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California Stream Condition Index (CSCI) Score Analysis of Streams Sampled from 1998 to 2017 in the San Francisco Bay Region

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This Master's Project

California Stream Condition Index (CSCI) Score Analysis of Streams Sampled from 1998 to 2017

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Acronyms and Abbreviations

ASCI	Algal Stream Condition Index
BMI	Benthic Macroinvertebrates
CALEPA	California Environmental Protection Agency
CALFED	California Federal Bay-Delta
CDFW	California Department of Fish and Wildlife
CEDEN	California Environmental Data Exchange Network
CEQA	California Environmental Quality Act
CSCI	California Stream Condition Index
EPA	United State Environmental Protection Agency
ESA	Endangered Species Act
ESRI	Environmental Systems Research Institute
FERC	Federal Energy Regulatory System
GIS	Geographic Information Systems
GPS	Global Positioning System
IBI	Index of Biological Integrity
IPI	Index of Physical Habitat Integrity
MAF	Millions of Acre Feet
MRLC	Multi-Resolution Land Characteristics
MMI	Multi-Metric Index
NEPA	National Environmental Policy Act
NGO	Non-governmental Organization
NHD	National Hydrography Dataset
NLCD	National Land Cover Database
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
O/E	Observed-to-Expected
RIVPACS	River Invertebrate Prediction and Classification System
SF Bay RWQCB	San Francisco Bay Regional Water Quality Control Board
SWAMP	Surface Water Ambient Monitoring Program
SWRCB	State Water Resources Control Board
USBR	United States Bureau of Reclamation
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey

Abstract

Human impacts to California's streams have altered the state's riparian and hydrological landscape. This is a critical issue with regard to natural resources, including ecosystem services such as water availability and water quality. Regulations have a limited amount of impact on the improvement of this landscape and can also become complicated by politics. Scientific advances have developed ways to quantify and describe the quality of streams, this includes the development of the California Stream Condition Index (CSCI) which is based on benthic macroinvertebrate (BMI) population numbers and functions. This index allows scientists to not only score the quality of a stream, but to analyze the details of the data that produce the CSCI scores. The CSCI scores also provide a means to spatially analyze large data sets of stream quality. This project evaluates the spatial distribution of CSCI scores for the San Francisco Bay region. Several streams within the San Francisco Bay region confirm that very urban and developed areas contain highly impacted streams, whereas areas that are less or not urban and developed (rural) have less impacted or higher quality streams. The variation in CSCI scores within a stream over time were analyzed for ten streams in the San Francisco Bay region. The data were limited, therefore spatial consideration of where samples were collected, was accounted for. Predictably, lower CSCI scores were indicative of urban and developed areas; and higher CSCI scores were indicative of less impacted areas. The CSCI quantitative scores were less indicative of possible temporal trends in stream quality, however the CSCI qualitative categories were more indicative of possible temporal trends in stream quality. More data analysis will be required to prove any definitive temporal trends in stream quality with regard to the CSCI number scores. These CSCI data will be more useful when compared with additional stream data such as physical habitat and water quality data.

Introduction

History of streams in California

All of the streams in the state of California have been altered due to human impacts (Power et al. 2016). Urban infrastructure, dams, mining, and water usage from agriculture have been major factors in these impacts. Some of the consequences of the impacts include an increase in erosion resulting in more gully and rill formations, more sediment deposition downstream (especially from historical hydraulic mining impacts most notably during the Gold Rush) a decrease in water flow. In addition to these fundamental hydrological impacts, ecological impacts have also occurred such as loss of biodiversity due to changes in flow patterns within watershed systems. Currently the changes associated with watershed flow discharge are most significantly caused by the presence of dams. Dam construction has resulted in changed watershed flow regimes so drastically that the ecological structure of any given stream in California has changed. More invasive species have colonized riparian zones and outcompete native species, and native anadromous fish are unable to travel upstream very far to spawn. In addition, climate change has tested the resiliency of native species (Kim et al., 2019 and Sun et al., 2016).

Since all streams in California have been altered, water quality has been impacted, and as a result, water quality has been a central issue in the state, both scientifically and politically for a very long time (Hanak et al., 2011). The concerns with water in California have been numerous but can be described as five types: 1) water availability; 2) water supply; 3) water demand; 4) water use; and 5) water quality. Water availability is a concern because the state of California has an arid Mediterranean climate that experiences rainfall (or snowfall in the mountains) during the winter months and then a long drought during the rest of the year. Water supply is a concern because many reservoirs exist in the state, but due to increased surface area of water in reservoirs coupled with warm weather large amounts of water evaporate each year. Water demand is a concern since the very populous state has a high human demand of water. Water use in California is assigned to three sectors categorized as urban, agriculture, and environment, which use most of the water supply each year. Water quality is a concern due to high levels of urban development and agricultural use in California. Water quality is potentially at risk and must be continuously monitored. The issues with water in California have resulted in constantly changing and evolving regulatory strategies for managing water in the state, however, this has not occurred without conflict. There have been some significant and influential legal decisions regarding water regulation in California until the year 2010 (Table 1) and until the present.

Table 1. Significant water regulation decisions in California from 1850 to 2010 (Hanak, 2017).

Year	Law/Policy/Regulation	Description
1850	English Common Law or Riparian rights	This established that anyone who owns land along a stream has a right to utilize the water.
1855	Right of prior appropriation	“First in time, first in right”. The entities who have used the water from a stream first have a right to use the water due to first use.
1868	Reclamation districts authorized	Creation of local reclamation districts so that landowners could fund land reclamation and flood control projects.

Year	Law/Policy/Regulation	Description
1886	Riparian rights superior to appropriative rights	It was determined in California that Riparian rights are superior to appropriative rights and riparian rights usually win over appropriative rights in course.
1887	Irrigation districts authorized (Wright Act)	Districts could acquire water rights, construct water projects, sell bonds, and impose property assessments to support water development and distribution.
1902	Reclamation Act	Allowed construction of dams and irrigation projects in the West and later formed the Bureau of Reclamation.
1913	Raker Act authorizes Hetch Hetchy	Authorized San Francisco's use of Hetch Hetchy as a reservoir.
1928	Reasonable use doctrine Federal Flood Control Act	A doctrine that establishes reasonable use of water in California and says that water shall be put to beneficial use and unreasonable use shall be prevented.
1933	Section 5937 Fish and Game Code	Required a minimum amount of water flowing over, around, and through a dam to sufficiently support fish populations.
1969	National Environmental Policy Act (NEPA) Porter-Cologne Act	Federal act that seeks to enhance the environment. State act that gave power to the State Water Resources Control Board to set water quality standards for California.
1970	California Environmental Quality Act (CEQA)	State act that seeks to enhance the state's environment.
1972	Clean Water Act California Wild and Scenic Rivers Act	Federal act that regulates water in the nation. Act that protects designated rivers in California.
1973	Federal Endangered Species Act (ESA)	Federal act that gives protections to listed species, or species listed as threatened or endangered.
1981	North Coast rivers declared wild and scenic	Rivers on the north coast of California afforded protections under the Wild and Scenic Rivers Act.
1983	Mono Lake Decision	Limited Los Angeles from extracting water from the lake.
1992	Central Valley Project Improvement Act	Added requirements for improvements for fish and wildlife, to the Central Valley Project.
1994	Bay-Delta Accord (CALFED)	For all agencies regulating water in California to create a long-term management plan for the California delta system.
2000	CALFED Record of Decision	7-year plan produced by Bay-Delta Accord.
2006	Collapse of CALFED	CALFED ultimately did not work due to political pressure.
2007	Central Valley Flood Legislation	Occurred due to climate change and other imminent impacts that would cause flooding in the Central Valley.
2009	Water Policy Legislation	Contemporary California water policy.
2010	Delta Stewardship Council (Delta Reform Act)	Charged with restoring the delta for all who use the water supply.

The water regulatory structure has changed and evolved many times in California and as such, it has failed in some cases to be an efficient and effective way to regulate water resources. However, there are efforts to link the importance of ecological health and ecosystem services to high water quality, with water providing a significant and essential ecosystem service. Ecosystem services include four services: provisioning services, regulating services, cultural services, and supporting services (Hanak et al. 2011).

Stream habitat in California

The ecological health of a stream and its surrounding land use and habitat are directly linked to the quality of water in the stream. Not only does a stream provide water to surrounding human populations, but a stream supports many biota such as fish, invertebrates, plants, algae, trees, birds, and other mammals. In California anadromous fish such as salmon and steelhead at one time were present in large populations that would return to streams to spawn and would provide an abundant food source to California. Fish populations have decreased drastically since the advent of the development of dams. More recently, agencies such as the California Department of Fish and Wildlife (CDFW) and the National Park Service (NPS) have made significant efforts through research and implementation, to mitigate this impact in California. They have attempted to reestablish fish populations in streams that once hosted significant populations of anadromous fish, one example being the Coho Salmon in Redwood Creek in Marin County, California (CDFW, 2019).

Stream habitats in California are numerous and varied due to the wide range of climatic and geologic patterns. However, there are patterns in creeks and streams that are universal and predictable (Power et al. 2016). These predictable patterns influence what biota colonize a part of a stream. These patterns in streams are physical or abiotic parameters or factors that in combination influence the ecosystems of streams. Physical habitat patterns include water temperature and chemistry, flow, sinuosity, elevation, and gradient.

Historically, with the Industrial Revolution and the Gold Rush, California’s streams were drastically impacted by hydraulic mining. Hydraulic mining at the headwaters forced sediment down to the mouth of rivers and streams and deposited large amounts of sediment, for example, in the San Francisco Bay and some of this sediment still remains in the Bay (Stanford, 2007).

The current stream habitats in California are very altered. The most unaltered stream habitats in California are small tributaries that are difficult to access (Johnson and Hering, 2009). Watersheds and streams that are surrounded by urban land cover are the most altered riparian habitats in California (Rehn et al., 2015).

Shift in California's stream landscape

As a result of the shift in the stream and watershed landscape in California, there has been a shift in the ecosystem services in California and how they are managed. As the population grows, so do land, water and other resource demands grow. Population demands place pressure and stress on an already strained ecosystem in the state. Because of this strain, the water regulations in California have continuously evolved and changed to attempt to maintain pace and progress with evolving and changing water demands and usage (Table 1). The water sources and water demand in California drive how water is currently used in California. As previously mentioned, freshwater in California contributes four ecosystem services. Provisioning services include the production of food, materials, freshwater, and hydropower. Regulating services include the regulation of flow, water quality, and climate. Cultural services include for example, recreation, ecotourism and the aesthetics of scenic open space. Supporting services include for example, soil fermentation and fertility, removal of carbon dioxide through photosynthesis, nutrient cycling and water cycling (supporting services are rarely measured) (Hanak et al., 2011). The way environmental managers more recently view water ecosystems services has changed to a more holistic view of all contributors to a watershed ecosystem that make it function optimally. The water cycle is an important aspect of watershed ecology and is used widely for illustrating where water comes from and influences how scientists understand and interpret water sources.

Where water comes from in California

Sources of water are generally divided into two categories, ground water and surface water. Ground water sources are underneath the surface of the earth and surface water sources are from waterbodies such as reservoirs, lakes, rivers/streams, and wetlands. California's water sources are no different: precipitation occurs, and this water then becomes available through ground water or through surface water. California's water supply is divided into ten categories based on the programs and processes that provide water to the state (Figure 1). Groundwater extraction provides the most water to California. In 2015, California's total water supply was 64.1 millions of acre feet (maf) (O'Daly, 2018).

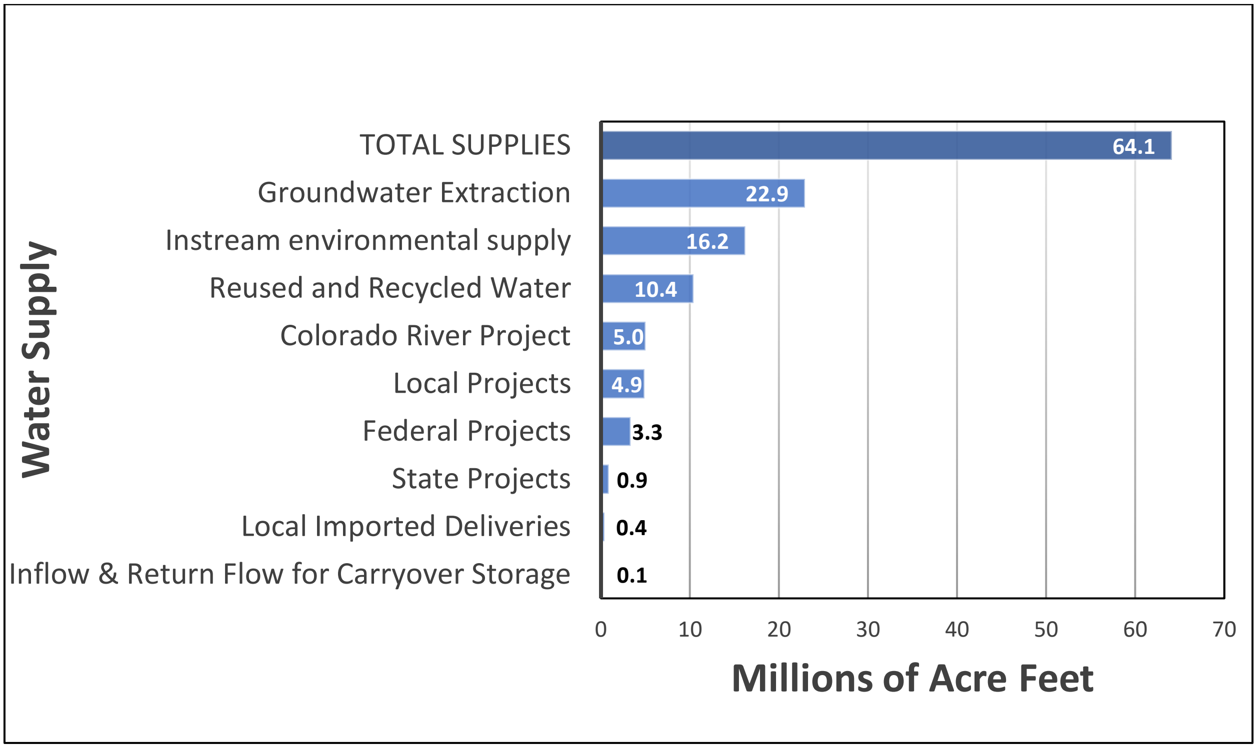


Figure 1. Water supply sources in California in 2015 (O'Daly, 2018).

How water is currently used in California

Water use in California is currently divided into three categories by the California Department of Water Resources (DWR) – agricultural, urban and environmental (O'Daly, 2018). California uses roughly 40% for agriculture, 10% for urban, and 50% for environmental. The percentages vary between high precipitation years and drought years (O'Daly, 2018). In 2015, each sector used a certain amount of water when the mean rainfall for that year was 77% of average regional rainfall or 143.3 maf of precipitation (Figure 1). The three categories contain the following subcategories:

1. Urban
    - Large Landscape
    - Commercial
    - Industrial
    - Energy Production
    - Residential – Interior

- Residential – Exterior
- Conveyance Applied Water
- Groundwater Recharge Applied Water

2. Agriculture
    - Applied Water – Crop Production
    - Conveyance Applied Water
    - Groundwater Recharge Applied Water
3. Environmental
    - Managed Wetlands
    - Minimum Required Delta Outflow
    - Instream Flow requirements
    - Wild & Scenic Rivers

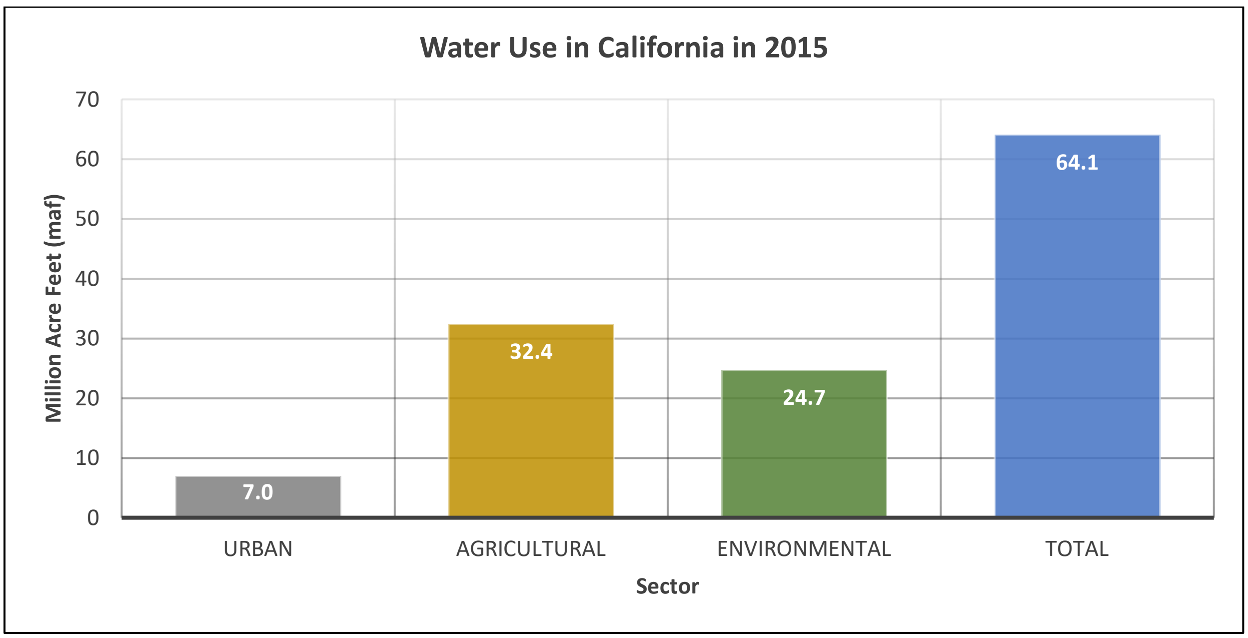


Figure 2. The water use in California in 2015 categorized by sector (O'Daly, 2018).

Stream quality in the San Francisco Bay region

Several factors contribute to measuring stream quality which include both abiotic and biotic factors. Both categories of factors then directly and indirectly contribute to the resulting water quality in a stream. And in turn, water quality drives the ecological quality of a stream system. In an environment where streams have been altered by human impacts, it becomes imperative to manage water resources efficiently and effectively to ensure that water needs are met. In more rural areas of California, the water supply is less impacted by urban development, and these less developed areas have more robust ecological stream (and watershed) systems with greater biodiversity.

In an area that is more urban and developed, such as the San Francisco Bay region, the ecological systems of streams (and watersheds) are more impacted and have more pollution inputs. These inputs are categorized as point source pollution and non-point source pollution according to regulatory and legal definitions (Salzman et al., 2014). Point source pollution is basically any pollution that comes out of a contained unit such as a pipe and is deposited into the water, for example, wastewater. Non-point source pollution is pollution that does not come out of a contained unit and is deposited into the water, for example, agricultural runoff. In the San Francisco Bay region, these inputs are highly concentrated due to high population concentrations, thus it is important for the entire water system (water cycle, ecological water systems, water use, etc.) to be continuously monitored for stream quality and water quality, in the San Francisco Bay region.

California's water regulators

Currently, the water in California is managed by six state agencies and eight federal agencies (Hanak et al, 2011):

State

1. State Water Resources Control Board
2. California Department of Water Resources (California Natural Resources Agency)
3. California Department of Fish and Game (California Natural Resources Agency) and Fish and Game Commission
4. California Department of Public Health
5. Central Valley Flood Protection Board
6. California Public Utilities Commission

Federal

1. U.S. Department of the Interior
2. U.S. Bureau of Reclamation (USBR) (U.S. Department of the Interior)

3. U.S. Fish and Wildlife Service (U.S. Department of the Interior)
4. National Marine Fisheries Service National Oceanic and Atmospheric Administration (U.S. Department of Commerce)
5. U.S. Environmental Protection Agency (EPA)
6. U.S. Army Corps of Engineers (U.S. Department of Defense)
7. Federal Emergency Management Agency (U.S. Department of Homeland Security)
8. Federal Energy Regulatory Commission (FERC)

These agencies regulate everything from surface water to water quality, water monitoring, water resources, flood plains, wetlands, wildlife (both the federal and state Endangered Species Acts), habitat, land use, and water emergencies.

Stakeholders have a great interest in water management issues such as water supply, water availability, water quality and water conservation. Stakeholders could include farmers, general consumers, property owners, and non-governmental organizations (NGOs), for example. Stakeholders have had great influence on laws, policies and regulations that are or are not passed. Another aspect of stakeholder involvement in water resources is the importance of good communication. The data acquired from water resource management and monitoring is not acquired without stakeholder involvement. Entities involved in water resource management and monitoring may own land that surrounds a stream, in which case permission and cooperation is needed to sample and monitor the water. In a densely populated area where many stakeholders have interest in involvement in water resource management decisions, the management strategy must incorporate stakeholder involvement and work with stakeholders to find common ground with water resource management solutions. Conflict can arise from disagreeing stakeholders and what one stakeholder values, may not be what another stakeholder values. In a very densely populated area where many stakeholders have interests in water resource management, like the San Francisco Bay Region, the importance of linking stream quality to water quality becomes important, but is also a unique challenge where human alteration such as channelization and slope stabilization in streams is very common and impacts the water quality greatly.

Tools for measuring stream quality

There is a large amount of research and information linking stream health to water quality, but the most recent challenges are how to quantify and analyze these data (Hawkins et al., 2010; Johnson and Hering, 2009; Lunde et al., 2013; Miller, 2019; Stribling and Dressing, 2015; and, Wright, 2000). Stream quality or health has been quantified in the past using many different types of indices or measurements in research studies. Notably, one study asked how taxonomic groups in streams would respond to gradients in resource and habitat characteristics (Johnson and Hering, 2009). They concluded that certain taxonomic groups respond similarly under certain stream conditions, and so key taxonomic groups could be chosen to be used for biological monitoring of stream health. Another way that scientists have measured stream quality through biological monitoring and assessment is by using benthic macroinvertebrate (BMI) counts. An index that has been used to analyze data like these are called the Index of Biological Integrity (IBI), which is also referred to as the Multi-Metric Index (MMI) when just referring to the numbers in the data (Stribling and Dressing, 2015). This index measures multiple metrics (such as types of functional feeding groups, for example) regarding BMI numbers, structure and function. There is an additional BMI tool that was developed in the United Kingdom called the River InVertebrate Prediction and Classification System (RIVPACS) (Wright, 2000). This is a software package that predicts the expected BMIs based on environmental characteristics, which are then compared to the observed BMIs. All of these tools use reference sites as a basis for calculating the conditions of the streams.

California Stream Condition Index (CSCI)

One current tool that has been developed is called the California Stream Condition Index (CSCI) (Rehn et al. 2015). This index is a calculation of several variables and combines two different indices: an observed-to-expected (O/E) index which measures taxonomic completeness; and a multi-metric index (MMI) which measures ecological structure and function. Previously, these indices were used separately. This tool uses a reference site comparison to analyze score values for each stream. This tool has been developed with cooperation between academics, government agencies, and NGOs, and is managed by the California State Water Resources Control Board under the Surface Water Ambient Monitoring Program (SWAMP).

The CSCI uses a numeric system to rank the condition of a stream based on the degradation of biological condition (Rehn et al., 2015). The biological condition is based on the O/E index and the MMI which both calculate scores based on BMIs. The CSCI score is calculated by using the equation of O/E. Taxonomic completeness of BMI species as well as measures of ecological traits (structure and function) are used to calculate the ‘Observed’ BMI value, and different environmental variables (e.g., geology, location, climate, watershed size) that influence BMI composition are used to calculate the ‘Expected’ BMI value:

$$CSCI\ Score = \frac{Observed\ BMI\ Species\ and\ Traits}{Expected\ BMI\ Species\ and\ Traits}$$

The scoring system is as follows: scores less than or equal to 0.62 indicate very likely altered stream conditions; scores between 0.63 to 0.79 indicate likely altered stream conditions; scores greater than or equal to 0.79 and up to 0.92 indicate possibly altered stream conditions; scores greater than or equal to 0.92 and up to 1.0 indicates likely intact stream conditions. Scores can be above 1.0 and in this case these streams are considered to be in better ecological and biological condition than was expected (Table 3) (Rehn et al., 2015). The CSCI score has proven to be a useful tool for informing water management decisions regarding the health or quality of streams and the links to water quality. For example, if a CSCI score is low, the reason for the low score can be deduced and management decisions can be made to improve the score while taking into consideration the other physical habitat factors and water quality factors, and therefore eventually improve the water quality.

Table 2. CSCI score ranges and associated categories (Rehn et al., 2015).

CSCI Score Range	CSCI Score Category
≤ 0.62	Very likely altered stream conditions
0.63 to 0.79	Likely altered stream conditions
≥ 0.79 up to 0.92	Possibly altered stream conditions
≥ 0.92 up to 1.00	Likely intact stream conditions
> 1.00	Better ecological and biological stream conditions than expected

Biological monitoring and water quality monitoring of streams in the San Francisco Bay region have been conducted since 1998 by the California Regional Water Quality Control Boards and the State Water Resources Control Board (SWRCB) and from these data, CSCI scores have been calculated. The current data available include the years 1998 to 2017 and contain several types of data: biological, nutrients, water chemistry, and physical habitat, as well as GPS location data. This project will analyze the data spanning the years 1998 to 2017 to address environmental management questions. This project will address the following questions:

- How do CSCI scores compare with surrounding land use?
- What are the California Stream Condition Index (CSCI) score trends for streams sampled in multiple years and where are these streams located?
- When stream CSCI scores decrease over time, why do they decrease?
- If the land use surrounding a stream is highly urban and developed, does this explain the CSCI score decrease?
- If not, what else would explain the decrease in CSCI score?
- What decisions can environmental managers make if CSCI scores are decreasing over time in a stream?

The hypotheses for this project are as follows: the CSCI scores that are low will most likely be located within or near urban areas. If the CSCI scores of a stream are decreasing over time, a combination of environmental factors may be contributing to this decrease, such as land cover, physical habitat, or water chemistry. Decisions that environmental managers could make if the condition of a stream is decreasing over time is to implement more temporal monitoring in addition to implementing stream improvement projects for ecological quality and water quality.

With appropriate quantification and analysis of data scientists, regulators, and stakeholders will have a better understanding of the important factors involved in improving and maintaining stream health and water quality.

Methods

Data acquisition

Data sets used for these analyses were acquired from the San Francisco Bay Regional Water Quality Control Board (SF Bay RWQCB), which represents Region 2 of the California Water Quality Control Board (Figure 4). The datasets were acquired directly from SF Bay RWQCB employees who manage the data. The data can also be downloaded through an online database portal called California Environmental Data Exchange Network (CEDEN). The data have been collected by the California Environmental Protection Agency (CalEPA), by the regional water boards under the umbrella of the CalEPA, since 1998, and continues to be collected each year. This study uses data collected between 1998 and 2017. The data include 2089 sampled sites across 345 streams and 113 watersheds mostly within Region 2 (Figure 4).

The National Land Cover Database (NLCD) data set was downloaded from the internet from the Multi-Resolution Land Characteristics consortium (MRLC) which is composed of federal agencies and can be found online at www.mrlc.gov. The stream layer data set for mapping was acquired from the SF Bay RWQCB, and the layer was derived from the National Hydrography Dataset (NHD) that is available through the United States Geological Survey (USGS) on the internet at www.usgs.gov/core-science-systems/ngp/national-hydrography. The SF Bay RWQCB had corrected the NHD data set for their region and the data set was acquired from their scientists.

Analyses of data

ArcGIS spatial analysis

Geographic Information Systems (GIS) analyses were initially conducted to determine the locations of the sample sites within the Bay Area region. ArcGIS developed by Environmental Systems Research Institute (ESRI) was used for this task. The next step was to do a spatial analysis of the CSCI scores for each locality so that a visual analysis could be completed. All sample sites were plotted on a map as points and then each sample site was assigned individual color symbology or colors for each point with regard to the CSCI score for that site. The locality data were taken from the data provided by the SF Bay RWQCB in the form of Global Positioning System (GPS) coordinates which were recorded during sampling times. Next, in order to spatially view and analyze the proximity of sample locations to urban or developed areas, a land cover data set or map layer from the NLCD was used to visually represent urban areas on the map (Figure 3). The urban land cover categories that were used, shown on the map, and assigned color symbology were: developed, open space; developed, low intensity; developed, medium intensity; developed, high intensity; hay, open pasture; and, cultivated crops (Figure 3). The remaining land cover categories that were not used are: open water; perennial ice/snow; barren land (rock/sand/clay); deciduous forest; evergreen forest; mixed forest; dwarf scrub; shrub/scrub; grassland/herbaceous; sedge/herbaceous; lichens; moss; woody wetlands; and, emergent herbaceous wetlands (Figure 3). The CSCI scores were then visually analyzed with regard to the proximity to urban or developed areas in the Bay Area region.

Next, a spatial analysis was completed for ten individual streams: Alameda Creek, Coyote Creek, Kirker Creek, Las Trampas Creek, Pinole Creek, San Lorenzo Creek, San Mateo Creek, San Pablo Creek, Saratoga Creek, and Stevens Creek (Figure 9). The ten streams were chosen based on the number of sampled sites. The number of sampled sites for each stream was required to be 30 or greater. This way, there was a higher chance that the streams were sampled in multiple years. For the stream analyses, each of the sample sites were plotted and represented spatially on a map along with land cover (Figure 9). This map was used to provide spatial representation for both stream analyses: CSCI score variation by year, and CSCI score variation by year and analyzed by land cover.

The final GIS analysis included calculating the percent land cover within a 2000-meter radius of a sample site for each stream. ArcMap was used to plot each sample site for each stream on a map. Next, the land cover was plotted on the map. Each land cover type chosen is categorized and known to contribute to water quality impacts to streams: developed, high density; developed, medium density; developed, low density; developed, open space; pasture/hay; cultivated crops (Figure 3) (NLCD, 2019; Rehn et al. 2015). After the land cover was plotted on the map, ArcMap was used to quantify how much land cover is within a 2000-meter radius buffer of each sample site. Calculations of land cover areas within these buffers were produced for each sample site. Finally, the percent land cover was calculated for each sample site within the 2000-meter radius buffer. These analyses were conducted to determine how much urban land cover is surrounding each sample site, and how that land cover may be impacting the quality of the stream. This technique for evaluating land cover around each sample site is a new approach that has not been used in published research.

It is important to note that not all streams in the San Francisco Bay region have been sampled for calculating CSCI (Figure 4). Because not all streams have been sampled, the current data have limitations. There are a few sample events and/or sample sites that occur outside of the Region 2 boundary. These sampling events are included in the data set and so are included in some mapping analyses in order to be a complete representation of the data available.

Class\ Value		Classification Description
Water		
	11	**Open Water**- areas of open water, generally with less than 25% cover of vegetation or soil.
	12	**Perennial Ice/Snow**- areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover.
Developed		
	21	**Developed, Open Space**- areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
	22	**Developed, Low Intensity**- areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.
	23	**Developed, Medium Intensity** -areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
	24	**Developed High Intensity**-highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.
Barren		
	31	**Barren Land (Rock/Sand/Clay)** - areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
Forest		
	41	**Deciduous Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
	42	**Evergreen Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
	43	**Mixed Forest**- areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.
Shrubland		
	51	**Dwarf Scrub**- Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20% of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation.
	52	**Shrub/Scrub**- areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
Herbaceous		
	71	**Grassland/Herbaceous**- areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
	72	**Sedge/Herbaceous**- Alaska only areas dominated by sedges and forbs, generally greater than 80% of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra.
	73	**Lichens**- Alaska only areas dominated by fruticose or foliose lichens generally greater than 80% of total vegetation.
	74	**Moss**- Alaska only areas dominated by mosses, generally greater than 80% of total vegetation.
Planted/Cultivated		
	81	**Pasture/Hay**-areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.
	82	**Cultivated Crops** -areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
Wetlands		
	90	**Woody Wetlands**- areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
	95	**Emergent Herbaceous Wetlands**- Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

NLCD Land Cover Classification Legend

- 11 Open Water
- 12 Perennial Ice/ Snow
- 21 Developed, Open Space
- 22 Developed, Low Intensity
- 23 Developed, Medium Intensity
- 24 Developed, High Intensity
- 31 Barren Land (Rock/Sand/Clay)
- 41 Deciduous Forest
- 42 Evergreen Forest
- 43 Mixed Forest
- 51 Dwarf Scrub*
- 52 Shrub/Scrub
- 71 Grassland/Herbaceous
- 72 Sedge/Herbaceous*
- 73 Lichens*
- 74 Moss*
- 81 Pasture/Hay
- 82 Cultivated Crops
- 90 Woody Wetlands
- 95 Emergent Herbaceous Wetlands

* Alaska only

Figure 3. NLCD land cover classifications with descriptions (left), and the NLCD land cover classification legend that was used for the GIS dataset (right).

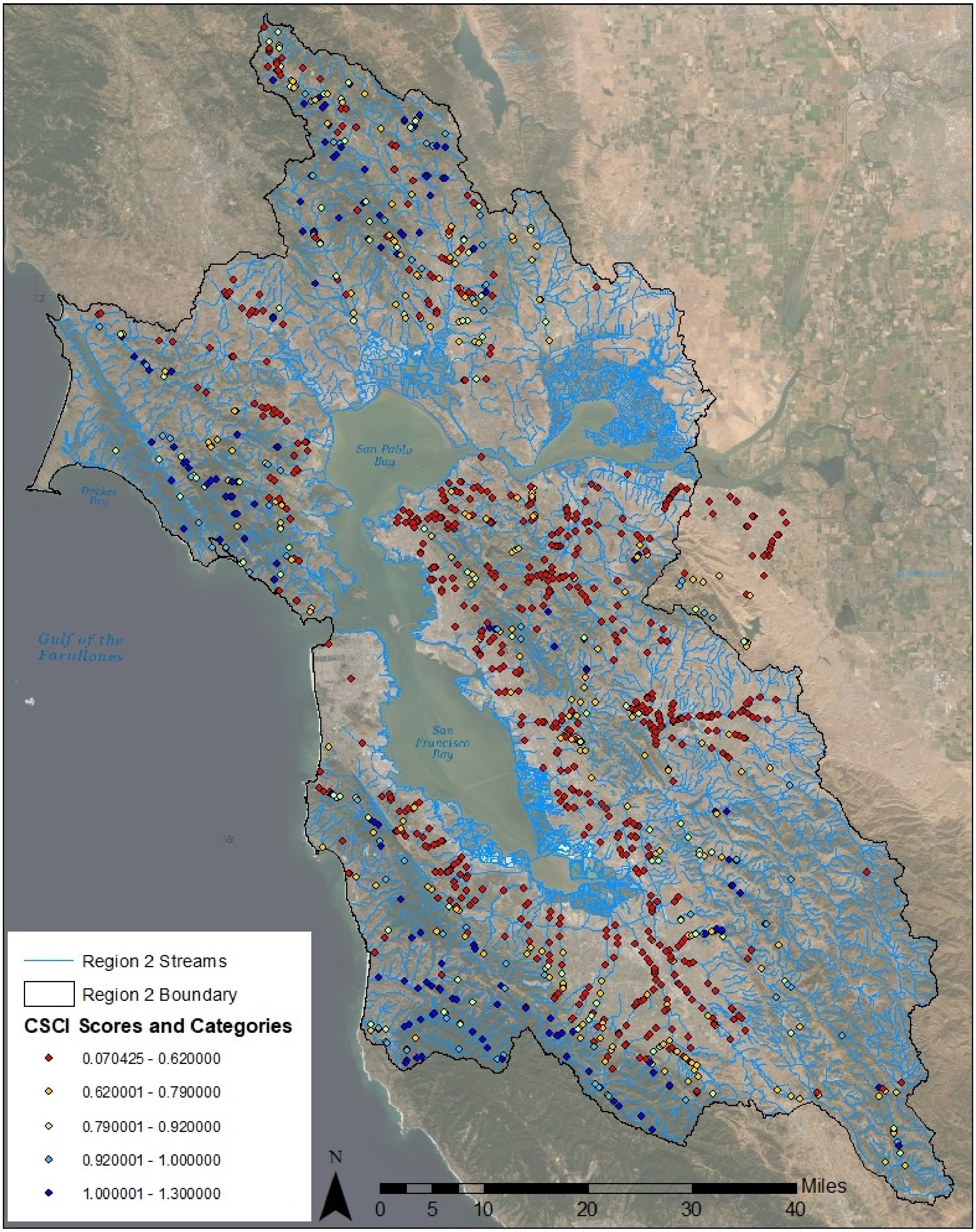


Figure 4. CSCI scores for streams of the San Francisco Bay region with a Region 2 or SF Bay RWQCB boundary and the NHD dataset of streams in Region 2.

Statistical analyses

JMP statistical software was used to analyze CSCI scores and produce metrics including the overall minimum, maximum, mean, median, number of CSCI scores, and standard deviation. A distribution of CSCI scores was calculated and visually displayed in a bar graph.

A watershed analysis was conducted initially for one watershed (Alameda Creek watershed) which has many associated sample sites. The CSCI scores and year sampled were graphed on an x-y plot and the points were assigned a color according to stream. This analysis was conducted to find a temporal trend of CSCI scores on the watershed.

Stream analyses were conducted for ten streams: Alameda Creek, Coyote Creek, Kirker Creek, Las Trampas Creek, Pinole Creek, San Lorenzo Creek, San Mateo Creek, San Pablo Creek, Saratoga Creek, and Stevens Creek (Figure 9). These streams were chosen because they have over 30 sample sites for each stream, and the streams were sampled in multiple years. The CSCI scores and year sampled were graphed on an x-y plot and the points were assigned a color according to individual sample site. This analysis was completed to analyze for a temporal trend of CSCI scores within each individual stream.

To look at a more detailed view of the CSCI scores, the variation of scores within each stream was calculated (minimum CSCI score, maximum CSCI score, and mean CSCI score). The number of sites sampled within each stream was tabulated.

For all of the streams, additional analyses were completed. For each individual stream analysis, the mean CSCI score was calculated for each sample year for each site. The mean CSCI score was calculated to show a comparison. Then the mean CSCI scores were assigned a corresponding CSCI score text category. The year, mean CSCI scores, and categories were recorded in a table for each stream and are presented in the next section.

Stream analyses show possible trends in CSCI scores for sites located in urban areas and for sites located in rural areas. For each of the ten streams, an x-y graph was produced of CSCI scores against year. Then each sample location was represented by one of two categories (two colors): 'urban' or green and 'rural' or orange. These categories were based on the GIS analysis described above, where 0% to 50% of urban area within a 2000 meter radius buffer of a sample site is categorized as 'rural', and 50% to 100% of urban area within a 2000-meter radius of a sample site is categorized as 'urban'. Previous research has shown ambiguity in how rural and urban areas are categorized as having impacts on streams or water bodies. Some studies show that as low as 10% to 20% urban land cover have significant impacts on streams, and some show that as high as 60% to 90% urban land cover is needed to have significant impacts on streams (Allan, 2004). First, all ten streams were graphed together, and then the mean for each land cover category (urban and rural) was plotted on the graph. Then each stream was individually graphed with sample sites categorized into one of the two land covers. Each land cover was again assigned a color. Each of these stream graphs was used to analyze each stream individually.

Results

CSCI, land use, and basic metrics

A spatial representation of CSCI scores and land cover showed that the sample sites with higher CSCI scores generally align with rural areas and the sample sites with lower CSCI scores generally align with urban areas (Figure 5). The spatially represented points on the map represent each sample location while the colors or symbology of the points represent the CSCI score ranges. Many of the sample sites have lower CSCI scores (red), meaning the majority of the stream sites are in 'very likely altered' stream conditions or are more impacted. The low CSCI scores are mostly located at or within proximity of urban or developed areas (Figure 5). As previous research has shown (Rehn et al., 2015; Allan et al., 2004), and as to be expected, streams are more impacted in urban areas. The NLCD map layer indicates different colors or symbology regarding the categories of urbanization. The areas with red and orange hues indicate the categories of development and the areas with green and yellow hues indicate agricultural areas, and pasture and grazing areas. Most of the lowest CSCI score sample sites are located in the areas with more development or urban land cover, while most of the highest CSCI score sample sites are located in areas with little to no development or urban land cover. The visual representation also shows that many of the intermediate CSCI score sample sites are located in between areas with more development (urban) and areas with little to no development (rural). This suggests that a transition area between urban and rural land cover areas may exist. The distribution of CSCI scores indicates that the majority of the sites have scores in the lower ranges which translate to lower quality (Figures 5 and 6).

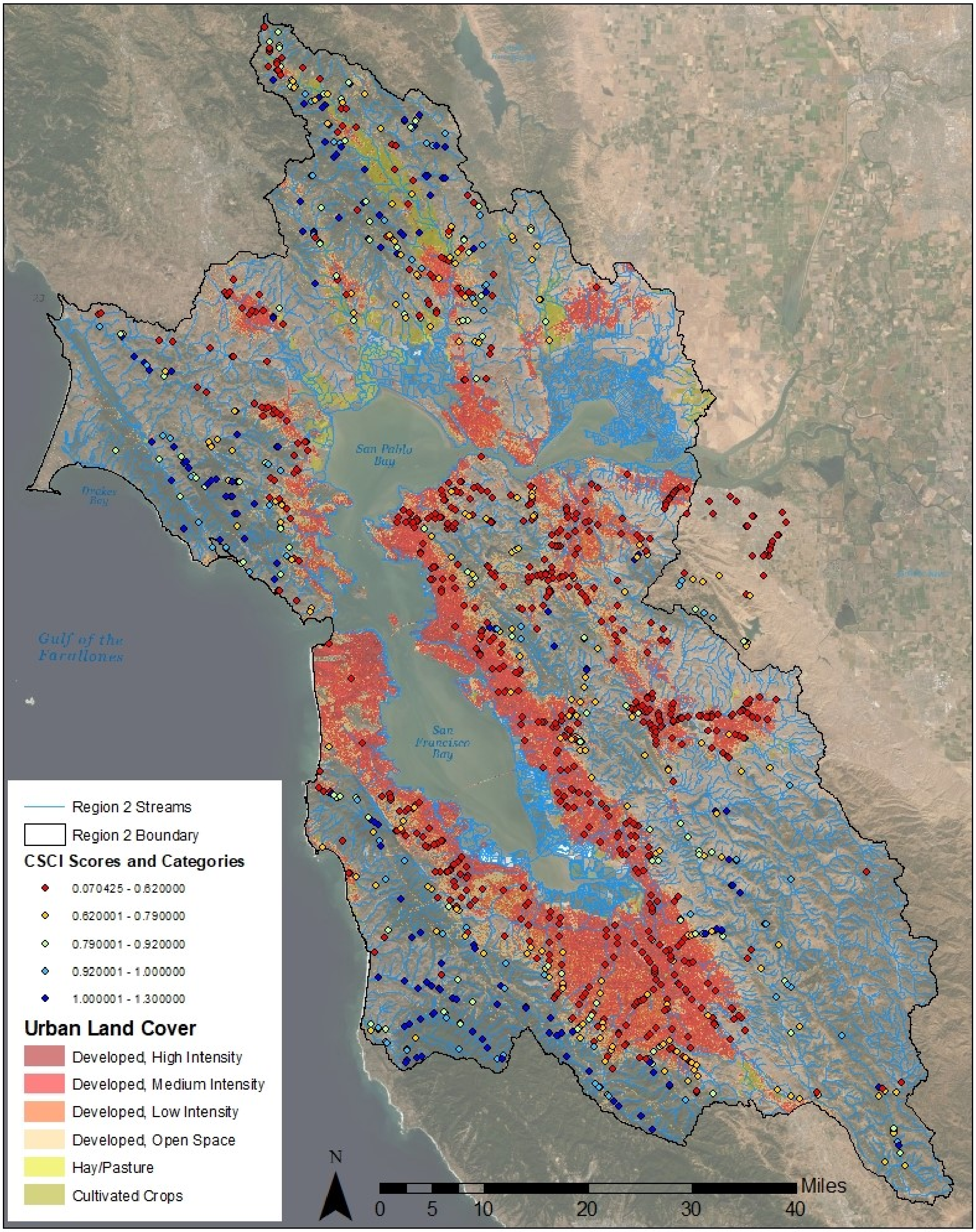


Figure 5. Spatial representation of CSCI sample sites of streams and watersheds sampled between 1998 and 2017 in the San Francisco Bay region.

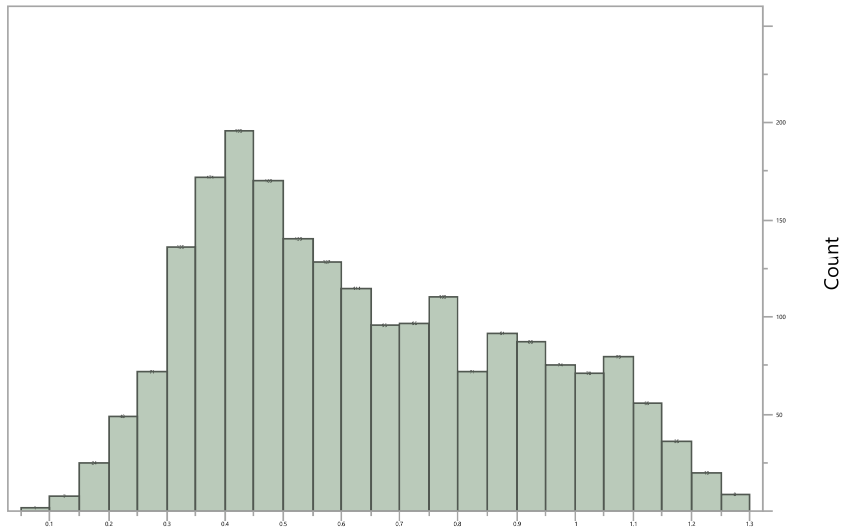


Figure 6. Distribution of CSCI scores of 2089 sampled sites in the San Francisco Bay Region. Numbers above bars indicate number of sampled sites in that range.

The minimum and maximum values of 2089 CSCI scores indicate a large variation between the worst quality streams and the best quality streams in the San Francisco Bay region; CSCI scores ranged from 0.07 to 1.28. The mean and the median are quite close in value where the median value of 0.58 falls within the 'very likely altered' CSCI category and the mean value of 0.63 is barely above this category in the 'likely altered' CSCI category (Rehn et al. 2015). The majority of sites fall under these two categories, 'likely altered' and 'very likely altered', in fact 1,501 of the sites sampled have CSCI scores below 0.79. The percent of sites in degraded conditions is about 72% and the remaining 588 sampled sites or 28% are not in degraded conditions with scores of 0.79 and above. Not every single stream or watershed in the San Francisco Bay region has been sampled (Figure 4).

Watershed analysis

The results of the CSCI variation within each watershed generally show extreme variation between the minimum and maximum CSCI scores for watersheds that have 20 or more sample sites. This is probably due to the extremely variable habitat, land cover, and gradient differences along the watershed as well as the many streams and tributaries along a main stem river that compose a watershed. Not all stream sample sites were sampled consistently each year. For example in the Alameda Creek watershed one stream, Arroyo Mocho, was mostly sampled in 2005, and then a different stream, Martin Canyon Creek, was mostly sampled in 2006 (Figure 7). In 2013, many more streams were sampled than in other years. Other watersheds showed similarly varied results with inconsistent sampling in streams and therefore no possibility of showing any statistically significant temporal trends.

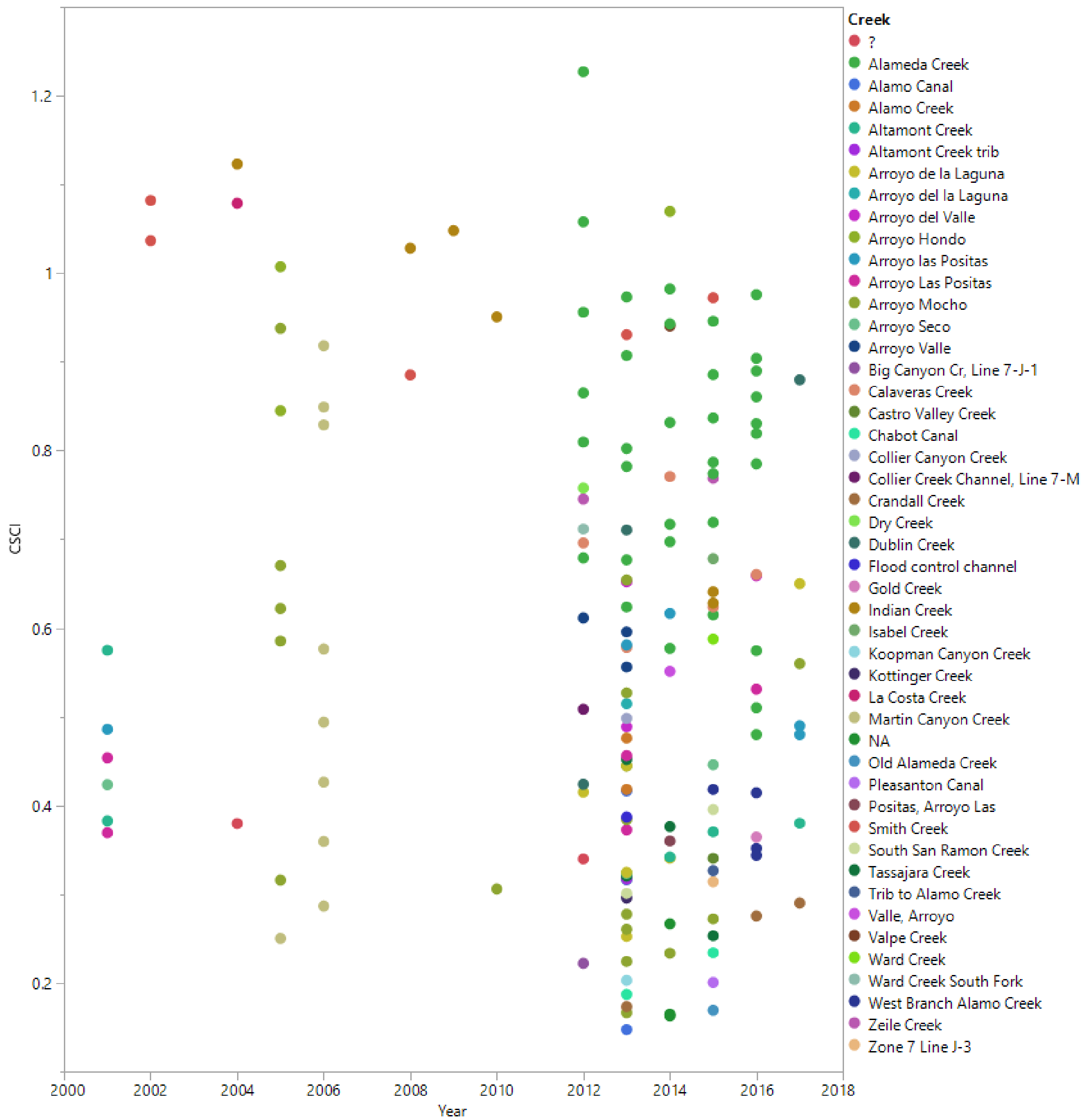


Figure 7. Alameda Creek watershed CSCI scores by year. Data presented also represent frequency of sampling. Each colored point represents a different creek.

Stream analyses

CSCI score variation by year

The results were extremely variable at the watershed level, so the next analyses focused on individual streams to analyze for temporal trends at a smaller scale. Each individual stream that was analyzed has sampling events that occurred in different years. These sampling events were analyzed to find temporal trends in mean CSCI scores for each year that sampling events occurred, for each stream (Figure 8). Similar to the watershed analysis, the results of temporal variation were so varied that none of the results were conclusive. The variable results can be attributed to inconsistent sampling: the same locations for sampling events were not used each year, instead, the same locations were occasionally used, but many times new locations were chosen for sampling events, from year to year. The number of sampling events each year were highly variable.

Alameda Creek

Alameda Creek is an individual stream in the Alameda Creek watershed (Figure 8A). Alameda Creek is located in Alameda County in the eastern area of the San Francisco Bay region. Sampling was conducted on Alameda Creek between 2012 and 2016 with 35 sampling events at 11 different sites (Figure 8A).

Coyote Creek

Coyote Creek is an individual stream in the Coyote Creek watershed. Coyote Creek is located in Santa Clara County which is in the southern area of the San Francisco Bay region and is a heavily impacted creek. Samples were collected between 2004 and 2015 with 49 sampling events at 31 different sites (Figure 8B).

Kirker Creek

Kirker Creek is located in Contra Costa County in the eastern area of the San Francisco Bay region. Sampling in Kirker Creek was completed between 2003 and 2011 with 41 sampling events at 18 different sites (Figure 8C).

Las Trampas Creek

Las Trampas Creek is located in Contra Costa County, in the eastern area of the San Francisco Bay region. Las Trampas Creek was sampled from 2003 to 2016 with 38 sampling events at 16 different sites (Figure 8D).

Pinole Creek

Pinole Creek is located in Contra Costa County, in the eastern area of the San Francisco Bay region, and the stream flows into the San Pablo Bay. Pinole Creek was sampled from 2002 to 2013 with 43 sampling events at 12 different sites (Figure 8E).

San Lorenzo Creek

San Lorenzo Creek is located in Alameda County in the eastern area of the San Francisco Bay region. The stream flows into the San Francisco Bay after passing through a very urban and developed area. San Lorenzo Creek was sampled from 1998 to 2017 with 33 sampling events at 11 different sites (Figure 8F).

San Mateo Creek

San Mateo Creek is located in San Mateo County, in the peninsula area of the San Francisco Bay region. The creek flows into the San Francisco Bay and is a part of a watershed that includes Crystal Springs Reservoir. San Mateo Creek was sampled from 2003 to 2017 with 43 sampling events at 18 different sites (Figure 8G).

San Pablo Creek

San Pablo Creek is located in Contra Costa County, in the eastern area of the San Francisco Bay region. The creek flows into the San Pablo Bay. San Pablo Creek was sampled between 2001 and 2014, with 36 sampling events at 14 different sites (Figure 8H).

Saratoga Creek

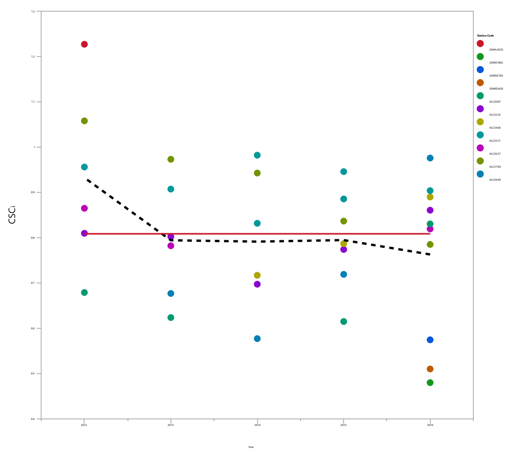
Saratoga Creek is located in Santa Clara County in the southern area of the San Francisco Bay region. The creek flows into the South San Francisco Bay. The creek flows through foothills as well as urban and developed areas. Saratoga Creek was sampled from 2004 to 2016 with 35 sampling events at 16 different sites (Figure 8I).

Stevens Creek

Stevens Creek is located in Santa Clara County, near Saratoga Creek, in the southern area of the San Francisco Bay region. The creek flows into the South San Francisco Bay. Stevens Creek was sampled from 2002 to 2017 with 35 sampling events at 19 different sites (Figure 8J).

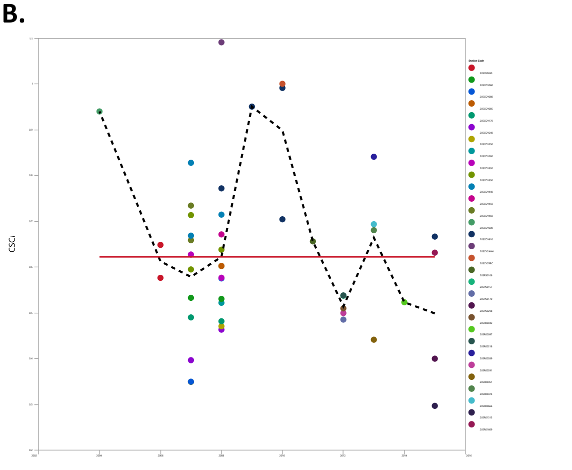
The stream analyses show how varied the temporal results are (Figure 8). Each point represents a sampling event and the color of the point represents a sampling site. It is very apparent that the point colors, or sample sites, are not consistent from year to year, and the mean CSCI scores generally do not have any temporal trends. For most of the ten streams, the sampled sites are different for each sampling event. In cases where the sample sites are the same for some sampling events, not enough sampling events in different years occurred for statistically significant temporal analyses to be completed. The streams were sampled in multiple years but were not always sampled in consecutive years.

A.



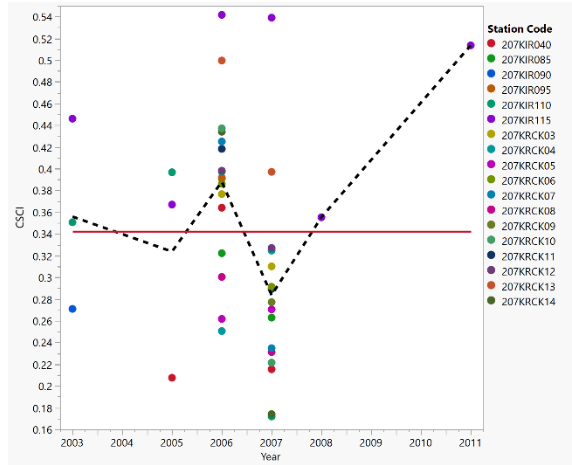
Year	Mean CSCI Score	CSCI Score Category
2012	0.932502	Likely intact
2013	0.794331	Possibly altered
2014	0.791409	Possibly altered
2015	0.79476	Possibly altered
2016	0.763051	Likely altered

B.



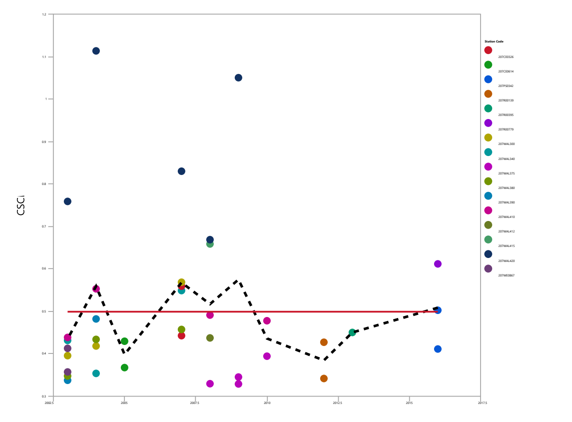
Year	Mean CSCI Score	CSCI Score Category
2004	0.940344	Likely intact
2006	0.612627	Very likely altered
2007	0.578744	Very likely altered
2008	0.622423	Very likely altered
2009	0.950909	Likely intact
2010	0.899003	Possibly altered
2011	0.656318	Likely altered
2012	0.514096	Very likely altered
2013	0.664308	Likely altered
2014	0.523201	Very likely altered
2015	0.498814	Very likely altered

C.



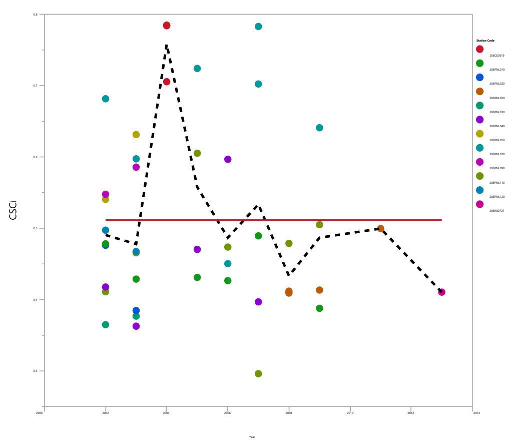
Year	Mean CSCI Score	CSCI Score Category
2003	0.355856	Very likely altered
2005	0.323645	Very likely altered
2006	0.387934	Very likely altered
2007	0.283546	Very likely altered
2008	0.355247	Very likely altered
2011	0.513581	Very likely altered

D.



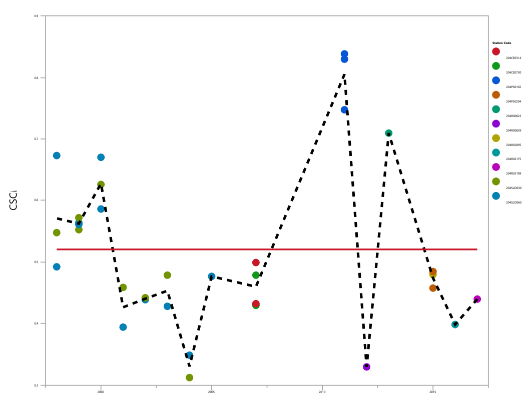
Year	Mean CSCI Score	CSCI Score Category
2003	0.435064	Very likely altered
2004	0.559166	Very likely altered
2005	0.398608	Very likely altered
2007	0.567876	Very likely altered
2008	0.517177	Very likely altered
2009	0.574899	Very likely altered
2010	0.436164	Very likely altered
2012	0.384578	Very likely altered
2013	0.450327	Very likely altered
2016	0.611812	Very likely altered

E.



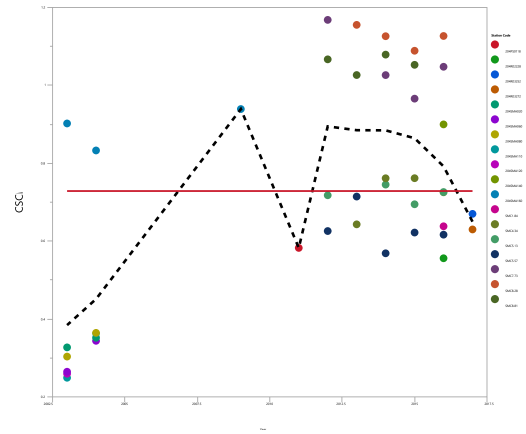
Year	Mean CSCI Score	CSCI Score Category
2002	0.49055	Very likely altered
2003	0.477815	Very likely altered
2004	0.758041	Likely altered
2005	0.557652	Very likely altered
2006	0.486798	Very likely altered
2007	0.533485	Very likely altered
2008	0.433246	Very likely altered
2009	0.486774	Very likely altered
2011	0.499587	Very likely altered
2013	0.41043	Very likely altered

F.



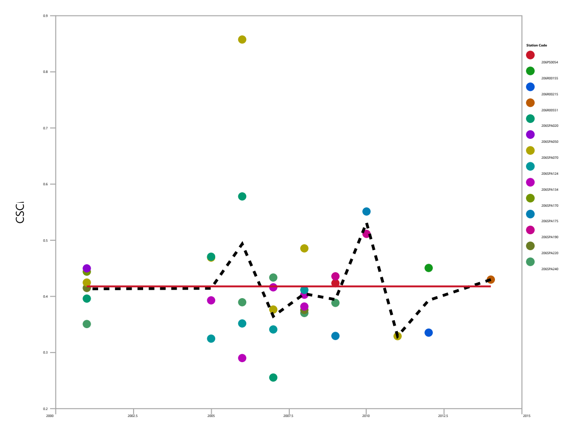
Year	Mean CSCI Score	CSCI Score Category
1998	0.571115	Very likely altered
1999	0.562492	Very likely altered
2000	0.627525	Likely altered
2001	0.426727	Very likely altered
2002	0.44058	Very likely altered
2003	0.453558	Very likely altered
2004	0.330727	Very likely altered
2005	0.476883	Very likely altered
2007	0.460124	Very likely altered
2011	0.804994	Possibly altered
2012	0.329903	Very likely altered
2013	0.709482	Likely altered
2015	0.474143	Very likely altered
2016	0.398707	Very likely altered
2017	0.440000	Very likely altered

G.



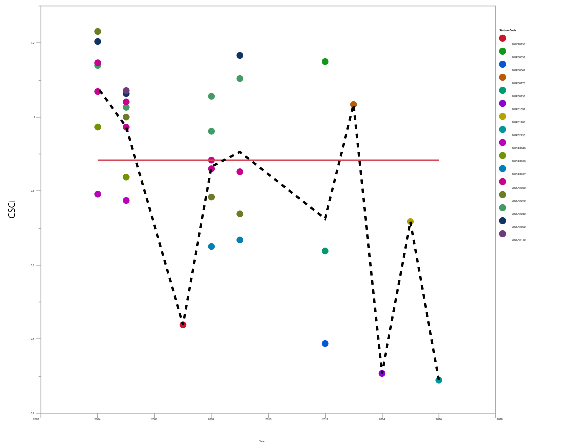
Year	Mean CSCI Score	CSCI Score Category
2003	0.384320	Very likely altered
2004	0.451245	Very likely altered
2009	0.939221	Likely intact
2011	0.582589	Very likely altered
2012	0.894670	Possibly altered
2013	0.884872	Possibly altered
2014	0.884501	Possibly altered
2015	0.864314	Possibly altered
2016	0.792061	Possibly altered
2017	0.650000	Likely altered

H.



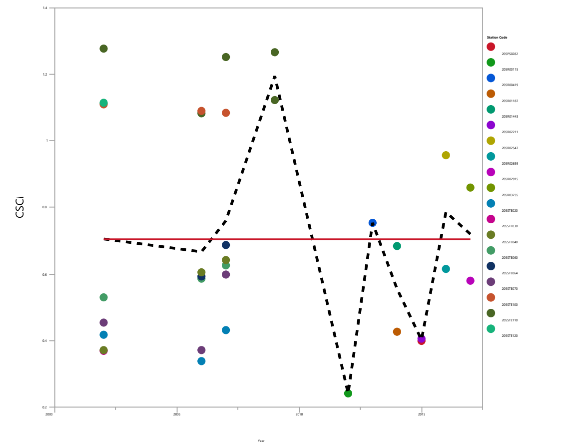
Year	Mean CSCI Score	CSCI Score Category
2001	0.413424	Very likely altered
2005	0.414380	Very likely altered
2006	0.493444	Very likely altered
2007	0.364582	Very likely altered
2008	0.404694	Very likely altered
2009	0.394324	Very likely altered
2010	0.531277	Very likely altered
2011	0.329142	Very likely altered
2012	0.393044	Very likely altered
2014	0.429910	Very likely altered

I.



Year	Mean CSCI Score	CSCI Score Category
2004	1.079283	Better than expected
2005	0.973366	Likely intact
2007	0.438842	Very likely altered
2008	0.866003	Possibly altered
2009	0.905849	Possibly altered
2012	0.72538	Likely altered
2013	1.033929	Better than expected
2014	0.307395	Very likely altered
2015	0.71767	Likely altered
2016	0.28918	Very likely altered

J.



Year	Mean CSCI Score	CSCI Score Category
2002	0.705638	Likely altered
2006	0.666825	Likely altered
2007	0.760399	Likely altered
2009	1.194935	Better than expected
2012	0.241259	Very likely altered
2013	0.753969	Likely altered
2014	0.555415	Very likely altered
2015	0.402463	Very likely altered
2016	0.786323	Likely altered
2017	0.720000	Likely altered

Figure 8. A through J, Bivariate fit of CSCI scores and year for each of ten focus streams: A. Alameda Creek, B. Coyote Creek, C. Kirker Creek, D. Las Trampas Creek, E. Pinole Creek, F. San Lorenzo Creek, G. San Mateo Creek, H. San Pablo Creek, I. Saratoga Creek and J. Stevens Creek. For each graph, the black dashed line indicates the mean CSCI score for each sampling year. The red solid line represents the mean CSCI score for all sampling events. Each colored point represents a sample site indicated in the legend as the Station Code. The corresponding tables represent each stream and indicate the mean CSCI scores for each year of sampling and their associated text category.

CSCI score variation by year and analyzed by land cover

Since the previous stream analysis of variation of CSCI score by year for each stream was not conclusive, the data was then categorized by land cover to evaluate any trends or patterns in the data. These analyses resulted in the calculation of percent land cover surrounding each sample site. The mapping analyses first show the selected ten streams in with their associated sample sites with corresponding CSCI scores for each site (Figure 9). At first glance, the lower CSCI scores appear to align with the urban land cover, and the higher CSCI scores appear to align with the rural land cover. The 2000-meter buffer around each sample site shows a substantial amount of area that will be analyzed and calculated for land cover area (Figure 10). The land cover calculation within a 2000-meter buffer for each sample site, shows that not all sites have land cover surrounding them, but many of the sample sites have a large area of surrounding urban land cover. Most of the sites within this analysis were categorized as “urban”, while fewer sites were categorized as “rural”. But, as was mentioned previously, not all streams within the San Francisco Bay region have been sampled, and many of the streams that have not yet been sampled appear to be in “rural” land cover areas (Figure 4). If all the “rural” land cover streams had been sampled and CSCI scores calculated, the results could be even more distinct where the differentiation between “urban” and “rural” sample sites would be more pronounced.

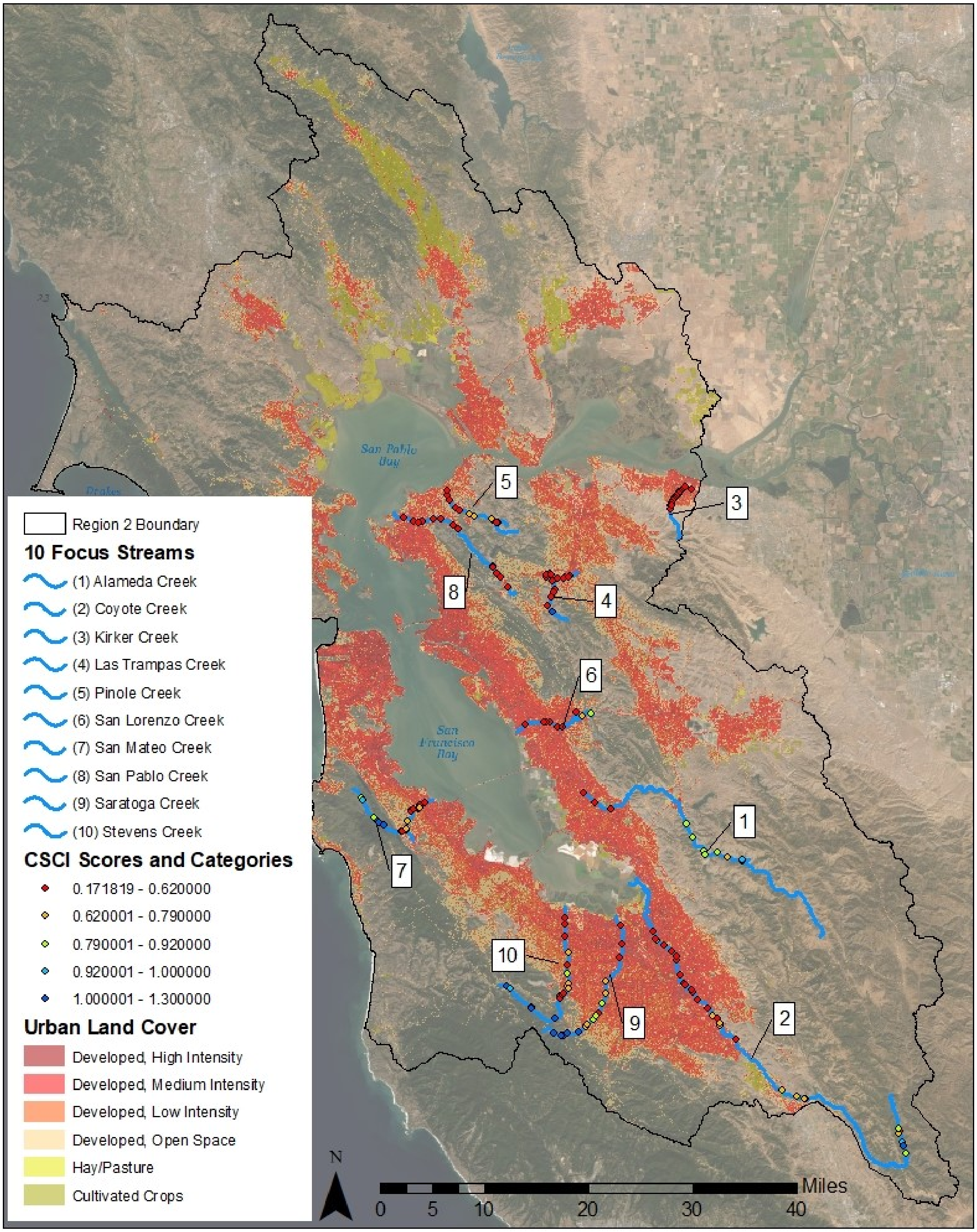


Figure 9. The ten focus streams chosen for analyses, mapped with the corresponding CSCI scores for each stream and the urban land cover from the NLCD. The map also includes the SF Bay RWQCB boundary (black solid line).

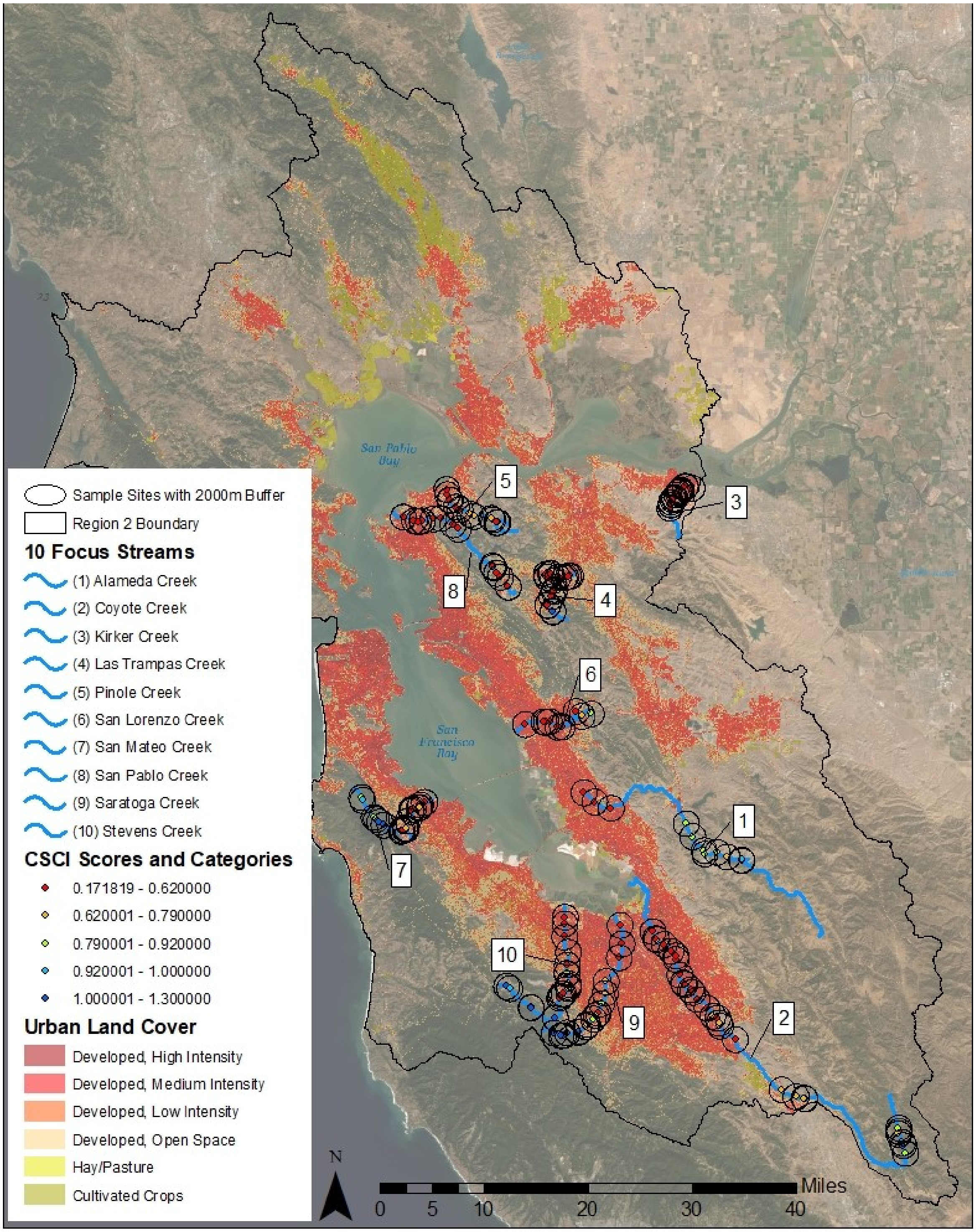


Figure 10. The ten focus streams for the individual site land cover analyses. Each individual site has a 2000-meter buffer around the site.

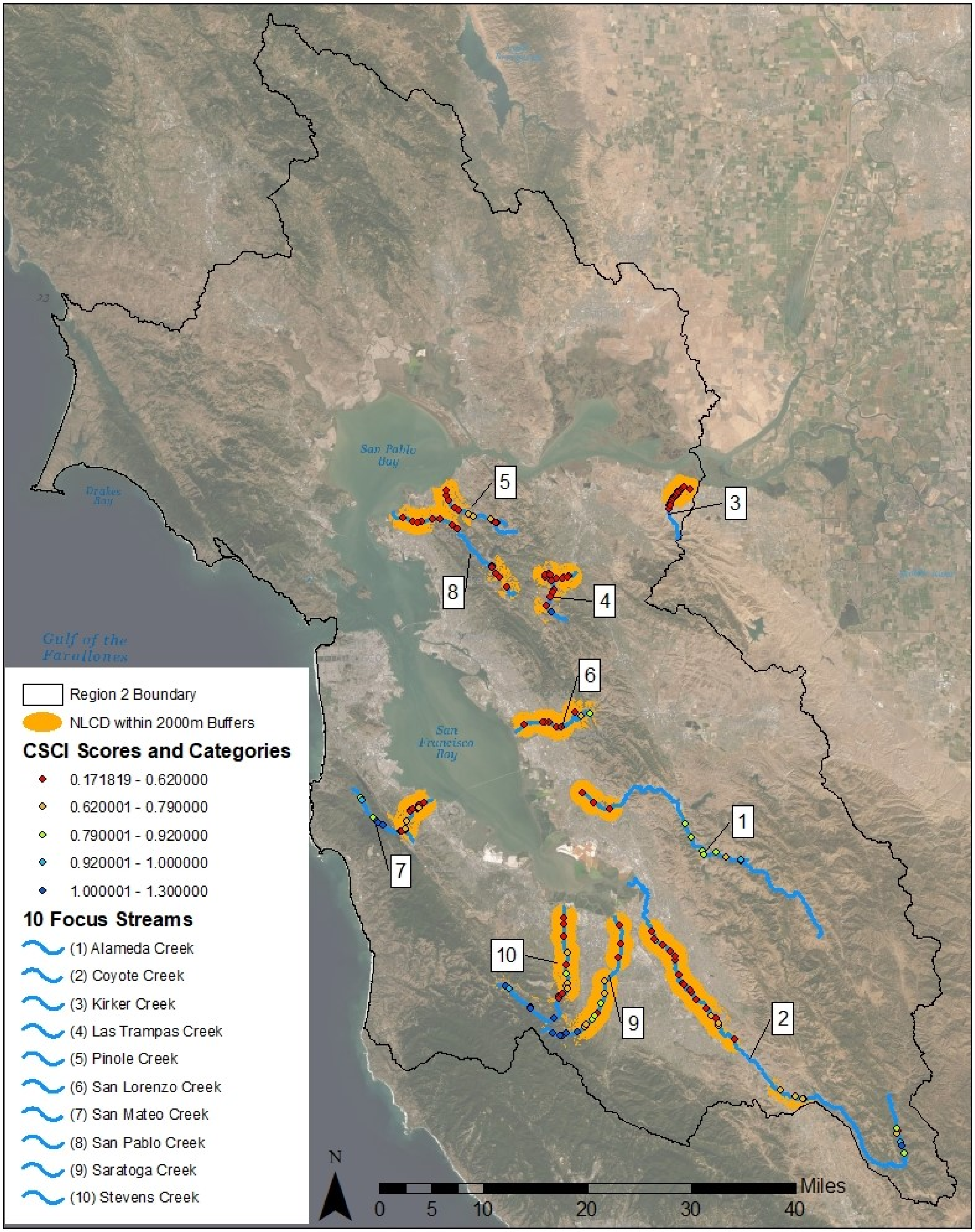


Figure 11. Ten focus streams for the individual site land cover calculation with the land cover area around each site that is within the 2000-meter buffer which was calculated in ArcMap.

Ten focus streams

When the ten focus streams are analyzed by plotting CSCI score by year, then categorizing each sample site into either an 'urban' category or a 'rural' category, the 'rural' sites mostly have higher CSCI scores, and the 'urban' sites mostly have lower CSCI scores (Figure 12). The mean CSCI score for 'rural' sample sites is 0.75, which corresponds with a 'likely altered' stream condition category. The mean CSCI score for 'urban' sites is 0.51, which corresponds with a 'very likely altered' stream condition category. A distinction between each land cover category is clear since most of the 'rural' sites are clustered toward the top of the graph, corresponding with higher CSCI scores, and most of the 'urban' sites are clustered toward the bottom of the graph, corresponding with lower CSCI scores (Figure 12). Clearly, there is a distinction between sites with higher urban land cover and sites with lower 'urban' land cover that are more representative of 'rural' conditions. These results are consistent with previous research which concludes that a higher percentage of urban and developed land cover surrounding streams, significantly impacts the quality of those streams, and that land cover influences the quality of streams (Allan, 2004).

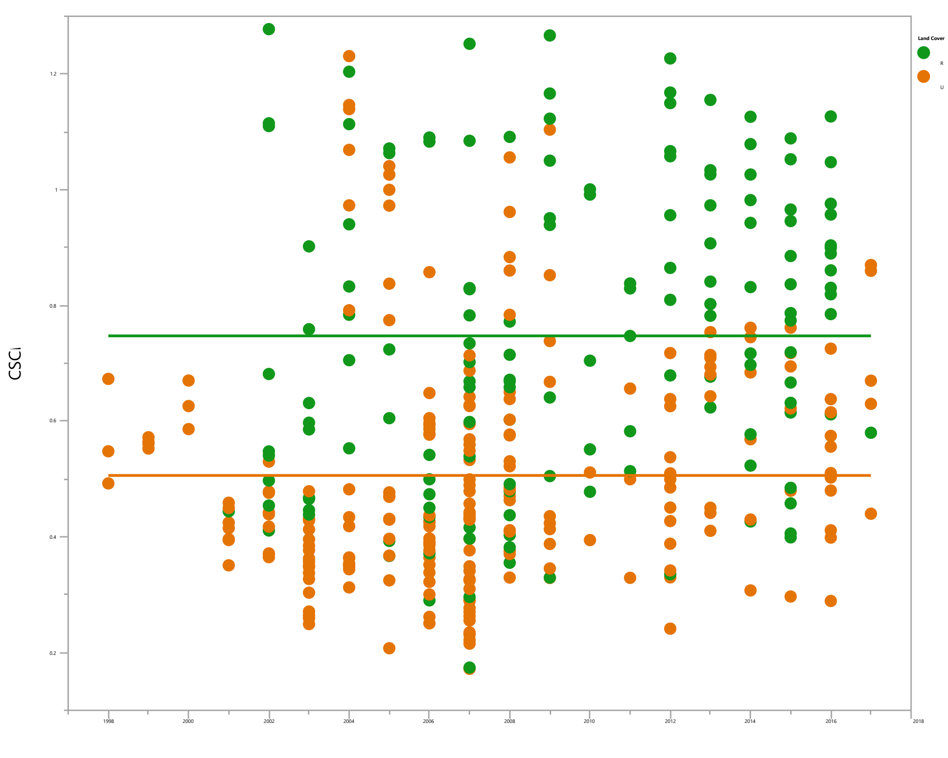


Figure 12. The CSCI scores from the ten focus streams graphed against the year of each sample. The green points indicate sample sites located in rural (R) land cover areas, and the orange points indicate sample sites located in urban (U) land cover areas, as shown in the legend.

Alameda Creek

In Alameda Creek rural sites have higher scores than the urban sites which is consistent with the trend (Figure 13A). The rural sites clearly have higher CSCI scores and the urban streams clearly have lower scores. However, the urban streams only include three sample sites which are not entirely representative of the entire reach of the stream that is located in urban land cover areas. Additional monitoring data would be useful for future analyses of the condition of this stream, especially to determine the condition of the urban areas of this stream.

Coyote Creek

In Coyote Creek rural sites generally have higher CSCI scores than the urban sites, which is consistent with analysis of all ten streams (Figure 13B). The rural sites mostly have higher CSCI scores than the urban sites, but there is some overlap. This could be due to several environmental factors, and for future studies, it will be important to consider these other factors (such as water chemistry or physical habitat, etc.), both with CSCI data analysis and with future monitoring efforts on Coyote Creek.

Kirker Creek

In Kirker Creek had a difference between the two land cover types (Figure 13C). This is an interesting result since the values of the CSCI scores do not go beyond 0.54, which shows that the stream reaches that were sampled may be highly impacted by urbanization and development. The 0.54 value corresponds with the CSCI score text category of ‘very likely altered’.

Las Trampas Creek

In Las Trampas Creek results are consistent with the first analysis of all ten streams as well as Alameda Creek (Figure 13D). The differences between sample sites in rural versus urban land cover sites are clearly defined, where rural sample sites have higher CSCI scores and urban land cover sample sites have lower CSCI scores.

Pinole Creek

In Pinole Creek the urban and rural land cover differences exist for this stream (Figure 13E). There are some sample sites from rural and urban land cover areas that overlap on the graph, and this may be due to other environmental factors such as water chemistry or physical habitat. These data will be available to analyze in the future.

San Lorenzo Creek

San Lorenzo Creek does not have many sample sites from a rural land cover area, and it appears that about half of these sites have higher CSCI scores while the other half of these rural land cover sites have lower CSCI scores (Figure 13F). This may be due to other environmental factors at the stream as well as perhaps a lack of sampling data. Additional monitoring data would be useful for future analyses of the condition of this stream.

San Mateo Creek

San Mateo Creek has a very distinct division between rural and urban land cover sites with only one rural land cover site that overlaps with urban land cover sites (Figure 13G). This overlap may be due to other environmental factors as indicated previously.

San Pablo Creek

San Pablo Creek does not have a distinct or definitive result (Figure 13H). The scores for both urban and rural land cover sites overlap with each other on the graph. The difference between sample sites that are located in either rural or urban land cover areas is not clearly defined. This could be due to several environmental factors, and for future studies, it will be important to consider these other factors (such as water chemistry or physical habitat, etc.), both with data analysis and with future monitoring efforts on the creek.

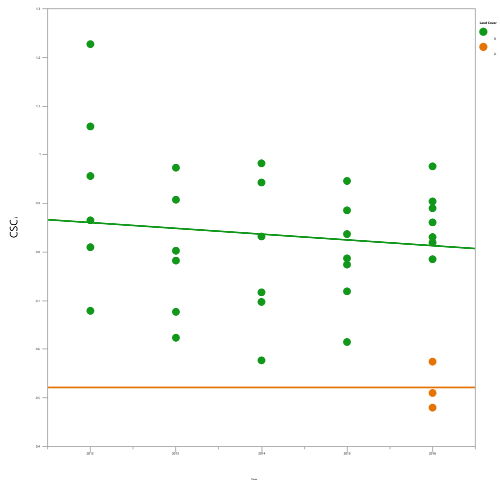
Saratoga Creek

Saratoga Creek has very few sites that qualify as having surrounding land cover that is rural, relative to the number of sites that qualify as having urban land cover (Figure 13I). Some of the urban land cover sites have higher CSCI scores. This could be due to other environmental factors such as physical habitat that may be of high quality in the urban areas. The higher CSCI scores could be due to how the creek is managed. Additional monitoring data would be useful in future analyses of this stream.

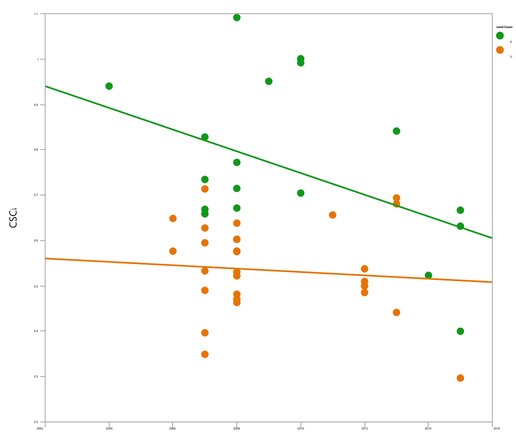
Stevens Creek

In Stevens Creek sites with lower CSCI scores are generally categorized as urban land cover sites, and sites with higher CSCI scores are generally categorized as rural land cover sites (Figure 13J). However, there is some overlap between site land cover types. This could be due to other environmental factors as mentioned previously.

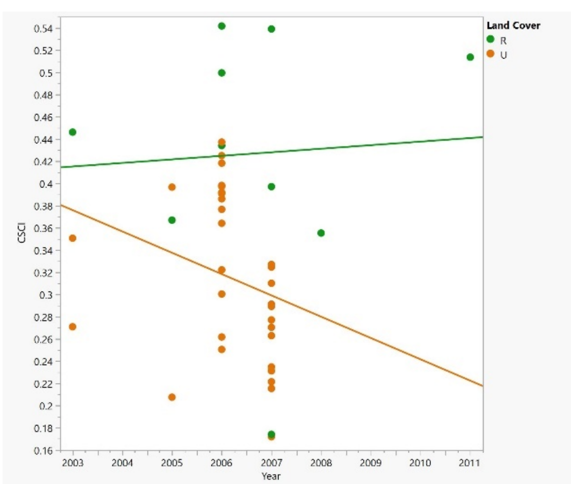
A.


CSCi

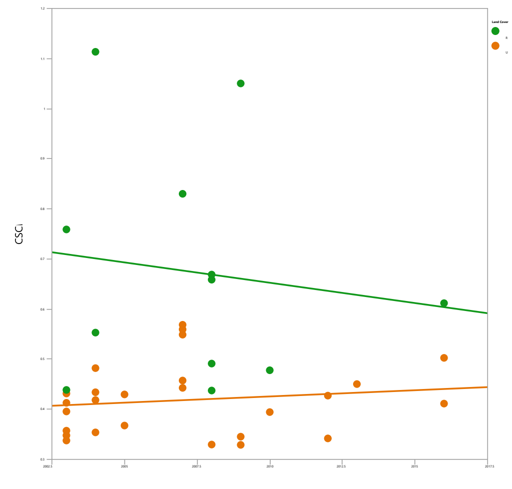
B.


CSCi

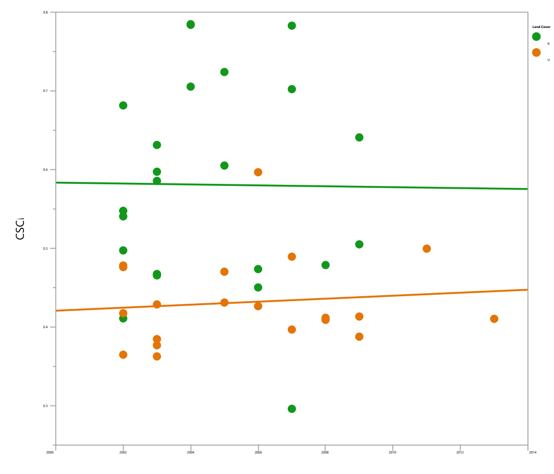
C.


Land Cover
R
U
CSCI
Year
0.54
0.52
0.5
0.48
0.46
0.44
0.42
0.4
0.38
0.36
0.34
0.32
0.3
0.28
0.26
0.24
0.22
0.2
0.18
0.16
2003
2004
2005
2006
2007
2008
2009
2010
2011

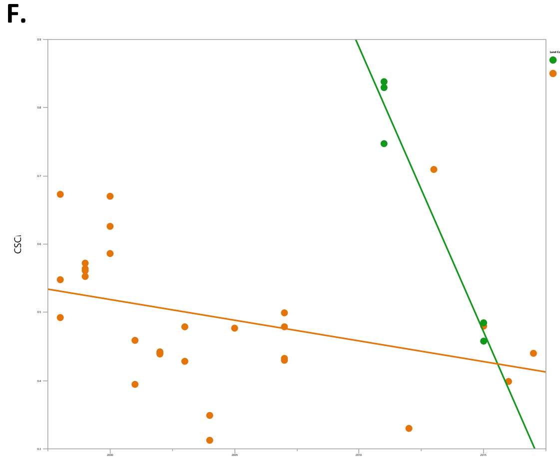
D.


CSCi

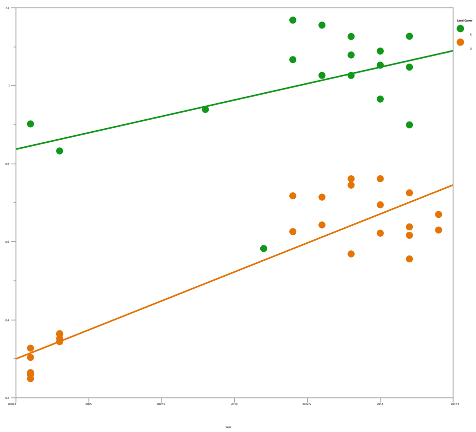
E.


CSCi

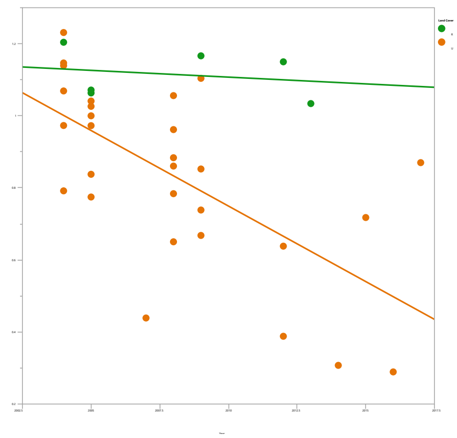
F.


CSCi

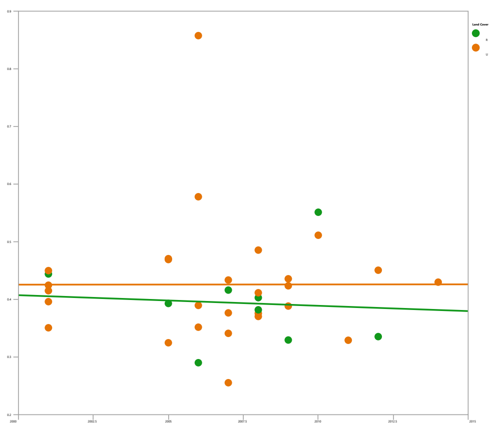
G.



I.



H.



J.

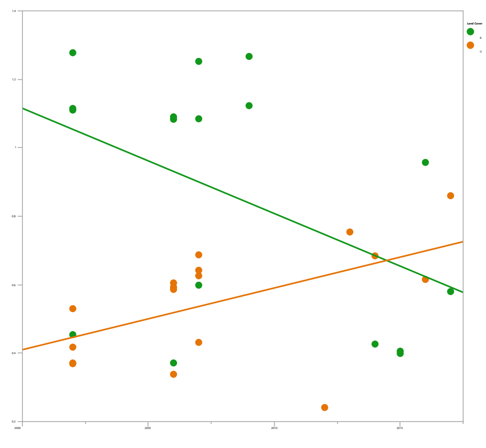


Figure 13. A through J, CSCI scores graphed on the y-axis against the year on the x-axis, according to sample site land cover (rural or urban). Each graph represents each of the ten focus streams: A. Alameda Creek, B. Coyote Creek, C. Kirker Creek, D. Las Trampas Creek, E. Pinole Creek, F. San Lorenzo Creek, G. San Mateo Creek, H. San Pablo Creek, I. Saratoga Creek and J. Stevens Creek. Rural land cover sample sites are indicated in green and urban land cover sites are indicated in orange.

Discussion

Spatial analysis of all CSCI scores versus land cover, and basic metrics

The spatial analysis of all CSCI scores in the San Francisco Bay region versus land cover from the NLCD indicated that most of the CSCI scores and categories correlate with land cover data, the greater area of urban land cover, the more likely the CSCI score will be lower, and vice versa. The types of land cover that were extracted from the NLCD data set included five types as classified by the NLCD: developed, high intensity; developed, medium intensity; developed, low intensity; developed, open space; hay, open pasture; and, cultivated crops (Figure 3). These land cover types include the categories that contribute the most pollution run-off into streams (Figure 3). The spatial analysis shows that the impacted streams are generally within urban areas. Spatially, a distinction was shown between the urban areas and the rural areas and shows that fewer impacts occur to stream reaches located in rural areas which is evidenced in the higher CSCI scores.

It is important to note that not all streams in the San Francisco Bay region have been sampled (Figure 4). Since not every stream has been sampled, the data are limited. Since the data are limited, the ability to conduct a variety of analyses are limited.

The summary statistics could be interpreted as representative of the San Francisco Bay region. The San Francisco Bay Area is very evenly spatially represented regarding area as well as land cover, habitat, and gradient (Figure 4). A safe evaluation would be that most of the streams in the San Francisco Bay region are altered.

Watershed analysis of CSCI scores

The watershed analysis approach revealed that it obviously would not work for evaluating possible temporal trends in the data. The data was too varied: the same streams were not sampled each year, and the number of streams sampled each year varied. The CSCI scores were extremely variable. It was determined that an analysis at a smaller scale should be completed, such as an analysis at the stream level scale.

Stream analyses of CSCI scores over time

The temporal data from the ten stream analyses of CSCI scores over time, did not have any conclusive results. There was not enough consistency in the data to have a statistically significant and robust result (Figure 8). Even when the CSCI text categories were identified for each mean for each year for each individual stream, there were rarely any apparent trends, and when trends did exist, again the data were not consistent and numerous enough to support any such trend.

Stream analyses of CSCI scores categorized by land cover

The next stream analysis was conducted to categorize sample sites by land cover depending on the percent of urban land cover that exists within at 2000-meter radius of the sample site. This analysis was done in order to follow metrics from previous research, but to also adapt the analysis to the data set for the San Francisco Bay region by taking the overall landscape into account. Previous research has used different types of buffers: sub-watersheds, entire streams, streams divided into reaches, and previous research has used different buffer sizes, specifically buffers around entire streams, and these have ranged from 50 meters to 2000 meters (Allan, 2004; Goddard et al., 2008; Richards et al. 1994; Sun et al. 2016; and, Yin et al., 2005). Previous research has rationalized and explained that it was important for their study to calculate the land cover based on the entire length of the stream since the water quality upstream could influence the water quality downstream, thus the stream quality would be influenced. Since the 10 streams used in this analysis flowed from upstream rural areas to downstream urban areas, it became more important to separate each sample site according to land cover. Therefore, a new GIS spatial analysis scheme was used for this study based on previous research and best scientific judgement.

The stream analyses which are based on categorizing each site according to land cover, show that a separation of CSCI scores between sites that have different land cover. The GIS spatial analysis technique was successful in proving that the land cover may have a significant impact on how these streams function in the San Francisco Bay region’s landscape. The CSCI scores show that the benthic macroinvertebrates are impacted by the change in land cover from upstream rural areas to downstream urban areas.

The stream analyses revealed that more monitoring data would be useful in some cases to address the overlap between rural and urban land cover sites. Additional data analyses may show that an interim land cover category may be necessary to evaluate this data, such as ‘mixed urban and rural’. Or additional data analyses may show that these outlier data are due to water chemistry, and/or physical habitat, and/or other parameters that were measured.

Conclusions

CSCI scores have a trend based on land cover

CSCI scores generally correlate with land cover, where lower scores occur in urban areas and higher scores occur in rural areas. These results are consistent with previous studies that evaluate land cover and benthic macroinvertebrate populations (Rehn et al., 2015, Hawkins et al., 2010). In previous studies, other techniques are used to evaluate the land cover around streams or watersheds. For example, some studies use the sub-watershed area, others evaluate the entire stream with a buffer zone, and even others evaluate individual stream reaches with a buffer zone (Allan, 2004). These different techniques were used and adapted to each study as they were applied and made sense to use for each particular landscape. For example, these studies used anywhere from a 50-meter buffer to a 2000-meter buffer. This project used a 2000-meter buffer to account for as much variation as possible within percent land cover area surrounding individual sample sites.

Different percent urban land cover or impervious area land cover were identified as having impacts to the benthic macroinvertebrate populations, and therefore impacts to stream quality. Essentially, in different studies and different study locations, there were different results. A study in Wisconsin, showed that a small percentage of urban land cover, between 8% and 12% contributed to BMI index declines (Allan, 2004). And similarly, other studies showed smaller percentages: a study in Delaware showed 8% to 15%, one in Maryland showed greater than 12%, another in Georgia showed 15% urban land cover (Allan, 2004). However, in yet another study where a comparison of sites around Seattle, Washington were studied, a decline in BMI indices occurred with 10% to 60% of impervious area, and 20% to 90% of urban land (Allan, 2004). These results separate impervious area from urban land area. Analyzing these land covers separately for this study could provide some insight into some of the variation that occurs in the differences between CSCI scores that occur in urban land cover areas and CSCI scores that occur in rural land cover areas.

Sample according to land cover

Sampling plans can be determined based on CSCI score and land cover results. When monitoring sampling events are planned, most of the time, funding is limited. Thus, the scientists are required to make decisions about sampling events that will strategically produce data that have significant results that will verifiably support environmental management decisions. Using land cover to plan sampling events could be a useful and strategic way to plan sampling events and use a budget efficiently. For example, if sampling were to occur in rural and urban areas, these sampling CSCI scores could then easily be compared to each other for different types of analyses, such as the one presented in this paper. In addition, other sampled parameters such as water chemistry and physical habitat could be compared or evaluated using this method by separating the sites into 'urban' and 'rural', and similarly to the CSCI score evaluation, water chemistry results and physical habitat results could be analyzed by comparing the 'urban' and 'rural' sample sites.

In studies like this where data for a point sample is analyzed, often additional samples or data are recorded at the same point location at a stream, such as water samples, water chemistry data, date and time of samples. Additional data that varies within an area of the streams such as land use or physical habitat are collected. These data are spatially different in that they cover a larger area than a buffer around a sample site location. In one research project, a team of scientists developed a model to account for the differences in sampling and data collection in order to more reasonably connect the response variable and the predictor, to develop a way to determine which type of land use is most impacting the water quality in a sub-catchment of a watershed (Ickowicz et al., 2019). The study uses the sub-catchment area to evaluate land use, which is different from this project, however, it could be useful guidance for developing a similar model for a different geographic region such as the San Francisco Bay region.

Analyze CSCI data at a stream level scale

The CSCI data do not have enough temporal data that are statistically supportable. Following the analyses of data at a watershed level scale to find any temporal trends, a stream level scale evaluation was conducted. Again, these analyses were completed to evaluate for temporal trends at the stream level scale, however, the data were inconsistent and not numerous enough. The same sites on the streams were not sampled each year, and in many streams, more sites were sampled in one or two years and fewer sites were sampled in other years. These data analyses resulted in varied results much like the watershed analysis. The results were so varied that no evaluations or conclusions could be determined.

However, when land cover analyses were conducted, it became important to analyze the data at a stream level scale as indicated and supported by previous research (Allan, 2004). Previous research indicated that land cover would need to be evaluated at a sub-catchment level, a stream level, or a stream reach level, so that the land cover could be quantifiable, but so that any upstream influences would be accounted for (Allan, 2004). Because my study did not involve upstream areas that would negatively impact the water quality in downstream areas, it was more relevant to evaluate the land cover surrounding each individual site, within each stream.

Additional monitoring is needed

More monitoring data would be needed to provide temporal trend data. The data used in this study were not consistent and were too varied to draw any conclusions. Additional monitoring data collection would have been more conducive to evaluating any possible temporal trends between CSCI scores. Even though more monitoring would cost money and take more time, the results would still be valuable. However, more sampling is not always an option for a scientific monitoring team, and when this is the case, limited data need to be evaluated in a strategic way to show valuable results that will support beneficial environmental and stream management decisions.

Monitoring data are necessary

Despite the limited amount of monitoring data available for these analyses, the data are necessary for environmental managers making decisions about water quality management. For scientists to know what conditions streams are in, collecting monitoring data are necessary. Monitoring data can show important trends that are occurring in streams and can drive decisions made later for management and regulation of stream quality and therefore water quality. Some decisions that could be made as a result of scientific monitoring could be to regulate certain inputs to streams. These decisions could factor into development decisions, such as placement of buildings farther away from streams rather than closer. Scientific monitoring must be implemented to support these types of environmental management decisions.

Funding for scientific monitoring is a constraint

The constraints of scientific monitoring include limited data and even limited time, and because of these limiting factors, the results of the data and the ways to evaluate the data are generally limited. Evaluating the data in a strategic way so that the limited results show as much information as possible, has become very necessary and almost required of scientists conducting monitoring data.

Recommendations

Look at details within the CSCI data

Other ways to evaluate limited data would be to look at the metrics or numbers that determined the data. For example, within the CSCI score are numbers of BMI as well as data on categories of BMI that separate them into groups like functional feeding groups. These data could be evaluated in detail and compared with other analytes such as water chemistry data to determine how BMI are affected at a site. This is one example of evaluating details within data, but many more could be completed such as evaluating species richness for BMI within the CSCI data.

Evaluation of data: robust temporal data sets or limited data sets

If temporal data are necessary and needed to evaluate the quality of a watershed or stream, it is important to sample on a rigorous temporal scale. Temporal data are indicative of what is happening over time to the quality of a stream. Whether or not the quality of a stream is decreasing or increasing, informs environmental managers not only of the trend but about what decisions can be made to manage the watershed or stream properly.

If robust temporal sampling is not possible, it is important to make environmental management decisions that can be supported by the limited data. This means collecting samples at strategically chosen sites and formulating a plan for how the resulting date could be analyzed to produce the most useful results.

Making the right decisions for water management in an altered landscape

Watershed and stream studies regarding stream quality and water quality have different approaches to evaluating stream conditions, and generally these predictably depend on the geographic location of the stream. The geographic location will dictate the general landscape where the stream is located, which will then govern the environmental management decisions that ensue. California's landscape has dictated the way the CSCI was developed and has subsequently been used to evaluate the quality of streams in a consistent and informative way. The index is based on California's landscape, as well as the relative conditions of the impacted streams. In an altered landscape like the state of California, it is important to make appropriate decisions about the environmental management of streams and water quality.

Future Considerations

Compare CSCI data with other data

When making environmental management decisions using this limited data, it is important to compare the data and results with additional supporting data. For example, this project compares the CSCI data with the NLCD data for California. The NCLD data are used to support conclusions determined for this study. Other indices exist such as the Index of Physical Habitat Integrity (IPI) and the Algal Stream Condition Index (ASCI) which could be compared with CSCI data as well as NLCD data. These indices use data (data collected from the same CSCI sites), to determine and score physical habitat condition and the condition of algae in streams.

Another evaluation of comparing CSCI data with other data that could be completed would be to compare reference sites of CSCI scores to non-reference sites of CSCI scores. In another example of how the data were limited, the analyses and data that are used to determine reference sites were not finished and available. If this data had been available, an analysis of comparing reference sites to non-reference sites could have been completed. Reference sites are calculated from CSCI scores based on the condition of the streams in California. Reference site and non-reference site conditions could be evaluated by comparing the data to other analyte and index data.

Since physical habitat data are measured, different wildlife data from the California Department of Fish and Wildlife (CDFW) and the US Fish and Wildlife Service (USFWS) could be compared to the riparian habitat or physical habitat data to determine the quality. Fish data from the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) could be used to compare with the conditions of the streams. Many agencies have data that are applicable to comparing with the stream data that are collected for CSCI, IPI and ASCI scores. Considering these additional data that could be used to compare with indices, it is important to use these additional data to verify any trends.

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