wall and fishway walls should follow the recommendations made by Miller Pacific Engineering Group during their geotechnical engineering analyses conducted on November 26, 2008.

The geotechnical report recommends the use of drilled cast-in-place piers or driven mini-piles. The methods of installation are not detailed in the geotechnical report. However care should be taken to minimize the impacts to aquatic organisms as a result of pile driving and the resulting acoustic vibration.

Fishway and Baffle Construction

Concrete required for the proposed fishway and baffles can be pumped from the roadway, requiring lane closure. The lane closure will be on an interim and as-needed basis, not continuously required for the full duration of construction. The closure efforts will likely include notification of adjacent property owners and temporary signage. A traffic control plan detailing the selected detour route and required signage is typically submitted by the contractor prior to commencing work and is strongly recommended for this site.

Miller Pacific (2008) recommends the use of anchor bolts instead of deep foundation anchor bolts to structurally connect the baffles to existing concrete floor.

New concrete work will require 30 days to cure before the streamflow can be released onto the new structures. However use of a DFG approved sealant can reduce the curing time to 7 days before streamflow can be applied.

Conclusions

Replacement of this 320 foot long culvert was considered cost prohibitive and generally infeasible. Therefore, the final concept design proposes retrofitting the existing culvert with center-aligned angled baffles and constructing a pool-and-chute fishway at the outlet that would replace a portion of the outlet apron and extend a few feet into the downstream channel.

The proposed retrofits will improve conditions for migrating steelhead and resident trout. The new baffles and fishway will meet current fish passage criteria from 1 to 180 cfs and likely provide suitable passage criteria at higher flows as well.

In addition to fish passage criteria, the design was guided by the requirement to maintain the existing capacity of the culvert by not raising the headwater elevation during the 100-year return flow as a result of the retrofit. Currently the crossing is inlet controlled. With the addition of the baffles and the inlet sill the crossing remains inlet controlled at the 100-year design flow and the headwater elevation remains unchanged. Some periodic monitoring and maintenance will be required to ensure that the culvert inlet, interior baffles and fishway remain clear of debris.

References

Bates, K. 2001. Fishway Design Guidelines for Pacific Salmon. Working paper 1.6 9/2001 Washington Department of Fish and Wildlife.

CDFG (California Department of Fish and Game). 2002. *Culvert criteria for fish passage*. 17 pages.

CDFG (in-press). Fish Passage Design and Implementation: PART XII of California Salmonid Stream Habitat Restoration Manual. California Department of Fish and Game.

Ead S.A., et. al. 2004. *Flow regimes and structure in pool and weir fishways*. Journal of Environmental Science 3:379-390

FHWA. 1985. Hydraulic Design Series No. 5 (HDS-5), *Hydraulic Design of Highway Culverts.* Report No. FHWA-IP-85-15

King, H.W. 1939. *Handbook of Hydraulics*, Third Edition, McGraw Hill Book Company

Lang, Margaret. 2008. Influence of fish passage retrofits on culvert hydraulic capacity. Funded by the California Dept. of Transportation.

McCuen, R.H. 1998. *Hydrologic Analysis and Design.* (2nd ed.). Prentice-Hall, Inc., Upper Saddle River, N.J.

Miller Pacific. 2008. *Geotechnical Investigation San Anselmo Creek Fish Passage, San Anselmo California*. Project No. 960.04 Prepared for Stetson Engineers Inc.

Rajaratnam, N. 1988. *Plunging and Streaming Flows in Pool and Weir Fishways.* Journal of Hydraulic Engineering ASCE. Vol. 114 No.8 Paper No. 22697-2

Taylor, R. 2006. *Corte Madera Stream Crossing Inventory and Fish Passage Evaluation. Final Report.* Prepared for the Friends of the Corte Madera Creek Watershed

National Marine Fisheries Service. 2001. *Guidelines for salmonid passage at stream crossings*. NMFS SW Region. 14 pages

Powers, P. 2004. *Pool and Chute Fishways, Discussion and Design Process, Proceedings* from the 3rd Annual Northwest Stream Restoration Design Symposium. River Restoration Northwest.

Shoemaker, R.H.. 1956. *Hydraulics of Box Culverts with Fish-Ladder Baffles*. Highway Research Board Proceedings 35:196-209, 1956.

Stetson Engineers. August 2007. *Draft Appraisal-Level Flood Study for Corte Madera Creek, San Anselmo to Larkspur, CA. Prepared for Marin County Flood Control and Water Conservation District.*

USFS. 2006. FishXing3.01b. *Software and Learning System for Fish Passage through Culverts.* USDA Forest Service. http://www.stream.fs.fed.us/fishxing/

USFS (2008). Stream simulation: an ecological approach to road stream crossings. San Dimas, CA, USDA United States Forest Service National Technology and Development Program.

USGS. 1982. *Guidelines for determining flood flow frequency*. Bulletin #17B of the Hydrology Subcommittee. Interagency Advisory Committee on Water Data, US Dept. of Interior, Geological Survey, Virginia.

Villemonte, J.R., 1947. Submerged weir discharge studies. *Engineering News Record, 866,* Dec.

WDFW (Washington Department of Fish and Wildlife) Environmental Engineering Division. 2003. *Fish passage design at road culverts: a design manual for fish passage at road crossings.* May 2003, http://www.wa.gov/wdfw/hab/engineer/cm/. Accessed Sept 15, 2003.

Waananen, A. O. and J.R. Crippen. 1977. *Magnitude and frequency of floods in California.* USGS, Water Resources Investigation 77-21, Menlo Park, CA 96 pages.