Fish Passage Feasibility Study

Use of Resting Pools to Improve Steelhead Passage within the San Lorenzo Creek Concrete Flood Control Channel

November 31, 2006

Prepared for:
The Alameda County Flood Control and Water Conservation District

Prepared by:

Michael Love & Associates
Hydrologic Solutions

PO Box 4477, Arcata CA 95518
(707) 476-8938, mlove@h2odesigns.com

In partnership with

DHI Water & Environment, Inc.

1440 Broadway, Suite 614
Oakland CA 94612 (510) 893-0760

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1 BACKGROUND

San Lorenzo Creek is a tributary to San Francisco Bay and flows through the cities of Hayward and San Lorenzo. The lower five miles of San Lorenzo Creek has been converted into a flood control channel designed and constructed by the US Army Corps of Engineers (ACOE). The overall objective of this project is to study the feasibility of improving upstream fish passage conditions for adult steelhead trout within the flood control channel. This study builds on previous work (MLA 2003) that identified portions of the flood control channel as inhibiting upstream passage of adult steelhead. This study is limited to evaluating the feasibility of constructing resting pools recessed into the channel floor to provide opportunities for steelhead to rest. The pools should also minimize loss of hydraulic capacity within the flood control channel and require minimal maintenance.

The project team consists of staff from Michael Love & Associates (MLA) and DHI Inc. MLA was responsible for developing design alternative for fish resting pools and evaluating their effectiveness. DHI was responsible for performing two-dimensional hydraulic modeling of the existing flood control channel and each proposed alternative, and for performing energy loss calculations associated with each alternative.

1.1 Fisheries Resources

Previous reports have identified San Lorenzo Creek as historically supporting healthy runs of native steelhead trout (Leidy, 1984; Kobernus, 1998). Fish habitat and fish populations were assessed by the Alameda County Flood Control and Water Conservation District (District) and Hagar Environmental Science and viable steelhead/rainbow trout habitat was identified in some of the tributaries to San Lorenzo Creek (ACFCWCD, 2002). However, the reports identified the Zone 2 Line B flood control channel as a severe barrier to migrating steelhead. In recent years adult steelhead have been observed holding within the upper reaches of the concrete channel after flows have receded. Additionally, during a site visit for this project on March 18, 2005 members of the project team and District staff observed an adult steelhead swimming in the channel about 1,200 feet from the upstream end of the flood control channel.

1.1.1 Previous Fish Passage Assessment

In 2003 Michael Love & Associates (MLA) analyzed fish passage conditions within the flood control channel and developed recommendations and concept design solutions for the District (MLA, 2003). The report identified the most severe steelhead migration barrier as the transition between the flood control channel and the upstream natural channel. This transition slopes at about 5% and is commonly referred to as the “Velocity Ramp”, since it produces extremely high water velocities. The 2003 report by MLA recommends constructing a fish ladder at the transition to provide for upstream passage of adult steelhead. Recently, MLA further developed the concept fish ladder design into a preliminary design for the District and recommended that providing fish passage at the

Velocity Ramp be the first priority in efforts to reestablish steelhead access to upstream spawning and rearing habitat within the San Lorenzo Creek watershed (MLA, 2006).

The 2003 report also identified the flood control channel located between the stilling basin and the Velocity Ramp to be a significant migration barrier. The combination of swift water velocities over a channel length of about 20,300 feet is believed to result in an exhaustion barrier for most steelhead at typical winter migration flows. The report recommended that further studies be conducted to determine the feasibility of using a series of constructed concrete pools to provide resting areas throughout the concrete channel while avoiding loss of flood capacity within the channel.

1.2 Description of Flood Control Channel

Completed in 1962, the flood control project encompassed approximately 27,670 feet of channel beginning at Foothill Boulevard in Hayward and ending at the stream's confluence with San Francisco Bay (Figure 1.1). Following completion, responsibility for the flood control project was transferred to the Alameda County Flood Control and Water Conservation District (District). The San Lorenzo Creek flood control project lies within Zone 2 of the District, and is officially referred to as Zone 2 Line B.

1.2.1 Lower Subcritical Channel

The lower 7,100 feet of channel was designed to create subcritical flow conditions, with the channel bed constructed at a mild slope of 0.0011 ft/ft. The lower 3,400 feet of the flood control channel is tidally influenced and consists of a trapezoidal earthen levee with a bottom width varying between 75-feet and 45-feet. Between station 34+00 and 71+00 the channel is trapezoidal with concrete-lined side slopes and a bottom width of 45-feet.

Although the earthen channel bed is relatively featureless, the 2003 fish passage assessment found the lower 7,100 feet of the flood control channel to be only a minor hindrance to steelhead passage (Figure 1.2a).

1.2.2 Stilling Basin

At station 71+00 the channel begins transitioning into a rectangular stilling basin and serves as a distinctive break between the lower trapezoidal channel and upper rectangular channel. The stilling basin, which is approximately 100 feet in length and 37 feet wide, has a row of six jump blocks placed across the bottom designed to force a hydraulic jump. However, the stilling basin is currently filled with fine sediment and aquatic vegetation, forming a gentle transition into the upper channel (Figure 1.2b).

1.2.3 Upper Supercritical Channel

The upper channel is the subject of this project. It consists of a rectangular reinforced-concrete channel that begins at the upstream end of the stilling basin and continues throughout the remaining 20,300 feet of flood control channel, ending at City Center Drive. Between stations 72+97 and 205+04 the channel is 37 feet wide with channel wall height varying between 12 feet and 14 feet. From station 205+04 to the end of the rectangular channel at station 276+00, wall height varies between 13 feet and 21 feet and the channel is 34 feet wide. A trapezoidal low-flow channel runs along the centerline throughout the entire upper reach. It is 1 foot deep and has bottom and top widths of 1 foot and 5 feet, respectively. Based on original ACOE design documents, the low-flow channel was constructed to improve fish passage, and is known as the **fish channel**.

The entire rectangular reinforced-concrete channel was designed to create supercritical flow conditions. The average slope of the channel bottom throughout this section is 0.0038 ft/ft. The channel has numerous bends and the alignment consists of a system of simple curves and modified spirals. Within each bend the channel bottom is superelevated, with the outside of the bend higher than the inside (Figure 1.2c). As the flood control channel meanders back-and-forth the orientation of the superelevated bottom alternates from side to side, pivoting around the channel centerline. In some locations the difference in elevation between the left and right sides of the channel exceeds 3.5 feet.

1.2.4 The "Velocity Ramp" Transition

At station 276+00 begins a reinforced-concrete transition channel that joins the upper end of the flood control channel with the culvert under City Center Drive and the adjoining bridge at Foothill Boulevard (Figure 1.2d). The transition is 70 feet in length and consists of a combination trapezoidal channel with vertical walls. The bottom slope of the transition is a constant 0.050 ft/ft and the bottom width decreases from 34 feet to 18 feet. Because of its steep slope, which produces extremely high water velocities, it is commonly referred to as the "Velocity Ramp". The Velocity Ramp was identified as a major barrier to steelhead migration and was the focus of a report recently completed by MLA (2006) that contains a preliminary fish ladder design for the site.

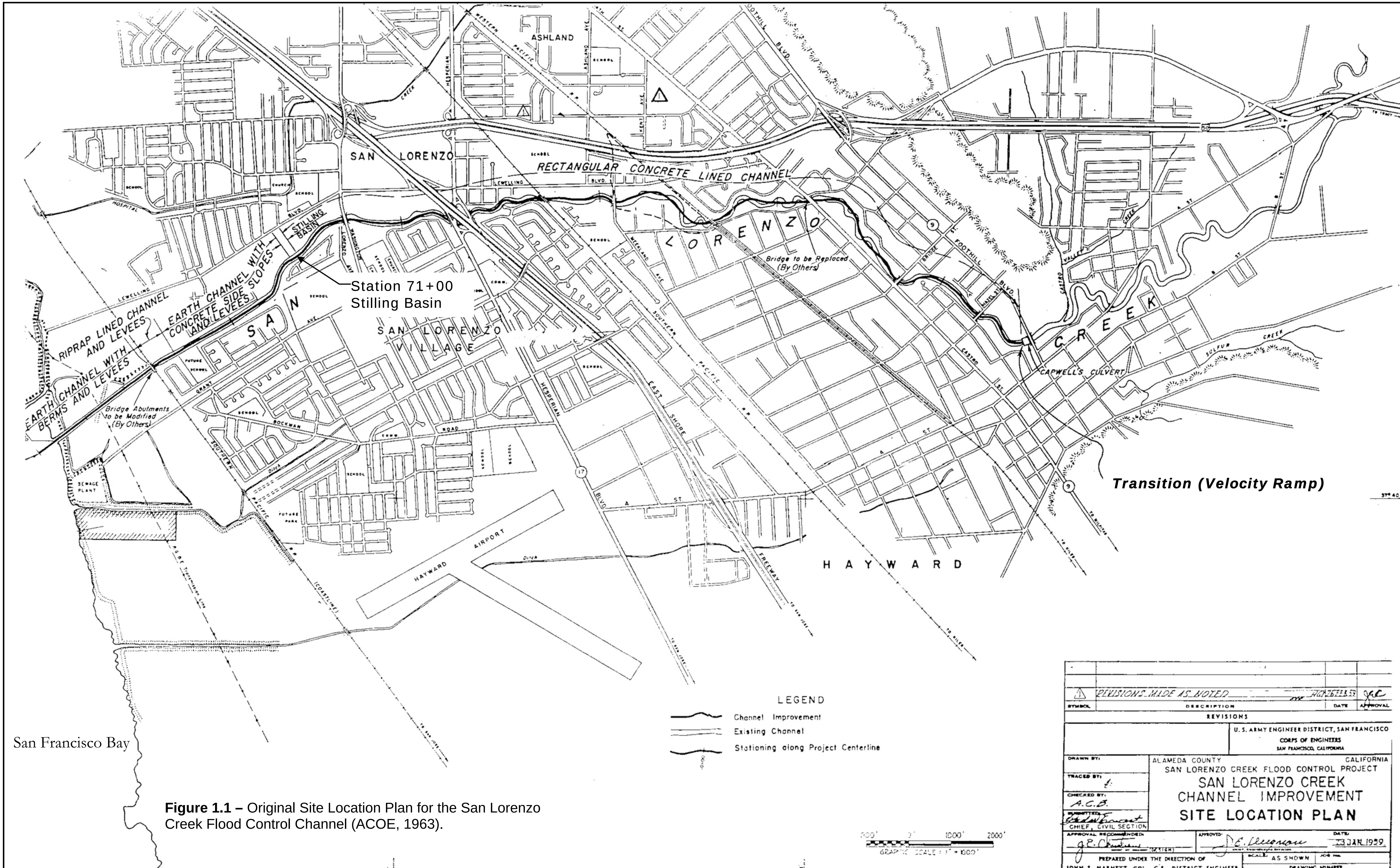


Figure 1.1 – Original Site Location Plan for the San Lorenzo Creek Flood Control Channel (ACOE, 1963).

Figure 1.2 –San Lorenzo Creek Flood Control Channel, Zone 2 Line B, (a) in the lower earthen bottom reach, at (b) the stilling basin, within the rectangular concrete channel (c) with superelevated bends and fish channel, and (d) at the "Velocity Ramp" transition channel immediately below City Center Drive and Foothill Boulevard.

2 APPROACH

2.1 Overview of Project Objectives and Constraints

The objective of this feasibility study was to develop concept designs for shape and placement of resting pools within the upper section of the flood control channel. The pools should create a hydraulic environment suitable for steelhead to rest and recover from exhaustion at flows associated with upstream steelhead migration. Besides satisfying specific resting pool criteria, the preferred pool design should avoid causing any water surface rise at the maximum channel capacity discharge, which was estimated by DHI as 12,000 cfs (Appendix A). Secondary design objectives include the need to design resting pools that will be self-scouring and require little to no maintenance.

Conceptually, the ideal resting pool will create an area of slower water during steelhead migration flows yet have little to no influence on channel hydraulics at infrequently occurring high flows.

2.2 General Approach

The following approach was used:

(1) Development a two-dimensional (2-D) hydraulic model of the existing flood control channel from the stilling basin to the Velocity Ramp below Foothill Boulevard. The model was created using MIKE 21C by DHI, and was calibrated for use at fish passage flows. The 2-D model was ran at eight individual flows: 20, 60, 80, 100, 120, 160, 200, and 280 cfs.

(2) Construction of a one-dimensional baseline hydraulic model for use in evaluating channel capacity flows. DHI used the MIKE 11 model to accomplish this task.

(3) Develop a model for steelhead locomotion (fish routing) through the existing upper flood control channel and model fish passage at the eight flows listed above. The MIKE 21C results were used to estimate the water velocities and depths that fish would encounter while swimming upstream. The results assisted in identifying locations within the channel where steelhead may become fatigued, requiring resting pools to allow them to recover before swimming further upstream.

(4) Selection of two pilot reaches for modeling the effectiveness of various resting pool shapes and spacing; one straight reach and one meandering reach.

(5) Development and modeling in MIKE 21C three resting pool designs for the straight pilot reach and three resting pool designs for the meandering pilot reach. Development of each pool shape was an iterative process based on hydraulic performance of the previously modeled pool shape.

(6) Calculation of the energy loss and potential induced water level rise associated with each pool shape within the pilot reach at the channel capacity flow of 12,000 cfs using MIKE11.

(7) Evaluated performance of each pool shape with respect to resting pool criteria and resulting induced water level rise at the channel capacity flow. A preferred resting pool shape for the straight and meandering reaches was then selected.

(8) Used the fish routing model to locate needed resting pools and predict the range of flows steelhead passage will be provided if the proposed resting pools are constructed.

The MIKE 21C and MIKE 11 results and energy loss calculations for each pool shape are summarized in the DHI technical memorandum (Appendix A). The fish routing model developed for this project is described in detail within the following section.

2.3 Development of Fish Routing Model

Quantifying existing steelhead passage conditions through the flood control channel and identifying locations where resting pools are needed involves development of a relatively detailed fish routing model. The model must account for the hydraulic environment the fish will swim through, the swimming capabilities, requirements and energetics of the specific fish, variability within the overall population, and behavioral factors. The following section describes in detail the fish routing model that was specifically developed for this project, along with its limitations.

2.3.1 Target Species and Lifestage

The target species for providing fish passage through the San Lorenzo Creek is an adult steelhead trout from the Central California Coast Distinct Population Segment (DPS) (Federal Register, 2006). Upstream passage of juvenile salmonids was not an objective of this project since there is no rearing habitat within the flood control channel (even if resting pools are constructed) and, if washed into the concrete channel, juvenile salmonids would not be able to swim back upstream due to the high water velocities.

2.3.2 Size Distribution of Adult Steelhead Population

The swimming capabilities of most fish species, including steelhead, is directly related to the fish's overall length. Therefore, to describe the range of swimming capabilities requires describing the range of body lengths that make up the population of sexually mature Central California Coast steelhead as they return to freshwater streams to spawn. Since only a few steelhead have been observed in San Lorenzo Creek within recent years, it was necessary to use other data sets containing steelhead body lengths. Body length data was obtained from four streams within the Central California Coast DPS: Pudding Creek near Fort Bragg (Neillands, Per. Com.2006), Scotts Creek near Santa Cruz, (Hayes, Per. Com. 2006) and Waddell Creek (Shapovalov and Taft, 1954). From this data it is apparent that the size of steelhead ranges widely, from 14 inches to 35 inches (Figure 2.1). As pointed out by both Hayes and Shapovalov and Taft, many of the smaller fish may have remained in the estuary and did not migrate to the ocean. This is especially likely when the estuary remains closed to the ocean during much, or all, of the year due to sandbar formation. Since the San Lorenzo Creek flood control channel extends well into San Francisco Bay, it does not have a significant estuary for steelhead to rear in. Therefore, it is likely that most of the target fish will be at least 18 inches in length.

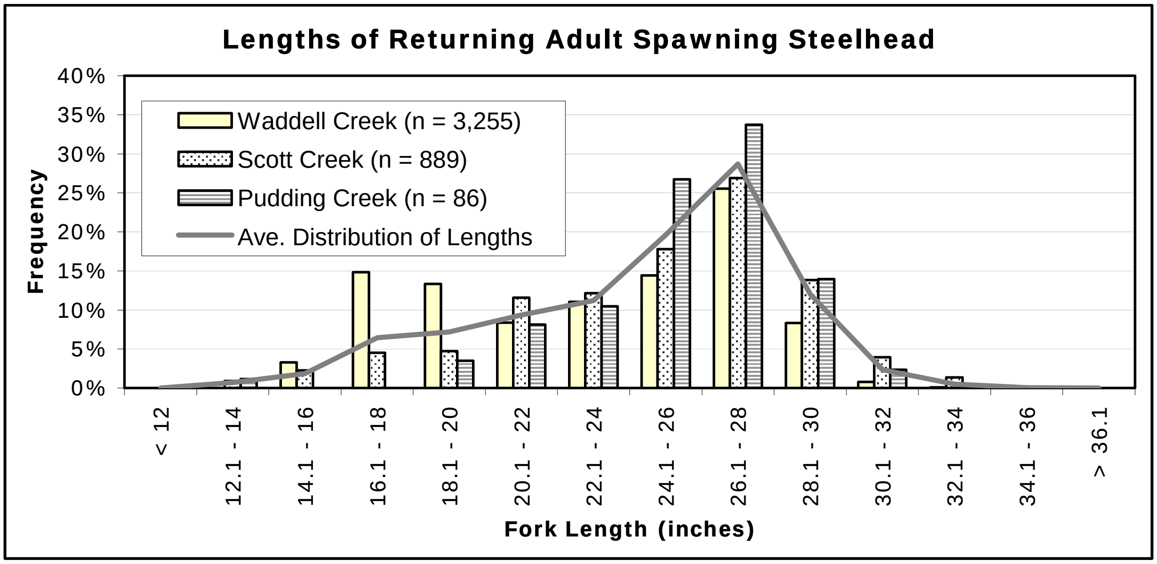


Figure 2.1 –Distribution of fish lengths for sexually mature steelhead trout in three streams within the Central California Coast Distinct Population Segment (DPS**)**. Average distribution of fish lengths was normalized by stream.

To describe the length distribution of the population, statistics for each stream were calculated and then averaged between streams. This reduced bias towards sample size and other stream specific factors, such as estuary connectivity to the ocean. The average fish length is 24.5 inches. The shortest and longest 10% of the population is 18.9 inches and 28.5 inches, respectively.

2.3.3 Period of Migration for Spawning Steelhead

In northern and central California, the vast majority of steelhead migrate from the ocean into coastal freshwater streams and rivers for spawning during high flow events occurring from December through March (Lang et al., 2004; Love, 2006). As part of this project, eight years of recorded observations of steelhead attempting to pass over a barrier in lower Alameda Creek, a tributary to southern San Francisco Bay were reviewed. The observations indicate that the majority of steelhead within the San Francisco Bay region migrate between early January and mid-March. A review of findings from Shapovalov and Taft's (1954) seminal study of coho and steelhead life histories on Waddell Creek in Santa Cruz County found that the vast majority of returning steelhead (98%) enter lower Waddell Creek from the ocean between December 1st and March 31st.

Based on these observations, a migration period from **December 1st through March 31st** was selected for developing fish passage migration flows for San Lorenzo Creek.

2.3.3.1 High Passage Flow

A migration flow range is defined by a low and high passage flow, with fish passage desired at all flows between the low and high fish passage flows. The standard method of defining fish passage flows is to use exceedance flows obtained from a flow duration curve for the project location. In larger drainages, such as San Lorenzo Creek (drainage area at Foothill Boulevard is 44.1 mi^2), a common high passage flow for salmon and steelhead is the 10% exceedance flow during the period of migration. The 10% exceedance flow is the stream discharge that is equaled or exceeded an average of 10% of the days for the indicated period; December through March in this case.

The San Lorenzo Creek at San Lorenzo stream gage is located below Washington Ave and has been operated by the USGS from 1968-1978 and 1988 to present (30 years of record). The gaging station is located in the lower portion of the project reach, about 1,500 feet upstream of the stilling basin, and has a contributing drainage area of 44.6 mi^2, which is only 0.5 mi^2 greater than at Foothill Boulevard. Using the historic daily average streamflow data for December through March, a flow duration curve was constructed for the project. (Figure 2.2). **The high fish passage flow as defined by the 10% exceedance flow for the migration period, is 115 cfs.**

2.3.3.2 Low Passage Flow

Previous fish passage feasibility studies for the San Lorenzo Creek flood control channel have concluded that retrofitting the channel with baffles or other objects to increase depth and decrease velocities is infeasible since it will result in substantial loss of channel capacity (MLA, 2003, URS Greiner Woodward Clyde, 1999). The use of resting pools is intended to improve passage without raising water depths within the channel. Therefore, for evaluating effectiveness of resting pools it is reasonable to define the low fish passage flow as the flow in which water depth within the channel becomes too shallow for steelhead to swim in for long distances. At flows below this threshold, steelhead would be expected to hold in the resting pools while waiting for flows to increase. As explained in section 2.3.4.1, we defined this water depth as 0.5 feet, which is roughly the depth of water needed to submerge all but the largest 10% of steelhead within the population. Water depths within the fish channel averages 0.5 feet at approximately 3 cfs. **Therefore, the low passage flow was set at 3 cfs.**

Examining the hydrograph from the relatively wet 2005 water year shows that the fish passage flow range for steelhead passage (3 cfs to 115 cfs) encompasses all but the highest peak flows during the migration period (Figure 2.3). Additionally, the hydrograph illustrates how streamflow responds to rainfall events, with flows rising and receding rapidly. Given the nature of the stream's hydrology, flows only exceed the proposed high fish passage design flow for short periods.

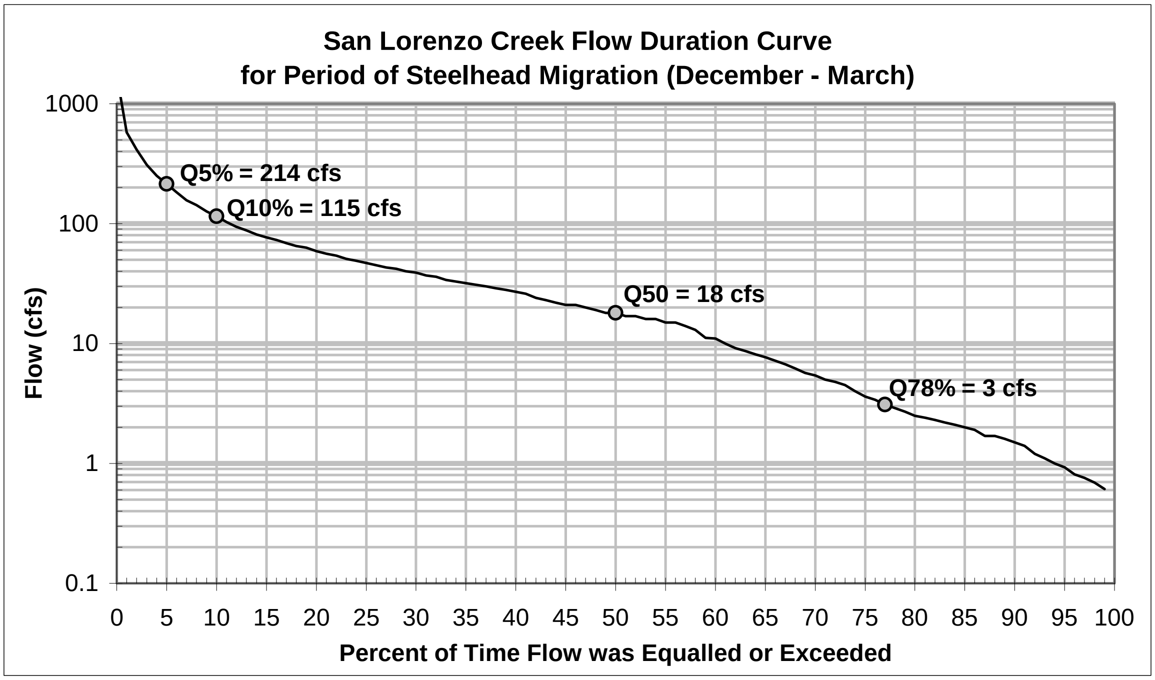


Figure 2.2 – Flow duration curve for the period of adult steelhead migration (December – March) within San Lorenzo Creek. Curve constructed using daily average flows from USGS Station 11181040 (Record Length = 30 years, Drainage Area = 44.6 mi^2).

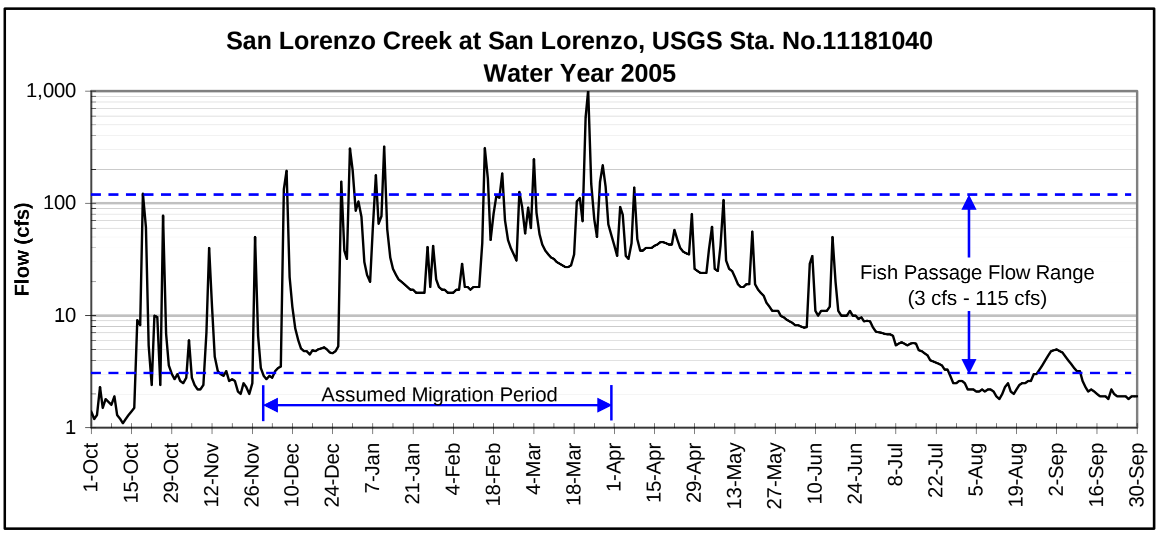


Figure 2.3 – Hydrograph for San Lorenzo Creek, Water Year 2005. Both the assumed migration period for adult steelhead (Dec 1 – March 31) and the fish passage design flow range (3 cfs – 115 cfs) are indicated on the hydrograph.

2.3.4 Steelhead Swimming Capabilities

An extensive literature search was conducted to identify studies that quantify (1) the relationships between steelhead swimming speeds and time to fatigue, (2) the swim speeds defining sustained, prolonged, and burst swimming, (3) the time required for an exhausted adult steelhead to rest before regaining its full stamina, and (4) the distribution of fish body lengths that generally describes the Central California Coast adult steelhead population as they enter freshwater to spawn.

2.3.4.1 Swim Speed – Fatigue Time Relationship

Most fish, including salmonids, are known to have three distinct modes of swimming: sustained, prolonged, and burst. Sustained swimming is a completely aerobic activity and can be maintained indefinitely. Prolonged swimming is a combination of aerobic and anaerobic metabolic activity that can be maintained between 20 seconds and 60 minutes before the fish becomes fatigued. Burst is the fastest mode of swimming and uses anaerobic muscles almost exclusively and can only be maintained between 1 and 20 seconds before the fish becomes fatigued (Beamish, 1978).

An examination of the literature regarding swimming capabilities of *Oncorhynchus mykiss* (steelhead/ rainbow trout) found only two studies concerning adult anadromous steelhead (Weaver 1963; Paulik and DeLacy, 1957). Of the two studies, only Paulik and Delacy swam the fish to fatigue. These fatigue tests were conducted using 21 wild steelhead captured in Soos Creek near Seattle, Washington. Fish ranged in length from 17.75 inches to 30.75 inches. Tests were conducted in a rotary fish tank and water temperature, which influences swimming performance, ranged between 50.0^0 and 53.5^0 F. Each fish was subjected to four constant water velocity tests, with a 24 hour resting period between tests. Velocities in the tests ranged between 4 ft/s and 10 ft/s. Most, if not all, of the speeds reported by Paulik and Delacy appear to be associated with swimming in prolonged mode.

We used the raw data published by Paulik and DeLacy, to develop swim speed – fatigue time relationships for use in modeling steelhead swimming performance within the San Lorenzo Creek flood control channel. The swim speed test results seem applicable to steelhead in San Lorenzo Creek since the range of fish lengths tested were within the same range as those that define the population of steelhead in the Central California Coast DPS. Additionally, water temperatures measured in the flood control channel by District staff during runoff events between December and March commonly ranged between 49^0 and 56^0 F, which is close to temperatures in the swim speed tests.

For swim speed – fatigue time relationships among a given species and life stage, swim speed has been shown to be directly proportional to the body length of the fish (Bainbridge, 1960) Therefore, swim speeds are commonly reported in terms of body lengths (BD) per second.

Swim speed – fatigue time relationships are frequently described by a log linear relationship of the following form (Beamish, 1978; Castro-Santos, 2002):

$$\ln T = aU_s + b \qquad \text{(Eq. 1)}$$

where,

T = time to fatigue (s)
U_s = Swim speed of the fish relative to the water (BL/sec)
a and b = constants for the slope and intercept of the line

This log-linear relationship was used to fit a regression line to the steelhead swim speed data (Figure 2.4) and prediction intervals were computed assuming the residual error is normally distributed, which was visually checked and verified. To maintain or restore a healthy fish population it is important to consider passage of both weak and strong fish within a population. The regression line represents the capabilities of the average steelhead. Prediction intervals may be used to describe the swimming capabilities of weaker and stronger potions of the steelhead population. For example, the prediction interval shown in Figure 2.4 indicate that 90% of the population would be expected to perform at a level above the lower line and 10% of the population would perform above the upper line.

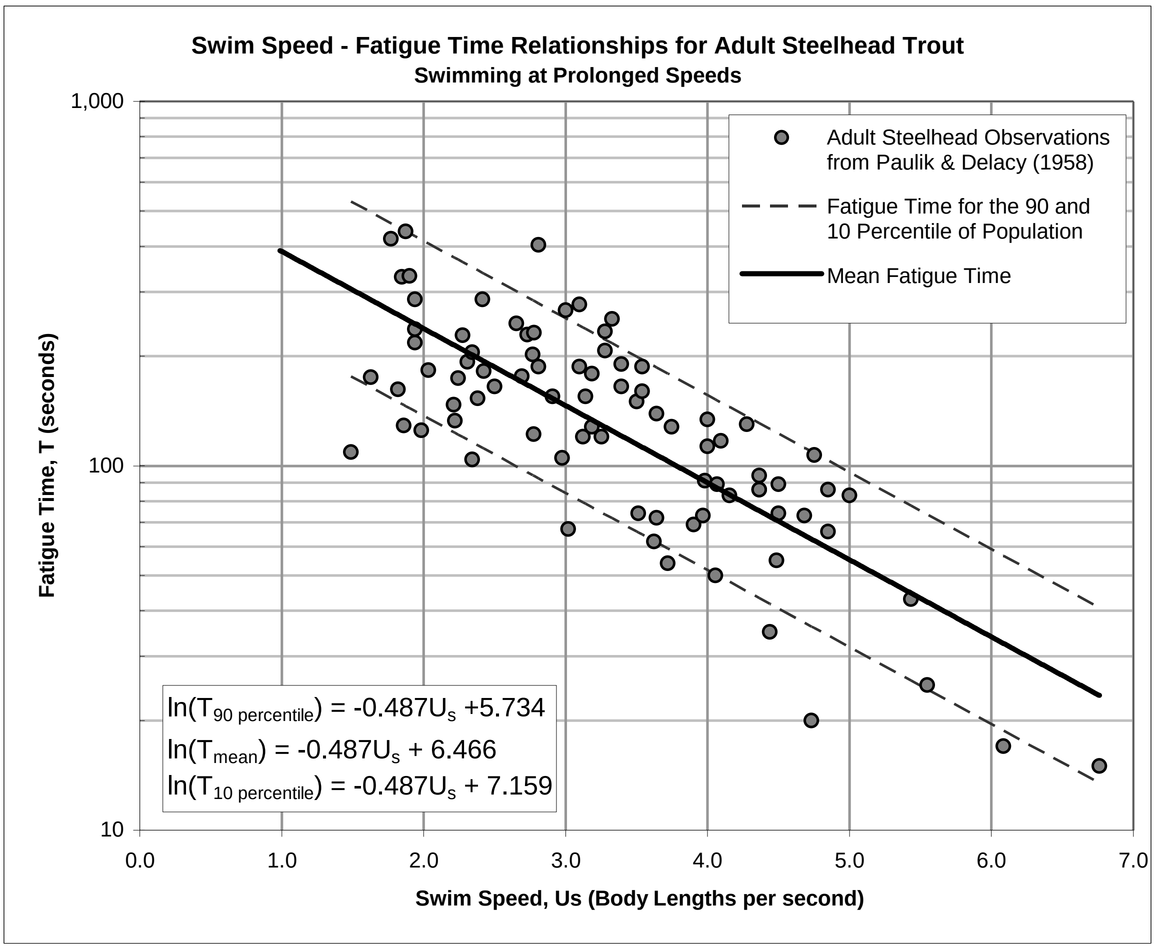


Figure 2.4 –Relationship of swim speed verses time to fatigue for steelhead trout swimming at prolonged speeds. Developed from data presented in Paulik and Delacy (1958).

2.3.4.2 Optimum Swim Speed

In Equation 1, the relative swim speed (U_S) is comprised of the water velocity the fish is swimming against (U_W) plus the speed of the fish relative to the ground (U_G).

$$U_S = U_W + U_G \qquad \text{(Eq. 2)}$$

If the time the fish can swim at U_S before fatiguing is known, the maximum distance the fish can travel (D) can be described as:

$$D = (U_S - U_W)T \qquad \text{(Eq. 3)}$$

For example, if the fish is swimming against water flowing at 6 ft/s and is progressing in the upstream direction at 2 ft/s, then the swim speed of the fish relative to the water is 8 ft/s. If the swim speed – fatigue time relationship indicates the fish can swim at 8 ft/s for 90 seconds before fatiguing, then the fish can travel upstream 180 feet before becoming fatigued.

Castro-Santos (2005) showed that for prolonged and burst mode of swimming there is a distance optimizing swim speed ($U_{S\text{-}opt}$), which results in the fish being able to swim the most distance before fatigue:

$$U_{S\text{-}opt} = U_W - 1/a \qquad \text{(Eq. 4)}$$

Substituting Equation 2 into Equation 4 gives:

$$U_{G\text{-}opt} = -1/a \qquad \text{(Eq. 5)}$$

In other words, a fish may maximize the distance it can swim before fatigue by maintaining the optimum ground speed ($U_{G\text{-}opt}$) regardless of the water velocity. It is important to note that $U_{G\text{-}opt}$ changes depending on the mode the fish is swimming in (prolonged or burst).

Castro-Santos demonstrated through swim speed tests, that certain species do swim in prolonged and burst at the optimum ground speed. However, of the six species studied, none of them were salmonids.

Weaver (1963) reported ground speeds of steelhead swimming through a 30 ft long timed section within a flume 85 ft in length. Test were conducted at water velocities ranging between 2 ft/s and 15.8 ft/s and involved swim speed tests of over 2,000 individual adult steelhead, with 80% of them ranging in size between 22 and 26 inches. For water velocities ranging between 2 ft/s and 6 ft/s the average recorded ground speed ranged between 4.0 ft/s and 4.8 ft/s. At higher speeds results were less conclusive, possibly because some of the fish were swimming in burst mode while others were swimming in prolonged mode.

From the prolonged swim speed – fatigue time relationships shown in Figure 2.4, the optimum ground speed for steelhead is 2.05 BL/sec. For a 24 inch steelhead, this gives in an optimum ground speed of 4.1 ft/s. Therefore, Weaver's results suggest that most steelhead, when swimming at prolonged speeds, swim (1) at a relatively constant ground speed and (2) their ground speed is relatively close to the optimum ground speed.

Based on this work, the swim speed model used to assess passage through the flood control channel assumed the steelhead swim at the optimum prolonged ground speed of 2.05 BL/sec. The model exclusively utilized the prolonged mode of swimming, since the long distances associated wit the flood control channel are not suited for swimming at burst speeds given the extremely short duration they can be maintained before fatigue (1 to 20 seconds).

2.3.4.3 Variable Speed Swimming verses Fatigue

The time to fatigue shown in Figure 2.4 assumes a constant swim speed. However, in our model we assume the fish is maintaining a constant ground speed, while its swim speed will change as the water velocity changes. For example, assume the fish maintains a constant ground speed of 4 ft/s. If at first it swims against 3 ft/s water velocities and then encounters 6 ft/s water velocities, the fish must change its relative swim speed from 7 ft/s to 10 ft/s to maintain the constant ground speed. Since these two swim speeds have different fatigue times associated with them a method was devised to keep track of the fish's fatigue (Castro-Santos, 2006). Determining the percent fatigue of the fish ($F\%$) while it swims at variable speeds requires summing the amount of time swam at each swim speed (t_{U_S}) divided by the fatigue time associated with that swim speed (T_{U_S}):

$$F\% = 100 \times \sum \frac{t_{U_S}}{T_{U_S}} \qquad \text{(Eq. 6)}$$

When fatigue reaches 100% the fish is assumed to be exhausted and must rest and recover before resuming swimming at prolonged or burst speeds.

2.3.4.4 Recovery from Fatigue

The ability of fish to exert themselves, recover, and swim again without hindrance has important ecological ramifications, especially for species such as salmon and steelhead that undertake extensive migrations to complete their life cycles. Farrell et al. (1998) examined prolonged swimming, recovery, and repeat swimming performance of adult sockeye salmon and found that when provided a 45 minute resting period most fish could repeat the critical swimming test three times. The 45 minute rest period did not allow for a full metabolic recovery and the fish swam in a slow current of approximately 0.4BL/second during the resting period. Full metabolic recovery may take up to several hours; for example, Brett (1964) estimated that after a critical swimming test oxygen debt was repaid in 3.2 hours by adult sockeye salmon. Similarly, for rainbow trout oxygen debt was repaid in two to three hours following a 5-minute exhaustive burst swim (Scarabello et al., 1992).

One study suggests that after swimming to exhaustion, rainbow trout recover quicker when slowly swimming against a current than in still water (Milligan et al., 2000). Study results showed that trout that swam at a prolonged speed of 0.9 BL/s after exhaustive swimming fully recovered (muscle glycogen completely re-synthesized and lactate cleared) within two hours, whereas trout subjected to the same exhaustive swim required more than six hours to recover when held in still water. This finding agrees with the idea that steelhead can recover from fatigue when swimming at sustained speeds. The swim speed data presented in Figure

2.4 suggests that the transition between prolonged and sustained speeds for adult steelhead is near 1 BL/s.

Based on these studies, a water velocity of 2 ft/s was selected as the maximum water velocity suitable for allowing an adult steelhead to rest and recover from fatigue. This was arrived at assuming a 24 inch steelhead and using a 1 BL/s threshold. Since the fish will need to rest and recover numerous times as it swims through the flood control channel, its necessary to allow the fish to become fully rested when water velocities are suitable. Therefore, a resting period of 2.5 hours was selected for use in routing the steelhead through the flood control channel.

2.3.5 Water Depth Requirements

2.3.5.1 Minimum Water Depth for Swimming

For modeling fish locomotion, its necessary to select a minimum water depth sufficient to allow the fish to swim freely. Steelhead are frequency observed swimming through extremely shallow water with their body only partially submerged. However, this is typically only done over short distances, such as over a shallow riffle. When swimming partially submerged the fish's tail is not providing as much thrust as when fully submerged, which would result in less than optimal swimming performance. Additionally, all swim speed – fatigue time relationships were developed from tests that involved the fish swimming fully submerged. Application of these relationships to partially submerged fish would likely lead to substantial inaccuracy. Therefore, when modeling steelhead locomotion its logical to set the minimum water depth to be equal to or greater than the body height of the fish.

Unlike body length, body height is not often measured. However, a body height to length ratio of 0.222 for steelhead has been established (FishBase, 2006). Using this ratio gives a 0.45 feet body depth for a steelhead of the average length and 0.53 feet for a steelhead from the largest 10 percentile. Based on this, a minimum water depth for swimming through the flood control channel was set at 0.50 feet.

2.3.5.2 Minimum Water Depth for Resting Pools

Besides requiring slow enough water velocities within the pools to allow the fish to rest, it is also necessary to ensure that the pools have sufficient depth. Depth within the pool provides cover from overhead predation. If a fish feels vulnerable to predation, it may not utilize the resting pool. Bates (2001) recommends providing at least 2.5 feet of cover for Pacific salmon and steelhead. Others recommend a minimum water depth of 2 feet for pools within a pool and weir fish ladder (CDFG 1998; FAO/DVWK, 2002).

Based on recommendations from these references, a minimum water depth for design of resting pools was set at 2.0 feet, with the expectation that the water depth will be substantially more at most migration flows.

2.3.6 Preferred Fish Route

Fish generally swim in portions of a stream channel containing the lowest water velocities. This is especially true when faced with water velocities that require them to swim in prolonged or burst mode. However, fish will generally not swim for long distances in exceedingly shallow water. Therefore, to model fish swimming through the flood control channel requires identifying a route that the fish would likely take. Assumptions and criteria used to identify the preferred fish route were steelhead (1) would not swim through water depths less than 0.5 feet and (2) would select a continuous route containing the lowest water velocities.

Using this criteria and output files containing the water depths and velocities predicted by MIKE21C, a preferred fish path was digitized in ArcMap 9.0. To account for the swimming motion of the steelhead, its overall width within the water column was conservatively assumed to be 2 feet. Therefore, the digitized fish path was given a 1 foot buffer on each side and the average water depth and velocity across this width was in thefish routing model.

2.4 Summary of Fish Passage Criteria and Fish Routing Parameters

The following table lists the various criteria and parameters used to model fish swimming through the existing flood control channel, from the stilling basin to the upstream end, as well as evaluate the effectiveness of different resting pool designs (Table 2.1).

Table 2.1 – Summary of criteria and parameters used to model fish locomotion through the upper section of the San Lorenzo Creek flood control channel, and for evaluating the effectiveness of proposed resting pool designs.

Steelhead Body Length (BL) and Body Depth Ranges	
Mean Body Length/Body Depth	24.5 inches/5.4 inches
10 Percentile	18.9 inches/4.2 inches
90 Percentile	28.5 inches/6.3 inches
Fish Passage Flows	
Steelhead Migration Period	Dec. 1 – Mar. 31
Low Passage Flow	3 cfs
High Passage Flow	115 cfs
Swimming Capabilities and Criteria	
<u>Sustained Swimming</u>	$\leq$ 1 BL/s
<u>Prolonged Swim Speeds</u>	1 BL/s - 6 BL/s
Swim Speed – Fatigue Time Relationships	$\ln(T_{mean}) = -0.487U_s + 6.466$
Optimum Ground Speed	2.05 BL/s
<u>Burst Swim Speeds</u>	> 6 BL/s
Swim Speed – Fatigue Time Relationships	Not Used
Width of Swimming Path	2.0 feet
Water Depth Required for Swimming	0.5 feet
Resting Pool Criteria	
Minimum Pool Depth	2.0 feet
Water Velocity for Resting	$\leq$ 2.0 ft/s
Recovery Time following Fatigue	2.5 hours

3 Existing Fish Passage Conditions

3.1 Hydraulics

DHI modeled channel hydraulics using the existing channel geometry and MIKE 21C. Grid spacing for the existing conditions model was approximately 5 feet in the streamwise direction and 1 foot in the direction normal to the flow. The model was ran at 20, 60, 80, 100, 120, 160, 200, and 280 cfs and results provided water depth and depth average 2-D water velocity for each node in the grid. ArcMap 9.0 was used to view and analyze model output. Table 3.1 summarizes water velocity and depth conditions at each of the flows within the entire upper channel and specifically within the fish channel, which consistently contains more depth but higher velocities.

3.2 Fish Routing Results

The fish routing model was ran for hydraulic conditions occurring at each of the eight flows listed above. For each flow three runs were conducted using three different sized steelhead: average length, smallest 10% of population, and largest 10% of population. The mean swim speed – fatigued time relationship shown in Figure 2.4 was used for all three.

Table 3.1 – Model results for water depths and velocities in the upper flood control channel. The table shows results for the entire channel, and within the low-flow fish channel only.

	Entire Channel		Fish Channel		
				Velocity	
Flow	Average Depth	Average Velocity	Average Depth	Average	Max*
20 cfs	0.2 ft	2.1 ft/s	1.1 ft	3.7 ft/s	4.8 ft/s
60 cfs	0.4 ft	3.5 ft/s	1.4 ft	4.5 ft/s	5.7 ft/s
80 cfs	0.5 ft	3.9 ft/s	1.5 ft	4.9 ft/s	6.1 ft/s
100 cfs	0.6 ft	4.3 ft/s	1.6 ft	5.3 ft/s	6.6 ft/s
120 cfs	0.7 ft	4.6 ft/s	1.7 ft	5.5 ft/s	6.7 ft/s
160 cfs	0.9 ft	5.2 ft/s	1.8 ft	6.3 ft/s	7.6 ft/s
200 cfs	1.0 ft	5.8 ft/s	1.9 ft	7.0 ft/s	8.4 ft/s
280 cfs	1.1 ft	6.7 ft/s	2.1 ft	8.4 ft/s	11 ft/s

* Highest water velocity, neglecting the “velocity ramp” channel transition reach near Foothill Boulevard.

3.2.1 Preferred Fish Route

ArcMap, was used to color code each grid point based on water depth and velocity to discern potential fish routes. It became apparent that at flows below roughly 80 cfs the only consistently continuous path was within the low-flow fish channel. Therefore, for flows from 20 cfs to 60 cfs the preferred fish route is the centerline of the fish channel. For each of the six flows modeled between 80 cfs to 280 cfs a unique fish route was drawn and average water velocities and depths along the route were calculated. The water velocity and depth encountered by the fish as they are routed upstream are referred to as the occupied velocity and occupied depth.

Figures 3.1 through 3.8 show the water depths and velocities encountered by the fish at each of the eight modeled flows. Notice that at 20 cfs and 60 cfs the water depths and velocities encountered by the fish have much less variability than at the higher flows. This is due to the fish remaining within the fish channel at 20 cfs and 60 cfs, providing a more constant depth than when the swim path routes the fish out of the fish channel.

Although water velocities within the channel increase as flows increase, there is little difference in the velocities encountered by the fish at 60 cfs and 80 cfs. At 80 cfs water depth is sufficient to allow the fish to swim through slower water located near the edge of the concrete channel.

3.2.2 Fish Fatigue and Location of Resting Pools

Using the methods outlined in Chapter 2, the degree to which the fish was fatigued was tracked as it was routed up the channel. Included in Figures 3.1 through 3.8 are the locations where the fish becomes fully fatigued. In order to route a fish up the length of channel it was assumed that at these locations a resting pool would be available for resting and recovery. The model assumed that these resting pools would contained water velocities less than 2 ft/s (resting velocity).

Locating where the fish becomes fully fatigued can be used to identify the number and placement of proposed resting pools. The number and placement depends on (1) the highest flow that passage should be provided and (2) the proportion of the population that should be passed at that flow. If the upper fish passage flow is set at 115 cfs and passage of the average sized fish (and larger) is to be accommodated, there needs to be at least 60 pools with an average spacing of 337 feet (Table 3.2)

3.2.3 Travel Time

Travel time of the fish was calculated as part of the fish routing model. Given the ground speed of the fish, the amount of time required for the fish to swim a given distance was calculated. Once the fish reached 100% fatigue, the model assumed that a resting pool would be provided and the fish would rest for 2.5 hours to fully recover before continuing upstream. The results show that at 120 cfs the average steelhead would require 60 rest periods and take 161 hours (6.7 days) to swim through the entire channel. However, the actual swim time is only 11 hours. Given the uncertainty around the amount of rest time needed to recover from fatigue, it is reasonable to assume an adult steelhead could ascend the channel more rapidly.

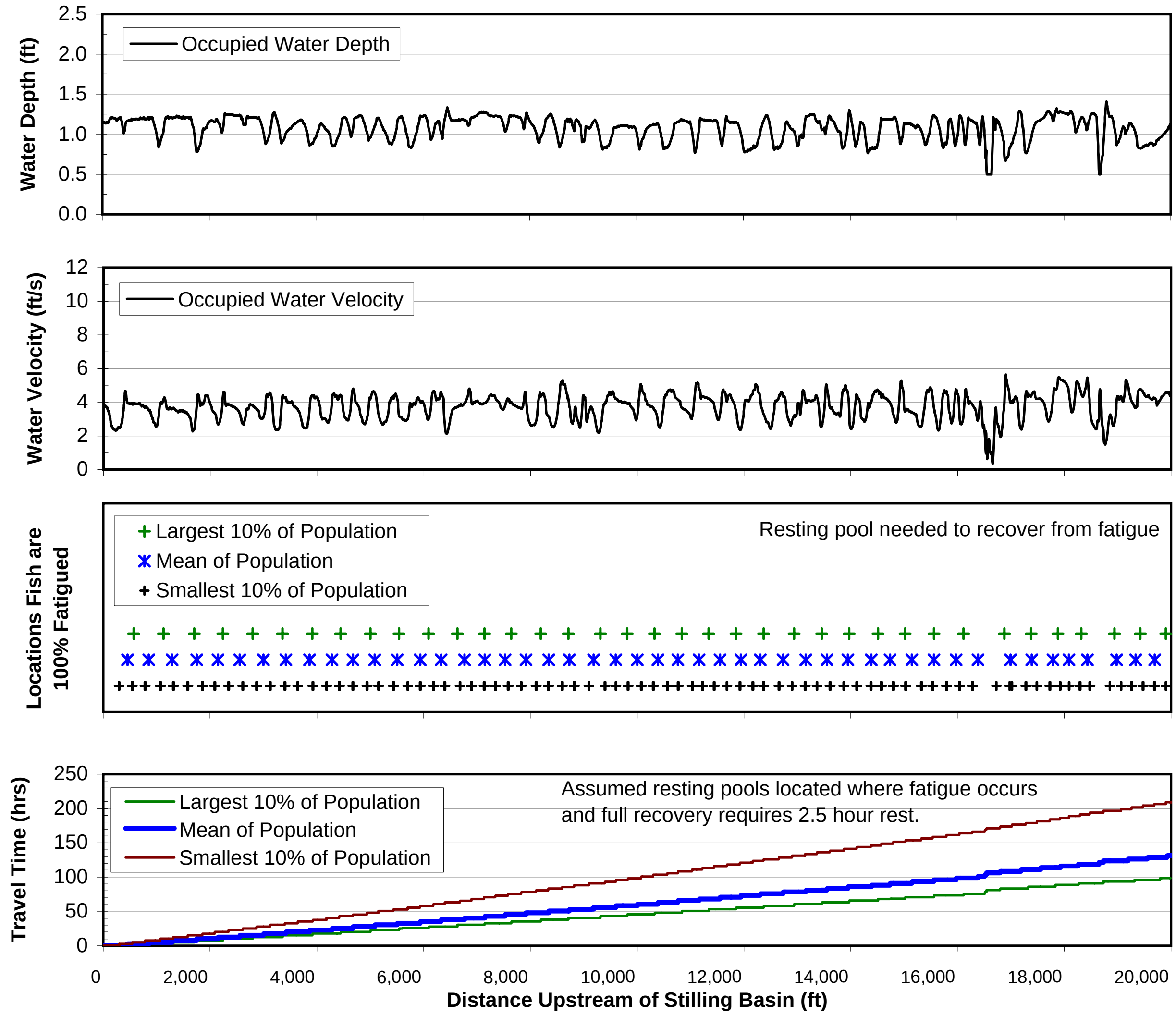


Figure 3.1 - At 20 cfs, the water velocities and depths encountered by the steelhead as it swims upstream along the preferred swim route. Fatigue and travel time of the fish was tracked assuming resting pools were available at locations when the fish was 100% fatigued and the fish rested for 2.5 hours before continuing upstream.

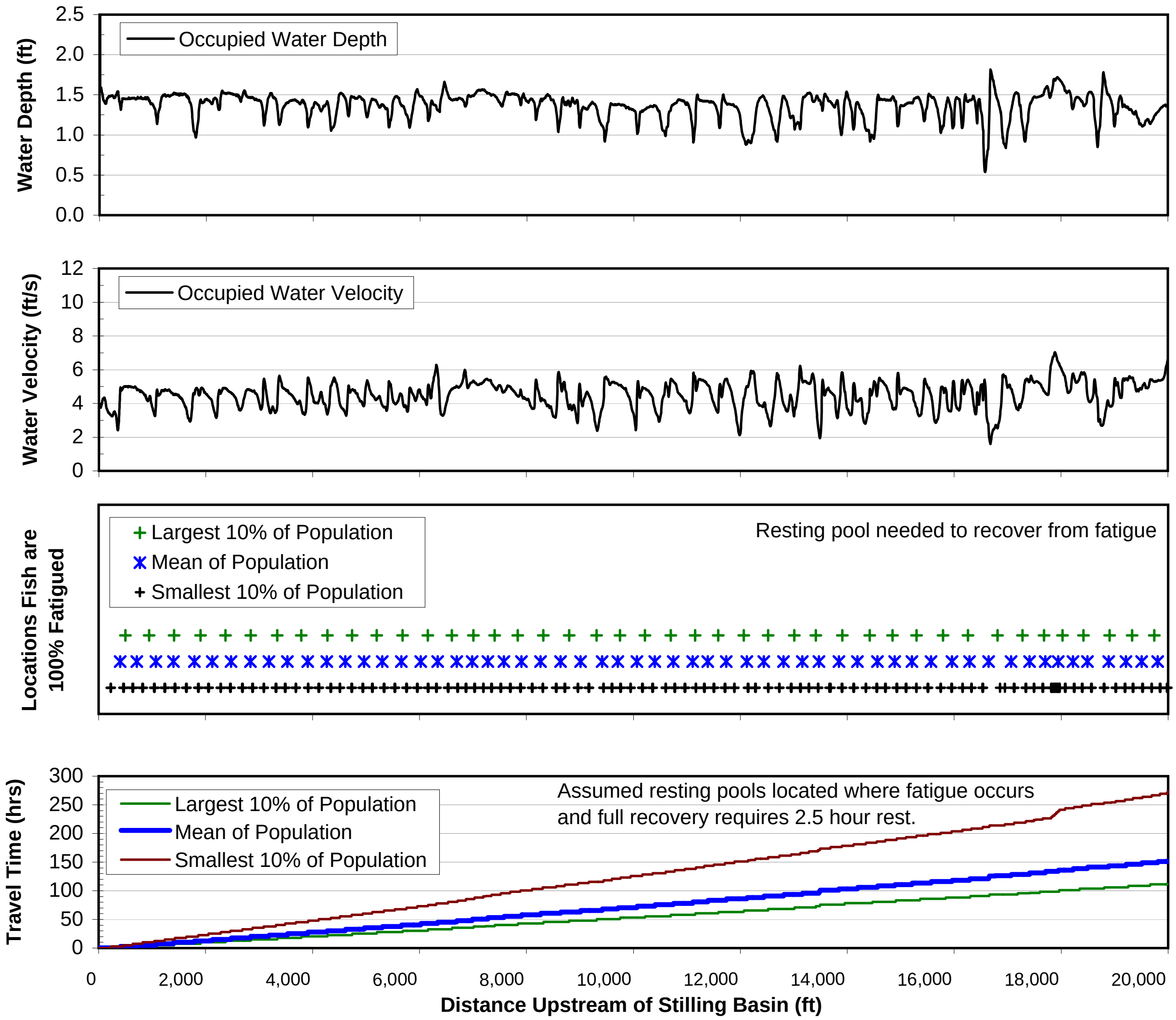


Figure 3.2 - At 60 cfs, the water velocities and depths encountered by the steelhead as it swims upstream along the preferred swim route. Fatigue and travel time of the fish was tracked assuming resting pools were available at locations when the fish was 100% fatigued and the fish rested for 2.5 hours before continuing upstream.

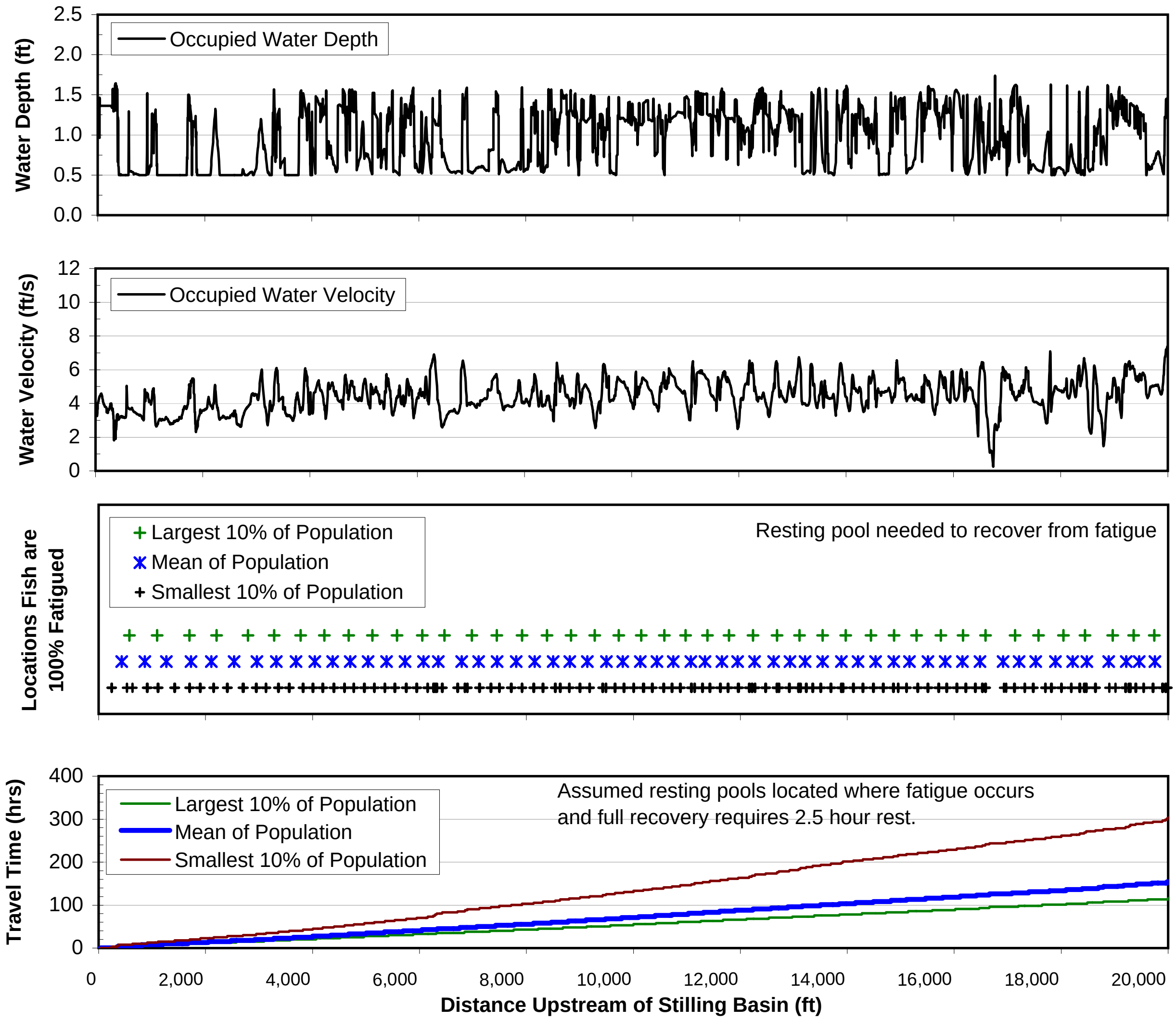


Figure 3.3 - At 80 cfs, the water velocities and depths encountered by the steelhead as it swims upstream along the preferred swim route. Fatigue and travel time of the fish was tracked assuming resting pools were available at locations when the fish was 100% fatigued and the fish rested for 2.5 hours before continuing upstream.

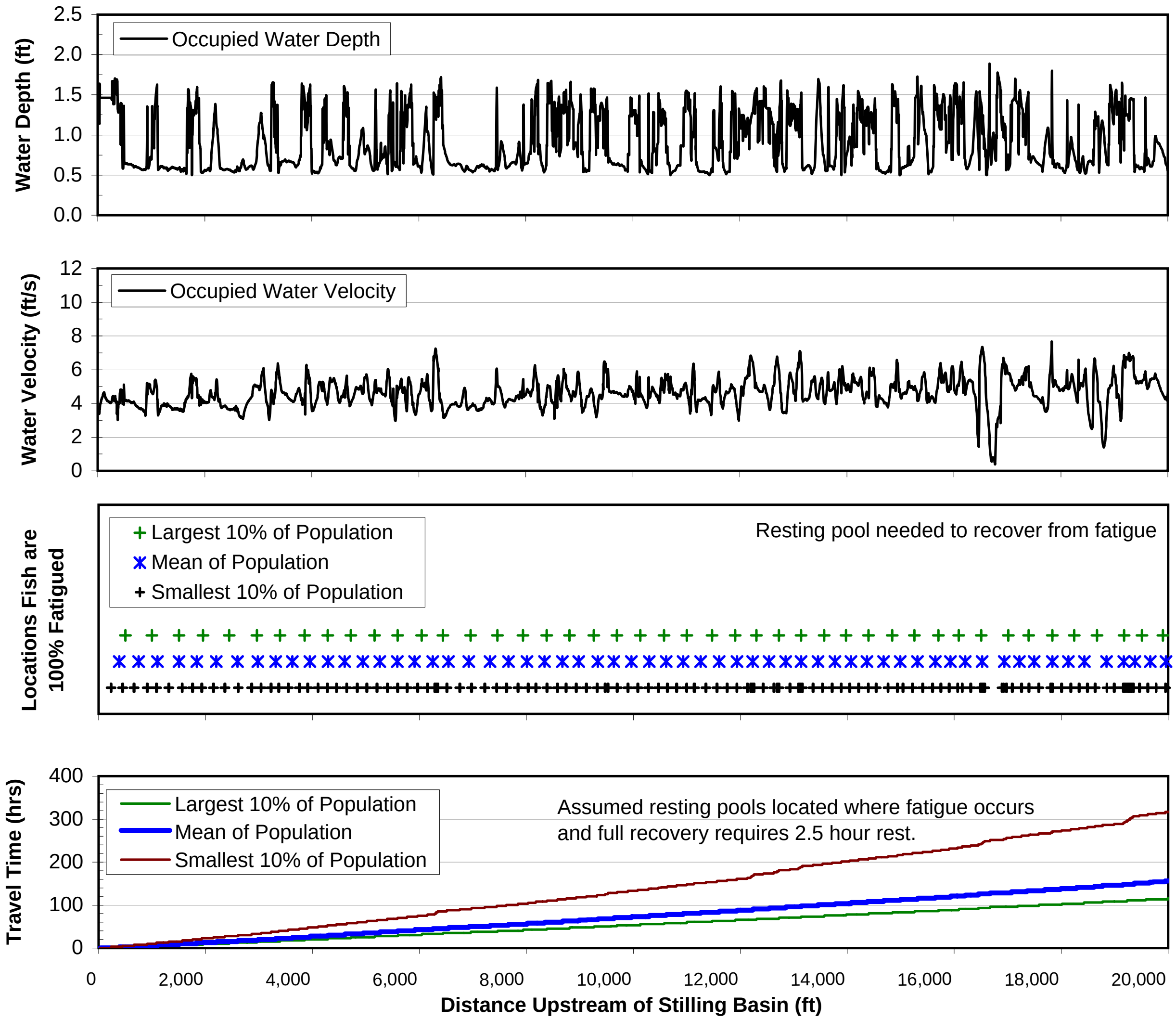


Figure 3.4 - At 100 cfs, the water velocities and depths encountered by the steelhead as it swims upstream along the preferred swim route. Fatigue and travel time of the fish was tracked assuming resting pools were available at locations when the fish was 100% fatigued and the fish rested for 2.5 hours before continuing upstream.

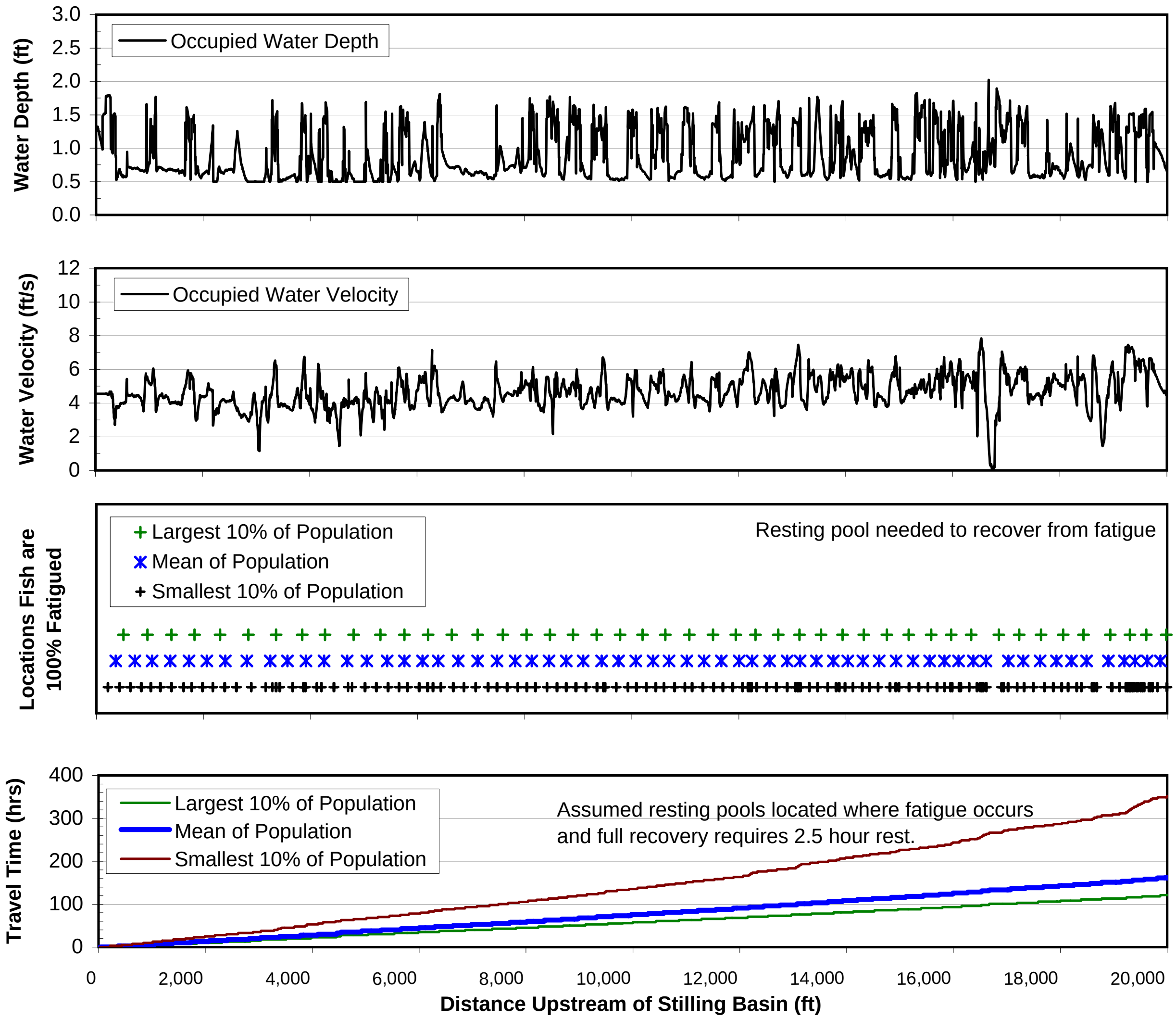


Figure 3.5 - At 120 cfs, the water velocities and depths encountered by the steelhead as it swims upstream along the preferred swim route. Fatigue and travel time of the fish was tracked assuming resting pools were available at locations when the fish was 100% fatigued and the fish rested for 2.5 hours before continuing upstream.

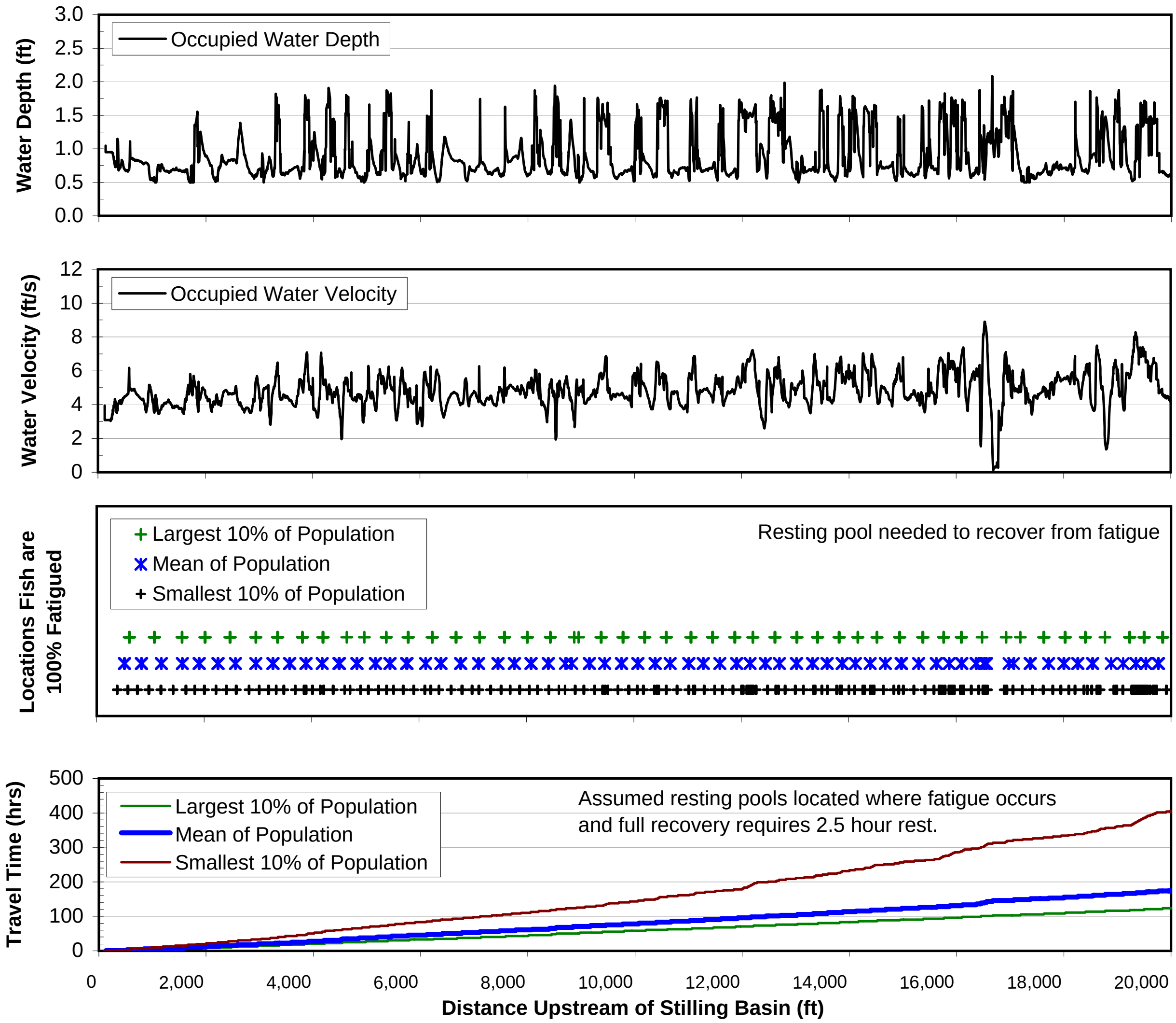


Figure 3.6 - At 160 cfs, the water velocities and depths encountered by the steelhead as it swims upstream along the preferred swim route. Fatigue and travel time of the fish was tracked assuming resting pools were available at locations when the fish was 100% fatigued and the fish rested for 2.5 hours before continuing upstream.

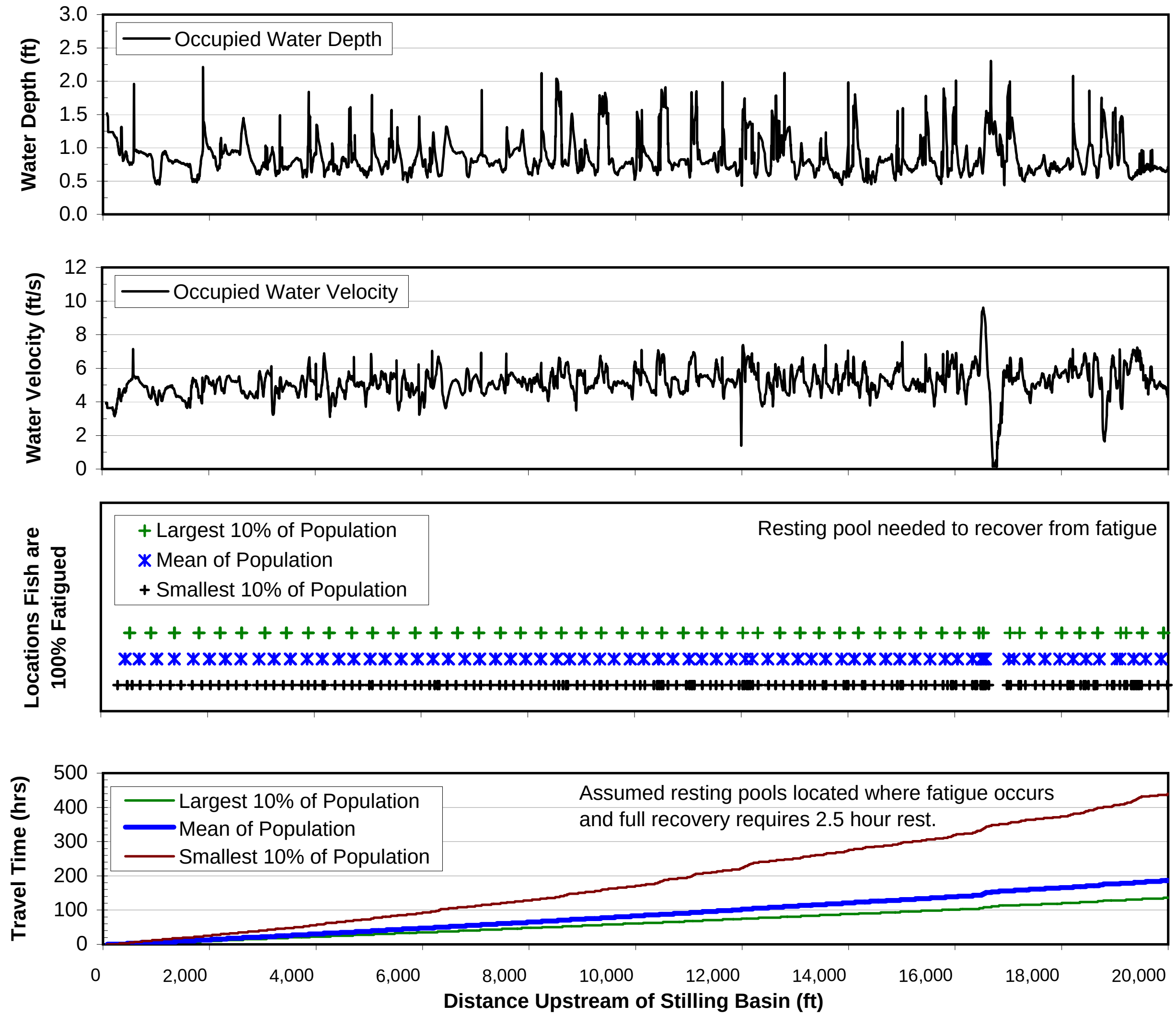


Figure 3.7 - At 200 cfs, the water velocities and depths encountered by the steelhead as it swims upstream along the preferred swim route. Fatigue and travel time of the fish was tracked assuming resting pools were available at locations when the fish was 100% fatigued and the fish rested for 2.5 hours before continuing upstream.

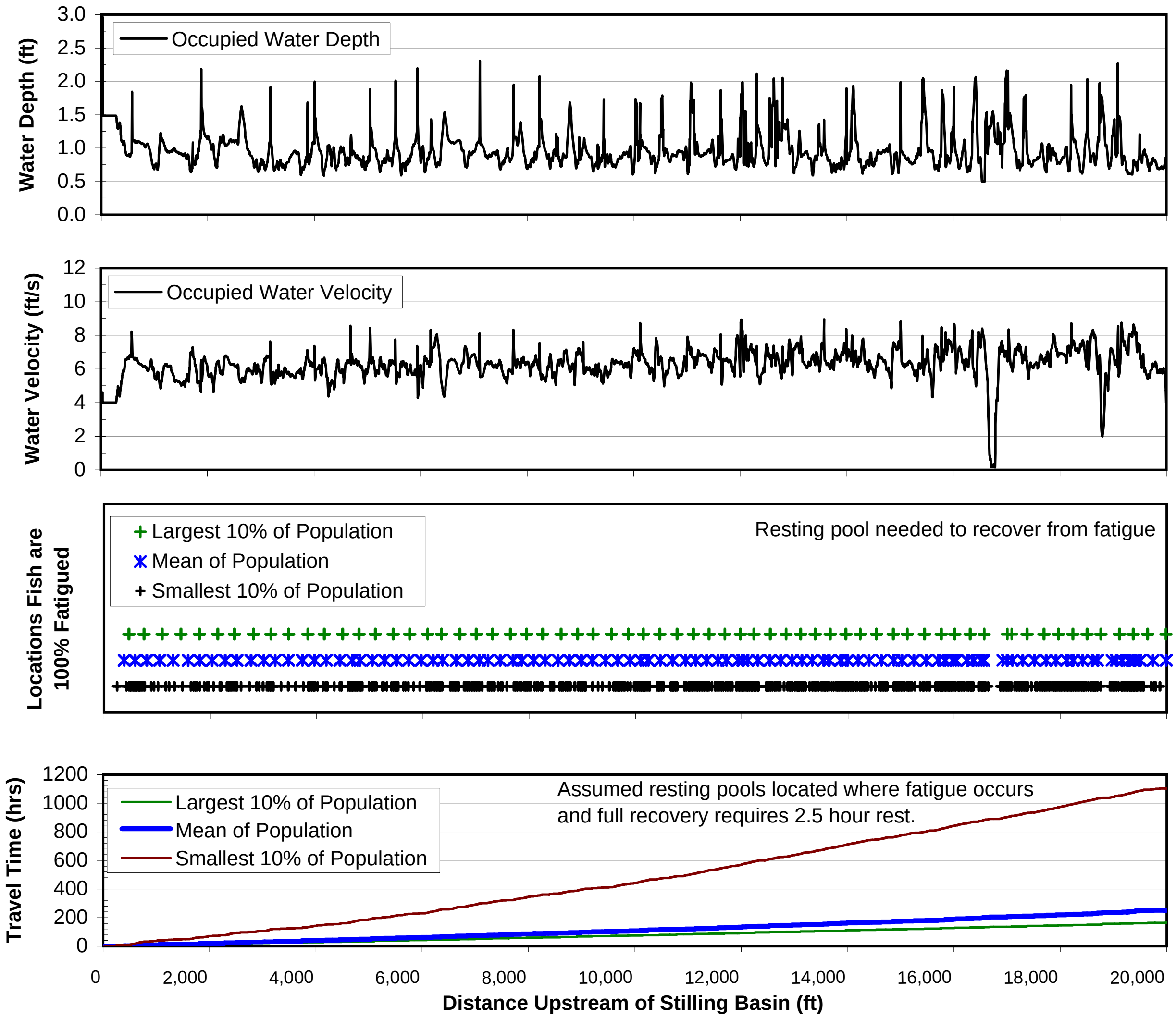


Figure 3.8 - At 280 cfs, the water velocities and depths encountered by the steelhead as it swims upstream along the preferred swim route. Fatigue and travel time of the fish was tracked assuming resting pools were available at locations when the fish was 100% fatigued and the fish rested for 2.5 hours before continuing upstream.

Table 3.2 – Minimum number of resting pools and average spacing between pools for small, average, and larger sized steelhead. Number and spacing based on predicted locations where fish would become fatigued and need to rest.

	Steelhead Size					
	Smallest 10%		Average		Largest 10%	
Flow	Number of Pools	Average Spacing	Number of Pools	Average Spacing	Number of Pools	Average Spacing
20 cfs	79	252 ft	48	415 ft	35	566 ft
60 cfs	106	189 ft	58	342 ft	42	468 ft
80 cfs	118	171 ft	58	349 ft	42	481 ft
100 cfs	123	164 ft	59	341 ft	43	469 ft
120 cfs*	131	152 ft	60	337 ft	44	461 ft
160 cfs	147	136 ft	64	318 ft	44	464 ft
200 cfs	166	121 ft	68	293 ft	48	412 ft
280 cfs	439	47 ft	99	209 ft	64	322 ft

* Resting pool number and average spacing for the high fish passage design flow.

3.2.4 Comparison of Fish Passage Results to Observations

According to the fish routing model results, the largest 10% of steelhead swimming at the distance optimizing speed could only ascend the first 577 feet of the channel during a flow of 20 cfs, and shorter distances at higher flows. However, upstream migrating steelhead have periodically been observed at various locations within the channel, including near the upstream end.

One explanation for the discrepancy is differences in the actual hydraulics to those predicted by MIKE21C. Although the overall flow patterns predicted by MIKE 21C appear relatively accurate, direct observations and video of the channel at various flows show small areas of lower velocity along the inside section of the bends. However, the hydraulic model shows these areas containing some of the highest water velocities. This is where the project team observed the steelhead holding in 60 cfs flow during a site visit. From observations, a steelhead requires only a couple square feet of slow velocity to hold and rest. Therefore, it is possible that the resolution used in MIKE 21C was not sufficient to identify these pockets of slow water where a fish could rest. Additionally, there was a lack of actual velocity measurements from the channel to fully calibrate and validate the velocity field predicted by MIKE 21C.

Other areas of potential inaccuracy include:

1. Steelhead swim speed – fatigue time relationship is based on a relatively small sample size, increasing potential inaccuracies.
2. Steelhead often swim through depths shallower than 0.5 feet for short distances, which could allow them to use a more optimum swimming path than predicted
3. Model assumes a fatigued steelhead rests until fully recovered. However, the relationship between resting time and degree of

recovery is non-linear and the fish may choose to only rest for short periods but more frequently.

In the end, this model and its results are intended to provide insight into the problem and viability of potential solutions. The conservative assumptions used with the fish routing model help ensure that proposed pool spacing is not excessive and that adult steelhead attempting to migrate through the channel will be successful.

4 Development of Resting Pool Designs

The analysis of existing conditions summarized in Chapter 3 provided an understanding of the number of resting pools needed and the average spacing between each pool. For development of resting pool designs, a constant pool spacing of 300 feet was selected. Results shown in Table 3.2 suggest that at least 60 pools would be required throughout the channel. Instead of modeling various resting pool alternatives for the entire channel, we selected a pilot reach located within the channel for testing pool shapes. Two pilot reaches were selected; one straight reach and one meandering reach. The straight reach starts 6,460 feet upstream of the stilling basin and is 1,000 feet long (Figure 4.1). This was selected because it is the longest straight segment within the upper flood control channel. The meandering pilot reach starts 11,660 feet upstream of the stilling basin and is 1,700 feet long. This reach was selected because is has five bends ranging from relatively small to large curvatures (Figure 4.2).

The effectiveness of each pool was evaluated based on need to produce a region containing water velocities less than 2 ft/s at flows up to 120 cfs. Although water velocities do not need to be less than 2 ft/s throughout the entire pool, there must be sufficient area of slow water to allow the steelhead to hold and rest. This area, which must contain water velocities less than 2 ft/s, was defined as a minimum of 2 ft wide x 3 ft long x 2 ft deep.

4.1 Pool Designs for Straight Reach

Pool shapes were first developed and modeled for the straight pilot reach. In total, three alternatives were developed and tested, each being a refinement of the previous shape based on model results.

4.1.1 Straight Reach - Alternative 1

Alternative 1 is a large pool similar in shape to those evaluated in the previous fish passage study (MLA, 2003). The bottom of the pool is placed 2 feet below the invert of the fish channel (Figure 4.3). The sides of the pool are vertical, 3 feet high, to provide cover for holding fish. To minimize energy loss associated with expansion and contraction of flow, the entrance and exit of the pool has a transition slope of 3(H):1(V) in the streamwise direction. The upstream end of the pool has a V-Shape to help concentrate water velocities towards the center of the pool. This is intended to create back-eddies and slower water along the sides of the pool and increase scouring forces in the center to minimize sedimentation. To provide sufficient area for two or more fish to rest and sufficient pool volume to avoid excessive turbulence associated with energy loss, the pool is 12 feet long (not counting entrance and exit transitions). This gave the pool an overall length of 24 feet.

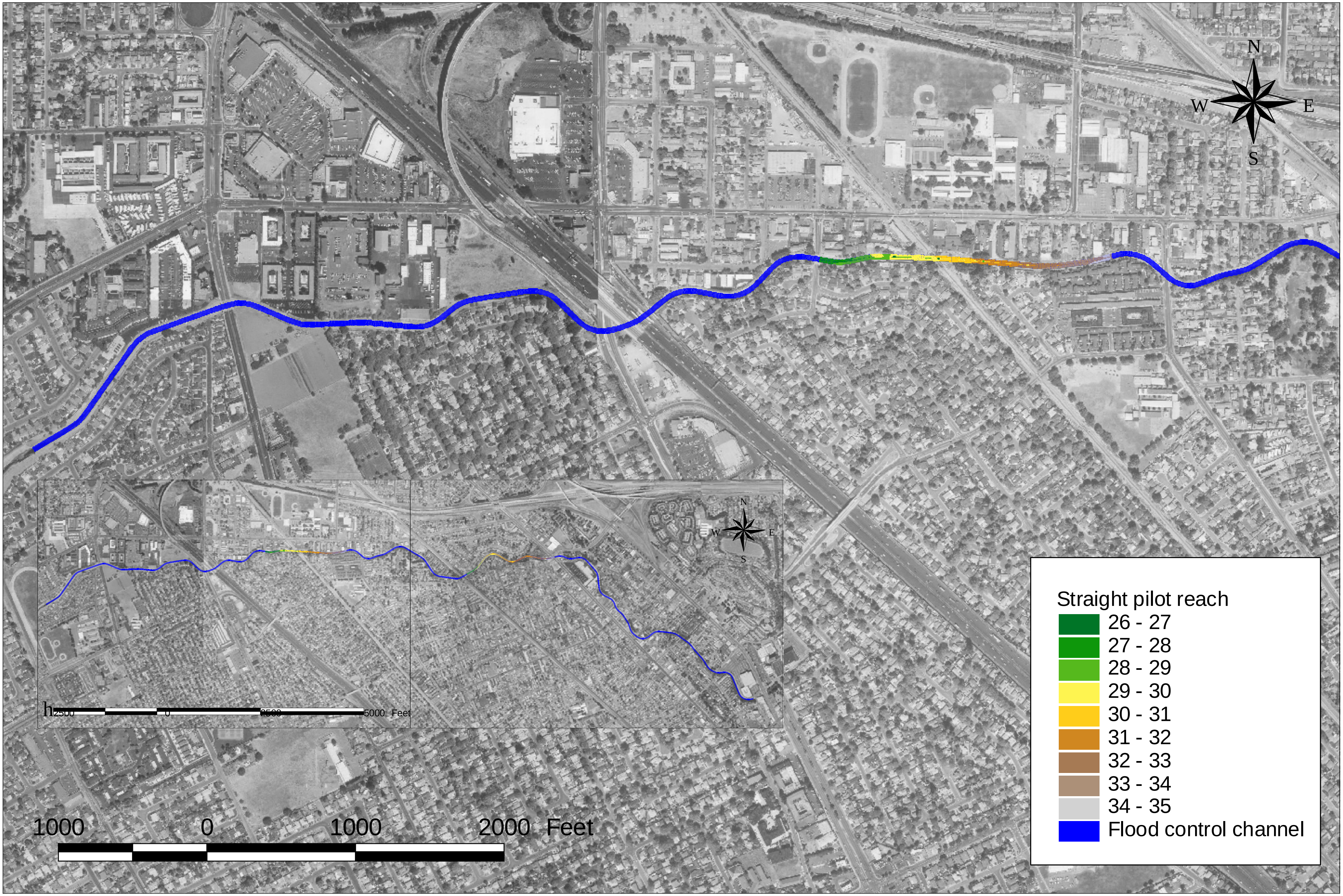


Figure 3.9 - Location and bathometry (in feet) of straight pilot reach.

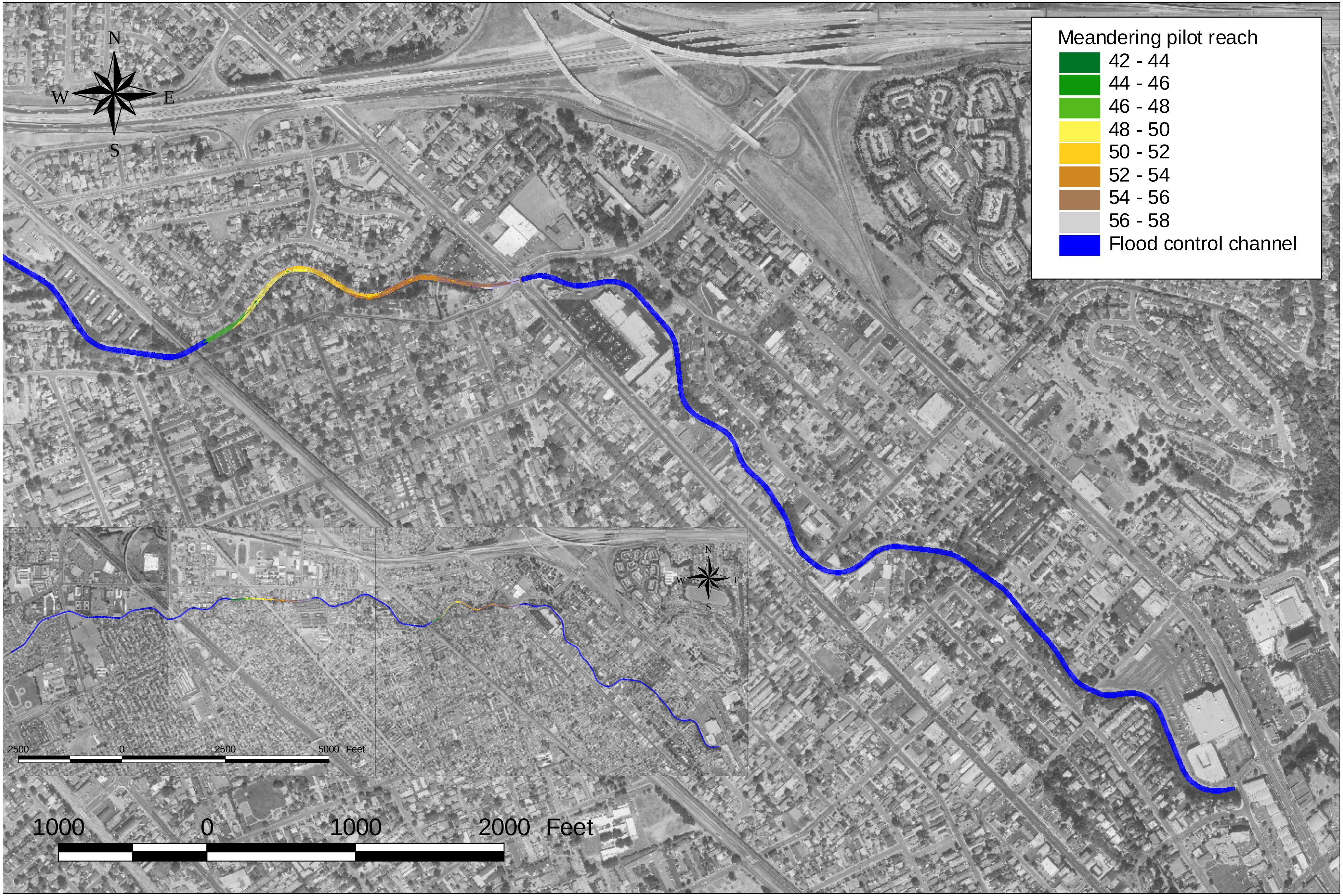


Figure 3.10 - Location and bathometry (in feet) of meandering pilot reach

4.1.1.1 Performance at Fish Passage Flows

This pool shape creates suitable water velocities for fish to hold and rest at flows exceeding 280 cfs. Although this pool shape would be suitable for fish, it results in a relatively large amount of energy loss from expansion and contraction of flow. Since this pool has water velocities below 2 ft/s at flows well in excess of the high fish passage design flow of 115 cfs, we chose to develop smaller pools with more gentle transitions for the other two alternative pool designs in the straight reach.

4.1.2 Straight Reach - Alternative 2A

Alternative 2A was proposed by the District as a minimal pool alternative. The pool is located to the left of the fish channel and its invert is set equal to the bottom elevation of the fish channel (Figure 4.5). The left side of the pool has a vertical wall 1 foot high. To provide sufficient area for two or more fish to rest and sufficient pool volume to avoid excessive turbulence associated with energy loss, the pool is 14 feet long (not counting entrance and exit transitions) and extends 7.5 feet to the left of the fish channel. The entrance and exit of the pool has a gradual slope of 10(H):1(V) and an overall length of 34 feet.

4.1.2.1 Performance at Fish Passage Flows

Straight Reach – Alternative 2A was modeled in the same runs as Alternative 2B. The upstream two pools in the pilot reach were of the Alternative 2A shape. The hydraulic analysis showed the Alternative 2A pool shape provides sufficient reduction in water velocities at flows up to 120 cfs, with velocities averaging 1.9 ft/s (Figure 4.7). However the pool shape fails to provide sufficient depth for the resting fish. Instead of providing the recommended minimum depth of 2 feet, the pool is only 1.2 feet deep at 20 cfs 1.9 feet and at 120 cfs.

The hydraulics created by this pool shape, when compared to the performance of Alternative 1, showed the importance of placing the pool along one side of the fish channel. This helps isolate the pool from the momentum of the water in the fish channel, keeping pool velocities low. Having the pool on only one side of the channel reduces flow expansion and contraction, resulting in less energy loss. Based on the characteristics of Alternative 2A, the remaining pool shapes tested for the straight and meandering reaches were placed along the side of the fish channel.

4.1.3 Straight Reach - Alternative 2B

Alternative 2B was a modification from 2A; lowering the bottom of the pool by 1 foot (Figure 4.6). The pool is also located to the left side of the fish channel and has a 2 feet tall vertical sidewall, which should provide sufficient cover for the fish. The entrance and exit of the pool has a gradual slope of 10(H):1(V) and an overall length of 54 feet.

4.1.3.1 Performance at Fish Passage Flows

Straight Reach – Alternative 2B was modeled in conjunction with Alternative 2A. The downstream two pools in the pilot reach were of the Alternative 2B shape. The hydraulic analysis showed the Alternative 2B pool shape provides adequate 2.1 feet of depth at 20 cfs and 3.5 feet of depth at 280 cfs. It also provides sufficient reduction in water velocities at flows exceeding 200 cfs (Figure 4.7). Since the velocities are only 1.0 ft/s at 120 cfs, approximately the high fish passage design flow, it may be possible to reduce the width of the pool by 3 feet and still maintain water velocities below 2 ft/s in an area sufficient for fish to hold and rest.

Of the three alternative shapes modeled for the straight reach, Alternative 2B provides the best balance between creating suitable resting pool conditions for steelhead and minimizing energy loss.

4.2 Pool Designs for Meandering Reach

Three alternative pool shapes were developed and modeled in the meandering pilot reach. For each alternative four pools were located in the meandering reach spaced roughly 300 feet apart. Pools for Alternative 1 and 2 are placed near the upstream end of the bend. Pools for Alternative 3 are placed further downstream, closer to the apex of the bends. Since each bend has a unique curvature and is superelevated to varying degrees, hydraulics from pool to pool varies.

4.2.1 Meandering Reach - Alternative 1

Alternative 1 for the meandering pilot reach is placed on the outside of the bend in a superelevated section of the channel (Figure 4.8). Placing it on the outside of the bend was done to keep the pool out of the main flow. There is little to no water flows on the outside of the bend at fish passage flows. Instead, the flow is concentrated in the fish channel and inside bend.

The pool bottom was set 0.5 feet below the invert of the fish channel and the pool width extended from the inside edge to 5 feet past the fish channel, giving it an overall width of 10 feet. The entrance and exit transition had a 10(H):1(V) slope. To provide sufficient area for two or more fish to rest and sufficient pool volume to avoid excessive turbulence associated with energy loss, the pool is 10 feet long (not counting entrance and exit transitions), giving the pool and overall length of approximately 40 feet.

4.2.1.1 Performance at Fish Passage Flows

Placing the pool on the outside proved to minimize interactions with the main flow, thus keeping water velocities low (Figure 4.9). Velocities remain below 2 ft/s at flows near or slightly above 120 cfs (depending on the specific pool). However, water depths are only 1.5 to 1.8 feet at 20 cfs and 1.8 to 2.0 feet at 120 cfs.

4.2.2 Meandering Reach - Alternative 2

Alternative 2 was based partially on recommendations provided in the earlier fish passage study (MLA, 2003), which suggested creating a better connection from the fish channel to the deeper water on the inside of the bend. Currently, at fish passage flows only sheeting flow exiting the fish channel flows into the inside bend, making it difficult for a steelhead holding along the deeper inside bend to return to the fish channel. The intent of the Alternative 2 pool shape was to have the edge of the pool extend into the deeper water along the inside bend, improving the connection to the fish channel.

The Alternative 2 pool has a similar shape to Alternative 1, but is located on the inside of the bend and extends to within 5 feet of the channel wall (Figure 4.10). The pool bottom was placed 0.5 feet below the invert of the fish channel and was 10 feet long (not including entrance and exit transitions). The total length was approximately 40 feet.

4.2.2.1 Performance at Fish Passage Flows

Alternative 2 pool provides suitable resting velocities at flows up to roughly 100 cfs, with the two pools on the smaller bends having suitable water velocities up to 120 cfs (Figure 4.11). However, water depth is only 1.3 feet at 20 cfs, and does not become sufficiently deep (2 feet) until 80 cfs. These pools do provide a reasonably good connection to the deeper water on the inside of the bend, but the model predicted water velocities along the inside bend appear to be excessive for fish resting. Additionally, since Alternative 2 pools are directly in the main path of the flow, they will induce more energy losses at higher flows than Alternatives 2 and 3.

4.2.3 Meandering Reach - Alternative 3

Alternative 3 for the meandering reach is a modification of Alternative 1; with the pool on the outside of the bend with the left side of the fish is left intact (Figure 4.12). Although this alternative would be more costly to construct due to the additional complexity of the shape, we anticipate that this shape will further minimize the interaction of the pool with the flow in the fish channel.

4.2.3.1 Performance at Fish Passage Flows

This pool shape did exceptionally well at isolating it from the momentum of flow within the fish channel. Even at 280 cfs, all four pools contain large areas with water velocities less than 2 ft/s (Figure 4.13). However, like Alternative 1, water depths were only 1.5 to 1.8 feet at 20 cfs and 1.8 to 2.0 feet at 120 cfs. This led to development of a fourth alternative with a deeper pool.

4.2.4 Meandering Reach - Alternative 3B

Alternative 3B is identical to Alterative 3, but with a pool bottom that is 1 foot below the fish channel invert instead of 0.5 feet (Figure 4.14). This increases the overall length of the pool.

4.2.4.1 Performance at Fish Passage Flows

Like Alternative 3, this pool shape maintained suitable velocities for resting at flows exceeding 280 cfs. Additionally, it provided water depths greater than 2 feet deep at 80 cfs and above (Figure 4.15). Unlike the straight reach, increases in flows do not necessarily result in increased pool depth. Instead, at fish passage flows the water spills out of the fish channel and sheets across towards the inside bend, thus increasing the depth along the inside bend instead of in the fish channel and pools located along the outside of the bend.

4.3 Pool Induced Water Level Rise

For each pool shape, energy loss calculations for "bankfull" flow of 12,000 cfs were conducted by DHI using MIKE 11. A detailed description of the approach used to estimate energy losses associated with each pool shape are included in Appendix A. Energy loss calculations were conducted using 300 foot pool spacing. To evaluate the effect of having a long series of pools on capacity of the channel, the reach was extended to have 20 pools. This allowed for evaluating the "fully developed" rise in water levels. Accounting for energy loss associated with the pools allowed for estimates of the resulting water level rise associated with the pool at 12,000 cfs. Table 4.1 shows the fully developed pool induced water level rises for each alternative at 12,000 cfs.

Table 4.1 shows that pools placed on the outside of the bend in the meandering reach produce less energy loss at high flows than similar shaped pools in the straight reach. This is due to the channel shape that directs a larger portion of the flow to the inside half of the channel.

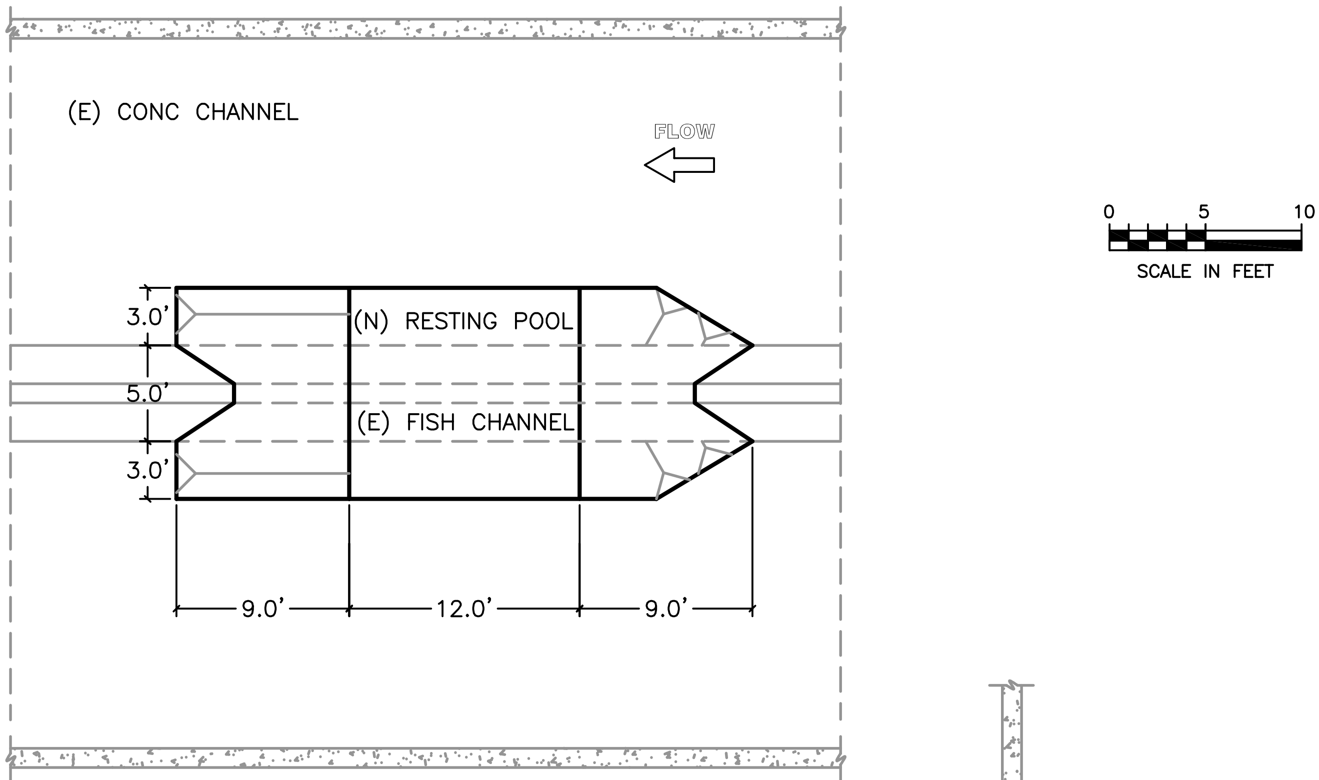
Table 4.1 – Predicted pool induced water level rise at the "bankfull" flow of 12,000 cfs for fully developed flow condition.

Pool Design Alternative	Water Level Rise at 12,000cfs for Fully Developed Flow Conditions
Straight 1	3.91 inches
Straight 2A	1.12 inches
Straight 2B	2.40 inches
Meandering 1	1.52 inches
Meandering 2	2.38 inches
Meandering 3	1.27 inches
Meandering 3B	1.68 inches

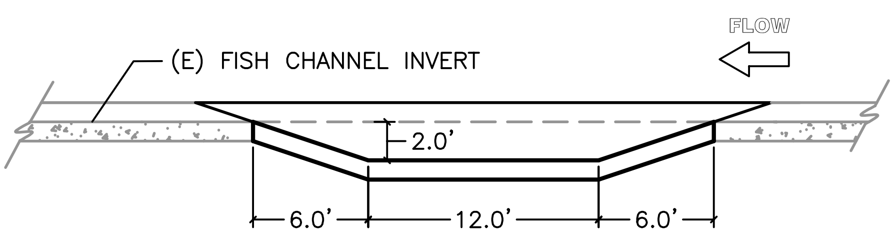
4.4 Preferred Pool Shape

For straight reaches Alternative 2B provides the best resting conditions while maintaining only a predicted 2.4 inches of water level rise at 12,000 cfs. At flows above the high passage flow of 115 cfs, Alternative 2B maintains water velocities less than 2 ft/s and water. It also maintains at least 2 feet of water at flows less than 20 cfs. This alternative appears to be a good choice. Additional alternative pool shapes could be modeled to further refine Alternative 2B, possibly decreasing the width slightly.

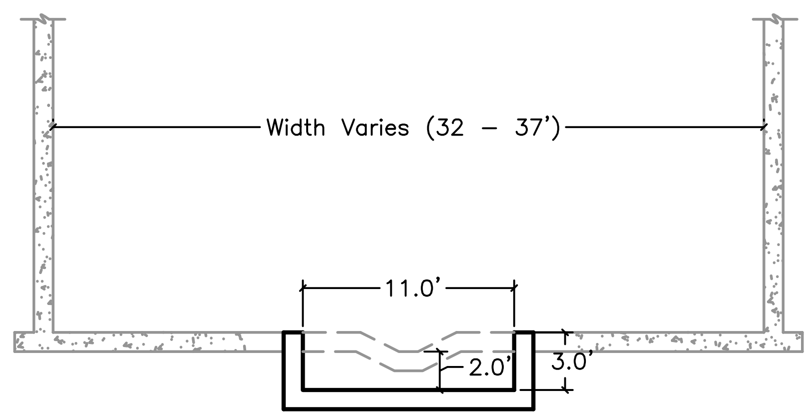
In meandering reaches, Alternative 3B performed best out of the four pool shapes, balancing fish passage and impacts on channel capacity. However, water depths within Alternative 3B failed to meet the 2 feet criteria at lower flows (<80 cfs). Therefore, it would be prudent to further refine this pool shape to increase water depths slightly at low flows. The potential rise in water surface for the Alternative 3B pool design is 1.68 inches at 12,000 cfs.



PLAN
Scale: 1"=10'



PROFILE
Scale: 1"=10'



SECTION
Scale: 1"=10'
(Looking Downstream)

Michael Love & Associates
Hydrologic Solutions
PO Box 4477 • Arcata, CA 95518 • (707) 476-8938

ALTERNATIVE 1

Resting Pool for Straight Channel Sections

SAN LORENZO CREEK FISH PASSAGE IMPROVEMENT PROJECT
Alameda County Flood Control and Water Conservation District

Date: 7/18/06	Design: ML	Drawn: AL	Figure 4.3

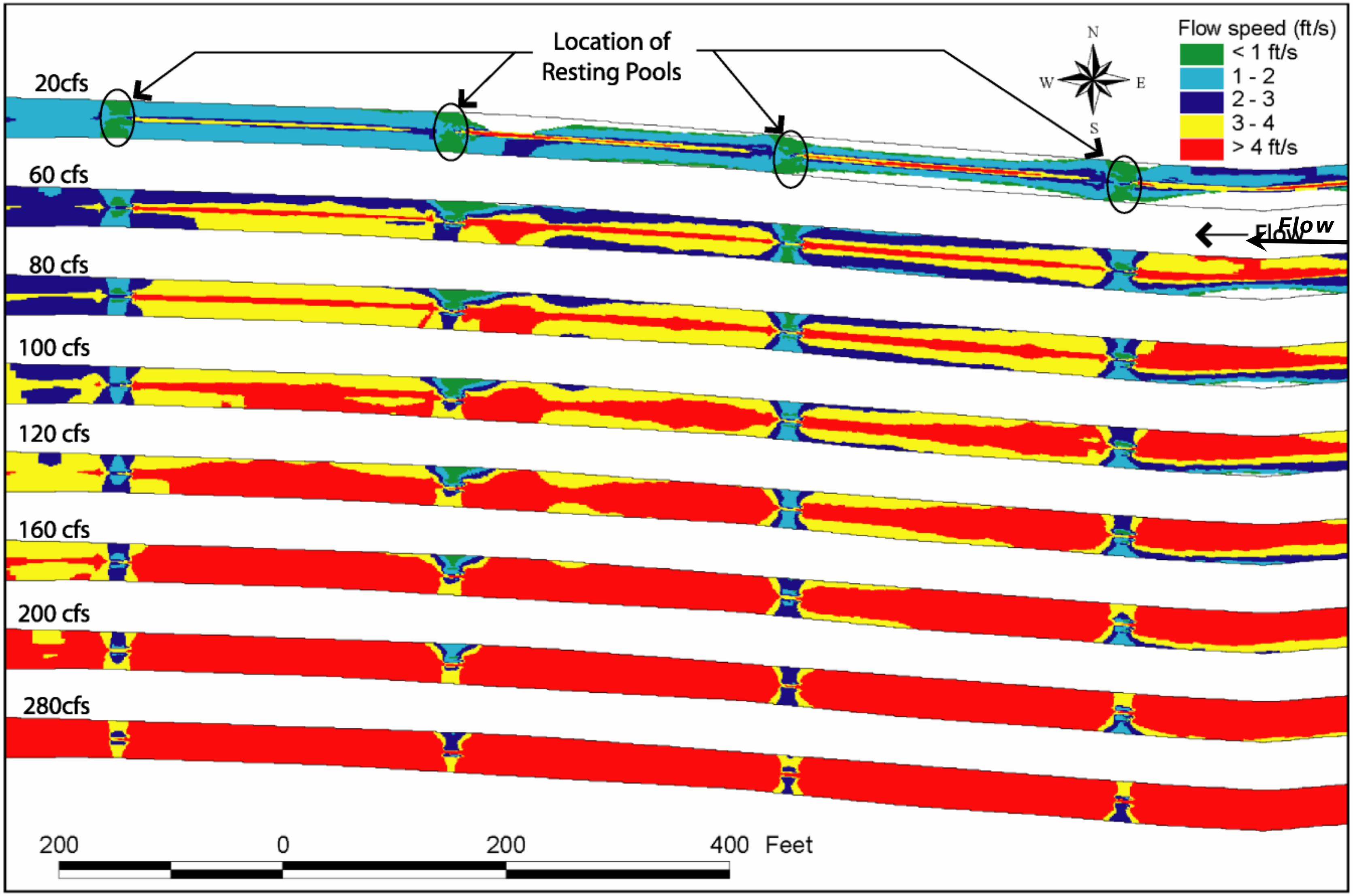
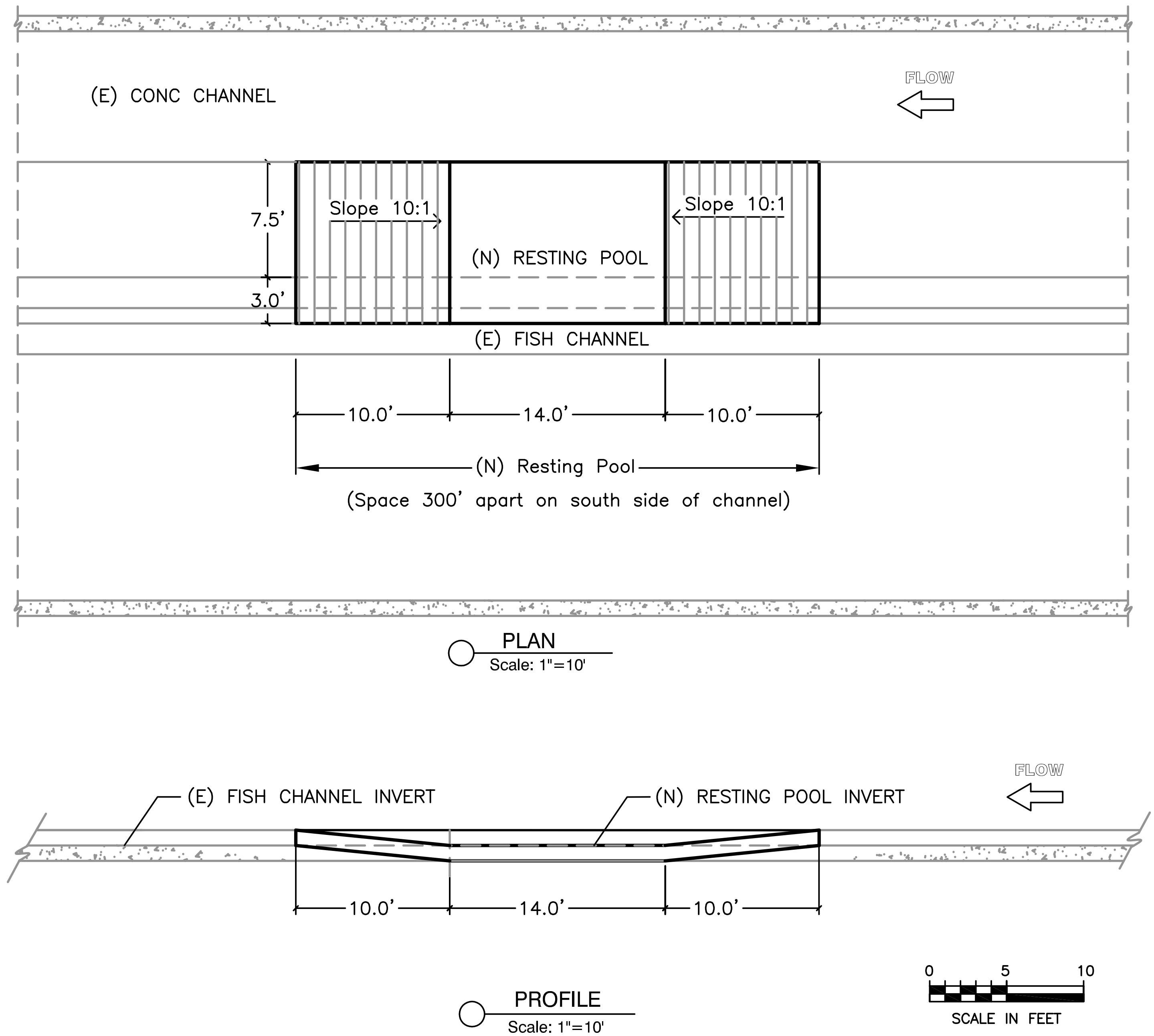


Figure 4.4 – Water velocities for straight reach resting pool: Alternative 1.



Michael Love & Associates
Hydrologic Solutions
PO Box 4477 • Arcata, CA 95518 • (707) 476-8938

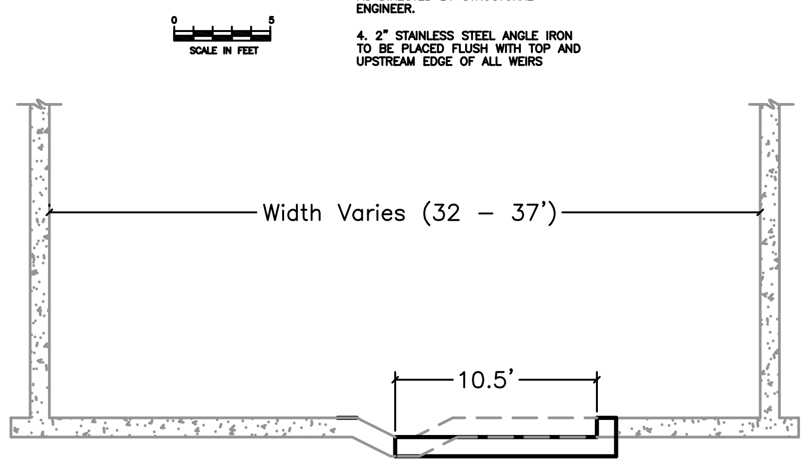
ALTERNATIVE 2

Resting Pool for Straight Channel Sections

SAN LORENZO CREEK FISH PASSAGE IMPROVEMENT PROJECT

Alameda County Flood Control and Water Conservation District

Date: 7/18/06	Design: ML	Drawn: AL	Figure 4.5



NOTES:

1. DROP HEIGHTS FOR WEIR CRESTS IS 0.70' EXCEPT FOR THE UPSTREAM TWO WEIRS WHICH HAVE A DROP OF 0.60'.

2. ALL CONCRETE TO BE CUT AND BLENDED TO NEW WORK AS DIRECTED BY A STRUCTURAL ENGINEER.

3. NEW CONCRETE TO BE REINFORCED AS DIRECTED BY STRUCTURAL ENGINEER.

4. 2" STAINLESS STEEL ANGLE IRON TO BE PLACED FLUSH WITH TOP AND UPSTREAM EDGE OF ALL WEIRS

SECTION
Scale: 1"=10'
(Looking Downstream)

Michael Love & Associates
Hydrologic Solutions
PO Box 4477 • Arcata, CA 95518 • (707) 476-8938

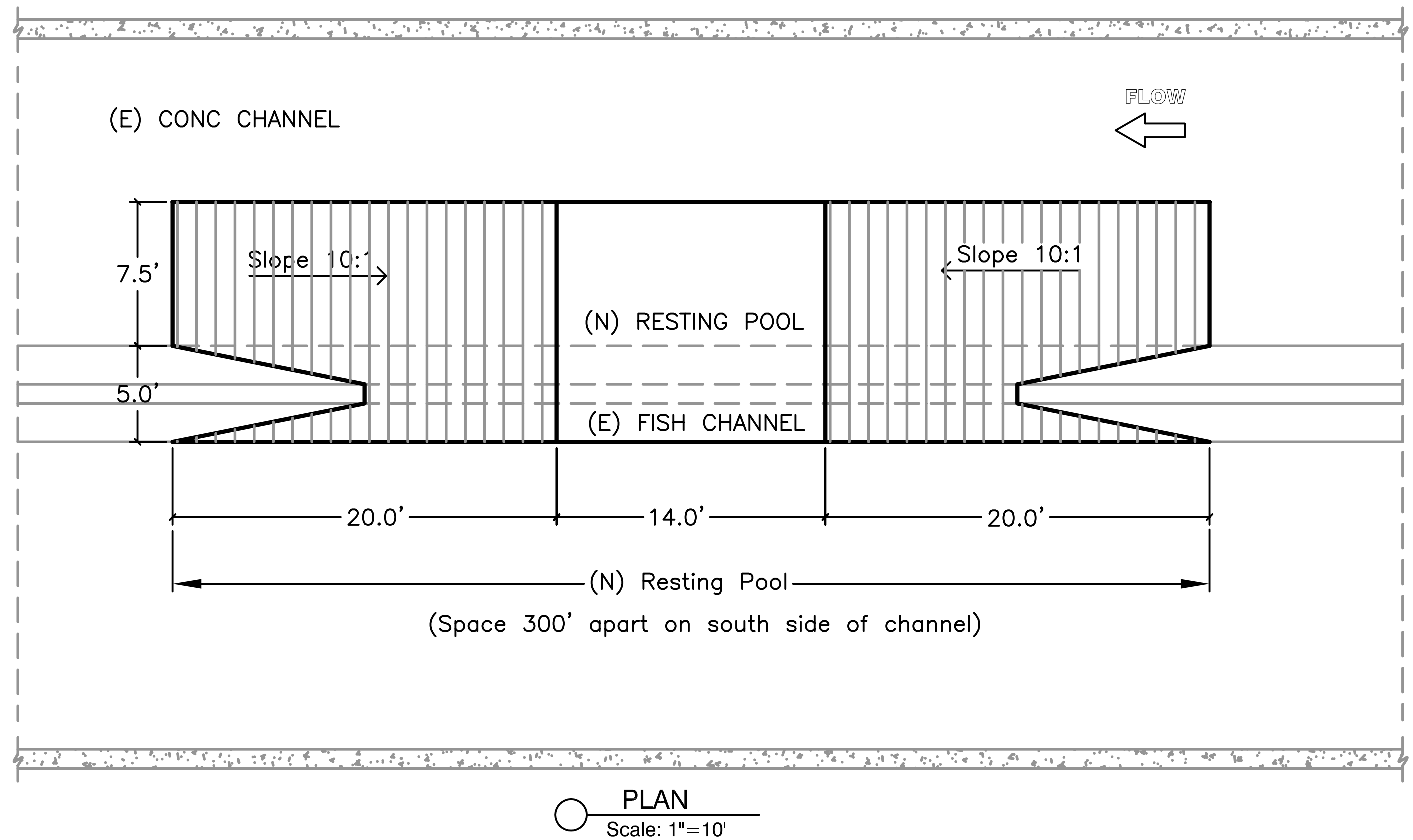
ALTERNATIVE 2

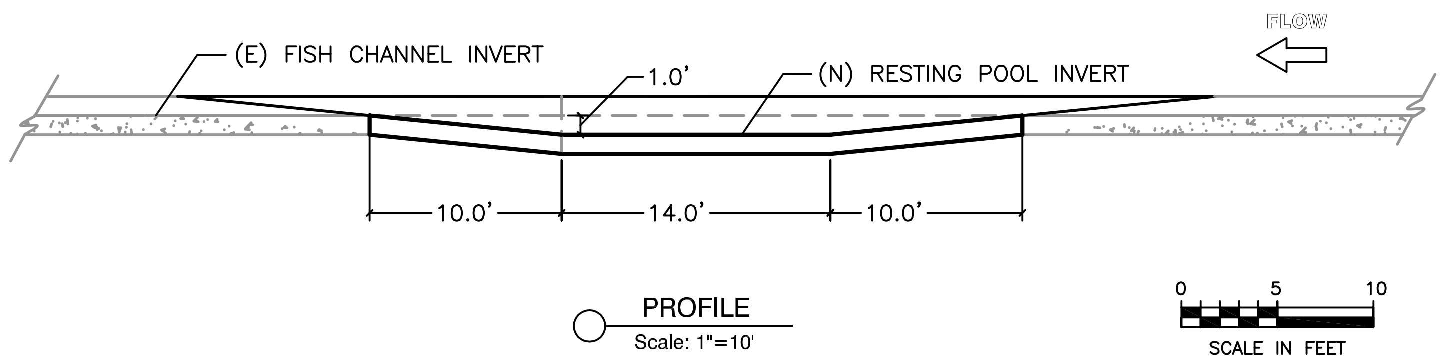
Resting Pool for Straight Channel Sections

SAN LORENZO CREEK FISH PASSAGE IMPROVEMENT PROJECT

Alameda County Flood Control and Water Conservation District

Date: 7/18/06	Design: ML	Drawn: AL	Figure 4.5 (cont.)





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ALTERNATIVE 2B

Resting Pool for Straight Channel Sections

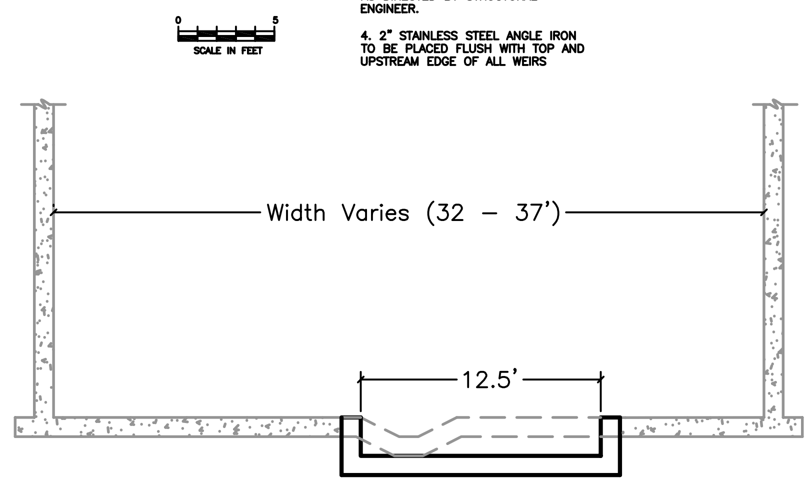
SAN LORENZO CREEK FISH PASSAGE IMPROVEMENT PROJECT

Alameda County Flood Control and Water Conservation District

Date: 7/18/06	Design: ML	Drawn: AL	Figure 4.6

NOTES:

1. DROP HEIGHTS FOR WEIR CRESTS IS 0.70' EXCEPT FOR THE UPSTREAM TWO WEIRS WHICH HAVE A DROP OF 0.60'.
2. ALL CONCRETE TO BE CUT AND BLENDED TO NEW WORK AS DIRECTED BY A STRUCTURAL ENGINEER.
3. NEW CONCRETE TO BE REINFORCED AS DIRECTED BY STRUCTURAL ENGINEER.
4. 2" STAINLESS STEEL ANGLE IRON TO BE PLACED FLUSH WITH TOP AND UPSTREAM EDGE OF ALL WEIRS



SECTION
Scale: 1"=10'
(Looking Downstream)

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ALTERNATIVE 2B

Resting Pool for Straight Channel Sections

SAN LORENZO CREEK FISH PASSAGE IMPROVEMENT PROJECT

Alameda County Flood Control and Water Conservation District

Date: 7/18/06	Design: ML	Drawn: AL	Figure 4.6 (cont.)

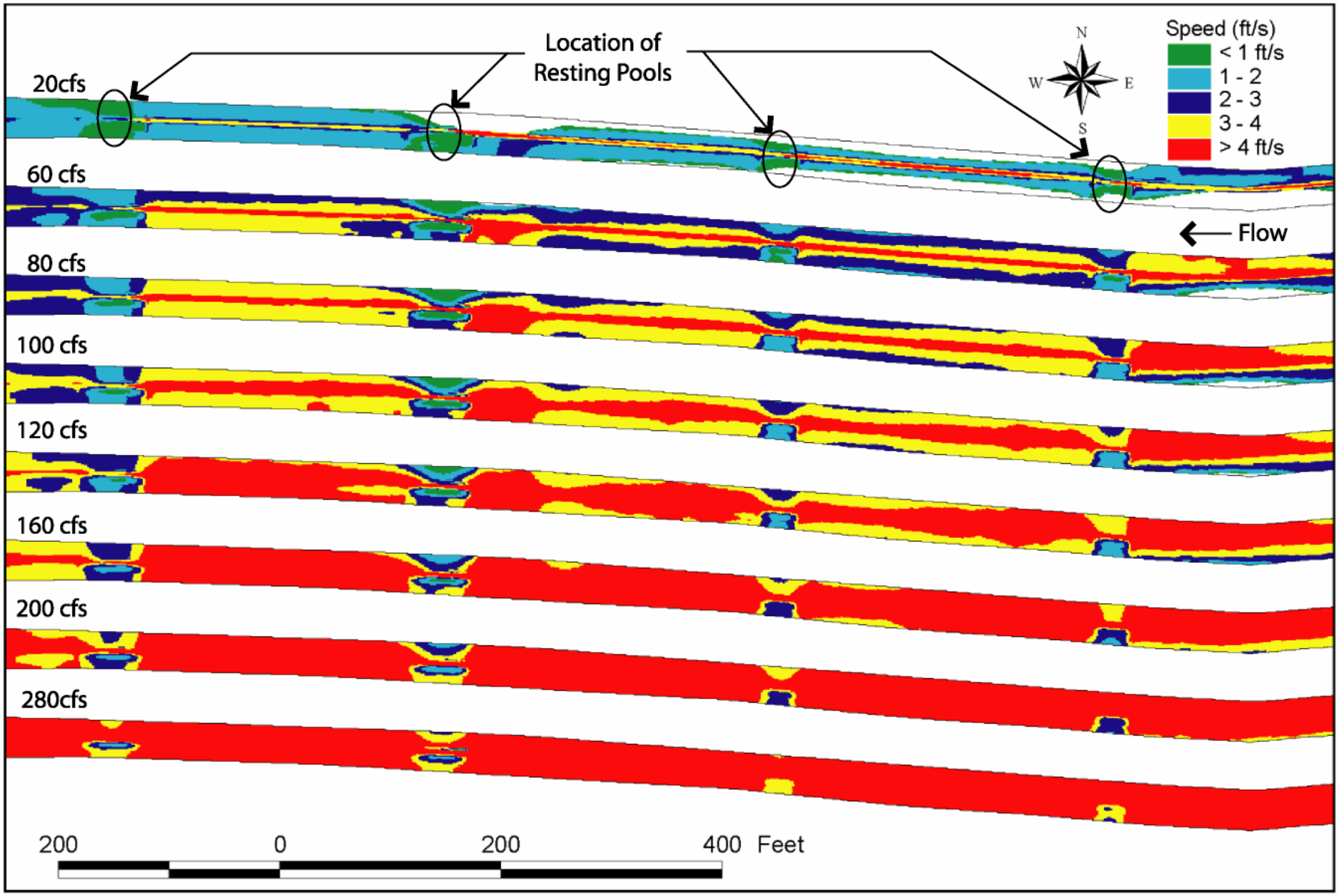
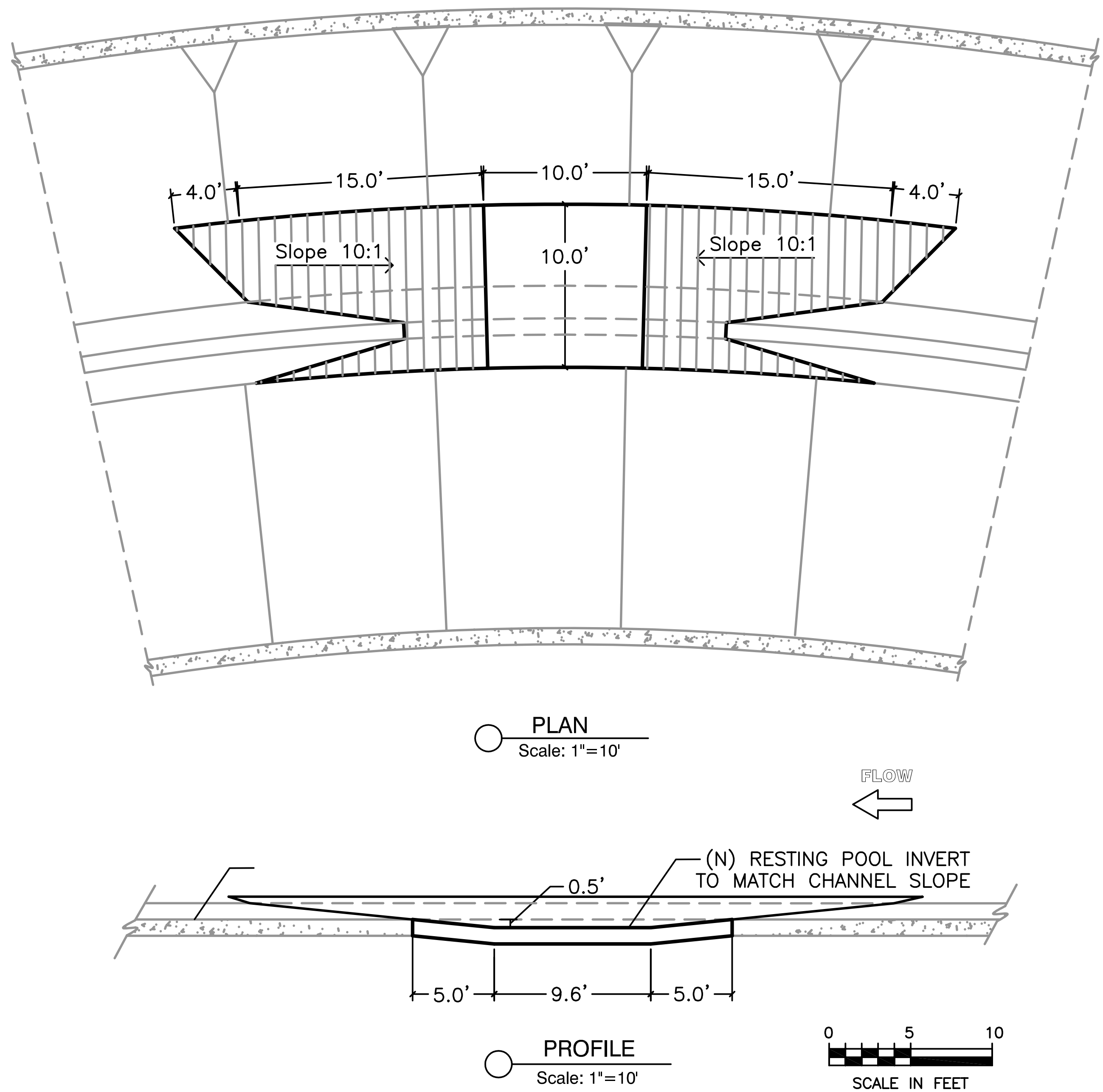
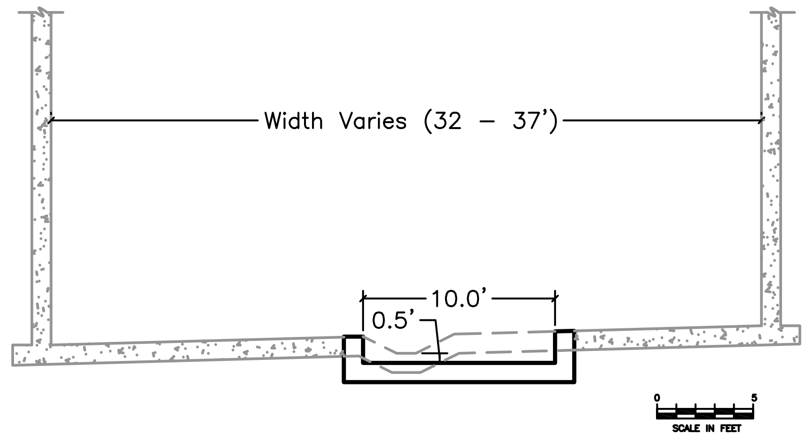


Figure 4.7 – Water velocities for straight reach resting pools: Alternative 2A and 2B.



Michael Love & Associates *Hydrologic Solutions* PO Box 4477 • Arcata, CA 95518 • (707) 476-8938	**ALTERNATIVE 1** Resting Pool for Meandering Channel Sections	SAN LORENZO CREEK FISH PASSAGE IMPROVEMENT PROJECT			
		Alameda County Flood Control and Water Conservation District			
		Date: 7/18/06	Design: ML	Drawn: AL	Figure 4.8



SECTION
Scale: 1"=10'
(Looking Downstream)

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ALTERNATIVE 1

Resting Pool for Meandering Channel Sections

SAN LORENZO CREEK FISH PASSAGE IMPROVEMENT PROJECT			
Alameda County Flood Control and Water Conservation District			
Date: 7/18/06	Design: ML	Drawn: AL	Figure 4.8 (cont.)

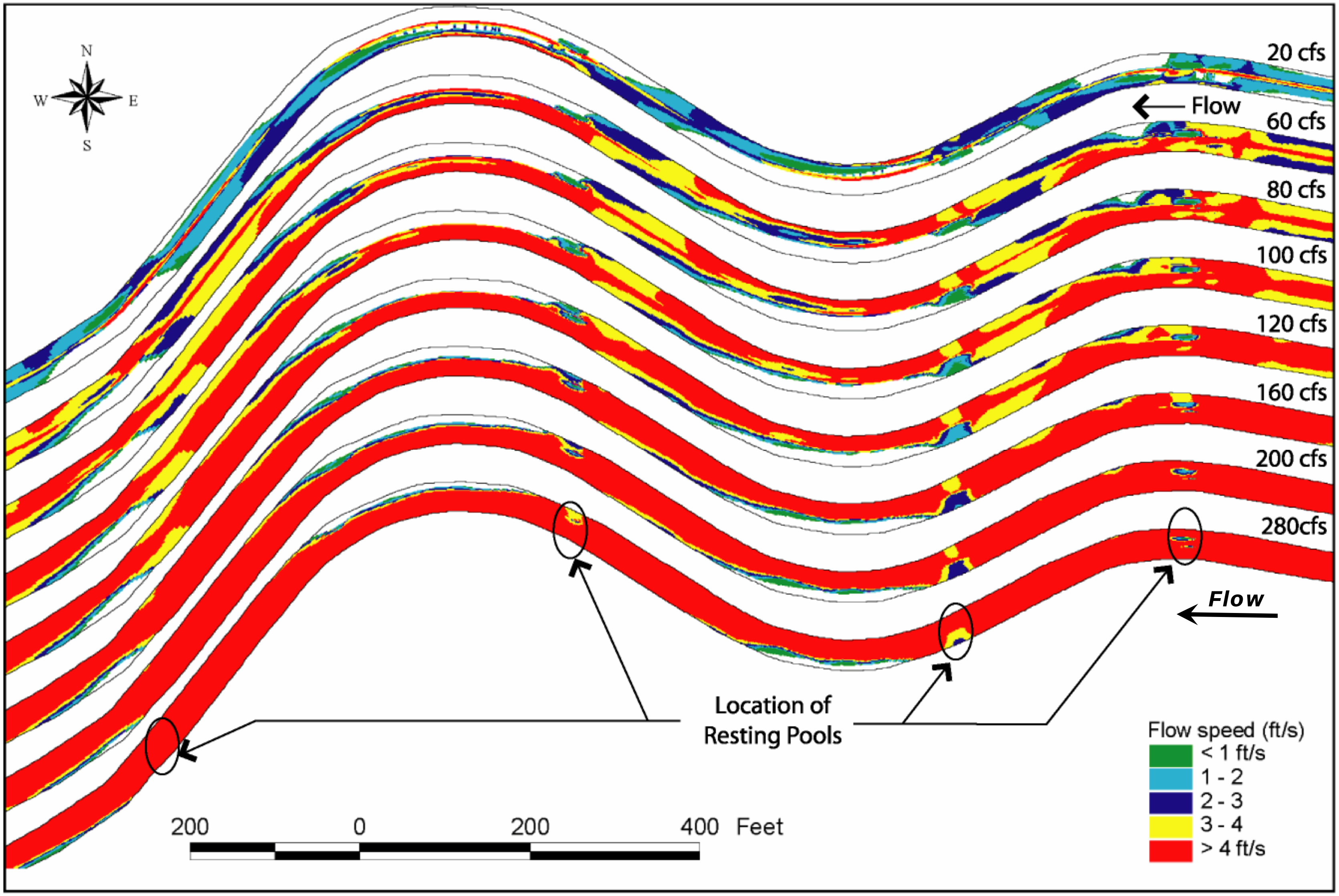
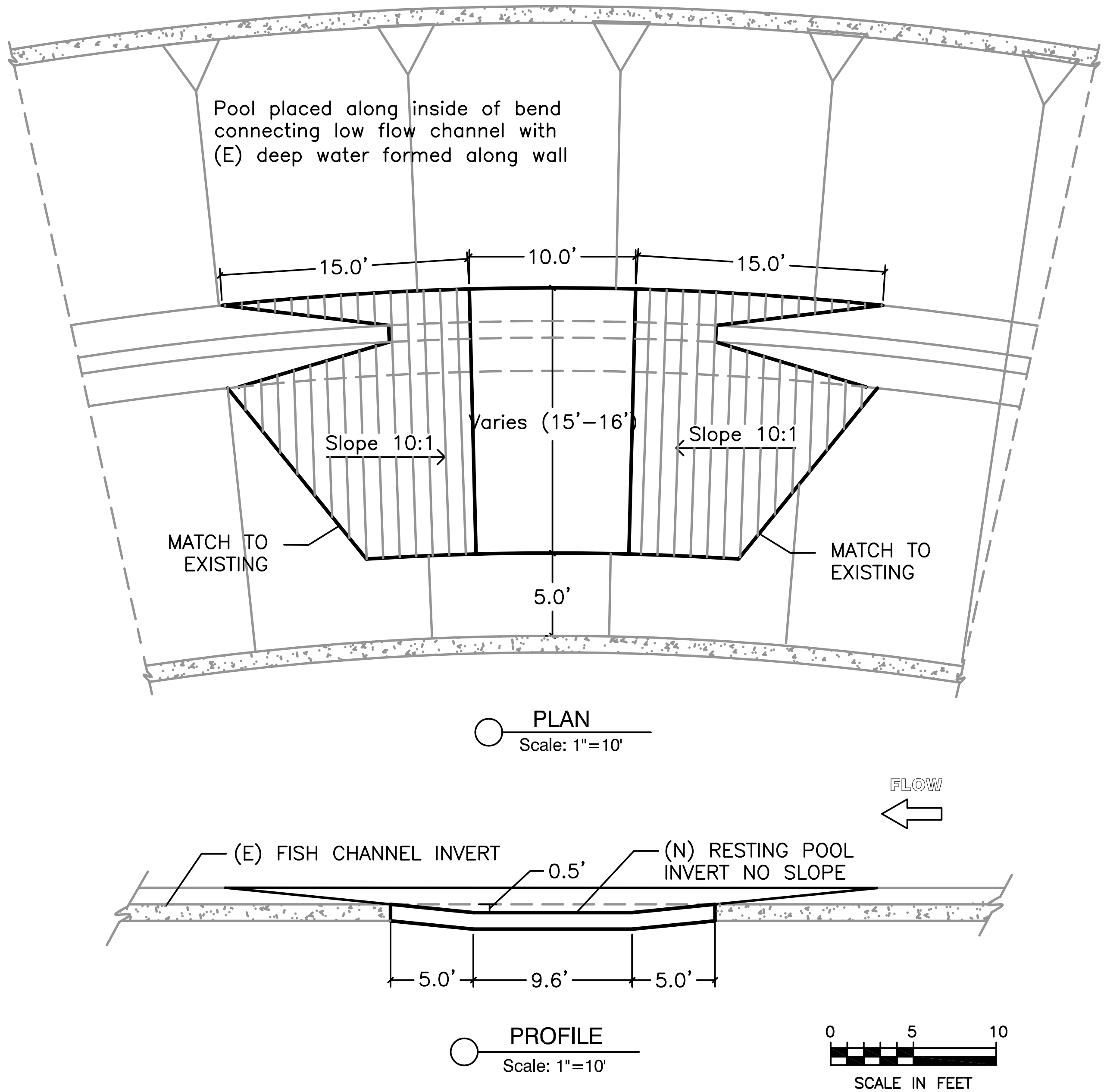


Figure 4.9 – Water velocities for meandering reach resting pools: Alternative 1.



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ALTERNATIVE 2

Resting Pool for Meandering Channel Sections

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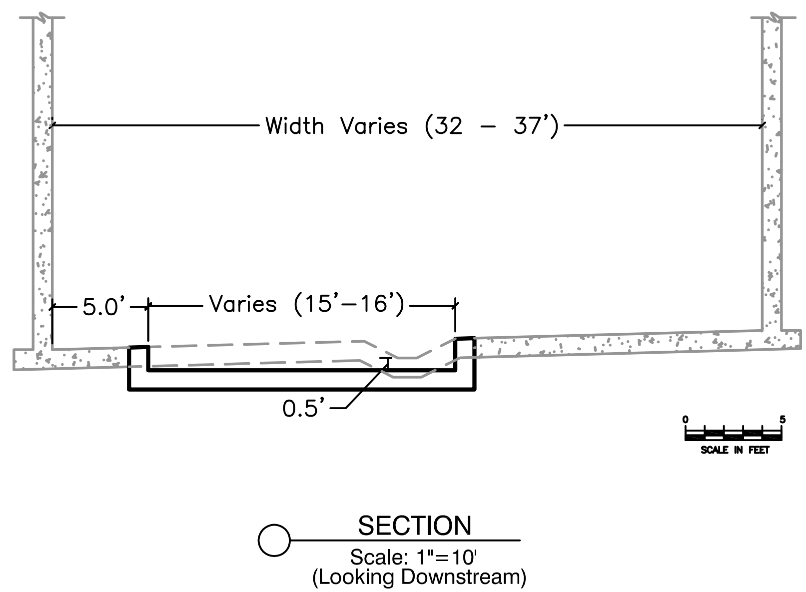
Alameda County Flood Control and Water Conservation District

Date: 7/18/06	Design: ML	Drawn: AL	Figure 4.10



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ALTERNATIVE 2

Resting Pool for Meandering Channel Sections

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Date: 7/18/06	Design: ML	Drawn: AL	Figure 4.10 (cont.)

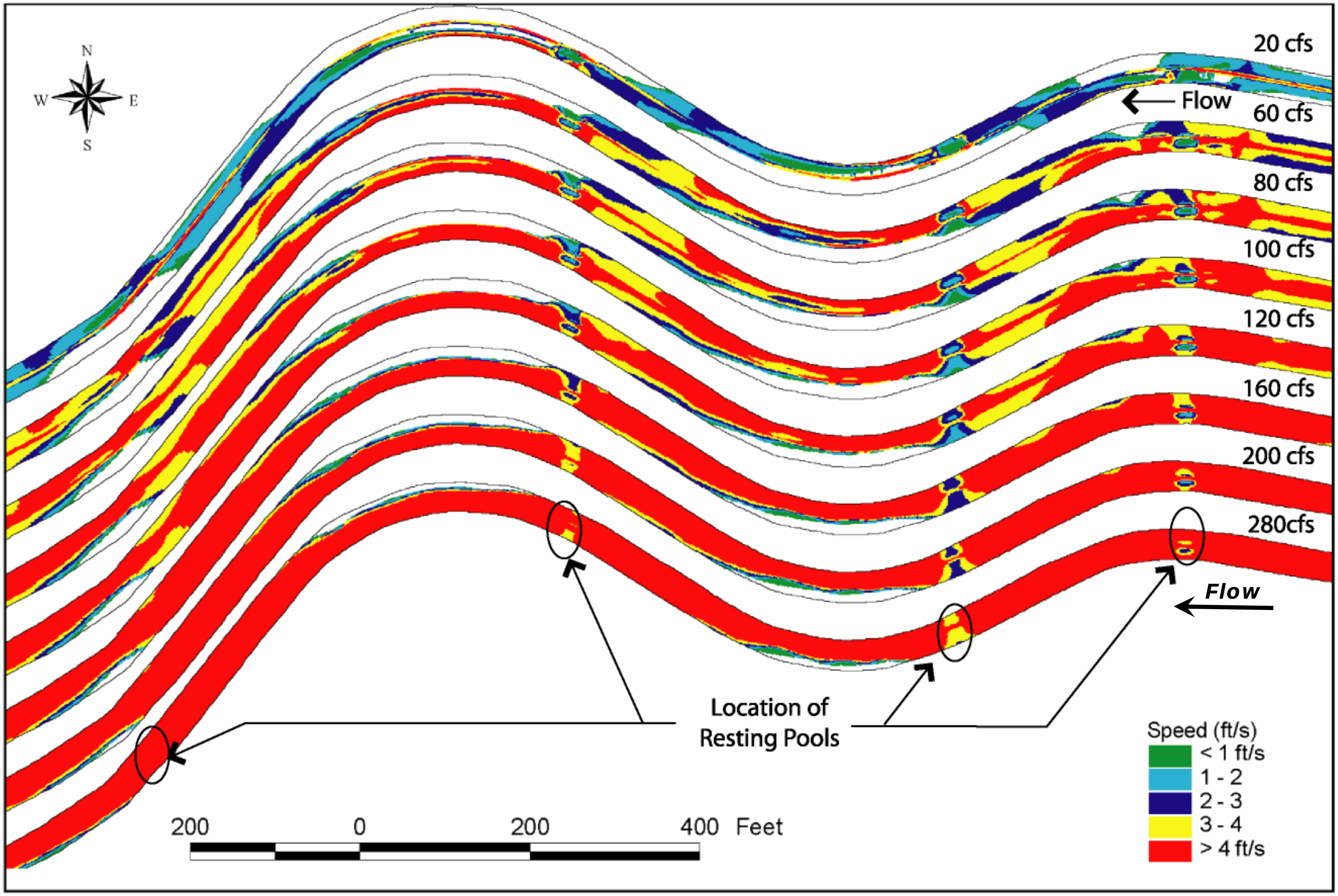
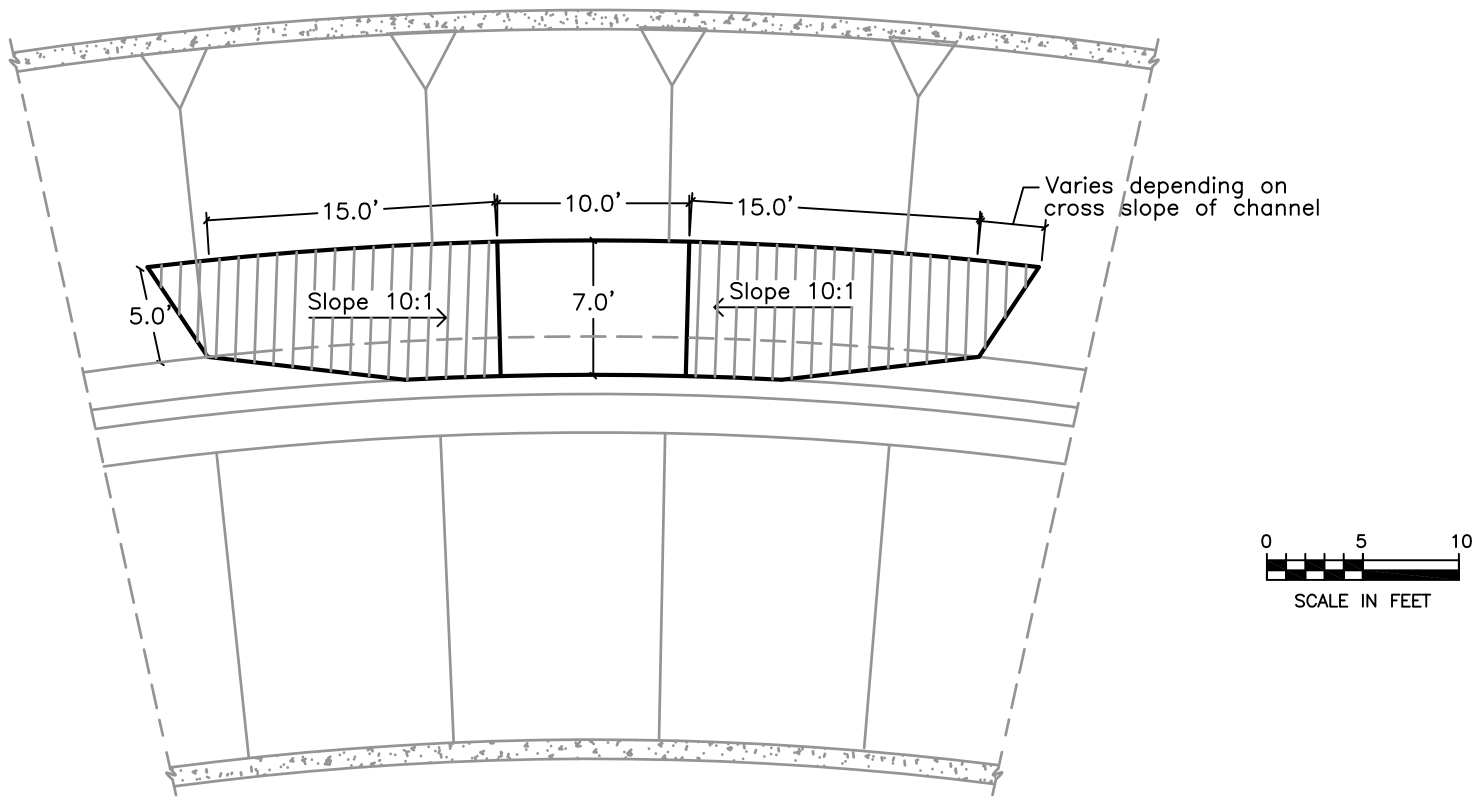
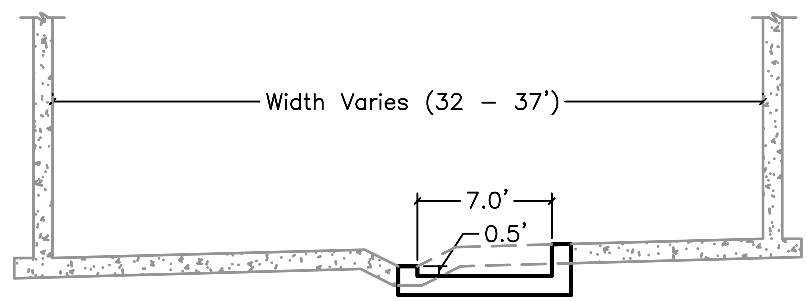


Figure 4.11 – Water velocities for meandering reach resting pools: Alternative 2.



PLAN
Scale: 1"=10'



SECTION
Scale: 1"=10'
(Looking Downstream)

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ALTERNATIVE 3

Resting Pool for Meandering Channel Sections

SAN LORENZO CREEK FISH PASSAGE IMPROVEMENT PROJECT

Alameda County Flood Control and Water Conservation District

Date: 7/18/06	Design: ML	Drawn: AL	Figure 4.12

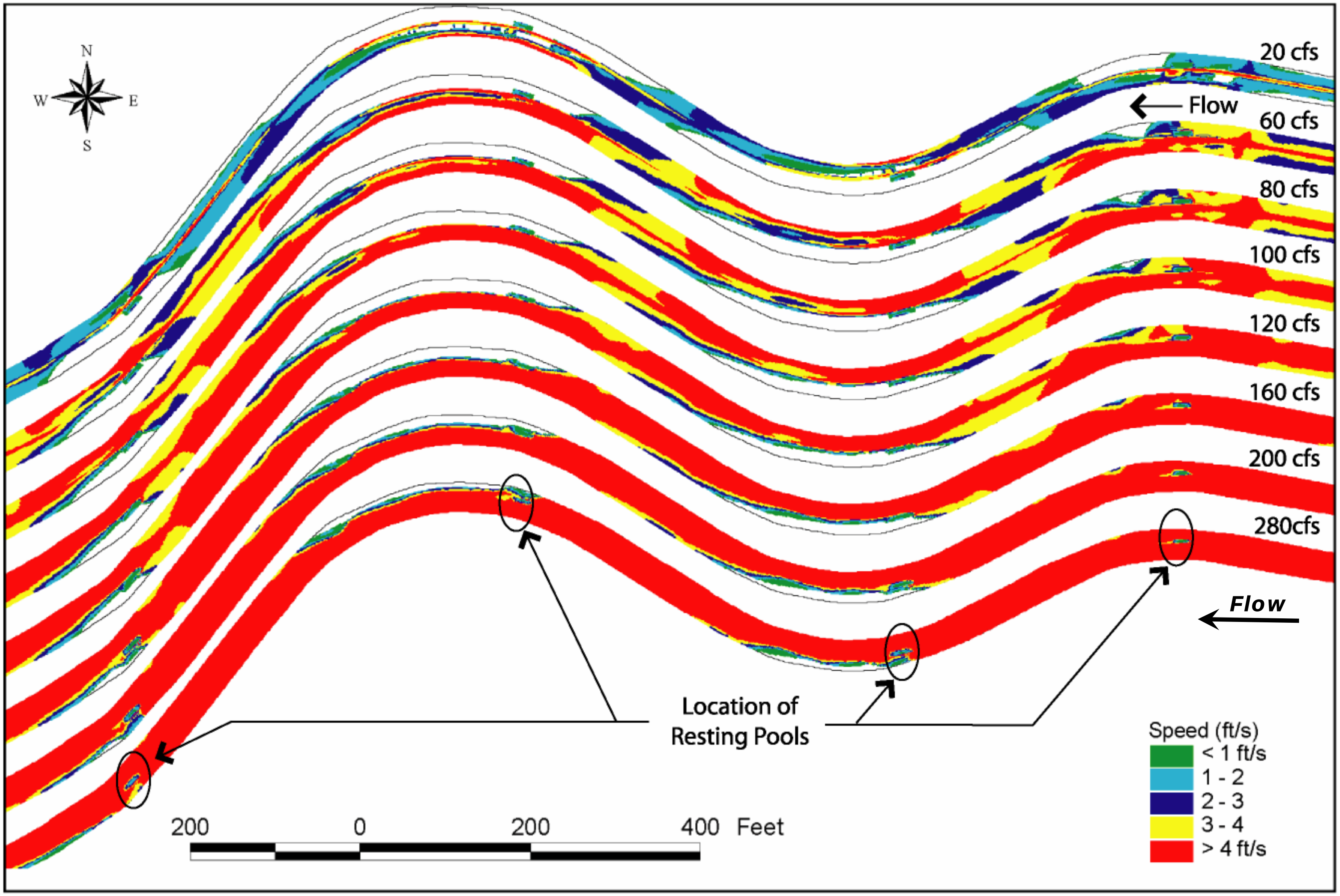
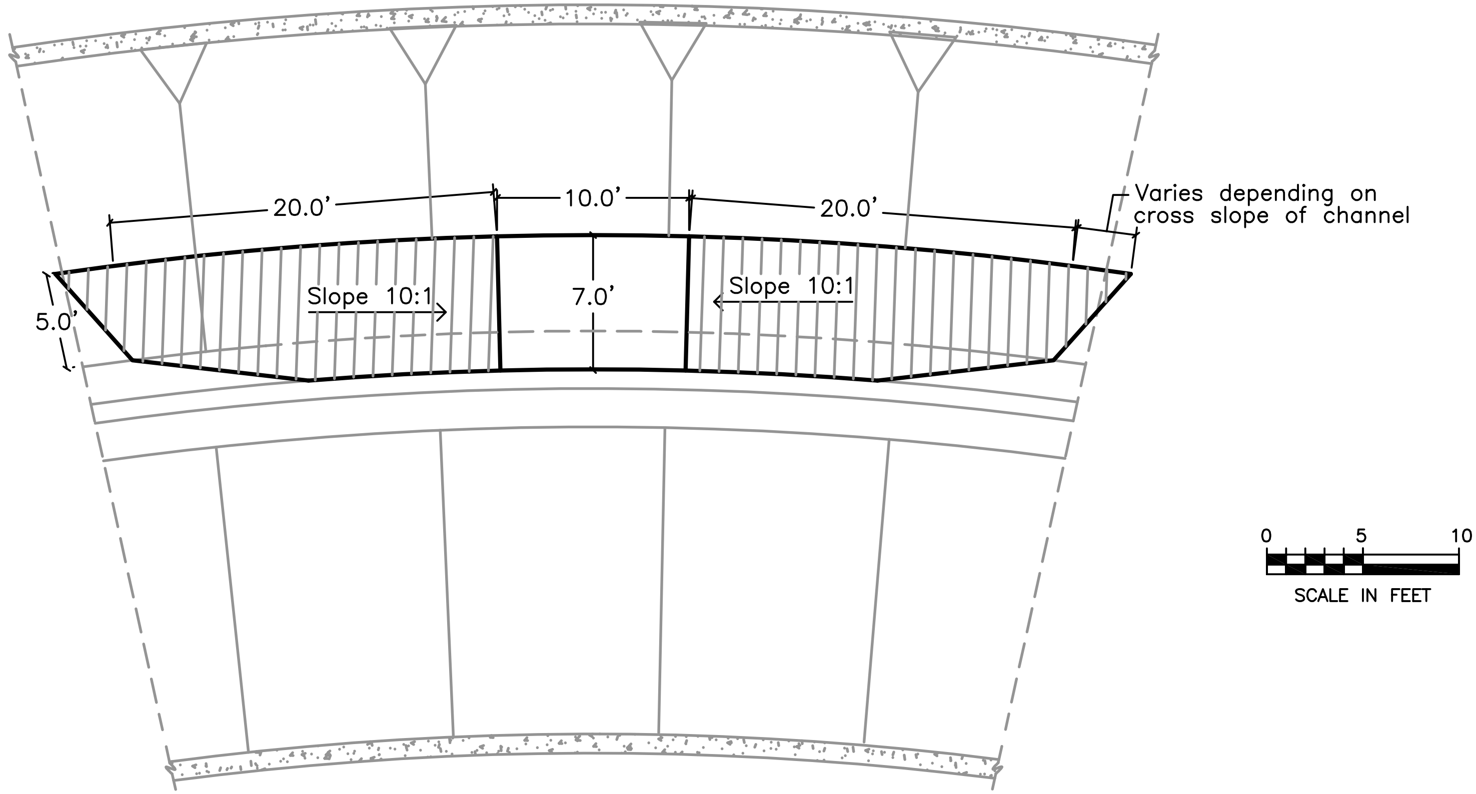
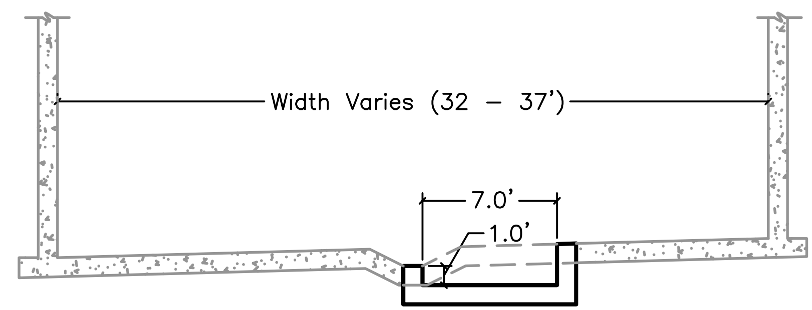


Figure 4.13 – Water velocities for meandering reach resting pools: Alternative 3.



PLAN
Scale: 1"=10'



SECTION
Scale: 1"=10'
(Looking Downstream)

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ALTERNATIVE 3

Resting Pool for Meandering Channel Sections

SAN LORENZO CREEK FISH PASSAGE IMPROVEMENT PROJECT

Alameda County Flood Control and Water Conservation District

Date: 7/18/06	Design: ML	Drawn: AL	Figure 4.14

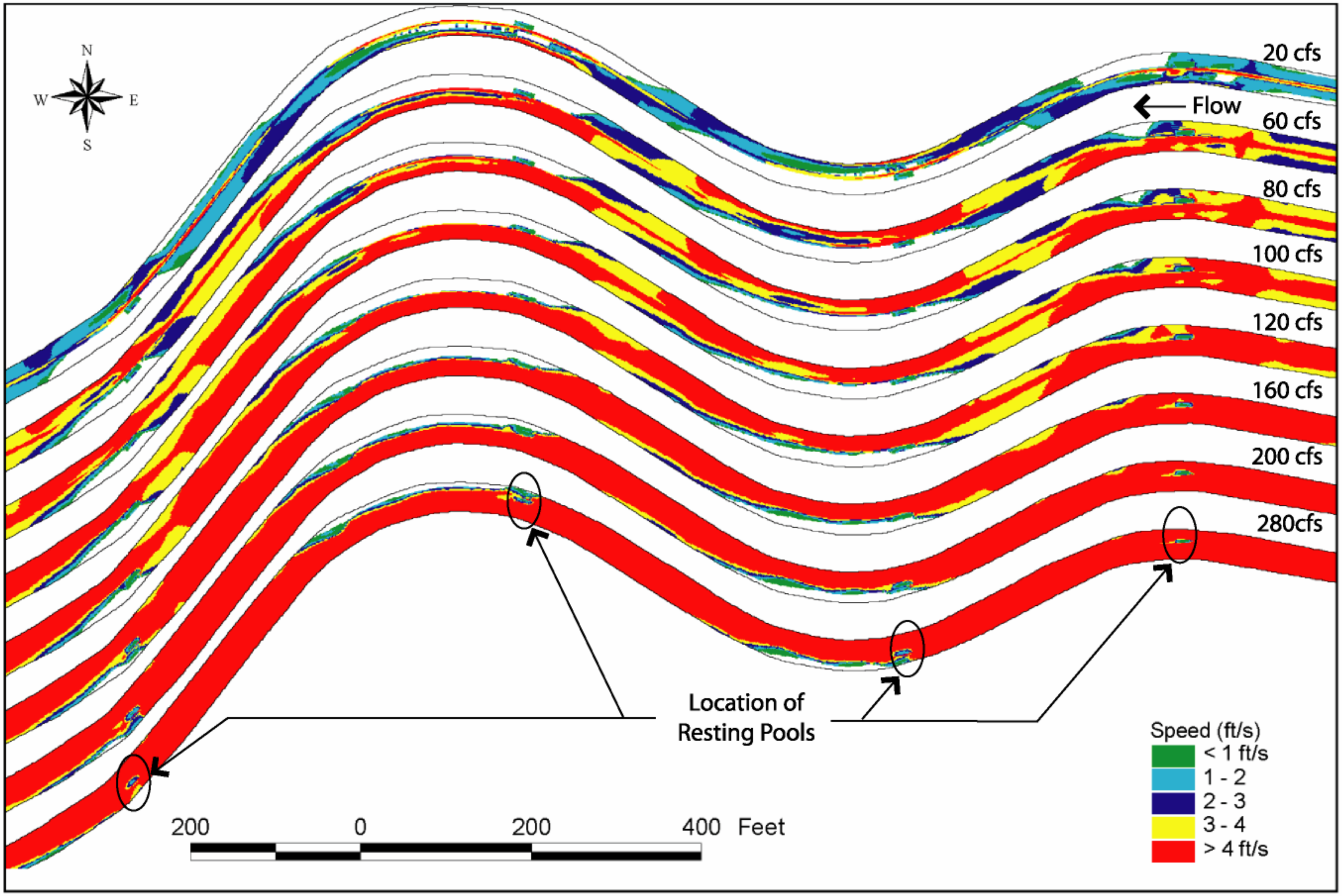

Figure 4.15 – Water velocities for meandering reach resting pools: Alternative 3B.

5 Conclusion and Recommendations

5.1 Conclusions

The fish routing model indicated passage conditions for steelhead are poor at all examined flows. The routing model also indicated where fish of different size and stamina would likely become exhausted and need resting pools. If the objective is to pass average sized steelhead (24.5 inches) and greater at flows up to 120 cfs, then the model results suggest that at least 60 resting pools would be needed, spaced roughly 300 feet apart.

Although the fish routing model suggested that even the larger and stronger steelhead would quickly become fatigued when swimming through the existing channel, adult steelhead have been observed well upstream of the stilling basin and sometimes close to the upstream end of the channel. The discrepancy between model results and observations could be due to several factors. Potentially most significant is differences between the velocity field predicted by the MIKE21C 2-D model and the actual velocities occurring in the existing channel. This project did not involve collection of velocity measurement from the channel to help calibrate and validate the model. It is likely that there are areas in the channel containing substantially slower water than predicted, thus providing areas that a fatigued steelhead can rest and recover.

A total of seven resting pool shapes were modeled, three for straight channel reaches and four for meandering channel sections. Each was evaluated based on its ability to meet steelhead resting criteria and minimize impacts on flood capacity of the channel. For the straight reaches, Alternative 2B performed best, and Alternative 3B performed best for the meandering reaches. However, water depths within Alternative 3B failed to meet the 2 feet criteria at lower flows (<80 cfs). Therefore, it would be prudent to further refine this pool shape to increase water depths slightly at low flows.

5.2 Recommendations

This study results suggest that use of resting pools could greatly improve passage conditions for upstream migrating steelhead trout while keeping pool induced water level rise to 2 inches, or less, at the “bankfull” flow of 12,000 cfs. The following are recommendations and suggestions for future work aimed at implementing fish passage improvements in the San Lorenzo Creek flood control channel:

1. Construct a fish ladder at the velocity ramp, since some steelhead are currently able to swim to the velocity ramp at the upstream end of the channel.
2. Further refine the preferred pool shapes and spacing using the same approaches applied in this study. To improve the accuracy of the MIKE 21C results, collect point velocity measurements at several channel locations at various fish passage flows. This data can be used to calibrate and validate the model for existing conditions.

3. Study sediment transport and deposition associated with the preferred pool shapes to ensure they will remain scoured clean at steelhead migration flows.
4. Prior to constructing pools throughout the entire channel, build a series of pools within a section of the channel that currently has more than adequate capacity and monitor their hydraulic performance.

With further refinement of the resting pool designs, it is apparent that satisfactory upstream passage of steelhead can be achieved, allowing repopulation of steelhead within the San Lorenzo Creek watershed.

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