Minimum Flow Requirements for Southern Steelhead Passage on the Lower Santa Clara River, CA

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Dedication

This report is dedicated to Professor Leal Mertes, who loved rivers, and was a great colleague and mentor. Leal started the work on the hydrology of the Santa Clara River to predict flows and their duration necessary to allow passage of the endangered southern steelhead trout. Her engaging spirit towards both work and life is greatly missed.

Acknowledgements

The authors wish to thank Peter Downs and William Sears, at Stillwater Sciences who helped us focus in on the key geomorphic aspects of the SCR, and provided comments on the draft manuscript that aided clarification of our ideas and inspired us to consider further analyses. Mark Capelli and Anthony Spina, of NOAA Fisheries both offered critical reviews and helpful discussions on an earlier draft. Colleen Cory of the Nature Conservancy also provided valuable feedback on the draft manuscript. We would also like to thank Arturo Keller for providing the WARMF model and offering guidance on treatment of the surface-groundwater interactions. Murray McEachron of United Water Conservation District generously provided unpublished data. Phil Mineart and Jeanne Hudson of URS Corp. Inc., provided the HEC-RAS model as well as a GIS shapefile of the 1993 Ventura County cross-sections. Funding was provided by the California Coastal Conservancy.

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Abstract

The migration of *Oncorhynchus mykiss* (steelhead trout) from the ocean to upstream spawning grounds is a critical component of the steelhead life-cycle. A depth of 0.6 ft represents the minimum depth of water required for adult steelhead passage, based on work by Thompson (1972). This analysis investigated the discharge required to maintain the minimum depth criteria of 0.6 ft on the lower Santa Clara River (SCR), California from the Pacific Ocean to Piru Creek. Model-based predictions found that a minimum flow of 800 cfs would be required to maintain a 0.6 ft. depth from the SCR estuary to Santa Paula Creek, while 500 cfs is needed to maintain this depth from Santa Paula to Sespe Creek, and 700 cfs would be needed between Sespe Creek and Piru Creek. Results from rainfall-runoff simulations found that the minimum flow criteria were met between Sespe and Santa Paula Creeks for 88-93% of the analysis period and for 96-99% of the time period from Santa Paula to the estuary, when flow in the mainstem near Piru was greater than 400-700 cfs. These results indicate that passage flows are likely to exist throughout the entire mainstem at the same time. Evaluation of the period 1955-2004 determined that 7-12, 1-day flow events meeting the depth criteria would have occurred over 36% of the flow period from Piru to Sespe Creek. The section of the mainstem SCR from Sespe to Santa Paula Creek had 12 or more 1-day flow events meeting the depth criteria for 68% of the analysis period, and from Santa Paula Creek to the estuary there were 12 or more 1-day flow events meeting the depth criteria for 45% of the time. A second analysis investigated the frequency of flow events with 0.6 ft. depth for a continuous 3-day period. Results found that the reach from Piru to Sespe experienced 7-12, 3-day flow events meeting the depth criteria 14% of the flow period, from Sespe to Santa Paula Creek there would have been 7-12, 3-day flow events meeting the depth criteria for 40% of the analysis period, and from Santa Paula Creek to the estuary 7-12, 3-day flow events meeting the depth criteria have occurred for 26% of the water years analyzed. The number of potential passage opportunities per year was found to be highly correlated with the total annual runoff, based on a simple regression model. During average and above average water years there appear to be multiple opportunities for fish passage, while during dry years fewer opportunities exist.

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1.0 Introduction

The migration of *Oncorhynchus mykiss* (steelhead trout) from the ocean to upstream spawning grounds is a critical component of the steelhead life-cycle. When favorable flow conditions exist, adult steelhead enter the estuary to begin their upstream migration. The migration window, which is highly variable between years, is dependent upon hydrologic connectivity between the ocean, estuary, lower mainstem and upper tributaries. In Southern California, this generally occurs following sizable rainfall events during late fall, winter, or early spring and is dependant on the stream flow discharge of that particular season. During years with prolonged stream flows, steelhead have a longer window of opportunity to migrate upstream. At present, the discharge required to maintain adequate migration conditions has not been established.

Migration and life history patterns of southern California steelhead depend more strongly on rainfall and stream flow than is the case for steelhead populations further north (Moore, 1980). Both upstream and downstream migrating fish have likely developed migration behavior that coincides with the relatively short duration peak flows common to Southern California river systems (*personal communication* Rogers, 2003). For the purposes of this study, we assumed that the migration run on the Santa Clara River (SCR) begins during the first storm large enough to break the sand barrier at the estuary mouth and that occurs after December 1st. The migration run, including out-migration of smolts, will be assumed to continue until June (Moore, 1980).

Historical documentation of an important recreational steelhead fishery occurs for the SCR into the mid 1900's. It is estimated that there was an annual trout run of 8,000 fish prior to the mid-1900's (Moore, 1980). Construction of dams and other migration barriers on the mainstem, Santa Paula Creek, Sespe Creek, Piru Creek, and other tributaries during the mid 1900's appear to be correlated with the demise of the steelhead run as habitat availability decreased and surface flows became highly manipulated (Outland, 1971; Moore, 1980; Capelli, 1983). Adult steelhead have continued to attempt migration up the SCR with several adults trapped at the Vern Freeman Dam since the installation of the fish passage facilities in 1993. Wild, self-sustainable resident *O. mykiss* populations still exist in Santa Paula and Sespe Creeks and are producing out-migrating steelhead smolts which pass to the Pacific Ocean.

1.1 Objectives and Scope

The goal of this project was to investigate the migration potential for the southern steelhead trout in the lower SCR watershed from the river mouth to Piru Creek. The two objectives were to: **1**) determine what discharge is required to maintain 0.6 ft depth (*after* Thompson, 1972) from the river mouth to Piru Creek and **2**) assess the historic frequency of potential passage opportunities for steelhead from 1955 – 2004. This period of record was chosen due to the availability of discharge data and does not necessarily reflect a local climatic cycle.

2.0 Physical Setting

2.1 Geologic Framework

The SCR watershed is located in southern California (Figure 1) and although parts are rapidly urbanizing, it is the last major river in this region that is not heavily channelized, with a catchment area of roughly 1,600 mi^2. The river's headwaters begin in the western Transverse Ranges and the river empties into the Pacific Ocean, near Ventura after crossing the Oxnard Plain.

Miocene spreading, volcanic activity and clockwise, vertical axis tectonic rotation characterize the early geologic history. Extension changed to contraction during the Plio-Pliestocene, forming the Topa Topa Mountains to the north and South Mountain to the south (Crowell, 1976). The SCR occupies a large tectonic, fault bounded, synclinal basin. The northern boundary of the basin is the San Cayetano thrust fault with a slip-rate of several m/1,000 years (Rockwell, 1988). The active, north dipping, fault tectonically faults Eocene sedimentary rocks over Pleistocene sediments. Presence of geologically young, soft Pliocene-Pleistocene sedimentary rocks delivers large volumes of fine-grained sediment, mixed with coarse-grained sandstone particles, from south draining tributaries such as Piru, Sespe, and Santa Paula creeks to the river. Hard granitic particles and sand are delivered from the upper portions of the basin in the western San Gabriel Mountains to the east.

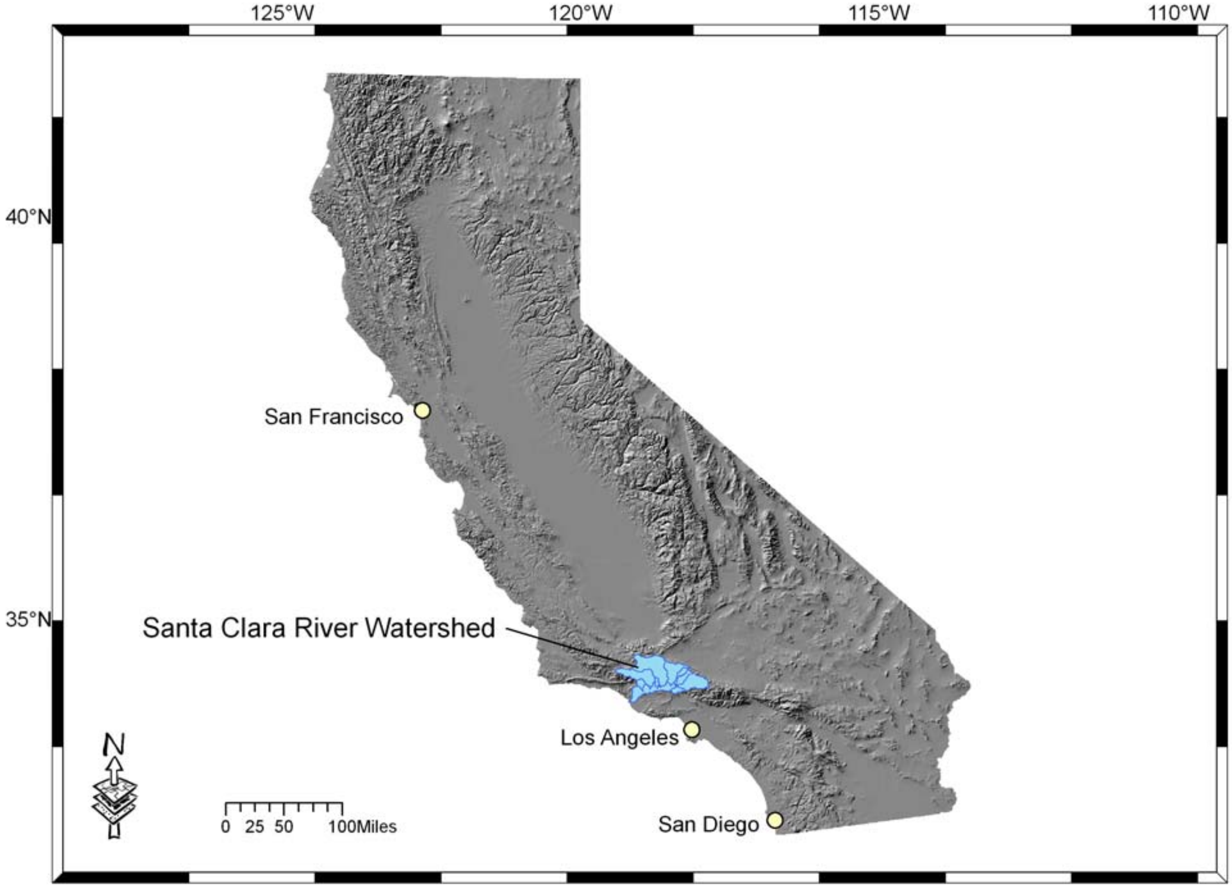


Figure 1. Location of the Santa Clara River basin.

The southern boundary of the basin from near Ventura east to Piru is South Mountain, underlain by the south-side-up Oak Ridge fault (Yeats, 1977, 1988; Azor *et al*., 2002). South Mountain is moving north and The Topa Topa Mountains are moving south. The rates of shortening across the basin are about 10 m per 1,000 years in response to the left bend and right lateral slip on the big bend segment of the San Andreas Fault to the east (Azor *et al*., 2002).

Rates of tectonic activity in the region are some of the most rapid in the world (Yeats, 1977; Rockwell, 1988). The Ventura Basin, between the San Cayetano and Oak Ridge faults, is one of the deepest, Plio-Pleistocene, sedimentary, fault bounded basins in the world. On shore it is known as the Ventura Basin and offshore the Santa Barbara Basin. The head of the basin is called the Soledad basin and the head is displaced by the San Andreas Fault, the boundary between the Pacific and North American Tectonic Plates.

The SCR Valley is tilted south by uplift and folding associated with the San Cayetano fault. Large alluvial fans emerge from the Topa Topa Mountains, delivering a high load of both water and sediment. Tectonic tilting and formation of alluvial fans during the Pleistocene have pushed the river south against South Mountain (Figure 2).

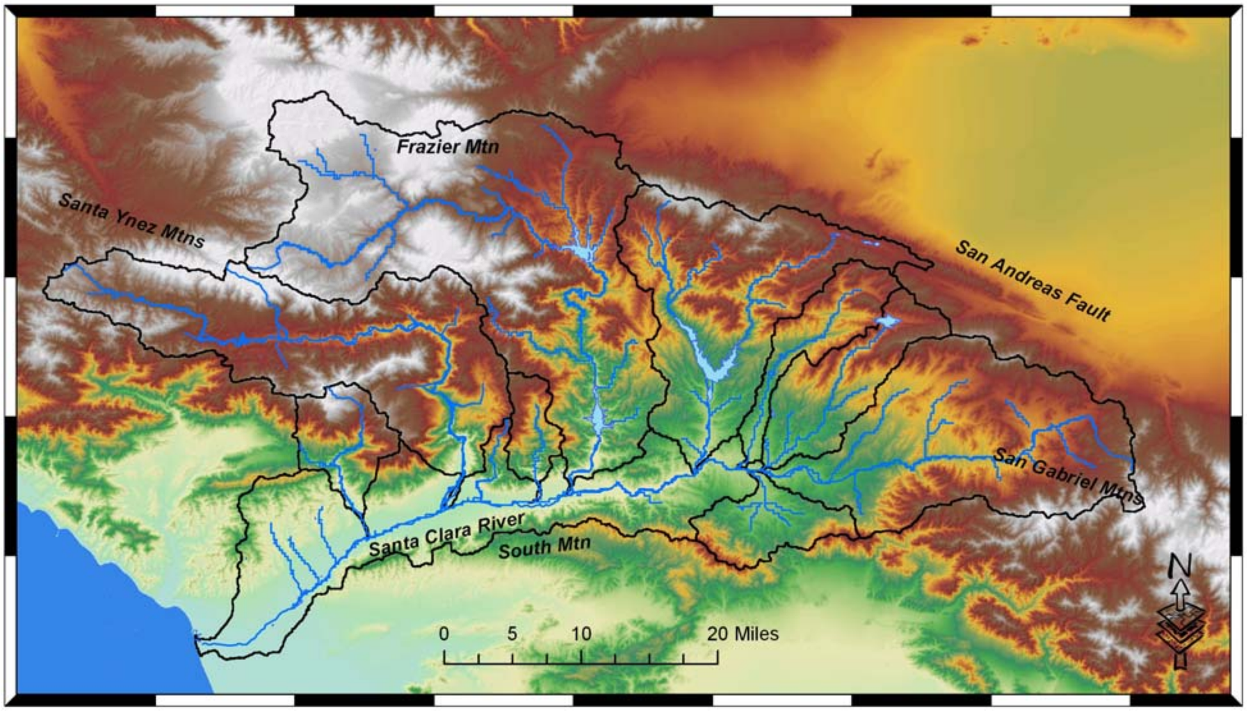


Figure 2. Digital elevation model of the SCR watershed (*source*: USGS 10m DEM).

2.2 Channel Morphology

The SCR transports coarse grained, sand and gravel bed load to the Oxnard Delta and Pacific Ocean. The channel is braided (Figure 3) with a bankfull discharge (based on the $Q_{1.5}$) near Ventura of approximately 6,500 cfs. River changes can be rapid during floods as large portions of the floodplain are inundated and eroded. During subsequent years the channel readjusts again to the more moderate and frequent flows. In the SCR, channel instability is the norm and wide variability exists. Predicting hydraulic conditions in the channel is typically reliant upon the assumption of a fixed bed during a flood event. However, in the SCR cross-sectional form will certainly change at a particular site over time. For the purpose of this analysis, we assume that the set of cross-sections used in the hydraulic model remain characteristic of the variability of the river. Thus, geomorphic and hydrologic evaluation of river behavior, based on morphology is possible even with the inherent instability of the entire system.

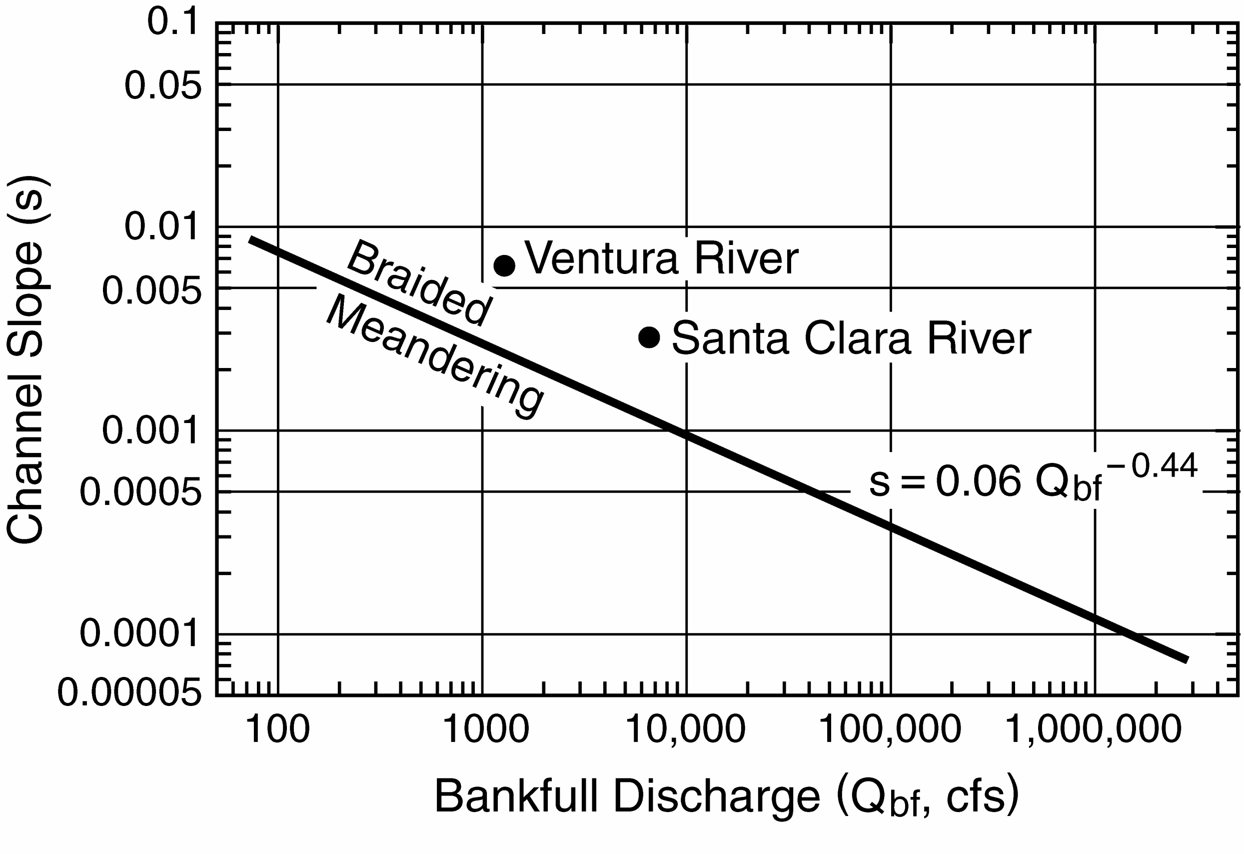


Figure 3. Channel pattern graph showing distinction between meandering and braided channels on the basis of a slope-discharge relation (*after* Leopold et al., 1964). The SCR and Ventura River are plotted for comparison.

2.3 Climate

The climate in this region is Mediterranean, which is typical of the southern California coast. Average annual precipitation ranges from 14 inches near the coast, to approximately 17 inches near Santa Paula and more than 25 inches in the mountains. Precipitation is typically concentrated over a few storms per year and runoff is highly episodic. The majority of the runoff is produced during wet years that alternate with dry years. Wet and dry cycles tend to be decadal (Mantua *et al*., 1997; Inman and Jenkins, 1999), but can vary in duration. Reasons for the cycles are not well understood but are thought to be dependent on periodic cycles in the Pacific Ocean that bring storms on a decadal scale (Burroughs, 2003). An occasional dry year can occur during a wet cycle as can an occasional wet year in a dry cycle. Variability is several hundred percent of the long term average, thus a regular repeating average rainfall does not exist. Flow in the SCR follows precipitation, with most of the runoff occurring from December-April (Figure 4).

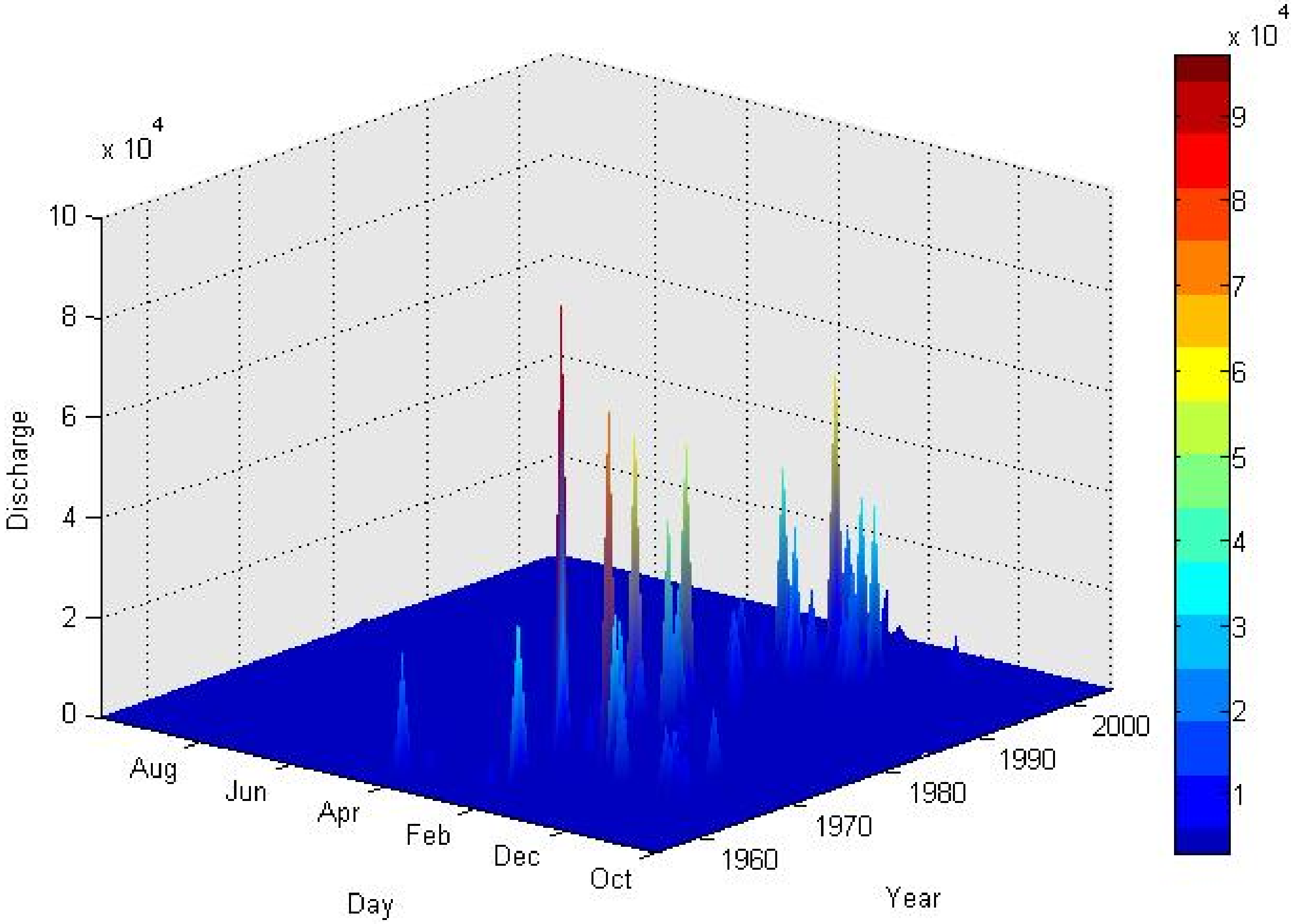


Figure 4. Flow history for the SCR based on mean daily discharge at USGS Montalvo Gage (1950-2004). Each water year begins on October 1 and ends on September 30.

The basin drains from the east through the SCR and its major tributaries, Piru, Hopper, Sespe and Santa Paula Creeks (Figure 5). Sespe Creek delivers the majority of flow and sediment and drives the majority of channel changing events in the mainstem. Under high flow conditions, the river is continuous from the headwaters to the ocean. This surface flow does not persist year round as the surface water percolates to the underlying ground water beginning in the Piru groundwater basin (Figure 6).

2.4 Water Balance

There are two major losses of water from the SCR, direct losses to the streambed (i.e. percolation), and diversions for irrigation. During the dry season, most of the water that flows in the river is lost through infiltration in the streambed. Estimates of streamflow losses are given by Reichard *et al*., (1999) and Hanson *et al*., (2003) as reviewed by URS Corporation Inc. (*in review*). The URS Corp. Inc. study has developed a water balance to account for the major gains and losses of water to the river.

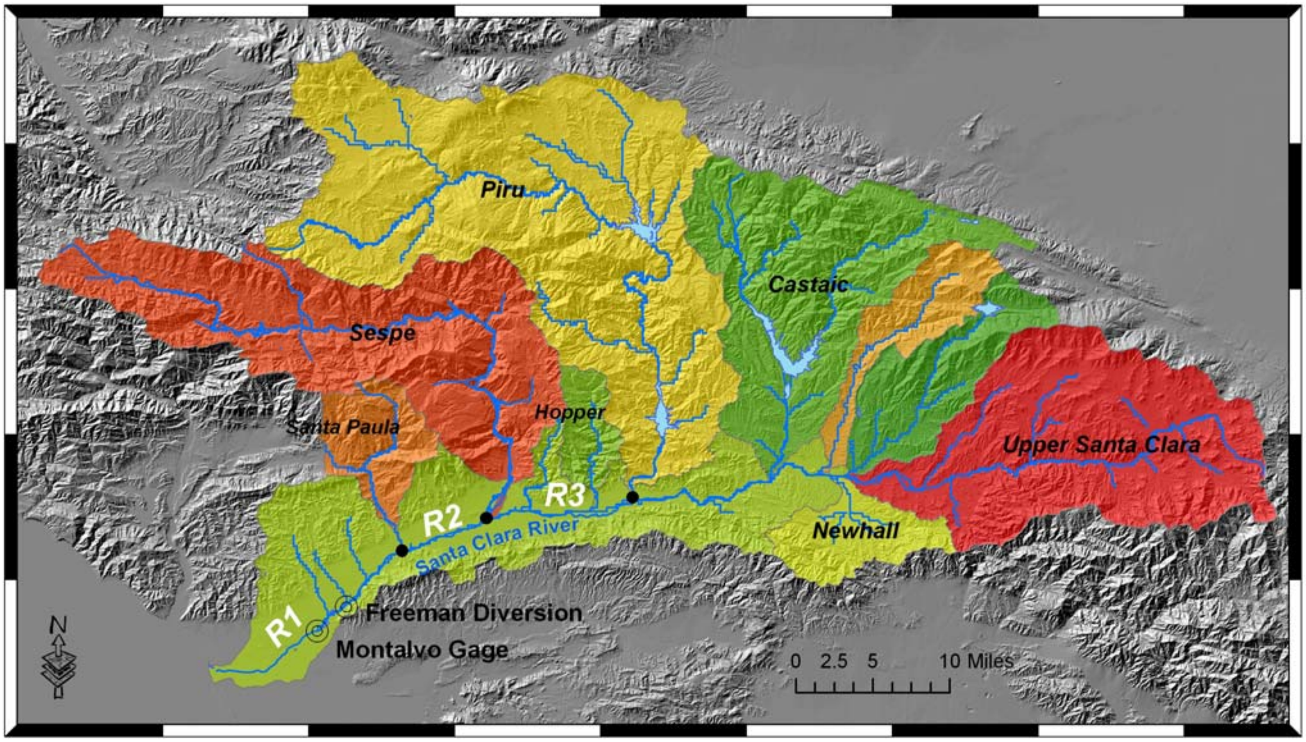


Figure 5. Major sub-watersheds overlain on 10 m hillshade DEM (*NED, USGS*). *R1*, *R2* and *R3* represent the three reaches used in the hydrologic analysis. Closed circles at the junction with the mainstem and Piru Creek, Sespe Creek and Santa Paula Creek indicate reach boundaries. The Vern Freeman Diversion and USGS gage at Montalvo are shown in reach 1 as open circles.

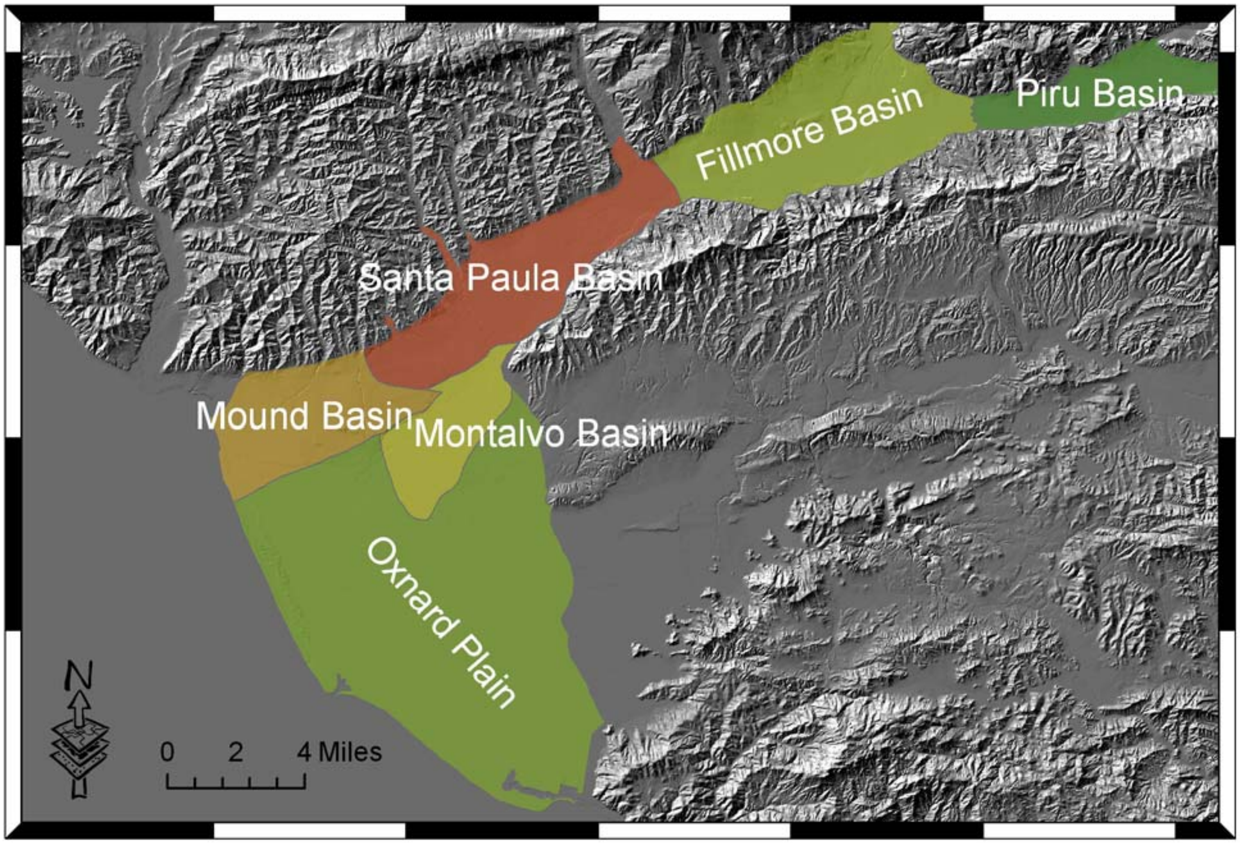


Figure 6. Ground water basins considered in the URS Corp. Inc. water balance and hydrologic analysis. The groundwater basin shapefiles are based on the SCREMP (1996) study and are shown over the 10 m hillshade DEM (*NED, USGS*).

A brief summary of the URS Corp. Inc. water balance is provided here (URS Corporation Inc., *in review*). Please refer to the original document for a more extensive discussion of the data and methods used in their analysis.

The two largest water losses occur in the Piru groundwater basin (Figure 6) and at the Freeman Diversion. Based on the URS Corp. Inc. water balance model, 56,000 acre-ft of water enter the system at the Los Angeles/Ventura County Line on an annual basis. Approximately one-third of this water is lost directly to infiltration into the streambed before the river confluence with Piru Creek. Piru Creek adds 40,000 acre-feet, primarily through flow releases from Santa Felicia Dam in the dry summer months. An additional 26,000 acre-feet is lost to infiltration before the river reaches Fillmore. Rising groundwater occurs at the transition between the Piru and Fillmore groundwater basins (Figure 6).

Sespe Creek is the largest input of water in the study area, adding approximately 115,000 acre-feet per year. Santa Paula Creek adds another 23,000 acre-feet and marks the transition from the Fillmore to the Santa Paula basin. An average of 175,000 acre-feet flows out of the system to the Pacific Ocean on an annual basis.

3.0 Methods

3.1 Passage Criteria

In this analysis, we used a modified form of the depth criteria developed Thompson (1972) to determine the discharge necessary to maintain 0.6 ft depth throughout the entire modeled reach. This criteria was developed on streams in Oregon, where it was determined that steelhead required 0.6 ft. depth to migrate upstream over 25% of the contiguous stream channel width. In a study of adult steelhead passage for the nearby Santa Ynez River, it was found that steelhead passage occurred with less than 25% of the contiguous channel width, though no evaluation was made of the efficacy of these conditions (SYRTAC, 1999). The study of fish passage on the Santa Ynez River found that adult steelhead in southern California were observed in streams with a total width of 10 ft. Given the broad channel width of the SCR, we found it reasonable that fish could navigate up a low-flow channel and thus adopted a minimum passage criterion of 0.6 ft depth over at least 10 ft of the contiguous channel width. However, it is recognized that the 0.6 ft depth criteria used in the Thompson (1972) methods was developed in higher gradient streams where the minimum depth was associated with changes in channel slope over short distances, and did not specifically consider depths over extended uniform shallow reaches, which occur in the SCR. For the purposes of this study, it is assumed that steelhead can pass Freeman Diversion using the existing, Denil-type fish ladder in use at the facility; while no evaluation of this facility was undertaken as part of this study, all passage facilities cause some delay of fish movement. Thus, the major limitation for fish passage in the lower SCR investigated in this study is adequate flow depth.

3.2 Hydraulic Model

To assess the hydraulic conditions on the SCR, we used the HEC-RAS hydraulic model developed by the Army Corps of Engineers (U.S. Army Corps of Engineers, 2001). HEC-RAS is a one-dimensional fixed-bed model that calculates the water surface depth and slope by solving the energy equation between cross-sections. HEC-RAS has been used extensively in applied river restoration projects and was selected for this study because of its ability to assess hydraulic variables over large spatial scales.

The boundary conditions include cross-sectional geometry, water surface elevation, Manning's roughness, and an appropriate expansion/contraction coefficient. The input data for the hydraulic model was imported from an existing project file provided by the URS Corp. Inc. This project was originally developed by Omrun Engineering in February 2003 for the Ventura County Watershed Protection District. The project consists of a geometric reach from the Los Angeles/Ventura County line to the ocean. The majority of cross-sections for the model were based on 5-foot contours from 1993 topographic data. A higher resolution field survey was conducted in 2001 by VTN over a 3-mile reach upstream of Fillmore Bridge. Model calibration and verification was performed on the SCR by URS Corp. Inc. using gage data at Montalvo (USGS gage # 11114000), Piru (USGS gage # 11109000) and County Line (USGS gage # 11108500). Further information on the model set-up and calibration procedure is documented in (URS Corporation Inc., *in review*).

To determine when adequate passage conditions exist on the SCR, flow simulations were performed for discharges ranging from 100-2,000 cfs. We assumed that flow was steady and evenly distributed throughout the modeled reach. This assumption allowed for identification of potential passage barriers, defined as a section that failed to meet the depth criteria at a specified discharge. Based on these runs, the study area was divided into three sub-reaches (refer to Figure 5 for reach locations) to provide finer scale depth predictions.

To test the model sensitivity to topographic input data, new cross-sections were cut from the 5-foot topographic data in the same locations as the surveyed transects and input into a new HEC-RAS model. A comparison of depth predictions was performed using the model based entirely on 1993 topographic data with the existing model which included the 2001 survey.

3.3 Hydrologic Model

Given the simplifying assumption of constant discharge that was used in the HEC-RAS analysis, a hydrologic model was used to examine how discharge would vary between reaches when percolation and rising groundwater were accounted for. This investigation allowed for a check on the correlation between achieving minimum potential passage requirements on overlapping days between the three reaches. The analysis was performed by selecting days that were above the minimum depth criteria at the upper end of reach 3, near Piru, and comparing the percentage of days meeting the passage criteria in the two downstream reaches. A secondary investigation repeated this step for a series of flows below the minimum depth criteria calculated for reach 3, to ascertain the percentage of days meeting the passage criteria in the two downstream reaches under lower flow conditions.

The Watershed Analysis Risk Management Framework (WARMF) model for the SCR developed by Keller *et al*. (2004) was used to simulate rainfall-runoff relations throughout the watershed. WARMF simulates catchment and stream hydrology by tracking the flow paths of precipitation to the canopy, surface layer, through the soil layers and to downstream waterbodies (Systech Engineering, 2001). A detailed description of the equations considered in WARMF is included in the technical guide (http://www.epa.gov/athens/wwqtsc/html/warmf.html).

The WARMF model utilized in this study was developed for the water years of 1990-2000. This period covered a series of wet and dry years, thus we assume that they are representative of typical conditions. To account for rising and falling groundwater throughout the groundwater basins (Figure 6), the percolation model developed by McEachron (2005) was incorporated into the WARMF calculations.

3.4 Potential Flow Passage Analyses

The final component of the analysis was to establish the frequency of potential passage events from December-June, 1955-2004. Using gage data of mean daily discharge, we evaluated the frequency of flows meeting the passage criteria in the three reaches (figure 5). For reach 1, the Montalvo gage was used to estimate mean daily flow conditions. For reach 2, we took the sum of mean daily discharge from the gages on Sespe Creek (USGS gage # 11113000), Hopper Creek (USGS gage # 11110500), and County Line (USGS gage # 11108500). Flows at reach 3 were estimated from the sum of Hopper and County Line gage data.

An evaluation was performed for the frequency with which the minimum flows of 0.6 ft depth over a continuous 10 ft of channel width would be available for periods of 1, 3, 5 and 10 consecutive days between December 1 and June 1. These are intended to represent the amount of time it might take an adult steelhead to migrate upstream to spawning areas in the major tributaries, though actual swim times for individual fish could vary considerably. A second analysis examined what percentage of years would provide a given number of potential passage opportunities for a continuous three-day period, based on mean daily flows through the three separate reaches.

To assess the role of both climatic fluctuations and managed flows on potential passage opportunities, we compared the number of days in exceedance of a predicted minimum passage flow with and without water diversions from Freeman Diversion for dry, average and wet water years (1956-2001). To determine the water year type, we use the classification of wet, dry and normal years developed by the United Water Conservation District (UWCD). This classification was developed using the total inflow entering Lake Piru over a given year, with an average year defined as having total inflows between 18,000-55,000 acre-feet. Total annual inflows less than 18,000 acre-feet were classified as a wet year, and inflows above 55,000 acre-feet were considered wet years (*personal communication* McEachron, 2006). The complete series of wet, dry and average conditions are given Figure A-10 in the Appendix. The period of record was partitioned into the number of days exceeding a minimum discharge both with and without water diversions at Freeman Diversion, by comparing the recorded flow at Montalvo with a data set of the total flow recorded at the Freeman Diversion, provided by UWCD. The total number of days, as well as the percent reduction was calculated to elucidate changes in the number of potential passage opportunities due to water year type and flow diversions.

4.0 Results

4.1 Hydraulic Model

Flow magnitudes required to meet the passage criteria of 0.6 ft. depth over 10 ft. of continuous channel varied between the three sub-reaches. A summary of minimum passage flows per reach is given in Table 1 and modeled depths for discharges ranging from 100 - 2,000 cfs are shown in the appendix (Figures A4-A8).

Table 1: Flow at which 0.6 ft depth is exceeded for each reach

Reach	*1*	*2*	*3*
	Mouth to Santa Paula Creek	*Santa Paula to Sespe Creek*	*Sespe to Piru Creek*
Minimum Flow	800 (cfs)	500 (cfs)	700 (cfs)

In general, the HEC-RAS model predicts that flows in excess of 500 cfs would be necessary to maintain 0.6 ft depth within the channel (Figure 7). There are several exceptions, including river stations 158,450 and 155,410 above Hopper Creek, 62,000 above Freeman Diversion, 23,950 and 19,550 below highway 101 (figure 7).

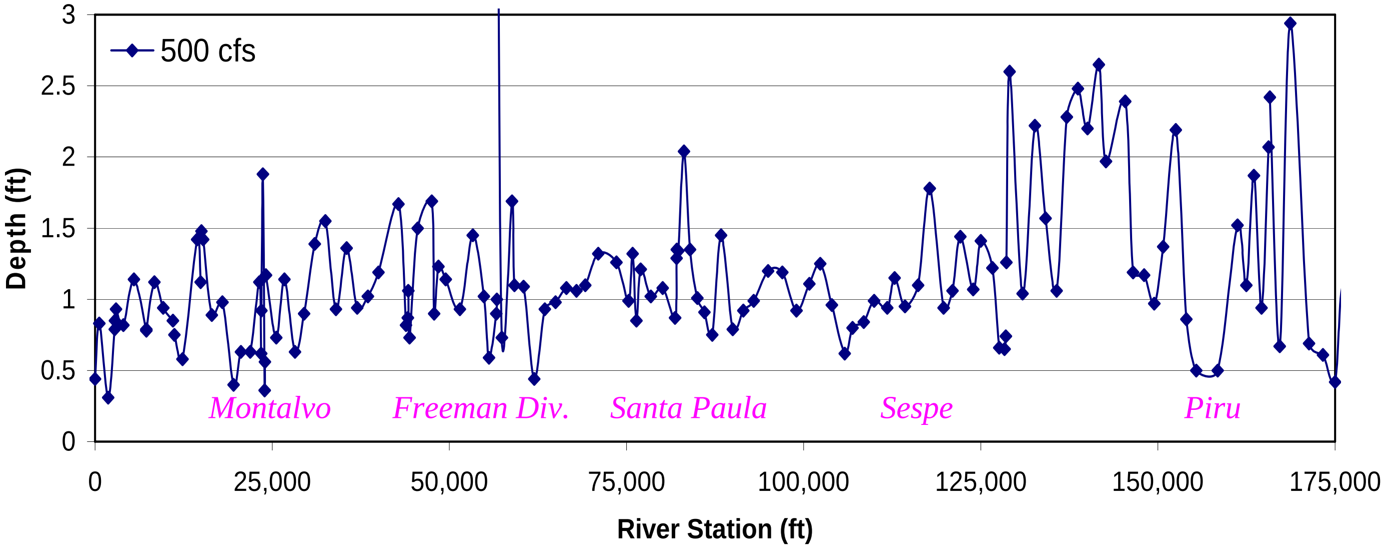


Figure 7. Predicted depths vs. river station (distance to river mouth in feet) for a discharge of 500 cfs. Location of tributary junctions as well as the Freeman Diversion and Montalvo stream gage are noted for reference.

The cross-sections at 62,000, 23,950 and 19,550 (Figures A2-A3) represent narrow areas where the channel slope increases rapidly, with water surface slopes of 0.017, 0.011, and 0.013, respectively at 500 cfs. These water surface gradients are an order of magnitude greater than the mean bed slope (0.003 – 0.005). In these locations, HEC-RAS predicts areas of near-critical or critical flow, with Froude (*Fr*) numbers between 0.7-1.0. The *Fr* is defined as:

$$Fr = \frac{u}{(gH)^{0.5}} \qquad (1)$$

where: g is gravitational acceleration, u is mean velocity and H = depth of flow. The Fr equals 1 at critical flow; when $Fr > 1$, the flow is termed supercritical, and when $Fr < 1$ the flow is subcritical. In a review of published data for the relation between channel gradient and Froude number, Grant (1997) found that in hydraulically steep streams (gradients in excess of 0.01), mean Froude numbers were commonly close to unity, indicating critical flow conditions.

Increasing flow velocity at cross-sections 62,000, 23,950 and 19,550 correspond with decreasing flow depths, by definition of the *Fr*. Thus, it is possible that these cross-sections would be potential passage barriers due to the presence of shallow depths forced by flow acceleration. Field investigations, in conjunction with additional hydraulic modeling using higher-resolution topographic data, would be required to test the extent to which these sections act as potential barriers to steelhead migration.

Station 1860, located in the Santa Clara River estuary also falls below the minimum depth requirement at 500 cfs. However, Swanson *et al*., (1990), (as cited in Stillwater, 2005), note that water surface elevations in the estuary range from + 3.5 ft MSL to + 9.3 ft. MSL for up to 3,000 ft from the Pacific Ocean. Therefore, we assume that stations within the estuary should be passable at 500 cfs due to the tidal influence, and that breaching is more likely to be the major impediment.

In terms of the depth criteria, we considered a modified form of the Thompson (1972) criteria, specifying a minimum depth of 0.6 ft for a contiguous channel width of 10 ft. Given the distance to reach the upper tributaries, a minimum depth of 0.6 ft is fairly shallow and could cause significant stress and energy expenditure to migratory fish. As an upper limit, we can consider the discharge required to maintain 1 ft depth for comparison. Based on the hydraulic modeling, a discharge between 1,800-2,000 cfs would be required to maintain the higher critical depth of 1 ft (Figure A-8).

4.2 Hydrologic Model

The HEC-RAS analysis found that a minimum flow of 700 cfs would be required at the upper end of the study area (reach 3) to get steelhead to Piru Creek (Table 1). Flow depth measurements recorded in May 2006 determined that the 0.6 ft. depth criteria was satisfied at several locations at a discharge of 240 cfs above Hopper Creek (United Water Conservation District, unpublished data). These measurements were taken over several riffles on the mainstem SCR and suggest that we may be overpredicting the minimum flow required to meet the depth criteria at a given location, though it does not provide evidence that the entire mainstem would meet the depth criteria at 240 cfs.

With this in mind, we attempted to determine what the flows would be at the lower two reaches when the discharge ranged from 400-700 cfs in reach 3. This analysis was preformed by taking all of the days from the WARMF output that exceeded 400 cfs at Piru Creek. The data was further separated into those days that exceeded 500, 600 and 700 cfs for comparison. The flow on these days was compared to the mean daily discharge at the two reaches downstream.

Results from this analysis are presented in Table 2. We found that the flow criteria were met, (that is reach 1 is at 800 cfs and reach 2 is at 500 cfs), between 96-99% of the time at reach 2 when the flow entering reach three was between 400-700 cfs during 1990-2000. The percentage of time that the flow criteria were met at reach 1 was slightly lower but the flow criteria was met during the majority of the modeled time period. These results suggest that once the discharge in the mainstem near Piru exceeds several hundred cfs, the lower reaches should have little difficulty meeting the minimum depth criteria.

Table 2: Percent of days in exceedance of flow criteria relative to flow conditions entering reach 3 (1990 – 2000)

Flow Entering Reach 3 (cfs)	*Reach 1*	*Reach 2*
	Mouth to Santa Paula Creek	*Santa Paula to Sespe Creek*
400	88%	96%
500	89%	97%
600	92%	99%
700	93%	99%

4.3 Potential Passage Opportunities

4.3.1 Frequency of Potential Single Passage Opportunities

Table 3 compares the percentage of years during which a single passage opportunity would occur based on the target flow level at each location. Steelhead could pass through reach 1 approximately 77 % of the time for at least one day and 63% of the time for a 3-day period. Five-day flows through this reach were exceeded about every two years and passage conditions for 10 or more days occurred about 1 in 3 years. Reach 2 had the greatest number of years on record that exceeded the minimum flow criteria. This is the result of high flows being delivered from the Sespe basin during storm periods. Given that Sespe Creek is located approximately 23 miles from the ocean, a passage window of between 1-3 days should be adequate. Access to reach 3 was more limited with access available for one day roughly 59%, and for three-days only 20% of the time. Based on this data, migration above Sespe Creek appears to be substantially more difficult to attain due to the hydrologic conditions.

Table 3: Percent of Years with at least one day exceeding minimum flow (December through June 1955 - 2004)

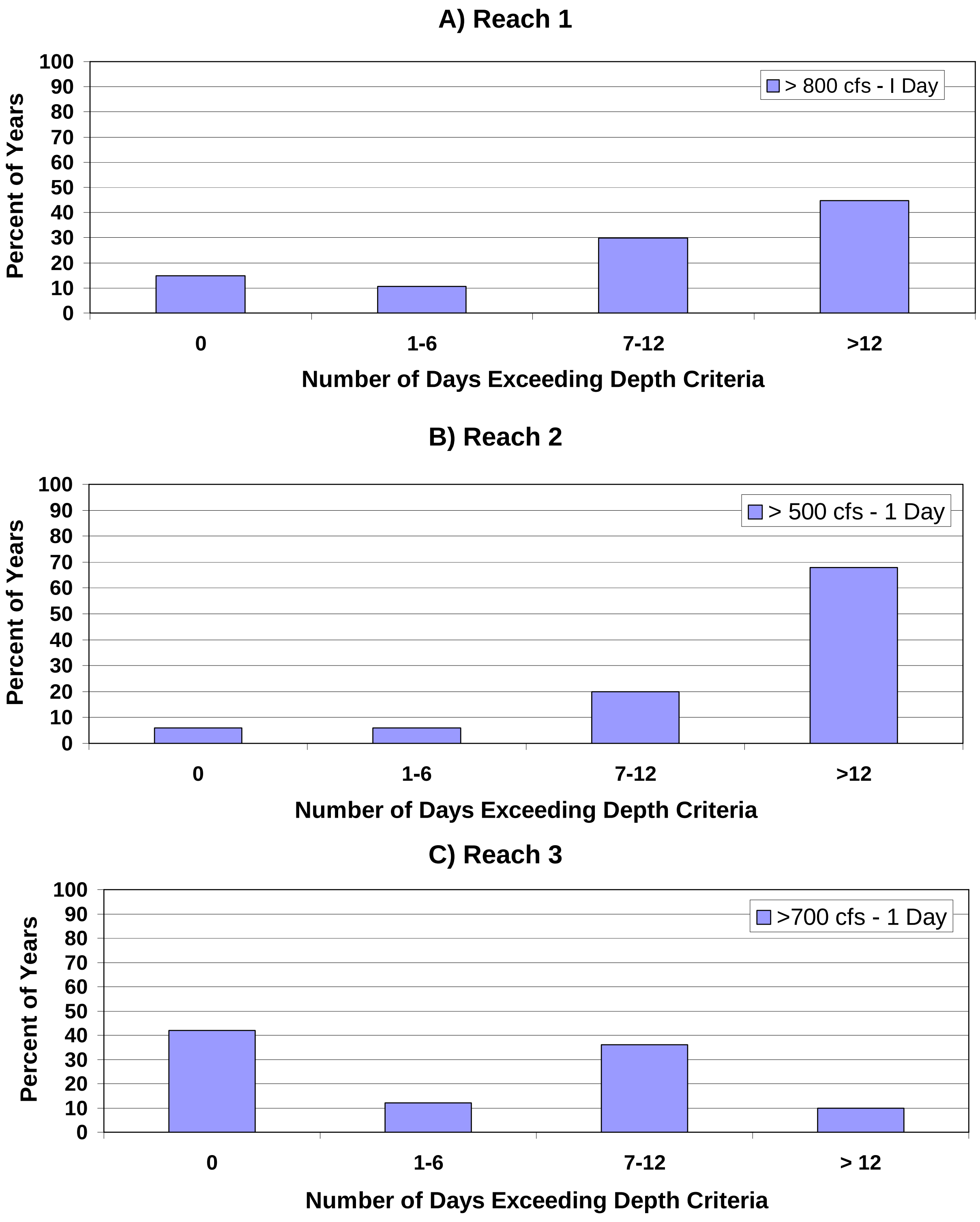
Reach	*1*	*2*	*3*
	Mouth to Santa Paula Creek	*Santa Paula to Sespe Creek*	*Sespe to Piru Creek*
Minimum Flow	800 (cfs)	500 (cfs)	700 (cfs)
Flow Exceeded for:			
1-Day	77%	90%	59%
3-Day	63%	80%	20%
5-Day	52%	76%	14%
10-Day	33%	59%	4%

4.3.2 Frequency of Potential Multiple Passage Opportunities

While a single passage opportunity may provide an index of the number of opportunities, clearly an adult steelhead must be in the correct location to take advantage of this opportunity (SYRTAC, 1999). However, if only one event occurs during a year some steelhead may miss the opportunity. Therefore it is preferable that steelhead have more than one migration opportunity in a given year. Here, we evaluate the frequency of years with multiple one-day and three day passage events. Figure 8 shows the percentage of years when a given number of 1-day passage opportunities are available, and Figure 9 shows the number of years when a given number of 3-day passage opportunities are available. These figures show that fish typically have many passage opportunities or none at all, reflecting the highly variable climate.

During the analysis period, reach 1 had 12 or more 1-day passage opportunities for 45% of the time (Figure 8), reach 2 had 12 or more 1-day passage opportunities for 68% of the time, and 7-12, 1-day passage opportunities would have occurred 36% of the time through reach 3. The number of years without a passage event for all three reaches would have ranged from 6-42%.

Over this same time period, 7-12, 3-day passage opportunities would have occurred for 26% of the time through reach 1, 7-12, 3-day passage opportunities would have occurred through reach 2 for 40% of the time, and reach 3 experienced 7-12, 3-day passage opportunities 14% of the time. The number of years without 3-day passage opportunities is greatest at 80% in reach 3, which further highlights the difficulty in accessing the mainstem SCR above Sespe Creek.


A) Reach 1

B) Reach 2

C) Reach 3

Figure 8. Percentage of Years in December - June (1955-2004) with Flows Exceeding: **A**) 800 cfs for One Day – Reach 1; **B**) 500 cfs for One Day - Reach 2; and **C**) 700 cfs for One Day – Reach 3.

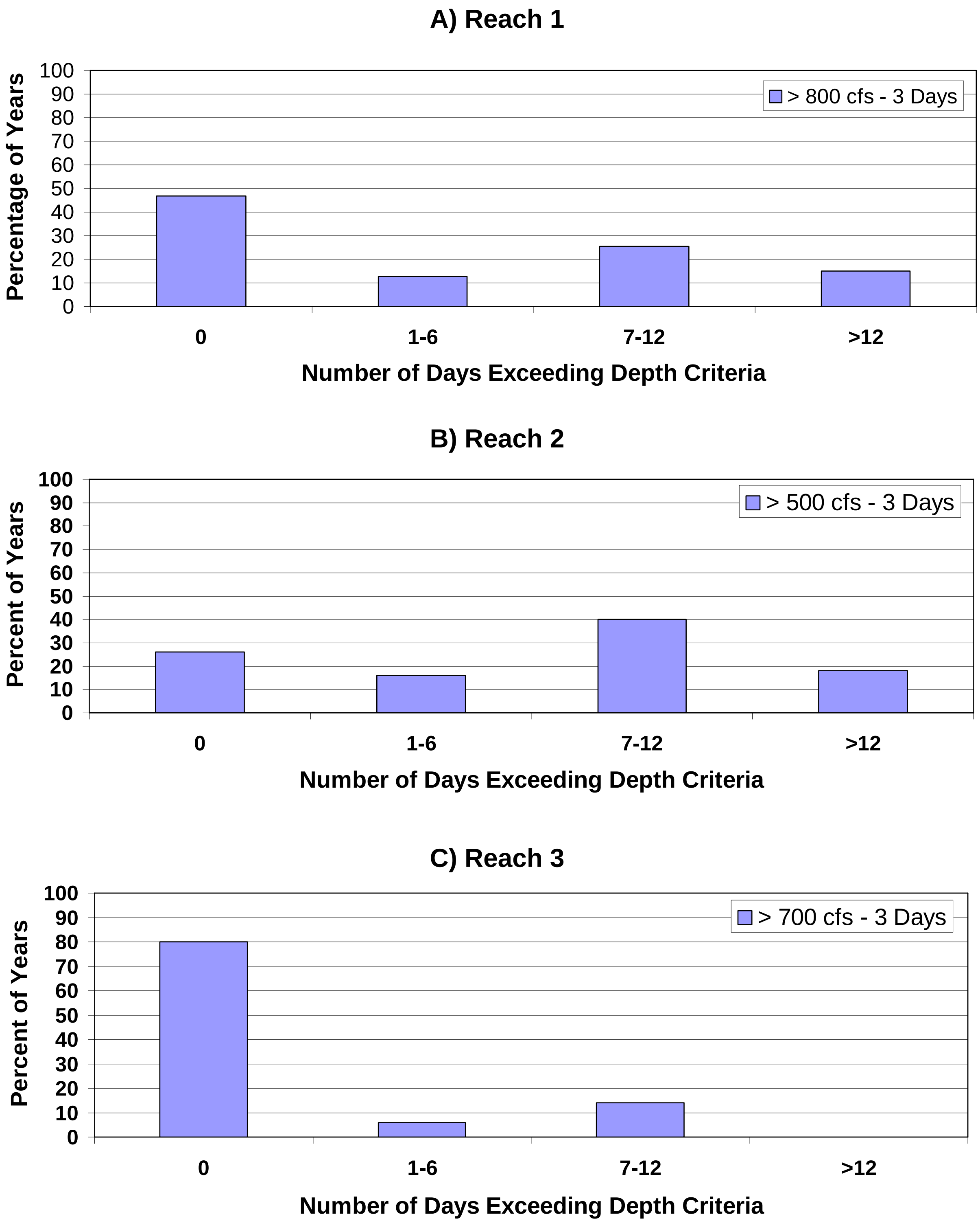


Figure 9. Percentage of Years in December - June (1955 - 2004) with Flows Exceeding: **A**) 800 cfs for Three Consecutive Days - Reach 31; **B**) 500 cfs for Three Consecutive Days - Reach 2; and **C**) 700 cfs for Three Consecutive Days - Reach 3.

4.3.3 Historical Flows

The last part of this analysis related to the duration of the historical flows as a way of discerning what the opportunities might be for fish to migrate upstream from the mouth were sufficient flow available. A regression analysis was completed comparing total annual flow volume (acre-feet) vs. the number of days exceeding 400 and 800 cfs (Figure 10). Results from this analysis produced the following regression equations:

$$y = 0.0015x^{0.82} \qquad (2)$$

for total annual flow volume vs. number of days exceeding 400 cfs, and

$$y = 0.0006x^{0.86} \qquad (3)$$

for total annual flow volume vs. the number of days exceeding 800 cfs.

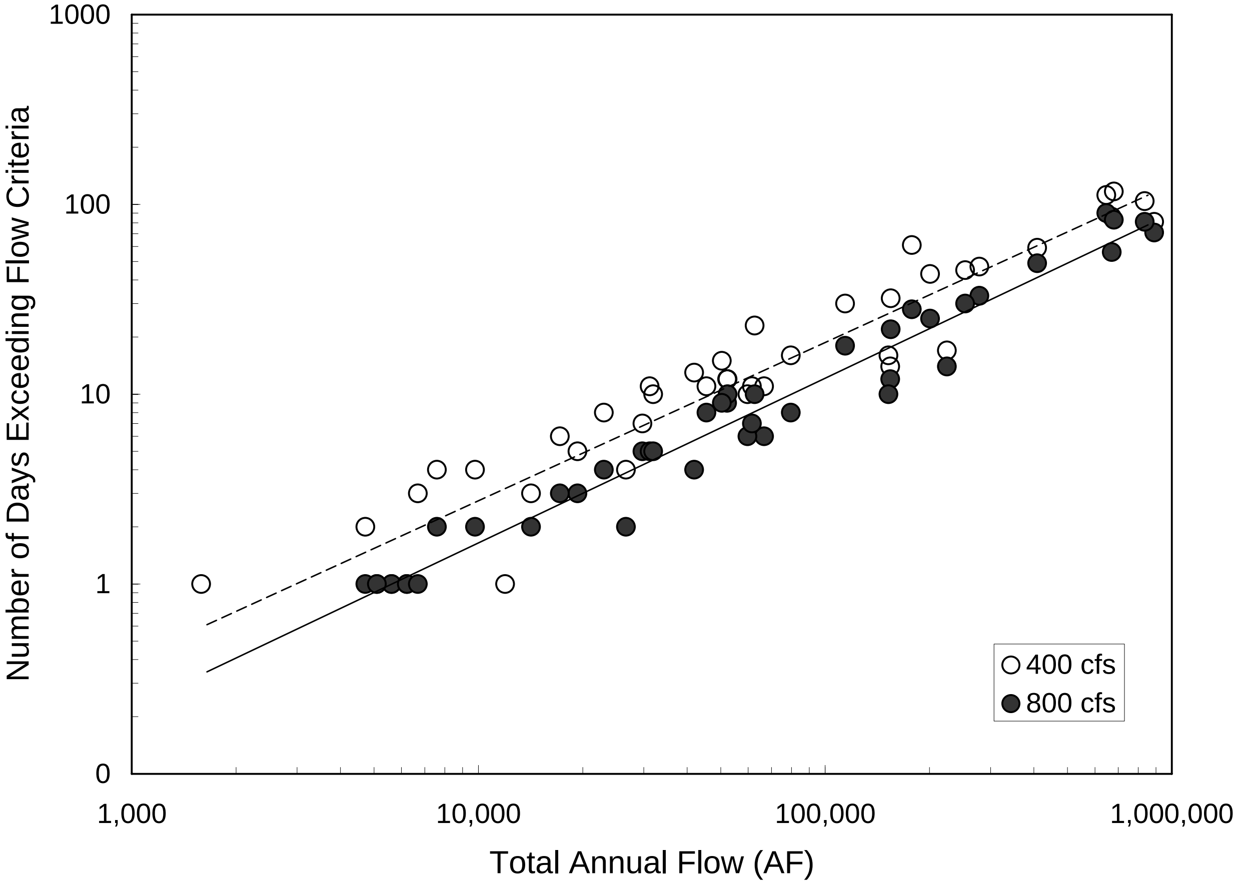


Figure 10. Regression plot of the total annual flow (acre-feet) vs. the number of days exceeding 400 and 800 cfs on the lower SCR, based on mean daily discharge at USGS Montalvo Gage (1955-2004). Data points representing the number of days exceeding 400 cfs are shown as open circles with a dashed regression line and days above 800 cfs are shown as closed circles with a solid trendline.

There is a high correlation between the total volume of flow and the number of days above both 400 and 800 cfs, as demonstrated by an R^2 of 0.91 for total annual flow (acre-feet) vs. days exceeding 400 cfs and 0.96 for total annual flow vs. days above 800 cfs ($n = 44$). While there is scatter about the fitted trendlines, the envelope between the two power functions produces a fairly narrow range. The spread in the data highlights the role of climatic fluctuations between wet and dry years as a major driver of fish passage opportunities.

Further analysis of historical flows was performed to assess the role of climatic fluctuations and flow diversions on the number of days per year that exceeded a discharge of 800 cfs during wet, dry and average water years. Calculated values of the number of days exceeding 800 cfs for each water year type are shown in Table 4. This data set was further separated into three time periods representing the entire period of record (1956-2001), the period before the Freeman Diversion was constructed (1956-1989), and the period following construction of Freeman Diversion (1990-2001).

Table 4: Comparison between the number of days in exceedance of 800 cfs with and without water diversions from Freeman Diversion for dry, average and wet water years (1956-2001). Also shown are data before Freeman (1956-1990), and after Freeman (1991-2001).

WY Type	*Period of Record*	*Avg. # Days > 800 cfs wo/diversion*	*Avg. # Days > 800 cfs w/diversion*	*Avg. # Days Reduced*	*Percent Reduction*
Dry	*1956-2001 (Total record)*	1.44	1.40	0.13	9
	1956-1990 (Before Freeman)	1.44	1.40	0.13	9
	1991-2001 (After Freeman)	0.00	0.00	0.00	0
Average	*1956-2001 (Total record)*	10.94	8.67	2.53	23
	1956-1990 (Before Freeman)	10.50	10.00	0.50	5
	1991-2001 (After Freeman)	11.67	6.00	6.60	57
Wet	*1956-2001 (Total record)*	54.64	44.23	5.69	10
	1956-1990 (Before Freeman)	44.33	41.22	2.83	6
	1991-2001 (After Freeman)	73.20	51.00	11.50	16

Beginning with the water year type and considering the total river flow, during dry water years the average number of days exceeding 800 cfs is approximately 1.4 days (1956-2001), 1.5 days from 1956-1989 and there were no years between 1990-2001 that were categorized as dry years. Please refer to Table A-1 in the Appendix for complete water year classification and raw data used in the analysis. During normal water years, there have been approximately 11 days exceeding 800 cfs, for each time period. The percent reduction of these flows has been approximately 23% for the entire period of record, 5 % pre-Freeman and approximately 57% following the construction of Freeman Diversion. During above average years, the number of flow days in excess of 800 cfs is considerably higher with an average of roughly 55 days per year when the whole record is included, 44 days during 1956-1989 and 73 days from 1990-2001.

5.0 Discussion

5.1 Hydraulic Model

The analysis completed with HEC-RAS was based a topographic survey conducted in 1993. The extensive set of over 175 cross-sections are representative of the river channel morphology, and we assume that the set of cross-sections represent the variability that we observe today. The principal limitation with the 1993 data set is the inability to closely examine the low flow hydrology. The majority of these cross-sections show a wide flat channel bottom (Figure A-9), with no low-flow channel. Based on this cross-sectional geometry, HEC-RAS predicts wide sheet flow across the wetted width of the channel. However, field observations indicate that a low-flow channel is typically present and this is likely what most adult steelhead would utilize in their upstream migration at flows between 500-800 cfs.

Based on the 11 detailed cross-sections above Fillmore surveyed in 2001, the 1993 data may underestimate the low flow maximum depth by up to 100% (Figure 11). A complicating factor that prevented a more rigorous error analysis between the two data sets is that the water years between 1993-2001were all categorized as average or above average in terms of the annual flow volumes, with 1995, 1998 and 2001 all experiencing high magnitude floods. It is possible that a narrow channel may have been scoured in between the 1993 and 2001 surveys, which could help to explain a portion of the variability between the predicted depths.

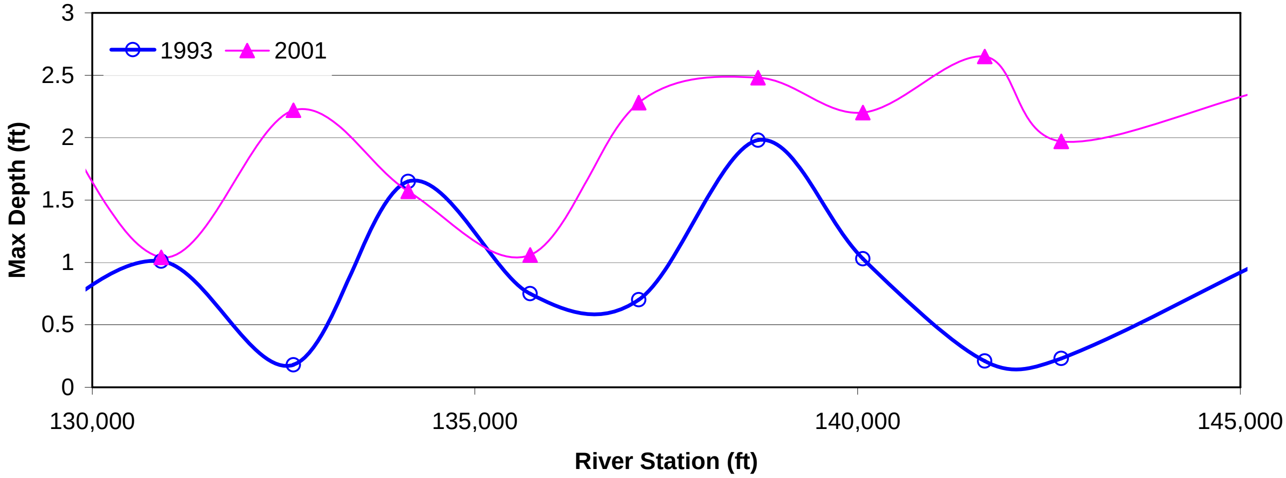


Figure 11. Comparison of predicted depths at 500 cfs using 1993 5-foot contour data versus 2001 channel survey.

Therefore, we view the minimum flows predicted in this analysis as being a conservative estimate. A new data set of surveyed cross-sections at a contour interval of 0.5 ft in the active low flow channel would provide for an improved analysis of water depths for discharges of 200-800 cfs.

The 2005 LiDAR topography is another potential data set that could be used to improve low-flow predictions. This data was collected during the winter of 2005 to assess flood conditions and there was several hundred to several thousand cfs present in the channel during the flight. As a result, the water surface is included sporadically in the data set (due to partial LiDAR signal attenuation through the water column), thus complicating delineation of a low-flow channel. New techniques are emerging that aim to retrieve the inundated topography with remote sensing algorithms designed to subtract the water depth from the bathymetry (Legleiter and Roberts, 2005). This technique or similar methods would need to be applied to the data set before the LiDAR could be used for low-flow hydraulic modeling.

5.2 Hydrologic Model

The goal of the hydrologic model was to determine what the flows would be at the lower two reaches when the discharge ranged from 400-700 cfs in reach 3. The utility of such an analysis is that we can account for surface and groundwater exchange in a spatially explicit manner. The results illustrate a general trend, which is that once natural flows in the mainstem near Piru exceed several hundred cfs, the lower reaches should have little difficulty meeting the minimum depth criteria. A broader conclusion can be drawn from this data, which is that passage flows through the three reaches along the mainstem SCR should exist everywhere at the same time.

5.3 Potential Passage Opportunities

Evaluation of the frequency of years with multiple one-day passage events found that reach 1 had 12 or more potential passage opportunities roughly every other year (45% of the time). Reach 2 experienced 12 or more potential passage opportunities approximately 2 out 3 years and reach 3 had 12 or more passage opportunities roughly 1 in 3 years (36% of the time). Analysis of 3-day passage opportunities found similar relations between the three reaches, with reach 2 having the greatest number of flows above the depth criteria, followed by reach 1 and then reach 3. Reach 3 had the greatest percentage of water years without adequate passage flows, which further highlights the difficulty in accessing the mainstem SCR between Sespe and Piru Creeks.

The regression models developed between total annual runoff and the number of days exceeding a threshold discharge (Figure 10) both highlight the importance of annual rainfall on the exceedance of the minimum flow criteria. This type of model could be used to assist in management of flow releases once a target discharge is specified. If flow criteria for fish passage were set in terms of the number of days exceeding a given flow (for example 10 days above 800 cfs), the power functions developed here could be used to assess the minimum flow volume needed to achieve these conditions.

Based on the historical flow analysis the greatest reduction in potential passage opportunities has occurred during the average water years, especially during the period from 1991-2001. It should be noted that there has been a disproportionate amount of normal and above normal water years during this period. During dry years, there are minimal potential passage opportunities and the diversion of flow does not appear to have significantly reduced the number of opportunities. While the number of flows above 800 cfs has been reduced by 10% during above average years over the entire period of record, there are still roughly 44 days above this discharge under current operations. Given the possibility that our estimates of the required minimum flow conditions are high, the percent reductions for the same duration were calculated for a discharge of 400 cfs. The results of this analysis are presented in the appendix as Tables A1-A3.

5.4 Future Work

As discussed in section 5.1, the hydraulic predictions from this study are conservative. This results because the 1993 topography is less than desirable to fully characterize the low-flow hydrology and maximum depth of flow across a given cross-section. The ability to determine 0.6 ft depth criteria with a vertical data resolution of 5 feet is questionable as it does not detect a low-flow channel. It is the secondary channels that may provide the depth of flow necessary for fish passage during low-flow conditions. We recommend that a new survey be done with a contour interval of 0.5 ft. across the low-flow channel bed to refine these findings. This will be sufficient to recognize secondary channels which may be important to fish passage.

In terms of fish passage opportunities, we assumed that the methods developed by Thompson (1972) were appropriate for the SCR. However, it is recognized that the 0.6 ft depth criteria used in the Thompson (1972) methods was developed in higher gradient streams where the minimum depth was associated with local changes in channel gradient, due to shallow riffles, and did not specifically consider shallow depths over extended reaches, which occur in the SCR. Future studies on the flow conditions utilized by migratory fish in the lower SCR would allow for a more thorough assessment of the applicability of this depth criteria in a wide, braided river.

6.0 Conclusions

This analysis investigated the discharge required to maintain the minimum depth criteria on the lower Santa Clara River (SCR), California from the Pacific Ocean to Piru Creek. The major findings are as follows:

1) Model-based predictions suggest a minimum flow of 800 cfs is required to provide a depth of 0.6 ft continually across 10ft of channel, from the SCR estuary to Santa Paula Creek; flow of 500 cfs is needed to provide the same depth and width of flow from Santa Paula to Sespe Creek; and 700 cfs would be needed between Sespe Creek and Piru Creek.

2) Rainfall-runoff simulations predict that the minimum flow criteria were met between 96-99% of the time between Sespe and Santa Paula Creeks and between 88-93% from Santa Paula to the estuary when flow in the mainstem near Piru was greater than 400-700 cfs. The results indicate that once natural flows in the mainstem near Piru exceed several hundred cfs, the lower reaches should have little difficulty meeting the minimum depth criteria. In addition, passage flows along the mainstem SCR should exist everywhere at the same time due to the hydrologic regime of the SCR.

3) Results from this study found that the number of days in exceedance of both 400 and 800 cfs were strongly correlated to the total annual flow volume. Thus, total annual runoff (or rainfall conditions), should control the number of passage opportunities in a given year. The regression models developed in this study could be useful management tools for determining flow release strategies for a variety of beneficial uses.

4) The number of days exceeding the minimum flow criteria can be explained further based on the water year type. The greatest reduction to the number of potential passage opportunities due to water diversions has occurred during the average water years. In general, migratory steelhead would have had many more potential opportunities in the past to access the upstream tributaries during average and wet years, and few if any during the dry years.

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8.0 Appendix

Supplemental Tables

Table A-1. Number of days in exceedance of 800 cfs with and without water diversions from Freeman Diversion for **A**) dry, **B**) average and **C**) wet water years (1956-2001). ND indicates that data were not available for the given water year at the Montalvo Gage.

A) Dry Years

Period of Record by WY	*#days>800 wo/diversion*	*#days>800 w/diversion*	*Days Reduced*
1956	3	2	1
1957	1	1	0
1959	3	3	0
1960	0	0	0
1961	0	0	0
1963	1	1	0
1964	1	1	0
1965	3	2	1
1968	2	2	0
1972	5	5	0
1976	2	2	0
1977	1	1	0
1985	1	1	0
1987	0	0	0
1989	0	nd	nd
1990	0	0	0

B) Average Years

WY	*#days>800 wo/diversion*	*#days>800 w/diversion*	*Days Reduced*
1970	9	9	0
1971	6	6	0
1973	25	25	0
1974	11	10	1
1975	10	10	0
1981	6	5	1
1982	5	5	0
1984	4	4	0
1986	25	22	3
1988	4	4	0
1991	15	8	7
1994	7	nd	nd
1996	8	6	2
1997	18	7	11
1999	7	0	7
2000	15	9	6

C) Wet Years

WY	*#days>800 wo/diversion*	*#days>800 w/diversion*	*Days Reduced*
1958	41	33	8
1962	16	14	2
1966	13	12	1
1967	18	18	0
1969	80	71	9
1978	58	56	2
1979	30	28	2
1980	50	49	1
1983	93	90	3
1992	41	30	11
1993	92	81	11
1995	116	nd	nd
1998	104	83	21
2001	13	10	3

Table A-2: Comparison between the number of days in exceedance of 400 cfs with and without water diversions from Freeman Diversion for dry, average and wet water years (1956-2001). Also shown are data before Freeman (1956-1990), and after Freeman (1991-2001).

WY Type	*Period of Record*	*Avg. # Days > 400 cfs wo/diversion*	*Avg. # Days > 400 cfs w/diversion*	*Avg. # Days Reduced*	*Percent Reduction*
Dry	*1956-2001 (Total record)*	3.13	2.47	0.87	28
	1956-1990 (Before Freeman)	3.13	2.47	0.87	28
	1991-2001 (After Freeman)	0.00	0.00	0.00	0
Average	*1956-2001 (Total record)*	22.38	15.20	7.20	32
	1956-1990 (Before Freeman)	21.20	17.50	3.70	17
	1991-2001 (After Freeman)	24.33	10.60	14.20	58
Wet	*1956-2001 (Total record)*	88.29	60.69	23.00	26
	1956-1990 (Before Freeman)	75.33	56.33	22.83	30
	1991-2001 (After Freeman)	111.60	70.50	32.00	29

Table A-3. Number of days in exceedance of 400 cfs with and without water diversions from Freeman Diversion for **A**) dry, **B**) average and **C**) wet water years (1956-2001). ND indicates that data were not available for the given water year at the Montalvo Gage.

A) Dry Years

Period of Record by WY	*#days>400 wo/diversion*	*#days>400 w/diversion*	*Days Reduced*
1956	3	2	1
1957	1	1	0
1959	3	3	0
1960	0	0	0
1961	0	0	0
1963	1	1	0
1964	1	1	0
1965	3	2	1
1968	2	2	0
1972	5	5	0
1976	2	2	0
1977	1	1	0
1985	1	1	0
1987	0	0	0
1989	0	nd	nd
1990	0	0	0

B) Average Years

WY	*#days>400 wo/diversion*	*#days>400 w/diversion*	*Days Reduced*
1970	9	9	0
1971	6	6	0
1973	25	25	0
1974	11	10	1
1975	10	10	0
1981	6	5	1
1982	5	5	0
1984	4	4	0
1986	25	22	3
1988	4	4	0
1991	15	8	7
1994	7	nd	nd
1996	8	6	2
1997	18	7	11
1999	7	0	7
2000	15	9	6

C) Wet Years

WY	*#days>400 wo/diversion*	*#days>400 w/diversion*	*Days Reduced*
1958	41	33	8
1962	16	14	2
1966	13	12	1
1967	18	18	0
1969	80	71	9
1978	58	56	2
1979	30	28	2
1980	50	49	1
1983	93	90	3
1992	41	30	11
1993	92	81	11
1995	116	nd	nd
1998	104	83	21
2001	13	10	3

Supplemental Figures

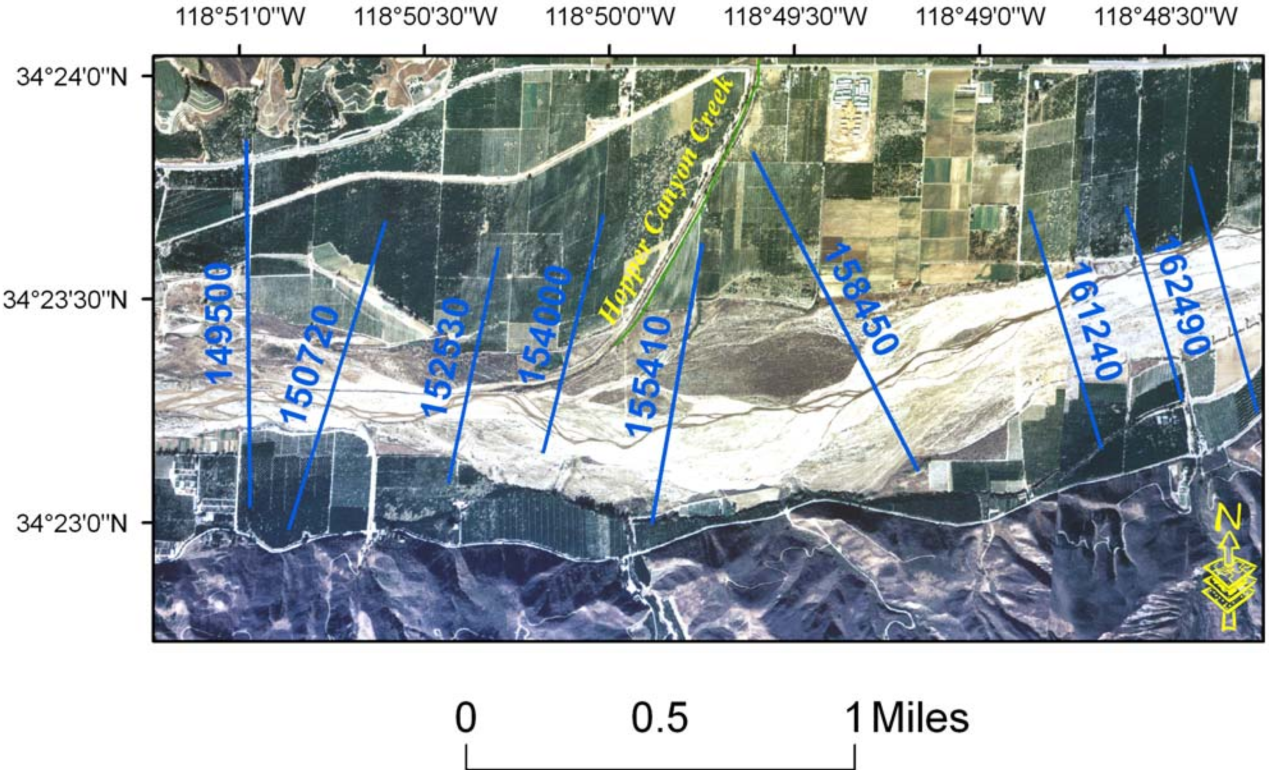

Figure A-1. 1992 aerial photograph showing potential passage barriers (sections 158,450 and 155,410) above Hopper Creek. *Source*: Pacific Western Aerial Surveys, Santa Barbara (georeferencing by Stillwater Sciences).

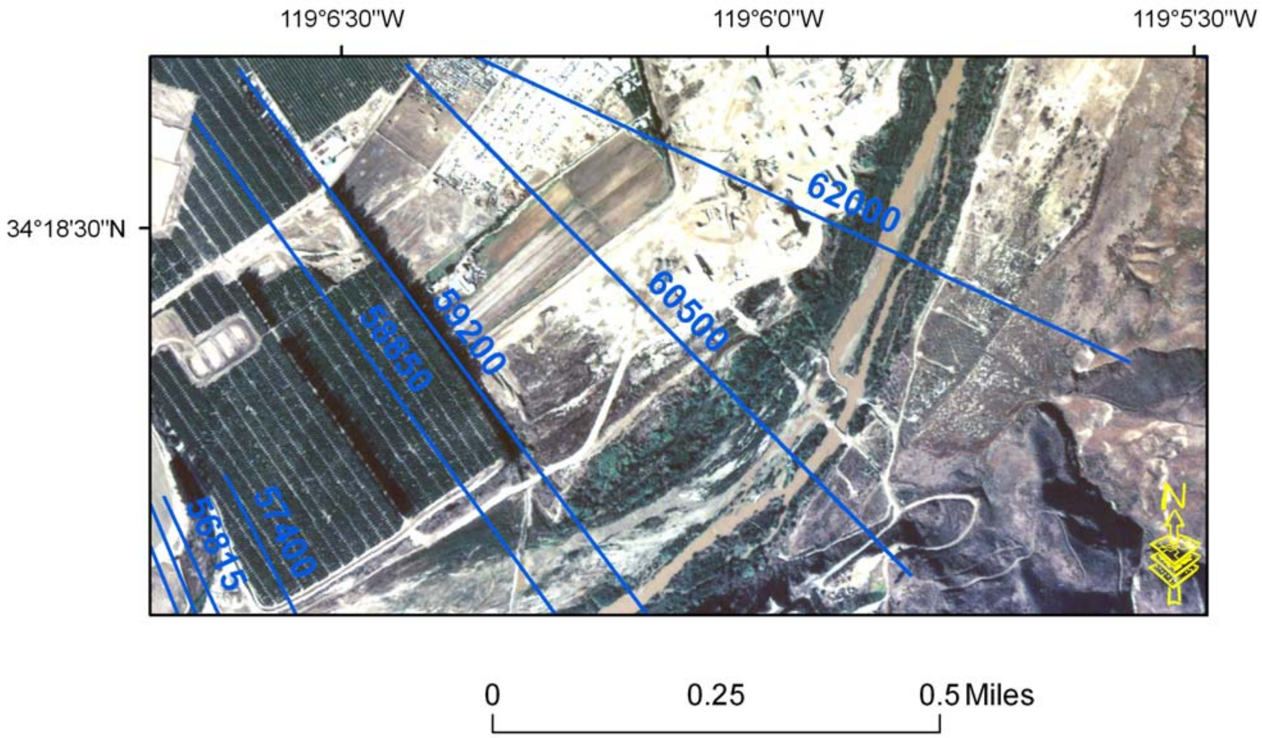

Figure A-2. 1992 aerial photograph showing potential passage barrier (sections 62,000), located approximately 0.5 miles upstream from Freeman Diversion. *Source*: Pacific Western Aerial Surveys, Santa Barbara (georeferencing by Stillwater Sciences).

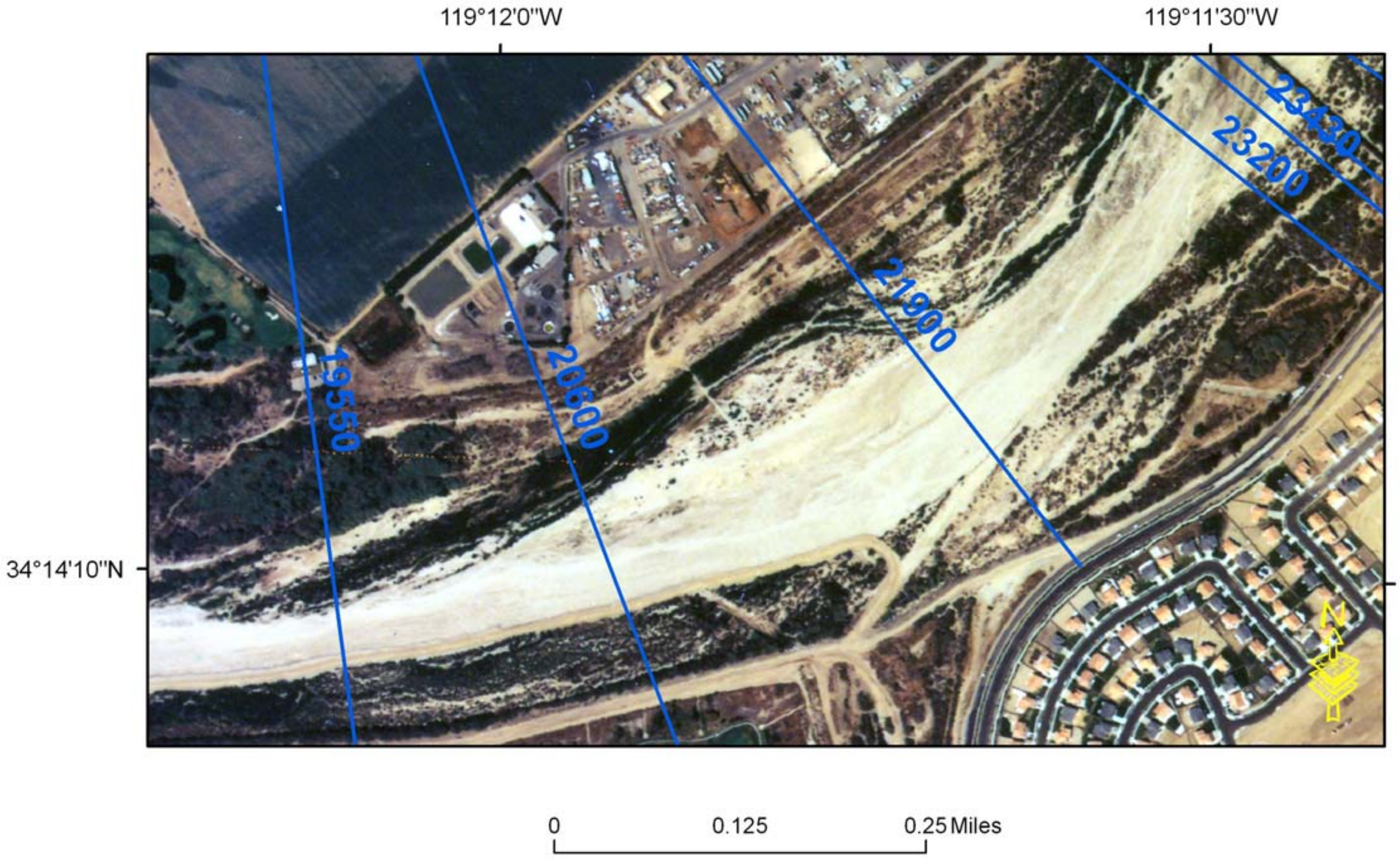

Figure A-3. 1992 aerial photograph showing potential passage barrier (section 19,550), located approximately 0.5 miles downstream from the Highway 101 bridge. *Source*: Pacific Western Aerial Surveys, Santa Barbara (georeferencing by Stillwater Sciences).

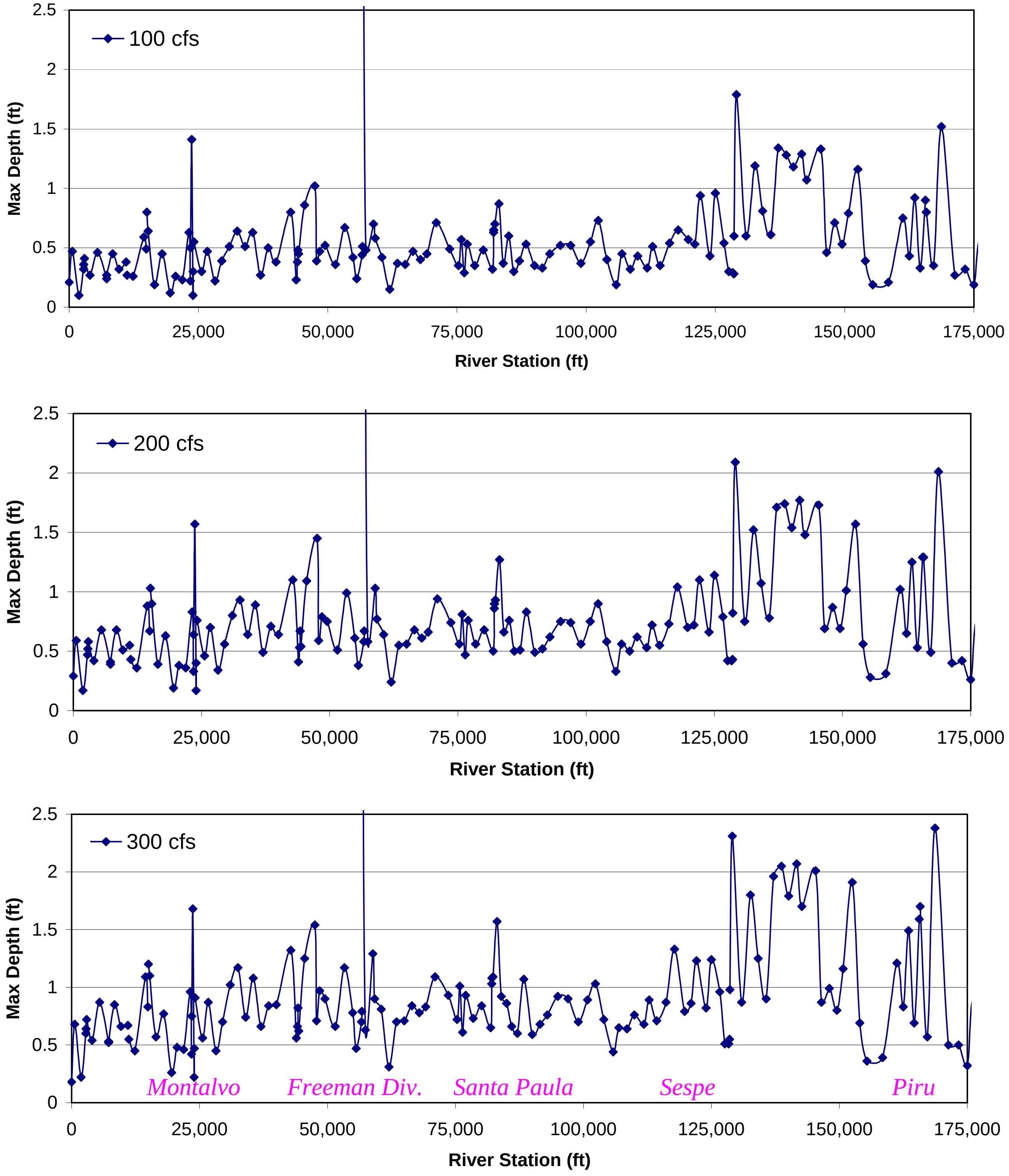

Figure A-4. Predicted depths vs. river station for 100,200 and 300 cfs.

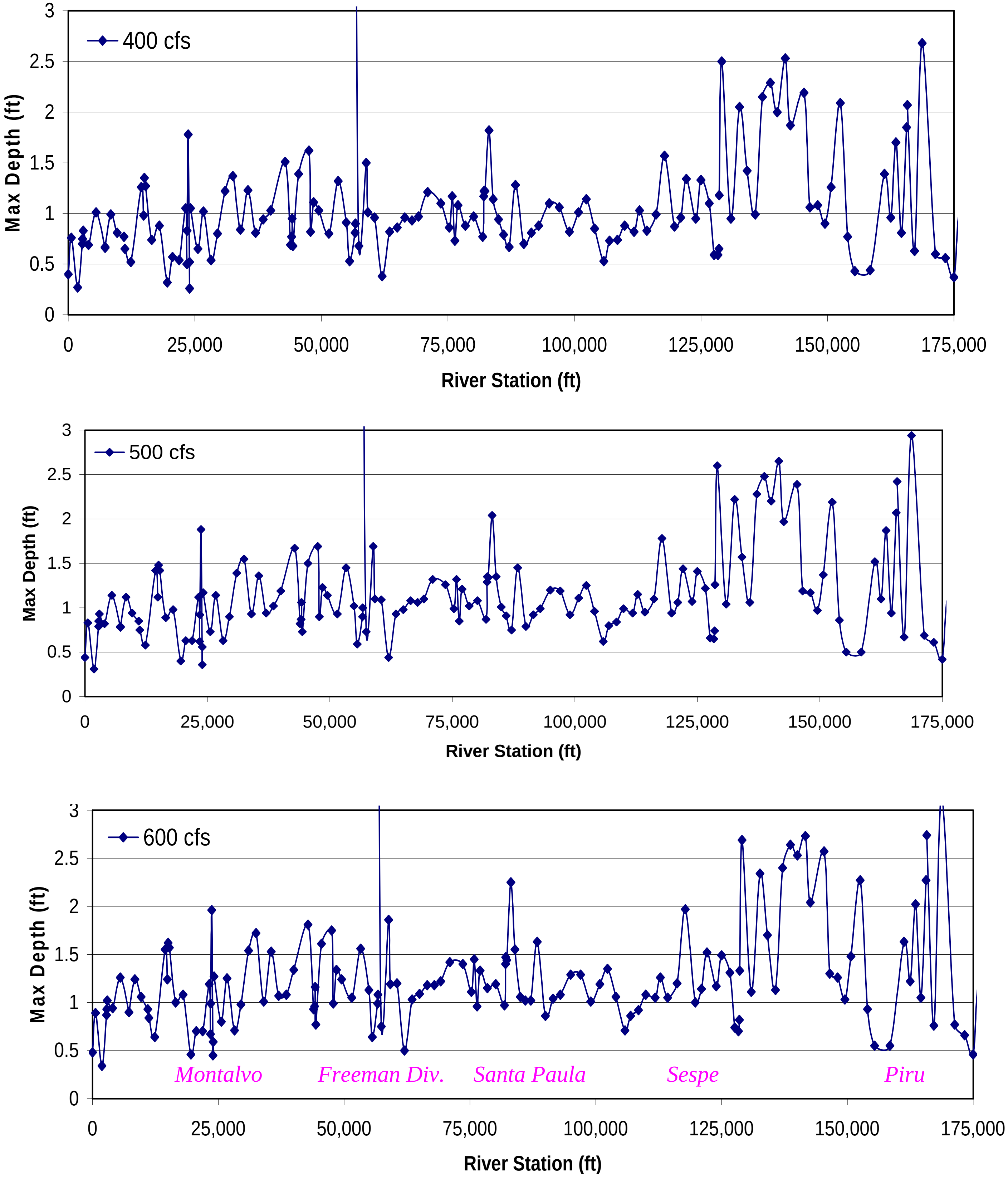

Figure A-5. Predicted depths vs. river station for 400, 500 and 600 cfs.

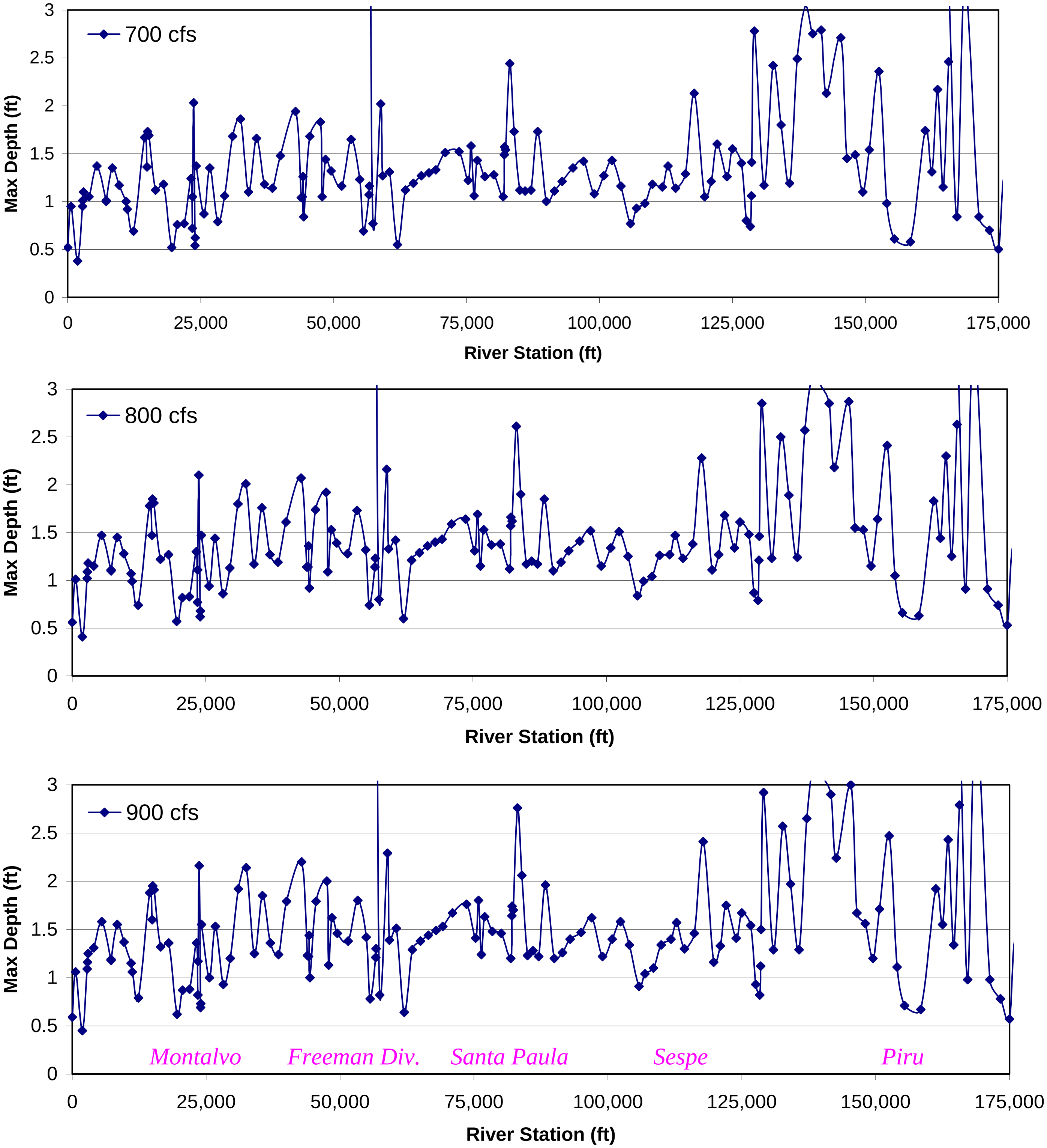

Figure A-6. Predicted depths vs. river station for 700, 800 and 900 cfs.

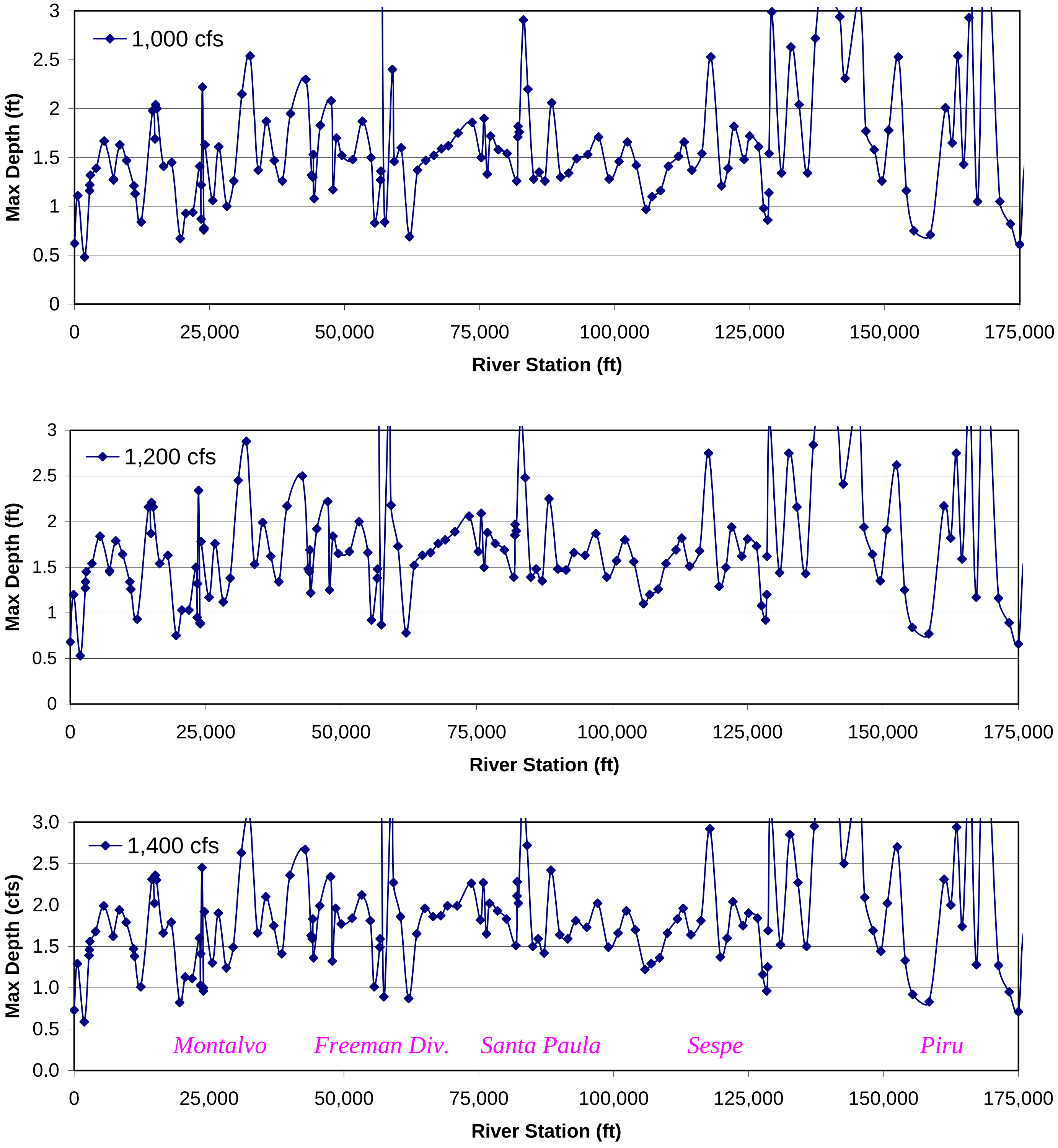

Figure A-7. Predicted depth vs. river station for 1,000, 1,200 and 1,400 cfs.

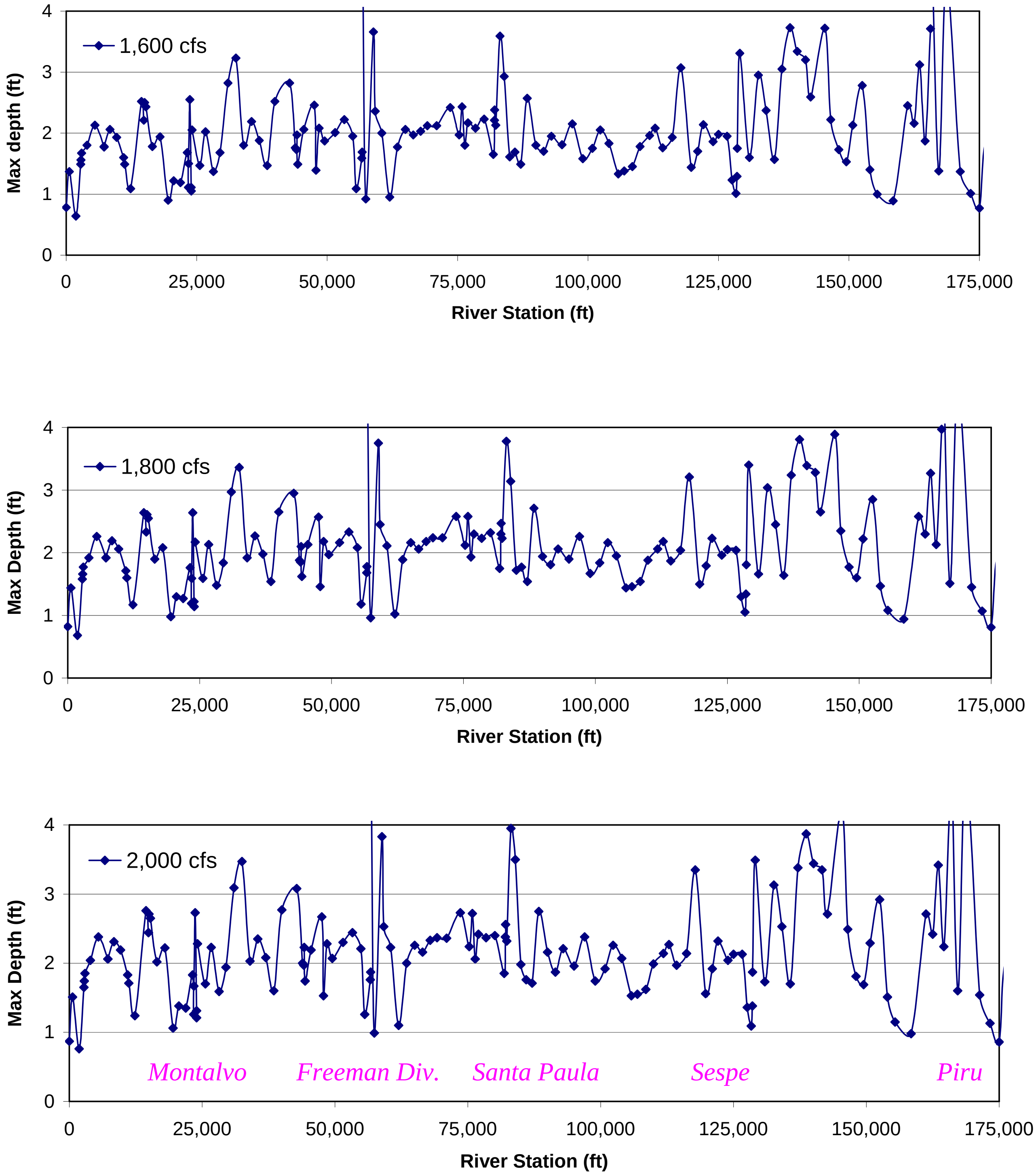

Figure A-8. Predicted depth vs. river station for 1,600, 1,800 and 2,000 cfs.

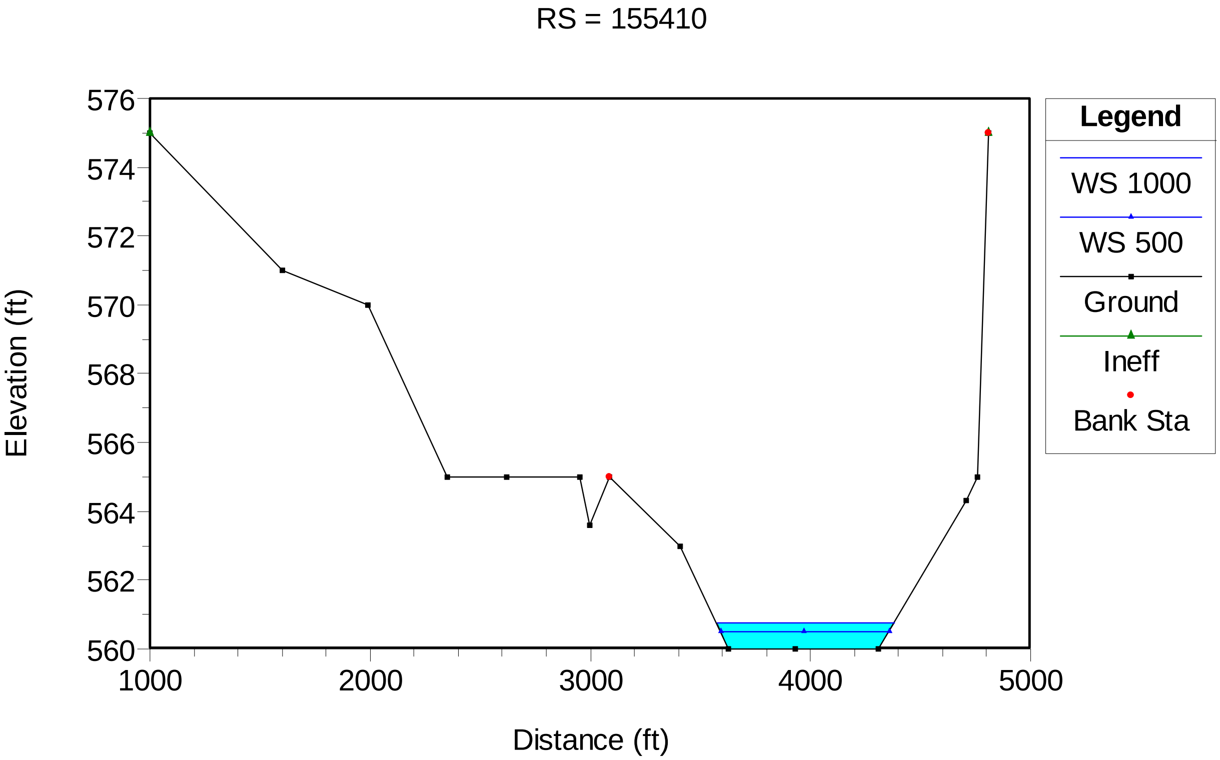

Figure A-9. Predicted water surface elevations for river station 155410 at 500 and 1,000 cfs. Note the constant bed elevation of 560 ft for nearly 700 ft across the channel width. The 5-foot contour data does not capture a low-flow channel, thus doubling the discharge from 500 – 1,000 cfs produces only a modest (0.25 ft) increase in depth.