Title
Water Temperature Suitability for Steelhead Trout (Oncorhynchus mykiss) in Codornices Creek

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Water Temperature Suitability for Steelhead Trout

(*Oncorhynchus mykiss*) in Codornices Creek

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Abstract

Codornices Creek is a small urban stream in Alameda County, California, that flows along the border between the cities of Albany and Berkeley. The creek provides habitat for *Oncorhynchus mykiss*, a species of salmonid known as steelhead or rainbow trout, depending on whether populations have an ocean-going life stage. Steelhead trout are a species of interest in Codornices Creek because they are listed as threatened under the Endangered Species Act. Populations in the creek have fluctuated over the past 30 years due to impacts from restoration projects, urban pollution, and climatic conditions. Previous reports have suggested that water temperature may be limiting steelhead trout success in some reaches, prompting our investigation into water temperature and potential drivers in Codornices Creek.

We analyzed spatiotemporal trends in water and air temperature recorded at eight sites along Codornices Creek during a 5-month period (June - November 2022), including potential drivers for water temperature trends such as rainfall and canopy cover. We analyzed canopy cover using spatial analysis and field observations. We obtained water temperature data from long-term monitors, a local stream gauge, and a thermocouple for instant field measurements. We downloaded air temperature and rainfall data from the National Weather Service weather station located at the Oakland International Airport (June - November 2022) and additional rainfall data from a local rainfall gauge (October - November 2022). We then calculated long-term water temperature suitability as maximum weekly average temperature and maximum weekly maximum temperatures. We compared water temperature to air temperature, rainfall, and canopy cover to determine primary drivers of water temperature. To evaluate canopy cover, we brought National Agriculture Imagery Program satellite imagery into ArcGIS and calculated the normalized difference vegetation index within a 30-meter buffer along open stream sections of Codornices Creek. We supplemented this analysis with field observations at each study site using a densiometer.

Our investigation indicated that air temperature affected long-term trends in water temperature, rainfall affected short-term water temperature trends, and canopy cover tended to moderate the effects of air temperature. Despite water temperatures in the upper half of the watershed being slightly cooler than downstream temperatures, water temperatures throughout Codornices Creek were generally within suitable range for steelhead trout. Only one location downstream reached temperatures stressful for steelhead trout. This location may require further investigation, as air temperature, rainfall and canopy cover do not explain elevated temperatures. Locating and addressing the source of elevated temperature may benefit steelhead trout populations.

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Introduction

Codornices Creek is a small stream originating in the Berkeley Hills and flowing west to San Francisco Bay (Figure 1). It is notably one of the least-culverted creeks in the San Francisco Bay and contains suitable habitat for steelhead trout (*Oncorhynchus mykiss*) (The Waterways Restoration Institute 2001; Leidy, Becker, and Harvey 2005). Local stakeholders are interested in maintaining and improving trout habitat to increase the population size. Fish populations in urban streams face many stressors. In this report, we investigate whether water temperatures could be limiting steelhead trout survival in Codornices Creek.

Codornices Creek drains roughly 1.5 square miles of land in the cities of Berkeley and Albany, in Alameda County, California (Kier Associates 2003). Land use in the watershed is primarily medium-density residential. Historically, the creek was fed by groundwater stored in the hills and petered out into a marsh before reaching the bay (Schwartz 2008; 2010). Channelization and straightening due to urbanization created a permanent channel discharging into the San Francisco Bay (Kier Associates 2003; Schwartz 2010). Steelhead trout likely started reproducing in Codornices Creek in the 1980s (Leidy, Becker, and Harvey 2005).

Steelhead trout are an anadromous salmonid species, spending part of their lives in freshwater and part in the ocean (National Marine Fisheries Service [NMFS] 2016). Adults migrate from the ocean to freshwater streams and lakes to spawn, typically between December and March (NMFS 2016). Unlike other species of salmon, steelhead adults may spawn more than once, returning to the ocean between spawning periods. Juveniles remain in freshwater streams or lakes for periods ranging from a single season to multiple years, after which they migrate to the ocean, where they are able to mature more quickly due to higher food availability (NMFS 2016). *Oncorhynchus mykiss* exhibit a second, non-anadromous life cycle pattern, where adults do not migrate to the ocean (NMFS 2016); populations following this pattern are known as rainbow trout. While there is evidence that *O. mykiss* can switch between anadromous and non-anadromous life cycles, populations are functionally distinct due to a combination of physical, physiological, ecological, and behavioral factors (NMFS 2016).

Steelhead populations along the central California Coast are substantially reduced from historical levels (NMFS 2016), to the point that they are listed as threatened under the Endangered Species Act (50 Code of Federal Registrations § 223.102). The most recent published report of spawning steelhead in Codornices Creek was in 2006, although local residents have reported seeing juvenile and adult *O. mykiss* in the last few years (Kier Associates 2007; S. Schwartz, Friends of Five Creeks, personal communication, December 2022). Additionally, in April 2019, a nearby fire caused an influx of Class A Firefighting Foam into Codornices Creek, resulting in the death of more than 100 *O. mykiss* (Raguso 2019; S. Schwartz, Friends of Five Creeks, personal communication, December 2022). Subsequent surveys and informal observations have found greatly reduced numbers of *O. mykiss* individuals (S. Schwartz, Friends of Five Creeks, personal communication, December 2022).

Local stakeholders have exhibited an interest in maintaining suitable habitat for steelhead in Codornices Creek (Schwartz 2010). In addition to morphological characteristics, suitable habitat depends on stream flow, water temperature, depth, velocity, and dissolved oxygen concentrations (NMFS 2016). We focused our investigation on temperature suitability, which has previously been identified as a potential limiting factor for steelhead trout (Kier 2007, Restoration Design Group [RDG] 2014).

Water temperature has a direct influence on steelhead metabolism, with cold temperatures slowing metabolism and therefore growth rate, while high heat causes metabolic rates to exceed food availability (NMFS 2016). Optimal temperatures for juvenile steelhead range from 12 to 19 degrees Celsius (°C), which corresponds to 54 to 66 degrees Fahrenheit (°F). Prolonged temperatures above 25°C (77°F) are often lethal, especially if food supply is limited (NMFS 2016). Temperature requirements are often reported in terms of maximum weekly average temperature (MWAT) or maximum weekly maximum temperature (MWMT). MWAT and

MWMT are measurements of the single highest rolling value over a season or year (Carter 2008). For MWAT the rolling value is daily average temperature, and for MWMT the rolling value is daily maximum temperature. Both are calculated over a 7-day window. MWAT and MWMT are preferred metrics because they indicate chronic conditions, which have more of an impact on steelhead than acute conditions (Carter 2008). While MWAT remains below 19.0°C and MWMT remains below 24°C, steelhead growth will be reduced by less than 20 percent of maximum rates (Sullivan, Martin, and Cardwell 2000).

Stream temperatures are dependent on a number of geomorphological, climatic, and hydrological factors. Solar radiation heats water through radiative forcing, although the amount of radiation that reaches the water can be decreased by channel morphology, orientation of the stream, and canopy cover (Webb et al. 2008). Canopy cover can increase temperature by decreasing evaporation rates, but in conditions with high radiative forcing, the cooling effect of canopy cover is likely an order of magnitude greater than the warming effect (Webb et al. 2008). Stream temperature is also impacted by air temperature through sensible heat transfer and by groundwater exchange, both of which can have a substantial impact on smaller streams (Webb et al. 2008). Another geomorphological driver of water temperature is friction between the water and stream bed and banks, though the effect of such friction-generated heat may not be measurable in many settings (Theurer, Voos, and Miller 1984, Webb et al. 2008). In urban settings like Codornices Creek, additional factors such as wastewater and stormwater runoff may influence stream temperature, typically having a warming impact (Webb et al. 2008). For example, rainfall events may create runoff that is abnormally warm from running over hot pavement. In this report, we focus on solar radiation, air temperature, and canopy cover as potential drivers of water temperature in Codornices Creek. We briefly discuss the impact of rainfall and channel morphology.

Methods

We investigated spatial and temporal trends in recorded water temperatures in Codornices Creek using long term monitors and instant field measurements. We then analyzed potential drivers for water temperature, specifically air temperature, rainfall, and canopy cover.

Data Sources

Long-Term Monitors

During Summer 2022, Friends of Five Creeks installed four HOBO TidbiT temperature loggers along Codornices Creek to measure the impacts of drought and climate change (Figure 1).[1] Loggers were installed in a pool and in a riffle near 4th Street and in a pool near 6th Street on July 15, 2022. The fourth logger was installed in a riffle near 6th Street on August 4, 2022. All loggers were configured to record temperature every 30 minutes. Friends of Five Creeks downloaded temperature records from the loggers on November 4, 2022.

In addition to temperature records from the HOBO TidbiT loggers, we obtained data from a stream gauge along Codornices Creek near Cornell Avenue that is owned and maintained by Balance Hydrologics, a local hydrology consulting firm. The stream gauge was originally installed in 2005 but broke prior to this year. A new data logger was installed on September 16, 2022. We received stream depth, temperature, and specific conductance records for the datalogger in 15-minute intervals between September 16 and November 11, 2022. Balance Hydrologics operates a rainfall gauge at the same location, from which we obtained rainfall records at 1-hour intervals between October 1 and November 15, 2022. We also obtained rainfall records at 1-hour intervals between July 1 and November 15, 2022 for a rainfall gauge installed at the Balance Hydrologics office in West Berkeley.

The closest National Weather Service (NWS) weather station is located at the Oakland International Airport (OAK) in Alameda, CA. We accessed these historical records through Iowa

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[1] Onset HOBO Tidbit MX2203

State University's Iowa Environmental Mesonet.[2] We obtained air temperature data from the weather station in 1-hour intervals between June 1 and October 31, 2022 and rainfall data in 1-hour intervals between June 1 and November 8, 2022.

Water Temperature Field Observations

To check the accuracy of installed monitors and compare conditions throughout the length of Codornices Creek, we collected surface water temperatures using a hand-held thermocouple device. On November 11, 2022, we recorded water temperatures at the four HOBO TidbiT locations, and where Codornices Creek intersects the Ohlone Greenway, Live Oak Park, and Codornices Park (upstream of Berkeley Rose Garden) (Figure 1). At each location, we measured water temperature three times to ensure the sensor was providing a consistent reading. At the two HOBO TidbiT locations in riffles, we recorded the instantaneous temperature that the logger displayed at the same time that we used the thermocouple.

Previous Reports

We reviewed reports published on the Friends of Five Creeks website to develop an understanding of site history and compare previously reported water temperatures. Monitoring reports were available for restoration projects conducted between 4th and 10th Streets, the most recent of which was published in 2020. Other reports included a watershed action plan published in 2004 and two student reports published in 2008 and 2011.

Analysis

We evaluated water temperatures spatially and temporally using both quantitative and qualitative analyses. To assess longer-term suitability of water temperatures, we calculated MWAT and MWMT for each of the HOBO TidbiT loggers. We calculated the seven-day moving average and maximum temperatures in R (version 4.2.1) following guidance from Carter (2008). We also calculated the arithmetic mean, maximum, and minimum temperatures throughout the observed time period. To compare to prior monitoring reports, we calculated the total time above

[2] https://mesonet.agron.iastate.edu/request/download.phtml?network=CA_ASOS

17.8°C and 21.1°C, thresholds which were selected based on trends in the 2014 data (RDG 2014). We also calculated total time above 19°C and 25°C, as chronic conditions above 19°C reduce growth rates and above 25°C may be fatal to steelhead trout (NMFS 2016).

Using data from the HOBO TidbiT loggers, Balance Hydrologics gauges, and NWS weather station, we conducted a qualitative comparison of water temperatures and air temperatures and rainfall events to determine the primary drivers of water temperatures in Codornices Creek. We also incorporated the instantaneous thermocouple readings throughout the length of the creek to evaluate longitudinal differences in temperature.

Riparian Canopy Cover

We analyzed canopy in two ways: 1) spatial analysis using remote sensing techniques and, 2) field measurements using a densiometer. To perform a spatial analysis of canopy cover along Codornices Creek, we collected data and images from the United States Geological Survey (USGS) EarthExplorer portal and the City of Berkeley. We then applied a normalized difference vegetation index (NDVI) to this information in ArcGIS to understand canopy cover health and density and its relation to water temperature trends.

We used a densiometer to measure canopy density at seven sites along the creek. Canopy cover is important for various reasons. Not only can it lower in-stream temperatures during summer months or heat waves (Roth et al. 2010; Johnson and Almlöf 2016), it also provides large woody debris which benefits aquatic habitat (Kondolf 2000). To further understand riparian vegetation along the creek, photographs were taken as reference.

Spatial Analysis

By accessing the National Agriculture Imagery Program (NAIP) through USGS, we obtained a high-quality aerial orthorectified digital photograph.[3] NAIP imagery has a 1-meter resolution and four bands: red, blue, green and near infrared (RGB and NIR). The high resolution RGB-NIR bands in the NAIP image can generate accurate vegetation classifications

[3] NAIP Entity ID: M_3712206_SE_10_060_20200524

(Li et al. 2012). In addition, we obtained a shapefile consisting of creeks in the City of Berkeley, from which we extracted Codornices Creek.[4] We then separated the creek between culverted and daylit portions. Locating the daylit areas of the creek was necessary because we wanted to analyze how canopy cover affected open water temperature trends along the creek. After locating the daylit areas, a 30-meter buffer was created to define the riparian canopy cover of those areas. To get a better sense of differences in canopy cover, we divided the daylit portions of the creek into four equal parts based on the mainstem length (Figure 2). The first section, Stream 1, is between the mouth of Codornices Creek to 8th Street. Stream 2 is between 8th Street and Peralta Avenue; Stream 3 is between Peralta Avenue and Milvia Street; and Stream 4 includes Codornices Creek and tributaries upstream of Milvia Street.

We performed the spatial analysis by applying NDVI to the NAIP image within the 30-meter buffer around daylit portions of Codornices Creek (Figure 3). This index is used to quantify vegetation greenness and is useful in understanding vegetation density and assessing changes in plant health.[5] An NDVI map is made by calculating the difference between the infrared and red bands as a ratio. The result of this ratio generates a value between -1 and 1. Low values represent sparse and less healthy vegetation while high values represent lush and healthy vegetation (Figure 4). Specifically, values between 0.2 and 0.5 indicate moderately healthy and dense while anything over 0.5 is very healthy and dense.[6]

Canopy Cover Field Observations

We measured percent canopy cover at seven sites along Codornices Creek. Starting downstream and moving upstream, the sites were the 4th Street pool, 4th Street riffle, 6th Street pool, 6th Street riffle, Ohlone Greenway, Live Oak Park, and Codornices Park (Figure 1). Because we did not have access to a high-end densiometer, we used a circular mirror roughly 3 inches in diameter with a total of 36 black dots on its surface. Each reading was done by holding

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[4] BMC 17.08 Creeks | Open Data | City of Berkeley
[5] https://www.usgs.gov/landsat-missions/landsat-normalized-difference-vegetation-index
[6] NDVI FAQs: Top 23 Frequently Asked Questions About NDVI (eos.com)

the device at waist level with the mirror facing directly towards the sky and counting the number of black dots that were covered by tree canopy. At each site, we took readings facing upstream, downstream, towards the left bank, and towards the right bank. To calculate percent canopy cover, we added the four measurements for each site and divided the total by 144. In addition to measuring percent canopy cover, we took reference photos (Appendix) of riparian vegetation to determine species, quality and age of trees.

Results

Water temperatures in the 4th Street pool and riffle sites remained within a healthy range for salmonids. Temperatures in the 6th Street pool were elevated slightly above those in the 4th Street pool, and temperatures in the 6th Street riffle site were consistently high enough to be stressful to salmonids. Average temperatures across the time period measured ranged from 15.3°C in the 4th Street pool to 19.7°C in the 6th Street Riffle (Table 1, Figure 5). Maximum temperatures remained below 19°C in the pool sites (17.7°C at 4th Street and 18.9°C at 6th Street) but exceeded 19°C in the riffle sites (20.4°C in 4th Street and 22.3°C at 6th Street). The MWMT exceeded 19°C in the 6th Street and 4th Street riffle sites. During the observed time period, temperatures in the 6th Street riffle exceeded 19°C 83.5% of the time (Table 2). Temperatures in the pools had smaller daily variation (less than 1°C) than in the riffles (between 1 and 2°C, Figure 6).

Temperatures recorded at the Balance Hydrologics gauge declined steadily between mid-September and early November, starting at approximately 18°C and ending at approximately 14°C (Figure 7). Daily variance was typically between 1 and 2°C. Depth records indicate that the sensor was dry for most of the monitoring period (September 16 through 18, September 22 through October 28, and October 29 through November 1).

Air temperatures measured at the OAK NWS weather station generally remained between 12 and 25°C between July and November (Figure 8). The average temperature was 17.21°C. The MWMT was 32.24°C and occurred on September 6, 2022. The MWAT was 22.88°C and occurred on September 7, 2022. Daily temperature range was typically approximately 10°C.

Between July 15 and November 15, 2022, major precipitation events occurred on September 18, November 1, and November 5 through November 8 (Figure 9).

Instantaneous temperature readings taken on November 11 using the thermocouple showed high agreement with the HOBO TidbiT loggers (Figure 10). The logger at the 4th Street riffle site read 11.85°C while thermocouple measurements averaged 12.1°C (12.0 - 12.1°C). At the 6th Street riffle site, the logger read 12.58°C while thermocouple measurements averaged 12.6°C (12.5 - 12.7°C). Starting in the upstream reaches of Codornices Creek, temperatures decreased from 11.7°C (11.6 - 11.7°C) in Codornices Park to 11.0°C (10.9 - 11.1°C) along Ohlone Greenway. Temperatures were highest in the 6th Street pool (14.0°C; 13.9 - 14.0°C) and riffle (12.6°C) and decreased almost to upstream levels in the 4th Street pool (11.9°C; 11.8 - 11.9°C) and riffle (12.1°C).

In 2013, 2014, and 2015, Restoration Design Group (RDG) placed water temperature monitors in culverts under 4th, 6th, 7th, and 8th Streets. The average temperature was higher at the 6th Street monitor than at the 4th Street monitor during all three years. It was 1.6°C higher in 2013, 2.1°C higher in 2014, and 1.7°C higher in 2015 (RDG 2013; 2014; 2015). During our monitoring period in 2022, the 6th Street riffle site averaged 4.0°C higher than the 4th Street riffle, and the 6th Street pool site averaged 1.9°C higher than the 4th Street pool (Table 3). In 2013, 2014, and 2015, RDG reported that temperatures at the 4th Street and 8th Street monitors were similar. In 2013 and 2014, temperatures at the 7th Street monitor were between those at the 6th and 8th Street monitors. RDG noted that records for 6th Street in 2014 and 8th Street in 2015 were influenced by air temperatures, as the monitors measured higher daily variance and overall temperatures than other monitors during the same time period or other records from the same monitor earlier and later in the season (RDG 2014; 2015).

The spatial analysis using NDVI yielded results in-line with previous stream restoration efforts and the creek's geography. As a whole, the 30 meter buffer around Codornices Creek gave us a maximum of 0.63, a minimum of -0.63, and a mean of 0.18 indicating a moderately healthy and dense canopy (Figure 3). Maximum and minimum density vegetation values did not vary significantly between our four stream reaches (Stream 1 through Stream 4). What is notable is that the mean from Stream 1 (Figure 11), located downstream, reflects previous restoration efforts from 4th Street to 8th Street and the mean from Stream 2 and 3 reflect disturbance and constraints on canopy health and density from urbanization (Figure 12 and 13). The mean in Stream 4 (Figure 14), located upstream, increased to levels seen in the downstream reach. Woody vegetation health and density is greatest in lower and upper reaches of Codornices Creek.

Using the densiometer we calculated percent canopy cover at our seven study locations (Table 4). Woody vegetation along 4th and 6th street consists of a dense canopy of mature willows (*Salix spp.*) roughly 15 years old. Canopy density at the 4th Street pool and riffle was 85% and 60% compared to the 6th Street pool and riffle at 95% and 88%. Canopy density at the Greenway was 60%. We believe that such a low percentage at the Greenway location was due to a lack of woody vegetation which consisted of three to four old Fremont cottonwoods (*Populus fremontii*). Live Oak Park had a canopy cover of 89% which we attribute to the several coast redwoods (*Sequoia sempervirens*). Codornices Park had a canopy cover of 78% and consisted of a variety of woody vegetation from coast redwoods to coast live oaks (*Quercus agrifolia*) and other understory vegetation.

Discussion

Over the period of our study, July - November 2022, which included a week-long heat wave in September 2022, we found that temperatures in pools along Codornices Creek were suitable for steelhead trout, as neither of the pool sites exceeded 19°C, but that temperatures in riffles were more variable and more likely to exceed 19°C. We observed significant spatial variation, with temperatures at the 6th Street pool and riffle sites consistently higher than temperatures in the rest of the creek, a finding that is consistent with monitoring data from previous years. Overall, the pool sites were cooler in 2022 than previous years while the riffle sites were similar or warmer. Below, we discuss potential drivers for our findings, including air temperature, rainfall, canopy cover, and urban runoff.

Based on records from the OAK weather station and Balance Hydrologics stream gauge, we believe canopy cover and stream channel topography are moderating water temperature. Air temperatures measured at OAK corresponded less with water temperatures than we expected, especially at pool sites. OAK is the closest federally regulated weather station to Codornices Creek; however, it is 12 miles from the creek and is not sheltered by trees or topography. We believe that the weather station is still close enough to provide a decent approximation of climatic conditions at Codornices Creek. During the September 2022 heat wave, air temperatures were approximately 10°C higher at OAK than before and after the heat wave, but the HOBO TidbiTs measured increases of only 1 to 2°C. Maximum temperatures in the pools were delayed compared to in the riffles and air, with the 4th and 6th Street pools reaching maximum temperatures on September 10 and September 9, respectively, and the 4th and 6th Street riffles and OAK air temperature reaching maximums on September 6. These results suggest that water temperatures are being protected from solar radiation and air temperature, but other mechanisms, such as the thermal storage capacity of water, likely also contribute to the lag effect.

Daily variance in recorded temperatures at the Balance Hydrologics stream gauge was more similar to the HOBO TidbiT 4th Street riffle monitors than the OAK NWS weather station, even though the gauge was dry for most of the monitoring period, therefore recording air temperature. The gauge is located in a heavily shaded section of the creek (S. Brown, Balance Hydrologics, personal communication, November 2022), which suggests that canopy cover and topographic features of the creek may be buffering air temperature within the creek channel by limiting solar radiation.

Considering that air temperature influenced the Balance Hydrologics sensor in 2022 and monitors in 2014 and 2015, it is possible the HOBO TidbiT monitors in riffles were influenced by air temperatures in 2022. However, we believe it is unlikely because the monitors are designed to record when they are exposed to air, and volunteers with Friends of Five Creeks observed the riffles flowing throughout the monitoring period (S. Schwartz, Friends of Five Creeks, personal communication, November 2022).

In addition to being higher than temperatures at other dataloggers, average daily temperatures at the 6th Street riffle monitor were consistently higher than average daily air temperatures measured at OAK, especially from mid-September through the end of October (Figure 15). It is highly unlikely that air temperatures would be higher in Codornices Creek than at OAK, leading to our conclusion that air temperature is not a primary driver of observed elevated water temperatures in the 6th Street reach.

Rainfall events temporarily decreased water temperatures measured at the 6th Street riffle site, while temperatures in the pools and 4th Street riffle increased slightly before returning to previous levels. Prior to the highest precipitation rates during the September 18 rainfall event, the 4th Street pool measured 15.7°C, the 4th Street riffle measured 16.5°C, the 6th Street pool measured 17.6°C and the 6th Street riffle measured 20.0°C. Following the rainfall, all four monitors converged around 17°C for eight hours before returning to their normal patterns. A similar pattern occurred during the November 1 rainfall event, although the monitors converged around 14°C. The lower temperature at convergence may be due to cooler overall conditions, as average air temperature prior to the November 1 rainfall event was 13°C as opposed to 18°C during the September 18 event. Because rainfall is not common during the hottest months, it is not a significant driver of water temperature. However, rare summer rainfall events may impact habitat suitability for steelhead trout positively by replenishing pools or negatively by introducing a high load of pollutants into the creek in conditions where water levels are already low (Friends of Five Creeks 2022).

To test the results from the NDVI studies on Codornices Creek, we used the same remote sensing technique on an area with little to no vegetation versus an area that was highly vegetated (Figure 4). The former had a mean of -0.13 and the latter a mean of 0.18, indicating an appropriate reading, as values closer to 1 are usually densely vegetated and values closer to -1 are not. Cross referencing the NDVI results with field observations was necessary because NDVI generalizes woody vegetation type, age, and health based on the amount of red and near-infrared light reflected from the canopy. One way to mitigate generalizing canopy density is by taking a different approach to remote sensing techniques. Studies have shown that segment-based methods outperform pixel-based methods in spatial analysis because segment-based methods delineate the complete shape of landscape features from image pixels (Erker et al. 2019; Li et al. 2012). Given the time constraints of the study, we were unable to complete the necessary classification algorithms and training samples for a model driven analysis.

Using the densiometer and recording qualitative data about woody vegetation in our study sites allowed us to gain an understanding of the nuances in canopy density. Canopy cover was most dense in lower reaches between 4th and 6th Street and upper reaches between Live Oak Park and Codornices Park. In mid-reaches, the riparian channel was narrower because it is constrained by residential properties. Canopy cover in this section is lower, although the creek bed is likely still shaded due to surrounding buildings and creek incision. Canopy cover between 6th and 10th Streets is similar to canopy cover between 4th and 6th Streets, thus it is not likely to be the significant driver of elevated water temperatures observed at 6th Street. It is possible that increased canopy cover following the 2010 restoration between 6th and 8th Street has lowered overall temperatures in this reach, but canopy cover does not explain the remaining difference in observed temperature.

As we have determined that air temperature, rainfall, and canopy cover do not explain high temperatures in the 6th Street reach, our hypothesis is that an urban water source is bringing much warmer water into Codornices Creek. Previous monitoring in 2013, 2014, and 2015 found that temperatures at 8th Street were similar to those observed at 4th Street, and temperatures at 7th Street were in between those at 6th and 8th Streets (RDG 2013; 2014; 2015). Based on these findings, we believe that an urban water source is reaching Codornices Creek between 8th and 6th Streets. The water may be draining into the creek via an above-ground outlet, but it also could be originating from a leak in a pipe underground. Resolving high temperatures in the 6th Street reach may facilitate steelhead travel upstream, expanding their range.

Conclusion

Water temperatures in Codornices Creek pools remained within a suitable range for steelhead trout from August through October 2022. Temperatures in the 6th Street riffle exceeded 19°C during 84% of the monitoring period, suggesting that temperatures in the reach may be a stressor to trout but likely are not a limiting factor for the population because they remained below the lethal level of 25°C.

An outstanding question remains of whether spawning steelhead trout will return to Codornices Creek, as reports of adults have been rare in the years since restoration was completed between 6th and 8th Streets, and the 2019 fish kill greatly reduced the population (S. Schwartz, Friends of Five Creeks, personal communication, December 2022). One potential limiting factor may be fish passage barriers, which, to our knowledge, have not been assessed since 2003 (Kier Associates 2003). While there are multiple barriers throughout the creek, the Albina Avenue culvert is thought to be a complete barrier, as no salmonids were found above the culvert (Kier Associates 2003). Another potential limiting factor may be behavioral traits, as spawning steelhead trout may not find Codornices Creek because they were hatched elsewhere (NMFS 2016). Addressing these limiting factors was outside the scope of this report.

According to the spatial analysis and field observations, we found that canopy cover was healthier and most dense in downstream and upstream reaches in relation to mid-reaches of Codornices Creek. These portions of the creek are relatively protected from hot air temperatures making canopy cover a driver in keeping water temperatures low. Based on our observations, mid-reach water temperatures may be benefiting from creek incision and shade from surrounding buildings.

Based on our analysis, canopy cover does regulate water temperature, limiting the effect of heat waves. Air temperature and rainfall also impact water temperatures, with air temperature affecting long-term trends and rainfall affecting water temperature over short time periods. However, the impact of canopy cover, air temperature, and rainfall do not explain the elevated temperatures consistently observed at 6th Street. Future research could attempt to identify the source of elevated water temperature by measuring temperatures at a higher resolution between 6th and 8th Streets and mapping observed outfalls into Codornices Creek.

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Tables

Table 1: HOBO TidbiT Summary

	Temperature (°C)				
Site	Average	Maximum	Minimum	MWAT	MWMT
4th Street Pool	15.276	17.747	10.433	16.884	17.016
4th Street Riffle	15.755	20.439	10.358	18.083	19.396
6th Street Pool	17.155	18.927	14.069	18.540	18.681
6th Street Riffle	19.728	22.263	13.382	20.931	21.766

Table 2: Time above thresholds

Site	4th Street Pool	4th Street Riffle	6th Street Pool	6th Street Riffle
Total hours logged	2,688	2,689.5	2,690.5	2,206.5
Hours above 17.8°C	0	180.5	635	2,061
Percent above 17.8°C	–	6.7%	2%	93.4%
Hours above 19°C	0	30.5	0	1,843
Percent above 19°C	–	1.1%	–	83.5%
Hours above 21.1°C	0	0	0	90
Percent above 21.1°C	–	–	–	4.0%
Hours above 25°C	0	0	0	0
Percent above 25°C	–	–	–	–

Table 3: Comparison to previously reported average water temperatures

Year	Temperature (°C)			
	4th Street		6th Street	
2013	15.9		17.6	
2014	16.8		18.9	
2015	16.2		17.8	
	4th Street Pool	4th Street Riffle	6th Street Pool	6th Street Riffle
2022	15.3	15.8	17.2	19.7

Table 4: Canopy Cover Measurements

Site	Downstream	Right Bank	Upstream	Left Bank	Percent Cover
4th St Pool	34	25	32	32	85%
4th St Riffle	26	21	15	24	60%
6th St Pool	33	35	35	34	95%
6th St Riffle	31	32	34	30	88%
Greenway	32	23	23	8	60%
Live Oak Park	31	32	36	29	89%
Codornices Park	29	33	24	27	78%

Figures

Figure 1: Site map

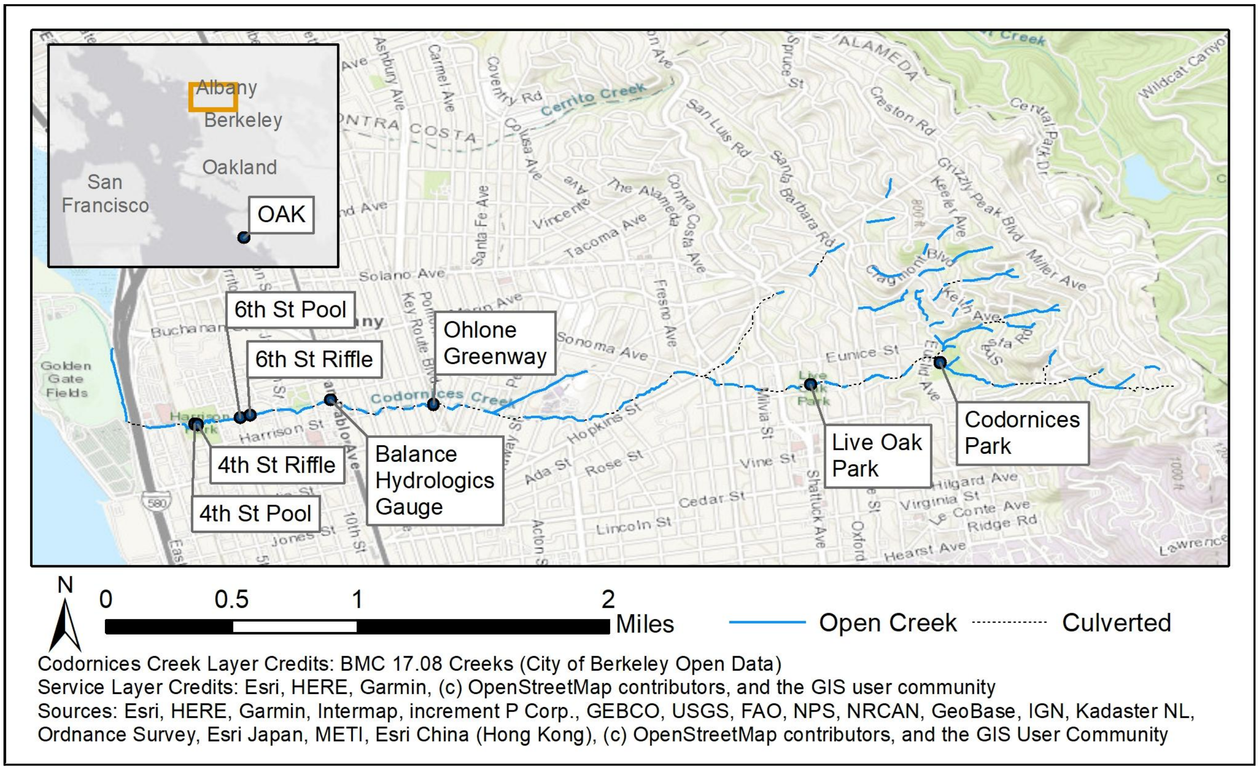


Figure 2: NDVI Sections

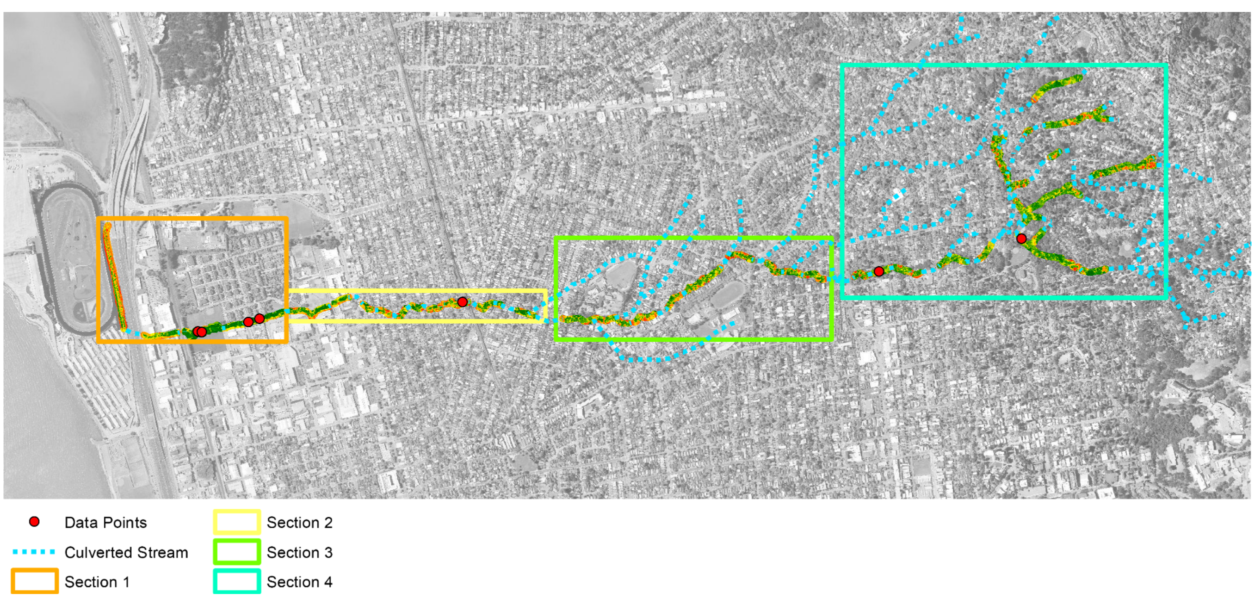


Figure 3: NDVI of daylit streams on Codornices Creek

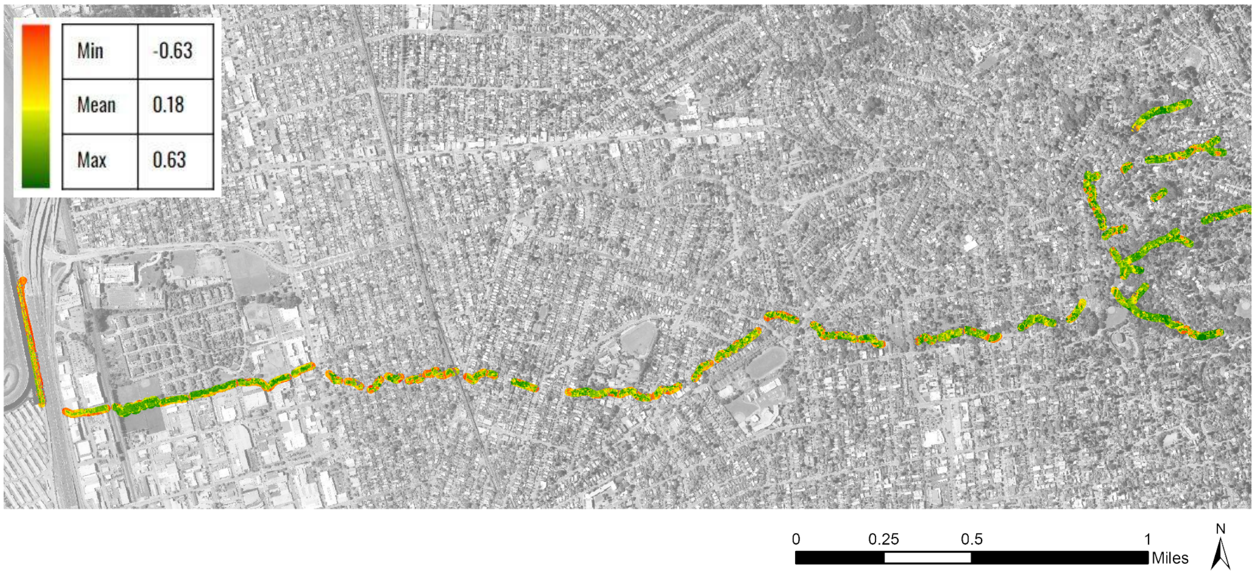


Figure 4: NDVI in area with little vegetation versus highly vegetated

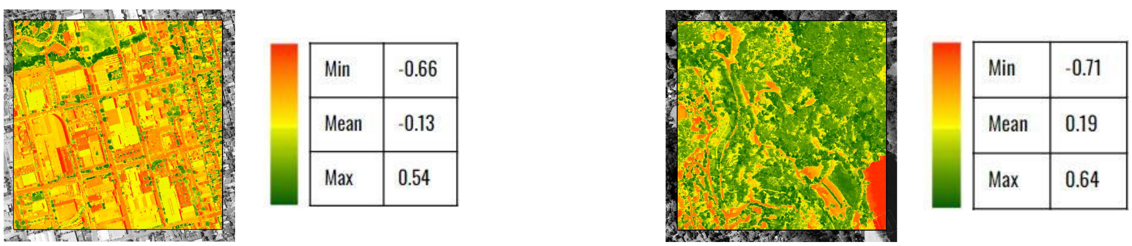


Figure 5: HOBO TidBit temperature data

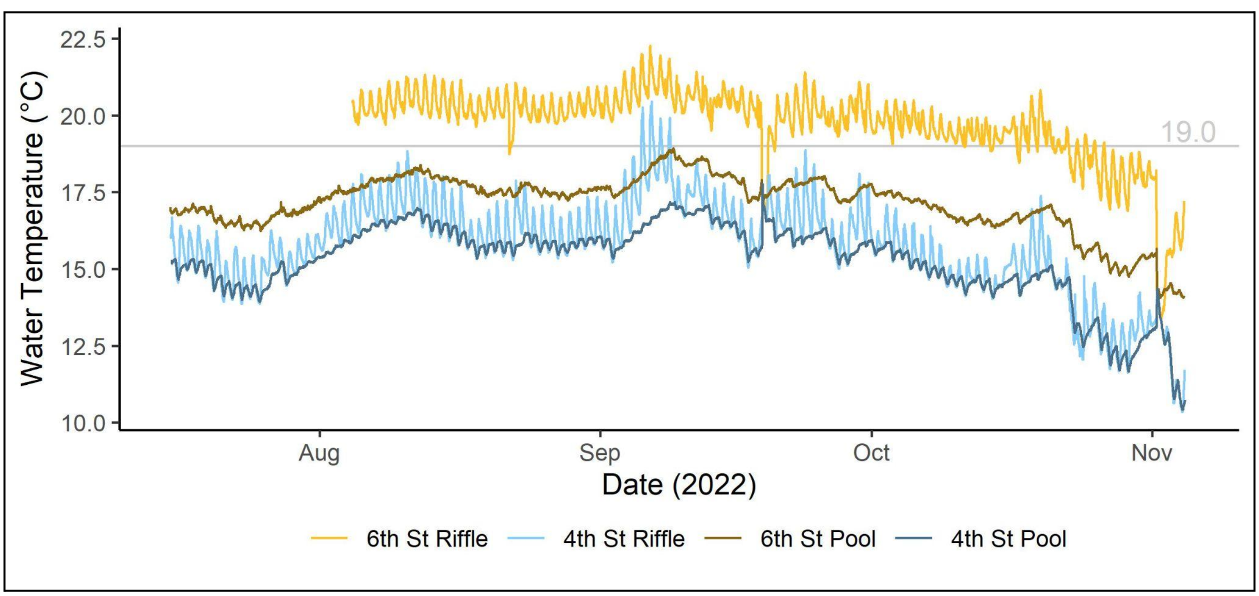


Figure 6: HOBO TidBit temperature data with weekly average temperature and weekly maximum temperatures

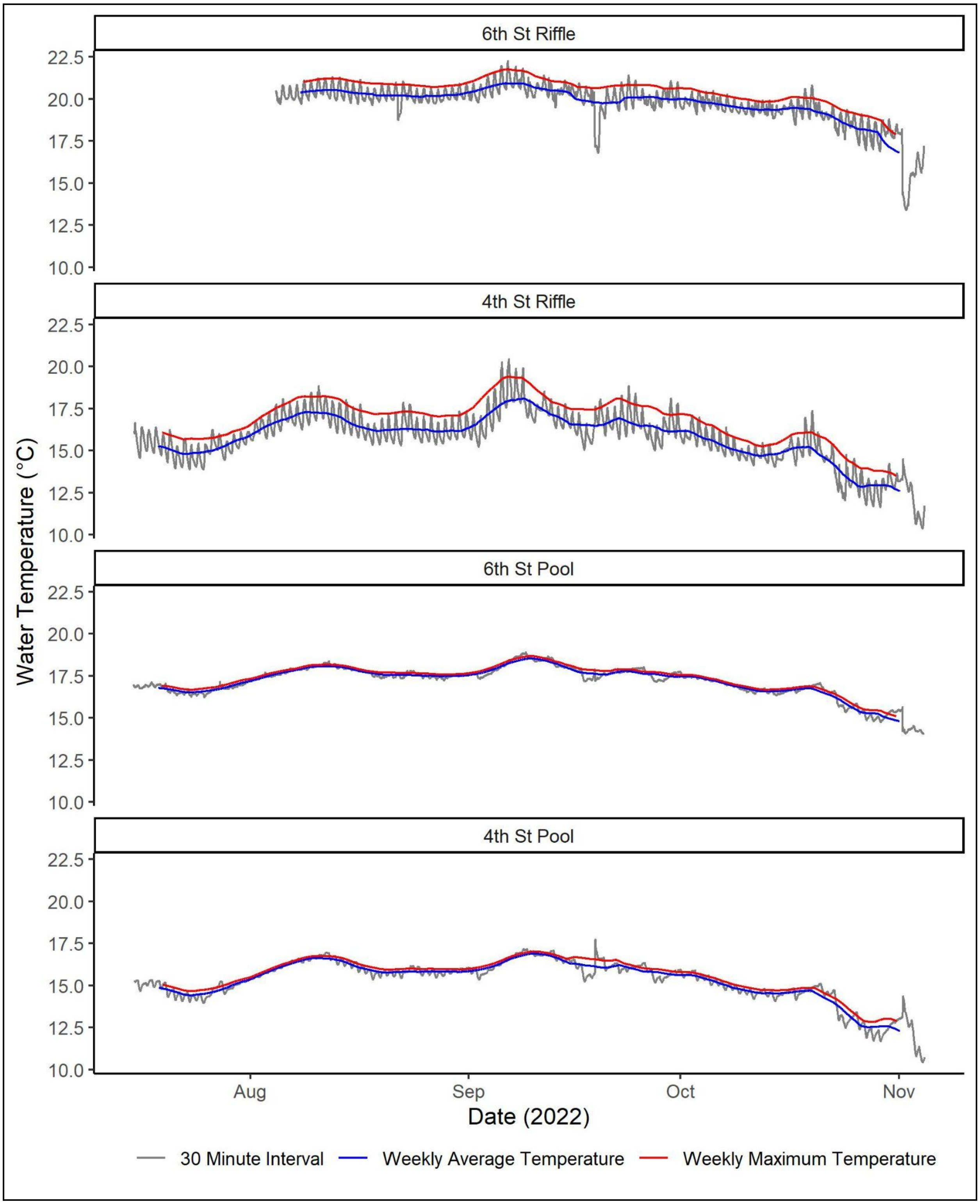


Figure 7: Balance Hydrologics gauge temperature data

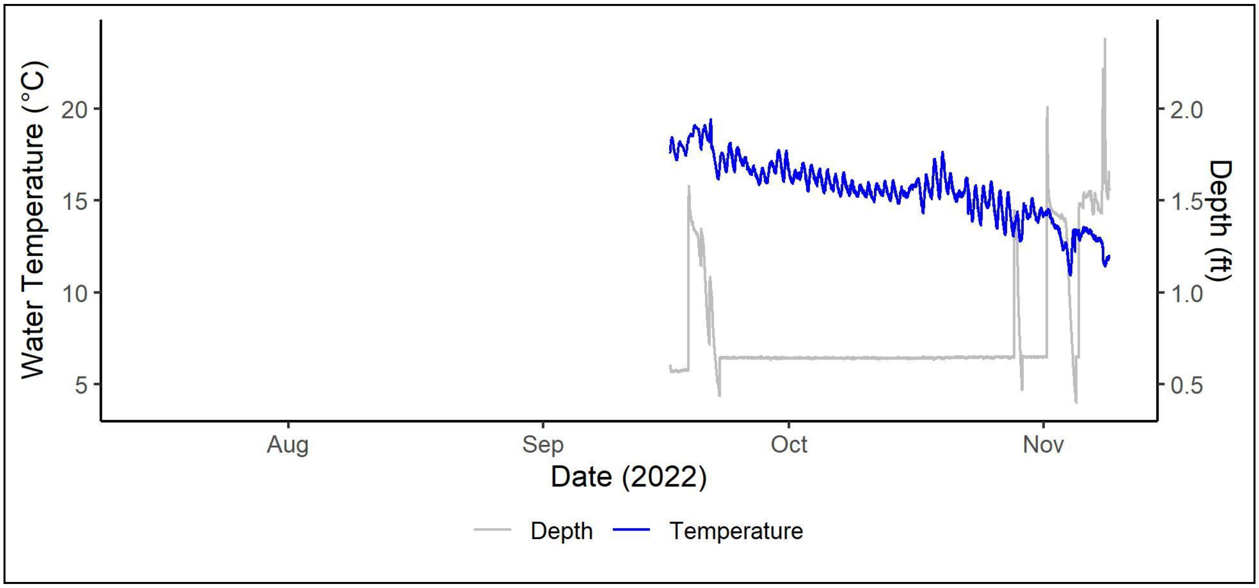


Figure 8: Air temperature measured at Oakland International Airport

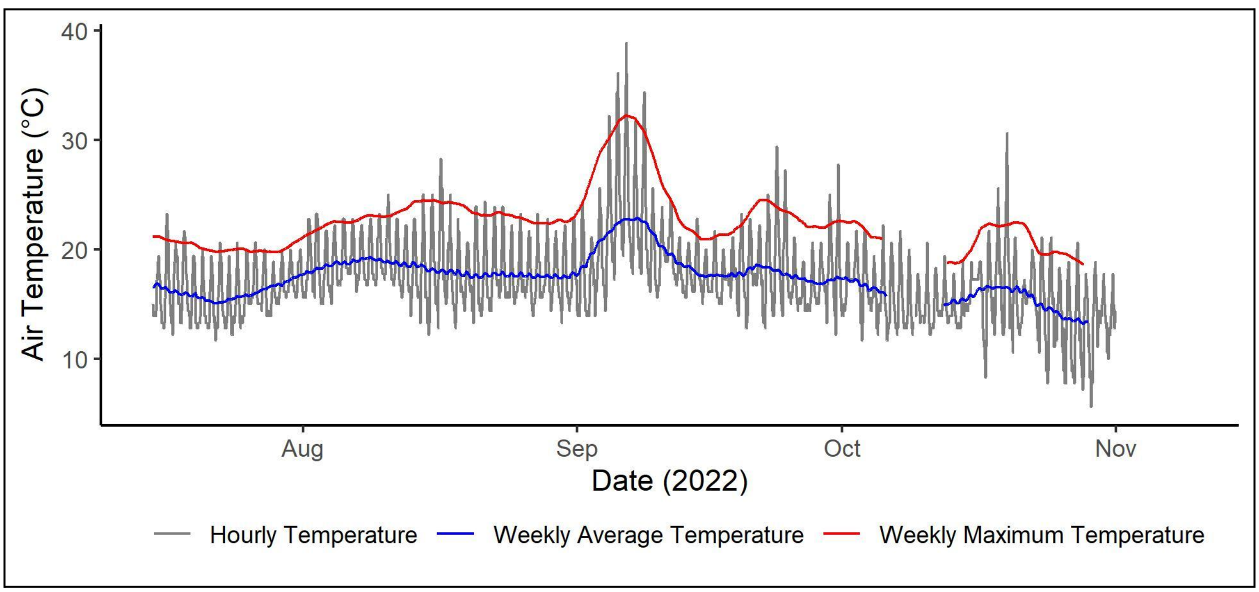


Figure 9: Cumulative hourly precipitation measured at Oakland International Airport

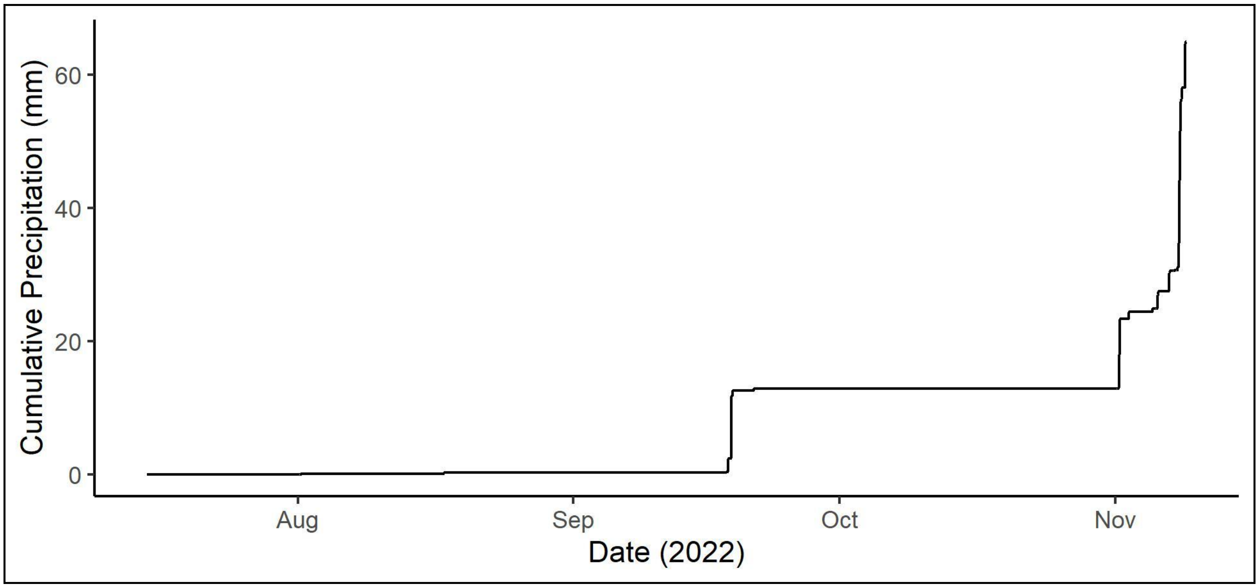


Figure 10: Water temperature on November 11, 2022

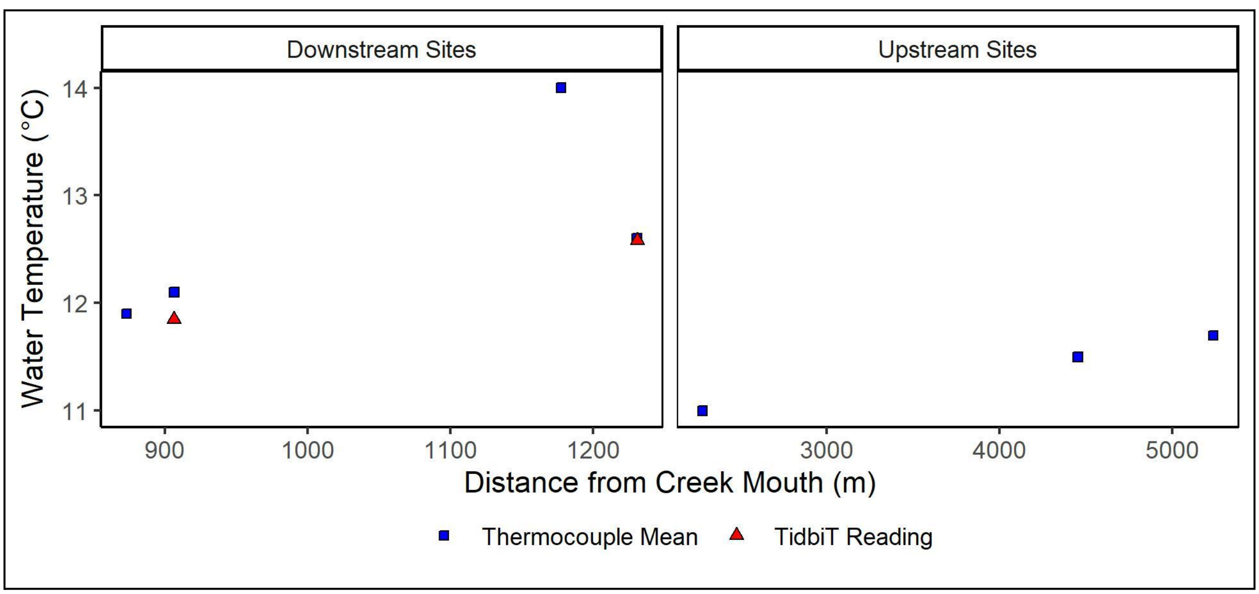


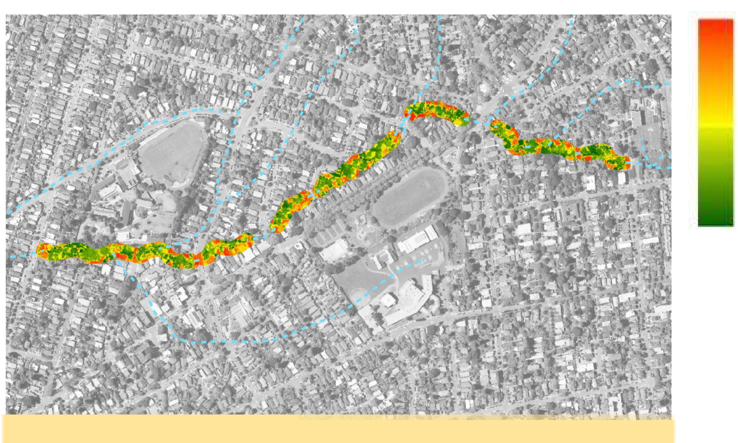
Figure 11: NDVI of stream section 1 (lower reach)

Min	-0.48
Mean	0.23
Max	0.55

Figure 12: NDVI of stream section 2 (mid-bottom reach)

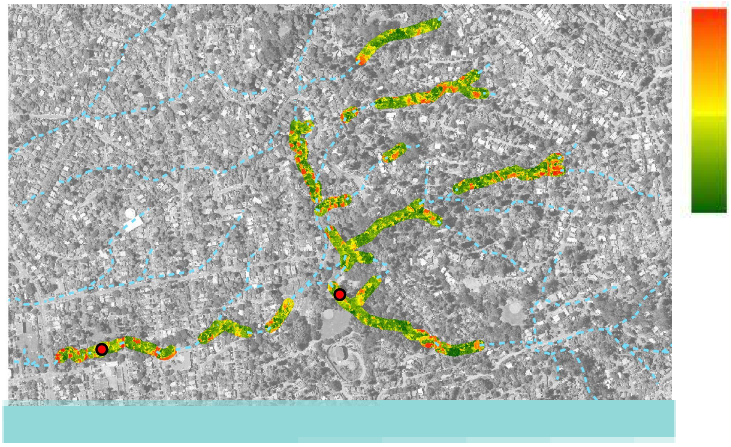
Min	-0.55
Mean	0.11
Max	0.57

Figure 13: NDVI of stream section 3 (mid-top reach)



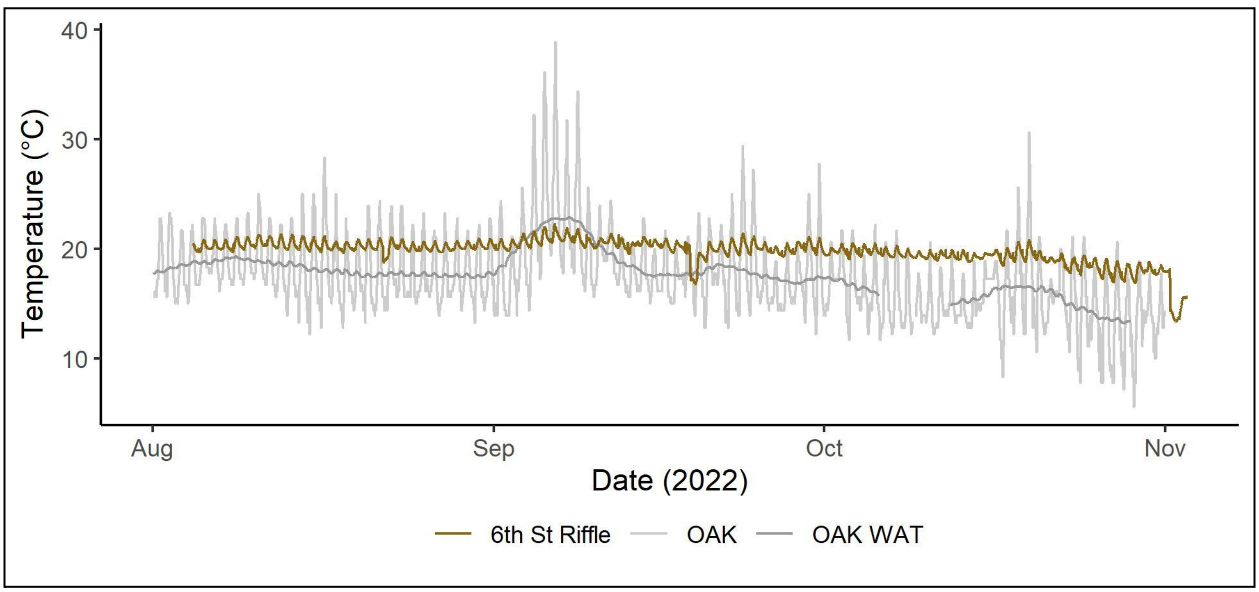
Min	-0.57
Mean	0.16
Max	0.58

Figure 14: NDVI of stream section 4 (upper reach)



Min	-0.53
Mean	0.24
Max	0.63

Figure 15: Water temperature recorded at 6th Street Riffle compared to hourly and weekly average air temperature recorded at OAK weather station



Appendix

4th Street Pool

4th Street Riffle

6th Street Pool

6th Street Riffle

Ohlone Greenway

Live Oak Park

Codornices Park