San Francisco Bay Region Flood Control Channel Classification

A Pilot Effort

July 2021

SFEI | AQUATIC SCIENCE CENTER

Primary Authors
Scott Dusterhoff
Sam Shaw
Katie McKnight

Funded by the San Francisco Bay Regional Water Quality Control Board

San Francisco Estuary Institute Publication #1046

Suggested citation

San Francisco Estuary Institute-Aquatic Science Center (SFEI-ASC). 2021. San Francisco Bay Region Flood Control Channel Classification: A Pilot Effort. An SFEI-ASC Resilient Landscape Program report developed in cooperation with the San Francisco Bay Regional Water Quality Control Board. Publication #1046. San Francisco Estuary Institute-Aquatic Science Center, Richmond, CA.

Report Availability

This report is available on SFEI's website at www.sfei.org/projects

Cover Credits

Guadalupe River in the Santa Clara Valley, courtesy of Google Earth

Acknowledgements

We are grateful for the support provided by Water Board staff, including project partners Dr. Kevin Lunde and Dr. Kristina Yoshida, and Naomi Fager and Dyan Whyte who initiated this effort. We are also grateful for the technical guidance provided by the Technical Advisory Committee: Dr. Derek Booth (University California Santa Barbara), Dr. Josh Collins (San Francisco Estuary Institute), and Dr. Raphael Mazor (Southern California Coastal Water Research Project). We would also like to thank the water agency staff who provided much of the information used in this effort. We owe a particular debt of gratitude to Chase Takajo (Sonoma Water) and Jill Bernard, Carole Foster, and Doug Titus (Valley Water). Paul Randall (EOA, Inc.) deserves many thanks for his help with the channel classification effort. SFEI scientists Sarah Pearce and Ellen Plane helped with report finalization.

This effort was funded by the San Francisco Bay Regional Water Quality Control Board.

Summary

This study was a pilot effort aimed at identifying stream ecological conditions associated with different types of fluvial (river and creek) flood control channels in two Bay Area counties, and identifying factors driving the best ecological conditions for the channel types considered. Ecological conditions were assessed using a type of bioassessment data collected from benthic macroinvertebrates (BMI) called the California Stream Condition Index (CSCI). CSCI is a predictive index that indicates the degree of biological alteration by comparing the presence or absence of observed macroinvertebrate species and metrics that describe the macroinvertebrate community composition to values expected under reference conditions.

The major results of the study are as follows:

- This study created a simple channel classification scheme (Hard, Mixed, Soft, Natural Unmodified, and Natural non-flood control channels) useful for supporting management decisions and successfully applied the scheme to categorize channel types at almost 300 locations in two Bay Area counties that have CSCI data.

- CSCI scores were correlated with the developed channel types in Sonoma and Santa Clara counties. Natural non-flood control channels had the highest median and maximum CSCI scores, Natural Unmodified and Soft flood control channels (both with soft earthen bed and banks) had lower maximum and median CSCI scores, and Mixed (soft earthen bed and hard rock- or concrete-lined banks) and Hard channels (hard rock- or concrete-lined bed and banks) had the lowest scores (see Figures 6 and 8).

- A detailed analysis of the controls on CSCI score was performed on just the Santa Clara County channels due to data availability. The percent impervious area upstream of channel locations with CSCI scores (henceforth called % impervious area) had a strong relationship with CSCI score. The data show an overall decrease in both the maximum CSCI score and the range of CSCI scores with increasing % impervious area values. There is a clearly defined ceiling of CSCI scores (i.e., the 90% percentile of CSCI scores over a discrete range of % impervious area) that decreases with increasing % impervious area. The ceiling for Soft and Natural Unmodified channels is higher than for Hard and Mixed channels, particularly for lower % impervious area values (see Figure 10).

- The ceiling CSCI scores represent the highest likely CSCI score for each flood control channel type over a discrete range of % impervious area. Such data can be useful for identifying the best possible CSCI score that could be expected for a given % impervious area when converting from one channel type to another.

- A suite of local drivers that could affect CSCI scores for the different channel types were examined in the context of % impervious area. The drivers considered were flow type (perennial or non-perennial), channel management activities (sediment removal, vegetation removal, herbicide application), degree of channel stability, channel physical

structure, and riparian biotic structure. A simple correlation analysis showed that none of the potential drivers have a strong relationship with the ceiling CSCI values for any of the flood control channel types.

- Qualitative observations of drivers for CSCI scores did not show definitive connections between driver characteristics and CSCI scores, but there were some connections that merit further investigation. For example, CSCI scores adjacent to or downstream of parks and other open spaces tended to be high, regardless of the upstream imperviousness. Almost all channel reaches with high CSCI scores had relatively dense riparian cover. Conversely, sites with low CSCI scores were often downstream of a dam or quarry, or had industrial surroundings clearly lacking riparian vegetation. These cursory findings suggest local land uses that promote cool water temperatures and provide beneficial allochthonous material for benthic macroinvertebrates could offset the cumulative impacts of upstream impervious area.

Introduction

The San Francisco Bay Regional Water Quality Control Board (Water Board) is responsible for protecting the beneficial uses of stream channels throughout the nine Bay Area counties. This protection extends to engineered flood control channels, which must be managed in a manner that protects residents and infrastructure from floods while supporting other beneficial uses related to habitat for aquatic life. To inform Section 401 Water Quality Certification and other permitting decisions for proposed flood management projects within these channels, the Water Board needs information to elucidate the likely impact of proposed actions on beneficial uses and help determine alternative or additional management actions that may support and enhance beneficial uses. Specifically, the Water Board needs information that directly relates baseline ecosystem conditions to a range of channel management approaches that are regularly used within the San Francisco Bay region. This would help determine expected biological baseline conditions based on information from similarly developed and modified streams, and develop an expectation for how a stream reach may respond to flood control management activities with respect to supporting beneficial uses. In addition, the Water Board could use this approach to examine how restoration from one channel type to another is likely to affect biological conditions.

Over the past several decades, a growing body of research has examined relationships between indices of stream ecosystem health and watershed, channel, and riparian characteristics in highly urbanized settings. In a number of studies, stream ecological condition measured by benthic macroinvertebrate (BMI) indices has been shown to decrease as impervious area increases for a range of spatial scales (Klein 1979, Lenat and Crawford 1994, Stepenuck et al. 2002, Roy et al. 2003, Cuffney et al. 2005). Within both Pacific Northwest and San Francisco Bay Area watersheds, the upper limit of BMI index scores has been shown to correlate well with the degree of urbanization, displaying a “factor ceiling distribution” or “predicted biological potential” regression line that defines the best biological condition associated with a given degree of watershed imperviousness (Morley and Karr 2002, Booth et al. 2004, Fend et al. 2005, Carter et al. 2009). Recent studies in urbanized coastal Southern California watersheds have shown channel bed and bank material to be controlling factors on BMI index scores, with natural channels having a higher median index score than channels with a hardened bed and banks (SCSMC 2017). In addition, natural channels have been shown to have higher BMI index scores overall for the same local conditions (e.g., riparian shading) than hardened channels (SCSMC 2017). Given the importance of both watershed-scale and local drivers on BMI index scores and thus stream ecological condition in urbanized landscapes, more information is needed in the Bay Area to understand the relative impacts of different drivers on index scores in different channel types, both natural and managed.

To further the body of knowledge needed to inform permitting decisions in the Bay Area, the Water Board funded SFEI to conduct a pilot channel classification study aimed at identifying stream ecological conditions associated with different types of fluvial flood control channels upstream of head of tide. For this effort, flood control channels are defined as natural or man-made channels that have historically been modified and/or are currently maintained to manage flood risk. The specific objectives of the pilot study were to:

- compile information necessary for examining relationships between stream ecological condition as indicated by benthic macroinvertebrate index scores and channel and riparian physical characteristics, and channel management approaches at selected channel locations;
- examine benthic macroinvertebrate indicator scores associated with each channel type considered; and
- assess factors associated with benthic macroinvertebrate indicator scores for each channel type considered, particularly those factors driving the best ecological conditions.

The pilot study was a 2-year effort conducted in partnership with Water Board scientists (Dr. Kevin Lunde and Dr. Kristina Yoshida) and a Technical Advisory Committee: Dr. Derek Booth (University California Santa Barbara), Dr. Josh Collins (San Francisco Estuary Institute), and Dr. Raphael Mazor (Southern California Coastal Water Research Project). The study focused on examining stream ecological conditions in channel locations in two Bay Area counties. The results from this pilot study will directly assist Water Board staff in making decisions that will support and enhance beneficial uses in the study area and possibly to the larger Bay Area.

Study Area

This pilot study focused on channels in Sonoma County that drain to San Pablo Bay (Figure 1) and channels in Santa Clara County that drain to Lower South Bay (Figure 2). In Sonoma County, the study included channel reaches in the Petaluma River and Sonoma Creek watersheds. In Santa Clara County, the study included channel reaches in ten watersheds: Matadero Creek, Adobe Creek, Permanente Creek, Stevens Creek, Calabazas Creek, San

Tomas Aquino Creek, Guadalupe River, Coyote Creek, Lower Penitencia Creek, and Upper Alameda Creek. These two counties were selected for this effort because they contain a range of hydroclimatic, geomorphic, ecological, and urbanized conditions that exist throughout the region, and have the data needed for the study analyses.

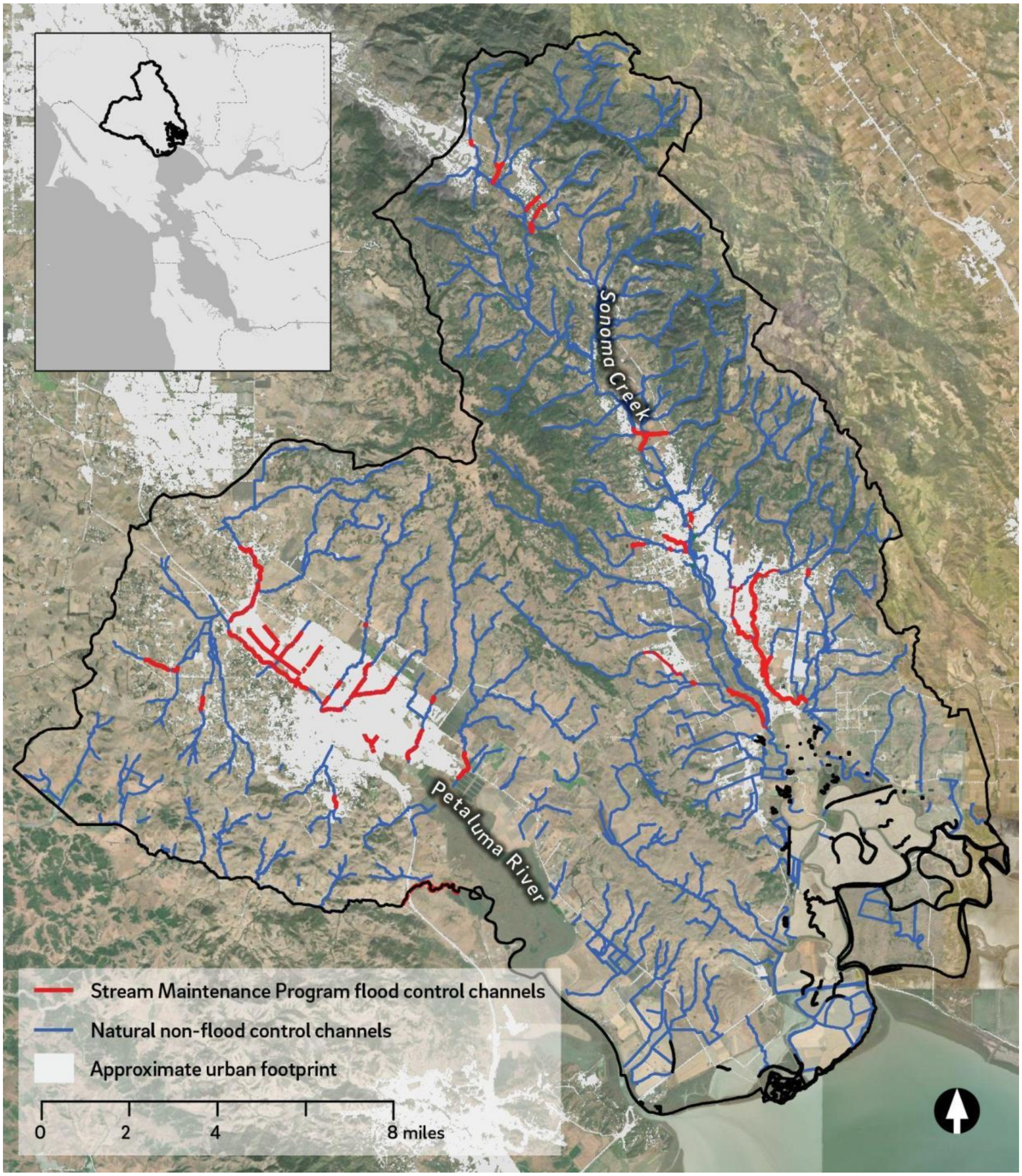


Figure 1. A map of flood control channels (red), and natural non-flood control channels (blue) above head of tide within Sonoma County that drain to San Pablo Bay.

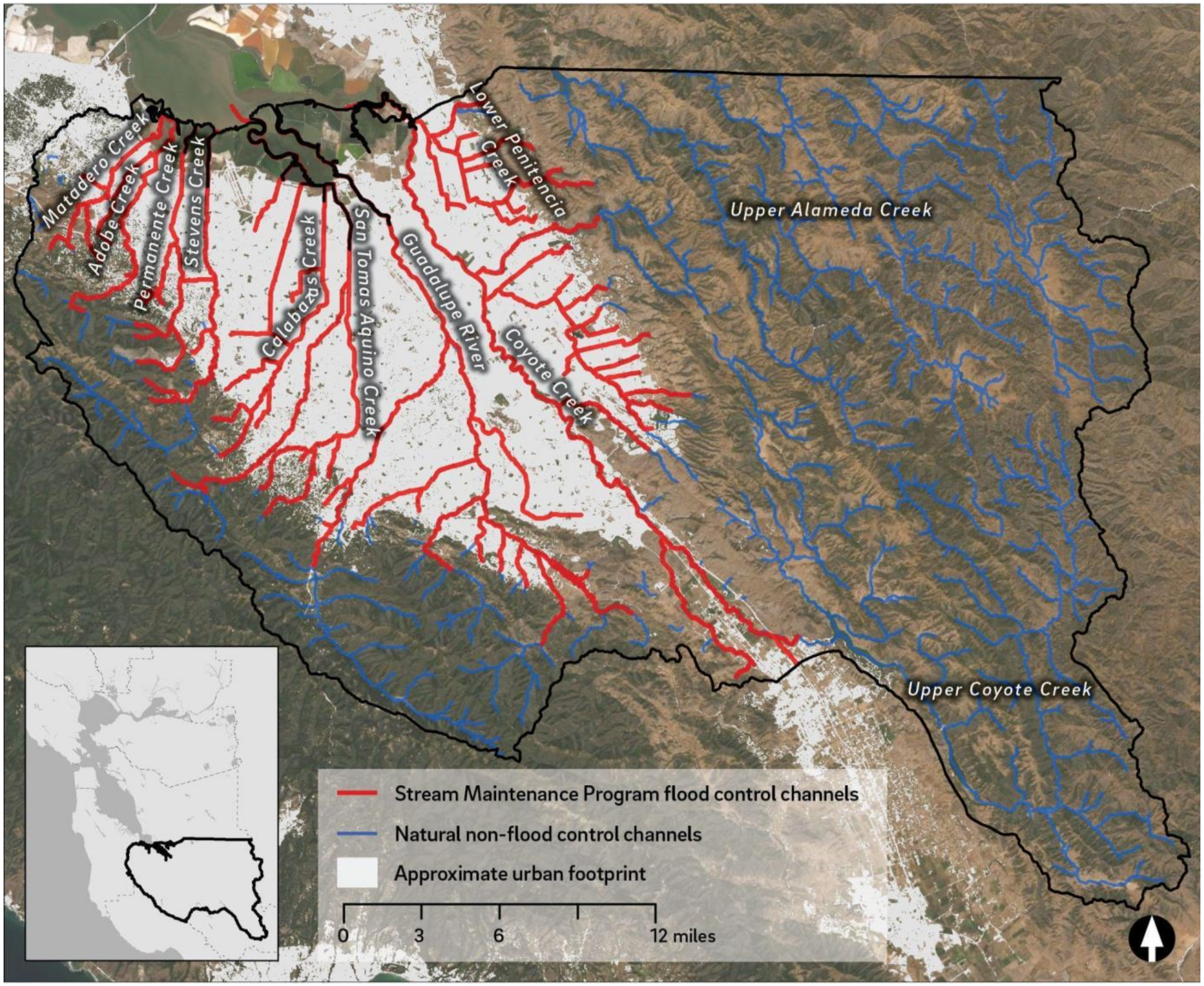


Figure 2. Flood control channels (red) and non-flood control channels (blue) in Santa Clara County that drain to Lower South Bay.

Methods

Overall approach

For this effort, we used the California Stream Condition Index (CSCI) to characterize in-channel ecological condition. CSCI translates sample benthic macroinvertebrate (BMI) diversity and abundance into a score that indicates overall stream health (Webster and Yang 2015). It is a predictive index that indicates the degree of biological alteration by comparing observed taxa and metrics to values expected under reference conditions based on site-specific landscape-scale environmental variables, such as catchment area, geology, and climate (Mazor et al. 2016). CSCI combines two types of information about the biological condition at a stream location: a multi- metric index (MMI) that measures ecological structure and function of the benthic macroinvertebrate assemblage, and an observed- to- expected (O/E) index that measures taxonomic completeness (Mazor et al., 2016). Data used to calibrate the CSCI are some of the most spatially complete and consistently measured stream health data available throughout the region.

For both Sonoma and Santa Clara counties, we examined the range of CSCI scores for the different types of flood control channels and for natural non-flood control channels. In Santa Clara County, we performed a detailed analysis that examined watershed-scale and local-scale drivers of CSCI scores for different flood control channel types. For the watershed-scale driver, we focused on percent of the contributing upstream area that is impervious (i.e., % impervious area), due to its simplicity and ease of calculation, and its previously studied local effects on macroinvertebrate populations (Fend et al., 2005). Building upon the % impervious values calculated for each CSCI reach, we explored several additional local drivers that would likely also affect BMI community composition, and thus the CSCI score. We selected drivers that are supported by existing data for most of the CSCI data locations, considering those that are directly related to local channel management approaches. The selected drivers were: dry season flow type, in-channel maintenance activities, channel physical structure complexity, degree of channel stability, and riparian vegetation characteristics. Data for these drivers were largely unavailable for Sonoma County, so our analysis focused on Santa Clara County. A previous study in Santa Clara County channels showed dissolved oxygen and temperature, both of which are controlled in large part by flow type and riparian vegetation characteristics, to be significantly related to BMI score within a given % impervious area range (see Carter et al. 2009). Finally, we qualitatively assessed additional local factors that could be driving high and low CSCI scores for different flood control channel types.

The following sections describe in detail the data sets that were obtained and developed to assess CSCI scores for flood control and non-flood control channels in Sonoma and Santa Clara counties, and to examine factors controlling CSCI scores for flood control channels in Santa Clara County.

CSCI scores

CSCI scores for benthic macroinvertebrate samples that had been collected in Sonoma and Santa Clara Counties over 20+ years were obtained from the California Waterboards Surface Water Ambient Monitoring Program (SWAMP). Data were collected using a standardized bioassessment protocol developed by California Department of Fish and Wildlife (CDFW) and regional Water Boards. CSCI scores indicate degree of ecological alteration and can be divided into four categories: scores below 0.62 are "very likely altered," scores between 0.62 and 0.79 are "likely altered," scores between 0.79 and 0.92 are "possibly altered," and scores above 0.92 are "likely intact" (see Rehn et al. 2015) (Figure 3).

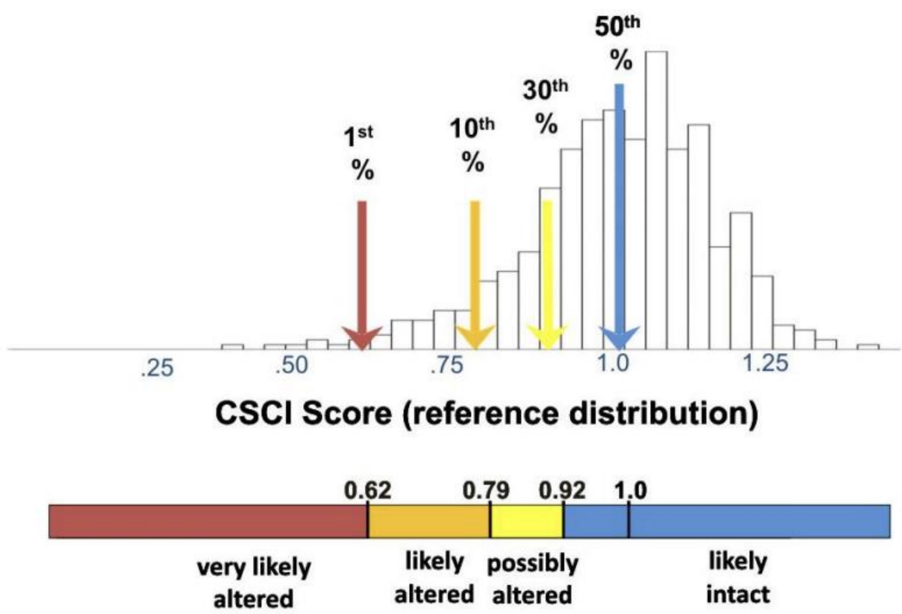


Figure 3. CSCI score distributions and associated categories (from Rehn et al., 2015).

In Sonoma County, we obtained a total of 65 bioassessment samples collected at 31 different locations in the Petaluma River and Sonoma Creek watersheds. These surveys were conducted between 2000 and 2016, with 2002 being the earliest year without any later surveys at the same location. In Santa Clara County, we obtained a much larger dataset of CSCI scores: a total of 355 bioassessment samples conducted at 256 different locations in the Santa Clara Valley. These surveys were collected between 1998 and 2017.

Channel classification at bioassessment locations

A central task in this effort was to classify flood control channels across differing data sources and locations according to their physical form and function. These classifications can then inform future permitting decisions and management actions. In order to classify channels by their physical characteristics, we first obtained channel data from the Sonoma Water Stream

Maintenance Program (SMP) manual (Horizon Water and Environment 2020) and Valley Water SMP manual (Valley Water 2014). Though these sources provided some limited information on channel physical characteristics, their channel classification schemes were not directly aligned with channel material and specific function; rather, they were grouped by management and ownership type or by a non-specific assessment of modification. Additionally, channel types were classified very differently between the two water agencies. We created a uniform classification system based on these two datasets as described below.

<u>Sonoma Water SMP channels</u>

Sonoma Water SMP channels within the study area are within Sonoma Water flood control zones 2A (Petaluma River watershed) and 3A (Sonoma Creek watershed). Abbreviated SMP manual descriptions of Sonoma Water channel types are:

1. Engineered channels - Owned in Fee

Engineered channels are channels that were designed and built to convey a design discharge. In the program area, engineered channels have typically been built with a trapezoidal cross-sectional shape. Most of the engineered channels have earthen banks and beds; however, some channels have hardened (i.e. concrete or rip-rap) banks and beds. Bed and bank hardening typically occurs at or near road and culvert crossings to protect these structures. All beds that were hardened were fully hardened across the bed and banks.

2. Engineered Channel–Easement Maintained

These channels are not owned by Sonoma Water, but Sonoma Water performs channel maintenance on them through permissive easement agreements. All channels of this type coinciding with bioassessment samples showed no signs of hardening.

3. Modified Channel–Easement Maintained

Modified channels have earthen beds and banks that have been modified either through vegetation removal, in-channel grading, channel widening or straightening, or debris clearing to improve flow conveyance. Though modified, these channels are not engineered or constructed to convey a design discharge.

4. Natural Channel–Easement Maintained

Natural channels are non-engineered and non-modified creek systems with a permissive clearing easement. Sonoma Water holds hydraulic easements to work within the channel banks for approximately 80 miles of natural channels. Natural channels may require maintenance activities to maintain flow conveyance and reduce the flooding hazard. Maintenance work in natural channels typically involves clearing debris or vegetation that is causing a flow obstruction.

These channel types are not classified strictly by channel material and physical characteristics, but primarily by the type of ownership and typical maintenance activity performed. As such, we used additional channel information provided by Sonoma Water to re-classify these channel types by their bed and bank composition and planform geometry. We developed three flood control categories: **Hard** (hardened bed with hardened or soft banks), **Soft** (soft bank and bed, recontoured and modified channel), and **Natural Unmodified** (soft bed and bank, original channel planform geometry) (see Table 1 and Figure 4). We classified the channels outside the SMP boundary as **Natural Non-flood control channels**.

Table 1. Sonoma SMP channel classifications and study reclassifications**.**

Sonoma SMP channel class	Classification criteria	Reclassified channel type
Engineered channels - owned in Fee	Cement bed and bank = Hard Earthen bed and bank = Soft	**SOFT or HARD** (by aerial assessment)
Engineered Channel – Easement Maintained	All channels were determined to have earthen bed and banks	**SOFT** (confirmed by aerial assessment)
Modified Channel – Easement Maintained	Visually straightened and rerouted channels = Soft All others = Natural unmodified	**SOFT or NATURAL UNMODIFIED** (by aerial assessment)
Natural Channel – Easement Maintained	All streams not meeting the criteria described above	**NATURAL UNMODIFIED**

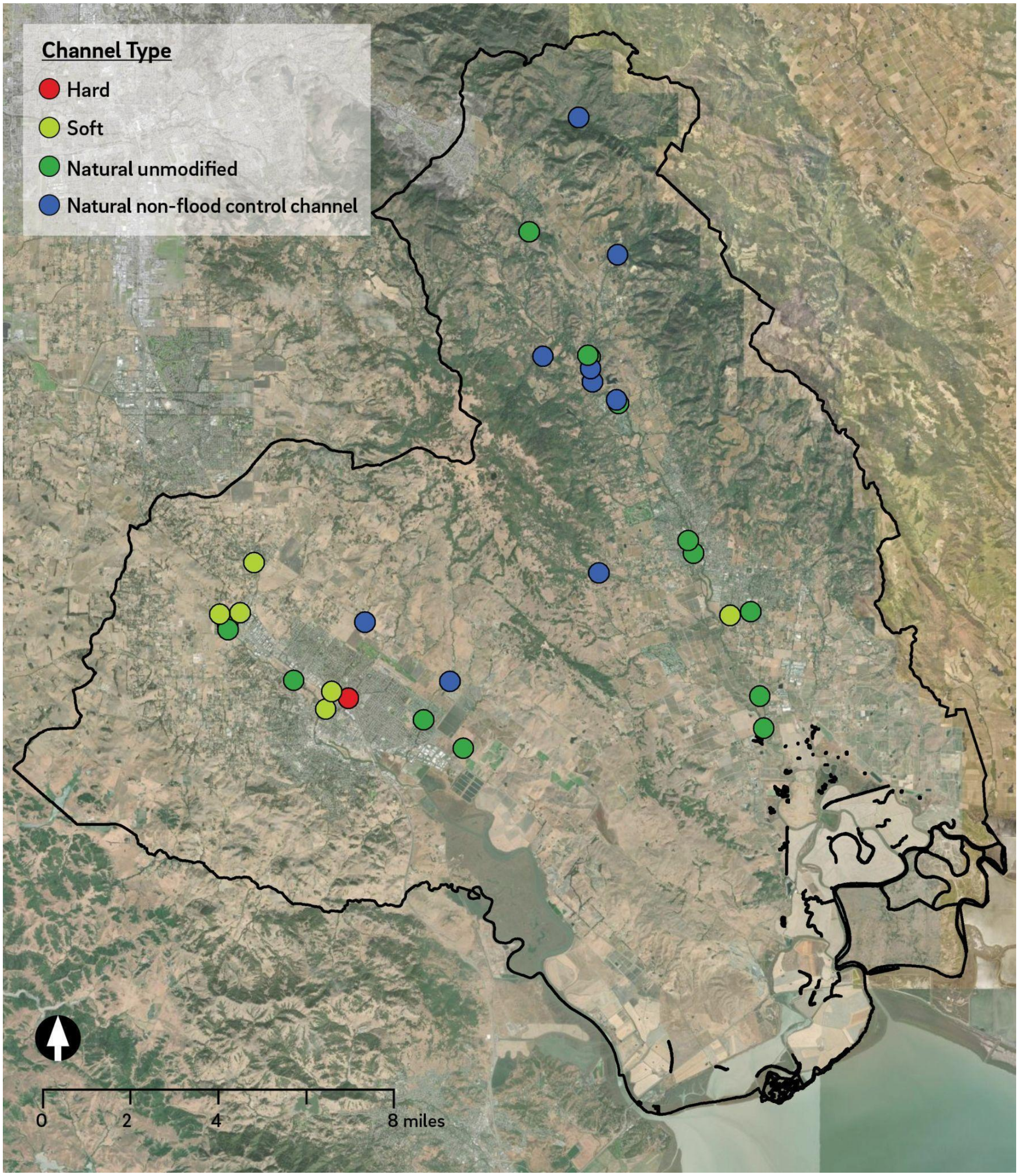


Figure 4. CSCI survey locations in Sonoma County draining to San Pablo Bay, colored by channel type.

Santa Clara Valley Water channels

Like the Sonoma Water SMP manual, the Valley Water SMP manual featured maps of classified channels within the maintenance program area. However, the classification scheme differed notably from the Sonoma Water classification. Abbreviated descriptions of channel types from the Valley Water SMP manual are:

1. Modified Channels

This type includes channels that have been substantially altered from historical conditions. Some modified channels have established and maintained flood flow conveyance criteria, while other channels clearly have been deliberately modified over time but not necessarily to an engineered design with established flood flow conveyance criteria. Modified channels typically include realigned, straightened, improved, or hardened reaches that have been designed to maximize efficient flow of water to minimize erosion. These channels generally are grass-lined, concrete-lined (bed or bank), and may include a high flow channel. This category also includes flood control channels that did not exist historically, but were constructed to convey urban flows.

2. Modified Channels with Ecological Value

Modified Channels with Ecological Value include channels significantly altered from historical conditions but also having features such as closed canopy riparian woodland, and/or being known to support special-status species. Some of these channels have established flood flow conveyance and are maintained to those criteria. These channels include realigned, straightened, improved, or hardened reaches, designed to move flood flows with minimal erosion. Modified channels with ecological values may or may not have concrete banks, but may not have concrete beds.

3. Unmodified Channel

Unmodified Channels are defined as creeks that generally have not been deliberately altered from historical conditions. Unmodified channels may have small areas of modification, including bridges, outfalls, culverts, gauges, or other structures. Unmodified channels usually are located in areas without other types of flood control and generally occur in the foothills or higher elevations of the Program area.

Like the Sonoma County scheme, this scheme also does not fully describe channel material composition and specific ecological functions within each channel type. Because the Santa Clara Valley contained the vast majority of the CSCI data, we sought other data sources for Valley Water flood control channel characteristics.

The most complete description of channel composition throughout the Santa Clara Valley came from a spreadsheet of channel compositions delineated by channel distance (station) and provided by Valley Water. Channel composition values were crosswalked to a Valley Water GIS creek routes layer with near-equivalent station codes, resulting in an approximate spatial layer of channel types throughout the Santa Clara Valley. Channel compositions in this layer were classified by two different attributes: channel bottom and waterways management (WWMM) channel type (specific channel materials and shape, see Table 2).

In order to sort channels based on how benthic macroinvertebrates may respond to their composition, we sorted the flood control channels into the three categories used for Sonoma County and one additional channel type: **Hard** (hardened bed with hardened or soft banks), **Mixed** (hardened banks, soft bed), **Soft** (soft bank and bed, recontoured and modified channel), and **Natural Unmodified** (soft bed and bank, original channel planform geometry) (see Table 2 and Figure 5). A fifth category, **Natural non-flood control channel**, was applied to all streams above 1000 ft elevation, which are outside the purview of the SMP purview and do not experience significant channel modifications or management actions by Valley Water.

Table 2. Santa Clara County SMP channel attributes with study channel classifications.

Channel Bottom	WWMM channel type	Reclassified channel type
Fixed	Pipe Culvert	**Hard**
Fixed	Arch Culvert	**Hard**
Fixed	Box Culvert	**Hard**
Fixed	U-Frame Concrete	**Hard**
Fixed	Trapezoidal Concrete	**Hard**
Fixed	Concrete (Bottom)	**Hard**
Fixed	Rock Lined (Sides and Bottom)	**Hard**
Fixed	Gabion (Sides and Bottom)	**Hard**
Unfixed	Sack Concrete	**Mixed**
Unfixed	Articulated Concrete Blocks	**Mixed**
Unfixed	Gabion	**Mixed**
Unfixed	Rock Lined (Sides)	**Mixed**
Unfixed	Flood Walls	**Mixed**
Unfixed	Earth Levees	**Soft**
Unfixed	Excavated Earth	**Soft**
Unfixed	Widened Channel	**Soft**
Unfixed	Bypass Channel	**Soft**
Unfixed	Modified Flood Plain	**Natural Unmodified**
Unfixed	Natural Unmodified	**Natural Unmodified**

Though this dataset is highly specific as to channel composition, it comes with two notable sources of error. First, these detailed channel descriptions are derived from a 1988 channel survey (SCVWD 1993). A number of changes in channel composition and geometry may have occurred throughout the Santa Clara Valley since then. Additionally, slight discrepancies in channel geometries have resulted in mismatched station codes between the source data and our channel network, resulting in varying offsets in channel types along creeks throughout the valley. These offsets typically varied from <1 to 120 meters (400 feet). We took measures to correct misattributed channel types at CSCI sites at these offsets (described in QA/QC below), but were only able to do so for the less variable reclassified channel type. As such, the WWMM channel type attribute associated with each CSCI site has much lower certainty in this study.

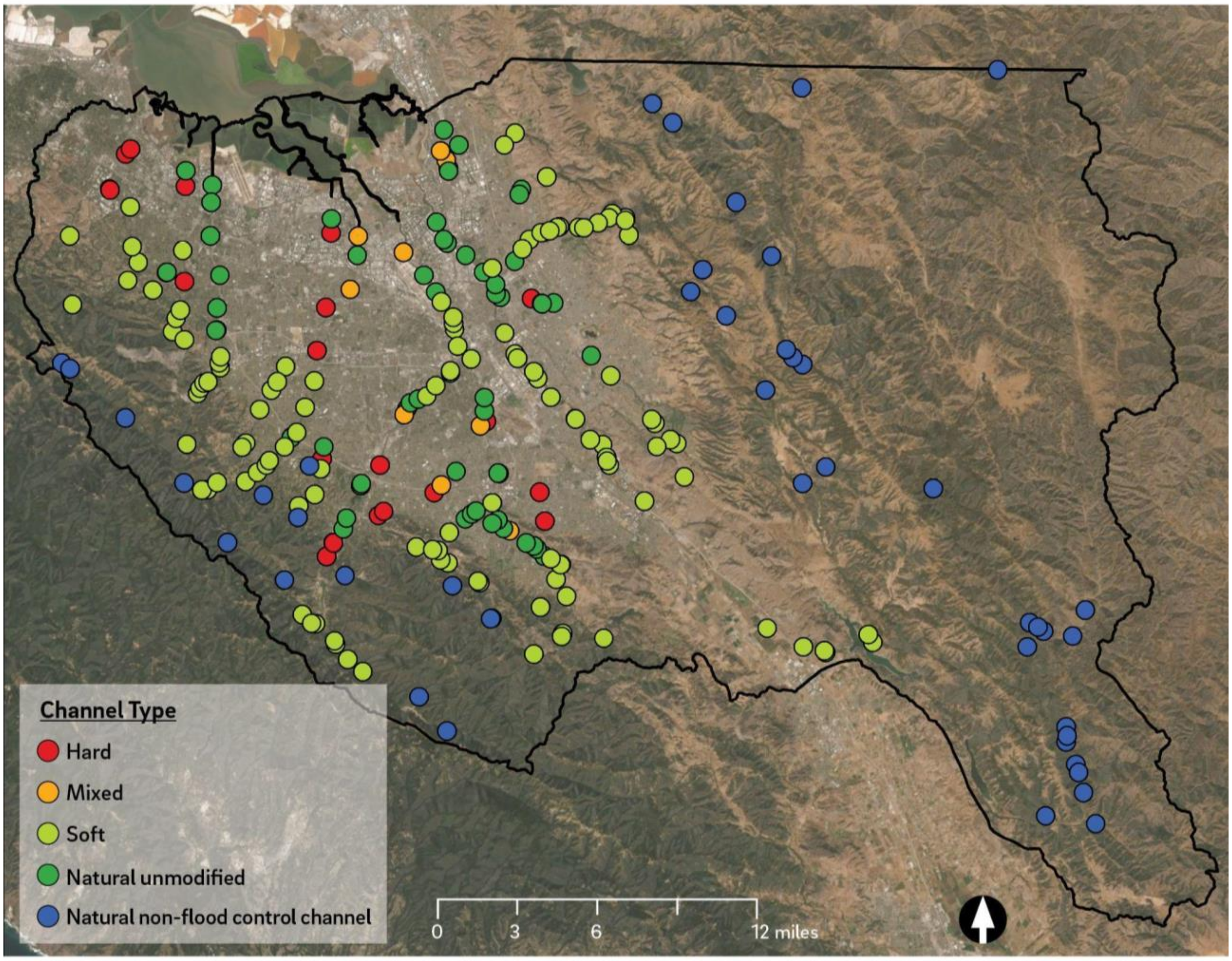


Figure 5. CSCI survey locations in Santa Clara County draining to Lower South Bay, colored by channel type.

QA/QC

The spatial offset described above between the flood control channel type information and the channel network layer led to some CSCI points with misattributed channel types. Correcting this misattribution required manual assessment of points that were recorded near channel type changes. First, we tried to assess the channel offset using specific channel changes visible in the GIS layer and in aerial imagery, such as bridges and culverts, then measuring the direction and magnitude of offset. If the direction and length of offset implied a different channel type was more appropriate, we manually changed the channel type. This quality assurance was performed on the general channel type attribute, rather than the more detailed WWMM channel type attribute, which changed frequently and did not allow for corroboration through aerial imagery.

CSCI sites are typically recorded at the downstream end of the survey reach, which is 100-150 m in length (Ode et al. 2016). However, the locations of some points indicated that an upstream survey reach would include significant portions of two very different channel types, which is typically avoided by practitioners (K. Lunde, personal communication). To assure that these CSCI sites corresponded with only one channel type, we checked with Paul Randall, a primary collector of CSCI data in Santa Clara County, to determine the correct channel classification. He ultimately confirmed or modified channel composition categories at approximately 15 sites.

Factors associated with CSCI scores in flood control channels

To better inform future channel assessments and permitting decisions, and to assess the relative effects of channel bed and bank composition on BMI communities, we investigated environmental factors from available data in Santa Clara County. Environmental and channel management data were insufficient for conducting this analysis in Sonoma County. For each flood control channel type, we examined the effects of different environmental drivers in controlling CSCI score variability. A simple correlation analysis was conducted to assess the relationship between CSCI scores and % impervious area, and a CSCI score ceiling was defined for the flood control channel types by the 90th percentile of CSCI scores within discrete 10% impervious area bins (i.e., 0-10%, 10-20%, etc.). We then examined the degree to which dry season flow type, in-channel maintenance activities, channel physical structure complexity, degree of channel stability, and riparian vegetation characteristics affect CSCI scores (particularly the highest scores) across the range of % impervious area values for each flood control channel type. The various environmental data used in the analysis are described below.

Urbanization and Impervious Area

As mentioned above, previous studies have shown that urbanization adversely affects many natural functions and features of fluvial channels, including BMI communities. As such, we included the degree of urbanization, or the amount of upstream impervious land cover, as a primary driver in our analysis of CSCI scores. The Water Board provided the percentage of impervious cover upstream (% impervious area) for the majority of CSCI sites for 2001, 2006, 2011, and 2016. Since the values showed minimal inter-annual variability (the greatest change in the amount of upstream impervious cover from 2001 to 2016 was 2%), we used the 2001 values. For the 27 bioassessment sites that were missing impervious cover values, we estimated impervious values based on nearby CSCI sites in the same channel.

Flow

BMI communities are affected by variability in stream hydrology (Lunde et al. 2013, White et al. 2017). We therefore decided to include available data on perennial versus non-perennial hydrologic classification as a potential driver for CSCI scores. Data on CSCI site hydrology was obtained from two sources: Water Board surveys and California Rapid Assessment Method (CRAM) surveys (CWMW 2013). The Water Board supplied hydrology data for 75 CSCI sites within the Santa Clara County dataset, with binary designations between “perennial” and “non-perennial.” All 82 CRAM surveys paired with CSCI points had hydrology designations of “perennial,” “intermittent,” or “ephemeral.” To facilitate use of both datasets, the latter two CRAM classifications were redesignated as non-perennial.

Channel maintenance activities

Channel maintenance activities were obtained from the 2014 Valley Water Stream Maintenance Program (SMP) manual. The SMP manual contains maps showing the locations of maintenance activities from 2002-2012, and expected maintenance activities from 2014-2023. The manual details three types of widespread maintenance activities: sediment removal, vegetation removal by hand, and herbicide application. Maps depicting the geographic extent of each activity were georeferenced and then attributed spatially to CSCI sites, so each site had a designation of no management actions or any combination of the three actions. Frequency and magnitude of channel maintenance were not given in the SMP manual, and as such, channel maintenance actions for a given CSCI site are binary (i.e., the action either did or did not happen at some time in the past).

Management data from 2014-2018 were provided by Valley Water. Channel maintenance activities were sorted into the same categories as the 2002-2012 dataset (sediment removal, vegetation hand removal, herbicide) (see Table 3). As with the SMP dataset, the management actions at the CSCI sites were categorized as either having occurred or not having occurred at all between 2014 and 2018.

Table 3. Reclassification of Valley Water management actions from 2014-2018 to match SMP manual management categories.

2014-2018 management action	**2002-2012 SMP management action**
Aquatic herbicide	Herbicide application
Post-emergent herbicide	Herbicide application
Limb removal >4”	Vegetation hand removal
Tree removal 6-12”	Vegetation hand removal
Vegetation removal <6”	Vegetation hand removal
Invasive Plant removal	Vegetation hand removal
Sediment Removal	Sediment Removal

Channel Stability and Riparian Characteristics

In order to assess other aspects of channel condition apart from bed and bank composition, we examined the relationship between CSCI scores and in-channel conditions such as channel stability and riparian characteristics. Channel stability and riparian characteristics information came from existing CRAM riverine surveys, largely collected by Valley Water to support their Safe, Clean Water and Natural Flood Protection Program. CRAM assesses the overall ecological condition of a discrete Assessment Area within the larger channel-riparian system using the following four Attributes: Buffer and Landscape Context, Hydrology, Physical Structure, and Biotic Structure. Each of these Attributes are in turn composed of 2-3 metrics which are individually assessed and aggregated to calculate the Attribute scores. For this study, we utilized the channel stability metric (which assigns a channel without net incision or aggradation as stable) contained within the Hydrology Attribute; the entire Physical Structure Attribute, which captures overall channel bed and bank conditions; and the entire Biotic Structure Attribute, which captures overall channel and adjacent riparian vegetative complexity and conditions.

CRAM assessment data for Santa Clara County were downloaded from EcoAtlas (ecoatlas.org). This yielded 539 points for Santa Clara County channels that drain to the Bay, spanning the years 2010-2019. To ensure CRAM scores were aligned with conditions present during CSCI assessments, we applied spatial and temporal restrictions to correlate CRAM scores with CSCI scores. After consultation with the Technical Advisory Committee, we decided to join CSCI and CRAM assessments that were within 1 year and 500 feet of each other (500 feet being about equal to the CSCI assessment length of 150 m). This yielded 82 CSCI sites where local CRAM data also existed, allowing for comparisons between CRAM metrics and CSCI scores.

Additional observations

Beyond the quantified environmental drivers described above, we performed a cursory, qualitative assessment at select CSCI survey reaches to examine local conditions that could be either beneficial or detrimental to CSCI scores for different channel types. We compared high-performing and low-performing survey reaches of the same channel type with similar % impervious area values through visual examination of recent aerial photographs. We examined relative presence of riparian vegetation, relative position in relation to the urban footprint, relative density of surrounding development, notable local characteristics (e.g., potentially beneficial tree canopy cover or adjacent parks, or potentially detrimental industrial sites or high-use developments), and notable watershed conditions upstream (e.g., presence of a dam). These qualitative assessments may inform future studies of environmental drivers that were unable to be systematically captured in this study with the time and data available.

Findings

Sonoma County

Distribution of CSCI scores by channel type

Within the Petaluma River and Sonoma Creek watersheds, CSCI scores for Natural-non flood control channels were generally higher than those for flood control channels (Figure 6 and Table 4). Natural non-flood control channel scores ranged from 0.58 (very likely altered) to 1.22 (likely intact), whereas flood control channel scores were lower overall, ranging from 0.11 (very likely altered) to 1.09 (likely intact). Within the flood control channels, the single Hard channel CSCI score was very low at 0.25 (very likely altered), the Soft channel CSCI scores ranged from 0.11 to 0.51 (very likely altered), and the Natural Unmodified scores ranged from 0.30 (very likely altered) to 1.09 (likely intact). A one-way ANOVA analysis indicated a statistical difference ($p<0.05$) between the mean CSCI scores for the Soft and Natural Unmodified channels and the Soft and Natural non-flood control channels. However, the mean difference of 0.199 between Natural Unmodified and Natural-non flood control channels was not significant. The one Hard channel could not be included in the ANOVA analysis due to small sample size.

For the most part, the Natural-non flood control channel CSCI scores in both watersheds are in forested areas upstream of the Sonoma Water SMP service area, so over half of the scores are in the “likely intact” range (Figure 7). As would be expected, the Soft and Natural Unmodified channel CSCI scores are generally lower in the more developed Petaluma River watershed. However, neither watershed’s CSCI scores show a strong decreasing trend moving downstream with increasing cumulative development and agricultural impacts.

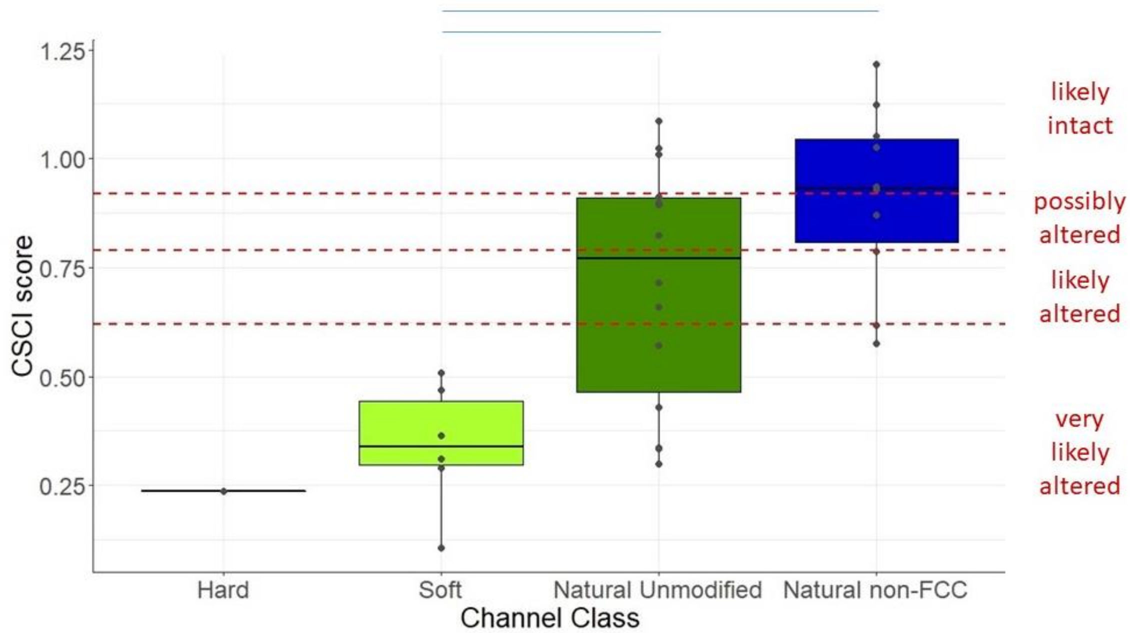


Figure 6. Sonoma County CSCI score distributions by classified channel type: Hard (n=1), Soft (n=6), Natural Unmodified (n=14), and Natural non-flood control channels (n=10). The horizontal lines above the plot indicate a statistically significant difference in the means between channel classes ($p<0.05$).

Table 4. Percentiles of CSCI scores for each channel type in Sonoma County.

Channel type		90th percentile	75th percentile	50th percentile (Median)	25th percentile	10th percentile
Flood control channels	Hard	0.24	0.24	0.24	0.24	0.24
	Soft	0.49	0.44	0.35	0.30	0.20
	Natural Unmodified	1.02	0.91	0.77	0.46	0.34
Natural non-flood control channels		1.13	1.05	0.93	0.81	0.61

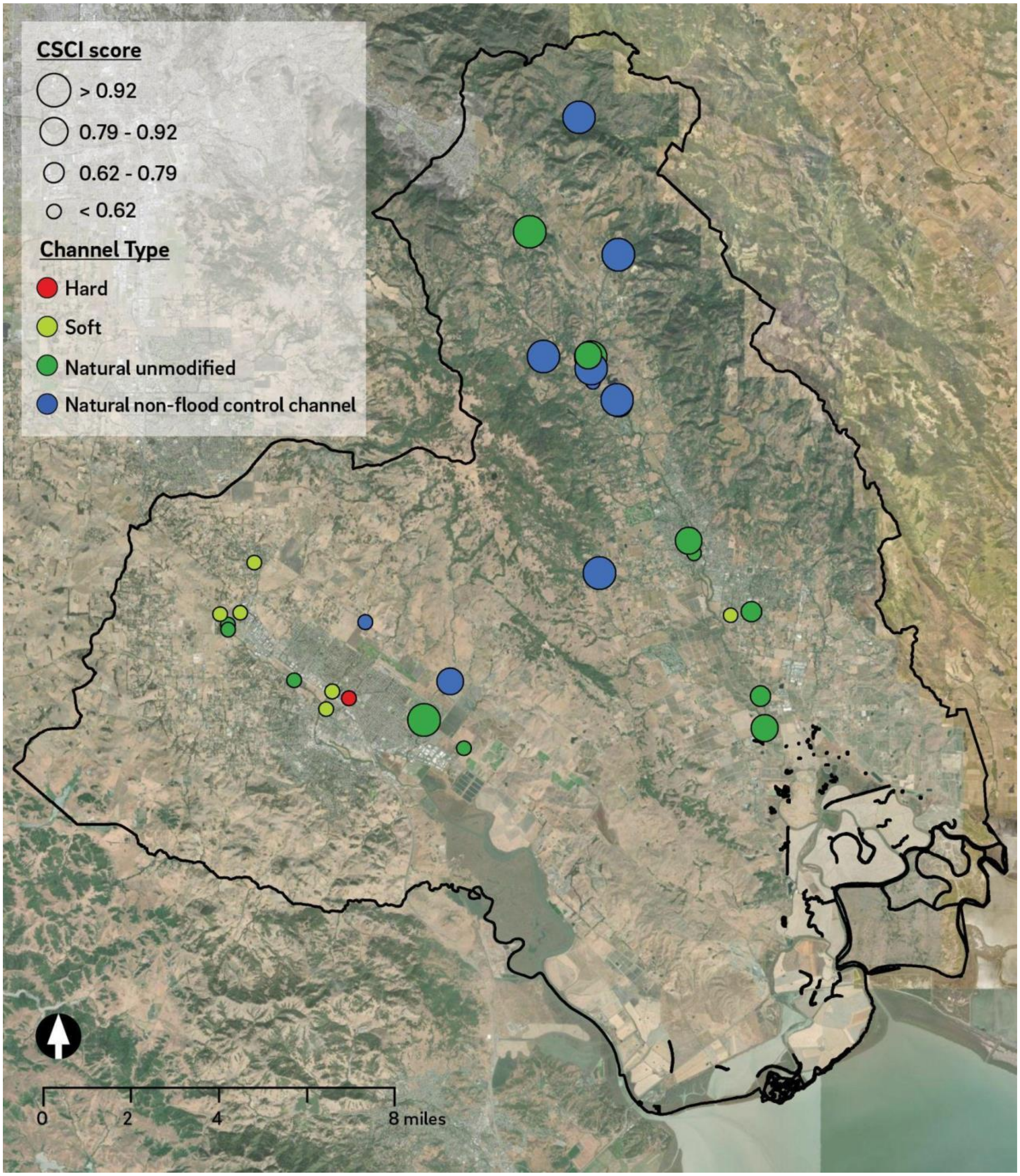


Figure 7. Locations and channel types of Sonoma County CSCI survey sites, sized by categorized scores (see Figure 3).

Santa Clara County

Distribution of CSCI scores by channel type

Within the Santa Clara County watersheds examined, CSCI scores for Natural-non flood control channels were similar to those in Sonoma County, ranging from 0.38 (very likely altered) to 1.28 (likely intact) (Figure 8 and Table 5). Within the flood control channels, CSCI scores for Hard channels and Mixed channels were similar, with Hard channel scores ranging from 0.17 (very likely altered) to 0.77 (likely altered) and Mixed channel scores ranging from 0.27 (very likely altered) to 0.70 (likely altered). The Soft channel CSCI scores were somewhat higher, ranging from 0.24 (very likely altered) to 0.88 (possibly altered). The range of CSCI scores for Natural Unmodified flood control channels was similar to the range for Natural-non flood control channels (0.29-1.26), but the median score was considerably lower (0.67 compared to 0.93). A one-way ANOVA analysis indicated a statistical difference ($p<0.05$) between all channel pairs except Hard and Mixed channels, Mixed and Soft channels, and Hard and Soft channels.

All of the Natural-non flood control channel CSCI scores are from upstream of the Valley Water SMP service area in relatively undisturbed forested land, leading to high scores overall (Figure 9). Within the SMP service area, there is a clear decrease in CSCI score in many watersheds moving downstream from Natural non-flood control channels at higher elevations to Natural Unmodified and Soft channels to Mixed and Hard channels. For example, Upper Penitencia Creek shows a decrease in CSCI score from 1.26 (likely intact) in forested land at the upstream extent of the SMP activities to 0.59 (very likely altered) in the urbanized valley floor near the confluence with Coyote Creek. Calabazas Creek is an example of a flood control channel with consistently low CSCI scores throughout and is located almost completely within the urbanized valley floor.

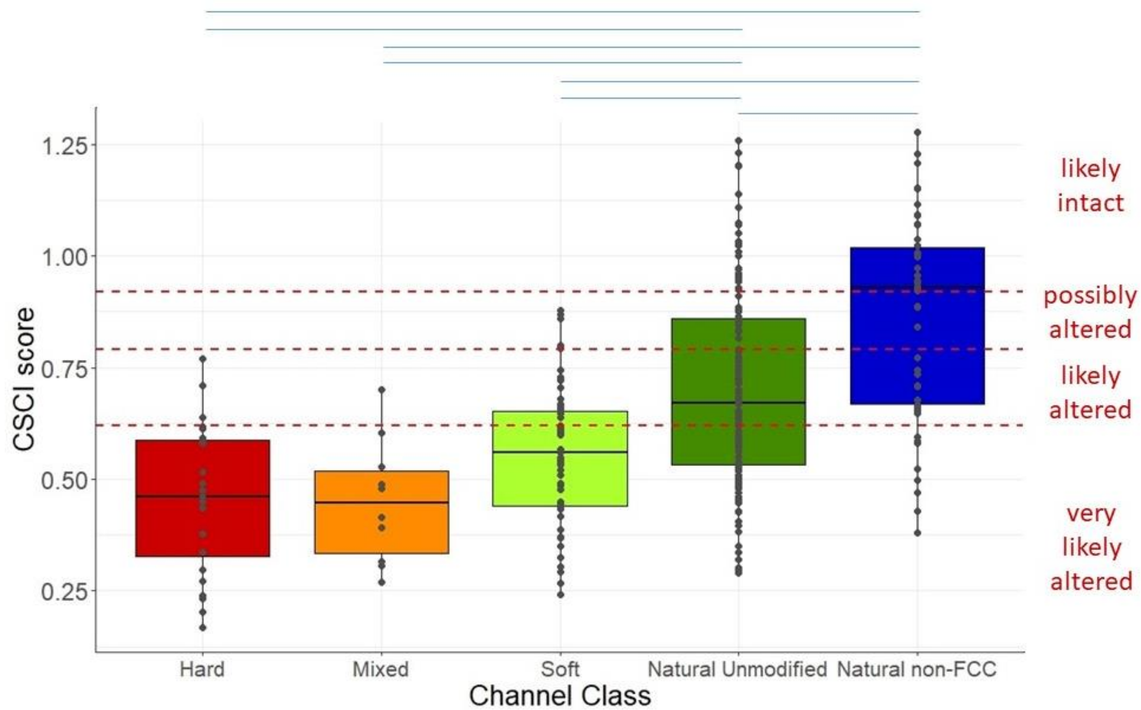


Figure 8. Santa Clara County CSCI score distributions by classified channel type: Hard (n=24), Mixed (n=10), Soft (n=55), Natural Unmodified (n=122), and Natural non-flood control channels (n=46). The horizontal lines above the plot indicate a statistically significant difference in the means between channel classes (p<0.05).

Table 5. Percentiles of CSCI scores for each channel type in Santa Clara County.

Channel type		**90th percentile**	**75th percentile**	**50th percentile (Median)**	**25th percentile**	**10th percentile**
Flood control channels	Hard	0.63	0.59	0.46	0.33	0.23
	Mixed	0.61	0.52	0.45	0.33	0.30
	Soft	0.74	0.65	0.56	0.44	0.36
	Natural Unmodified	1.02	0.86	0.67	0.53	0.45
Natural non-flood control channels		1.13	1.02	0.93	0.67	0.52

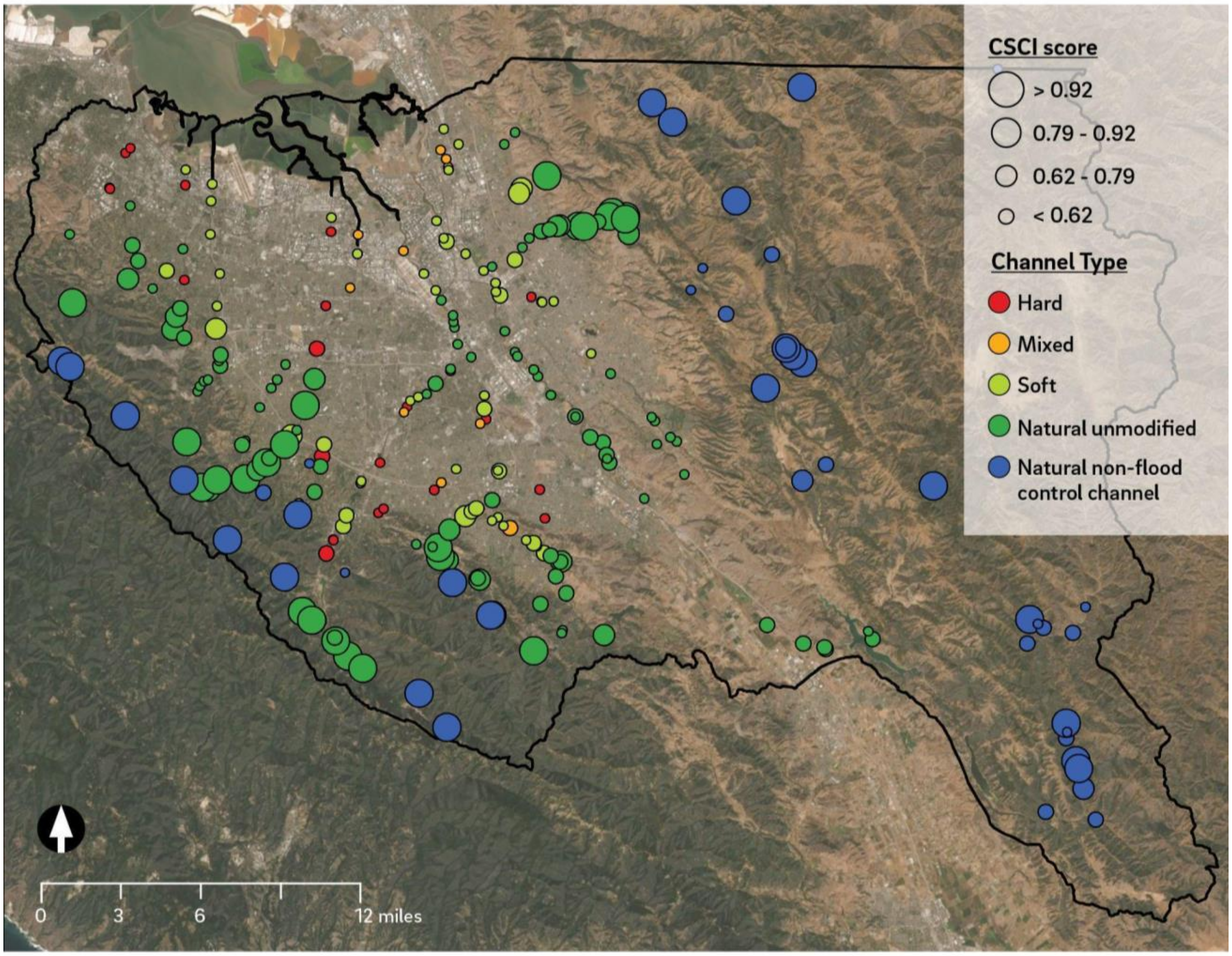


Figure 9. Locations and channel types of Santa Clara County CSCI survey sites, sized by categorized scores (see Figure 3).

Factors controlling CSCI scores within flood control channel types

To examine the factors controlling CSCI scores in Santa Clara County flood control channels, we kept Hard and Mixed channels separate but combined Soft and Natural Unmodified channels to simplify the analysis and cover the full range of bed and bank materials with just three channel types. In addition, the Mixed channel data were very limited and there were sufficient data to examine only a subset of the controlling factors.

% Impervious Area

The Santa Clara County data show a decreasing trend in CSCI score with increasing % impervious area, with differences among the flood control channel types in the maximum CSCI score for a given % impervious area (Figure 10). Overall, CSCI scores for all channels combined range from 0.41 (very likely altered) to 1.28 (likely intact) for <1% impervious area to 0.27 to 0.48 (very likely altered) for >50% impervious area. For <1% impervious area, Natural non-flood control channels and Soft/Natural Unmodified channels have similar ceiling CSCI values (i.e., the 90th percentile of CSCI scores for a given % impervious area) close to 1.3 whereas the ceiling for Hard and Mixed channels is close to 0.8. Between 1% and 20% impervious area, the CSCI ceiling for all three flood control channel types decreases with increasing % impervious area, with the Soft/Natural Unmodified channel ceiling showing the greatest decrease and Hard and Mixed channels having similar ceiling values. Beyond 20% impervious area, the Hard and Mixed channel ceilings remain at a CSCI score of ~0.45. At 40% impervious area, the ceiling for Soft/Natural Unmodified channels approaches the ceiling for Hard and Mixed channels.

These results are similar to those from previous studies in Santa Clara County relating BMI indices with degree of urbanization. Carter and Fend (2005) showed a decrease in Ephemeroptera, Plecoptera, and Trichoptera (EPT) species richness and percentage EPT with increasing percent urbanization, defining an upper-boundary condition (factor-ceiling) for the EPT score. Similarly, Carter et al. (2009) showed a decrease in scores for a biological index based on EPT richness, Shredder richness, and % clinger with increasing values for an urban index based on human population density, road density, and % urban land cover, also defining a factor-ceiling (or predicted biological potential boundary) for the biological index. A large portion of the CSCI data used in the present study were derived from the BMI dataset used in both of these previous studies. This effort, therefore, can be seen as the next in the series BMI index-% urbanization studies in Santa Clara County, relating a widely available and widely used predictive BMI index to a single measure of urbanization to define a factor-ceiling for different flood control channel types.

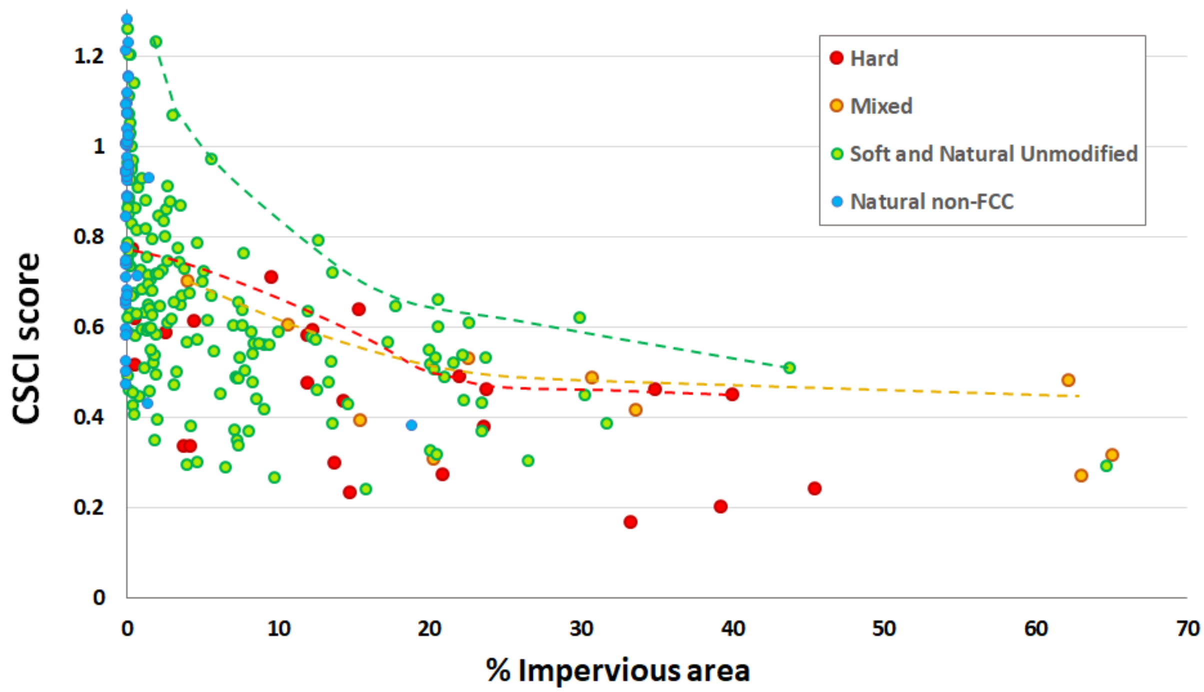
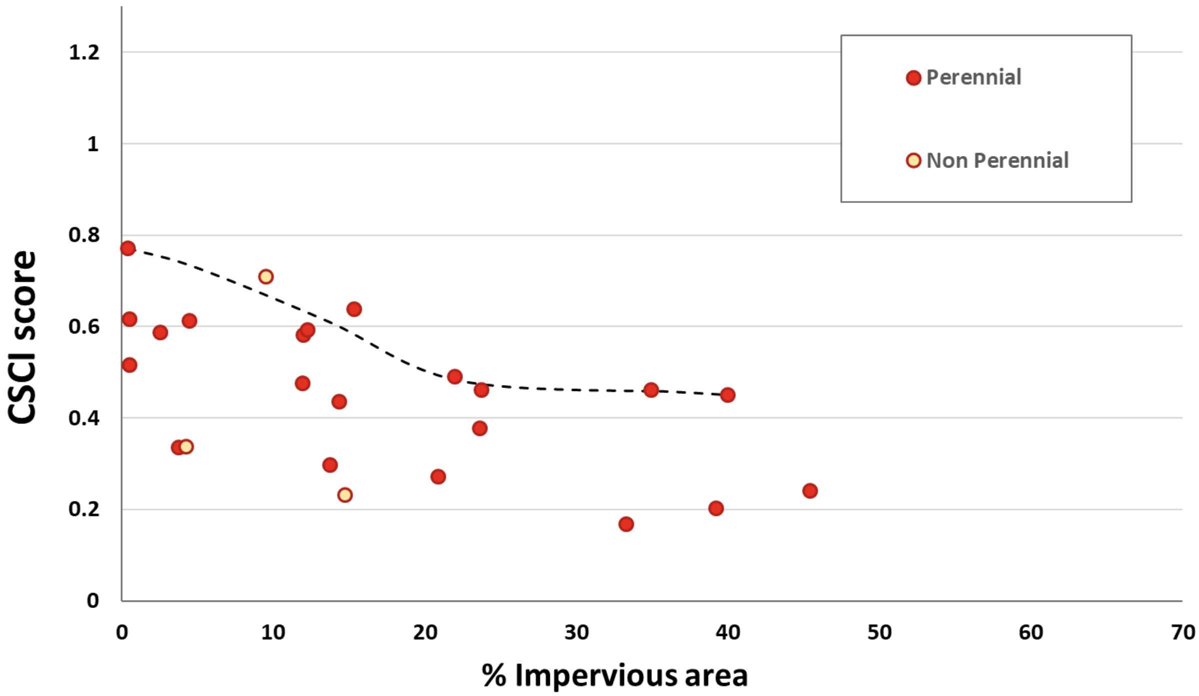


Figure 10. Flood control channels and Natural non-flood control channel (non-FCC) CSCI scores in Santa Clara County plotted against percent impervious cover within each point's contributing watershed. CSCI score ceilings (dashed lines with colors matching channel type) are defined by the 90th percentile of scores within discrete 10% impervious area bins (i.e., 0-10%, 10-20%, etc.).

Flow type

The compiled flow type dataset shows no correlation between dry-season flow type and CSCI scores for flood control channels (Figure 11). For the Hard channels, the sites with perennial flow had CSCI scores ranging from 0.23 to 0.71 and sites with non-perennial flow had CSCI scores ranging from 0.17 to 0.77, with all sites with >20% impervious area in the urbanized valley floor having perennial flow. For <20% impervious area, sites with perennial and non-perennial flow had CSCI scores at the CSCI ceiling. The Soft/Natural Unmodified channel locations with perennial flow had CSCI scores ranging from 0.24 to 1.26, while locations with non-perennial flow had CSCI scores ranging from 0.28 to 1.07. As with the Hard channels with low % impervious area, the Soft/Natural CSCI score ceiling is defined by sites with perennial and non-perennial flow.



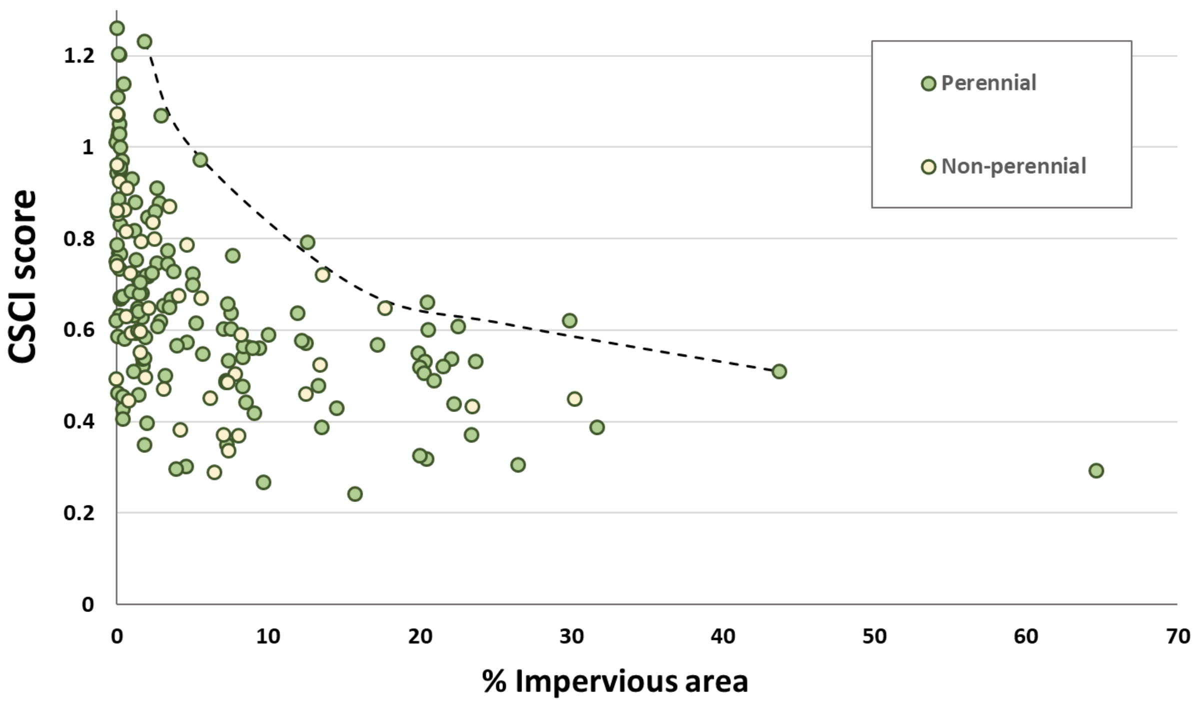


Figure 11. CSCI scores plotted against percent impervious upstream area for Hard channels (top) and Soft/Natural Unmodified channels (bottom) in Santa Clara County, colored by flow type. Dashed lines indicate the CSCI score ceilings.

Channel maintenance activity

For all flood control channel types, channel maintenance activities are not shown to be a primary driver for ceiling or minimum CSCI scores (Figures 12-14). Sites within Hard and Mixed channels that are subject to sediment removal, vegetation removal, and herbicide application have both high and low CSCI scores across the % impervious area values observed. This is also the case for Soft/Natural Unmodified channels, except at a low % impervious area (<5%) where the range of CSCI scores without channel maintenance is much less than for sites with channel maintenance. It is important to note that, unlike other drivers analyzed, the timing of CSCI scores and channel maintenance activities are not necessarily closely matched. Some of the CSCI scores could have been measured during a long interval between maintenance activities when there was no influence of channel/riparian disturbance on BMI characteristics. Therefore, these results should be considered a cursory examination of the relationship between CSCI score and channel maintenance activities.

Channel conditions from CRAM data

For Hard and Soft/Natural Unmodified channels, the relatively limited dataset shows that CRAM metrics of channel physical structure and channel stability were not a primary driver for ceiling or minimum CSCI score over the % impervious area values observed (Figures 15 and 16). For Hard channels, the sites with <25% impervious area and CSCI scores at or close to the ceiling have "low" physical structure and "medium" channel stability scores (i.e., moderate aggradation[1]). Sites with >25% impervious area with CSCI scores at the ceiling and the minimum CSCI score range all have "low" structure and "low" channel stability. For Soft/Natural Unmodified channels, the sites with <25% impervious area have "high" and "moderate" physical structure and channel stability scores associated with a wide range of CSCI scores, including scores at the CSCI score ceiling. For >25% impervious area, both sites with CRAM data have "low" physical structure. The one site at the CSCI score ceiling has a "high" channel stability score and the one site near the minimum CSCI score has a "moderate" channel stability score. While this finding suggests that highly stable Soft/Natural Unmodified channels may be defining the CSCI ceiling for channels with high % impervious area, it is by no means conclusive and more research is needed.

[1] According to the CRAM protocol, artificially hardened channels should automatically receive a "D" (3) stability score, indicating the inability for the bed to incise. However, it is possible that the CRAM practitioner assigned a "moderate" stability score, "B" (9), because there was some aggradation observed.

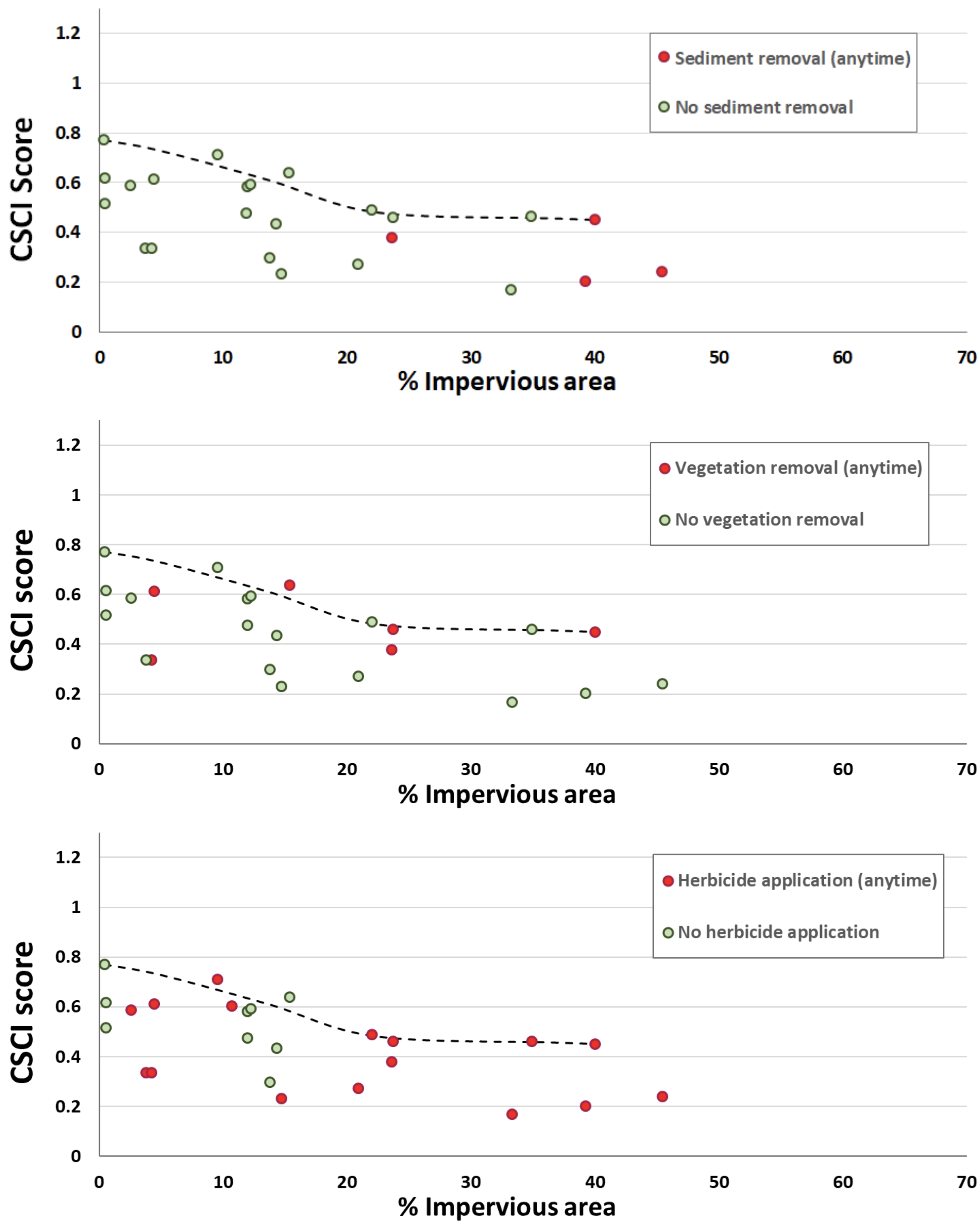


Figure 12. Channel maintenance activity (sediment removal, vegetation removal, herbicide application) in Hard channels within Santa Clara County. Dashed lines indicate the CSCI score ceilings**.**

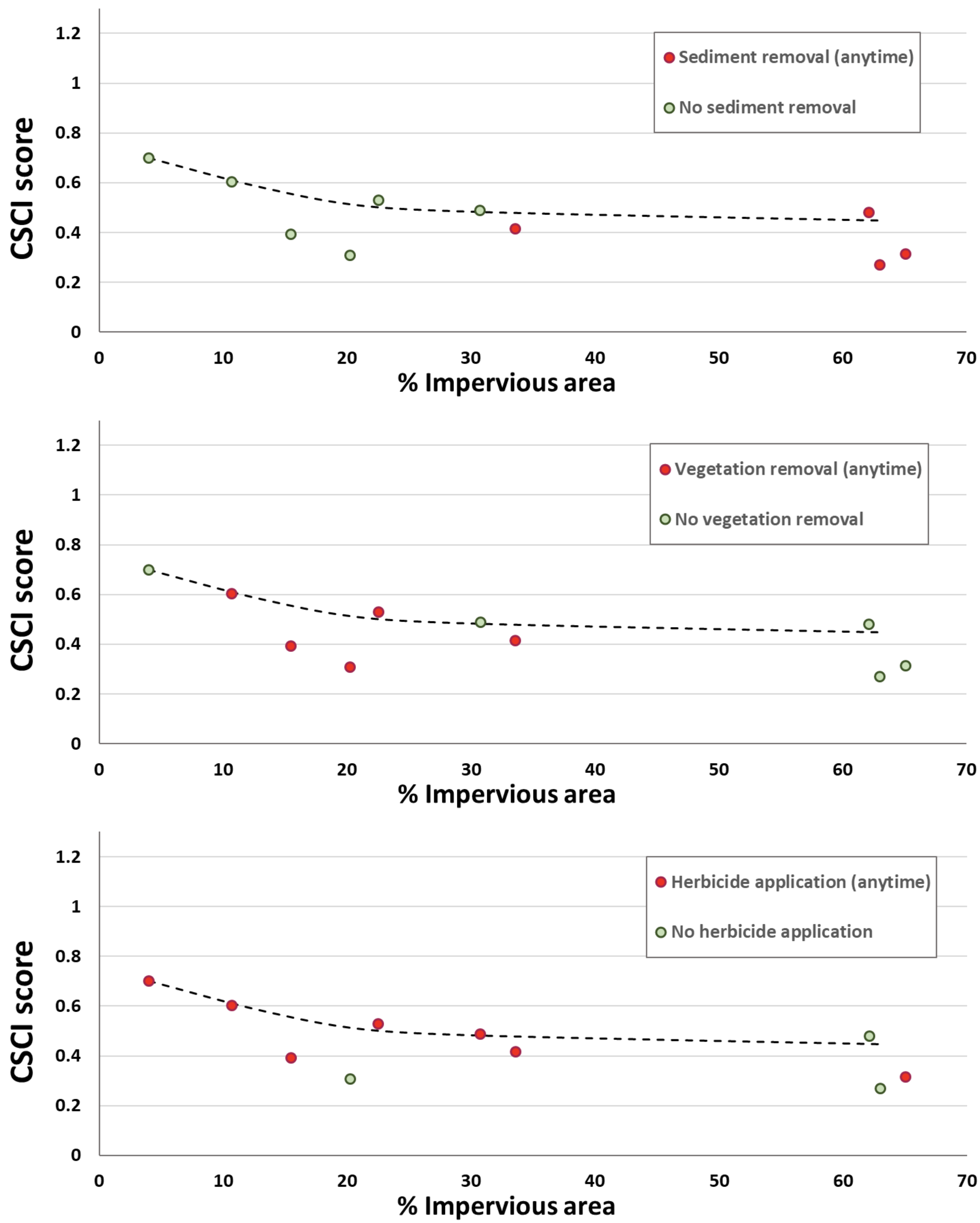


Figure 13. Channel maintenance activity (sediment removal, vegetation removal, herbicide application) in Mixed channels within Santa Clara County. Dashed lines indicate the CSCI score ceilings**.**

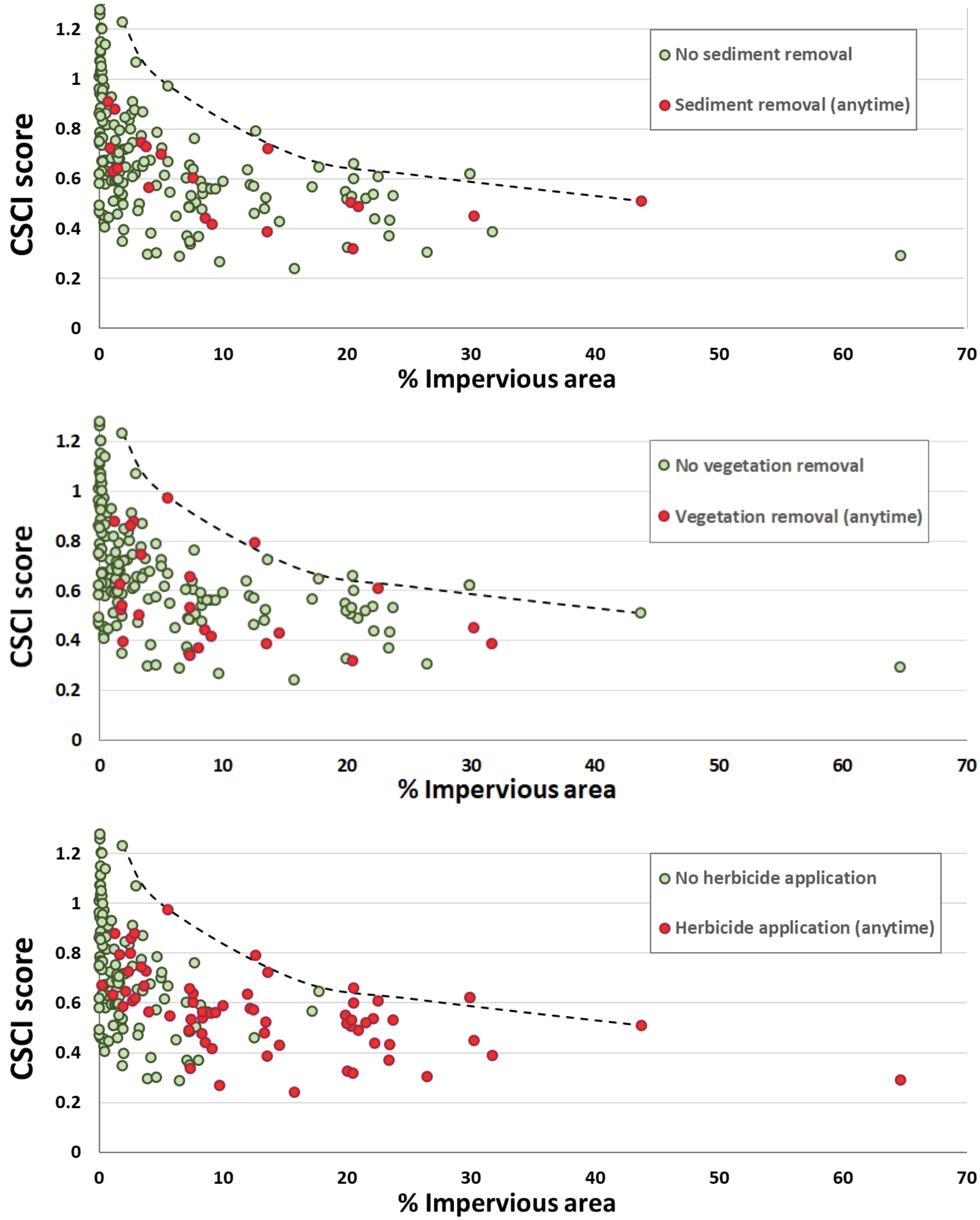
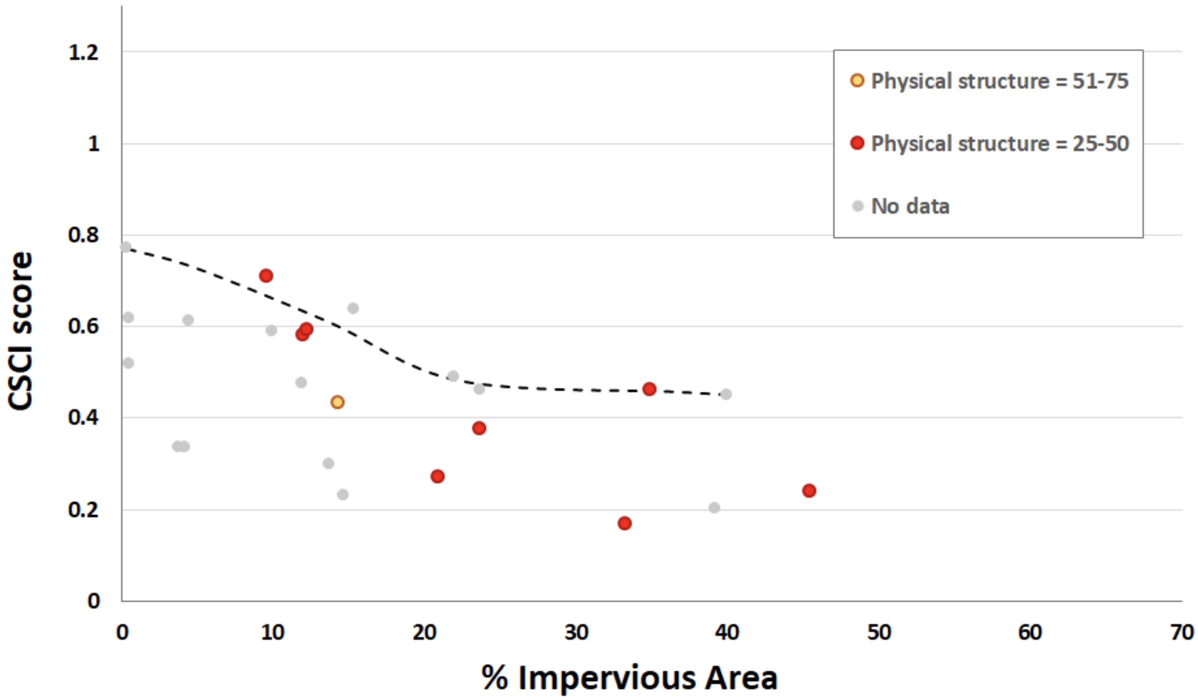


Figure 14. Channel maintenance activity (sediment removal, vegetation removal, herbicide application) in Soft & Natural Unmodified channels within Santa Clara County. Dashed lines indicate the CSCI score ceilings.



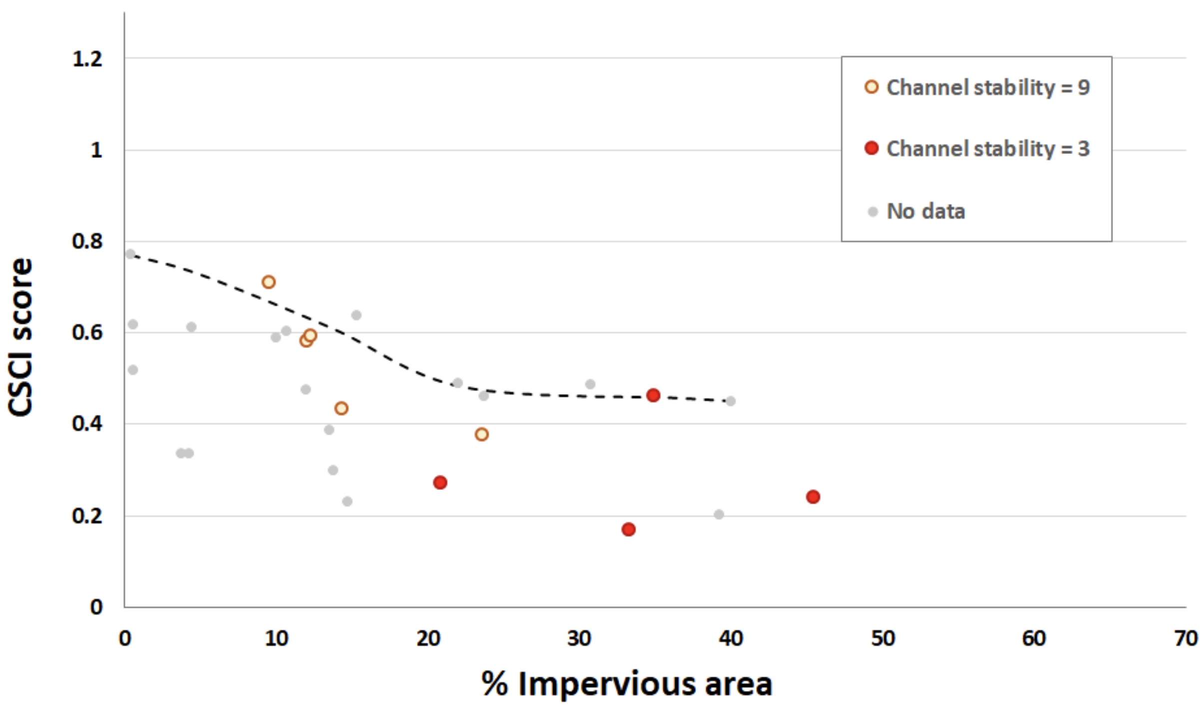


Figure 15. CSCI scores, percent impervious area, and channel physical conditions (CRAM Physical Structure attribute and channel stability metric) for Hard channels within Santa Clara County. Dashed lines indicate the CSCI score ceilings**.**

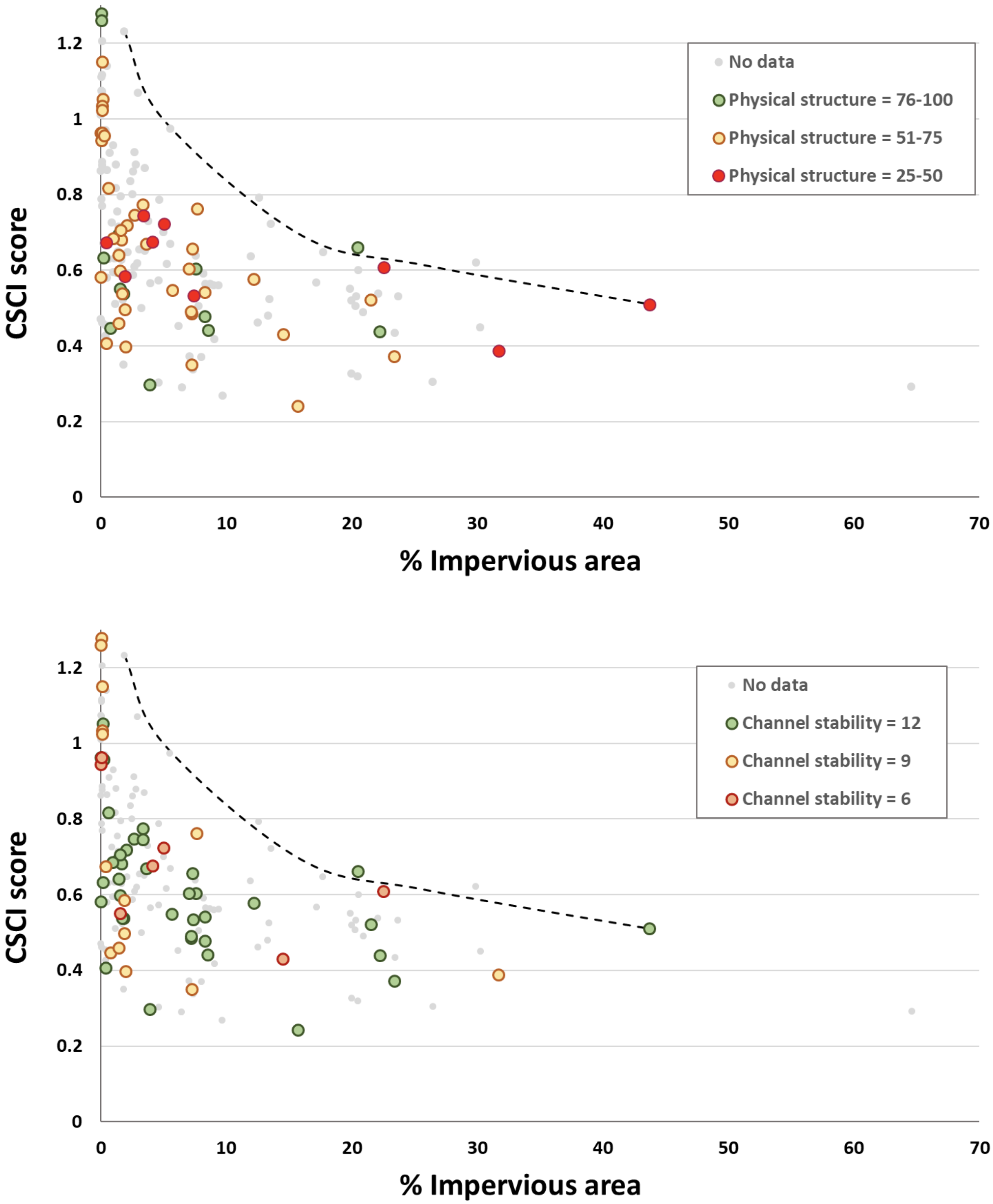


Figure 16. CSCI scores, percent impervious area, and channel physical conditions (CRAM Physical Structure attribute and channel stability metric) for Soft & Natural Unmodified channels within Santa Clara County. Dashed lines indicate the CSCI score ceilings**.**

CRAM Riparian characteristics

As with channel conditions, the relatively limited CRAM riparian Biotic Structure Attribute dataset shows that biotic structure was not a primary driver for ceiling or minimum CSCI score for Hard and Soft/Natural Unmodified channels over the % impervious area values observed (Figure 17). For Hard channels, the sites with <20% impervious area with CSCI scores at or close to the ceiling have both “low” and “high” biotic structure scores. Hard channel sites with >20% impervious area all have “low” biotic structure scores, including sites at the CSCI ceiling and sites with among the lowest CSCI scores. For Soft/Natural Unmodified channels, the sites with <25% impervious area have “high” and “moderate” biotic structure scores associated with a wide range of CSCI scores, including CSCI ceiling and minimum values. For >25% impervious area the one site at the CSCI score ceiling has a “medium” biotic structure score and one site near the minimum CSCI score has a “low” biotic structure score. This finding suggests that for Soft/Natural Unmodified channels, sites with “moderate” biotic structure may be defining the CSCI ceiling for sites with high % impervious area. However, like with channel stability at high % impervious area values, it is not possible to draw definitive conclusions from one data point and more research is needed.

Additional observations for the highest CSCI scores

Qualitative observations of high- and low-performing sites with similar channel types and impervious values did not yield any standout local drivers for CSCI scores and BMI health. Some local conditions point to possible inputs that may affect CSCI score and overall stream health, and may merit further local investigation. Channels with higher CSCI scores across many impervious values were often adjacent to or downstream of parks and other open spaces. For example, CSCI station 205R00547, a hardened channel, scored 0.46, which is “very likely altered,” but well-performing compared to hard channels with similar impervious upstream cover (35% impervious). It is located directly adjacent to Pomeroy Elementary School’s ~3 acre grassy play field, and is just downstream of 7.5 acre Earl R. Carmichael Park. Almost all high-performing channels also had relatively dense riparian cover from surveys of aerial imagery. In contrast, poorly-performing channels, especially those in the Soft/Natural Unmodified category, often had some clear local input that would be presumed to lower channel CSCI scores, such as a dam or quarry, or clearly industrial surroundings lacking any tree cover. For example, CSCI stations 205SAR110 and 205R02211 are both Soft/Natural Unmodified channels with similar low impervious values upstream, at 0.11% and 0.42%, respectively. The former has a high CSCI score of 1.07, and has full riparian cover, and is surrounded by open space with low-density development. The latter, with a CSCI score of 0.42, is directly downstream of Stevens Creek Reservoir, with its accompanying dam and quarry. These features likely lead to significant ill effects on water quality, flow, and sediment properties that benthic macroinvertebrates rely upon. See Appendix A for a qualitative assessment of these sites.

It is important to note that these qualitative trends were not consistent enough to draw definitive conclusions about dominant drivers for CSCI scores in this analysis. Further site-specific investigation of low-and high-performing survey reaches may elucidate the role of tree cover, open space, industrial inputs and other local inputs on macroinvertebrate health and diversity.

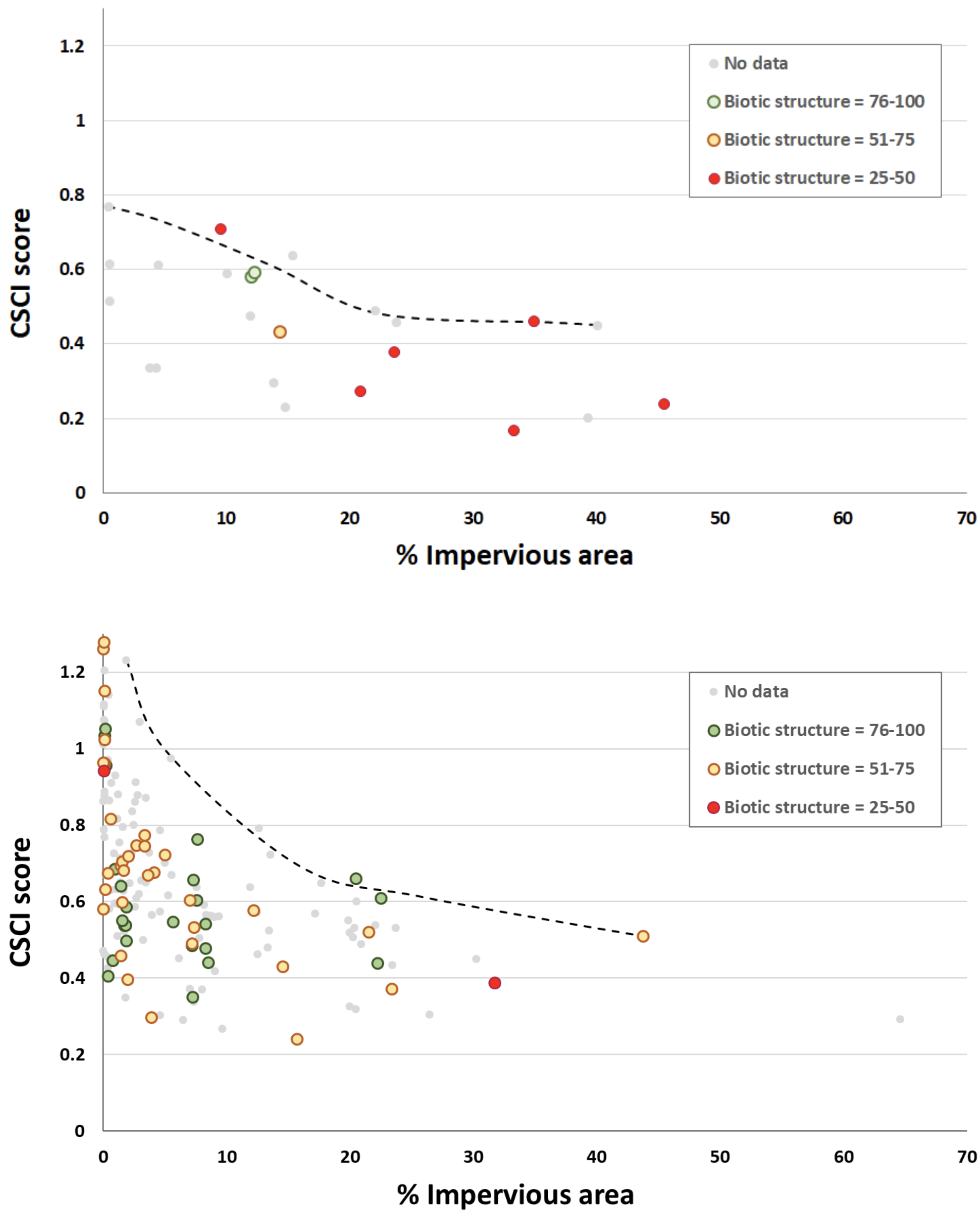


Figure 17. CSCI scores, percent impervious area, and channel riparian conditions (CRAM Biotic Structure Attribute) for Hard (top) and Soft/Natural Unmodified (bottom) channels within Santa Clara County. Dashed lines indicate the CSCI score ceilings**.**

.

Recommendations

The results from this pilot effort provide Water Board staff with information in Sonoma and Santa Clara counties that can be used to help determine expected biological baseline conditions for flood control channels based on information from similarly developed and modified streams, and to develop an expectation of how biological conditions could be improved by changing channel composition. This effort clearly shows for Sonoma and Santa Clara counties that CSCI scores are generally highest for Natural non-flood control channels and lowest for Hard channels (hardened bed and banks). For Santa Clara County, a detailed analysis showed that CSCI scores for all flood control channels generally decrease with increasing % impervious area. The best stream ecological condition indicated by CSCI score (i.e., the CSCI score ceiling) was lower for Hard and Mixed channels compared to Soft/Natural Unmodified channels across a range of % impervious area values, which is similar to findings in Southern California (SCSMC 2017) and the Pacific Northwest (Booth et al. 2004). It was not possible to show with certainty which local factors drive high CSCI scores for a given channel type and % impervious area value. However, a cursory examination of the relationship between CSCI score and surrounding land use directly upstream suggests a positive correlation between CSCI score and adjacency to riparian vegetation and parks or other open spaces. These cursory findings suggest local land uses that promote cool water temperatures and provide beneficial allochthonous material for benthic macroinvertebrates could offset the cumulative impacts of upstream impervious area. These findings can also help managers develop an initial idea of the likely range of CSCI scores for a given % impervious area value based on adjacent land use and land use immediately upstream.

This pilot effort provides a solid foundation for flood control classification efforts aimed at identifying drivers for ecological health in different types of flood control channels in the remaining seven counties that surround San Francisco Bay. For the next phase, the understanding of the connection between stream ecological health and controlling factors for various flood control channel types could be improved by including the following:

- **Additional indices of stream ecological health** - For the pilot effort, CSCI was chosen as the index of stream ecological health because of its abundant availability in watersheds throughout the Bay Area relative to other biotic indices. However, there are other indices that could be selected for use in the next phase in addition to CSCI that would require additional data collection and analysis. For example, there is now a statewide algae indicator based on the diatom community that may be used to evaluate biological condition. Also, additional measures of biological integrity that are more relevant to human uses (e.g., support for bird and fish communities) should be explored. It could also be possible to use CRAM metrics as stream ecological health indicators. Scoping for the next phase should include an investigation of the costs and benefits of including additional health indices. It should also include an investigation on the suitability of CSCI for a region-wide flood control channel classification effort.

- **Additional drivers of stream ecological health** - The pilot effort focused on readily available watershed-scale drivers and local drivers of stream ecological health. The next phase could include additional drivers that are known to affect BMI indices of stream ecological health. At the watershed scale, % impervious area directly adjacent to the channel has been shown to impact BMI index score (Fend et al. 2005) and could be a relatively simple and easily calculated variable to include in the analysis. At the local scale, this effort showed that adjacency to riparian vegetation and distance from an upstream open space natural areas has a strong impact on CSCI score This local driver should be explored further. In addition, direct field measurements of riparian shading could be very useful for understanding differences in health index scores for the same channel type with similar % impervious area.

- **Close timing and proximity of index scores and driver values -** The difference in the timing and location of CSCI scores and driver information was a possible issue in the pilot effort analysis. In many instances, the dates of the CSCI data collection and the local driver data collection were separated by up to several years. In particular, it was not possible to closely match the date of CSCI data collection with channel maintenance activities. At many sites, CSCI data were collected during a long interval between channel maintenance activities and therefore may not capture the impacts of maintenance on stream health. It was also not possible in this effort to compile detailed information at all CSCI sites on the proximity of channel maintenance activities, the magnitude of maintenance activities (e.g., targeted vegetation removal or complete vegetation clearing), or the maintenance frequency. The next phase should focus on collecting or obtaining stream ecological health index information and driver information that are closely matched in time and space.

- **Protocol for rapid assessment of channel type and condition** - Applying the approach developed in this pilot effort to the other Bay Area counties will require a rapid and cost-effective protocol for collecting essential channel type and condition information. At the very least, each channel site should be visited and classified as Hard (hardened bed and banks), Mixed (soft bed and hardened banks), Soft (soft bed and banks but modified for flood control), or Natural (soft bed and banks but not modified for flood control). Additional information about bed and bank material (e.g., concrete, gabion rip rap) should also be collected if possible. Ideally, this effort would occur at the same time as the collection of local driver information (e.g., riparian shading).

References

Booth, D.B., J.R. Karr, S. Schauman, C.P. Konrad, S.A. Morley, M.G. Larson, and S.J. Burges. 2004. Reviving urban streams: land use, hydrology, biology, and human behavior. Journal of the American Water Resources Association, 40(5):1351–1364.

California Wetlands Monitoring Workgroup (CWMW). 2013. California Rapid Assessment Method (CRAM) for Wetlands, Version 6.1 pp. 67

Carter, J.L. and S.V. Fend. 2005. Setting limits: the development and use of factor-ceiling distributions for an urban assessment using macroinvertebrates. In American Fisheries Society Symposium (Vol. 47, pp. 179-191).

Carter, J. L., A. H. Purcell, S. V. Fend, and V. H. Resh. 2009. Development of local-scale urban stream assessment method using benthic macroinvertebrates; an example from the Santa Clara Basin, California. Journal of the North American Benthological Society 28:1007–1021.

Cuffney, T.F., H. Zappia, E.M. Giddings, and J.F. Coles. 2005. Effects of urbanization on benthic macroinvertebrate assemblages in contrasting environmental settings: Boston, Massachusetts; Birmingham, Alabama; and Salt Lake City, Utah. In American Fisheries Society Symposium (Vol. 47, pp. 361-407).

Fend, S. V., J. L. Carter, and F. R. Kearns. 2005. Relationships of field habitat measurements, visual habitat indices, and land cover to benthic macroinvertebrates in urbanized streams of the Santa Clara Valley, California. In Brown, L. R., R. H. Gray, R. H. Hughes & M. R. Meador (eds), Effects of Urbanization on Stream Ecosystems. American Fisheries Society Symposium 47, Bethesda:193–212

Horizon Water and Environment. 2020. Sonoma County Water Agency Stream Maintenance Program: Program Manual.

Klein, R. D. 1979. Urbanization and stream quality impairment. Water Resources Bulletin, 15:948–963.

Lenat, D. R., and J. K. Crawford. 1994. Effects of land use on water quality and aquatic biota of three North Carolina Piedmont streams. Hydrobiologia, 294:185– 199.

Lunde K.B., M.R. Cover, R.D. Mazor, C.A. Sommers, and V.H. Resh. 2013. Identifying reference conditions and quantifying biological variability within benthic macroinvertebrate communities in perennial and non-perennial northern California streams. Environmental Management, 51:1262–1273.

Mazor, R.D., A.C. Rehn, P.R. Ode, M. Engeln, K.C. Schiff, E.D. Stein, D.J. Gillett, D.B. Herbst, and C.P. Hawkins. 2016. Bioassessment in complex environments: designing an index for consistent meaning in different settings. Freshwater Science, 35(1):249-271.

Morley, S.A. and J.R. Karr, 2002. Assessing and Restoring the Health of Urban Streams in the Puget Sound Basin. Conservation Biology, 16:1498-1509.

Ode, P. R., A. E. Fetscher, and L. B. Busse. 2016. Standard operating procedures (SOP) for the collection of field data for bioassessments of California wadeable streams: Benthic macroinvertebrates, algae, and physical habitat. California State Water Resources Control Board Surface Water Ambient Monitoring Program, Sacramento, California.

Roy, A. H., A. D. Rosemona, M. J. Paul, D. S. Leigh, and J. B. Wallace. 2003. Stream macroinvertebrate response to catchment urbanization (Georgia, U.S.A.). Freshwater Biology, 48:329–346.

Rehn, A.C., R.D. Mazor and P.R. Ode. 2015. The California Stream Condition Index (CSCI): A New Statewide Biological Scoring Tool for Assessing the Health of Freshwater Streams. Swamp Technical Memorandum SWAMP-TM-2015-0002.

Santa Clara Valley Water District (SCVWD). 1993. Maps of Flood Control Facilities and Limits of 1% Flooding. Prepared by the Flood Control Planning Division & the Engineering Services Drafting Section.

Stepenuck, K. F., R. L. Crunkilton, and L. Wang. 2002. Impacts of urban land use on macroinvertebrate communities in southeastern Wisconsin streams. Journal of the American Water Resources Association, 38(4):1041–1051

Southern California Stormwater Monitoring Coalition (SCSMC). 2017. 2015 Report on the Stormwater Monitoring Coalition Regional Stream Survey. SCCWRP Technical Report 963. Southern California Coastal Water Research Project. Costa Mesa, CA.

Valley Water. 2014. 2014-2023 Stream Maintenance Program Manual. Prepared by Sunny Williams, July 3, 2014.

Webster, L. and C. Yang. 2015. The California Stream Condition Index (CSCI) Factsheet. A product of the Surface Water Ambient Program (SWAMP) Bioassessment Program. December 2015.

White, J.C., D.M. Hannah, A. House, S.J. Beatson, A. Martin, and P.J. Wood. 2017. Macroinvertebrate responses to flow and stream temperature variability across regulated and non- regulated rivers. Ecohydrology, 10(1), p.e1773.

APPENDIX A

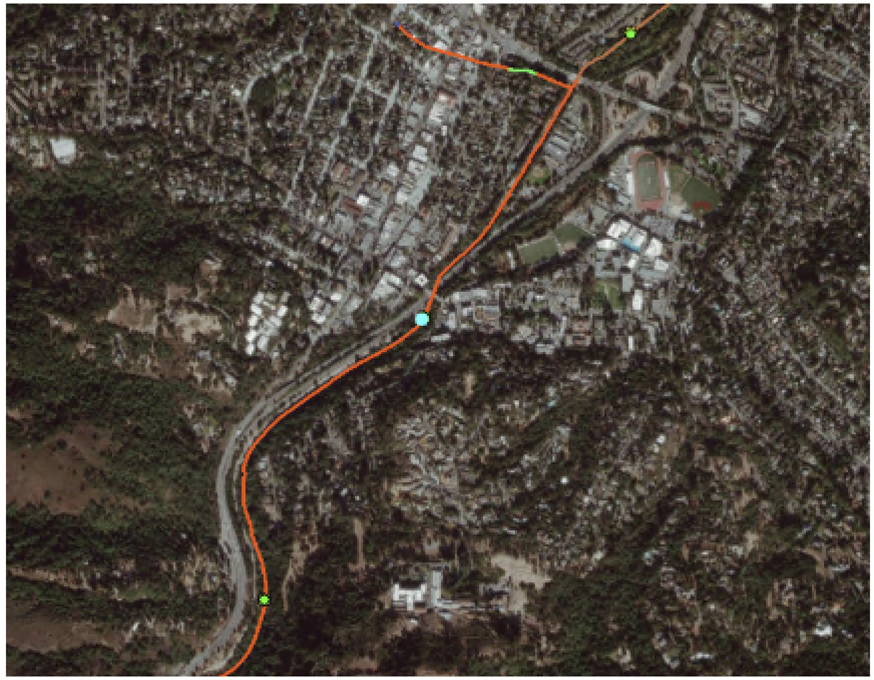
Side-by-side qualitative aerial comparisons of high and low-performing benthic macroinvertebrate survey reaches of the same channel types and similar % impervious value

Hard Channels - High CSCI Scores

Station Code	205LGBxxx	**Lat/long**	37.21334, -121.98654
% Impervious	**0.41**	**Watershed**	Los Gatos Creek
CSCI	**0.77**	**Riparian**	HIGH
Notes	outside of urban footprint, downstream of dam	**Distance from Development**	Upstream of urban boundary

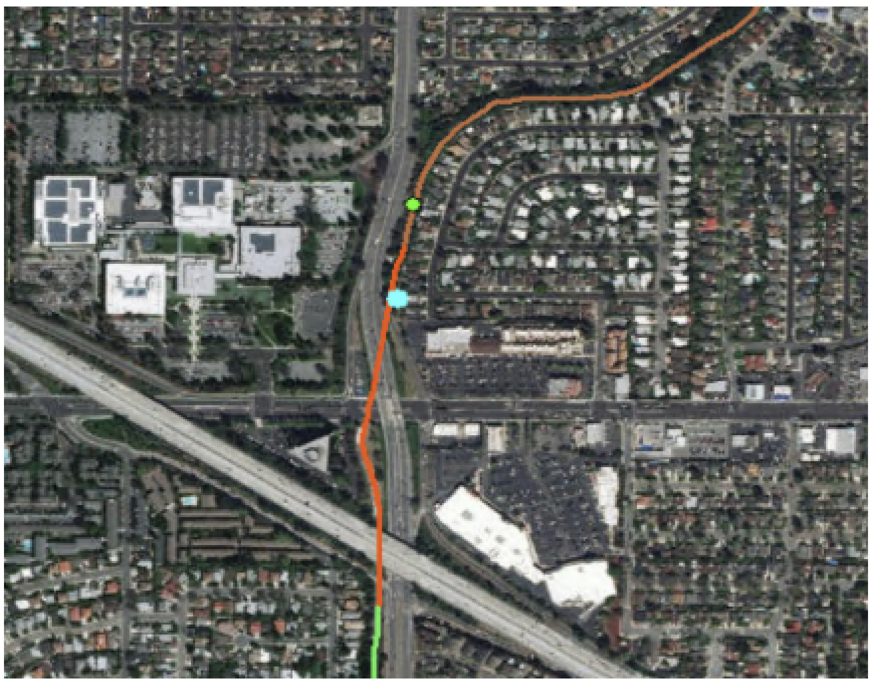
Hard Channels - Low CSCI Scores

Station Code	205GUA080	**Lat/long**	37.22079, -121.98212
% Impervious	**0.52**	**Watershed**	Los Gatos Creek
CSCI	**0.52**	**Riparian**	HIGH
Notes	Just downstream of the point to the left	**Distance from Development**	On urban boundary



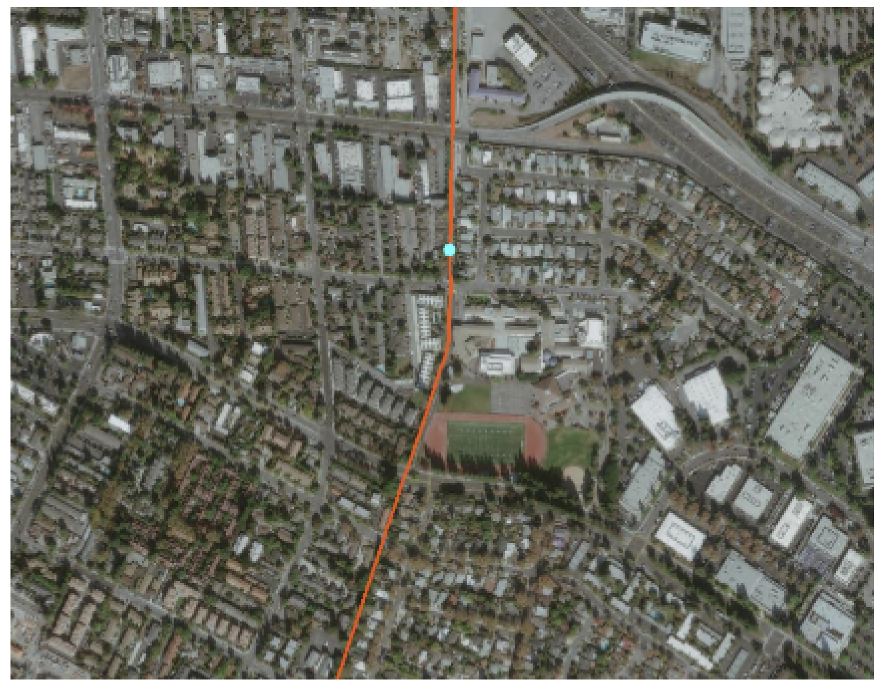
Hard Channels - High CSCI Scores

Station Code	205R00355	**Lat/long**	37.32473 -121.99532
% Impervious	**15.34**	**Watershed**	Saratoga Creek
CSCI	**0.64**	**Riparian**	Moderate
Notes	Downstream of culvert = possibly cooler water. Saratoga Ck cobbles likely help CSCI.	**Distance from Development**	Embedded, residential/ office parks



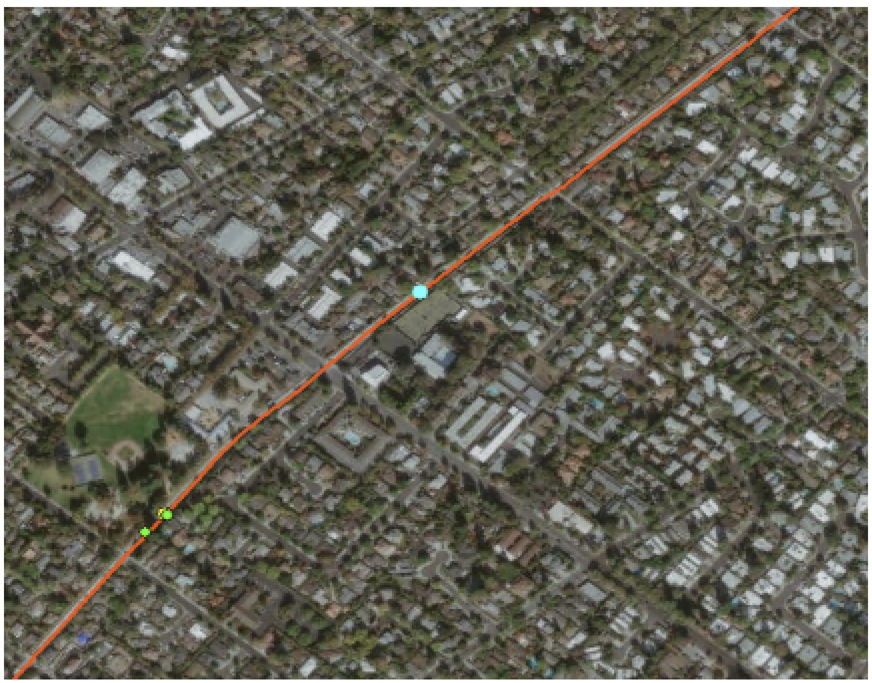
Hard Channels - Low CSCI Scores

Station Code	205PER020	**Lat/long**	37.41268, -122.08679
% Impervious	**14.72**	**Watershed**	Permanente Creek
CSCI	**0.23**	**Riparian**	NONE
Notes	Extensive non-riparian concrete channel upstream	**Distance from Development**	Embedded, residential/ industrial



Hard Channels - High CSCI Scores

Station Code	205R02787	**Lat/long**	37.432204, -122.124836
% Impervious	22	**Watershed**	Matadero Creek
CSCI	0.49	**Riparian**	NONE
Notes	Fully hardened channel, fairly good tree cover in surrounding area	**Distance from Development**	Embedded, residential/ office parks



Hard Channels - Low CSCI Scores

Station Code	205R00739	**Lat/long**	37.42967, -122.12816
% Impervious	20.9	**Watershed**	Matadero Creek
CSCI	0.27	**Riparian**	NONE
Notes	Adjacent to park, but low score. Very hardened upstream.	**Distance from Development**	Embedded, residential/ suburban

Hard Channels - High CSCI Scores

Station Code	205R00547	**Lat/long**	37.34836 -121.98952
% Impervious	**34.92**	**Watershed**	Calabazas Creek
CSCI	**0.46**	**Riparian**	ALMOST NONE
Notes	Adjacent recreational field upstream as well on one side	**Distance from Development**	1 acre open field directly adjacent but otherwise embedded

Hard Channels - Low CSCI Scores

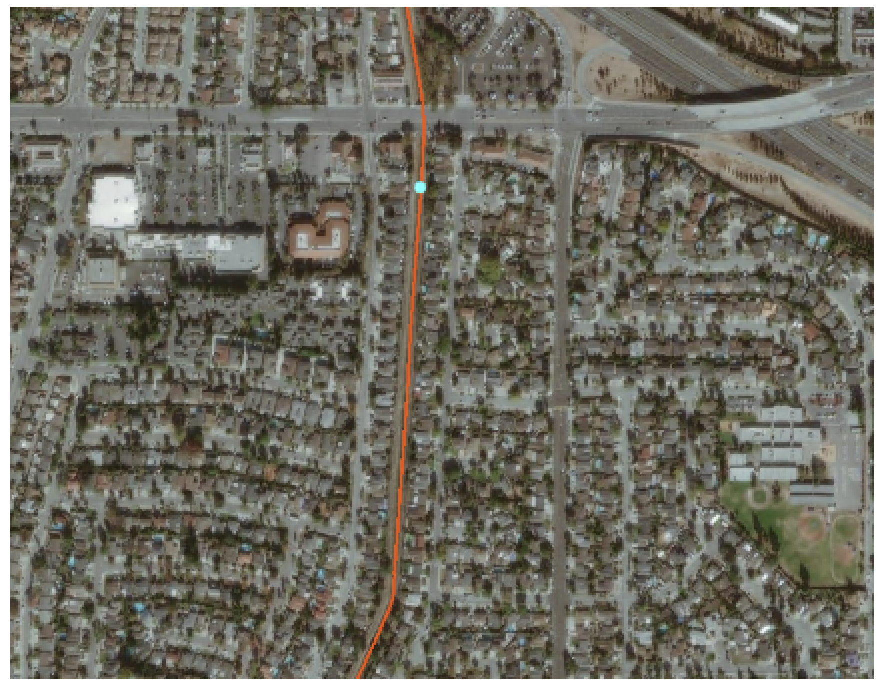
Station Code	205R00154	**Lat/long**	37.23419, -121.83801
% Impervious	**33.29**	**Watershed**	Canoas Creek
CSCI	**0.17**	**Riparian**	NONE
Notes	Small upper watershed, very impervious, straightened	**Distance from Development**	Embedded, residential/ suburban, open space <0.5km away

Hard Channels - High CSCI Scores

Station Code	205R03443	**Lat/long**	37.388639, -121.986842
% Impervious	**40**	**Watershed**	Calabazas Creek
CSCI	**0.45**	**Riparian**	None, thin trees adjacent
Notes	Near some open space downstream	**Distance from Development**	fully embedded, office parks, parking lots

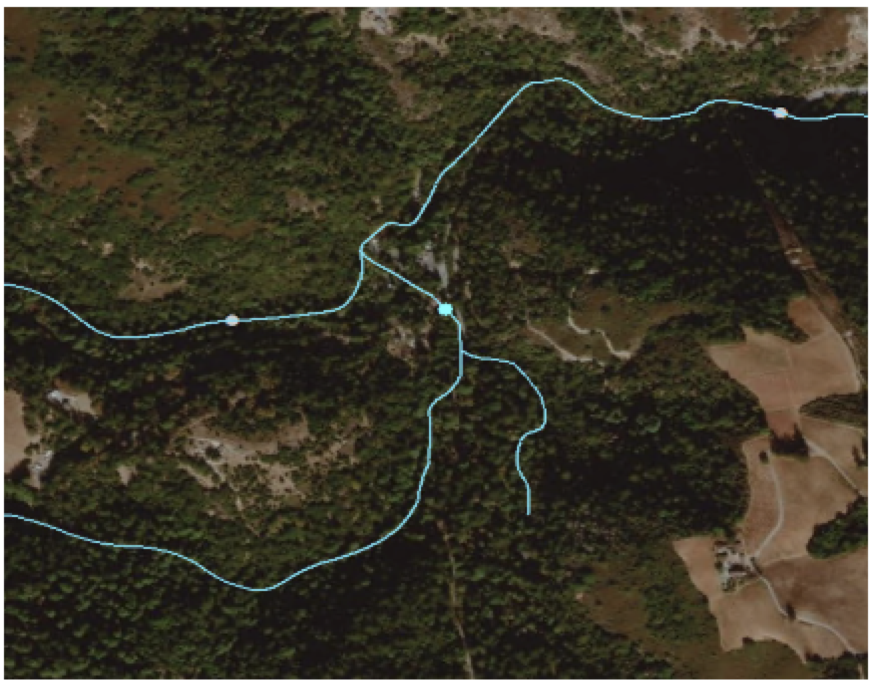
Hard Channels - Low CSCI Scores

Station Code	205GUA140	**Lat/long**	37.24985, -121.84186
% Impervious	**39.24**	**Watershed**	Canoas Creek
CSCI	**0.20**	**Riparian**	None
Notes	Fairly low neighborhood tree cover	**Distance from Development**	Embedded residential/ suburban



Soft Channels - High CSCI Scores

Station Code	205SAR110	**Lat/long**	37.248463, -122.068302
% Impervious	0.11	**Watershed**	Saratoga Creek
CSCI	1.07	**Riparian**	Almost total cover
Notes	Far up in foothills, relatively steep	**Distance from Development**	Adjacent housing but almost all natural setting



Soft Channels - Low CSCI Scores

Station Code	205R02211	**Lat/long**	37.306, -122.07194
% Impervious	0.42	**Watershed**	Stevens Creek
CSCI	0.41	**Riparian**	Near full coverage
Notes	Dam + quarrying upstream	**Distance from Development**	Just outside urban footprint

Soft Channels - High CSCI Scores

Station Code	205SAR060	**Lat/long**	37.27219, -122.01633
% Impervious	**2.96**	**Watershed**	Saratoga Creek
CSCI	**1.07**	**Riparian**	Total cover
Notes	Additional open field with planting across the street	**Distance from Development**	Embedded, suburban, but adjacent to park and wide buffer

Soft Channels - Low CSCI Scores

Station Code	205COY250	**Lat/long**	37.32444 -121.85983
% Impervious	**1.83**	**Watershed**	Coyote Creek
CSCI	**0.35**	**Riparian**	Full coverage
Notes	205R01315 upstream also has low CSCI (0.2968), low impervious (3.9%)	**Distance from Development**	Contained within large open space, surrounded by development

Soft Channels - High CSCI Scores

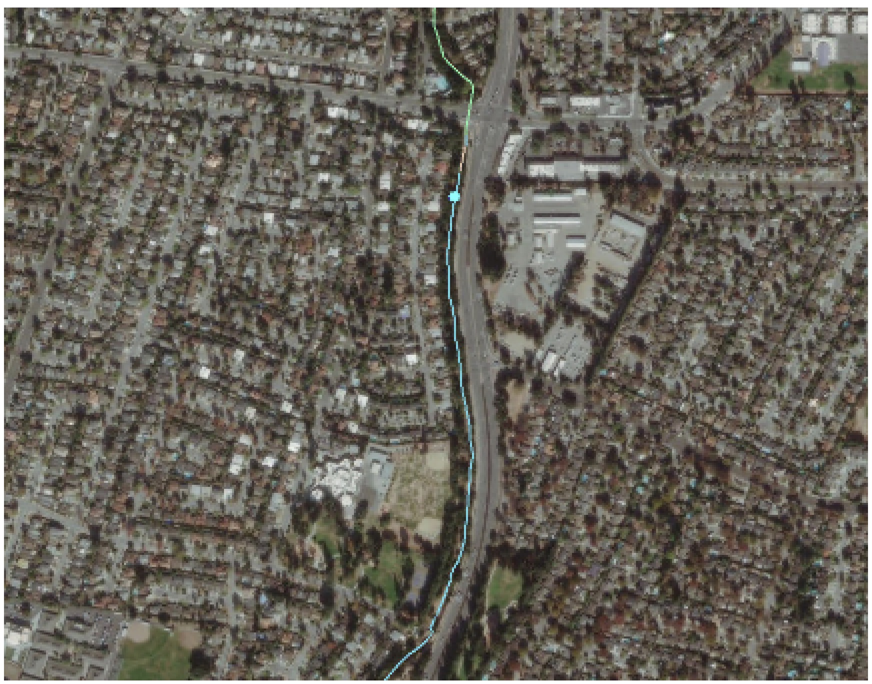
Station Code	205SAR050	**Lat/long**	37.293897, -122.00276
% Impervious	**5.53**	**Watershed**	Saratoga Creek
CSCI	**0.97**	**Riparian**	Total cover
Notes	School rec fields ~300m upstream	**Distance from Development**	suburbia embedded

Soft Channels - Low CSCI Scores

Station Code	205R00241	**Lat/long**	37.27548, -121.76224
% Impervious	**4.61**	**Watershed**	Silver Creek
CSCI	**0.30**	**Riparian**	Some coverage
Notes	Embedded in golf course -- monoculture surrounding	**Distance from Development**	Somewhat embedded, exurban

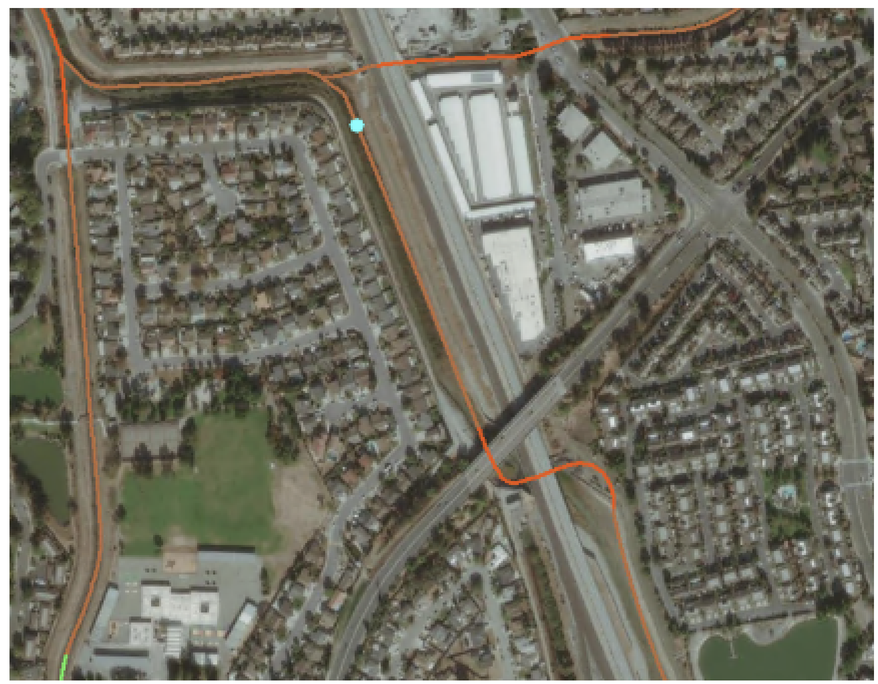
Soft Channels - High CSCI Scores

Station Code	205SAR040	**Lat/long**	37.3083 -121.996589
% Impervious	12.62	**Watershed**	Saratoga Creek
CSCI	0.79	**Riparian**	Thin buffer but almost full cover
Notes	adjacent to thoroughfare, large park <.5km upstream	**Distance from Development**	embedded, single-family housing



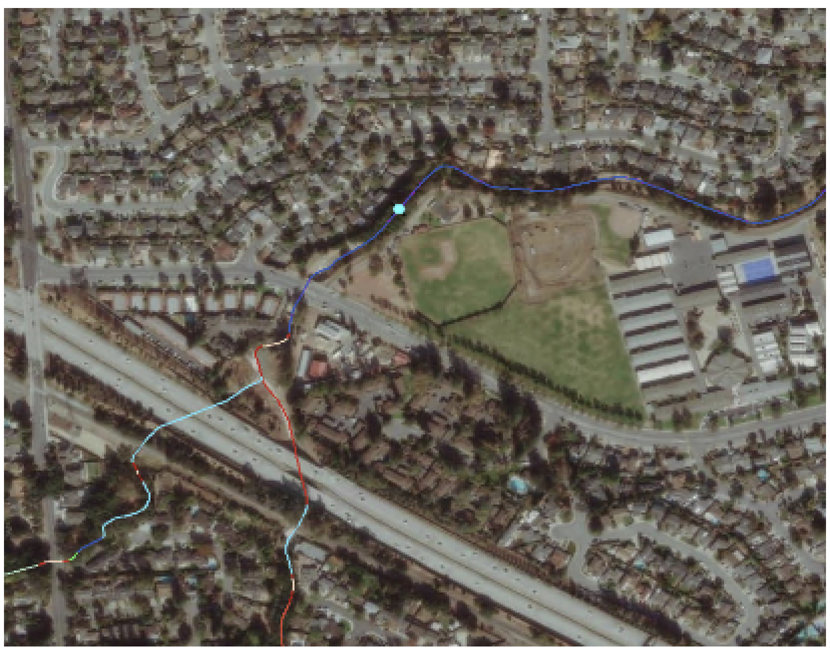
Soft Channels - Low CSCI Scores

Station Code	205R00387	**Lat/long**	37.44558, -121.91085
% Impervious	9.69	**Watershed**	Lower Penitencia
CSCI	0.27	**Riparian**	NONE
Notes	Straightened/ excavated channel, highly modified upstream	**Distance from Development**	Embedded, mixed residential/ industrial



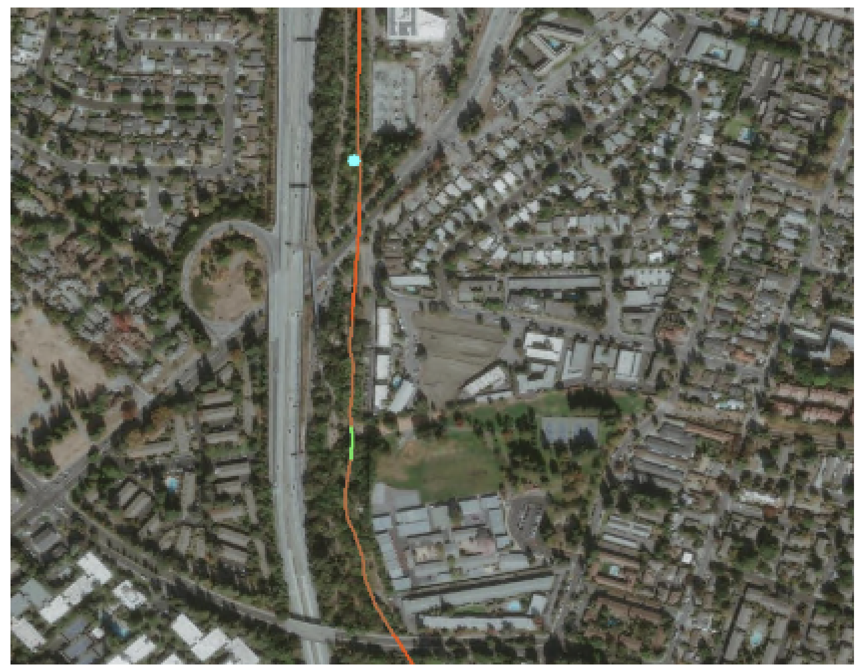
Soft Channels -High CSCI Scores

Station Code	205STQ060	**Lat/long**	37.272475, -121.989436
% Impervious	**13.58**	**Watershed**	San Tomas Aquino
CSCI	**0.72**	**Riparian**	Open for section, otherwise total
Notes	Directly adjacent to park, just downstream of confluence	**Distance from Development**	embedded suburban



Soft Channels - Low CSCI Scores

Station Code	205R00115	**Lat/long**	37.40427, -122.06911
% Impervious	**15.72**	**Watershed**	Stevens Creek
CSCI	**0.24**	**Riparian**	Partial
Notes	Bound above and below by hard channels, next to freeway	**Distance from Development**	Fully embedded, residential/ industrial

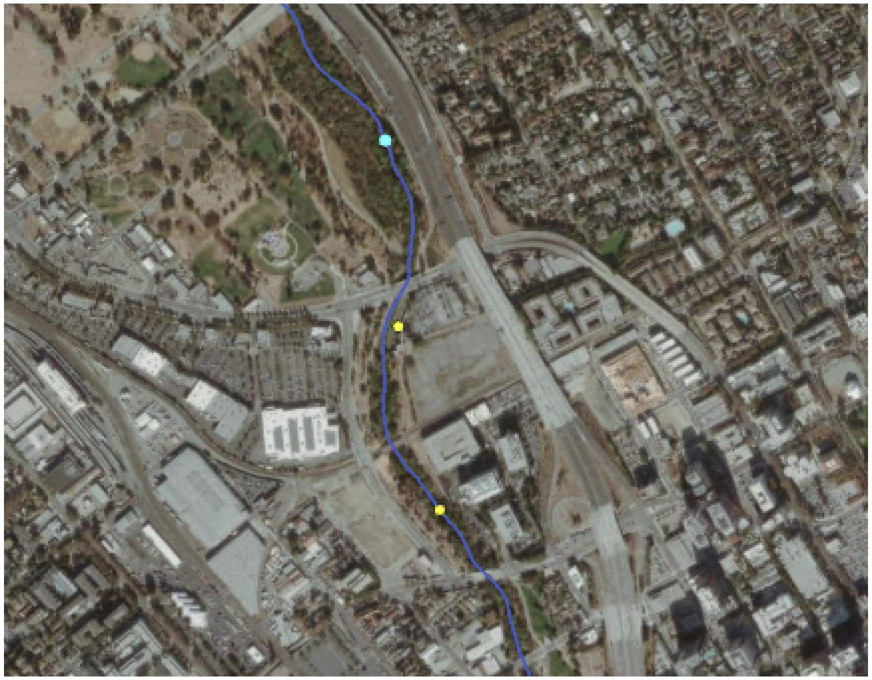


Soft Channels - High CSCI Scores

Station Code	205PS0109	**Lat/long**	37.293398, -121.880417
% Impervious	**20.49**	**Watershed**	Guadalupe R.
CSCI	**0.66**	**Riparian**	Near total
Notes	Fair tree coverage W. side, just downstream of confluence (Guadalupe/ Canoas)	**Distance from Development**	Embedded, single family housing west side, mixed use east side

Soft Channels - Low CSCI Scores

Station Code	205R02051	**Lat/long**	37.34409, -121.90251
% Impervious	**20.47**	**Watershed**	Guadalupe R.
CSCI	**0.32**	**Riparian**	Mostly covered
Notes	Downstream of industrial but large open space buffer	**Distance from Development**	Embedded, but Guadalupe R. Park on west side, wide buffer



Soft Channels - High CSCI Scores

Station Code	205R00099	**Lat/long**	37.30758 -122.02201
% Impervious	**22.52**	**Watershed**	Calabazas Ck.
CSCI	**0.61**	**Riparian**	Moderate coverage
Notes	downstream of confluence and large park	**Distance from Development**	embedded suburban

Soft Channels - Low CSCI Scores

Station Code	205R01747	**Lat/long**	37.35207, -121.84184
% Impervious	**23.39**	**Watershed**	Thompson Ck.
CSCI	**0.37**	**Riparian**	Minimal
Notes	Near field, but straightened/ modified, low surrounding tree coverage	**Distance from Development**	Embedded, residential, near soccer field