TECHNICAL MEMORANDUM ◦ MAY 2023

Potential Effects of Suspended Sediment on Adult Steelhead Migrating in the Santa Clara River

PREPARED FOR

United Water Conservation District
1701 North Lombard St., Suite 200
Oxnard, CA 93030

PREPARED BY

Stillwater Sciences
996 S. Seaward Ave., Suite 102
Ventura, CA 93001

Stillwater Sciences

Suggested citation:
Stillwater Sciences. 2023. Potential Effects of Suspended Sediment on Adult Steelhead Migrating in the Santa Clara River. Prepared by Stillwater Sciences, Ventura, California for United Water Conservation District, Oxnard, California.

Cover photos: Santa Clara River at the Freeman Diversion during high-flow events. Photos provided by John Carman, United Water Conservation District.

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1 PURPOSE

United Water Conservation District (United) is developing a Multiple Species Habitat Conservation Plan (MSHCP) as part of an incidental take permit application under Section 10(a)(1)(B) of the federal Endangered Species Act (ESA). The MSHCP includes design, construction, and operation of a new fish passage system, proposed diversion/instream flow operations, and an effects analysis that analyzes and describes the effects of the covered activities on the covered species in the MSHCP. The federally endangered southern California steelhead (anadromous *Oncorhynchus mykiss*) distinct population segment is one of the covered species in the MSHCP.

To inform United's decision-making process with regard to fish passage design, proposed operations, and assumptions for the effects analysis in the MSHCP for steelhead, United tasked Stillwater Sciences with assessing the best available scientific and commercial data regarding the potential effects of suspended sediment concentrations (SSC) (also referred to as total suspended solids [TSS])[1] on the upstream migration of adult steelhead in the Santa Clara River with the specific goal of answering the focal scientific questions presented in Table 1 using direct empirical evidence as well as reasonable scientific inference when empirical data are not available.

Table 1. Four focal scientific questions for evaluation to inform management decisions regarding the covered activities, conservation strategy, and effects analysis of United Water Conservation District's Multiple Species Habitat Conservation Plan.

Question number	Question
1	What are the potential behavioral and physiological effects of SSCs on migrating adult steelhead?
2	At what range of SSC are migrating, pre-spawning adult steelhead likely to actively swim in an upstream direction in the lower Santa Clara River?
3	At what range of SSC are migrating, pre-spawning adult steelhead not likely to actively swim in an upstream direction in the lower Santa Clara River?
4	What are the ranges of discharge in the Santa Clara River that would be associated with the identified ranges of SSC for Questions 2 and 3?

To address Questions 1 through 3, a review of peer reviewed literature, grey literature, expert opinion, and empirical measurements of SSC (as well as turbidity converted to SSC) was conducted to summarize any evidence of physiological and behavioral effects of SSC on steelhead and characterize empirical and observational relationships between adult steelhead migration behavior and SSC. Where information is lacking for adult steelhead, data regarding other salmonids and other fish were reviewed to assess if reasonable inferences can be made for steelhead. To address Question 4, relationships between SSC and discharge in the Santa Clara River are presented and described, then compared to the ranges of SSC described for Questions 2 and 3.

[1] The analytical methods for estimating SSC and TSS differ. **SSC** data are produced by measuring the dry weight of all the sediment from a known volume of a water-sediment mixture. **TSS** data are produced by several methods, most of which entail measuring the dry weight of sediment from a known volume of a subsample of the original. In this memo, we utilize the metric used in the source research, when identified.

The effects of turbidity on behavior and physiology are not explored in this report. The focus of this report is suspended sediment, which correlates with turbidity. While the degree to which water loses its transparency due to suspended particulates (turbidity) is not the direct aim of the focal questions, turbidity is often used to infer relative SSC and changes in SSC (i.e., increasing or decreasing). Therefore, turbidity is discussed occasionally as a measure of relative suspended sediment, particularly when direct measurements of SSC were not available. It is understood that turbidity may be associated with behavioral effects (e.g., predation avoidance and effects to visual feeding), but that was not the focus of the current evaluation.

2 GEOGRAPHICAL SETTING: SUSPENDED SEDIMENT IN THE SANTA CLARA RIVER

Sediment transport, as used herein, refers to the movement of organic and inorganic particles by water. Sediment transport is especially influential on the morphology of the Santa Clara River because the watershed has extremely high sediment production rates (Farnsworth and Warrick 2007, Stillwater Sciences 2011). Production and delivery of sediment to the river are driven by the episodic and intertwined effects of tectonic uplift, rainstorms, wildfires, earthquakes, and human and other disturbances. The watershed is in a tectonically active region; with the San Andreas Fault nearby, it experiences episodic earthquakes and tectonic uplift at some of the highest rates in the western United States (Hammond et al. 2017). The rapid uplifting triggers landslides, causing the input of sediment into tributary creeks and eventually the mainstem Santa Clara River. Furthermore, the area is highly affected by wildfires, which makes it more susceptible to sediment runoff when vegetation mass is diminished and soil permeability altered. This decreases slope stability, which causes high rates of dry ravel on hillslopes (Florsheim et al. 1991). Sediment produced by these conditions is delivered by streamflow from the tributaries to the mainstem Santa Clara River, which flows downstream past the Freeman Diversion to the estuary and the Pacific Ocean. Overall, the watershed's sediment production rate has been calculated at approximately 9.0 million tons per year, or 5,600 tons per square mile per year, averaged across the entire watershed area (Stillwater Sciences 2011). Considering that the dams on Piru, Castaic, and Bouquet creeks intercept water and sediment from nearly one-third of the total watershed, the predicted sediment production rate for the watershed is approximately 5.6 million tons per year, or 5,400 tons per square mile per year (exclusive of the watershed area above the dams).

Seasonally intense rainfall and the resulting runoff are the primary mechanisms for sediment transport through the drainage network. Rainfall events can change the morphology of the Santa Clara River, which does not change progressively in response to small floods but instead experiences significant episodic changes associated with much larger floods (Stillwater Sciences 2007). The amount of sediment available to be transported during storms depends on the grain size of sediment delivered to the river and the amount of sediment already in the stream channel. This is reflected in the grain size distributions of suspended sediment and bedload in tributary streams. Sediment transported in the river includes silts, clays, and fine sands, along with coarse sands and gravels (Stillwater Sciences 2011). Prediction of sediment loading is complicated by the fact that sediment delivery is episodic, depending on the frequency, magnitude, and relative timing of stochastic events such as storms, fires, landslides, and earthquakes (Stillwater Sciences 2011, Downs et al. 2013).

In addition to sediment contributed by natural events, human activities affect sediment transport, particularly in the lower Santa Clara River. Past activities such as aggregate mining, the construction of dams on tributaries, urban growth, and levee development have interrupted the downstream sediment transport process to the estuary. Aggregate mining was the single largest anthropogenic impact that changed the channel form of the lower Santa Clara River (Stillwater Sciences 2011). Prior to the construction of the Freeman Diversion in 1990, aggregate mining and levee development downstream of the Freeman Diversion contributed to narrowing and deepening of the channel. The construction of the Freeman Diversion stabilized the river's bed elevation on the upstream side of the diversion and eliminated historic downcutting that resulted from mining operations.

Samples of suspended sediment collected from the Santa Clara River near the Freeman Diversion indicate that sediment concentration typically increases with flow magnitude (Warrick and Mertes 2009, Stillwater Sciences 2011, NHC 2015). Sediment concentrations in the river near the Freeman Diversion increase exponentially with discharge, and for a given discharge are higher earlier in the water year[2] than later (i.e., the early storms carry more wash load) (Stillwater Sciences 2011, NHC 2015). Based upon empirical evidence obtained in recent decades, the lower river conveyed approximately 2 million tons of total sediment load annually, with most sediment transport occurring during the largest flood events of 1969, 1978, 1993, and 2005 (Stillwater Sciences 2011). Sediment transport models indicate that the river has the potential to transport a total sediment load of approximately 400,000 tons per day during a 100-year discharge event near the Freeman Diversion, with most of the sediment made up of very fine to coarse sand (AECOM 2016).

The total sediment load of any given river is composed of bedload (coarse sands and gravels), suspended load (fine sands, silts, and clays), and dissolved load (chemical constituents). Studies conducted on the lower Santa Clara River by the U.S. Geological Survey (USGS) in the 1960s and 1970s observed the total sediment load was composed of approximately 10% bedload (coarse sands and gravels) and the remainder being suspended and dissolved load (fine sands, silts, and clays) (Williams 1979). Most of the total sediment load was transported during only a few days of flood flow each year. During the 1968–1975 water years, approximately 55% of the total sediment was transported in two days and 92% was transported in 53 days. Suspended sediment measured as SSC in the river at the former Montalvo gaging station between 1969 and 1993 ranged from concentrations of 253 to 91,400 milligrams per liter (mg/L). The sample data showed a positive trend between SSC and discharge. More recent samples of TSS by United Water at the Freeman Diversion headworks and fish bay confirmed these general trends and magnitudes of suspended sediment in the river under varied flow conditions. Figure 1 presents measured TSS concentrations at various flows at sample stations along the lower Santa Clara River. Figure 1 only includes data from November to May because, conservatively, these are the months when adult steelhead could enter the river based on data collected from central California (Shapovalov and Taft 1954a) and the Santa Clara River (Booth 2016).

[2] Water year is defined as the 12-month period from October 1 to September 30 and designated by the calendar year in which it ends (e.g., the water year ending September 30, 2019 is referred to as the "2019 water year")

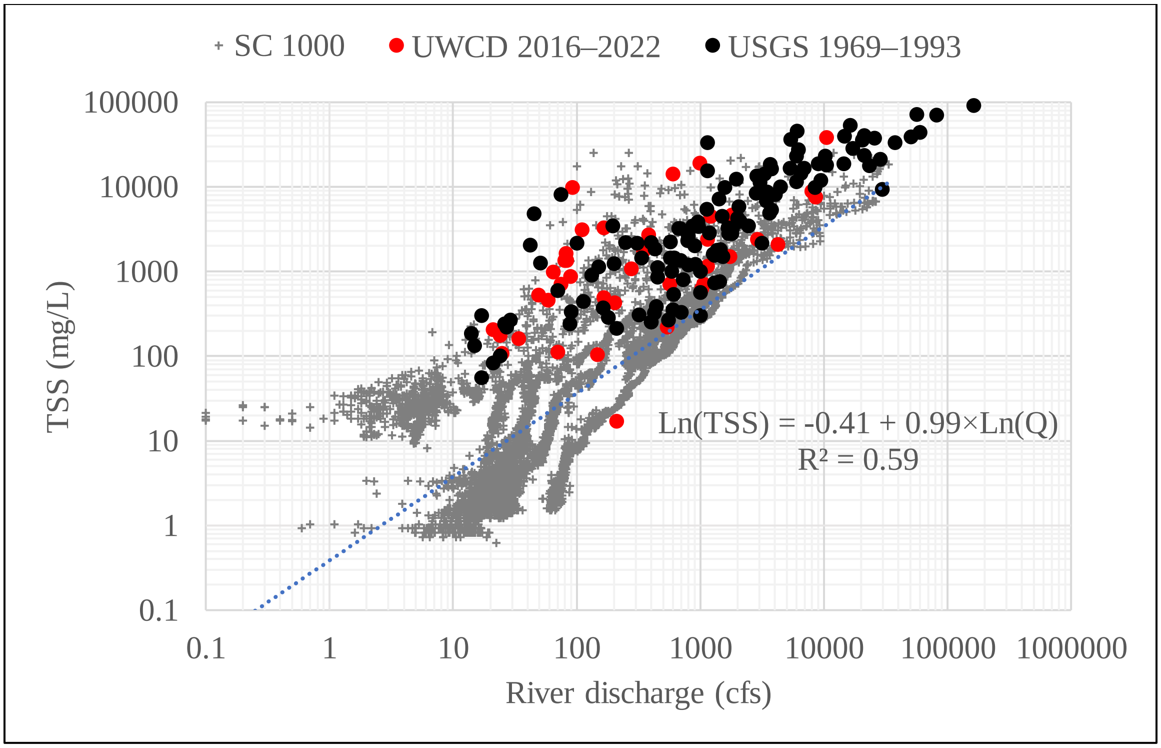

Figure 1. Relationship between measured TSS and Santa Clara River discharge (Q). USGS samples were taken at the Montalvo gaging station (measured in SSC); United samples at the Freeman Diversion headworks and fish bay (measured in TSS). SC1000 data were collected by United at the Freeman Diversion from December 2018 to September 2022 (turbidity is measured in Nephelometric Turbidity units [NTU] and then converted into a measurement of total suspended solids based on empirical relationships; see United 2019). Only data collected between November and May are shown. Confidence intervals (95%) were visibly indistinguishable from the regression line and were excluded.

The relationship between TSS and discharge in the Santa Clara River can be used to infer the following. First, there is a positive relationship between TSS and discharge (Figure 1). Results from a linear regression model relating flow to TSS showed the relationship was significant (F = 9118, df = 6211, $p < 0.0001$) and that flow explained 59% of the variability in TSS ($R^2 = 0.59$), but these models did not account for autocorrelation. The significant relationship is likely related to basic hydrogeomorphic processes whereby increased rainfall and flow are associated with increased erosion. However, there is variability in TSS across the range of discharge. For example, the data show that TSS can range from less than 10 mg/L to approximately 20,000 mg/L at a discharge of 100 cubic feet per second (cfs). This variability is reflected in an R^2 value that is less than 1, and the remaining variance is likely associated with different hydrogeomorphic processes operating temporally (e.g., first rainfall event moves more sediment compared to subsequent events) and at different spatial scales (e.g., within different tributaries). Next, it is apparent that, despite variability, there are minimum suspended sediment concentrations observed at a given river discharge. For example, a minimum TSS of approximately 200 mg/L has been observed at a discharge of 1,000 cfs, and a minimum TSS of approximately 2,000 mg/L has been observed at a discharge of 10,000 cfs. Thus, although we cannot reliably predict TSS based on discharge in the Santa Clara River due to variability, we can be reasonably certain that there is a "lower envelope" of TSS that can occur at a given discharge.

There are also differences in measured TSS among data sources shown in Figure 1. SC1000 data collected by United tend to show lower TSS values compared to data measured by either USGS or United using alternative approaches. This is especially apparent when discharge is less than 1,000 cfs (Figure 1). It is unclear what influenced variability among data sources, but including the SC1000 data would result in underpredicting TSS based on discharge. In addition, the SC1000 data show two diverging patterns for flows less than 100 cfs, which is due to TSS patterns that occur along a storm hydrograph. Indeed, the lower diverging TSS values at flows less than 100 cfs were measured mostly during the descending limb of a hydrograph following a storm event.

Assigning measured TSS values to either the ascending or descending limb of a hydrograph accounts for some of the variability in the data and shows that TSS is generally higher along the ascending limb of the hydrograph compared to the descending limb and the slope is not as steep (Figure 2). Higher TSS values along the ascending limb are due to basic hydrogeomorphic processes related to rainfall and erosion. Results from linear regression models relating flow to TSS separately for the ascending vs. the descending limb of the hydrograph showed the relationships were significant (F = 222, df = 242, $p < 0.0001$ and F = 7312, df = 2991, $p < 0.0001$, respectively) and that flow explained 48% and 71% of the variability in TSS ($R^2 = 0.5$ and 0.7), respectively, but once again, these models did not account for autocorrelation.

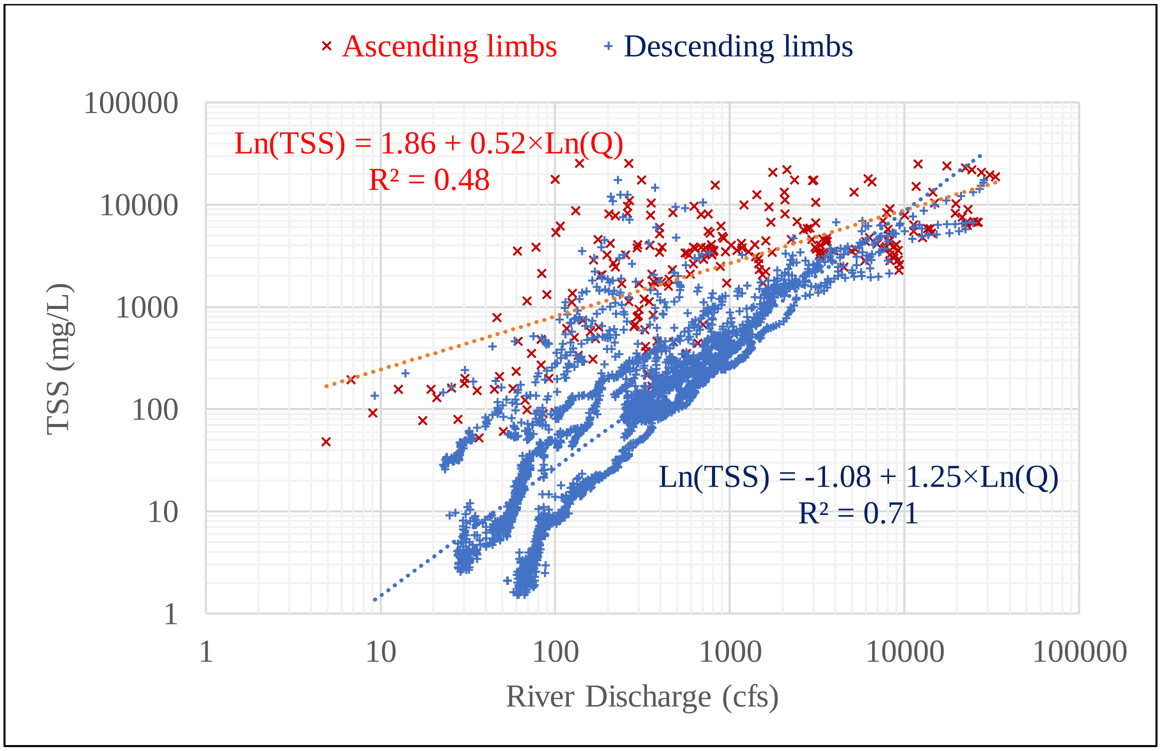

Figure 2. Relationship between measured TSS and Santa Clara River discharge (Q) for ascending (red) or descending (blue) limbs of a storm hydrograph. Only SC1000 data are displayed. SC1000 data were collected by United at the Freeman Diversion from December 2018 to September 2022 (turbidity is measured in Nephelometric Turbidity units [NTU] and then converted into a measurement of total suspended solids based on empirical relationships; see United 2019). Only data collected between November and May are shown. Confidence intervals (95%) were visibly indistinguishable from the regression line and were excluded.

Sediment transport to the Santa Clara River estuary occurs through both fluvial and littoral processes (Stillwater Sciences 2016). The estuary aggrades and migrates landward during low flows and smaller flood events but can scour and migrate ocean-ward during large flood events. The mouth of the Santa Clara River is often closed with a sand barrier but is breached periodically by high flows during storm events, tidal activity, and anthropogenic breaching. In addition to increased urban developments in the upper watershed, climate change-associated changes in precipitation and fire regimes will likely result in changes to sediment transport in the watershed. The overall sediment transport down the Santa Clara River may change in the future; however, the direction and amount of change is uncertain due to potentially counterbalancing changes. Sediment transport is expected to decrease during longer dry periods but increase during more extreme episodic flood events (ESA PWA 2013), especially given the interaction of more extreme storm event coupled with increased wildfire frequency and intensity.

3 QUESTION 1: WHAT ARE THE POTENTIAL BEHAVIORAL AND PHYSIOLOGICAL EFFECTS OF SUSPENDED SEDIMENT ON MIGRATING ADULT STEELHEAD?

3.1 Approach

To address Question 1, we conducted a review of available studies, data, and expert opinion, and synthesized conclusions from the available information. When information on adult steelhead was not available, relevant studies on other life stages, salmonids, and fish were used to inform the review. While there are marked differences in gross anatomy of fish gills across all types of fishes (Agnathans, Elasmobranchs, and Teleosts), the cellular constituents of the epithelium are remarkably similar (Wilson and Laurent 2002), suggesting comparison among species is informative for understanding suspended sediment effects on gills and respiration across fish taxa.

It is assumed that there is inter- and intraspecific variability in responses and tolerances to suspended sediment, and thus we relied more heavily on information from closely related taxa (e.g., *Oncorhynchus* spp.) where possible. Life stage is also an important factor to consider, and we considered studies on juvenile salmonids and steelhead if they related to suspended sediment impacts on behavioral and certain relevant physiological end points, such as physiological stress response and respiration. Studies focusing on incubation, juvenile feeding, and juvenile growth were removed from consideration (except for cases where these studies were included in broader review articles) because incubation and juvenile rearing were not relevant to the focal scientific questions. Due to higher sensitivity to suspended sediments, early life stages have been more extensively studied compared to the adult life stage despite the potential for adverse effects of suspended sediments on the physiology, energetics, and behavior of migrating adult salmonids. In toxicological studies, it is common practice to assume that adults will have higher tolerance for constituents; therefore, the synthesis of the information considered that adults may have higher tolerance to a given SSC compared to juveniles. We discuss how information from different life stages and taxa could influence our inferences within the results.

The best available scientific and commercial information that was identified in our review is summarized in Appendix A. Information was classified based on the source (i.e., peer-reviewed, technical report, or expert opinion). All three types of information can inform the best available science, with peer-reviewed articles providing the most vetted information in the scientific community, technical reports having less peer vetting but still containing potentially valuable information, and expert opinion demonstrating hypotheses or educated guesses synthesized by experts in relevant fields.

Next, information was categorized by type of study or analysis: experimental manipulation, scientific review/models, and observational/correlational studies. Last, information was evaluated based on the species and life history stage of the fish with more weight given to studies, reports, models, and expert opinion aimed at adult *O. mykiss* (rainbow trout or steelhead). Studies aimed more generally at adult salmonids, studies aimed at juvenile salmonids, and, finally, general studies of a variety of fish were also considered, but with less weight to inform a better understanding of the broader context of SSC effects on fish, particularly salmonids.

3.2 Results

Based on a review of the scientific literature, both positive and negative effects of suspended sediment on salmonids were identified. Positive effects included increased foraging opportunities and reduced predation in more turbid conditions, whereas negative effects of suspended sediment on salmonids noted in the literature include: (1) avoidance of turbid waters in homing adult anadromous salmonids, (2) avoidance or alarm reactions by juvenile salmonids, (3) displacement of juvenile salmonids, (4) reduced feeding and growth, (5) physiological stress and respiratory impairment, (6) damage to gills, (7) reduced tolerance to disease and toxicants, (8) reduced survival, and (9) direct mortality (reviewed in Newcombe and MacDonald 1991, Newcombe and Jensen 1996, Kemp et al. 2011, Kjelland et al. 2015). Information regarding reduced feeding and growth was considered irrelevant to the focal study questions since migrating adult steelhead do not feed and were eliminated from further evaluation. The remaining effects are explored in more detail below. Finally, due to the importance of exposure duration and concentration of suspended sediments (Newcomb and Jensen 1996), we provided descriptions of these parameters within our discussion of results below, when feasible.

3.2.1 Physiological and bioenergetic responses

Suspended sediment can influence fish physiology directly (e.g., damage to gills) or indirectly by affecting water quality. For example, sediment particles can result in direct gill trauma through abrasion of gills, erosion of gill mucous coating, and accumulation in gill filaments (Berg 1983). Fish can respond to accumulation of sediment in gill filaments by opening and closing the gills (i.e., gill flaring), “coughing” (interruption in the normal ventilatory cycle, which serves to clean the gills of accumulated particulate matter), and production of additional protective mucous (Berg 1983). Secondary effects from gill trauma include increased energy use and interference with respiration (Berg 1983) and ion exchange (Berg 1983, Redding et al. 1987, Servizi and Martens 1992). Gill tissue injury could also introduce sites where infection could occur (Redding et al. 1987).

Impaired respiration from either direct gill damage or accumulation of sediment in the gills (or from reduced oxygen [O_2] in the water; see below) affects fundamental life functions that are based on well-established bioenergetic principles related to oxygen supply and demand. Simply put, an animal generates CO_2 and water using food/energy stores and O_2, which, in the process of mitochondrial respiration, generates ATP to fuel all essential life functions. Importantly, this defining principle says nothing about which of the life functions O_2 is used for at any given moment in time. What it does imply, however, is that if an animal cannot supply sufficient O_2 for an activity, it cannot perform the activity as well or at all. This simple concept has been endlessly demonstrated by exposing animals to environmental hypoxia, which reduces O_2 supply and at some level reduces how an animal performs.

Impaired respiration resulting from exposure to elevated suspended sediment has also been demonstrated in the literature on suspended sediment effects on salmonids. For example, a study by Berli et al. (2014) found that hatchery rainbow trout exposed to suspended sediment at concentrations from 110–440 mg/L experienced reduced swimming performance (U_{crit}) and altered metabolic pathways consistent with an impaired ability to acquire oxygen. Redding et al. (1987) found increased hematocrit in juvenile steelhead and coho exposed to suspended sediment, which is indicative of a compensatory mechanism for impaired respiration. In another study, Newcombe and Flagg (1983) concluded that Chinook salmon mortality observed following exposure to volcanic ash (82,400 mg/L for 6 hours) was likely caused by impaired oxygen exchange based on visual inspection of gills. Exposure to elevated SSC following wildfire was also thought to result in mortality due to asphyxiation of salmonids in streams in Yellowstone National Park (Bozek and Young 1994). In the Bozek and Young (1994) study, a maximum SSC of 9,680 mg/L was measured in the stream, but they could not reliably determine peak SSC or SSCs that caused mortality. Indeed, impaired respiration from exposure to elevated SSCs may be a key mechanism that influences the ability of an adult salmonid to migrate upstream, and in extreme cases, can result in mortality.

Due to potential impacts of SSCs on gills and associated physiological and bioenergetic processes, suspended sediment is considered a stressor (i.e., capable of displacing a fish from homeostasis) and would invoke a physiological stress response in fish. Depending on the magnitude and duration of the stressful event, stress responses can range from minor, short-term changes in physiological processes to death (see Schreck et al. 2001, Barton 2002, A.A. Rich and Associates 2010 for a more thorough discussion of stress physiology in fish).

Indeed, elevated indices of physiological stress have been shown in juvenile salmonids exposed to elevated SSC as indicated by increased corticosteroid, glucose, and hematocrits, and by reduced leukocrit levels (Redding et al. 1987, Lake and Hinch 1999, Berli et al. 2014). Juvenile steelhead demonstrated a measurable stress response when exposed to 400 mg/L SSC for a seven- to eight-day duration (Redding et al. 1987), and hatchery rainbow trout demonstrated a measurable stress response when exposed to 440 mg/L SSC during swim trials (Berli et al. 2014). Lake and Hinch (1999) found evidence of a stress response in juvenile coho salmon exposed to SSC of 40,000 mg/L for 96 hours. The stress response results in secondary and tertiary effects on fish physiology such as immunosuppression, disruption of ion exchange, and increased energy use (i.e., increased oxygen demands), which can reduce growth, reduce reproductive output, and/or ultimately result in mortality (Barton 2002, Schreck et al. 2001). For example, fish exposed to a stressor, such as high concentrations of suspended sediments, may be more susceptible to pathogens that cause disease and ultimately lead to mortality (Redding et al. 1987).

Lethal levels of suspended sediment have been evaluated for salmonids, including adult anadromous salmonids (Newcomb and Flagg 1983, Servizi and Martens 1991, Lake and Hinch 1999). Collectively, these studies demonstrate that mortality can occur when salmonids are exposed to SSC as little as 1,400 mg/L to more than 40,000 mg/L for 36 hours, but species, life stage, temperature, exposure duration, and concentration influence mortality rates. For example, Newcombe and Flagg (1983) found no mortality occurred when adult Chinook salmon were exposed to 39,300 mg/L of volcanic ash for 36 hours, 60% mortality occurred when exposed to 82,000 mg/L for 6 hours, and 100% mortality occurred when exposed to 207,000 mg/L for one hour. Juvenile Chinook salmon experienced mortality at much lower SSCs (mortality observed at

1,400 mg/L for 36 hours) compared to adult Chinook and sockeye salmon (Newcombe and Flagg 1983), demonstrating that adult life stages are more tolerant of suspended sediment than earlier life stages.

Variability among studies in exposure duration and how mortality is quantified limits the ability to compare across studies, species, and life stages. However, using a standardized evaluation method based on 96-hour LC50 (LC = "lethal concentration"; the concentration at which 50% mortality is observed), juvenile coho salmon, juvenile sockeye salmon, and juvenile Chinook salmon had 96-hour LC50s of 22,700 mg/L, 17,600 mg/L, and 31,000 mg/L, respectively (Servizi and Martens 1987, 1991 Servizi and Gordon 1990). Strangely, in a separate study, juvenile coho salmon were shown to have a much higher 96-hour LC50 of 164,500 mg/L (Lake and Hinch 1999), which the authors attributed to the use of anthropogenic (Lake and Hinch 1999) versus natural (Servizi and Martens 1987, Servizi and Gordon 1990) suspended sediments. These results demonstrate species-specific tolerances to suspended sediments and that results can vary depending on the type of suspended sediment (e.g., anthropogenic vs. naturally derived), but other studies that used combinations of anthropogenic and natural suspended sediments found no significant differences in responses among sediment types (Redding et al. 1987). What is clear is that when common suspended sediment particle types and life stages are evaluated, species-specific variability is present, but observed effects occur within similar ranges of suspended sediment across anadromous salmonids.

Suspended sediment also influences water quality, which can have indirect effects on salmonids. Suspended sediment can deplete oxygen in the surrounding water (Bruton 1985, Henley et al. 2000) or can act as a vector for transportation and deposition of contaminants in the environment (Collins et al. 1997). Reduced oxygen concentrations or increased contaminants in water may act cumulatively with other stressors associated with suspended sediment or could attenuate the acute stress response thereby reducing the ability of fish to successfully cope with stress (Lloyd et al. 1987, Barton 2002).

3.2.2 Behavioral responses

Some fish have been shown to be attracted to turbid water over clear water, most likely to avoid predators or to conceal themselves from their prey (Gradall and Swenson 1982, Cyrus and Blaber 1992, both as cited in Wilber and Clarke 2001). Low levels of turbidity can function as cover to reduce predation in riverine, estuary, and nearshore marine environments (Gregory and Levings 1998, Wilber and Clarke 2001, Gadomski and Parsley 2005). However, as SSC and turbidity increase, there will be an inherent tradeoff where the camouflaging benefits of turbidity will be outweighed by the physiological impacts of suspended sediment on the fish. When salmonids encounter elevated SSCs, they have been shown to display behavioral responses such as avoidance (Berg and Northcote 1985), reduced swimming performance (Berli et al. 2014), or cessation of movements (Bjorn and Reiser 1991) depending on exposure magnitude and duration.

Laboratory experiments have shown that juvenile coho avoid turbid waters (>70 Nephelometric Turbidity units [NTU]) in favor of less turbid waters (<20 NTU) (Berg and Northcote 1985), and swimming performance (U_{crit}) was reduced in juvenile rainbow trout and brown trout exposed to turbidity as low as 13 NTU (~110 mg/L SSC) for ~1.4 hours (Berli et al. 2014). Based on their results, Berli et al. (2014) inferred that prolonged swimming activity in the wild could be compromised for fish exposed to elevated suspended sediment, and further suggested their results indicated rainbow trout were more sensitive to elevated suspended sediment compared to brown trout. Reduced swimming performance was also observed in juvenile Chinook salmon from the

San Joaquin River that were exposed to turbidity equivalent to a maximum SSC of 15 mg/L (Lehman et al. 2017).

A series of studies evaluated the effects of volcanic ash (a type of suspended sediment) on behavior and survival of anadromous salmonids, including adult Chinook salmon and adult steelhead (Whitman et al. 1982, Newcomb and Flagg 1983, Leider 1989). It was hypothesized by the authors that exposure to volcanic ash could negatively influence the ability of salmonids to detect olfactory cues used for navigation due to stress-induced damage of the olfactory epithelium or blocking of the nares (i.e., the sensory organ used to detect olfactory cues). Damage to the olfactory epithelium was not observed in these studies, and in one study, homing rates did not differ between control and ash-exposed (650 mg/L for seven days) adult Chinook salmon (Whitman et al. 1982). However, the exposure concentration of volcanic ash used in homing experiments in Whitman et al. (1982) was orders of magnitude lower than concentrations measured in the rivers during migration (approximately 1,000–3,400 mg/L).

Other results indicated elevated volcanic ash increased straying rates of adult steelhead (Leider 1989) and reduced preference for a natal water source when volcanic ash was added at levels of 350 mg/L compared to a non-natal water source with no added volcanic ash (Whitman et al. 1982). The authors of these studies hypothesized that observed straying was likely caused by avoidance of volcanic ash rather than an inability to detect olfactory cues (Whitman et al.1982, Leider 1989). Since the studies showed fish could still detect olfactory cues in the presence of volcanic ash, avoidance was likely a behavioral response to minimize physiological stress associated with volcanic ash exposure. Volcanic ash may contain different chemical properties as well as size and angularity of particles compared to other forms of suspended sediment, resulting in different effects, but Redding et al. (1987) found no difference in responses from yearling coho salmon and steelhead to three different types of suspended sediments: volcanic ash, topsoil, and kaolin clay.

Many studies on suspended sediment rely on controlled laboratory experiments, which are beneficial for measuring responses to a single variable in isolation, such as suspended sediment, but results from laboratory studies often vary from those under “natural” conditions. Discharge, temperature, and other environmental factors can all influence behavior and physiology of a migrating salmonid in natural settings, making it difficult to separate out the effects of a single variable. Typically, these parameters would act additively and exacerbate a stress response in natural settings. For example, stress associated with exposure to elevated suspended sediment would be exacerbated if also accompanied by exhaustive swimming during a high-flow event. However, controlled, manipulative field studies that evaluate behavioral responses to suspended sediment in “real-world” conditions are challenging for a variety of reasons: such studies are logistically difficult, statistical power is often limited by low sample sizes, elusive fish behavior makes trapping and tagging challenging, and/or there are permitting challenges for handling threatened or endangered individuals or manipulating their environment. For these reasons, the best available field studies that examine the effects of suspended sediment on fish behavior have been observational rather than experimental (except homing experiments in Whitman et al. 1982).

Therefore, we describe the most relevant observational studies below while acknowledging interpretation limitations because they represent the best available science to date regarding adult steelhead migration limitations associated with suspended sediment in real-world conditions.

Casitas Municipal Water District (2008) reported that in 2008, the six observed migrating adult steelhead in the Ventura River (adjacent to the Santa Clara River) all migrated upstream following (not during) high-flow events, when the turbidity levels at the time of passage ranged from 2 NTU to 22.5 NTU (~100 mg/l SSC). Often high turbidity can limit the effective range of observations in high sediment river systems, but the Vaki Riverwatcher monitoring equipment operated in conditions up to 200 NTU in 2008, meaning no observations of migrating steelhead occurred between 22.6 and 200 NTU despite significant monitoring effort. Although these data provide some evidence that there could be an effect of SSC on adult steelhead migration, the observational data can only reasonably confirm that steelhead can migrate in SSC levels of 100 mg/L because the lack of detection of fish during other conditions does not necessarily mean they cannot migrate during that time.

Similarly, Thomas R. Payne & Associates (2005) analyzed telemetry tracking data by the CDFW on migration of adult steelhead in the Mad River (northern California) in relation to sediment data from the watershed (collected by Sparkman 2003). From this analysis, Thomas R. Payne & Associates (2005) concluded that, “Steelhead movement appeared to be reduced at higher turbidities. There were some movement observations at turbidity values between 400 and 500 NTU while no movement occurred above 500 NTU.” Alternative explanations for reduced movement at higher turbidities include reduced attraction flows from their natal hatchery relative to total river flow, which highlights the difficulties in evaluating the effects of a single variable under “natural” conditions.

Although we were unable to locate the primary source, a study cited in Bell (1986) and NMFS Biological Opinions found that salmonids ceased movements when suspended sediment exceeded approximately 4,000 mg/L following a landslide in the Chilcotin River, British Columbia, Canada. Overall, there are limited numbers of studies evaluating the effects of suspended sediment on salmonids in natural settings (Kjelland et al. 2015), and field manipulation studies combined with controlled lab studies are needed to advance our understanding of these relationships.

3.2.3 Compensatory mechanisms

As highlighted above, there can be considerable variability in physiological and behavioral responses of fish to suspended sediment. Producing additional protective mucous to coat gills, increased frequency of gill flaring/coughing, or increasing hematocrit to increase the capacity of blood to transport oxygen are examples of compensatory mechanisms noted above that could allow fish to tolerate higher levels of suspended sediment. Below, we expand on factors that could contribute to variability in adult steelhead tolerance to suspended sediment in the Santa Clara River.

Species- (Kjelland et al. 2015, Wenger et al. 2017) and population-specific (Berli et al. 2014) responses to suspended sediment have been noted, and steelhead may be more or less sensitive to elevated suspended sediment compared to other salmonids. A migrating adult steelhead could be more resilient to the effects of suspended sediment compared to other taxa due to local adaptation or acclimation. In particular, suspended sediment conditions within the Santa Clara River, which are notably high compared to other river systems where steelhead occur, could provide opportunities for adaptation or acclimation through physiological, morphological, or behavioral mechanisms. The metapopulation dynamics within the Southern California steelhead DPS assume high rates of straying in the region (NMFS 2012), which may preclude adaptive capacity to an individual watershed over evolutionary time in this DPS.

Fish are more likely to tolerate or behaviorally avoid acute stressors (Nielsen et al. 1994, Keefer et al. 2018) and acclimate or adapt to chronic stressors (Narum 2013). The “flashy” nature of the Santa Clara River means that, generally, the largest increases in SSCs are acute (days to a week) and associated with episodic storm events. Thus, a migrating adult steelhead could endure additional stress during high SSCs but then recover from this stress once SSCs decline to more tolerable levels, assuming the absence of gill trauma. For example, one of the primary concerns with exposure to high SSC during migration is reduced ability for oxygen exchange at the gill, which would lead to more reliance on anaerobic respiration. Any accumulated oxygen debt during migration must be repaid, and it is expected that an adult steelhead migrating in the Santa Clara River could recover from short-term oxygen debt and physiological stress once SSC returned to lower concentrations or by reaching tributaries with lower SSC. However, it would be expected that at some SSC, an adult steelhead would not be physiologically capable of providing enough O_2 to actively swim upstream, and under these conditions, would be forced to hold, drift downstream, or swim downstream and wait for SSC to decrease. The SSC under which swimming would be impaired or prevented is a central question of this memo and is addressed below in Section 4.

Adaption is more likely to occur when steelhead are exposed to chronic stressors. Low to moderate levels of suspended sediment within the Santa Clara River can persist over longer durations (weeks to months) and thereby could be considered a chronic stressor. As described in detail with Section 4 below, even the lowest levels of sediment measured in the Santa Clara River are predicted to cause minor physiological stress; thus, it is reasonable to assume that steelhead from the Santa Clara River may have adaptations (including the ability to acclimate) to tolerate low to moderate levels of suspended sediment. In support of this, a study by Berli et al. (2014) on non-anadromous *O. mykiss* exposed one strain of rainbow trout and one strain of brown trout from a common hatchery alongside a strain of rainbow trout from a different hatchery to elevated suspended sediment then measured behavioral (swimming performance) and related metabolic responses. They found that strains of fish from a common hatchery showed a more similar response to suspended sediment exposure compared to fish of the same species from different hatcheries, which suggests local adaptation or acclimation to suspended sediment is possible (Berli et al. 2014). However, it should be noted that the study treatments only went up to 440 mg/L. Also, regardless of hatchery origin, all fish in Berli et al. (2014) had decreased swimming performance when exposed to elevated suspended sediment and there was evidence that hatchery rainbow trout were more sensitive to suspended sediment compared to brown trout, indicating there are interspecific differences in suspended sediment tolerances even between species from a common hatchery.

Although there is some evidence of adaptation/acclimation to high SSC within the literature, there are very few studies that have evaluated mechanisms of adaptation to high suspended sediment. As described elsewhere in this review, high suspended sediment could impose selective pressure on a migrating steelhead through a variety of pathways, most notably through blocking olfaction, infection from gill damage, and reduced aerobic function. Interestingly, some of the mechanisms associated with preventing gill damage, such as producing additional mucous or growth of additional epithelial cell layers at the gill (Hess et al. 2015), come with a tradeoff by increasing the diffusion distance of oxygen, thereby reducing efficiency of oxygen transport to organs (Evans et al. 2005). Reduced oxygen available in the water during high suspended sediment conditions could further exacerbate the effects of SSC on aerobic respiration. Given the relationship between high SSC and respiration, we would predict that adaptations to suspended sediment would be similar to adaptations to hypoxia, a topic that has been more extensively studied. In response to hypoxia, animals use a variety of strategies including sustained aerobic metabolism that enhances oxygen uptake, transport, and delivery (e.g., increased gill surface area, increased hemoglobin-oxygen binding affinity, increased hemotaocrit), increased use of anaerobic metabolism, and metabolic rate depression (Mandic and Regan 2018). Similar to responses to hypoxia, increases in hematocrit has been shown in salmonids in response to high suspended sediment (Redding et al. 1987), which provides some evidence that responses to high SSCs are similar to responses to hypoxia. There are energetic and ecological costs associated with these strategies, and it is uncertain whether a migrating adult steelhead could use similar strategies to contend with high SSCs in the Santa Clara River or if it is less energetically costly to use behavioral strategies to avoid exposure to high suspended sediment.

Adult steelhead entering the Santa Clara River could potentially acclimate to higher SSC prior to initiating migration through exposure to higher SSC in the estuary. Studies on juvenile rainbow trout have shown that fish may be able to acclimate to elevated SSCs after eight days of exposure and in the absence of physical damage to gills (Michel et al. 2013). Michel et al. (2013) also observed no mortality in rainbow trout exposed to daily pulses of SSCs of 5,000 mg/L over 24 days. Metabolic changes were observed, but there was no observed physical damage to the gills present. However, being a laboratory study, fish were not given the option to respond behaviorally and were not challenged during the experiment to determine if performance was compromised. Avoidance of elevated suspended sediment has been frequently observed in both field and laboratory studies (see Section 3.2.2 *Behavioral responses* for more details) when fish are given the opportunity to behaviorally respond, and reduced swimming performance has also been found in juvenile rainbow trout and Chinook salmon exposed to much lower concentrations of suspended sediment (Berli et al. 2014, Lehman et al. 2017). Ultimately, behavioral avoidance is expected at lower levels of SSC than levels that lead to major physiological stress because animals use behavior to mediate their physiology when needed and/or possible.

Behavioral mechanisms that could help fish avoid or reduce the impacts of high SSCs include holding (i.e., delaying migration) during high SSC levels to avoid excess energy use or avoiding high SSC by locating suitable refugia. Refuge from elevated SSC could occur in tributaries, along river margins, or within estuarine environments if SSCs are lower. Indeed, anecdotal evidence has suggested salmonids utilize river margins for migration during high SSCs as an avoidance mechanism (Carlson et al. 2001), but utilization of river margins could also be related to avoidance of higher water velocities and turbulence associated with the thalweg, once again demonstrating the complexity of evaluating SSC effects under natural conditions. As it relates to the Santa Clara River, turbidity measured laterally across locations in the Santa Clara River downstream from the Freeman Diversion showed SSCs were consistent and not substantially reduced along river margins (United, unpubl. data), and thus would not provide opportunity for avoidance.

An additional behavioral strategy to prevent exposure to high SSCs would be for a fish to stray. Leider (1989) observed that migratory steelhead bypassed their natal streams when sediment levels were high and spawned elsewhere (following Mt. St. Helens eruption), but it is uncertain whether these fish were avoiding high suspended sediment or were unable to detect natal olfactory cues used for homing to natal spawning grounds. Santa Clara River steelhead could stray and bypass the Santa Clara River entirely if conditions are unfavorable, but there are limited alternative spawning opportunities accessible in this region. Straying is common in California steelhead (Clemento et al. 2009, Pearse et al. 2009, Donohoe et al. 2021), but it would be unlikely for a steelhead to bypass the Santa Clara River due to high SSCs because other watersheds in the region tend to experience similar high SSCs during the same events. Moreover, delaying upstream migration to wait for SSCs to decrease (usually on the descending limb of the hydrograph) would be energetically favorable and less risky compared to seeking an alternative watershed with spawning habitat, which would involve more energy expenditure and exposure to predation.

Life stage also plays a critical role in the response of salmonids to suspended sediment, with adults generally having higher tolerance compared to juvenile and fry stages (Servizi and Martens 1991), but their tolerance is not infinite. Of specific relevance to this memo, adult salmonids approaching spawning grounds undergo a number of physiological and energetic shifts, including increased circulating cortisol (Hinch 2006) and increased use of anaerobic pathways and protein catabolism (Brett 1995, Miller et al. 2009) that could make them more resilient to acute stressors (Raby et al. 2013). Indeed, it is logical that migrating reproductive salmonids would be equipped to cope with repeated stressors and anaerobic activity during migration such as burst swimming and competition for mates. Finally, migrating, reproductive fish may also be more "motivated" to expose themselves to a stressor to secure reproductive fitness, but there is uncertainty about how "motivation" would differ between semelparous and iteroparous species of salmonids; there is a body of literature that suggests that potentially iteroparous steelhead may engage in less risk-taking behavior compared to semelparous salmonids (Wingfield and Sapolsky 2003, Øverli et al. 2005).

Although there is certainly variability among species, populations, and life stages in responses to suspended sediment, the physiological mechanisms driving migrating adult anadromous salmonids are similar (Hinch 2006), and based on the literature described above (e.g., Newcombe and Flagg 1983; Servizi and Martens 1987, 1991), behavioral and physiological responses to suspended sediment are generally comparable among species and populations within an order of magnitude of SSC exposure as long as life stage is accounted for. Among anadromous salmonids, the literature indicates that Chinook salmon are the most tolerant to suspended sediments (Newcombe and Flagg 1983), although few direct comparisons have been made among species in their response to suspended sediment. Additional studies evaluating both species and population-specific adaptation or acclimation ability to varying SSCs are needed. Finally, variation in tolerance and responses to SSC should be expected among individuals, and this individual-level variation is what natural selection can act upon, leading to adaptation.

Environmental conditions (e.g., exposure duration, temperature, particle size, particle type, particle angularity), which are site- and case-specific, also greatly influence how suspended sediment affects fish directly and indirectly (Servizi and Martens 1991, Newcombe and Jensen 1996, Lake and Hinch 1999). For example, particle size can influence the extent of gill injury, which in turn can influence respiration and infection. The effects of particle size have not been extensively studied, but a study by Lake and Hinch (1999) found no significant differences in responses of salmonids exposed to particles with different angularity. However, lethal concentrations of SSC in Lake and Hinch (1999) were much higher compared to other studies on salmonids, which they inferred could be related to the use of anthropogenic versus natural sediment types. They hypothesized that naturally derived sediments may have effects at lower concentrations because they have electrostatically absorbed heavy metals and other organic molecules that diffuse across or are taken up by the gill epithelia.

Although poorly understood, the chemical properties of the type of suspended sediment could influence the response of fish (Brinkmann et al. 2015). For example, there have been a number of studies on the effects of volcanic ash on salmonids (Whitman et al. 1982, Newcombe and Flagg 1983, Leider 1989), but only one study by Redding et al. (1987) evaluated how responses could differ between volcanic ash and other suspended sediments (topsoil, kaolin clay). In their study, Redding et al. (1987) found no significant differences in physiological responses of fish to the different suspended sediment types evaluated.

The stress response from exposure to suspended sediment can be exacerbated in the presence of above-optimal temperatures (or other sub-optimal environmental conditions) due to increased metabolic demands and reduced ability to fight infection and/or increased virulence. Indeed, reduced tolerance of yearling coho salmon to suspended sediment was observed when temperature was increased (Servizi and Martens 1991). Infection from gill trauma would potentially have delayed effects on fish survival and fitness, whereas impaired respiration could result in both acute and chronic stress responses depending on severity.

4 QUESTIONS 2 AND 3: AT WHAT RANGE OF SSC ARE MIGRATING, PRE-SPAWNING ADULT STEELHEAD LIKELY TO OR NOT LIKELY TO ACTIVELY SWIM IN AN UPSTREAM DIRECTION IN THE LOWER SANTA CLARA RIVER?

Two alternative hypotheses can explain how steelhead cope with suspended sediment in the Santa Clara River watershed. The first is that southern California steelhead evolved in high sediment systems and therefore have physiological adaptations that allow them to persist in a high SSC environment. The potential for adaptation or acclimation was discussed in Section 3.2.3, and although there is evidence that salmonids can adapt/acclimate to elevated SSC, the evidence also suggests adaptation does not allow salmonids to tolerate orders of magnitude differences in SSC (Berli et al. 2014) and acclimation occurs over longer periods of time (Michel et al. 2013) compared to the expected exposure duration of adult steelhead in the Santa Clara River.

An alternative hypothesis is that steelhead have evolved behavioral responses for avoidance or minimization of negative impacts of suspended sediment at concentrations that could challenge their survival (e.g., Berg and Northcote 1985, Whitman et al. 1982). Given the assumption that adult steelhead have a tolerance range and upper tolerance limit to suspended sediment, it follows that there would be ranges of suspended sediment where migrating, pre-spawning, adult steelhead would be expected to: (1) not initiate movement upstream, (2) stop movement upstream and seek refuge, or (3) actively swim in a downstream direction. These behavioral responses would be triggered by impaired respiration limiting physical performance and/or are strategies to minimize physiological stress, injury, immunosuppression, and/or mortality. Each of these three behaviors would not be compatible with actively swimming in an upstream direction.

Although no studies have experimentally evaluated SSC thresholds for migrating adult steelhead specifically, Newcombe and Jensen (1996) performed a meta-analysis based on 80 published reports of fish responses to suspended sediment in laboratories, streams, and estuaries. Using the 80 studies, Newcombe and Jensen (1996) established a set of regression models that could be used to calculate "severity of ill effect" (SEV) indices (see Table 1 in Newcombe and Jensen 1996), which ranged from zero (no effects) to 14 (80–100% mortality). SEV indices fall under categories for behavioral effects (SEV = 1–3), sublethal effects (SEV = 4–8), and paralethal and lethal effects (SEV = 9–14). Of note, although there are no SEV indices specifically for "migration," there are SEV end points involving homing, respiration, physiological stress, and mortality, which are all related to or underlie fundamental components of migration. In order to move upstream and migrate successfully, an adult steelhead must home, breathe, mediate physiological stress, and survive. Impaired homing (SEV = 7), increased respiration (SEV = 5), physiological stress (SEV = 5–6, 8), and mortality (SEV = 10–14) are all potential SEV end points in Newcombe and Jensen's (1996) equations. The suite of six models evaluate the effects of suspended sediment (at various concentrations, durations of exposure, and particle sizes) on various taxonomic groups of fishes and life stages of species within those groups. One of the models is specific to adult salmonids and was based on 63 "experimental units" of testing specific to adult salmonids or closely related species.

We applied the model specific to adult salmonids to predict SEV levels for migrating steelhead across a range of SSCs that are relevant to the Santa Clara River. This analysis assumed a two-day (48-hour) travel time from the ocean to the Freeman Diversion and, therefore, an associated two-day exposure duration to a given SSC. The two-day exposure duration assumption was based on migration rates presented in the Vern Freeman Dam Fish Passage Panel report (VFDFPP

2010), which was corroborated by evaluations presented in Appendix B of this memo. Figure 3 shows predicted SEV across SSC based linear regression using adult salmonid data from Newcombe and Jensen (1996) (Table A.1) that was standardized for a two-day exposure duration.

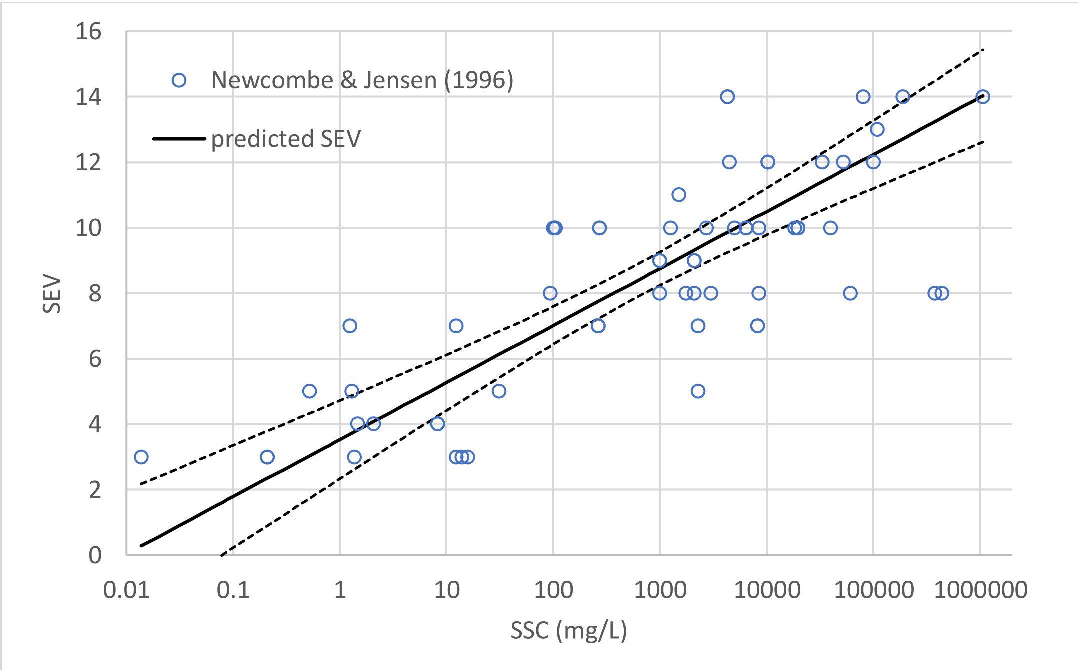

Figure 3. Predicted levels of SEV based on SSCs. Data points represent data for adult salmon taken from Newcombe and Jensen (1996) that were standardized to a two-day (48 hours) exposure duration. The solid line was fitted using linear regression. Dashed lines show 95% confidence intervals.

Approximately 75% of measured concentrations of suspended sediment in the Santa Clara River are greater than ~3 mg/L, which equates to an SEV of 4 (SEV 95% CIs = 3–5) and is above the level where avoidance responses (SEV 3) are predicted. Over half (59%) of SSC measurements in the Santa Clara River are greater than 10 mg/L, which is predicted to result in minor physiological stress (SEV 5; 95% CIs = 4–6) with a two-day exposure duration. However, there is scientific literature that suggests that both acclimation and adaptation is possible for small to moderate increases in SSC (Michel et al. 2013, Berli et al. 2014). Also, it is typical for animals to endure some physiological stress during reproductive life history stages; therefore, these lower SSCs and associated acute physiological stress probably do not prevent swimming behavior in an upstream direction by a reproductively motivated adult steelhead.

Similarly, moderate physiological stress (SEV 6) and impaired homing (SEV 7) may not stop a reproductively motivated adult fish from swimming upstream during migration, but SSC conditions (30–100 mg/L) that are predicted to have an SEV of 6 or 7 SEV probably require more strenuous effort during swimming compared to SSC below 30 mg/L. Under these conditions, repeat reproductive events (kelting) would become less likely if elevated physiological stress does not subside, but adult steelhead would likely still endure even moderate levels of stress when reproductively motivated. Furthermore, the flashy nature of suspended sediment pulses in the Santa Clara River mean that exposure is generally short-term, lasting days to a week, after which adult steelhead would have the opportunity to recover from moderate physiological stress. This inference is consistent with the data collected by Casitas Municipal Water District (2008) that showed adult fish moving through the vertical slot fish ladder when SSC was ~100 mg/L or less.

When exposed to SSC levels at ~400 mg/L for two days (SEV 8; 95% CIs = 8–9), it is inferred that adult salmonids experience major physiological stress. When exposed to SSC levels at ~1,400 mg/L for two days (SEV 9; 95% CIs = 9–10), it is inferred that adult salmonids experience paralethal effects and some mortality may be observed. When exposed to SSC levels at ~5,200 mg/L for two days (SEV 10; 95% CIs = 9–11), it is inferred that up to 20% of adult salmonids will experience mortality, with mortality rates inferred to increase as SSC increases above 5,200 mg/L. Major physiological stress is the result of not being able to cope with a stressor, and the fish would be on the pathway to mortality unless conditions change or the fish changes its behavior to escape life-threatening conditions. At that juncture, it seems less likely that a migrating adult steelhead would expose themselves to additional exhaustive exercise associated with swimming upstream and instead would be more likely to locate refuge or hold station to minimize additive stressors. Reproductively motivated anadromous salmonids can tolerate acute stress and potentially even major physiological acute stress, but most anadromous salmonids are semelparous and only have one opportunity to reproduce in a lifetime. Iteroparous steelhead that can reproduce multiple times may be less willing to expose themselves to major physiological stress compared to other salmonids.

The maximum recorded SSC in the Santa Clara River is ~91,400 mg/L. Up to 60% mortality (SEV 12; 95% CIs = 11–13) is inferred for adult salmonids given two days of exposure at this maximum measured SSC if fish were not able to behaviorally avoid. Based on an assumption that the highest SSCs would be relatively short-lived due to the flashy nature of flows in the Santa Clara River, using a shorter exposure duration of 24 hours would still be predicted to result in up to 60% mortality (SEV 12). Even a two-hour exposure to 91,4000 mg/L SSC is predicted to result in up to 40% mortality (SEV 11). The physiological feasibility for an adult steelhead to actively swim in an upstream direction in such extreme conditions is highly questionable. Although adult steelhead were not evaluated, Newcombe and Flagg (1983) reported adult Chinook salmon exposed to SSC (volcanic ash) of 82,000 mg/L for 6 hours experienced 60% mortality. Chinook salmon are thought to be more tolerant of elevated SSC compared to other anadromous salmonids (Servizi and Martens 1991), and thus we can be reasonably confident that mortality predicted for adult steelhead exposed to 91,400 mg/L SSC for two days based on the Newcombe and Jensen (1996) equation is appropriate.

5 QUESTION 4: WHAT ARE THE RANGES OF DISCHARGE IN THE SANTA CLARA RIVER THAT WOULD BE ASSOCIATED WITH THE IDENTIFIED RANGES OF SSC FOR QUESTIONS 2 AND 3?

We applied data collected on discharge and SSC in the Santa Clara River (i.e., all the data points in Figure 1) to estimate ranges of discharge associated with SEV level (n=6,379). Variability is observed across the relationship of SSC and discharge in the Santa Clara River (Figure 1). The unexplained variance is probably a result of natural processes such as differences in sediment mobilization on the ascending versus the descending limb of the hydrograph or increased sediment mobilization during storm events that occur earlier in a season or after drought conditions (see discussion in Section 2). A range of discharges can carry similar sediment concentrations, which is the variable predictive of SEV effects in this analysis. Hence, there was variability in the relationship between discharge and SEV levels, which is shown in Figure 4 and Table 2.

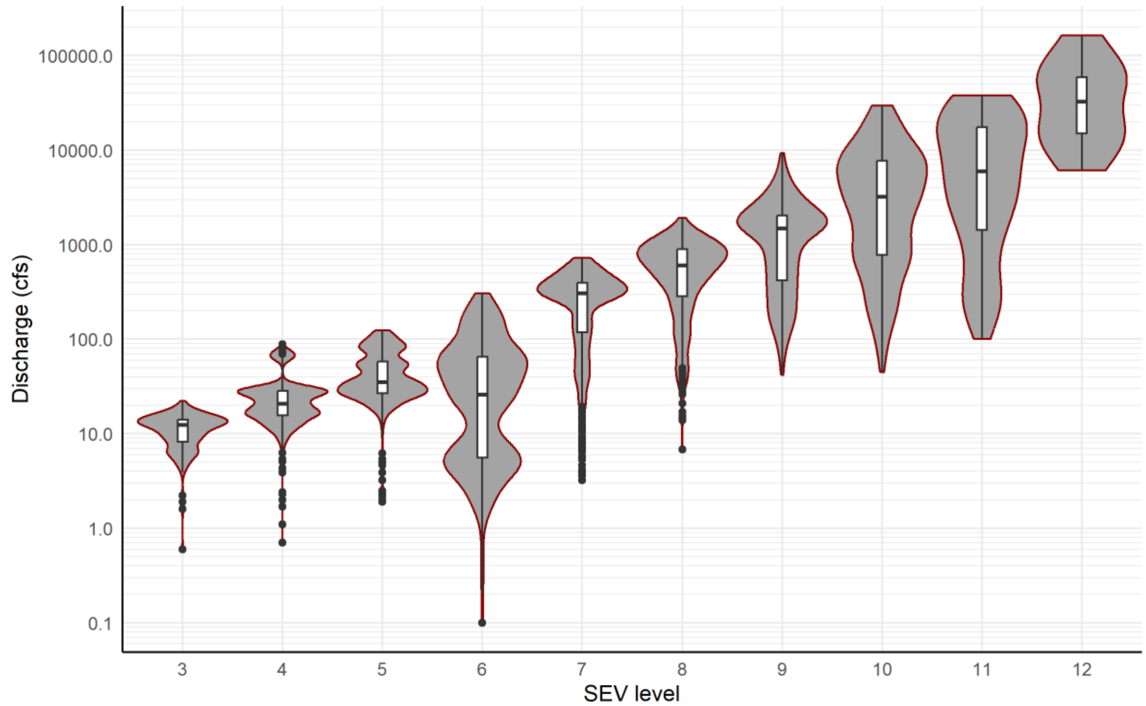

Figure 4. Violin plot showing probability density of discharge in the Santa Clara River associated with each SEV level. Variability in discharge for each SEV level is due to variability in the relationships between discharge and SSC in the Santa Clara River (see Figure 1). The ranges of discharge associated with each SEV level were determined by measured relationships between discharge and SSC in the Santa Clara River. Boxplots within each violin plot show the median and quartiles (all outliers are plotted as individual points).

Table 2. Exceedance values (expressed as percentiles) of discharge in the Santa Clara River associated with each level of SEV. SEV levels are only presented for those predicted given observed SSC concentrations in the Santa Clara River. A description of each SEV level shown is included.

SEV level	SEV description	Discharge (cfs)				
		5%	25%	50%	75%	95%
3	Avoidance behavior	5	8	12	14	17
4	Sublethal effects begin	10	16	21	28	67
5	Minor physiological stress	16	27	35	58	105
6	Moderate physiological stress	2	6	26	65	179
7	Impaired homing	21	119	304	393	594
8	Major physiological stress	49	285	605	894	1299
9	Lethal and paralethal effects begin	130	419	1,490	2,038	4,179
10	0–20% mortality	174	777	3,192	7,701	20,751
11	20–40% mortality	222	1,430	5,980	17,541	28,555
12	40–60% mortality	8,093	15,125	35,800	58,875	126,595

Because there is limited data on adult steelhead migration in the Santa Clara River as well as variability across relationships between both SSC and SEV and SSC and discharge, establishing definitive SSC threshold levels (and thus discharge) is challenging. However, using the best available data, we can reasonably infer that migration is less likely when SSC levels result in major physiologic stress (SEV = 8) and especially when there is a risk of mortality (SEV ≥9).

Given these assumptions, the above data can be used to interpret ranges of discharge when actively swimming in an upstream direction may be more likely or less likely for adult steelhead in the Santa Clara River. For example, assuming a two-day exposure duration, any discharge above 594 cfs is very likely (95% chance) to be associated with SSC concentrations that would result in impaired homing (SEV = 7); any discharge above 1,299 cfs is very likely (95% chance) to be associated with SSC concentrations that would result in major physiological stress (SEV = 8); any discharge above 4,179 is very likely (95% chance) to be associated with SSC concentrations that would result in paralethal effects and the onset of lethal effects (SEV = 9); and any discharges above 20,751 are very likely (95% chance) to result in some level of mortality (SEV ≥ 10).

However, the flow thresholds are notably lower if we accept the 75% probability as an appropriate level of uncertainty. For example, a discharge above 393 cfs is likely (75% chance) to be associated with SSC concentrations that would result in impaired homing (SEV = 7); any discharge above 894 cfs is likely (75% chance) to be associated with SSC concentrations that would result in major physiological stress (SEV = 8); any discharge above 2,038 is likely (75% chance) to be associated with SSC concentrations that would result in paralethal effects and the onset of lethal effects (SEV = 9); and discharges above 7,701 are likely (75% chance) to result in some level of mortality (SEV ≥ 10).

6 ASSUMPTION TESTING

Key biological assumptions within the analyses above could influence results and conclusions. Some of these biological assumptions can be evaluated using available data including: (1) a two-day travel time for adult steelhead to reach the Freeman Diversion, which would influence the duration of exposure in equations predicting SEV; and (2) steelhead migration during any phase of a storm hydrograph (i.e., ascending limb, peak, descending limb). In this section, we evaluate the sensitivity of results to these assumptions.

6.1 Travel Time

For the analysis presented above, we assumed a two-day travel time for adult steelhead reaching the Freeman Diversion. This assumption was based on information presented in VFDFPP (2010) and supplemental review of the literature on adult steelhead migration rates (e.g., Keefer et al. 2004, Salinger and Anderson 2006, English et al. 2006, Jepsen et al. 2012; see Appendix B). The literature on steelhead migration rates in natural flowing systems (English et al. 2006) supports the average two-day travel time assumption presented in VFDFPP (2010), but the literature also indicates that travel time could be as little as one day or more than three days using quartiles of the data (a three-day travel time is also consistent with the “slow” migration rate assumption presented in VFDFPP [2010] report). Exposure duration is a key factor to consider and is a variable included in the Newcombe and Jensen (1996) equations. To evaluate the effects of exposure duration and implications of the two-day travel time assumption, we briefly present results based on either a one-day or three-day exposure duration below. We focus comparisons of effects of exposure duration on SEV levels associated with sublethal (SEV = 4–8) and lethal (SEV = 9–12) effects due to these impacts being most likely to affect upstream movements of adult steelhead.

As expected, if we assume a shorter exposure duration based on one-day's travel time to the Freeman Diversion, higher SSCs and discharge are predicted to result in similar SEV levels to those seen with a two-day travel time. For example, exposure to an SSC of ~600, 2,000, and 8,000 mg/L would be predicted to result in major physiological stress (SEV = 8), paralethal effects (SEV = 9), and mortality (SEV = 10), respectively, under a one-day travel time (i.e., one-day exposure) assumption (Table 3). Therefore, assuming a one-day exposure duration, any discharge above ~1,600, 6,000, and 24,000 cfs would be very likely (95%) to be associated with SSC that would result in major physiological stress (SEV = 8), paralethal effects (SEV = 9), and mortality (SEV = 10), respectively (Table 3).

If we assume a longer exposure duration based on a three-day travel time to the Freeman Diversion, lower SSCs and discharge are predicted to result in similar SEV levels to those seen with a two-day travel time. For example, exposure to an SSC of ~400, 1,000, and 4,000 mg/L would be predicted to result in major physiological stress (SEV = 8), paralethal effects (SEV = 9), and mortality (SEV = 10), respectively (Table 3) assuming a three-day exposure duration. Assuming a three-day exposure duration, any discharge above 1,000, 3,000 and 17,000 cfs would be very likely (95%) to be associated with SSC that would result in major physiological stress (SEV = 8), paralethal effects (SEV = 9), and mortality (SEV = 10), respectively (Table 3).

Table 3. Comparison of the effects of exposure duration on SSC and discharge predicted to result in SEV levels associated with sublethal and lethal effects (see Table 2 for description of SEV levels). The 95% exceedance values of discharge in the Santa Clara River associated with each level of SEV are presented.

SEV level	SSC (mg/L)			95% percentile discharge (cfs)		
	24-hr exposure duration	48-hr exposure duration	72-hr exposure duration	24-hr exposure duration	48-hr exposure duration	72-hr exposure duration
4	3	2	1	75	67	64
5	11	7	5	133	105	93
6	41	26	20	262	179	170
7	153	99	76	764	594	507
8	572	369	286	1,645	1299	1,158
9	2,145	1,386	1,073	6,687	4,179	2,870
10	8,045	5,196	4,024	24,363	20,751	17,438
11	30,170	19,487	15,090	35,964	28,555	28,305
12	113,146	73,081	56,592	154,910	126,595	106,370

6.2 Migration Along the Hydrograph

Flow is an important environmental condition that influences upstream migrations of anadromous salmonids, and it has been postulated that historical flow patterns were likely important selective pressure associated with species- and population-specific adaptations in morphology and migration behavior (Quinn 2005). Flow can influence movements and behavior of adult salmonids during their reproductive migration due to its influence on navigational cues, energy use, habitat connectivity, and water quality. Flow provides a directional cue for upstream migration because adult salmon display positive rheotaxis, and salmon rely on olfactory cues transported within river flow to navigate to natal waters for reproduction (termed 'homing') (Quinn and Dittman 1990, Thorstad et al. 2008). It is perhaps not surprising then that upstream migrations of salmon have been associated with increased flow in many studies (see reviews by Banks [1969], Jonsson [1991], Thorstad et al. [2008], and Taylor and Cooke [2012]). However, high flows can impede migration or result in migration delay due to increases in locomotor activity required during periods of high flows (Cocherell et al. 2010, Peterson et al. 2017) and/or due to exposure to high suspended sediment loads. Migration can also be impeded when flows are low due to reduced connectivity and changes in water properties (e.g., higher temperatures and lower dissolved oxygen) (Thorstad and Heggbert 1998).

The influence of flow on migration is an important consideration when evaluating the conditions (e.g., SSC) that a migrating adult steelhead would experience. It is generally thought that adult steelhead in southern California migrate upstream during the descending limb, and to a lesser extent, the ascending limb of a storm hydrograph, and that migration does not occur at high flows due to high water velocities, high suspended sediment concentrations, and/or high debris loads associated with peaks in the hydrograph. In a study involving direct observations of numerous adult steelhead migrating upstream through critical riffles in the Eel River, CA under varying stream flows, VTN Oregon, Inc. (1982) reported that steelhead tended to hold when flows were stable and migrate during changes in flow both increasing or decreasing. During extended periods of stable flows, steelhead would eventually migrate (mostly at night), but migration during either peak or stable flows did not appear to be associated with flow magnitude. Lang et al. (2004) PIT tagged 45 adult steelhead and monitored upstream migration through a culvert. They observed that adults tended to migrate upstream through the culvert (fish passage obstacle) on the falling limb of the hydrograph during the recession flows. Shapovalov and Taft (1954b) reported that adult migrating steelhead ascend both on the rising and falling limb of the hydrograph but cease movement during peak floods. Finally, there are more opportunities for migration along the descending limb of a hydrograph because ascending limbs are of relatively short duration compared to descending limbs.

As described in Section 2 – *Geographic Setting: Suspended Sediment in the Santa Clara River*, data collected from the Santa Clara River showed that SSCs are typically higher for any given discharge during the ascending limb of the hydrograph compared to the descending limb. Thus, it would be expected that, for a given flow, an adult steelhead migrating during the descending limb would be exposed to lower SSCs (and thus experience lower SEV effects) compared to an adult steelhead that migrated during the ascending limb (or peak) of the hydrograph. To evaluate how the assumption of migration along the descending limb would influence relationships between predicted SEV, SSC, and flow in the Santa Clara River, we evaluated these relationships separately using data from either the ascending or descending limb of the hydrograph, the results of which are presented in Table 4. Individual data points were manually assigned to either the ascending or descending limb of hydrographs based on upward/downward flow trends. Peak flows were manually identified. Any flows on the ascending limb and the peak flow were grouped with ascending limb flows. A brief and minor flow decrease during a larger peak event was also considered ascending. Flows after the peak were assigned descending limb. For subsequent storms, the transition from descending to peak flows was when flows started to increase consistently before a peak. Visual assessment and best professional judgement were used to determine the start of baseflows at the end of the descending limb, which could be in-between storms or at the end of the wet season. Baseflows were not included in the analysis.

Table 4. Comparison of the effects of assuming migration along the ascending versus descending limb of hydrographs on discharge predicted to result in SEV levels associated with sublethal and lethal effects (see Table 2 for description of SEV levels). The 95% exceedance values of discharge in the Santa Clara River associated with each level of SEV are presented.

SEV level	95% percentile discharge (cfs)		
	All hydrograph	Descending limb	Ascending limb
4	67	78	-
5	105	114	-
6	179	242	4.9
7	594	605	328
8	1,299	1,312	619
9	4,179	4,179	4,743
10	20,751	19,941	22,408
11	28,555	28,348	29,282
12	126,595	-	-

As expected, the discharge associated with a given SEV level is higher for fish that migrate along the descending limb of the hydrograph compared to the ascending limb, but only for lower SEV levels that would not be associated with paralethal effects and mortality (SEV < 9). For example, discharge above ~1,300 cfs would be very likely (95%) to be associated with SSC that would result in major physiological stress (SEV = 8) for a fish that migrates along the descending limb of a hydrograph compared to a discharge of only 619 cfs for a fish migrating along the ascending limb. However, discharge that would be very likely (95%) associated with paralethal effects (SEV = 9) and mortality (SEV = 10–12) are similar between fish migrating along the descending versus ascending limb of a hydrograph (Table 4). Similarities in discharge associated with higher SEV levels between fish that migrate along descending and ascending limbs are due to convergence of observed SSC along ascending and descending limbs of the hydrograph at higher discharge. Overall, these data indicate that a steelhead could behaviorally avoid exposure to higher SSC for any given level of discharge by delaying migration until after peak flows.

7 CONCLUSIONS

The goal of this memo was to use the best available scientific and commercial data to answer the four questions in Table 1. Inferences made on the effects of SSC on adult steelhead and associated discharge in the Santa Clara River are summarized in Table 5.

Table 5. Synthesis of quantitative and qualitative conclusions for answers to the focal questions using the best available science.

Effect	Suspended sediment concentration (given two-day exposure time)	95% exceedance discharge for given SSC in the Santa Clara River at Freeman Diversion	Likelihood of adult steelhead actively swimming upstream
Avoidance behavior; minor physiological stress; increased respiration rate (SEV <5)	<7 mg/L	<100 cfs	Very Likely
Moderate physiological stress; impaired homing (SEV 6–7)	30–100 mg/L	180–600 cfs	Likely
Major physiological stress; reduced tolerance of pathogens (SEV 8)	400 mg/L	1,200 cfs	Unlikely
Paralethal and lethal effect begin (SEV 9)	1,400 mg/L	4,200 cfs	Very Unlikely
0–20% mortality (SEV 10)	5,200 mg/L	20,800 cfs	-
20–40% mortality (SEV 11)	20,000 mg/L	29,000 cfs	-
40–60% mortality (SEV 12)	73,000 mg/L	127,000 cfs	-

It was clear from relationships between SSC and discharge measured from the Santa Clara River that there is variability in SSC across ranges of discharge, likely due to hydrogeomorphic processes operating across temporal and spatial scales within the watershed. Despite this variability, a large amount of the variability in SSC was explained by discharge, and there are "lower envelope" thresholds for SSC at any given discharge, which is related to a general rule that there is increased erosion under higher discharge. Moreover, SSC in the Santa Clara River routinely surpasses thresholds that are predicted to impair physiological performance and even result in mortality of adult salmonids.

The results from application of the Newcombe and Jensen (1996) equation based on SSC and discharge measured from the Santa Clara River provide predictions for behavioral, physiological, paralethal, and lethal effects on adult steelhead. These effects include reduced swimming performance, impaired homing, and major physiological stress, all of which would influence the ability of an adult steelhead to actively swim in an upstream direction, which is required for upstream migration. However, it is challenging to predict at what levels of SSC a steelhead would no longer be physiologically capable of (or would choose to avoid) swimming upstream due to limitations on respiration, homing, ionoregulation, or due to acute stress. Due to the uncertainties described in this memo and limitations of the Newcombe and Jensen (1996) equations, it would be inappropriate to designate specific thresholds for SSC (and thus flows) when an adult steelhead would not swim upstream. Instead, we predict that as the negative effects of SSC increase from moderate to major physiological stress and then to lethal levels, there would be a decrease in the likelihood of steelhead swimming upstream. For example, we would predict that a migrating adult steelhead would be capable of enduring acute moderate and major physiological stress because they are adapted to cope with challenging conditions during migration, and they also could have the ability to recover from stress due to spatial and temporal variability in SSC. Thus, we predict that an adult steelhead could migrate during SSC associated with major physiological stress, but adult steelhead would be more likely to not impose additional metabolic costs on themselves during these conditions and instead would hold to wait for more suitable conditions. An analogous example of delaying migration in response to stressful conditions comes from studies on the Columbia River where both summer steelhead and Fall Chinook salmon "pause" migration during elevated temperatures (Keefer et al. 2018).

We further predict that once SSCs reach levels associated with mortality, it is unlikely that an adult steelhead would choose (or be physiologically capable) of swimming upstream. We base this on bioenergetic principles related to oxygen demand discussed earlier. Although we predict reduced upstream movements under high SSC associated with mortality (as predicted by the Newcombe and Jensen [1996] equation), we do not necessarily think an adult steelhead would experience mortality under these conditions unless gill damage resulted in delayed mortality from infection. There is of course much uncertainty with regard to these predicted effects, but based on our scientific expertise, we believe our approach of using the concept of likelihood of moving upstream and the 95% exceedance values of discharge across ranges of SSC is conservative (i.e., it underpredicts the impacts on an adult steelhead). Additional data collection from both field and laboratory studies would be needed to evaluate our predictions and decrease uncertainty.

Two types of relationships were explored in this memo: (1) the relationship between SSC and fish response (behavioral and physiological), and (2) the relationship between SSC and discharge in the lower Santa Clara River. Both relationships include uncertainty, with a large amount of uncertainty attributed to the relationship between SSC and discharge as observed in Figure 3. Using a 95% exceedance value of discharge to make inferences from the relationship between SSC and discharge acknowledges uncertainty while providing rigorous guidance for estimating SSC at a given discharge. The best available scientific and commercial data, including the meta-analysis by Newcombe and Jensen (1996), clearly indicate that fish, including anadromous adult salmonids, respond to suspended sediment in their environment. As SSC increases, adult steelhead would experience physiological stress and increased oxygen demands and begin to use behavioral strategies to avoid and minimize stress and increase oxygen consumption. Results from our analysis suggest that once SSC exceeds ~1,400 mg/L for a duration equivalent to expected transit time between the ocean and the Freeman Diversion (~2 days), adult steelhead would experience major physiological stress and the onset of paralethal effects, resulting in a high probability that the fish would seek out cleaner water in tributaries, the estuary, or channel margins and cease migrating in an upstream direction until high SSCs subside.

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Appendices

Appendix A

Best Available Information Related to Suspended Sediment Effects on Salmonids

Table A-1. Best available information related to suspended sediment effects on salmonids.

Citation	Information type	Experiment/ Observation/ Review/ Model/Opinion	Species	Origin	Life stage	Relevant results
Berg and Northcote 1985	Peer-reviewed	Experiment	Coho	River	Juvenile	Reduced territory defense and increased gill flaring in turbid waters (30 and 60 NTU) compared to lower turbidities (<20 NTU); (No relation to SSC provided).
Berli et al. 2014	Peer-reviewed	Experiment	Rainbow trout and brown trout	Hatchery	Juvenile	Swimming performance (U_{crit}) reduced when exposed to 13 NTU (~110 mg/L) for ~1.4 hours.
Bozek and Young 1994	Peer-reviewed	Observational	Rainbow trout, cutthroat trout, brook trout, hybrid trout	River	Juvenile and adult	Exposure to elevated SSC following wildfire was also thought to result in mortality due to asphyxiation of salmonids in streams in Yellowstone National Park.
Lake and Hinch 1999	Peer-reviewed	Experiment	Coho	Hatchery	Juvenile	Stress response and gill damage observed after 96-hour exposure to SSC of 40,000 mg/L and mortality observed after exposure to 100,000 mg/L.
Lehman et al. 2017	Peer-reviewed	Experimental	Chinook	Hatchery	Smolt	Reduced swimming performance was also observed in juvenile Chinook salmon from the San Joaquin River that were exposed to turbidity equivalent to a maximum SSC of 15 mg/L.
Michel et al. 2013	Peer-reviewed (Dissertation)	Experiment	Rainbow trout	Hatchery	Juvenile	Rainbow trout can adapt physiologically to 0–5,000 mg/L sediment pulses after eight days of exposure, and particle pulses over 24 days can cause structural and metabolic changes in rainbow trout, even when gill damage is absent.
Redding et al. 1987	Peer-reviewed	Experiment	Steelhead and coho	Hatchery	Juvenile	Exposure to 2,000–3,000 mg/L for up to eight days resulted in increased stress levels and reduced tolerance to pathogens.
Servizi and Gordon 1990	Peer-reviewed	Experimental	Chinook	Hatchery	Juvenile	Juvenile Chinook salmon 96-hour LC50s equal to 31,000 mg/L.
Servizi and Martens 1987	Peer-reviewed	Experimental	Sockeye	Hatchery	Juvenile	Juvenile sockeye salmon 96-hour LC50s equal to 17,600 mg/L.

Citation	Information type	Experiment/ Observation/ Review/ Model/Opinion	Species	Origin	Life stage	Relevant results
Servizi and Martens 1991	Peer-reviewed	Experimental	Coho	Hatchery	Juvenile	Reduced tolerance of yearling coho salmon to suspended sediment was observed when temperature was increased. Juvenile coho salmon 96-hour LC50s equal to 22,700 mg/L.
Servizi and Martens 1992	Peer-reviewed	Experiment	Coho	Hatchery	Juvenile; subyearling	Avoidance by 25% of population observed at SSC of 7,000 mg/L for four days.
Sigler et al. 1984	Peer-reviewed	Experiment	Steelhead	Hatchery	Juvenile	102 mg/L for 336 hours associated with reduced growth rate.
Whitman et al. 1982	Peer-reviewed	Experiment	Chinook	Hatchery	Adult	Reduced preference for natal water source when volcanic ash was added at levels of 350 mg/L compared to a non-natal water source with no added volcanic ash.
Clark et al. 2016	Peer-reviewed	Observational	Sockeye	River	Juvenile; smolt; migratory	Higher predation rates in clear sections of river compared to turbid sections; hypothesized higher rates of predation by bull trout in clear sections.
Newcombe and Jensen 1996	Peer-reviewed	Review/Model	Various (including steelhead adults)	Various	Various	Scientific review of SSC on fish; created models for predicting the severity of ill effects from SSC exposure based on SSC concentrations and exposure duration. Used previously collected data to create model including a model specific to salmonids. Relevant review conclusions from review: Impaired homing in adult migrating salmonids is predicted at SSC as low as 148 mg/L; adult steelhead exposed to 500 mg/L for 3 hours showed signs of sublethal stress; steelhead exposed to coarse sediment of 2,000 mg/L for one day would experience major physiological stress; exposure up to 10,000 mg/L can be lethal for adult steelhead
Bash et al. 2001	Technical report	Review	Various (including steelhead)	Various	Various	Reviewed literature on SSC effects on fish.
Kemp et al. 2011	Peer-reviewed	Review	Freshwater fish (including steelhead)	River – various	Juvenile and Adult	Literature review of fine sediment effects on riverine fish.

Citation	Information type	Experiment/ Observation/ Review/ Model/Opinion	Species	Origin	Life stage	Relevant results
Coats et al. 1985	Peer-reviewed	Observational – after a 150-year rain event	Steelhead	River – Zayante Creek, lower San Lorenzo River, CA	Adult	With longer exposures (10 days) to SSCs around 1,600 mg/L, complete avoidance and loss of habitat has been observed.
Leider 1989	Peer-reviewed	Observational – following eruption of Mt. St. Helens	Steelhead	River – Columbia River system, WA	Adult	Steelhead bypassed natal streams with high SSC to spawn in upstream tributaries; "Compelling circumstantial evidence suggests that for 1–3 yr after the eruption, large numbers of adult steelhead migrating toward affected tributaries entered two non-affected tributaries flowing into the Columbia River upstream of natal streams."
Casitas Municipal Water District 2008	Technical Report	Observation	Steelhead (southern California DPS)	River	Adult	Six observed migrating adult steelhead in the Ventura River (adjacent to the Santa Clara River) all migrated upstream following (not during) high-flow events, when the turbidity levels at the time of passage through the Robles Diversion ranged from 2 NTU to 22.5 NTU despite the Vaki Riverwatcher monitoring equipment functioning up to 200 NTU; there were no observations of migrating steelhead between 22.6 and 200 NTU. (22.5 NTU is associated with ~100 mg/L SSC).
Thomas R. Payne & Associates 2005	Technical Report	Review	Salmonids (including steelhead)	Various	Juvenile and Adult	Review of best available scientific and commercial data as of 2005.
Redding et. al. 1987	Technical Report	Experiment	Steelhead	Hatchery	Juvenile	Volcanic ash exposure at 500 mg/L for 3 to 9 hours associated with signs of sublethal stress, blood cell count and chemistry change, elevated plasma cortisol.

Citation	Information type	Experiment/ Observation/ Review/ Model/Opinion	Species	Origin	Life stage	Relevant results
NMFS 2000	Expert Opinion	ESA - Final Biological Opinion for U.S. Army Corps of Engineers Regional General Permit for Stream Restoration	Salmonids	River	Juveniles and Adults	"Elevated Total Suspended Solids (TSS) conditions have been reported to enhance cover conditions, reduce piscivorous fish/bird predation rates, and improve survival. Elevated TSS conditions have also been reported to cause physiological stress, reduce growth, and adversely affect survival. Of key importance in considering the detrimental effects of TSS on fish are the frequency and the duration of the exposure (not just the TSS concentration). Behavioral avoidance of turbid waters may be one of the most important effects of suspended sediments (DeVore et al. 1980; Birtwell et al. 1984; Scannell 1988). Salmonids have been observed to move laterally and downstream to avoid turbid plumes (McLeay et al. 1984, 1987, Sigler et al. 1984, Lloyd 1987, Scannell 1988, Servizi and Martens 1992). Juvenile salmonids tend to avoid streams that are chronically turbid, such as glacial streams or those disturbed by human activities, except when the fish need to traverse these streams along migration routes (Lloyd et al. 1987). In addition, a potentially positive reported effect is providing refuge and cover from predation (Gregory and Levings 1988). Turbidity, at moderate levels, has the potential to adversely affect primary and secondary productivity, and at high levels, has the potential to injure and kill adult and juvenile fish, and may also interfere with feeding (Spence et al. 1996). Newly emerged salmonid fry may be vulnerable to even moderate amounts of turbidity (Bjornn and Reiser 1991). Other behavioral effects on fish, such as gill flaring and feeding changes, have been observed in response to pulses of suspended sediment (Berg and Northcote 1985). Fine redeposited sediments also have the potential to adversely affect primary and secondary productivity (Spence et al. 1996), and to reduce incubation success (Bell 1991) and cover for juvenile salmonids (Bjornn and Reiser 1991)."

Citation	Information type	Experiment/ Observation/ Review/ Model/Opinion	Species	Origin	Life stage	Relevant results
NMFS 2006	Expert Opinion	ESA – Final Biological Opinion on the Condit Dam Removal	Salmonids, including steelhead	River – White Salmon River, WA	Juveniles and Adults	"Individual salmon and steelhead that cannot avoid the sediment plume during the first 24 hours following dam breaching could experience physiological stress, increase maintenance energy, reduced feeding and growth (juveniles), respiratory impairment, and possibly gill damage (Herbert and Merkens 1961; Redding et al. 1987; Lloyd et al. 1987; Servizi and Martens 1991). The peak TSS concentration is anticipated to last for less than a day in the Columbia River. Exposure duration is a critical determinant of the occurrence and magnitude of physical or behavioral effects (Newcombe and MacDonald 1991)."
NMFS 2008a	Expert Opinion	ESA – Final Biological Opinion on United Water Conservation District for Operations of Freeman Diversion Dam	Steelhead	River – Santa Clara River, CA	Adult	"During the wet season, the Santa Clara River is turbid and can exceed 3,000 nephelometric turbidity units… The high turbidity concentrations are of concern because reports suggest high turbidity levels (> 4,000 mg/l) may temporarily halt upstream migration of adult salmonids (Bjornn and Reiser 1991)." Bjornn and Reiser cite Bell (1986), which reported that following a landslide migrating adult salmonids stopped migrating when SSC exceeded 4,000 mg/L. Bell (1990) reports that, "Studies conducted after a natural slide in the Chilcotin River in British Columbia indicated that salmonid fish will not move in streams where the silt content is above 4,000 ppm."

Citation	Information type	Experiment/ Observation/ Review/ Model/Opinion	Species	Origin	Life stage	Relevant results
NMFS 2008b	Expert Opinion	ESA – Final Biological Opinion on United Water Conservation District for Operation of the Santa Felicia Hydroelectric Project	Steelhead	River – Santa Clara River and Piru Creek, CA	Adult	"Low discharge, high water temperature, physical barriers, low dissolved oxygen, and turbidity[3] (high levels) may delay or halt upstream migration of adults and timing of spawning, and downstream migration of juveniles and subsequent entry into the estuary, lagoon, or ocean." Footnote 3: "Defined as "suspended particulate matter affecting the amount of light that is scattered or absorbed by a fluid." With regard to the influence of turbidity on migration of steelhead, the ecological literature provides no unequivocal causal relationship between turbidity and migration. Therefore, whether turbidity in fact influences migration is currently unknown. Challenges related to developing a clear understanding of whether turbidity influences upstream migration of adult steelhead includes (1) the relationship between turbidity and discharge, which can be positively related to one another, and (2) discharge alone has been found to influence migration." "During the wet season, the Santa Clara River is turbid and can exceed 3,000 nephelometric turbidity units. The elevated turbidity probably reflects accelerated inputs of sand and smaller particles due to anthropogenic disturbances throughout the watershed. The high turbidity concentrations are of concern because reports suggest high turbidity levels may temporarily halt upstream migration of adult salmonids (Bjornn and Reiser 1991)."

Citation	Information type	Experiment/ Observation/ Review/ Model/Opinion	Species	Origin	Life stage	Relevant results
NMFS 2012a	Expert Opinion	ESA – Final Biological Opinion on the removal of dams from the Elwha River	Salmonids, including steelhead	River – Elwha River, WA	Juveniles and Adults	"NMFS expects sediment loads to have a serious short-term adverse effect on both winter and (if still extant) summer steelhead populations, particularly those fish residing in the mainstem channel. Suspended sediment loads are expected to increase drastically during the dam removal with in-river peak sediment loads projected to be as high as 51,000 mg/l for 1 to three days (Randal et al. 1996) and are expected to be elevated for up to 3 years post dam removal. Sediment loads above 350 mg/l have been shown to increase the rate of straying for Chinook salmon (Whitman et al. 1982, Leider 1989), and may reduce the number of adult returns for spawning for other salmonid species including PS [Puget Sound] steelhead. Loads of 150 mg/l or higher, for [up to an hour], is likely to cause sublethal harm to salmonids within the action area (Newcombe and Jensen 1996). Fish that remain exposed to fine-grained sediment loads above 1000 mg/l for 48 hours or more are likely to experience increased mortality (Newcombe and Jensen 1996)."

Citation	Information type	Experiment/ Observation/ Review/ Model/Opinion	Species	Origin	Life stage	Relevant results
NMFS 2012b	Expert Opinion	ESA – Final Biological Opinion for bridge replacement	Salmonids	River – Yakima River, WA	Juveniles and Adults	"Increased turbidity levels over time can adversely affect the physiology, behavior, and habitat of steelhead. Tissue injury can result from abrasive silt particles entering delicate fish gills, interfering with respiration. Salmon that experience elevated suspended solids have been shown to react with an alarm reaction by abandoning cover and avoiding the area. The resulting stress can affect the parr-smolt transformation, resulting in impaired migratory behavior and reduced early marine survival. Turbidity can also affect feeding rates, reaction distance, prey selection and abundance due to the reduction in visibility. The reduced underwater visual range of fish may either act as a protective cover from predators (e.g., larger fish or piscivorous birds) or reduce the ability of these species to detect predators (Sigler et al. 1984; Bash et al. 2001; Berg and Northcote 1985; Newcombe and Jensen 1996). Elevated turbidity levels that reduce light penetration into water limit primary food production for aquatic life due to lowered photosynthetic activity of algae and rooted plants (Ward 1992)."
NMFS 2016	Expert Opinion	ESA – Final Biological Opinion on dredging in Humboldt Bay	Salmonids	Estuary – Humboldt Bay, CA	Juvenile and Adult	"Concentrations of suspended sediments and associated turbidity that are significantly elevated above the natural level, limit the visibility and successful capture of prey by visual feeders, because prey detection depends on light intensity, water clarity, and prey characteristics such as movement, pigmentation, and size (Clarke and Wilbur 2000; De Robertis et al. 2003)."

Citation	Information type	Experiment/ Observation/ Review/ Model/Opinion	Species	Origin	Life stage	Relevant results
Berg 1983	Peer-reviewed (Dissertation)	Review	Salmonids	Various	Juvenile	Sediment particles associated with direct gill trauma through abrasion of gills, erosion of gill mucous coating, and accumulation in gill filaments; noted behavioral changes include opening and closing the gills (i.e., gill flaring), "coughing," and producing additional protective mucous; secondary effects from gill trauma include increased energy use and interference with respiration and ion exchange.
Pess et al. 2008	Peer-reviewed	Review/Observational	Salmonids, including steelhead	River – Elwha River, WA	Juvenile and Adult	Sediments released from Elwha dams could lead to increased straying and "barrier" to migration due to turbidity Decrease in spawning habitat quality (short-term).

Appendix B

Adult Steelhead Migration Rate Review

Migration rate is a function of the physical conditions of a river (e.g., slope, water velocity, resting locations, etc.) and fish morphometrics, physiology, and energetic state. Energetic tradeoffs exist between the amount of energy expended during migration and energy available for gamete development and reproductive behaviors. Thus, fish should attempt to minimize energy use during migration by selecting pathways with lower water velocities while maximizing migration rate.

Migration rates reported for adult steelhead in rivers are highly variable, ranging from less than 0.6 miles per day (mi/d; 1 kilometer per day [km/d]) to more than 25 mi/d (40 km/d) (Keefer et al. 2004, Salinger and Anderson 2006, English et al. 2006, Jepsen et al. 2012, 2015). Differences in migration rate among river systems are a result of environmental complexity along migratory routes (e.g., variable flows, physical structure), differences in run timing (i.e., winter versus summer-run fish), and variation in individual fish condition and physiology. The most extensive data on adult steelhead migration rates are from tagging studies in the Columbia River basin, but these data include migration rate estimates from fish migrating through heavily altered systems with regulated flow patterns due to hydropower infrastructure. Comparisons of steelhead migration rates between the Columbia River and naturally flowing rivers indicated that Columbia River steelhead generally migrate faster compared to steelhead from naturally flowing rivers (English et al. 2006). English et al. (2006) noted that migration rates among rivers are inversely related to channel gradient because gradient controls water velocity, and hence faster migration rates are observed in impounded rivers that have lower gradients and lower flows (i.e., fish do not have to swim against higher flows in lower gradient rivers).

Few data exist on migration rates and behavior of steelhead at the southern extent of their range. Compared to northern populations, adult steelhead migrating in southern locations contend with different challenges, such as flashy flows, high suspended sediment loads, and high temperatures, making it challenging to infer migration rates based on data from northern rivers. For example, steelhead in southern California evolved in river systems characterized by high seasonal flow variability and rapidly rising and falling (“flashy”) storm flows. Steelhead enter these rivers in the winter and spring when storms create pulses of high flows that breach sandbars, causing rivers mouths to connect with the ocean and providing migration opportunities. Periods of low flows can occur between flow pulses in these rivers with sections becoming dry in some locations depending on river geomorphology. This contrasts with northern river systems that have perennial flows that provide continuous longitudinal habitat connectivity that facilitates steelhead migration. Interrupted migration and isolation in disconnected habitats in low-flow conditions, which can occur between storm events, is a major risk to steelhead in southern rivers because it would expose fish to poor water quality (high temperature and low dissolved oxygen), increased predation risk, and overall increased risk of physiological stress and mortality. In addition, holding habitat can be limited in lower river sections. Due to the risks associated with migrating in southern rivers, it is generally assumed that steelhead in southern California have evolved directed (and relatively fast) upstream migration behaviors to avoid stranding and increase reproductive success.

In the absence of data on southern steelhead behavior, migration rates for steelhead in the Santa Clara River are assumed to be similar to steelhead migrating in naturally flowing rivers. Steelhead migration rate averaged 7.3 mi/d (11.8 km/d) (sdev = ± 4.5 mi/d [7.3 km/d]; range = 0.56–17.7 mi/d [0.9–28.5 km/d]) in naturally flowing rivers in British Columbia, Canada (English et al. 2006). Based on this average migration rate applied to adult steelhead in the Santa Clara River, it is expected that adult steelhead would take 1.5 days on average to reach the Freeman Diversion ~11 miles (18 km) upstream from the estuary. These estimates are consistent with the two-day travel time assumption presented in the final Vern Freeman Dam Fish Passage Conceptual Design Report (VFDFPP 2010). Using the first (3.7 mi/d [6.0 km/d]) and third (11 mi/d [17.75 km/d]) quartiles of migration rate from English et al. (2006), steelhead would take a maximum of three days and a minimum of one day to reach the Freeman Diversion. The three-day travel time maximum is consistent with what was considered the "slow" migration rate within the VFDFPP (2010) report.

It should be noted that the average migration rate of 7.3 mi/d (11.8 km/d) is from data collected on summer-run steelhead stocks (English et al. 2006), whereas steelhead in southern California are considered winter-run stocks. As their name implies, summer-run steelhead enter rivers during the summer months and then overwinter prior to spawning in the spring. In contrast, winter-run steelhead enter rivers in winter and spawn shortly thereafter. Due to differences in river entry versus spawning time, summer-run steelhead may migrate at slower rates than winter-run steelhead. There is little data on migration rates of winter-run steelhead, but winter-run steelhead in the Willamette River, Oregon, averaged approximately 18.6 mi/d (30 km/d) (Jepsen et al. 2012) with a median migration rate of 16.5 mi/d (26.6 km/d) (Jepsen et al. 2015), which is substantially higher than our estimate of 7.3 mi/d (11.8 km/d). Similar to the Columbia River where migration rates are higher, flows in the Willamette River are modified by dams and thus may not be truly representative of free-swimming fish in a river that experiences episodic high-flow events.

Assuming the slowest migration rate reported in the literature (0.6 mi/d [1 km/d]; Jepsen et al. 2012), steelhead would take a maximum of 18 days to reach the Freeman Diversion. This conservative migration rate estimate is based on data collected in the Columbia River with highly modified flow regimes and extremely low gradients (Jepsen et al. 2012). Additional studies using mark-and-recapture or radio telemetry are needed to better understand adult steelhead movements in southern California rivers.

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