TASK 2.11 SUMMARY REPORT: SCIENTIFIC STUDIES OF SUISUN CREEK TO ENHANCE STREAM FLOWS

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INTRODUCTION

This report summarizes the results of the following tasks:

- Task 2.1 Coordination with Creek Landowners
- Task 2.2 Establish Creek Reaches
- Task 2.3 Calibration and Deployment of Air/Water Temperature Data Loggers
- Task 2.4 Installation of Stream Flow Gages
- Task 2.5 Dissolved Oxygen Monitoring
- Task 2.7 Riparian Corridor Surveys
- Task 2.8 Fish Surveys

Ca. Land Stewardship Institute (CLSI) carried out several different types of monitoring from 2017-2021 along Suisun Creek. Monitoring included streamflow, water temperature, canopy cover, dissolved oxygen, pH and specific conductance. A survey and mapping of the riparian corridor was completed in 2018. Cramer Fish Sciences completed fish surveys between 2017-2020.

Creek reaches (Figure 1) were established based on geomorphic features of Suisun Creek. CLSI contacted all of the landowners along Suisun Creek and requested access for the monitoring and fish and riparian surveys. As can be seen on Figure 1 most landowners were interested in the studies and provided access while those areas marked as no access indicate where the landowner who would not grant access. A series of monitoring stations were established along the creek (Figure 2).

GIS was used to determine distance of each station from a location in the Suisun Marsh (the downstream terminus of channelized flow (38º 12' 8.259" N, 122º 6' 12.751"). The stations are shown from downstream to upstream in Table 1. The column labeled Upstream Reach Length gives the distance to the next station upstream. This study uses the cumulative distance from the Gordon Valley Dam to locate stations or to calculate the distance between stations.

Table 1. River Mile of Each Station on Suisun Creek.

STATION	Cumulative Distance from Suisun Marsh miles	Cumulative Distance from Suisun Marsh feet	Upstream Reach Length feet	Cumulative Distance from Gordon Valley Dam feet	Cumulative Distance from Gordon Valley Dam miles
Suisun Marsh	0.00	0	45,912	76,053	14.4
SC-5.0	8.70	45,912	1,305	30,141	5.7
SC-5.5	8.94	47,217	806	28,836	5.5
SC-5.6	9.10	48,023	6,029	28,030	5.3
SC-6.0	10.24	54,052	860	22,001	4.2
SC-6.2	10.40	54,912	579	21,141	4.0
SC-7.0	10.51	55,491	2,353	20,562	3.9
SC-7.5	10.96	57,844	1,609	18,209	3.4
SC-7.8	11.26	59,453	135	16,600	3.1
SC-8.0	11.29	59,588	5,303	16,465	3.0
SC-8.4	12.29	64,891	90	11,162	2.1
SC-8.5	12.31	64,981	540	11,071	2.15

STATION	Cumulative Distance from Suisun Marsh miles	Cumulative Distance from Suisun Marsh feet	Upstream Reach Length feet	Cumulative Distance from Gordon Valley Dam feet	Cumulative Distance from Gordon Valley Dam Miles
SC-8.6	12.41	65,521	796	10,532	2.0
SC-8.7	12.56	66,317	581	9,736	1.8
SC-8.8	12.67	66,898	615	9,155	1.7
SC-9.0	12.79	67,513	2,447	8,540	1.6
SC-9.4	13.25	69,960	375	6,093	1.2
SC-9.5	13.32	70,335	681	5,718	1.1
SC-9.6	13.45	71,016	4,179	5,037	1.0
SC 10.0	14.24	75,195	858	858	0.2
SC 10.1	14.40	76,053	0	0	0.0

Stations are listed in upstream-to-downstream order in Table 2. The total number-of-days-of-record shown in this table includes an unknown number of days when the dataloggers, at various stations each year, were out of the water or in a dry channel. Estimates of when the channel became dry were made by examining the temperature records.

Table 2. Total Number of Days of Water Temperature Records for Each Station

Station	2017 Total Days	2018 Total Days	2019 Total Days	2020 Total Days	2021 Total Days	Total Days of Record
SC-10 Air	94	141	120	131	0	486
SC 10.1	129	148	0	0	0	277
SC-10.0	88	105	105	152	141	591
SC-9.6	137	148	131	119	0	535
SC-9.5	96	105	105	152	119	577
SC-9.4	137	148	144	119	0	548
SC-9.0	137	148	144	114	0	543
SC-8.8	137	148	0	0	0	285
SC-8.7	137	148	0	0	0	285
SC-8.6	137	148	133	114	0	532
SC-8.5	137	148	133	114	0	532
SC-8.4	95	148	105	152	119	619
SC-8.0	137	66	131	114	0	448
SC-7.8	137	148	144	10	0	439
SC-7.8 Air	137	138	146	131	0	552
SC-7.5	137	148	131	115	0	531
SC-7.0	103	134	105	152	119	613
SC-6.5	137	148	131	43	0	459
SC-6.2	137	148	144	43	0	472
SC-6.0	75	0	151	70	119	415
SC-5.6	97	96	74	61	119	447
SC-5.5	137	148	131	50	0	466
SC-5.0	137	41	131	25	0	334

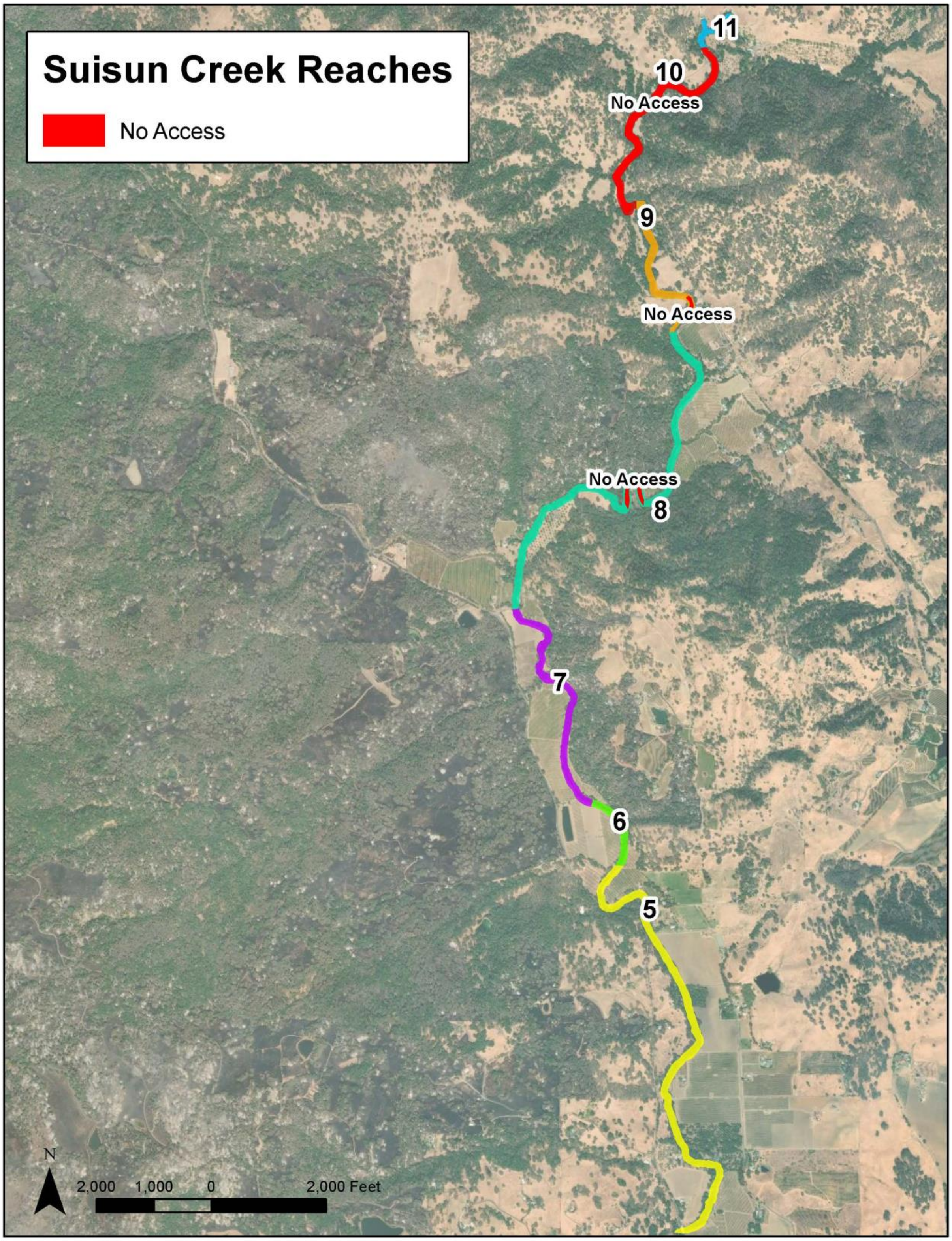


Figure 1. Stream reaches along study area of Suisun Creek.

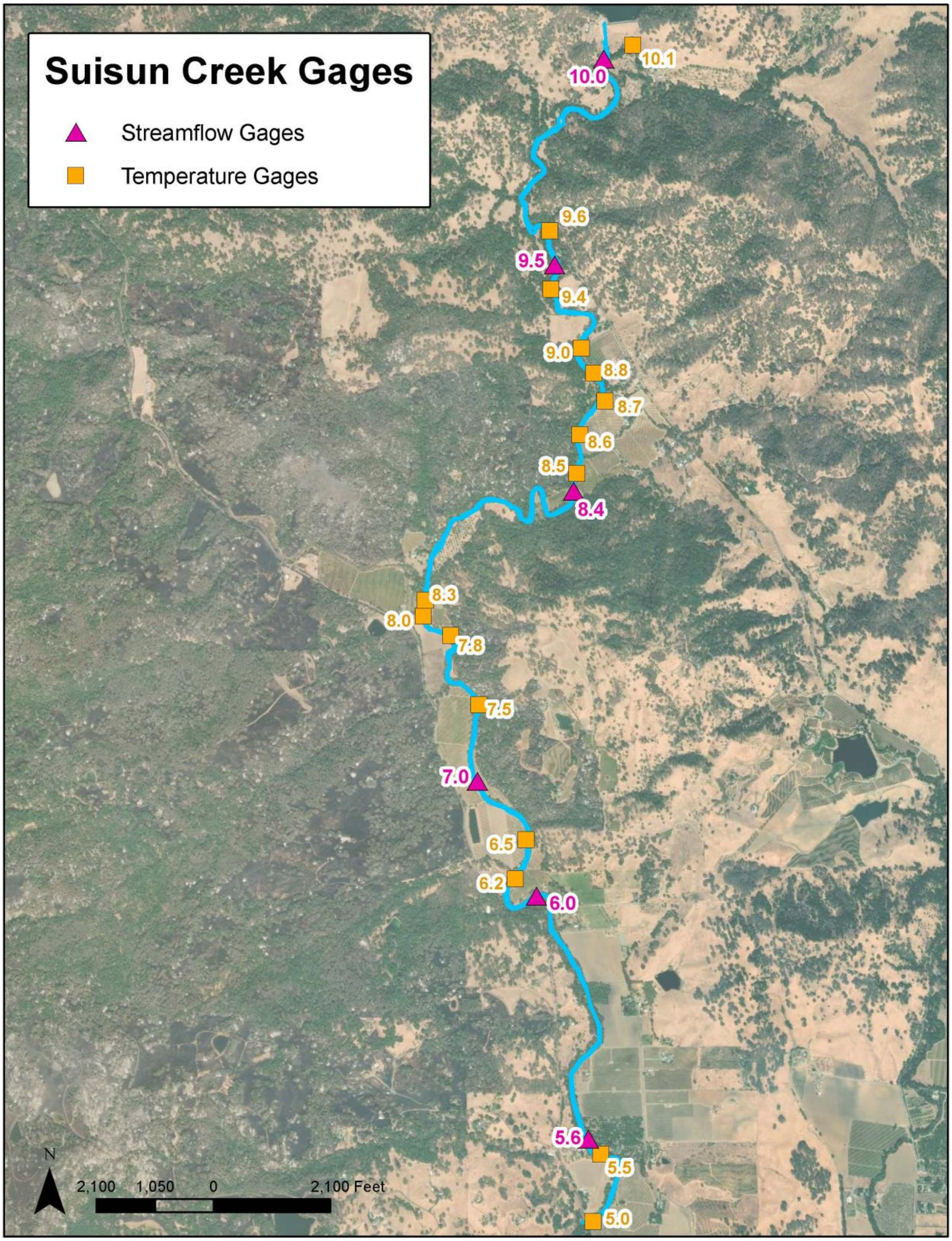


Figure 2: Map of upper Suisun Creek watershed showing locations of monitoring stations

Table 3 provides data from the Department of Water Resources, California Data Exchange Center for the amount of precipitation for each year of the study.

Table 3. Water-Year Precipitation at the Napa Fire Station.

Water-Year Oct 1- Sept 30	Precipitation inches	Percent of Long-Term Average	Dry. Normal or Wet year
2016-17	45.00	186%	Wet
2017-18	19.22	79%	Dry
2018-19	33.29	138%	Wet
2019-20	14.26	59%	Dry
2020-21	10.26	42%	Dry

METHODS

STREAMFLOW

Pressure transducers were installed at six locations along Suisun Creek where channel conditions were best for streamflow measurement. Gages recorded year-round for the 2017-2021 period. Initially, vented pressure transducers were used to measure stream stage at six stations. These vented transducers malfunctioned apparently due to problems with the venting tubes. As a result, some data collected in 2017 and 2018 were not useful for determination of streamflow. The vented transducers were replaced in Spring 2019 with non-vented transducers. Records for the non-vented transducers were compensated using barometric data collected at SC 10.0 and SC 5.6. For both types of transducers, recording interval was 15 minutes.

Periodically, discharge measurements were made using a vertical-axis minimeter and were used to develop arithmetic ratings for each gage. Ratings were limited to relatively low flows owing to limitations in measuring high flows. Points of zero flow were measured annually with a graduated wading rod and used for rating development.

Methods for selecting stations, collecting and evaluating data followed U.S. Geological Survey protocols (Rantz 1982a and b).

WATER TEMPERATURE AND WATER QUALITY

Water temperatures in Suisun Creek were monitored with two networks of sensors. One network was comprised of the transducers used at stream flow gages, which measure water temperature in addition to stage. The other network consisted of HOBO temperature sensors (Hobo Water Temp Pro v.2) installed at locations between gaging stations (Figure 2). Monitoring stations were selected to provide for a series of instruments along most of the creek. Several of the HOBO sensors were lost or damaged during the study, so the number of sensors is not the same for all years of the study.

Water temperature dataloggers were checked for accuracy prior to deployment. The HOBO sensors were calibrated at room temperature and in an ice bath annually using a NIST mercury thermometer (Forest Science Project 1997). Each logger was also checked for battery status and launched by computer to record at 30-minute intervals. The instruments were deployed in deeper areas of the channel—pools and glides—to monitor water temperatures for rearing salmonids. Sensors were deployed in the Spring and removed in the Fall 2017-2020. At the time of Hobo sensor deployment, the

Figure 3. Stream flow gage with pressure transducer and outside staff gage

Figure 4. YSI sonde in creek measures water temperature, pH, dissolved oxygen, specific conductance and depth.

depth and width of the water is measured. A sketch of the site is done and photos are taken. Riparian canopy cover is measured on a transect across the creek at the station. A spherical densiometer is used with a 4-corner measurement at each point on the transect. The transect will have at least 3 points that are generally 5-7 ft. apart. Canopy cover is reported as an average of all the measurements. Water depth and width are also measured at retrieval of the instrument.

A YSI multi-parameter submersible sonde was used to monitor water temperature, dissolved oxygen, pH, specific conductance, and water depth. Each probe used for the sonde was calibrated using standard solutions as described in the YSI manual, and batteries were replaced prior to each deployment. The sonde batteries last for two to three weeks. Similar to the hobo dataloggers the sondes were placed in pools and glides where salmonids rear in summer. Canopy cover, width and depth of flow, and overall station conditions were recorded at deployment. The sonde was deployed at gaging stations or temperature monitoring stations (Figure 2). One to three locations were monitored each summer of the study.

QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

As part of prior monitoring programs completed on Suisun Creek a Monitoring Plan (MP) and Quality Assurance Project Plan (QAPP) were completed and approved by the Regional Water Quality Control Board (LMA 2005). These plans were utilized in this study as well. Data quality objectives included: accuracy, precision, completeness, and representativeness. Table 4 lists the data quality objectives for water temperature and water quality parameters. These objectives were carried out for water temperature/quality monitoring through the following procedures:

- The accuracy of the Hobotemp dataloggers was checked by performing a comparison of each datalogger to a NIST thermometer for a room temperature water bath and an ice bath. Precision was checked before and after deployment. Completeness was evaluated by the number of days of the May to October period that data was collected. Representativeness was achieved by monitoring in numerous locations.

- The accuracy for the YSI sondes was determined by measuring known standards for dissolved oxygen and pH and calibrating the instrument for any difference from the standard. Precision was checked before and after deployment. Completeness was determined by data collection over the deployment period per station. Representativeness was achieved by deploying the sondes in a number of stations.

Table 4. Data Quality Objectives for Water Temperature and Water Quality Parameter

Parameter	Method / Range	Units	Detection Limit	Sensitivity	Accuracy	Precision	Complete-ness
Temperature	Hobotemp datalogger	°C	.01	0.01	± 0.5	± 0.2	90%
Dissolved oxygen	YSI sonde	mg/L	0.01	0.01	± 0.5	± 0.2	90%
pH	YSI sonde	pH	0.5	0.5	+/- 0.5	20%	90%
Specific conductance	YSI sonde	mS/cm	N/A	+/-0.2	+/-0.2	+/-0.2	90%

MONITORING RESULTS

STREAMFLOW

For this study, flows were monitored at 6 stream gages between Lake Curry and Station 5.6 about 5 miles downstream (Figure 2). The gage furthest upstream is SC 10.0, which monitors lake releases about 500 feet downstream of the outlet from the lake. Gage numbers decrease downstream to the furthest downstream gage, SC 5.6.

Streamflow records (Figures 5-10) show that flows generally increased between SC 10.0 and SC 8.4, and then decreased from that point to SC 5.6. Flows decreased to zero at downstream stations when releases from the lake were reduced below 1 CFS (Figures 6-10). Field observations indicated that tributary streams, including Wooden Valley Creek, ran dry by early summer and did not provide flow to Suisun Creek beyond the end of June. Appendix A contains hydrographs from all the stations.

The stream flow monitoring was completed to provide data to answer the following questions:

- **How do Lake Curry releases change flow on Suisun Creek in the dry season?**
- **Are diversions of the released water occurring along Suisun Creek?**
- **How do Lake Curry releases change flow on Suisun Creek in the wet season?**

Downstream Changes in Streamflow in the Dry Season

Increases in flow

Flow increases between SC 10.0 and SC 8.4 may result from shallow hillslope groundwater seepage. Throughout the study, small amounts of seepage were observed entering the channel downstream of SC 10.0 near the Lake Curry spillway. This seepage may have been water from the lake or groundwater from local aquifers. Data from winter and spring of 2021 indicate persistent influent groundwater between the lake and SC 8.4, which may be a result of the 2020 LNU wildfire that killed many trees in the watershed and may therefore have reduced transpiration.

During periods when the channel at SC 5.6 was dry, water was observed seeping into the channel downstream of the gage. This seepage may have been related to irrigation of vegetation near the channel. This seepage is not reflected in our streamflow records as it occurred downstream of our gages.

From Dec 2017-June 2018 the City of Vallejo released no water from Lake Curry resulting in Suisun Creek drying up in almost all areas (Figures 6-8). During the fall of 2019, releases from the lake outlet were stopped to allow repairs to be made. The City of Vallejo pumped water over the spillway during the repairs, increasing flows at downstream stations in September 2019 (Figure 9).

Decreases in flow

After cessation of seasonal flow from Wooden Valley Creek, streamflow decreased each year between SC 8.4 and SC 5.6 (Figures 5-10). Flow decreases downstream of SC 8.4 might have resulted from diversions, evaporation, and seepage to groundwater.

Diversions

Water rights held on Suisun Creek do not provide for legal diversions during summer low-flow conditions. Appropriative rights have required bypass flows that prohibit diversions when streamflow is less than 3 cfs. Riparian rights do not allow diversion of water released from storage, which is almost all of the flow in Suisun Creek during summer. Figure 11 shows an example of the effect of diversion on flow in a hydrograph form the Russian River. The streamflow records at each gage were reviewed for sudden drops in flow level coincident with a pump form a direct diversion being turned on. Our streamflow records do not provide any clear evidence of such diversions during summers. Evaporation

Streamflow measurements made in late July 2020 at SC 10.0 and SC 5.6 were used to estimate evaporative losses between the stations. Streamflow at SC 10.0 was measured as 0.8 cfs and streamflow at SC 5.6 was measured as 0.1 cfs. Evaporation from open water surfaces on small streams in central California can be equivalent to roughly 0.03 ft/day (Blaney, 1960). Based on this evaporation rate, the estimated average width of the wetted channel (30 ft), and the length of the stream between the two gages (25,000 ft), evaporative loss would amount to 22,500 ft^3/day, equivalent to 0.3 cfs. This would represent roughly 40% of the streamflow loss observed between the two stations.

Seepage to groundwater

The limited available groundwater level data from wells along the creek (USGS 2021) near the Solano-Napa County line indicate that groundwater levels have generally remained 17 to 42 feet below land surface. As the stream is generally not incised as deeply as 17 feet, the elevation of the channel bed is higher than the local water table. Seepage is therefore likely to be directed from the stream to the aquifer. Seepage losses would be consistent with the estimates of evaporative losses discussed above, which indicated that not all of the decrease in streamflow could be attributed to evaporation alone.

Winter flows

Releases from Lake Curry can maintain fish habitats in Suisun Creek when winters rainfall is not sufficient. As shown in Figure 12, when releases from the lake were stopped during a dry winter, downstream flows also rapidly ceased. More recent data shown in Figure 14 indicate some increases in flow downstream of the lake during a dry winter. However, this period followed a major wildfire in the summer of 2020 that killed most of the trees in the upstream watershed. The destruction of woody vegetation may have resulted in reduced evapotranspiration and therefore increased groundwater seepage (Bart, 2014; Wine and Cadol, 2016) during the winter of 2020-2021. If so, this effect will be transitory, and groundwater seepage to the stream will likely be reduced in the future.

Summary

In summary, almost all of the flow in Suisun Creek during summers was water released from Lake Curry. Streamflow decreased downstream of the lake due to evaporation and seepage. During periods when lake releases were reduced below 1 CFS, connected flows throughout the study reach were not maintained. A release of 2-2.5 is required to maintain connected flow. Clear examples of the effects of decreased lake releases on downstream flows can be seen in Figures 6-10, which show flow at downstream gages decreasing to zero. During winters when rainfall is limited, releases from the lake will be the only reliable source of water to maintain the connected flow needed for steelhead migration. Although streamflow data for the dry winter of 2020-2021 indicate some groundwater seepage to the stream, this seepage may have resulted from the loss of woody vegetation following a major wildfire. Seepage to the stream is likely to decrease as vegetation recovers.

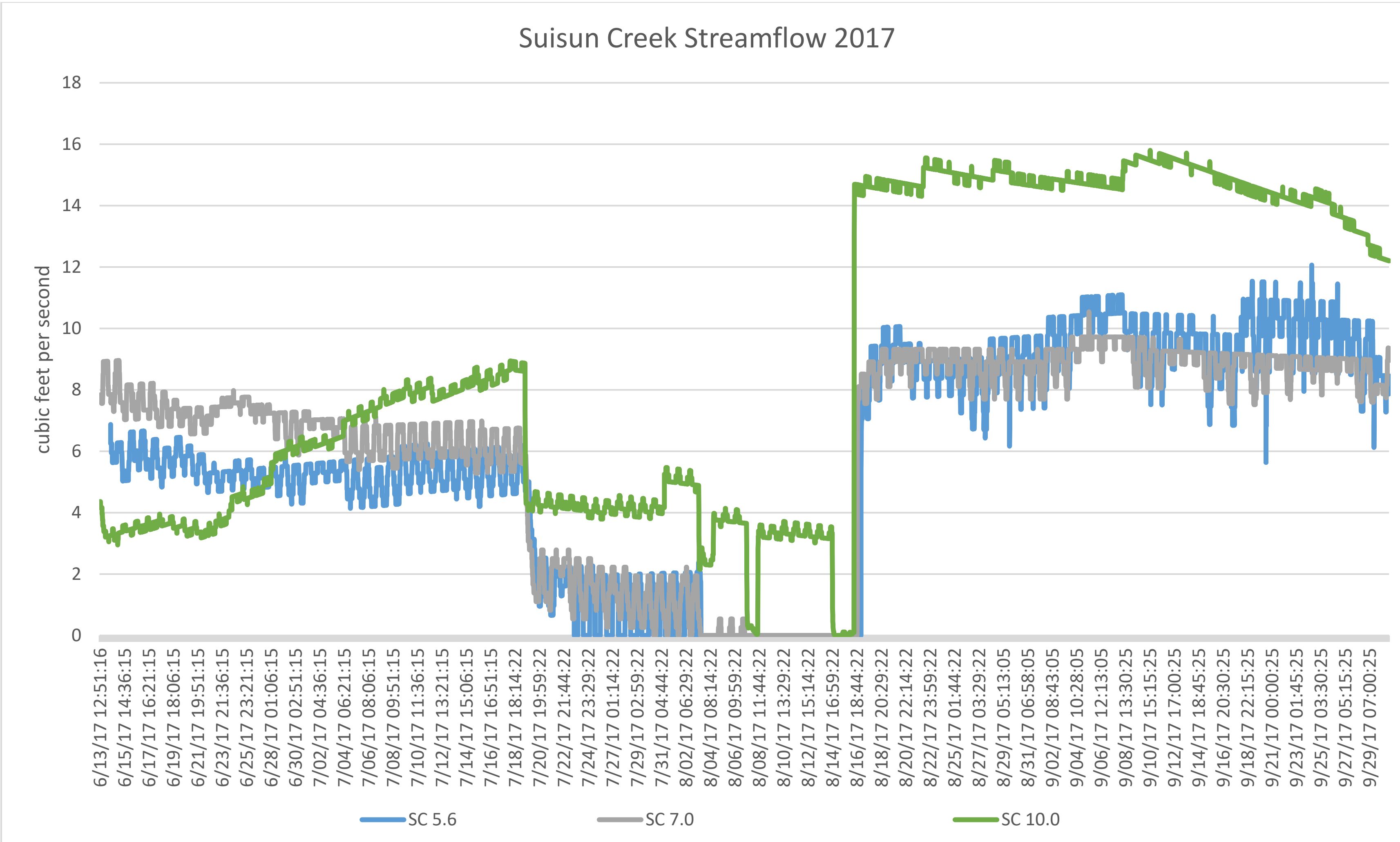
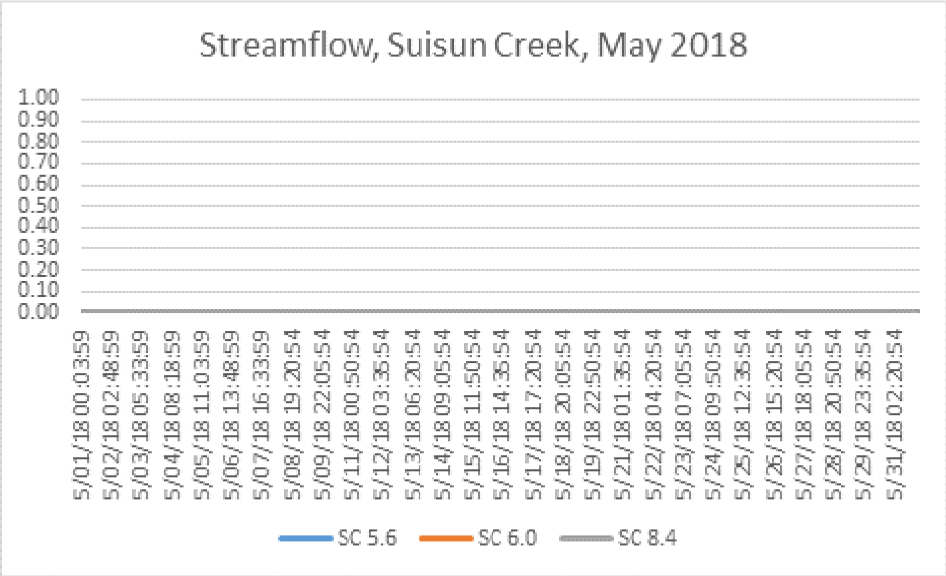
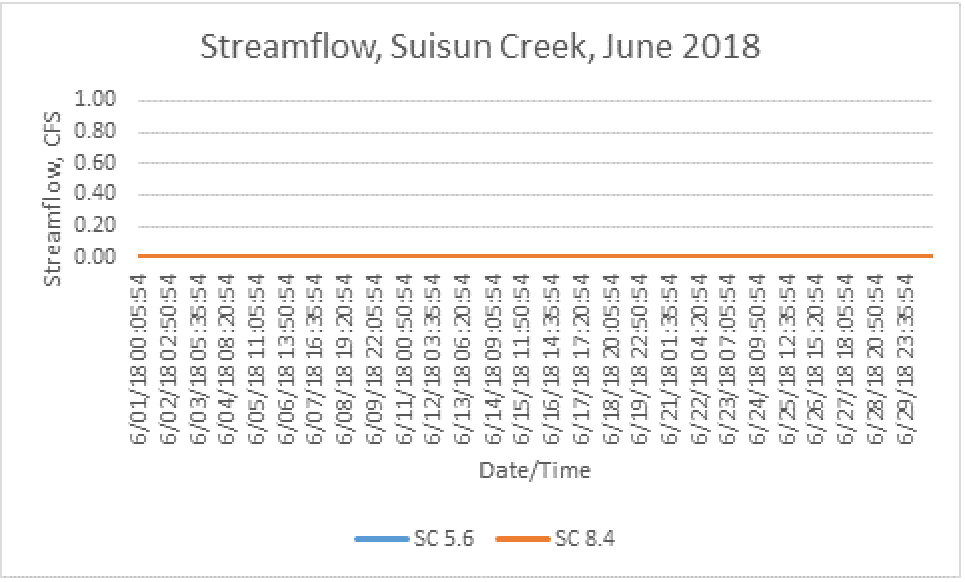


Figure 5. Summer streamflow, Suisun Creek, 2017. Green line (station 10) shows the release from Lake Curry; silver line (station 7) is 3.9 miles downstream from dam; blue line (station 5.6) is 5.3 miles downstream from dam. Flow at downstream stations shows changes of releases from Lake Curry.





Figures 6-8. Summer streamflow, Suisun Creek, 2018. Releases from Lake Curry were shut off by the City of Vallejo for over 6 months of 2018. This resulted in flows 2 miles downstream (station 8.4) of 0 and flows downstream at 4.2 miles (station 6.0) and 5.3 miles (station 5.6) of 0.

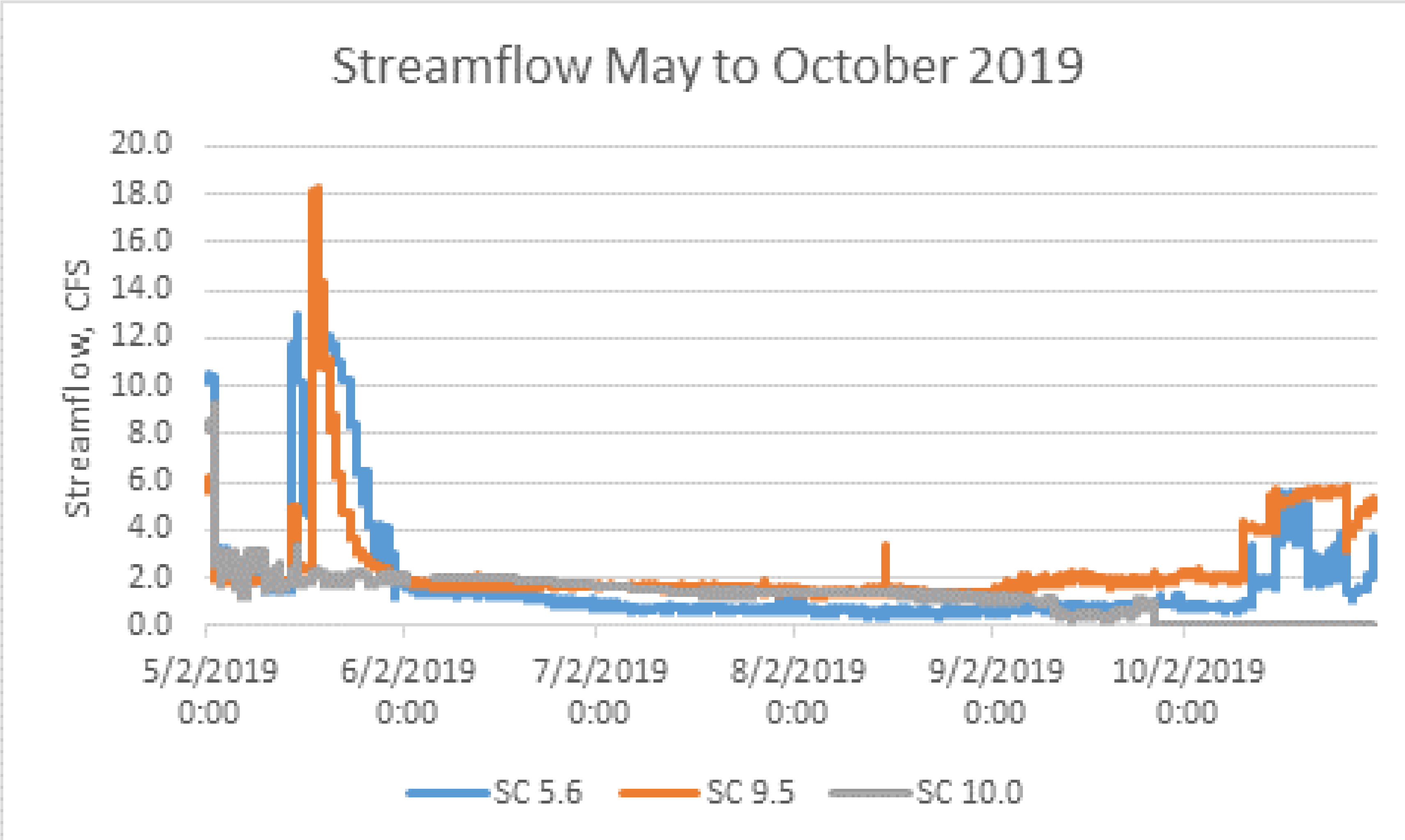


Figure 9. Summer streamflow, Suisun Creek, 2019. Releases from Lake Curry (silver line) vary between 0-2 cfs. May to Sept. Flows at station 9.5 (orange line) 1.1 miles downstream of dam are similar. Flows at station 5.6 located 5.3 miles downstream of dam (blue line) are close to 0. Hydrograph shows effect of water pumped over spillway in October as a result of National Marine Fisheries Service request to avoid impacts to threatened steelhead trout.

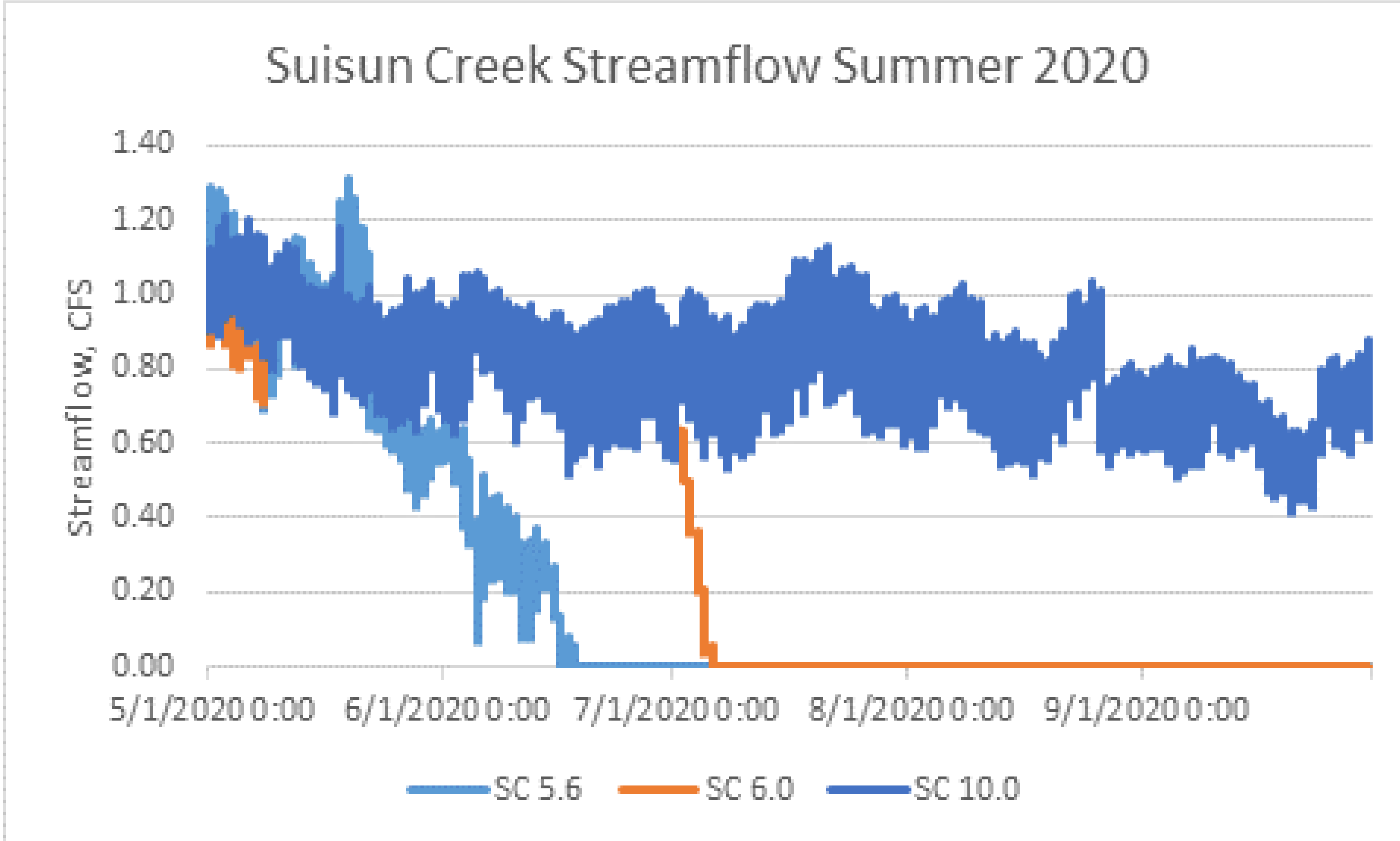


Figure 10. Summer streamflow, Suisun Creek, 2020. Releases from Lake Curry (dark blue line) vary between 0.5-1.25 cfs from May to Sept. Flows at station 6.0 located 4.2 miles downstream of dam (orange line) go to 0 in July. Flows at station 5.6 located 5.3 miles downstream of dam (light blue line) go to 0 in July. 2020 was a dry year showing that a release of 1.0 cfs will not maintain connected flow.

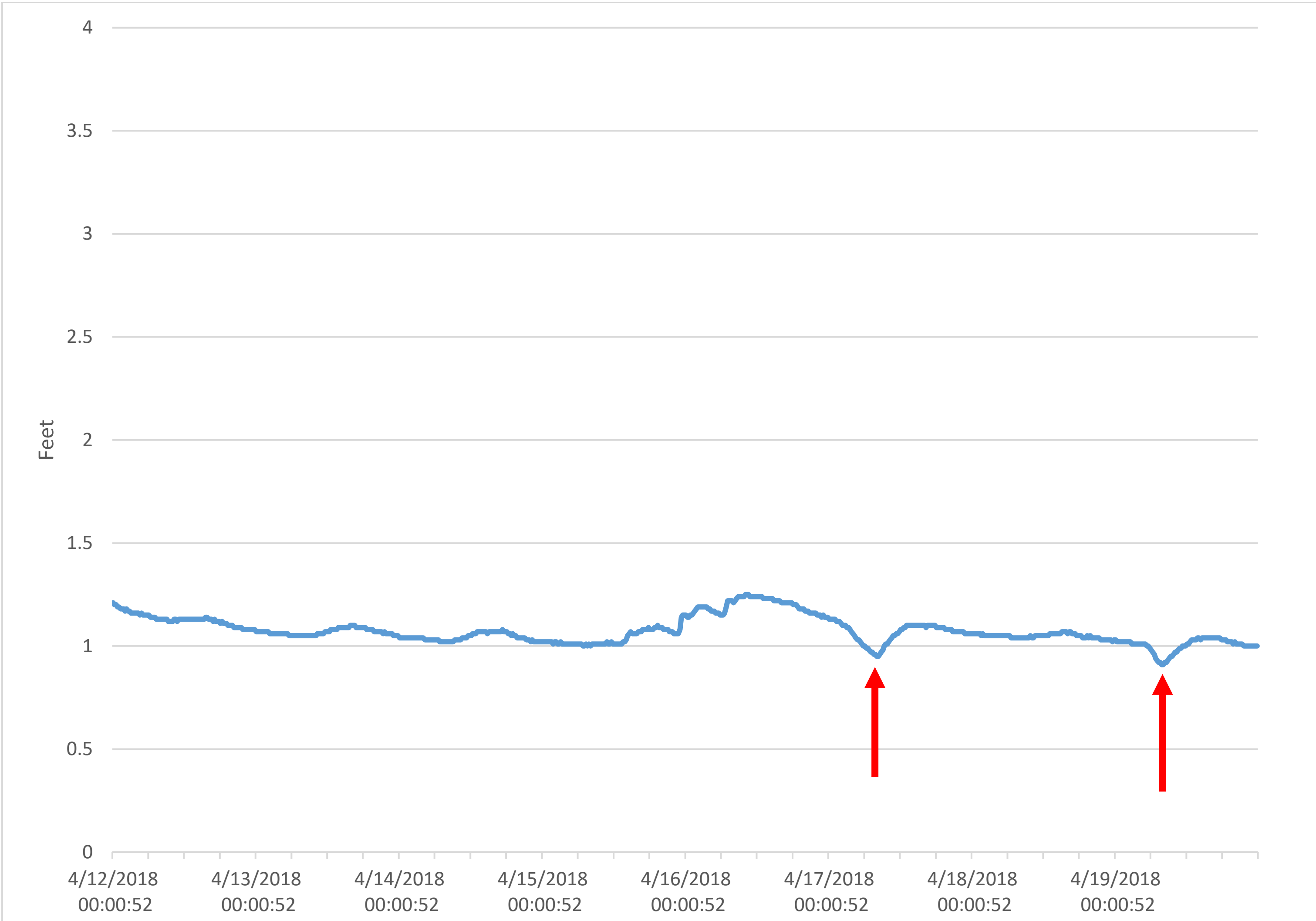
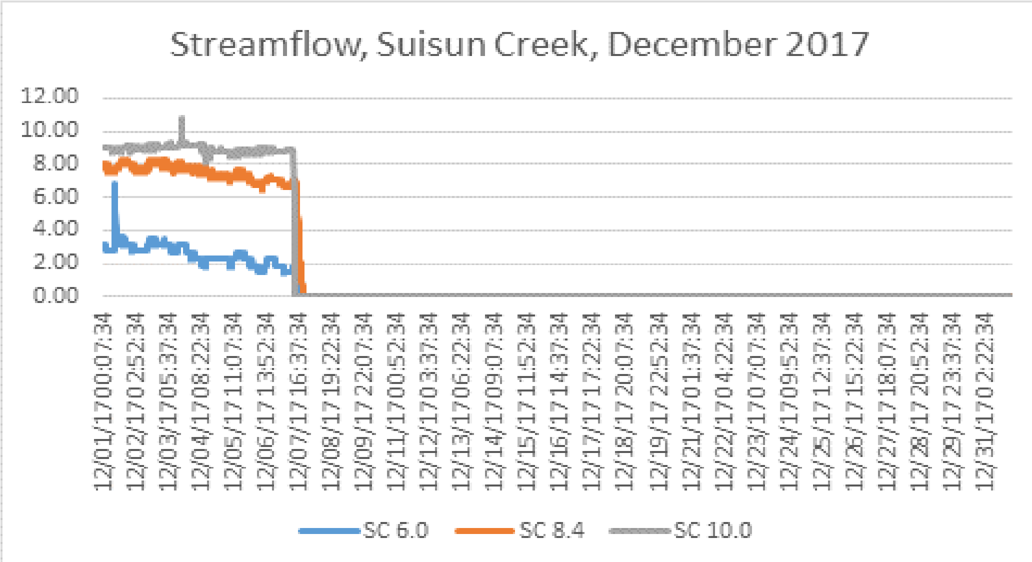
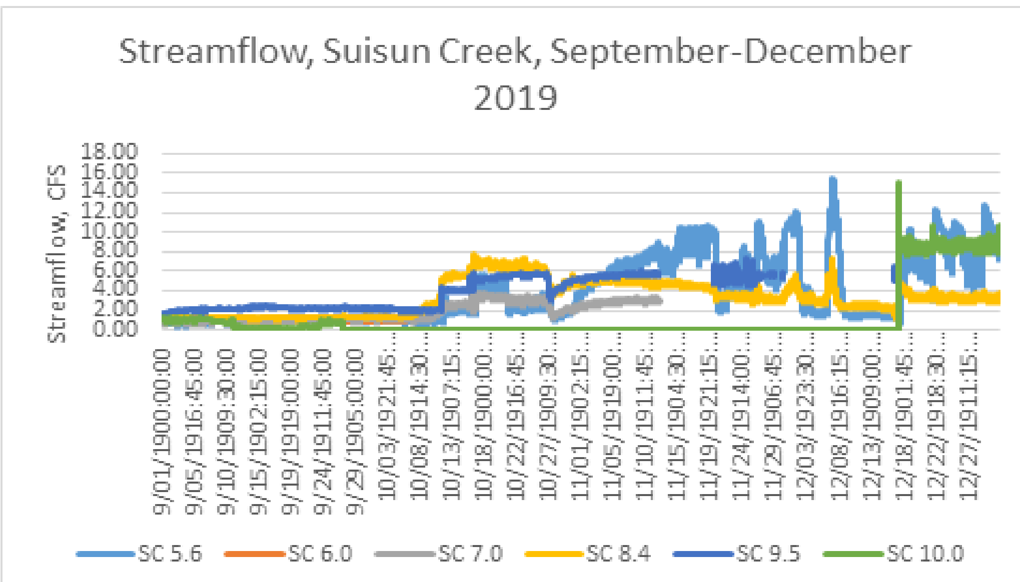


Figure 11. Example hydrograph showing abrupt changes in flow indicative of diversion of flow. The data from the six stream flow gages on Suisun Creek were analyzed for this type of change during summer months and none were found.





Figures 12-13. Effects of releases from Lake Curry on winter flows. With no release out of Lake Curry in December 2017 flows on Suisun Creek go to zero between storms. Releases were also stopped in 2018 between Sept and Dec but rainfall provided base flows for a portion of this time. Releases could maintain creek habitats between storms

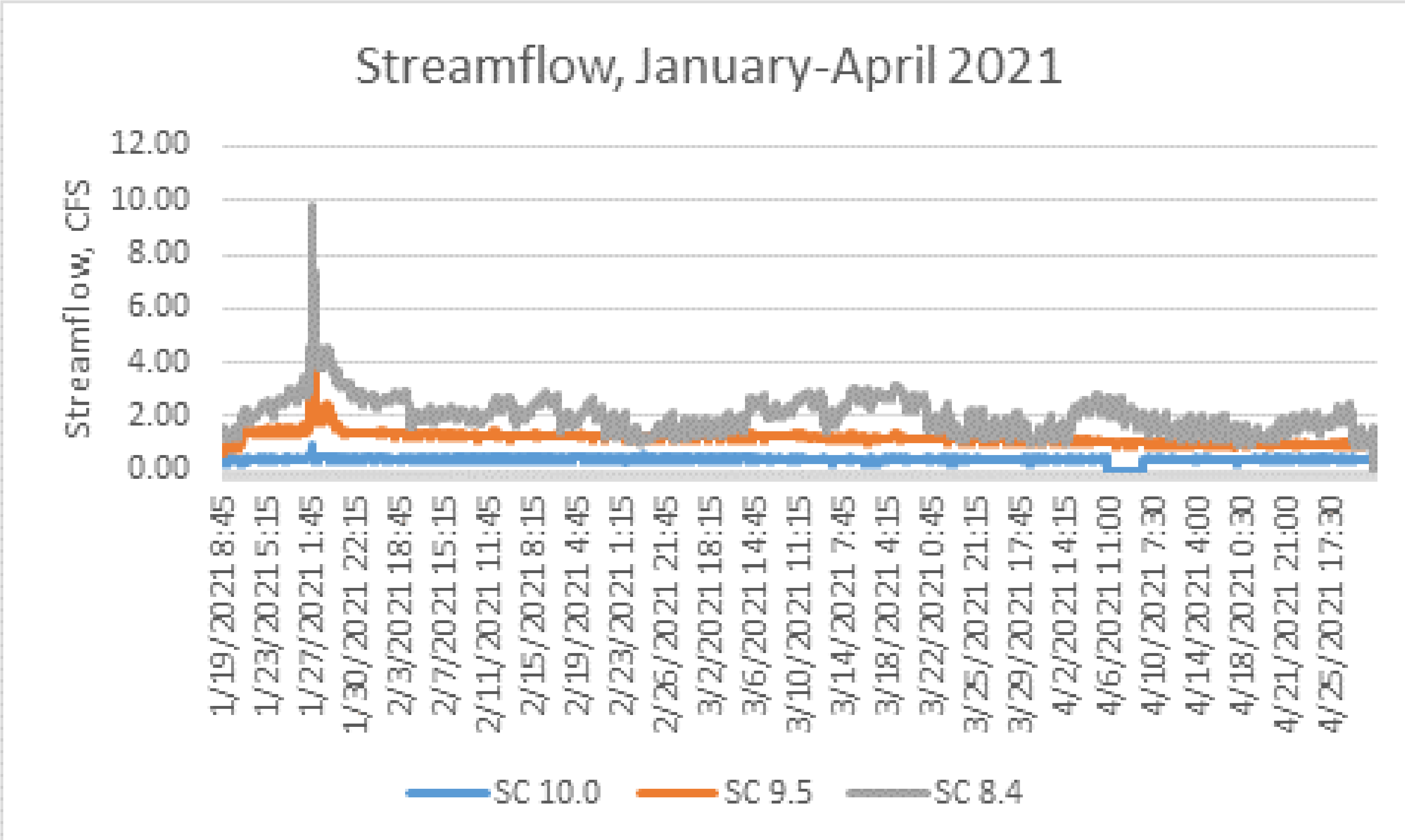


Figure 14. Releases from Lake Curry are around 1 cfs with rainfall providing most of baseflow in the upper portion of the creek

WATER TEMPERATURES

The objective of the water temperature monitoring is to assess habitat suitability for steelhead trout and to identify projects needed to increase habitat values. The effects of warm water on steelhead trout are complex. We identified criteria to determine when stream water is too hot for fish based on information in the literature. Sullivan et al. 2002 report that growth of juvenile steelhead trout declines when water temperatures exceed 70^{o} F or if water temperatures fall below 58.1^{o} F. Growth of juvenile steelhead trout is an important factor in determining the probability of whether a young steelhead trout will survive in the ocean and eventually return to spawn. Larger juveniles have a higher probability of returning to spawn. For this study, we selected 70^{o}F as the threshold for the onset of chronic stress on juvenile steelhead trout, due to elevated water temperature. Extended exposure to water temperatures above 75.2^{o} F can result in mortality for steelhead trout. For example, 77.7^{o} F water can pose a threat of mortality if fish are exposed to it for more than 9.6 hours. Appendix B contains all the water temperature data for the 2017-2020.

The water temperature monitoring was completed to provide data to answer the following questions:

- **How do water temperatures change from upstream to downstream?**
- **How do water temperatures change with a change in releases from Lake Curry?**
- **How does canopy cover change water temperatures?**

Temperatures change from upstream to downstream

As shown by the HOBO sensor data in Figures 15 to 18, water temperatures in Suisun Creek show two subtle trends during summers: temperatures generally increase downstream and water temperatures at each station increase over the summer. Water temperatures downstream of SC 8.0 exceeded the 70^{o} F threshold that is considered stressful to steelhead. Temperatures at downstream stations occasionally exceed 80^{o} F, a temperature considered lethal for steelhead. Temperatures at the stations upstream of SC 8.0 remained below 70^{o} F. Figure 19 compares the water temperature measured at SC 9.6 and SC 5.0 which are separated by 4.7 stream miles. Appendix B has water temperature graphs for each station for each year.

Water temperatures at the lake outlet were not constant during the study, and variations in temperatures of water released from the lake may have affected downstream temperatures. Records for SC 10.0 showed seasonal and diurnal changes, as well as temperature changes that may have been related to outlet valve configurations. For example, the temperatures of water released from the lake in the wet year of 2019, when the lake was full in June, never exceeded 60 ^{o} F (Figure 20). However, in the dry year of 2020, when the lake level was well below the spillway in June, exceeded 70^{o} F from July 24 to the end of September (Figure 21).

In order to better understand the relative contributions of downstream warming and diurnal changes in lake outlet temperatures to temperature increases downstream of the lake, we compared diurnal temperature ranges at SC 10.1 with temperature ranges at all downstream stations in 2017, the year with the most complete data set (Figure 22). Diurnal range is the difference between daily temperature minima and maxima, and indicate the amount of warming each day. The diurnal range for SC 10 at the lake outlet was small (about 1 degree F) because the large volume of water in the lake as well as evaporation from the lake surface buffered changes due to solar radiation. From SC 9.6 to 7.8, the diurnal temperature range increases to 5-6 degrees F. From SC 7.5 to SC 6.2, the diurnal temperature range increases, approaching 8 degrees F at SC 6.2. Then from SC 5.6 to SC 5.0, the diurnal temperature range decreases to roughly 5 degrees F, possibly due to groundwater seepage as described previously.

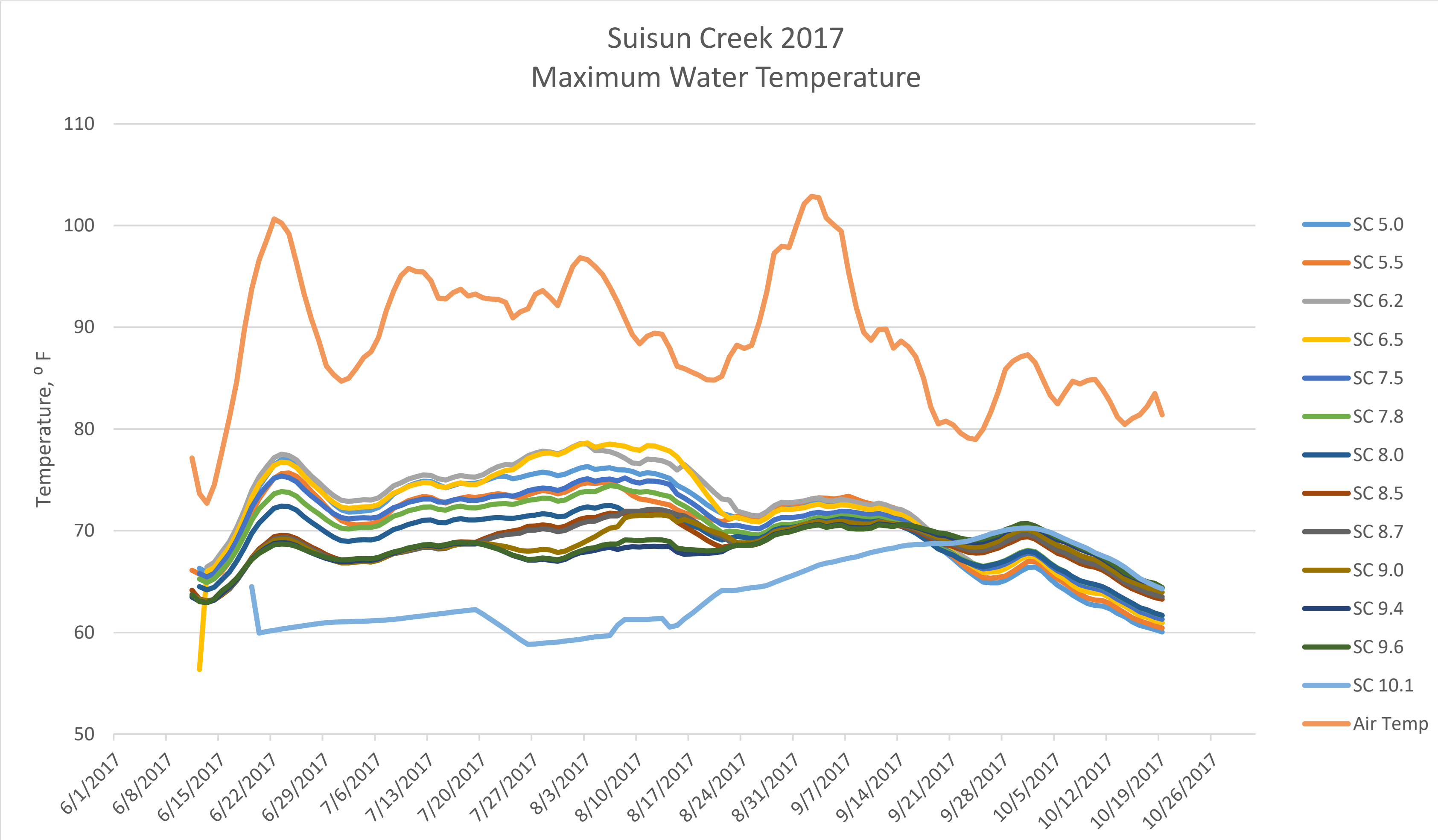


Figure 15. Suisun Creek daily maximum water temperatures for 2017 at selected stations. Air temperature data is from station 7.8 located about 3 miles downstream of Lake Curry. Rainfall for the 2017 water year was 45.0 inches in Napa.

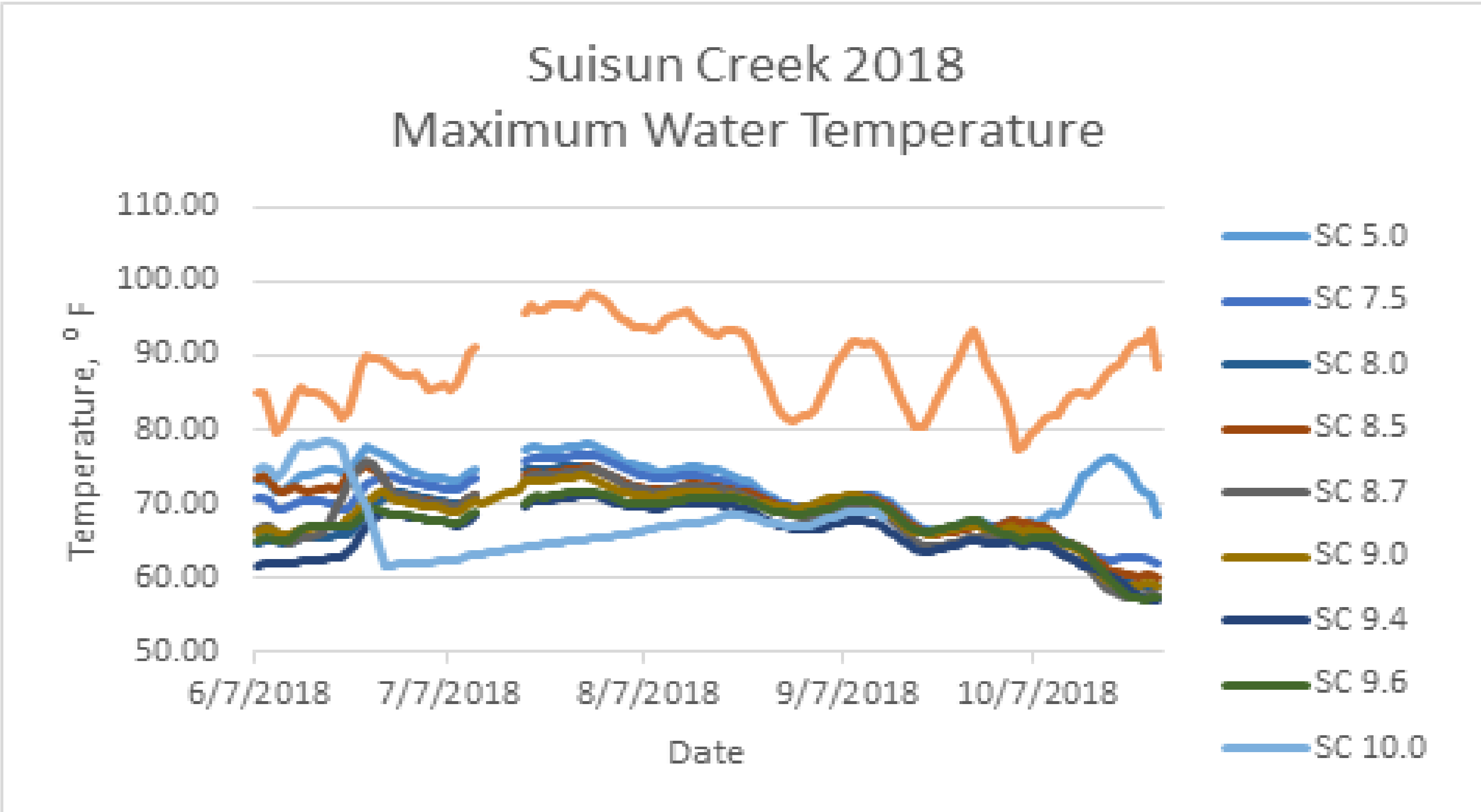


Figure 16. Suisun Creek daily maximum water temperatures for 2018 at selected stations. The gap in data in July represents a time when temperature sensors were removed and not redeployed for a few days to allow maintenance. Air temperature data is from station 7.8 located about 3 miles downstream of Lake Curry. Rainfall for the 2018 water year was 19.22 inches in Napa.

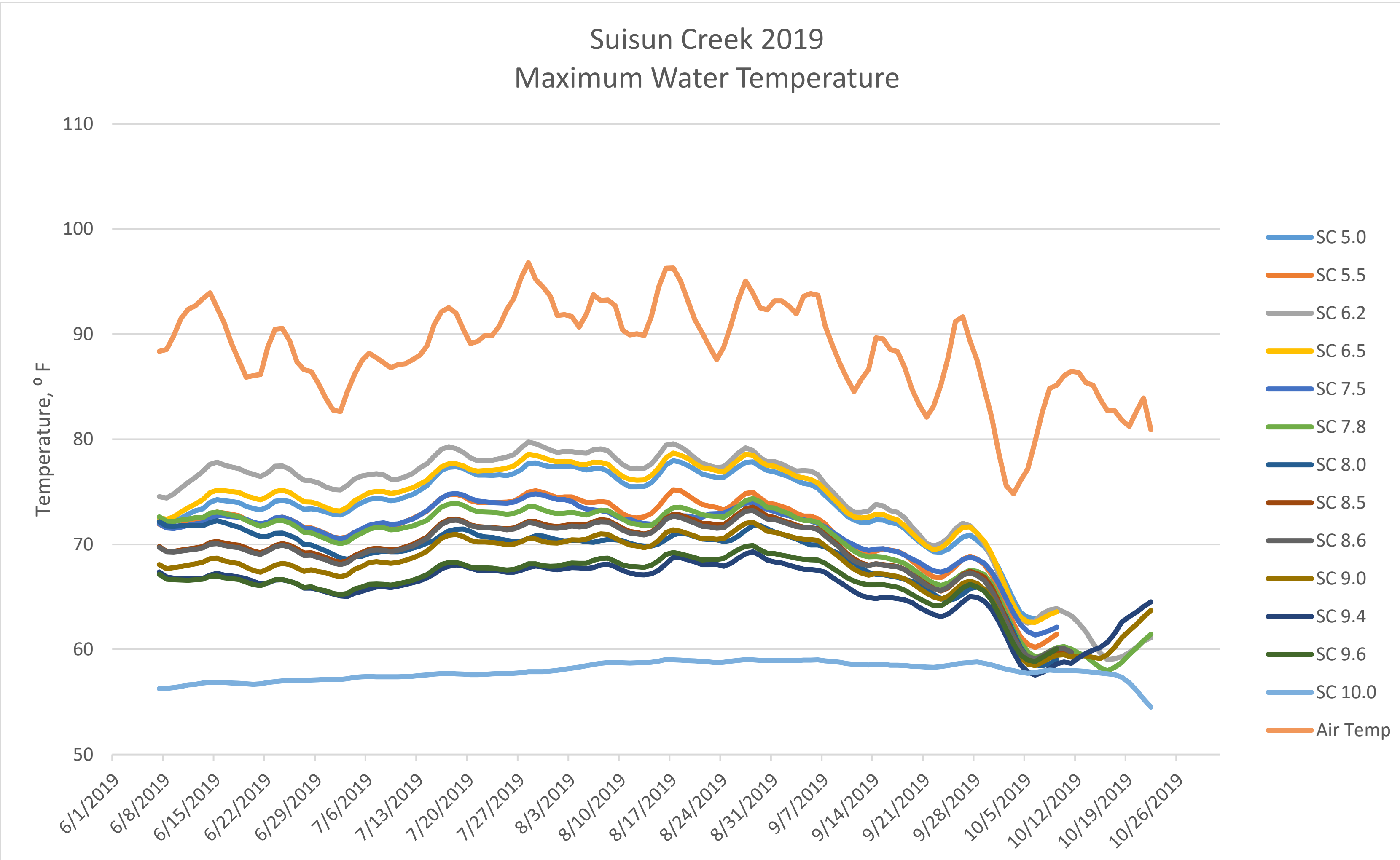


Figure 17. Suisun Creek daily maximum water temperatures for 2019 at selected stations. Air temperature data is from station 7.8 located about 3 miles downstream of Lake Curry. Rainfall for the 2019 water year was 33.29 inches in Napa.

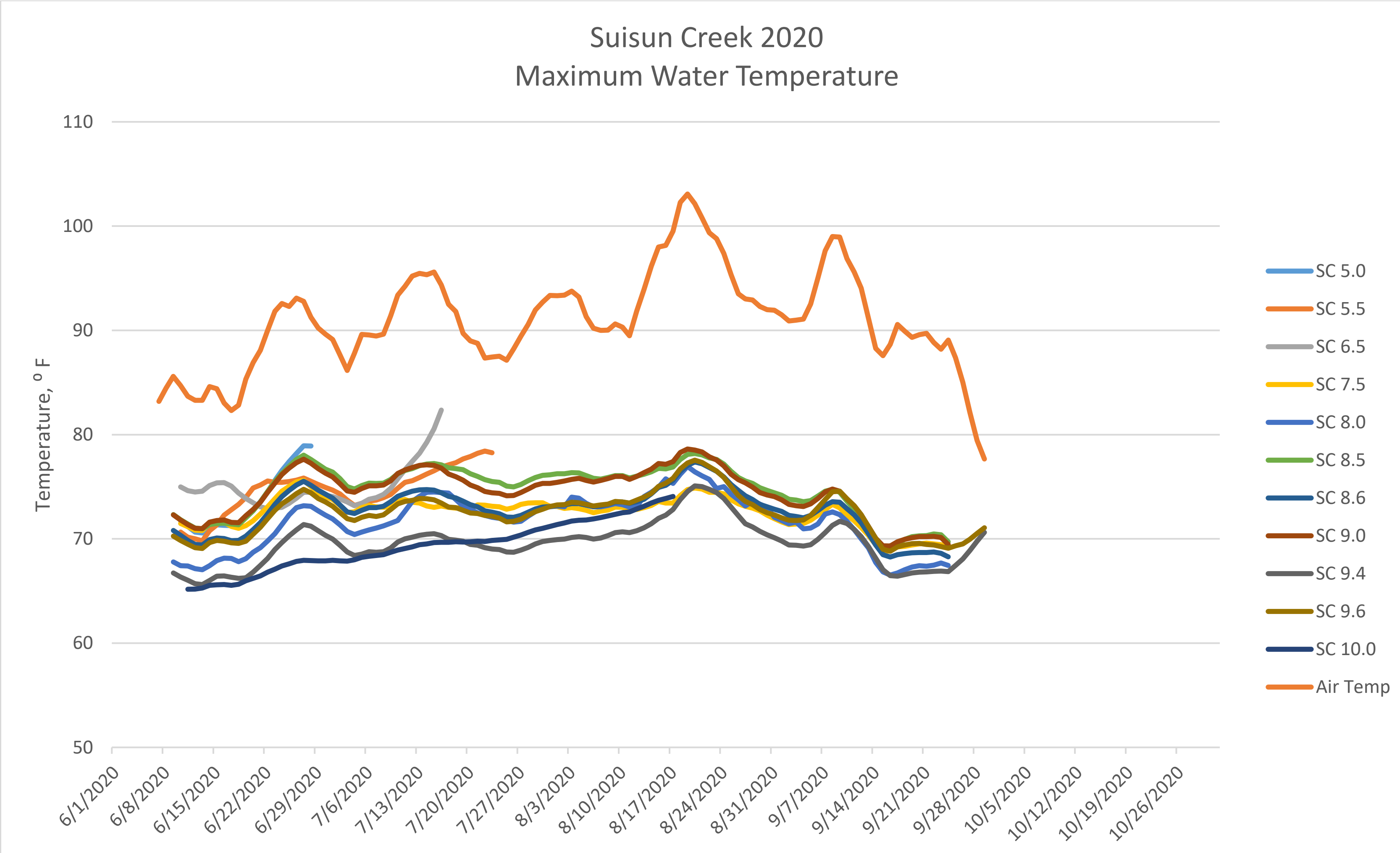
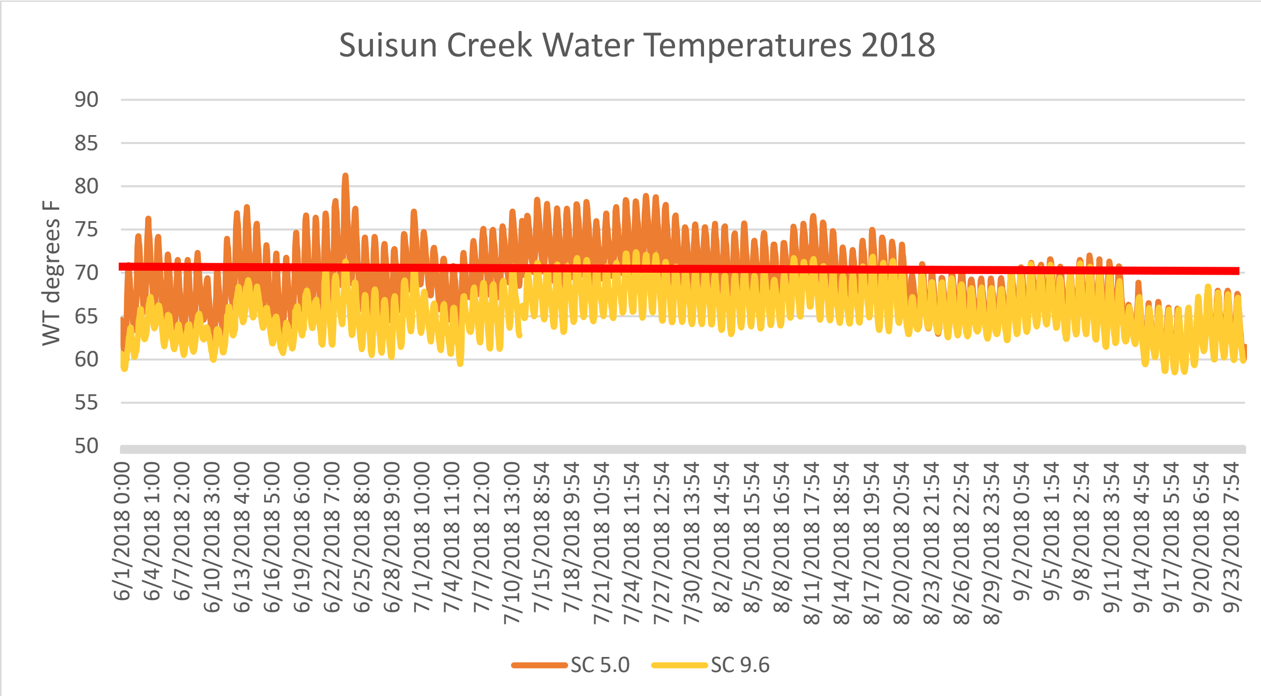


Figure 18. Suisun Creek daily maximum water temperatures for 2020 at selected stations. Air temperature data is from station 7.8 located about 3 miles downstream of Lake Curry. Rainfall for the 2020 water year was 14.26 inches in Napa. Incomplete lines are due to the creek drying up.



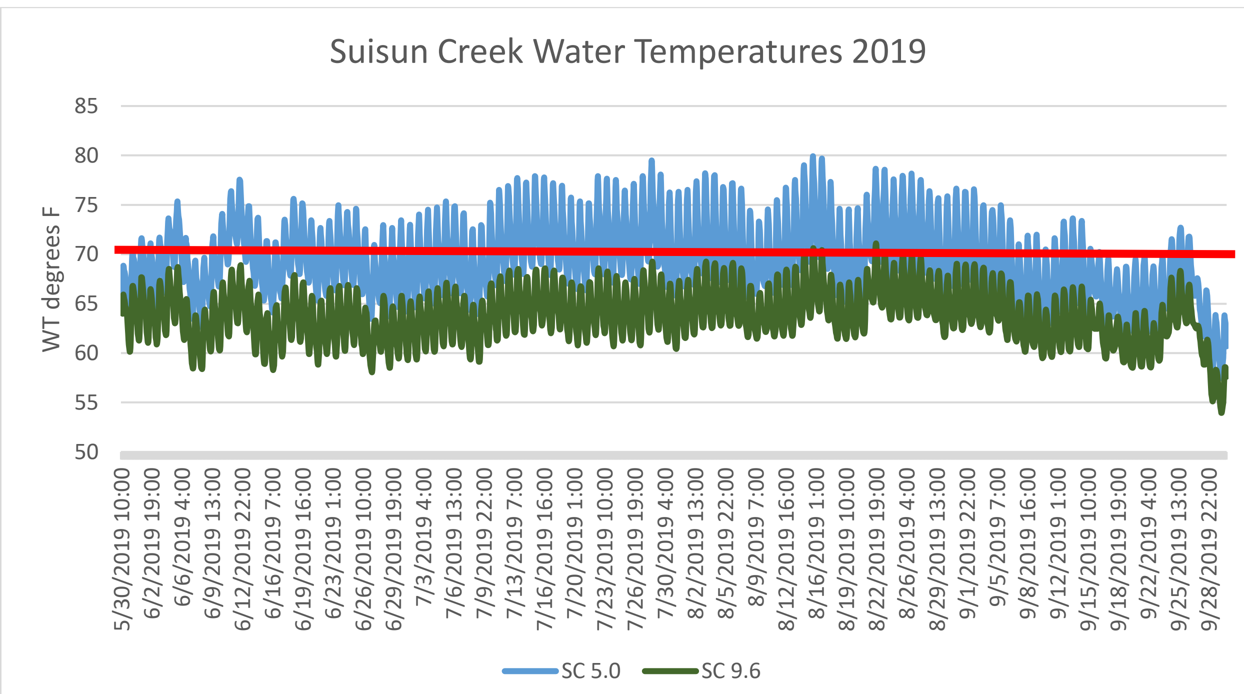


Figure 19. Comparison of station 9.6 located 1.0 miles downstream of Lake Curry and station 5.0 located 5.7 miles downstream of Lake Curry in 2018 and 2019

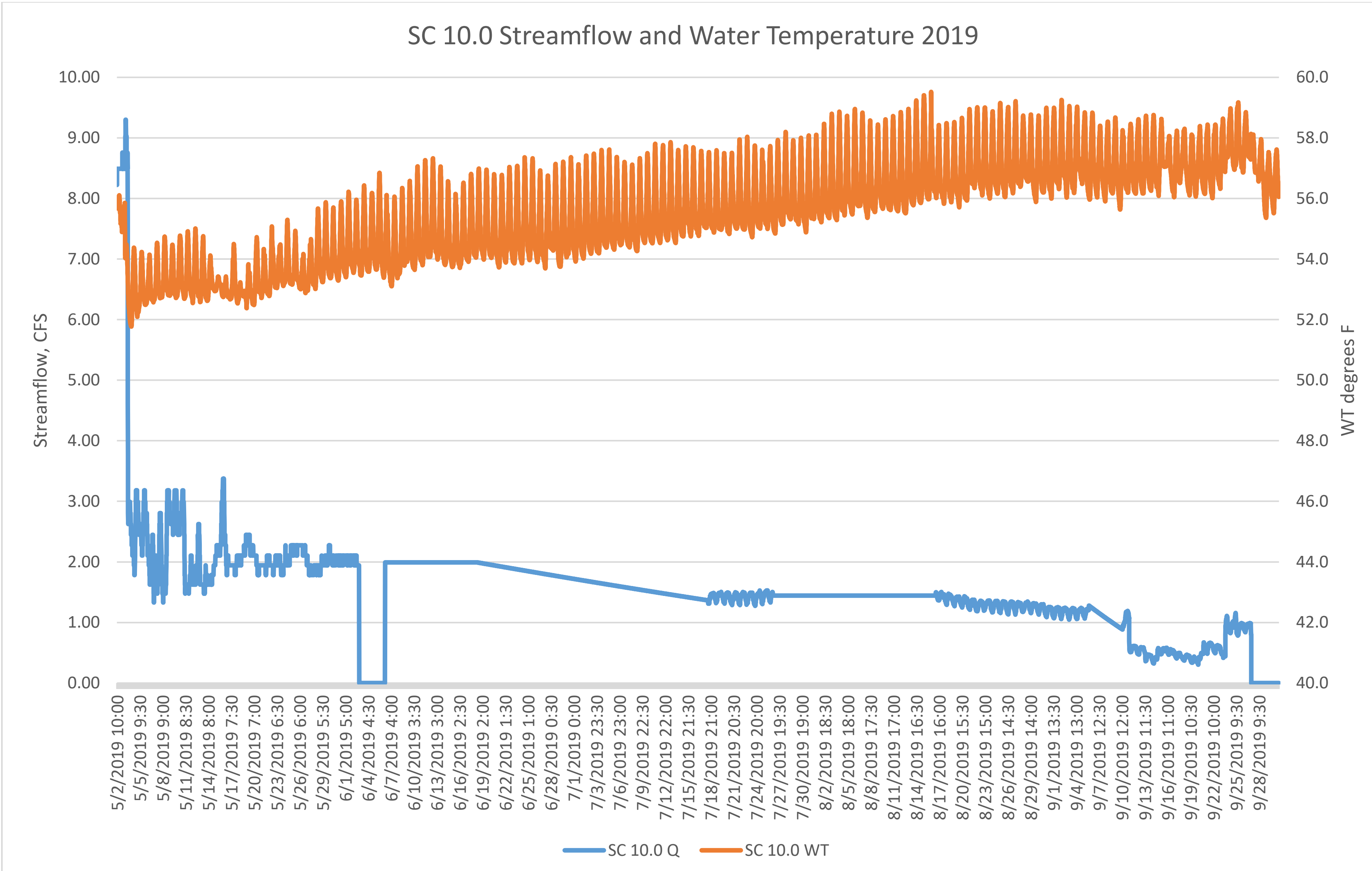


Figure 20. Streamflow and water temperature at station 10.0 in summer 2019.

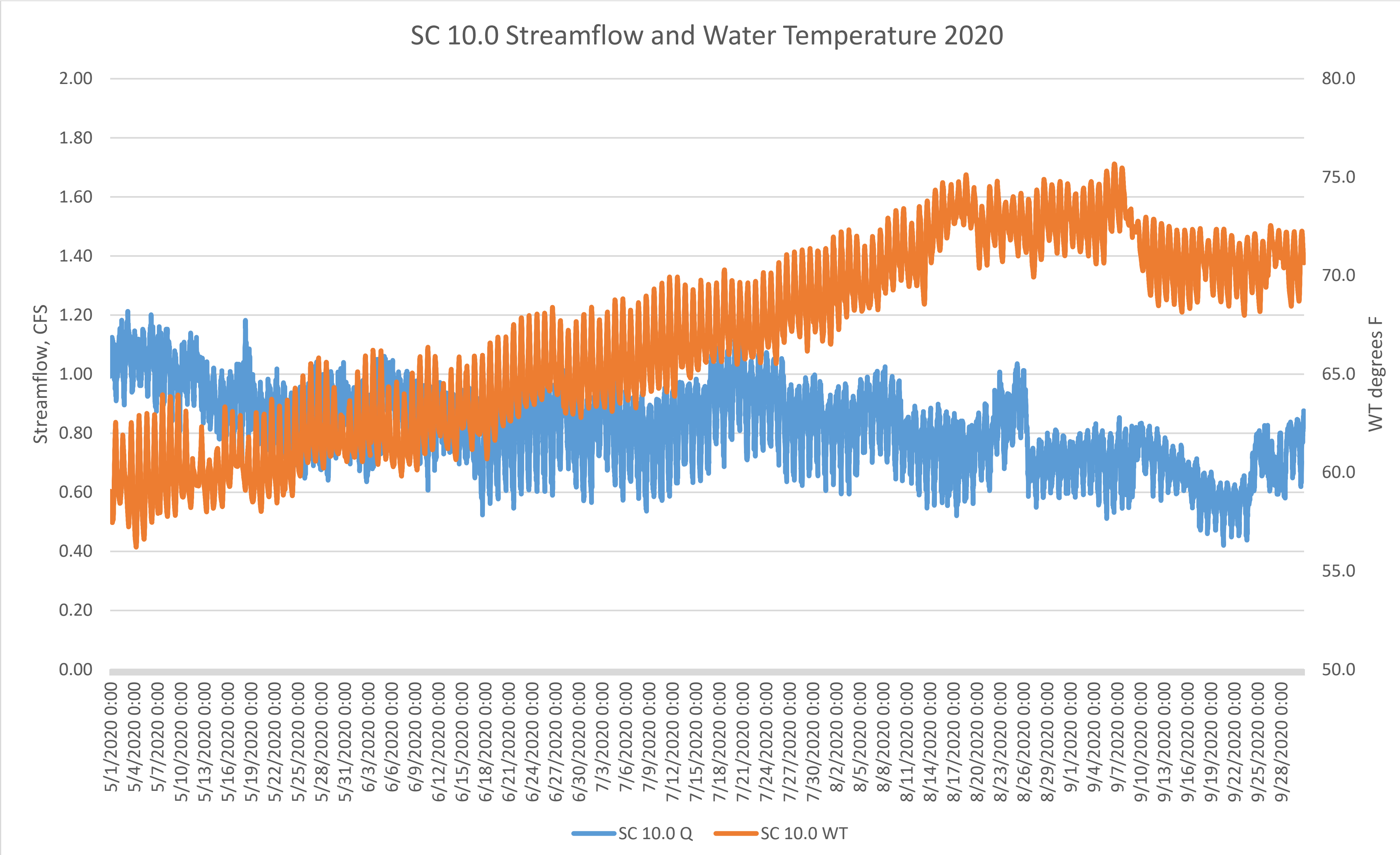


Figure 21. Streamflow and water temperature at station 10.0 in the summer 2020.

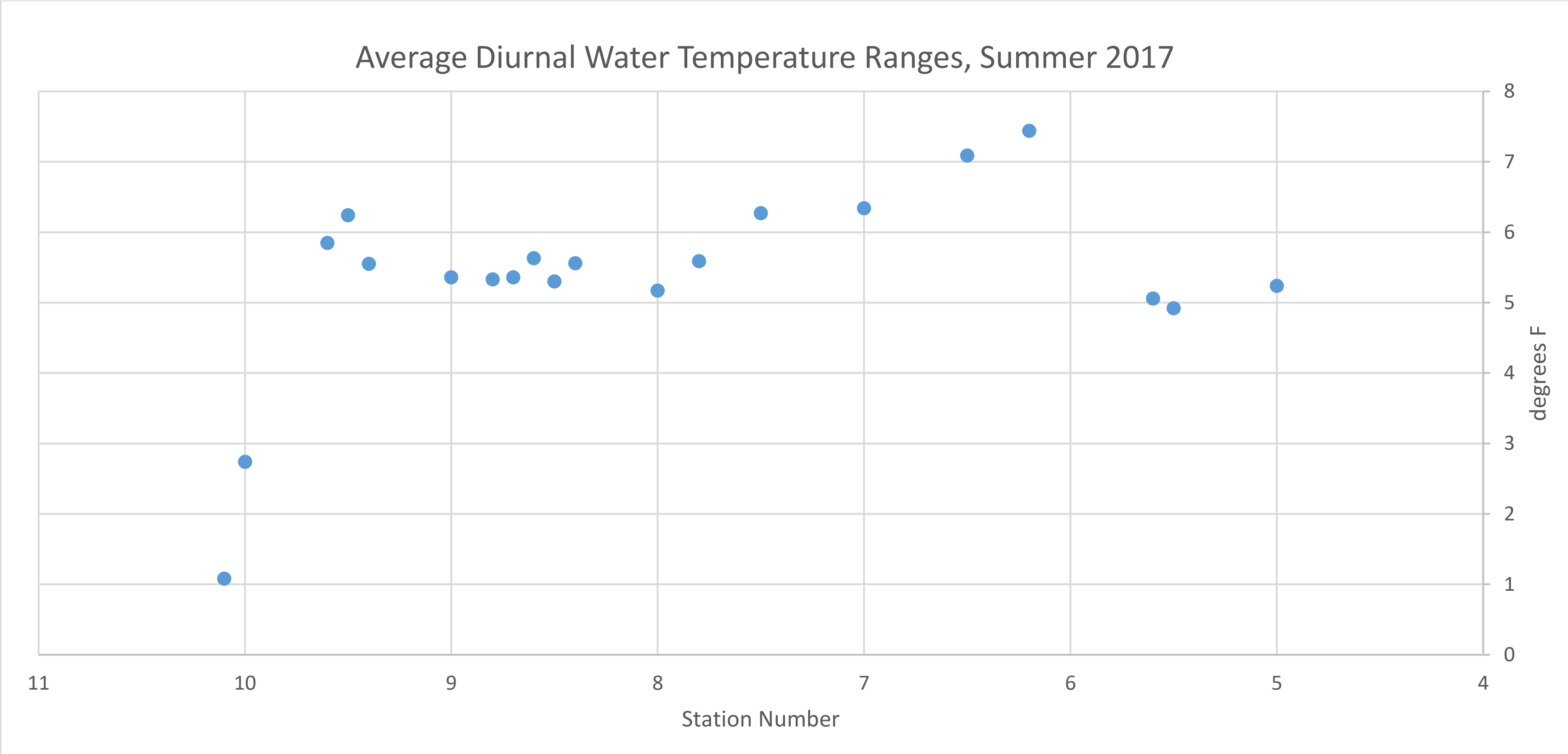


Figure 22. Average diurnal water temperature ranges in summer 2017.

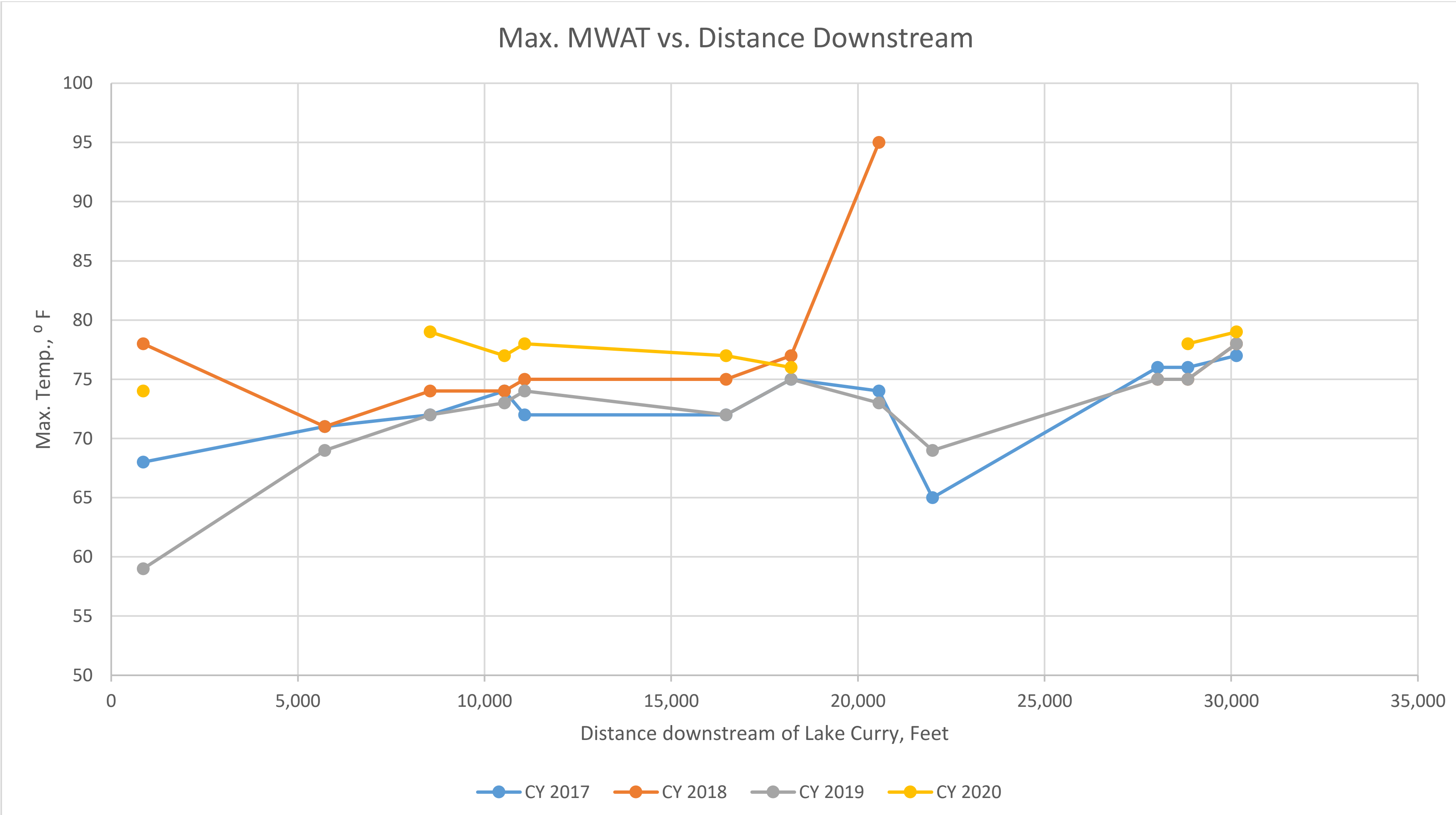


Figure 23. The Maximum Annual MMWAT (7-day moving average of maximum water temperatures) versus Distance Downstream from Gordon Valley Dam. The line for 2020 has a large gap due to dry conditions in the creek. In 2018 the creek had low flows and high temperatures.

<u>Changes in Water Temperature with Changes in Releases from Lake Curry</u>
We evaluated this question using both a model and an analysis of monitoring data.

Spatial Stream Network (SSN) Model
Water temperatures downstream of Lake Curry are affected by a number of factors other than the temperature of the water released from the lake. These include flow rates, air temperatures, and the level of riparian canopy cover. To evaluate these factors CLSI worked with Cramer Fish Sciences to create a spatial stream network (SSN) model (Appendix C). There are two primary benefits of developing an SSN model for Suisun Creek. First, by accounting for spatial autocorrelation and the nested nature of rivers, an SSN model allowed us to predict and evaluate habitat conditions (i.e., water temperatures) in areas of Suisun Creek that are inaccessible (e.g., landowner restrictions) or haven't previously been monitored. Second, the SSN model improved our understanding of how the surrounding landscape, flow conditions, and climate impact instream temperatures because the model allows us to spatially link characteristics of the drainage basin (e.g., aspect, canopy cover, geology) to instream habitat conditions.

We built an SSN model (Peterson and Ver Hoef 2010, Ver Hoef et al. 2012), for Suisun Creek using stream temperature data collected by CLSI in 2006 and 2017. We developed a spatial generalized linear model using the SSN model framework to test the collective effects of air temperature, canopy cover, and Lake Curry discharge on stream temperatures in Suisun Creek. This modelling framework also allowed us to consider the spatial autocorrelation inherent in these data. Our approach allowed us to conduct a robust evaluation of how altering discharge from Lake Curry changes downstream temperatures in Suisun Creek while accounting for other key factors.

Water temperature data collected in 2006 and 2017 coincide with records of mean daily discharge from Lake Curry. Collectively these data represent 3,388 daily maximum temperature records (°F) collected from 30 unique monitoring locations. We obtained spatially explicit mean daily air temperature records from the PRISM Climate Group that is based out of Oregon State University (http://prism.oregonstate.edu/). Estimates of canopy cover throughout the Suisun Creek watershed were either obtained from point measurements taken at the time of water temperature logger deployment or from professional judgement of areal imagery. Discharge data from Lake Curry was provided by the City of Vallejo lake operations management staff.

One of the key benefits of modelling these temperature data in the SSN framework is that it provides a mechanism for predicting water temperatures throughout the stream network. Furthermore, this framework allows us to make these predictions of how altering air temperature, canopy cover, and/or discharge rate from Lake Curry will impact stream temperatures. We examined how daily maximum water temperatures would change at approximately 70 sites stratified uniformly along the mainstem of Suisun Creek under several different scenarios. These scenarios are described below and include variations in air temperature, canopy cover, and discharge rate from Lake Curry.

The following scenarios were modeled. Table 5 shows the model results.
1. Current conditions; mean daily air temperatures in July, current canopy cover, and 2 CFS discharge.
2. Increase in mean daily air temperatures by 2.8°C from July mean (estimated A1B impact from climate warming), current canopy cover, and 2 CFS discharge.
3. Decrease in canopy cover; mean daily air temperatures in July, 0% canopy cover, and 2 cfs discharge.
4. Increase in canopy cover; mean daily air temperatures in July, 100% canopy cover, and 2 cfs discharge.
5. Lake discharge at 1 cfs; mean daily air temperatures in July, current canopy cover.

6. Lake discharge at 4 cfs; mean daily air temperatures in July, current canopy cover.
7. Lake discharge at 6 cfs; mean daily air temperatures in July, current canopy cover.

Table 5 Generalized results across prediction sites from each modeled scenario for the upper watershed model. Values reported are of predicted daily maximum water temperature. Scenarios are ranked from coolest to warmest average temperature.

Rank	Scenario	Average (°F)	SD (°F)	Max (°F)	Δ From Baseline (°F)
1	4	68.70	0.42	69.33	-5.02
2	7	72.18	4.68	84.26	-1.55
3	6	72.95	4.67	85.01	-0.77
4	1	73.73	4.67	85.75	0.00
5	5	74.11	4.66	86.12	1.16
6	2	74.83	4.67	86.86	1.88
7	3	85.21	0.42	85.84	10.38

There is broad agreement within the scientific community that air temperature is considered a very good predictor of water temperature (Stefan and Preud'homme 1993, Caissie 2006, Webb and Nobilis 2007, Webb et al. 2008, Kaushal et al. 2010). In fact, some biological and water quality research of streams often use air temperature as a surrogate for water temperature because water temperature data are sometime scarce or are relatively difficult to obtain (Smith 1981, Stefan and Preud'homme 1993, Webb et al. 2008). It is therefore reasonable to assume that climate warming over the next century will invariably warm stream temperatures in Suisun Creek as the model predicted.

It is important to highlight that we identified a significant interaction between air temperature and lake discharge. This significant interaction means that increasing discharge rate from Lake Curry, even for short periods of time (e.g., pulse flow), will decrease stream temperatures and the relative benefit of this elevated discharge rate will increase as air temperatures increase. Therefore, pulses during very hot periods could provide the greatest cooling benefit to the stream.

Shading provided by riparian vegetation, tall trees, and steep terrain may control the amount of shortwave radiation that reaches streams and rivers, which influences stream temperatures (Allen 2008). Riparian restoration is a potential tool that can be applied in Suisun Creek to decrease stream temperatures and/or mitigate for the expected impacts from climate warming. Small streams, such as Suisun Creek, are considered more vulnerable to the thermal effects of increasing solar radiation because they have a low thermal capacity relative to larger systems (Moore et al. 2005, Caissie 2006). Increasing the water volume in small tributaries will increase their thermal mass and therefore reduce their vulnerability to warming temperatures.

Monitoring Data

The water at the bottom of Lake Curry is usually cooler than the water in Suisun Creek, so larger releases of cool lake water should reduce downstream temperatures. Conversely, reduced releases would be expected to result in higher downstream temperatures. Water temperatures in 2019 and 2020 at station 9.6 located 1 mile downstream of the lake (Figures 24 and 25) show temperatures did not exceed 70^{o} F with release of 2.0 cfs. However, in 2020 when releases were below 1.0 cfs temperatures exceeded 70^{o} F.

Figures 26-29 show flows and temperatures at Station 8.4 located 2.2 miles downstream from Lake Curry. In 2017 when releases from Lake Curry varied from 2 to 15 cfs water temperatures at Station 8.4 exceed 70^{o} F a few times when flows are low. Flows in 2019 and 2020 where 1.5-2.0 cfs and temperatures exceeded 70^{o} F a number of times. Figures 30-31 show flows and temperatures in 2017 and 2020 at Station 5.6 located 5.3 miles downstream of Lake Curry. In the wet year 2017 where flows varied greatly temperatures ranged from 70-75^{o} F. In 2020 releases from Lake Curry were less than 1.0 cfs and the creek went dry. These data demonstrate that flow levels, as defined by releases from Lake Curry, affect temperatures of aquatic habitat particularly in upper Suisun Creek between stations 10 and 8. Downstream of station 8 the releases are less effective in creating cooler water temperatures. Additionally, releases below 2.5 cfs result in disconnected flow on Suisun Creek.

Figures 32-37 depict the water temperature data as daily maximum, daily minimum, daily median and the moving 7-day average of maximum temperatures. This type of analysis shows us how often high-water temperatures occur and may affect steelhead habitats. For station 9.6 flow releases of 0.5-1.5 cfs in 2020 show temperatures that frequently exceed 70^{o} F compared to 2017 that had higher flows. For station 8.5 the pattern is very similar to station 9.6 with excessive temperatures in 2020 with very low releases. At station 6.5 water temperatures exceeded 70^{o} F in both 2017 and 2020. This data is consistently shows the creek downstream of station 8 have higher summer water temperatures. Tables 7-10 summarize the temperature data which is also included as graphs in Appendix B.

Air Temperatures

Air temperatures were monitored with HOBO sensors at station 10.0 (Dam Air) and at station 7.8 (7.8 Air). Air temperatures at both stations exceeded 90^{o} F for much of each summer, and frequently exceeded 100 ^{o}F (Figure 38). These daytime high temperatures greatly exceeded temperatures measured in the stream. Nighttime air temperatures generally fell to temperatures cooler than stream temperatures (Figure 38).

Stream temperatures were positively correlated with air temperatures (Table 6). Correlation coefficients indicate the degree of association between two variables, and can range from 0 (no association) to 1.00 (all of the variation in one variable can be explained by variation in the other variable). Correlation coefficients ranged from 0.38 for SC 9.6 to 0.82 for SC 6.2. These results indicate that variations in air temperature are associated to a degree with variations in stream temperatures, but that other factors also affect stream temperatures.

Table 6. Correlation Coefficients for Air and Water Temperatures, Summer 2019

Air Temperature Station	Water Temperature Station	Correlation Coefficient
Dam	9.6	0.38
Dam	9.4	0.52
Dam	9.0	0.70
Dam	8.6	0.63
Dam	8.5	0.64
7.8	8.0	0.60
7.8	7.5	0.71
7.8	6.5	0.58
7.8	6.2	0.82
7.8	5.5	0.60
7.8	5.0	0.45

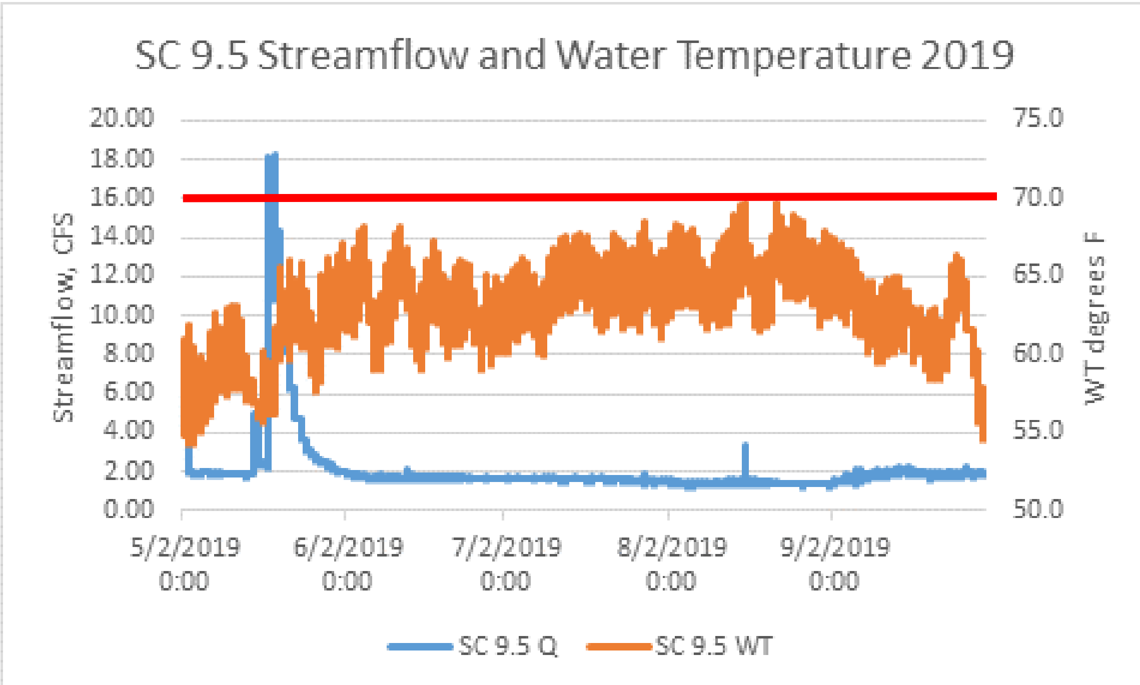


Figure 24. Temperatures at station 9.5 with a flow of 2 cfs are below 70^{o} F

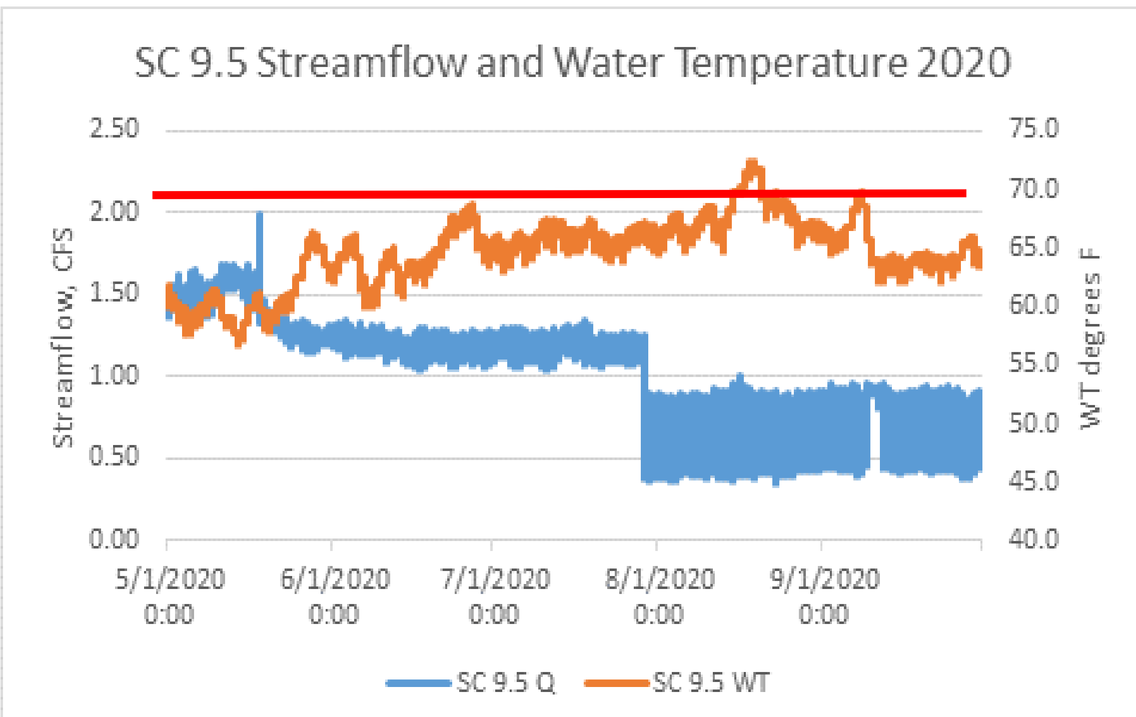
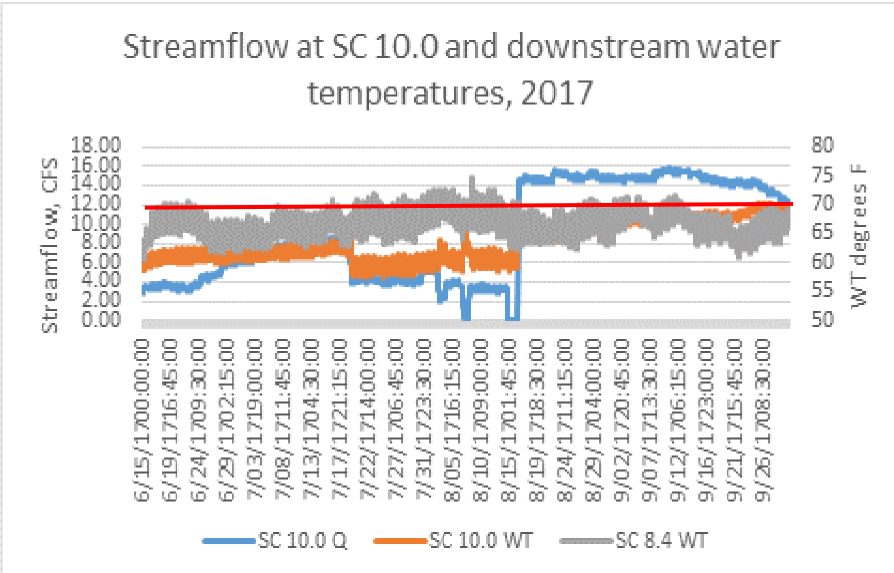
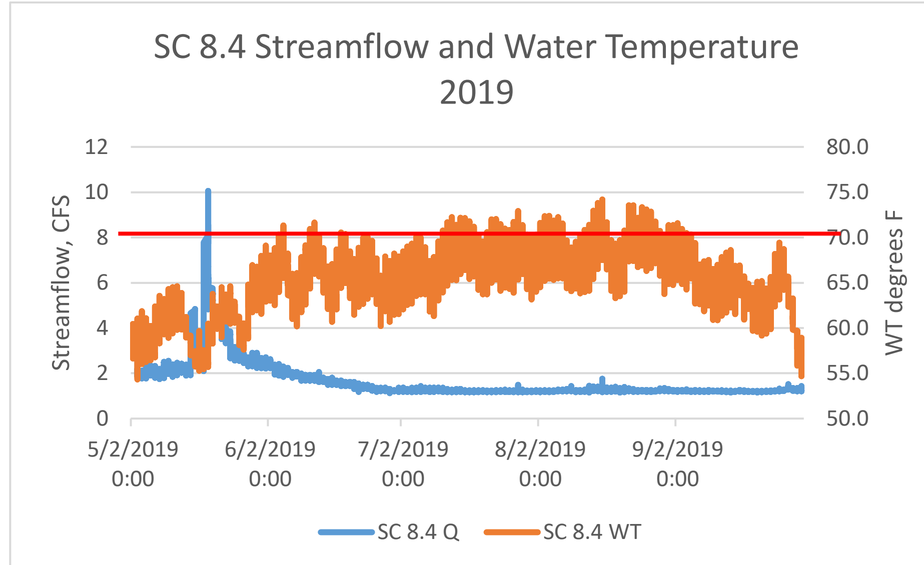
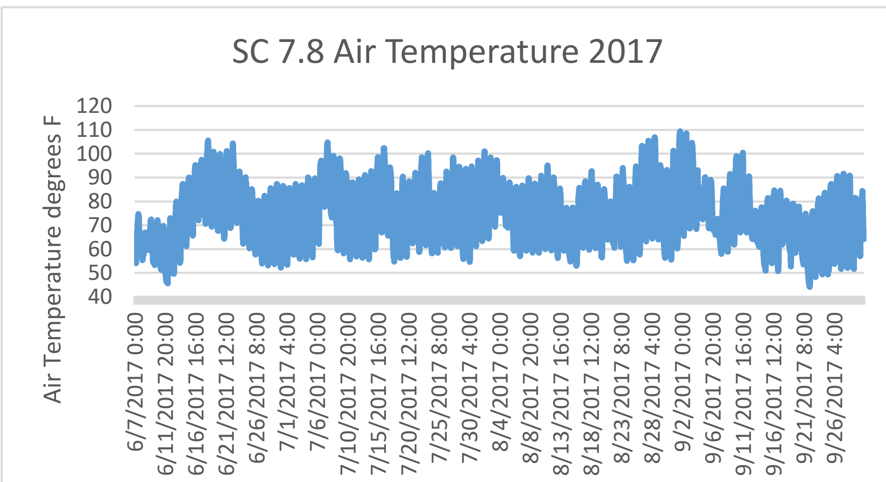
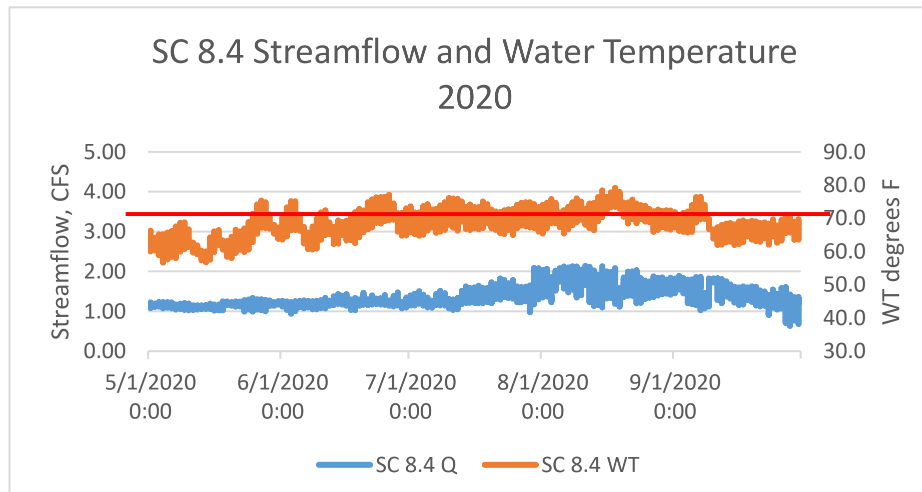


Figure 25. Temperatures at station 9.5 with a flow of 1.5-1.0-.5 cfs and temperatures exceed 70^{o} F for a short period as flows are reduced.

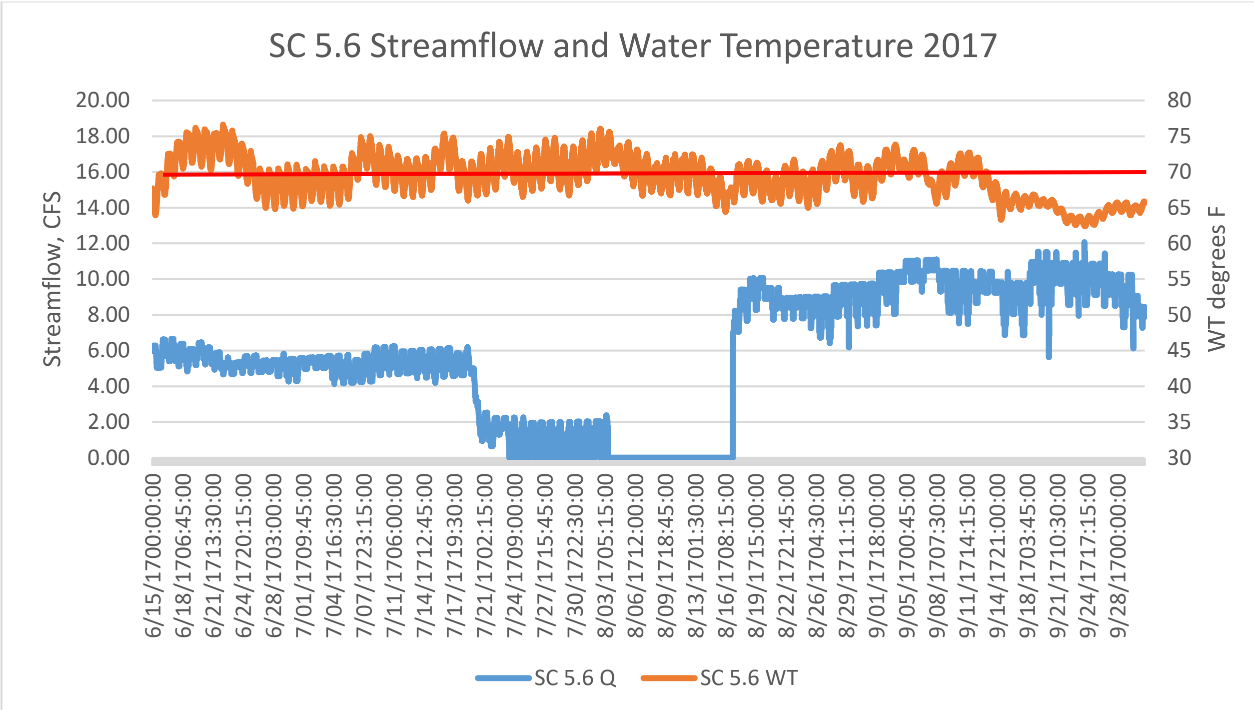


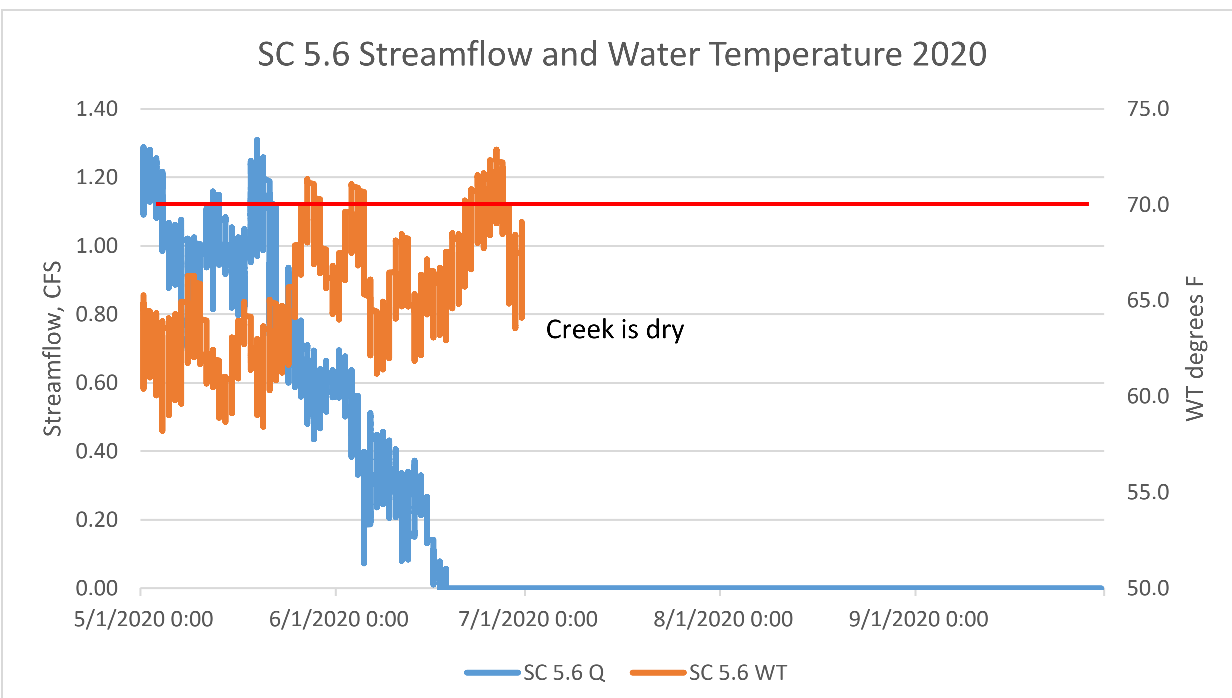




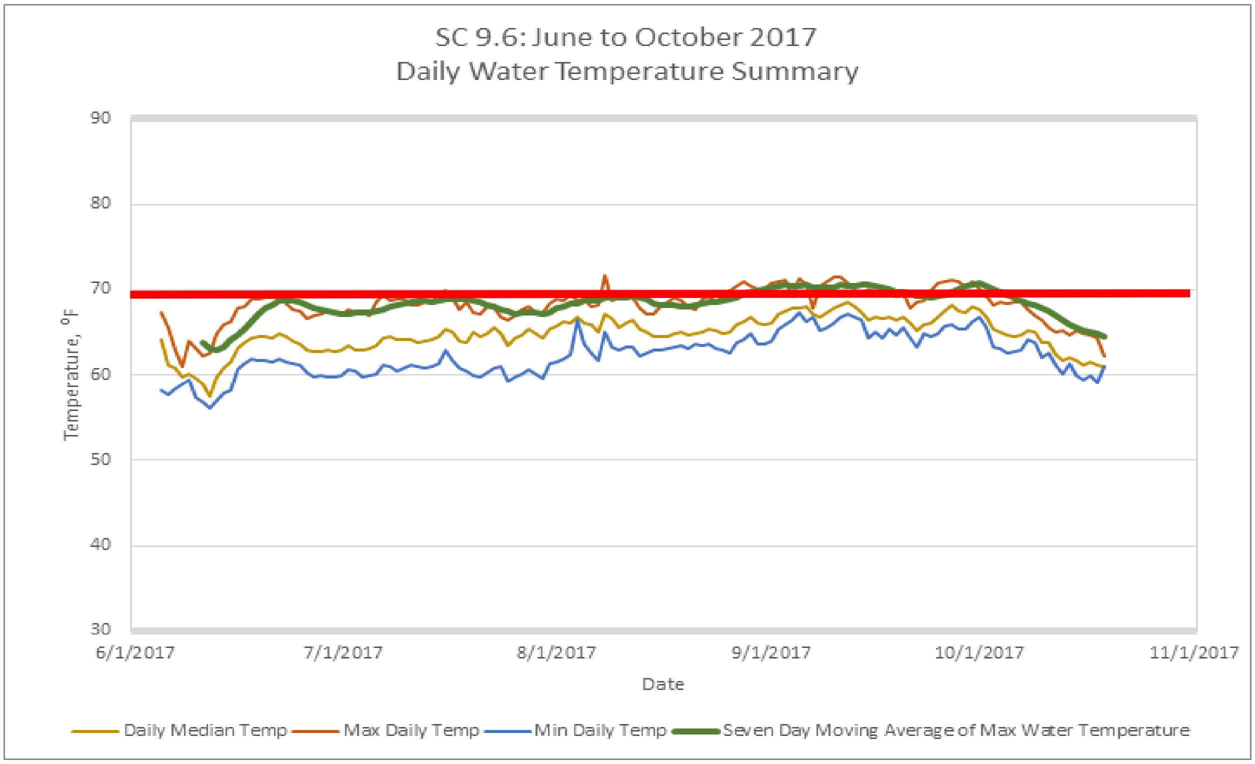


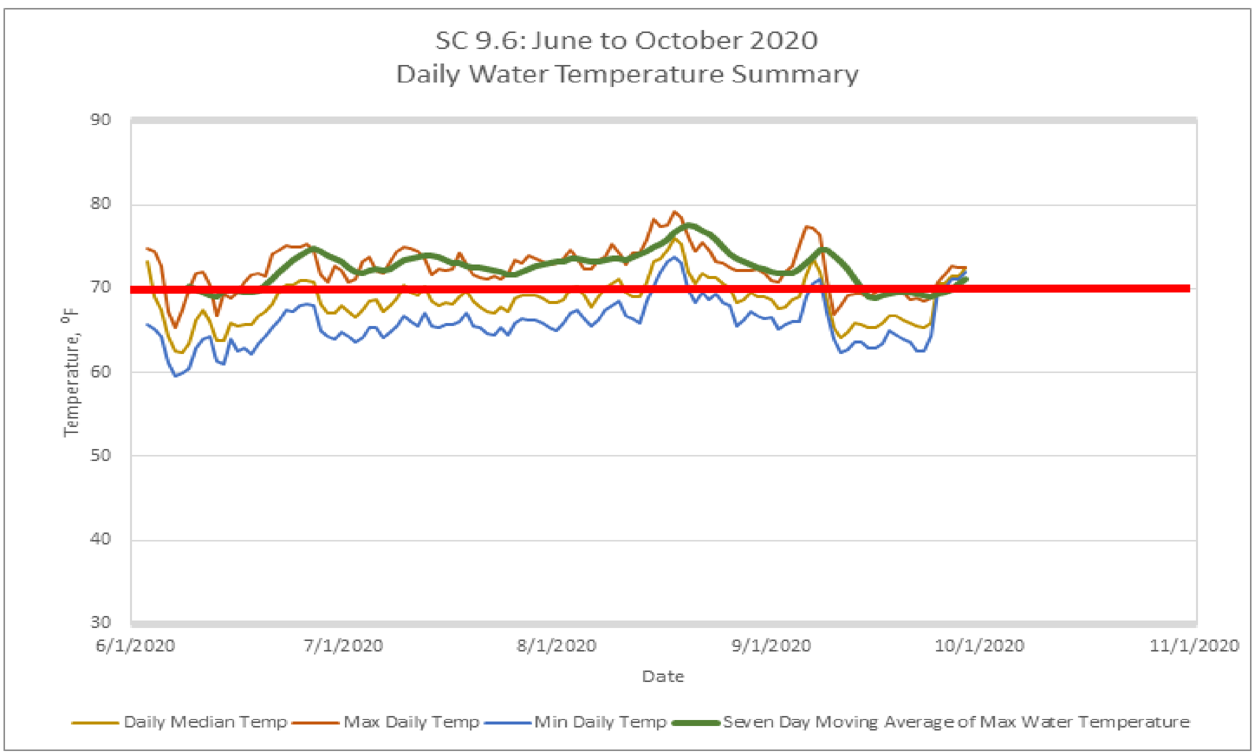
Figures 26-29. Flows and water temperatures at station 8.4 show that low releases of less than 2 cfs result in high water temperatures



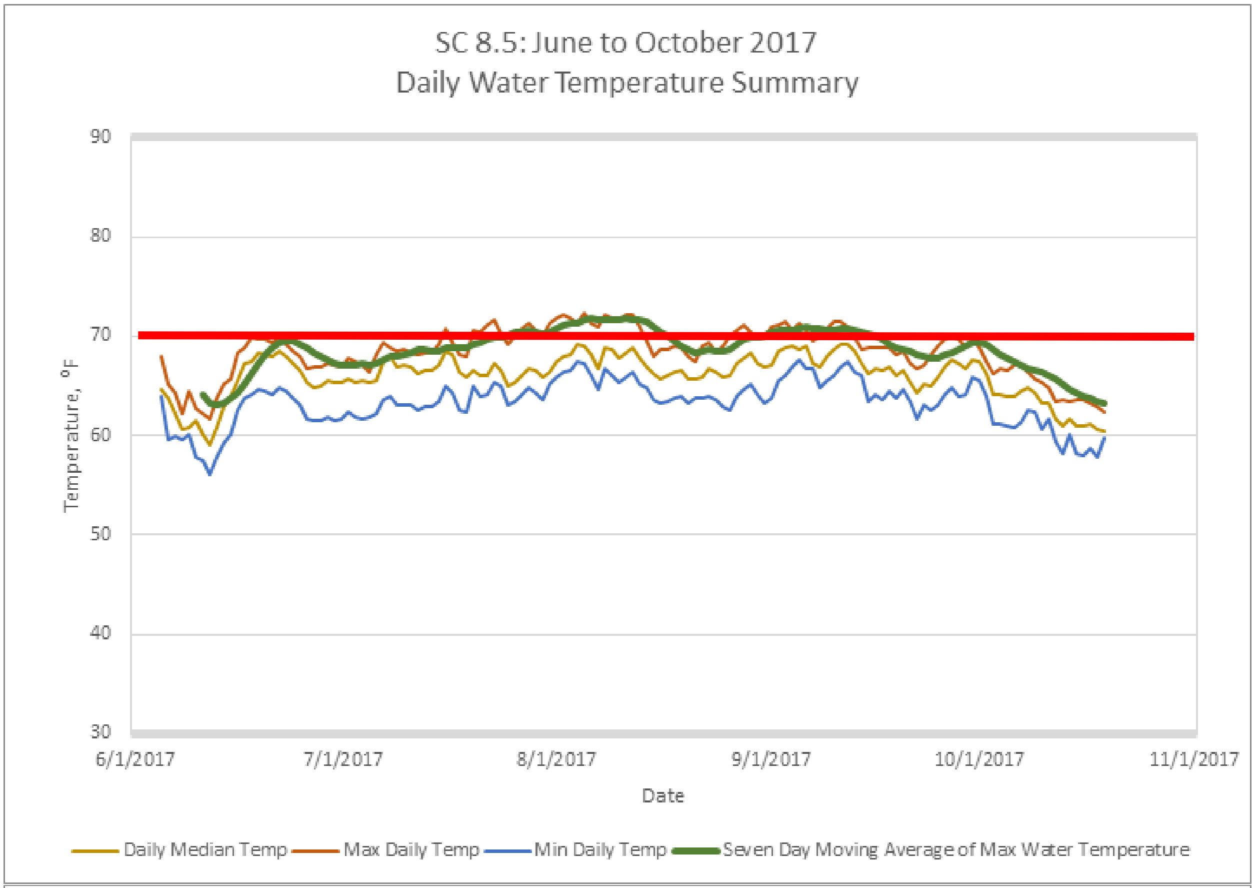


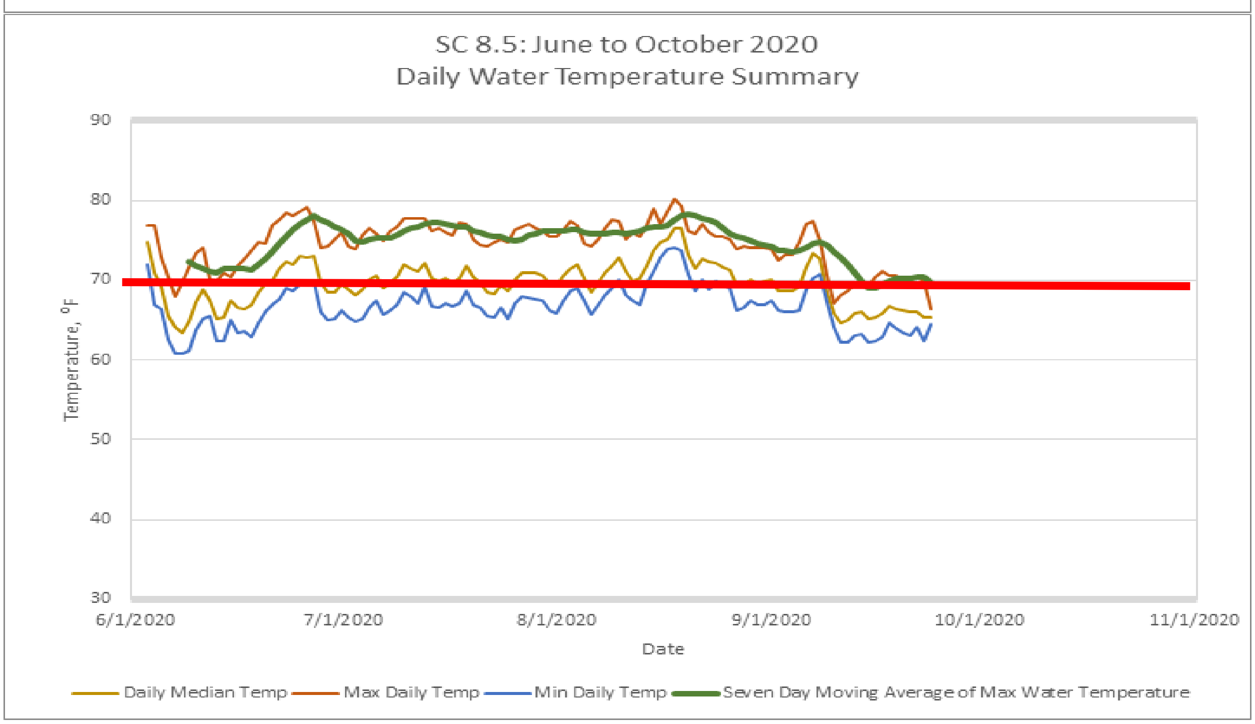
Figures 30-31 Releases from Lake Curry maintain fairly cool water temperatures in the upper Suisun Creek but temperatures can become too hot for steelhead downstream of station 8.0. Releases less than 2.5 cfs result in intermittent flow downstream of station 8.



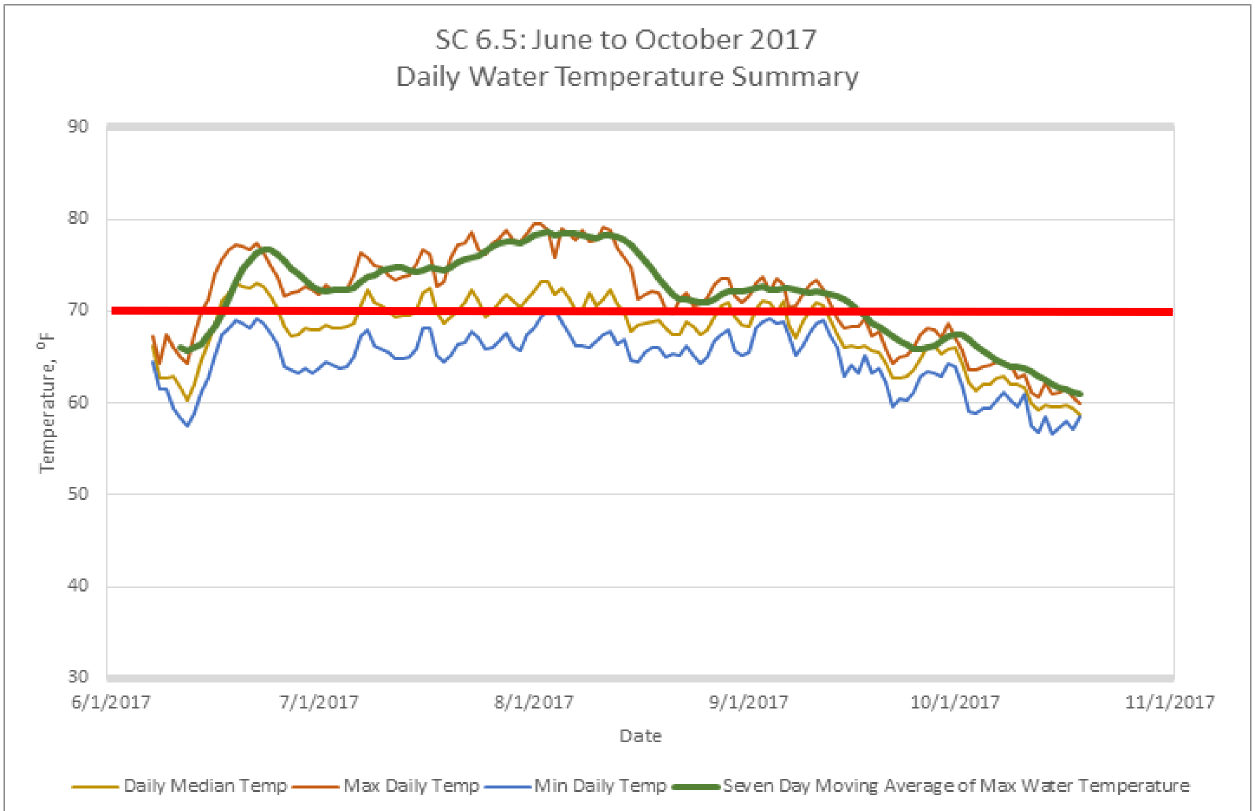


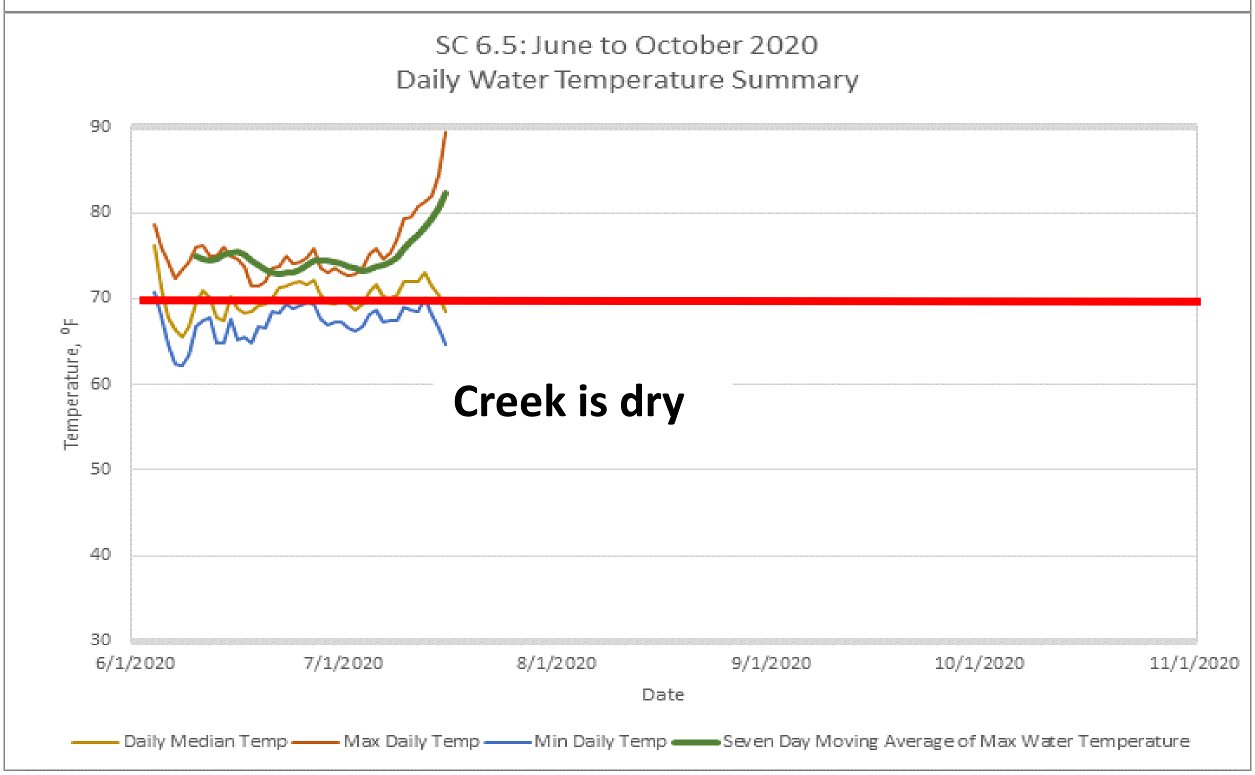
Figures 32-33. Releases from Lake Curry in 2017 ranged from 1-15 cfs and was a wet year. In 2020 releases were 0.5-1.5 and was a dry year. Temperatures at station 9.6 averaged much higher with lower releases.





Figures 34-35. Releases from Lake Curry in 2017 ranged from 1-15 cfs and was a wet year. In 2020 releases were 0.5-1.5 and was a dry year. Temperatures at station 8.5 averaged much higher with lower releases.





Figures 36-37. Releases from Lake Curry in 2017 ranged from 1-15 cfs and was a wet year. In 2020 releases were 0.5-1.5 and was a dry year. Flows at station 6.5 dried up in 2020 and averaged much higher in 2017 than upstream stations.

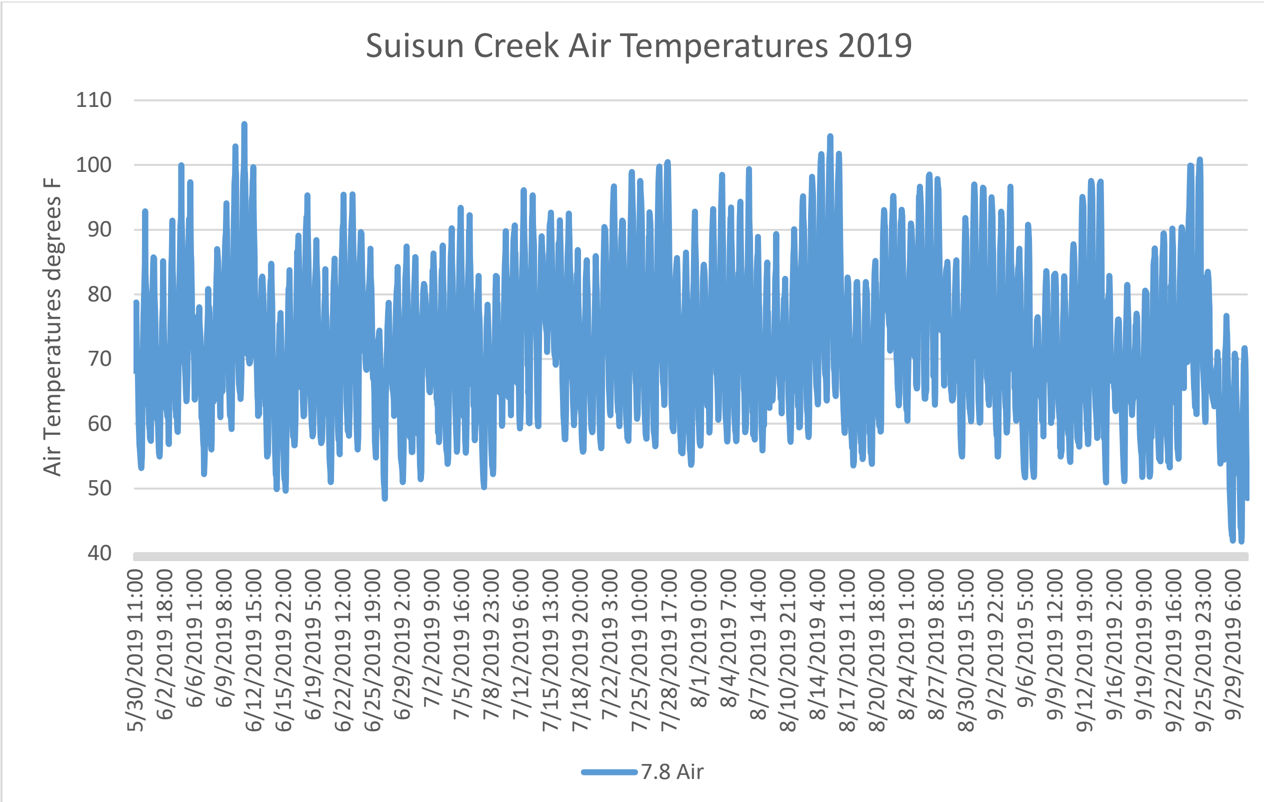


Figure 38. Example air temperature graph for station 7.8.

Table 7. Suisun Creek Water Temperature (℉) Monitoring Summary, 2017

Station	Month	7-Day Moving Average of Daily Average Temperature		7-Day Moving Average of Daily Maximum Temperature		Daily Range of Temperature		Number of Hours per Day > 70℉	
		Min	Max	Min	Max	Min	Max	Min	Max
5.0	Jun - Jul	63.4	74.2	65.9	77.0	1.9	8.6	4	24
	Aug - Sep	63.2	72.6	63.2	76.3	2.5	9.2	2	24
5.5	Jun - Jul	63.0	73.7	65.3	75.7	1.7	6.5	3	24
	Aug - Sep	63.2	72.2	63.2	74.7	2.9	6.4	1	24
5.6	Jun - Jul	62.8	73.5	65.2	75.7	3.3	6.8	1	24
	Aug - Sep	68.1	72.0	68.1	74.8	2.5	6.7	3	24
6.0	Jun - Jul	59.4	63.1	60.3	64.4	0.3	2.5	0	0
	Aug - Sep	63.2	67.5	63.2	69.8	0.9	5.5	0	4
6.2	Jun - Jul	62.7	72.7	66.2	77.8	3.0	11.5	3	20
	Aug - Sep	63.7	72.9	63.7	78.6	3.1	17.6	2	24
6.5	Jun - Jul	62.8	72.5	65.7	77.7	2.7	11.9	6	20
	Aug - Sep	63.8	73.0	63.8	78.6	2.9	12.4	2	24
7.0	Jun - Jul	61.8	71.0	64.5	74.5	2.3	8.6	1	17
	Aug - Sep	67.0	71.4	67.0	74.3	2.2	9.2	0	24
7.5	Jun - Jul	62.4	71.3	65.4	75.4	2.4	8.5	2	17
	Aug - Sep	64.2	72.1	64.2	75.2	2.7	11.0	1	24
7.8	Jun - Jul	62.1	70.4	64.9	73.8	2.0	7.9	1	15
	Aug - Sep	64.3	71.4	64.3	74.4	2.4	6.7	1	24
8.0	Jun - Jul	61.7	69.7	64.2	72.4	2.0	6.6	1	13
	Aug - Sep	64.3	70.3	64.3	72.5	1.8	6.5	1	16
8.4	Jun - Jul	60.8	67.8	63.0	70.8	2.4	7.1	2	8
	Aug - Sep	66.2	69.1	66.2	72.5	2.3	8.8	0	11
8.5	Jun - Jul	60.7	67.4	63.1	70.6	2.6	6.9	1	5
	Aug - Sep	65.4	68.7	65.4	71.7	2.7	7.5	1	10
8.6	Jun - Jul	60.8	67.8	63.2	71.0	2.4	7.0	2	8
	Aug - Sep	65.3	69.3	65.3	73.9	2.7	23.0	1	12
8.7	Jun - Jul	60.7	67.3	63.1	70.2	2.7	6.4	1	4
	Aug - Sep	65.6	68.7	65.6	72.1	2.6	8.5	1	10
8.8	Jun - Jul	60.5	66.7	63.0	69.0	2.9	6.7	0	0
	Aug - Sep	65.7	68.3	65.7	71.6	2.5	7.8	1	9
9.0	Jun - Jul	60.5	66.6	63.1	69.1	2.9	6.9	0	0
	Aug - Sep	65.9	68.4	65.9	71.5	2.3	10.7	1	9
9.4	Jun - Jul	60.0	65.2	62.9	68.8	2.7	8.1	0	0
	Aug - Sep	64.7	68.1	64.7	70.7	1.5	7.5	1	8
9.5	Jun - Jul	60.4	65.5	63.2	69.3	2.1	8.5	1	4
	Aug – Sep	65.0	68.2	65.0	71.0	1.2	7.7	3	7

Station	Month	7-Day Moving Average of Daily Average Temperature		7-Day Moving Average of Daily Maximum Temperature		Daily Range of Temperature		Number of Hours per Day > 70°F	
		Min	Max	Min	Max	Min	Max	Min	Max
9.6	Jun - Jul	60.0	64.8	62.9	68.8	2.1	8.3	0	0
	Aug - Sep	64.4	68.1	64.4	70.7	1.1	7.4	1	7
10.0	Jun - Jul	59.2	62.4	61.0	65.4	1.8	5.4	0	0
	Aug - Sep	59.5	67.1	59.5	67.6	0.3	8.3	0	0
10.1	Jun - Jul	58.4	61.9	58.8	64.5	0.4	4.3	0	0
	Aug - Sep	58.9	69.9	58.9	70.2	0.2	7.7	1	13

Table 8. Suisun Creek Water Temperature (°F) Monitoring Summary, 2018

Station	Months	7-Day Moving Average of Average Temperature		7-Day Moving Average of Daily Maximum Temperature		Daily Range of Temperature		Number of Hours per Day > 70°F	
		Min	Max	Min	Max	Min	Max	Min	Max
5.0	Jun - Jul	66.8	73.6	71.7	78.1	5.5	12.7	1	24
	Aug - Sep	62.9	72.5	62.9	76.9	3.6	9.3	1	18
5.5	Jun - Jul	64.4	72.8	67.0	75.3	2.8	8.0	1	24
	Aug - Sep	60.9	71.8	60.9	74.5	2.0	6.9	4	24
5.6	Jun - Jul	62.4	71.9	64.1	74.7	2.2	8.1	0	24
	Aug - Sep	64.3	70.7	64.3	73.4	2.5	6.5	2	20
6.2	Jun - Jul	66.7	74.1	74.7	120.2	4.7	76.9	5	24
	Aug - Sep	62.6	73.3	62.6	78.8	3.6	11.3	1	20
6.5	Jun - Jul	66.2	74.3	70.1	80.8	4.6	14.4	3	24
	Aug - Sep	63.6	73.4	63.6	79.7	3.4	12.2	1	19
7.0	Jun - Jul	66.2	72.2	70.4	75.5	4.5	12.5	1	24
	Aug - Sep	61.5	71.2	61.5	74.2	3.6	7.4	2	18
7.5	Jun - Jul	65.5	73.3	69.3	76.7	3.9	12.6	1	24
	Aug - Sep	63.2	72.6	63.2	75.9	3.0	7.8	1	20
7.8	Jun - Jul	66.3	73.0	68.4	76.3	1.9	8.3	1	24
	Aug - Sep	62.4	72.2	62.4	75.3	2.8	7.2	1	21
8.0	Jun - Jul	62.6	72.0	64.7	75.2	3.0	9.1	1	15
	Aug - Sep	63.1	70.9	63.1	73.9	1.3	6.7	3	8
8.4	Jun - Jul	64.2	72.4	67.4	75.0	4.1	8.3	1	24
	Aug - Sep	61.8	71.6	61.8	74.2	2.8	7.3	3	21
8.5	Jun - Jul	63.6	71.3	69.7	75.2	4.8	23.7	1	17
	Aug - Sep	61.8	70.6	61.8	74.0	4.2	9.0	1	14
8.6	Jun - Jul	62.4	70.9	63.8	74.4	1.1	12.9	1	15
	Aug - Sep	61.7	70.2	61.7	73.7	2.6	7.5	3	12
8.7	Jun - Jul	61.9	70.7	64.8	75.8	4.3	30.7	1	15
	Aug - Sep	61.8	70.0	61.8	73.7	2.8	7.7	1	11

Station	Months	7-Day Moving Average of Average Temperature		7-Day Moving Average of Daily Maximum Temperature		Daily Range of Temperature		Number of Hours per Day > 70°F	
		Min	Max	Min	Max	Min	Max	Min	Max
8.8	Jun - Jul	63.4	70.2	64.8	74.3	1.4	11.3	1	13
	Aug - Sep	61.8	69.6	61.8	73.4	2.5	8.5	1	9
9.0	Jun - Jul	64.4	70.2	65.9	73.7	1.6	11.5	1	15
	Aug - Sep	61.9	69.2	61.9	72.5	4.0	8.4	1	9
9.4	Jun - Jul	61.0	68.6	61.7	71.2	0.8	8.4	1	8
	Aug - Sep	62.0	68.0	62.0	70.6	1.2	6.6	1	6
9.5	Jun - Jul	63.5	68.8	64.7	70.8	1.9	5.8	0	9
	Aug - Sep	65.5	68.2	65.5	70.0	0.4	5.1	1	6
9.6	Jun - Jul	62.7	68.3	64.9	71.7	3.0	8.6	3	8
	Aug - Sep	62.5	67.7	62.5	71.0	1.9	8.7	1	7
10.0	Jun - Jul	59.7	65.3	61.8	78.5	2.2	27.7	5	10
	Aug - Sep	63.8	66.8	63.8	69.0	0.3	5.3	1	1

Table 9. Suisun Creek Water Temperature (°F) Monitoring Summary, 2019

Station	Months	7-Day Moving Average of Average Temperature		7-Day Moving Average of Daily Maximum Temperature		Daily Range of Temperature		Number of Hours per Day > 70°F	
		Min	Max	Min	Max	Min	Max	Min	Max
5.0	Jun - Jul	67.9	71.9	72.0	77.7	5.6	10.9	3	24
	Aug - Sep	65.2	72.1	65.2	77.9	4.5	10.7	2	21
5.5	Jun - Jul	67.6	71.7	70.6	75.1	4.7	8.2	1	24
	Aug - Sep	65.2	72.3	65.2	75.2	1.7	7.4	1	24
5.6	Jun - Jul	67.2	71.2	70.2	74.9	3.9	8.3	1	24
	Aug - Sep	68.9	70.5	68.9	74.0	4.7	6.7	3	14
6.0	Jun - Jul	61.8	65.8	64.1	68.7	2.2	7.0	0	0
	Aug - Sep	62.7	65.4	62.7	67.2	0.0	4.7	0	0
6.2	Jun - Jul	67.9	72.4	74.4	79.7	7.3	14.2	4	22
	Aug - Sep	64.7	73.1	64.7	79.6	3.6	12.6	1	24
6.5	Jun - Jul	68.0	72.4	72.4	78.6	6.2	12.8	1	22
	Aug - Sep	65.2	73.2	65.2	78.7	3.9	11.7	1	24
7.0	Jun - Jul	65.4	70.6	66.4	72.4	1.3	5.2	2	21
	Aug - Sep	67.2	71.9	67.2	73.5	2.8	4.8	0	24
7.5	Jun - Jul	67.6	71.7	70.5	74.8	5.1	7.6	1	20
	Aug - Sep	65.3	71.5	65.3	74.3	1.9	6.3	1	24
7.8	Jun - Jul	67.2	71.3	70.1	73.9	4.0	8.7	1	22
	Aug - Sep	64.5	72.2	64.5	74.3	1.9	5.2	3	24
8.0	Jun - Jul	66.0	69.5	68.6	72.2	2.6	8.8	1	15
	Aug - Sep	63.5	70.4	63.5	71.8	1.3	4.8	1	20

Station	Months	7-Day Moving Average of Average Temperature		7-Day Moving Average of Daily Maximum Temperature		Daily Range of Temperature		Number of Hours per Day > 70°F	
		Min	Max	Min	Max	Min	Max	Min	Max
8.4	Jun - Jul	64.7	68.9	67.6	71.8	4.4	7.8	1	10
	Aug - Sep	64.7	69.9	64.7	72.9	4.5	7.5	2	15
8.5	Jun - Jul	65.0	69.1	68.3	72.4	5.2	8.1	1	12
	Aug - Sep	62.9	70.1	62.9	73.5	3.2	7.9	1	15
8.6	Jun - Jul	64.6	68.5	68.1	72.3	4.9	8.1	1	9
	Aug - Sep	62.6	69.5	62.6	73.2	3.0	8.2	2	13
9.0	Jun - Jul	63.9	67.6	66.9	70.9	3.7	6.6	1	6
	Aug - Sep	62.1	68.7	62.1	72.1	2.6	6.6	1	9
9.4	Jun - Jul	62.3	65.6	65.0	68.0	3.6	5.7	0	0
	Aug - Sep	61.3	66.9	61.3	69.3	2.1	5.3	1	3
9.5	Jun - Jul	63.5	68.8	64.7	70.8	1.9	5.8	0	9
	Aug - Sep	65.5	68.2	65.5	70.0	0.4	5.1	1	6
9.6	Jun - Jul	62.7	68.3	64.9	71.7	3.0	8.6	3	8
	Aug - Sep	62.5	67.7	62.5	71.0	1.9	8.7	1	7
10.0	Jun - Jul	59.7	65.3	61.8	78.5	2.2	27.7	5	10
	Aug - Sep	63.8	66.8	63.8	69.0	0.3	5.3	1	1

Table 10. Suisun Creek Water Temperature (°F) Monitoring Summary, 2020

Station	Months	7-Day Moving Average of Average Temperature		7-Day Moving Average of Daily Maximum Temperature		Daily Range of Temperature		Number of Hours per Day > 70°F	
		Min	Max	Min	Max	Min	Max	Min	Max
5.0	Jun	66.5	72.7	70.6	78.9	5.1	12.4	4	18
	No data after June 28								
5.5	Jun - Jul	65.3	70.1	69.8	78.4	5.1	14.0	1	13
	No data after June 28								
6.2	Jun	67.5	67.5	78.5	78.5	9.9	27.5	1	9
	No data after June 10.								
6.5	Jun - Jul	68.8	72.7	72.9	82.4	4.7	24.7	4	24
	No data after July 16.								
7.5	Jun - Jul	67.3	72.2	70.8	75.6	4.2	8.8	3	23
	Aug - Sep	66.2	72.3	66.2	74.9	2.4	8.1	2	24
8.0	Jun - Jul	64.7	70.1	67.0	74.5	3.2	13.2	1	16
	Aug - Sep	64.7	72.8	64.7	76.9	1.3	12.2	1	24
8.5	Jun - Jul	66.2	72.6	71.0	78.0	4.6	10.9	1	23
	Aug - Sep	65.6	74.8	65.6	78.2	1.8	9.6	1	24
8.6	Jun - Jul	66.0	71.9	69.4	75.5	3.8	9.0	3	22
	Aug - Sep	65.6	74.6	65.6	77.4	1.8	7.7	5	24

Station	Months	7-Day Moving Average of Average Temperature		7-Day Moving Average of Daily Maximum Temperature		Daily Range of Temperature		Number of Hours per Day > 70°F	
		Min	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
9.0	Jun - Jul	66.1	72.0	71.0	77.6	5.1	11.8	1	17
	Aug - Sep	65.8	74.8	65.8	78.6	1.7	10.5	1	24
9.4	Jun - Jul	64.3	69.8	65.6	71.4	1.6	5.1	1	16
	Aug - Sep	65.3	73.5	65.3	75.1	0.8	4.1	1	24
9.6	Jun - Jul	64.9	70.6	69.1	74.8	4.9	9.5	1	15
	Aug - Sep	65.5	73.9	65.5	77.5	0.5	9.1	2	24
10.0	Jun - Jul	62.4	68.6	65.2	71.2	2.7	6.1	2	8
	Aug - Sep	68.8	73.2	68.8	74.9	1.4	5.5	2	24

Changes in Canopy Cover and Water Temperatures
Canopy cover was measured using a solar densiometer annually at all locations where HOBO temperature sensors were deployed to determine how the level of shading on the creek affects water temperatures. The solar densiometer measures the percent of tree canopy cover. Measurements were taken at both banks and at mid-stream, with the observer facing upstream, downstream, toward the right bank, and toward the left bank.

During the 2017 to 2021 study period, riparian vegetation in the Suisun watershed was affected by major wildfires in 2017 and 2020. The riparian corridor was also affected by drought conditions in 2014 to 2016 and in 2020. In addition to trees lost to the fires, a large number of trees, mostly white alders, died from drought-related stress, and riparian cover was mechanically removed near station 7.0 in 2020. Average stream temperatures generally increase with distance downstream of Lake Curry, and show a reasonably consistent inverse relation to canopy cover (Figures 39 to 42). This relation is most clearly seen in the data for 2017, prior to the large wildfires (Figure 39). In subsequent years, both stream temperatures and canopy cover showed a less consistent downstream pattern except at the upstream 3 stations where cover remained high and temperatures remained low (Figures 40 to 42).

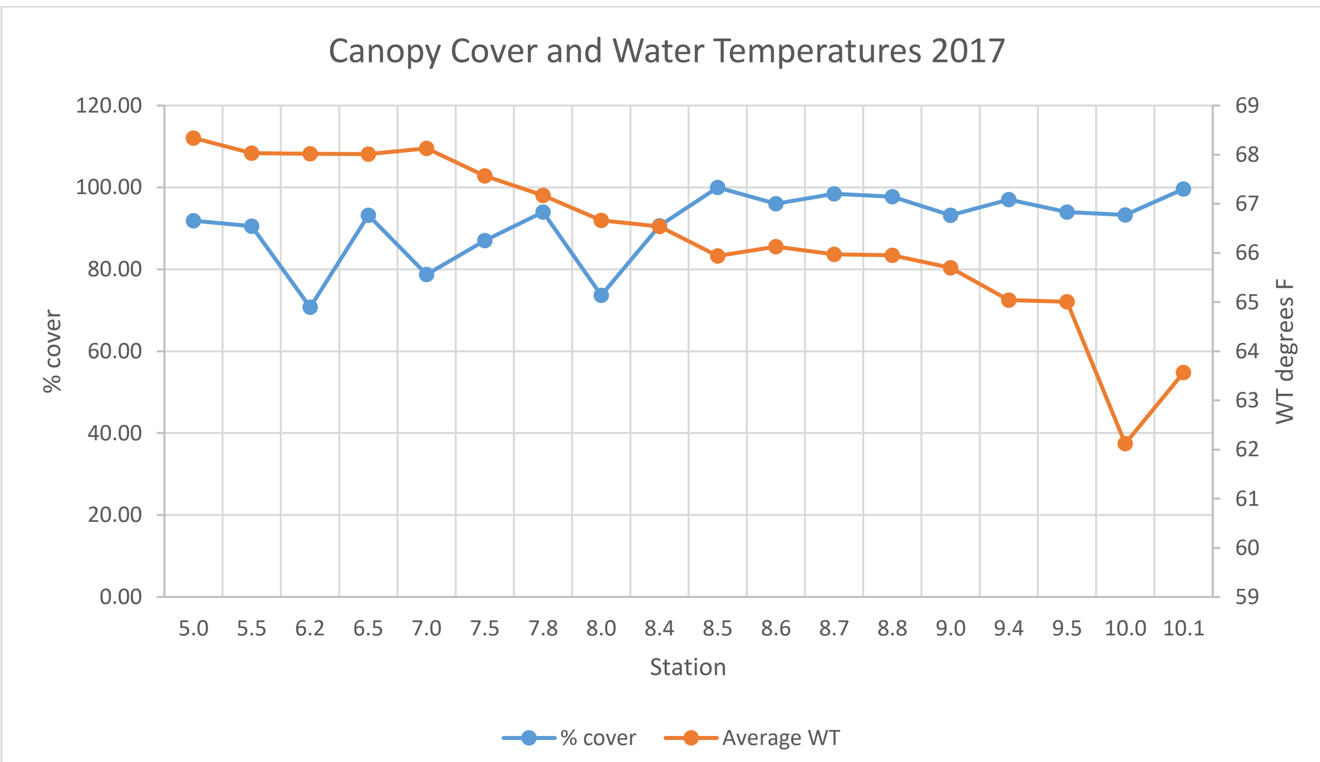


Figure 39. Canopy cover and average summer water temperatures at all stations in 2017

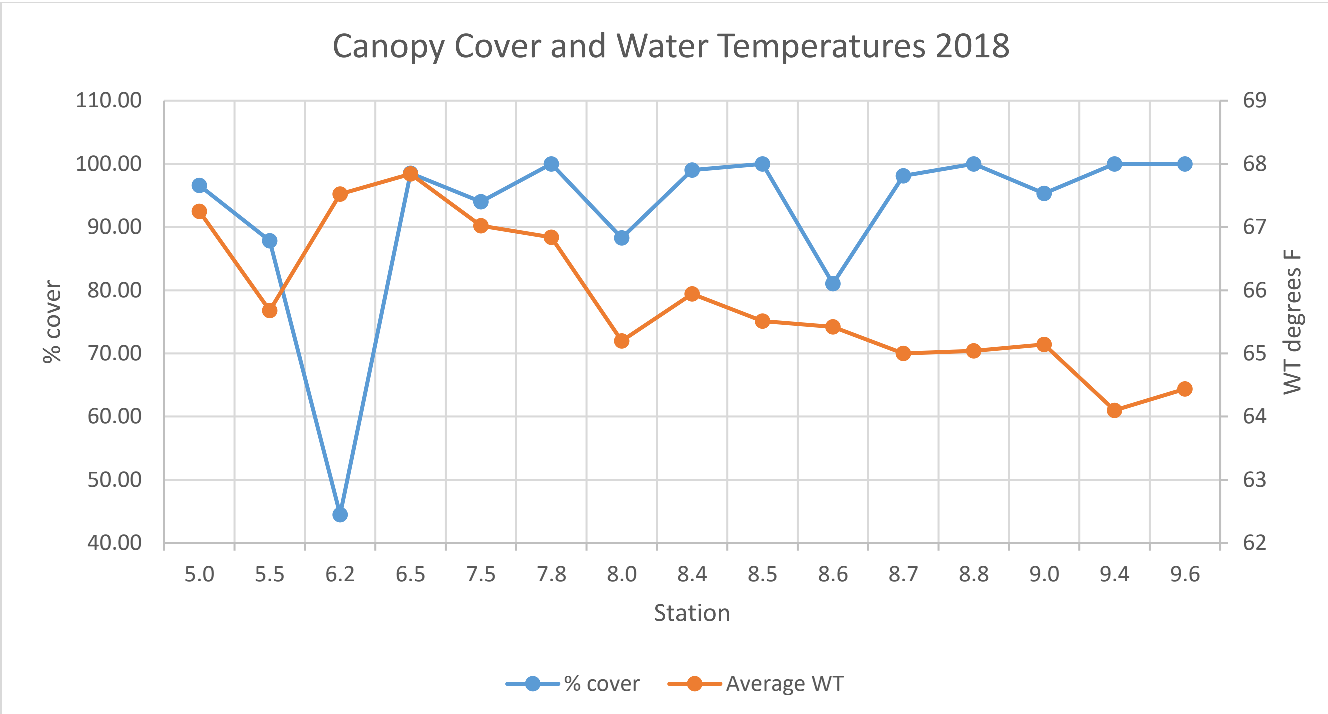


Figure 40. Canopy cover and average water temperatures at all stations in 2018

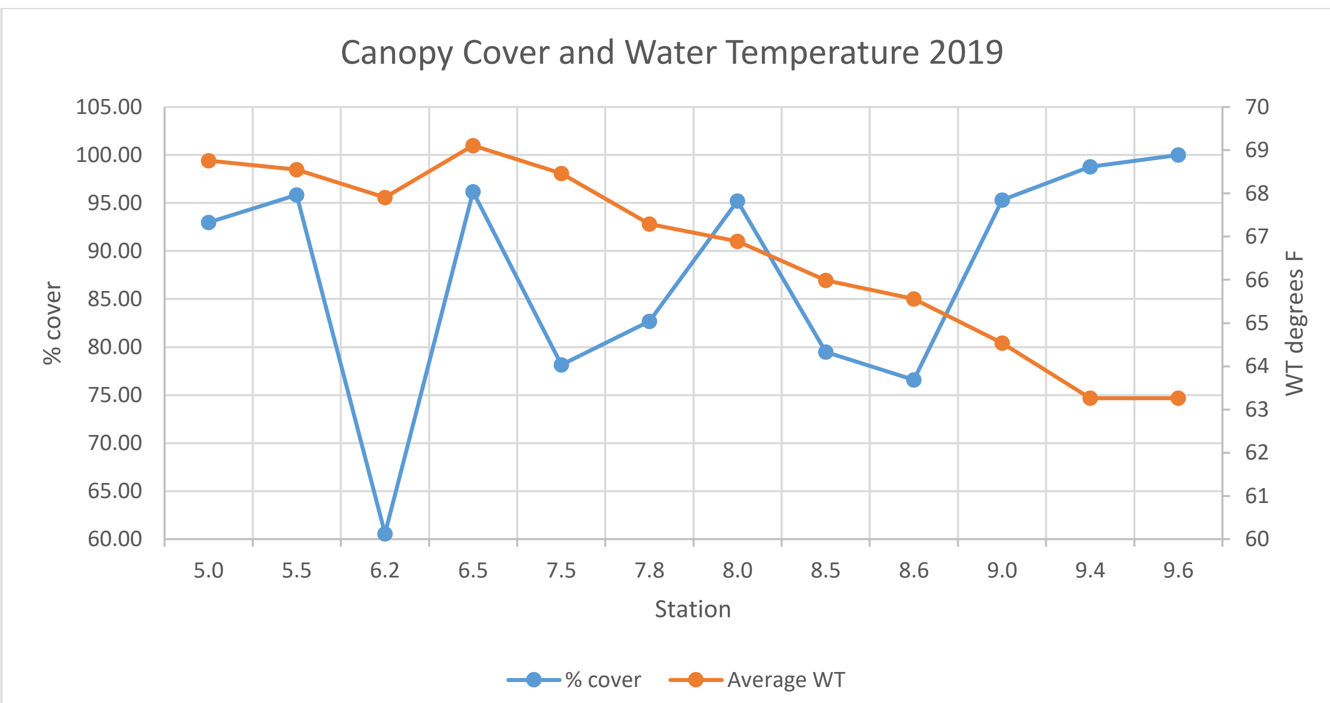


Figure 41 Canopy cover and average water temperatures at all stations in 2019

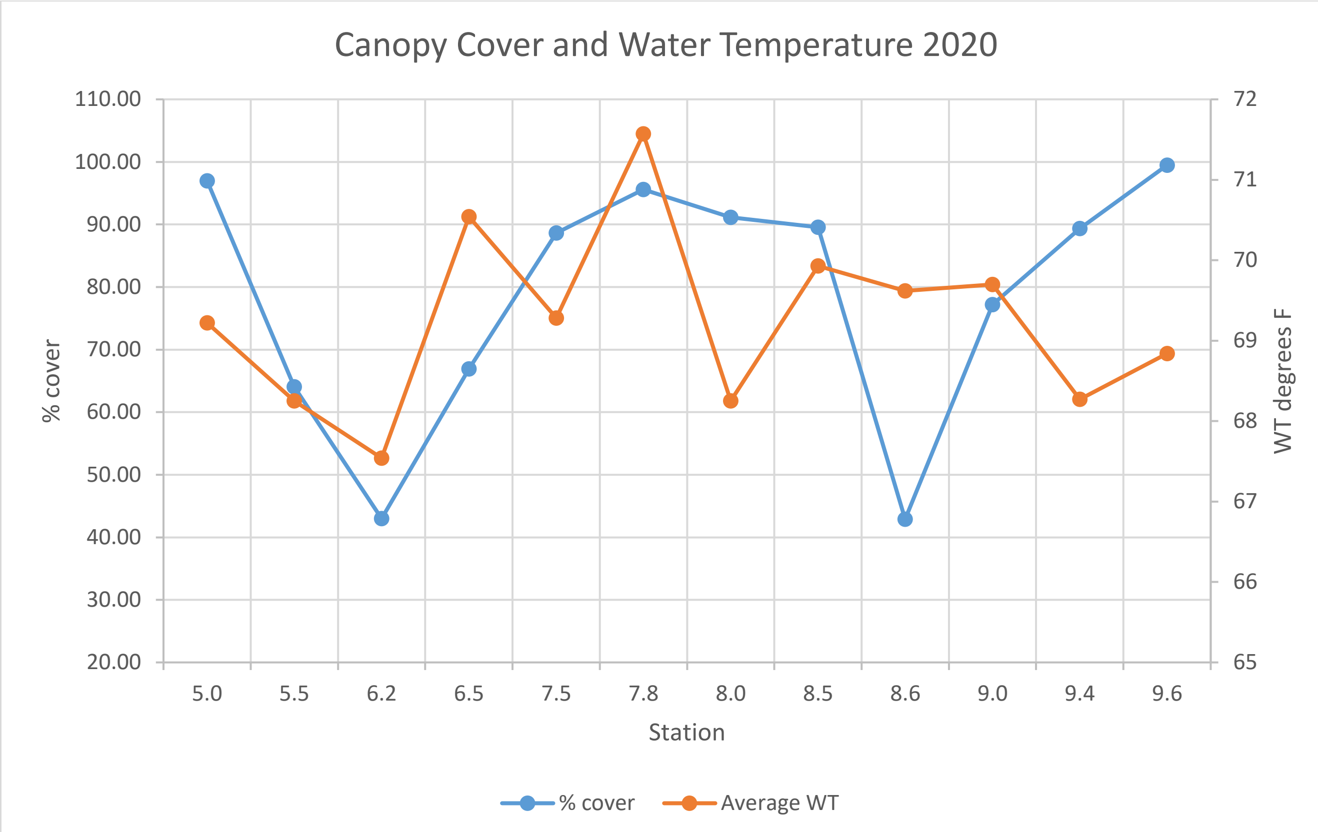


Figure 42. Canopy cover and average water temperatures at all stations in 2020

Correlation coefficients for canopy cover and water temperature for all stations were -0.48 in 2017, -0.36 in 2018, -0.30 in 2019, and 0.24 in 2020. These results indicate that the relation between canopy cover and water temperature became weaker and shifted from negative to positive between 2017 and 2020, probably as a result of reduced canopy cover.

To better understand the role of canopy cover in maintaining stream temperatures, we plotted average annual values of canopy cover and stream temperature at each station for the 4 years of the study (2017 to 2020). An example is shown below in Figure 43. Of the 11 stations analyzed, 8 showed the pattern depicted in Figure 43, in which canopy cover decreased and water temperature increased. These results indicate that reduced canopy cover and increased solar radiation were responsible in part for observed increases in stream temperatures downstream of Lake Curry between 2017 and 2020.

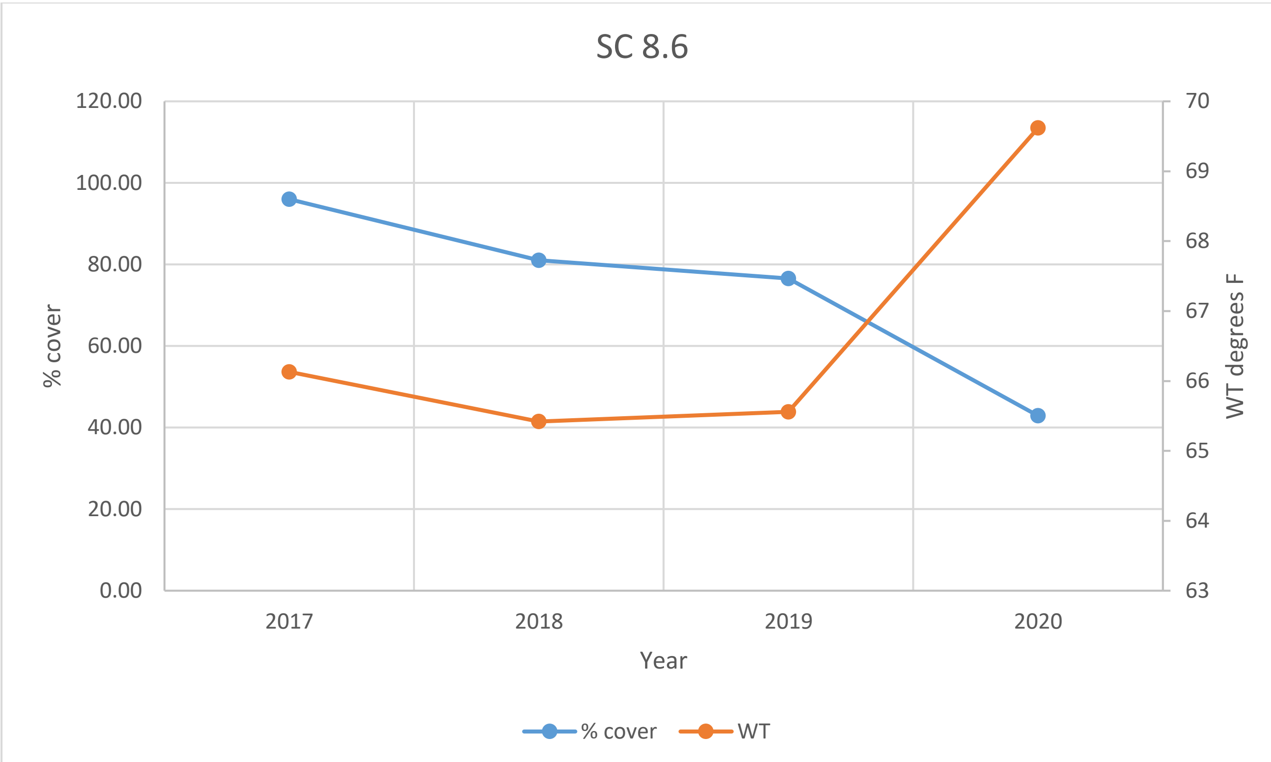


Figure 43. Canopy cover and water temperature at station 8.6 from 2017 to 2020.

DISSOLVED OXYGEN

Dissolved oxygen (DO) concentrations were measured at selected locations on upper Suisun Creek using a YSI multi-parameter submersible sonde that also monitored water temperature, specific conductance, and pH. The water quality monitoring was done to answer the following questions:

- **How do flows affect dissolved oxygen levels?**
- **How do water temperatures affect dissolved oxygen levels?**

We focus here on the monitoring results for DO and water temperature as the most critical determinants of water quality for steelhead habitat. DO concentrations below 4 mg/L are considered lethal for steelhead while DO concentrations of 7 mg/L will sustain steelhead (San Francisco Bay Regional Water Quality Control Board 2017).

Results for selected stations are shown in Figures 44 to 47 to illustrate the range of DO concentrations in the creek. Appendix D contains graphs of all the water quality monitoring completed. Generally, dissolved oxygen concentrations were high but showed pronounced diurnal fluctuations. These fluctuations were probably driven by daily cycles of photosynthesis and respiration by algae (Figures 44 and 45). Daytime peaks in DO were markedly lower in 2019 at station 6.0 during a low-flow period (Figure 46). DO concentrations in an isolated pool with no surface water flowing in or out of the pool reached typical daytime highs, but plunged at night to near 0 mg/L without aeration from surface flows. These results indicate that DO concentrations in Suisun Creek are generally adequate to support steelhead during summers. However, long periods of low or no flow can result in DO concentrations lethal to steelhead trout.

Table 11. The Dissolved Oxygen Concentration and Temperature Measured at Selected Stations on Suisun Creek, 2017 to 2020.

	SC-9.5 9/14 to 10/20/17	**SC-7.0** 9/12 to 9/18/18	**SC-6.0** 8/30 to 9/11/19	**SC-9.5** 7/29to 8/19/20
Temp ≤ 68° - DO ≥ 7 mg/l	79.7%	81.2%	47.5%	2.5%
Temp ≤ 68° - DO < 7 mg/l	0.0%	2.4%	7.0%	13.7%
68° < Temp < 77° - DO ≥ 7 mg/l	20.3%	15.4%	0.0%	33.3%
68° < Temp < 77° - DO < 7 mg/l	0.0%	0.0%	43.4%	48.9%
Temp ≥ 77° - DO ≥ 7 mg/l	0.0%	0.9%	0.0%	0.4%
Temp ≥ 77° - DO < 7 mg/l	0.0%	0.0%	1.8%	1.1%

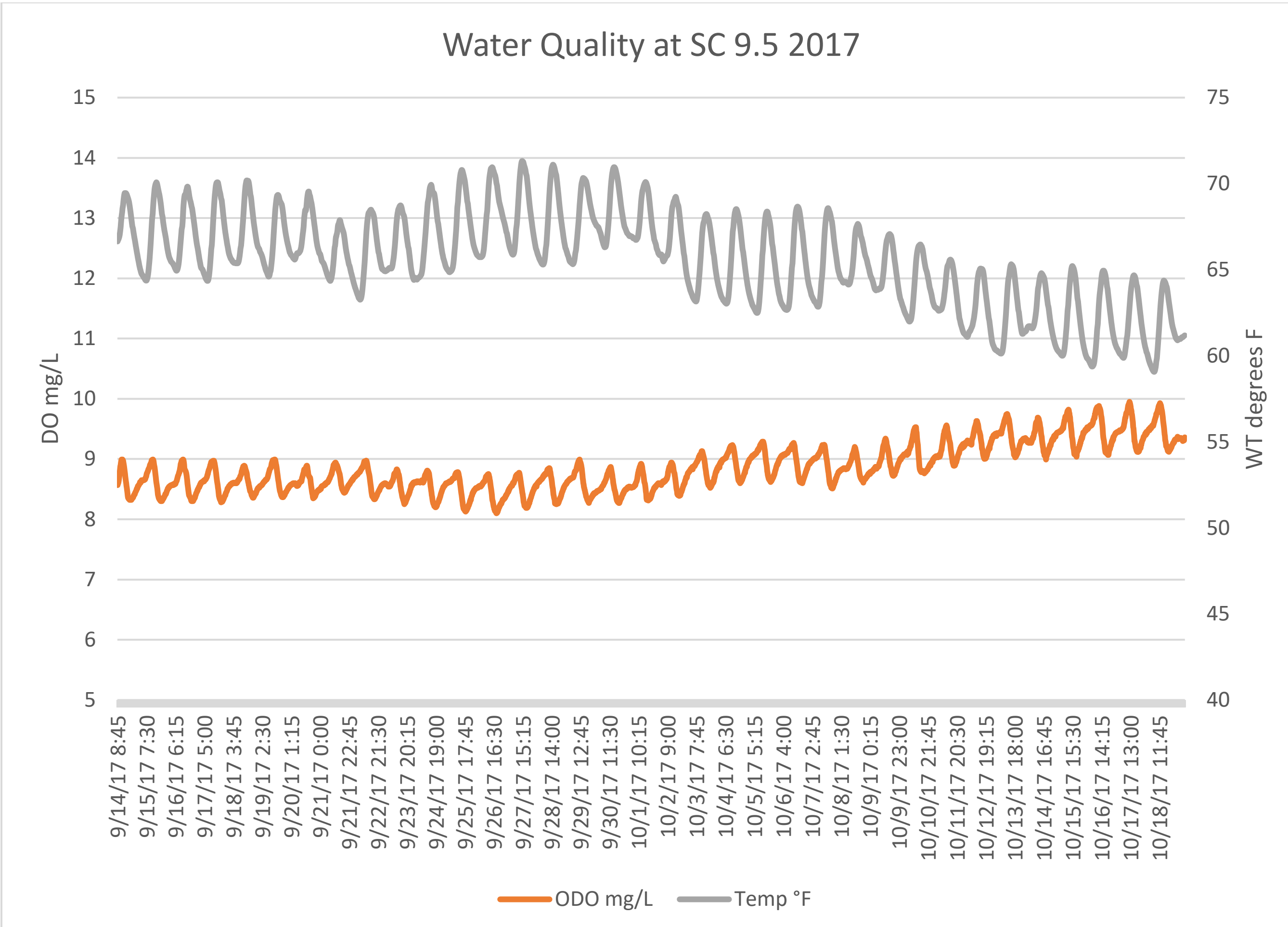


Figure 44. Water temperature and dissolved oxygen at station 9.5, 2017

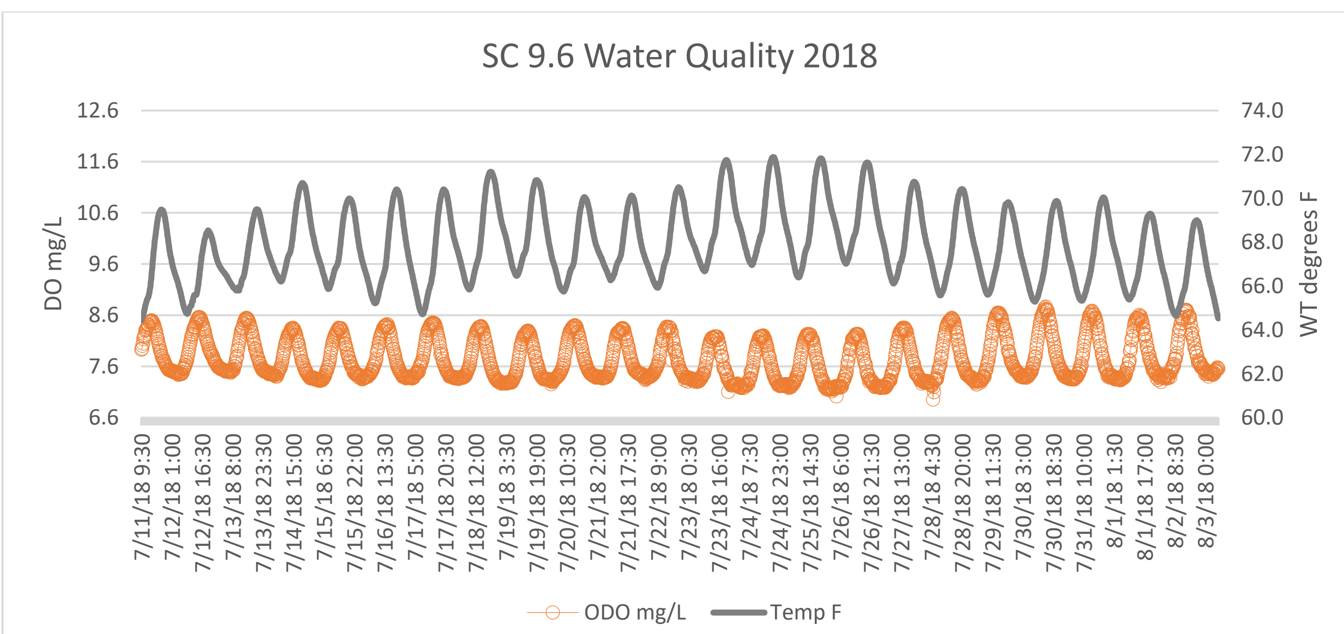


Figure 45. Water temperature and dissolved oxygen at station 9.6, 2018

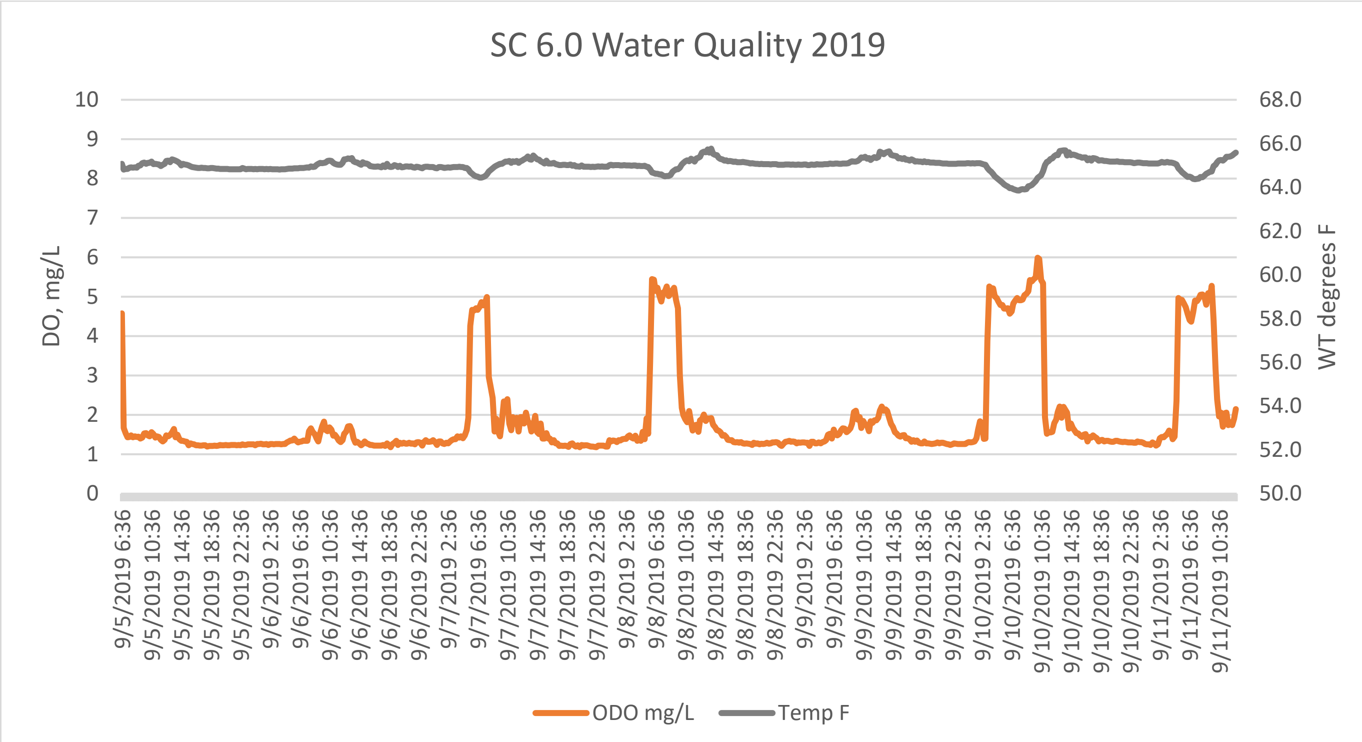


Figure 46. Water temperature and dissolved oxygen at station 6.0, 2019

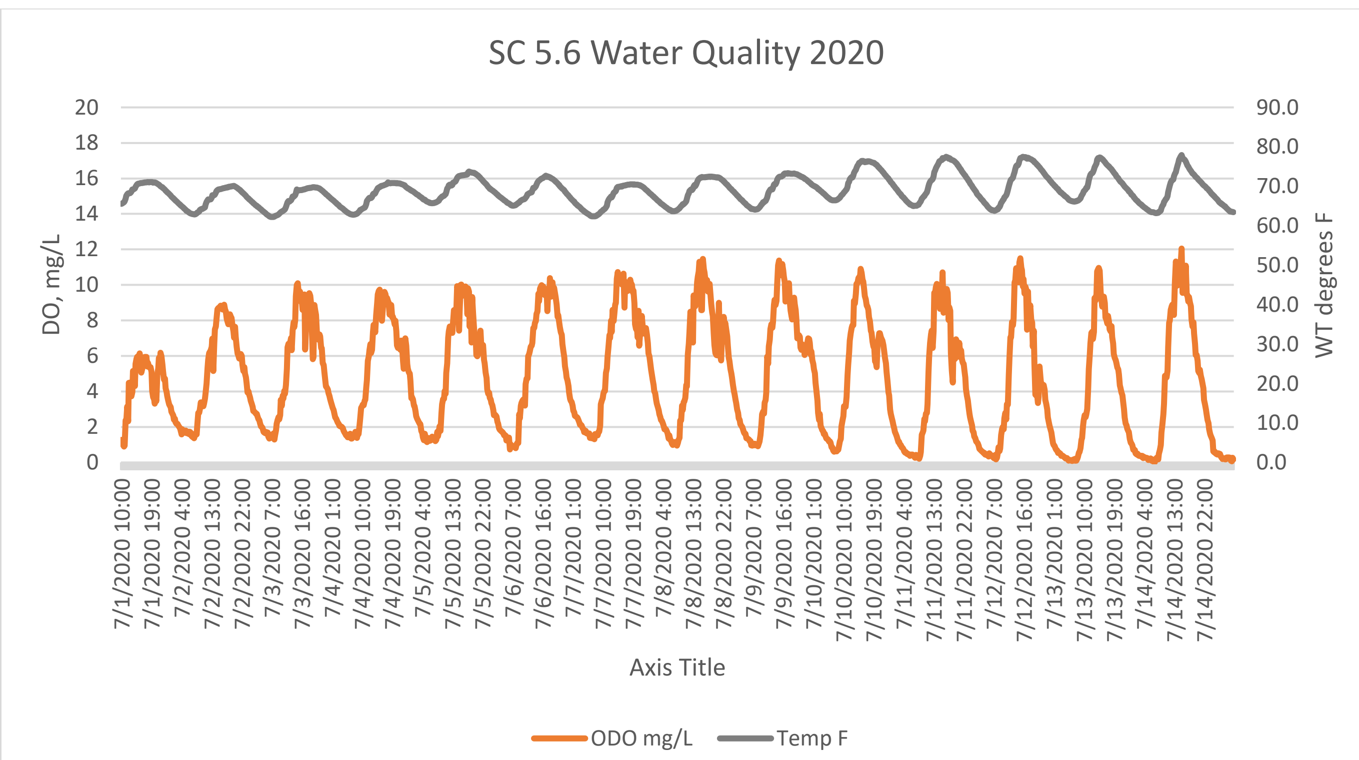


Figure 47. Water temperature and dissolved oxygen at station 5.6, 2020

Table 12. Dissolved Oxygen Concentrations for Selected Sonde Deployments in Suisun Creek, 2017 to 2020

Impairment Level	**Level of Effect Water Column DO (mg/L)**	**SC-9.5** 9/14 to 10/20/17 Dissolved Oxygen Percentile	**SC-7.0** 9/12 to 9/18/18 Dissolved Oxygen Percentile	**SC-6.0** 8/30 to 9/11/19 Dissolved Oxygen Percentile	**SC-9.5** 7/29 to 8/19/20 Dissolved Oxygen Percentile
No Production Impairment	8	none	67%	54%	87%
Slight Production Impairment	6	none	0.2%	52%	31%
Moderate Production Impairment	5	none	none	49%	1.2%
Severe Production Impairment	4	none	none	45%	none
Limit to Avoid Acute Mortality	3	none	none	45%	none
Maximum Oxygen Conc. mg/l		11.9	9.7	9.3	9.1
Median Oxygen Conc. mg/l		8.8	7.2	5.1	6.4
Minimum Oxygen Conc. mg/l		8.1	5.8	1.2	4.1

As shown in Table 12, dissolved oxygen concentrations were frequently low enough to be harmful to steelhead in Suisun Creek at station 6. The most deleterious oxygen levels were observed in 2019 during low-flow conditions, when 45% of the observations were below the threshold for avoiding acute mortality.

Summary

Summer streamflow in upper Suisun Creek results almost entirely from releases from Lake Curry. Tributaries run dry in early summer, and groundwater inflows are not a significant source of streamflow except immediately downstream of the lake. Streamflow diminishes with distance downstream of the lake owing to evaporation and seepage. Streamflow data do not show summer diversions occurring along Suisun Creek. Water released from the lake varied in temperature during the study owing to variations in lake level management. Released water remains relatively cool in the first three miles downstream of the lake, but warms as it flows down the stream below station 8.0. Data demonstrate that flow levels, as defined by releases from Lake Curry, affect temperatures of aquatic habitat particularly in upper Suisun Creek between stations 10 and 8. Downstream of station 8 the releases are less effective in creating cooler water temperatures. Water temperatures at upstream stations are generally below 70^{o} F, but at the stations farthest downstream (station 7.0 to 5.0), water temperatures often exceed 70^{o} F. Riparian shading is an important control on stream warming. Loss of canopy cover due to wildfires and drought have resulted in higher water temperatures. Dissolved oxygen levels remain near 10 mg/L when flows are high enough to provide aeration. In disconnected pools, DO levels decline to near zero at night. Releases below 2.5 cfs result in disconnected flows on Suisun Creek with low DO levels and high water temperatures not supportive of steelhead trout.

RIPARIAN CORRIDOR SURVEYS

Riparian vegetation was mapped by species and size class along all areas of Suisun Creek where access was available (Appendix E). The mapping was done in August 2018 to define the ecological status of the riparian corridor and to measure canopy cover or shading of the creek. Polygons were delineated along the Suisun Creek channel (Figure 48). Within each polygon we recorded the condition of the channel and banks, presence of erosion, number and location of bank revetments and invasive species, the number and size class of each tree species, understory species and density and any other conditions of note.

Surveys of open water or unshaded areas were completed in 1999 and 2010 (Figures 49 and 50). These surveys show an increase in canopy cover between these two dates. Figure 51 shows the widespread loss of mature white alders along the creek due to the drought in 2014-15. The 2018 survey found this species along with Fremont cottonwoods were actively regenerating with numerous seedlings along the creek.

Figure 52 depicts the biodiversity of tree species surveyed on Suisun Creek in 2018. Over 11 native species were recorded as were a number of non-native species.

Size class – seeding, sapling. small/medium tree and large tree, were recorded for each native tree species. The most common pioneer species, or species that rapidly germinate and grow into channel areas, were cottonwood and white alder; willow is much less common. Fremont cottonwood has a high number of seedlings compared to other size classes (Figure 53).

Most common mid and upper bank species were Ca. bay laurel and live oak. Live oak, Ca. bay laurel, Ca. black walnut and Oregon ash had the highest number of seedlings for the mid and upper bank species (Figure 54).

The 2018 survey also documented the locations of invasive non-native trees such as Acacia, Eucalyptus, fig and tree of heaven (Figure 55). Other invasive plants species that were mapped include Arundo, Himalayan blackberry, blue periwinkle, poke weed, cape ivy and English ivy (Figure 55). Figure 56 is an example of the maps of the locations of invasive species produced by the survey. Additional maps are in Appendix D.

Summary

There is a fairly good level of biodiversity with regeneration in both pioneer and mid and upper bank species along upper Suisun Creek. The most recent drought killed many white alders but both alder and cottonwood seedlings are abundant to replace these dead trees.

The thin riparian corridor along the top of the bank is being undercut by bank failures in many locations. The base of hillslopes in semi-confined channel areas also has many erosion sites.

Invasive non-native trees (fig is most common) and invasive understory species interfere with native tree seedling germination and growth. An invasive species eradication program in collaboration with landowners is needed.

Only half of the canopy cover readings along the creek are in the 80-100% range indicating a need for additional revegetation and large trees on top of bank completed in collaboration with landowners. CLSI completed several revegetation plans with landowners.

Figure 48. Polygons defined along Suisun Creek for riparian mapping

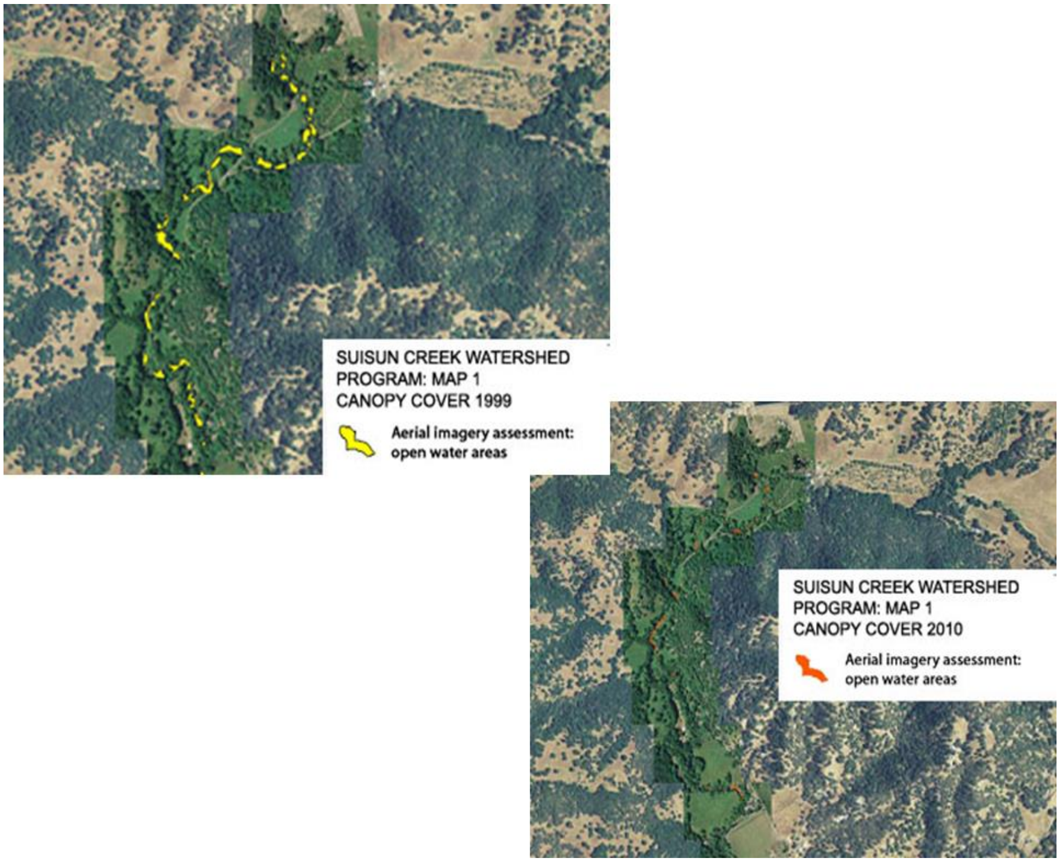


Figure 49. Comparison of canopy cover on upper Suisun Creek between 1999 and 2010.

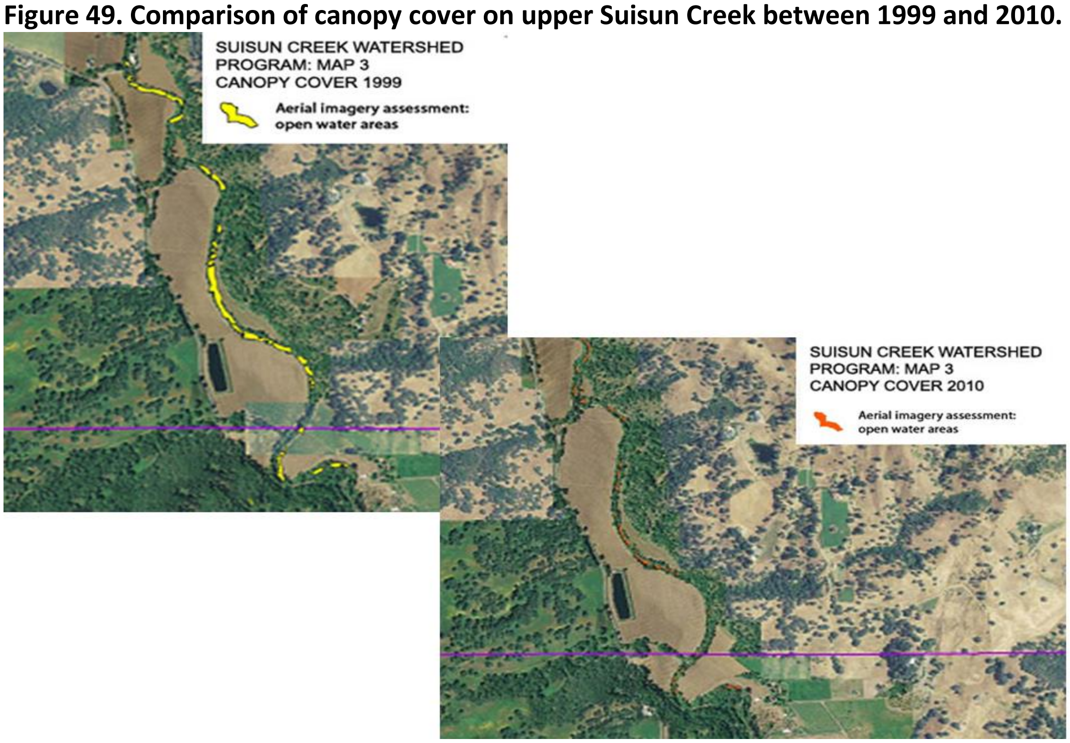


Figure 50. Comparison of canopy cover on Suisun Creek between 1999 and 2010. Cover generally increased along the creek.

Figure 51. Examples of dead alders along Suisun Creek following the 2014-15 drought

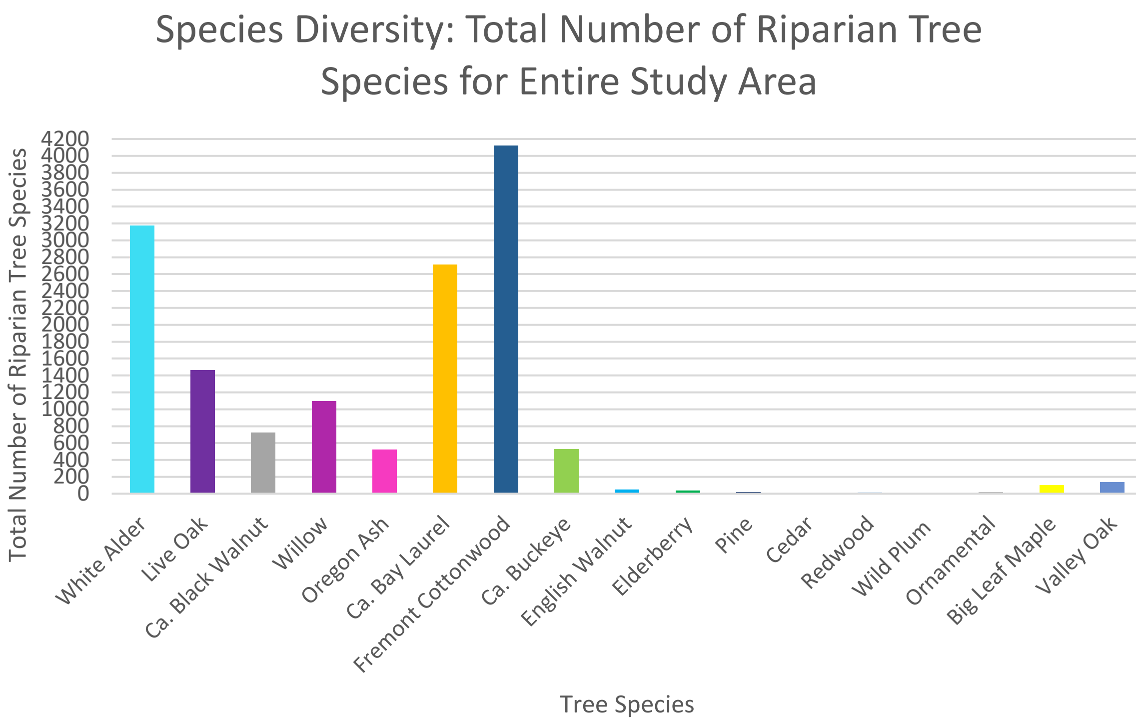
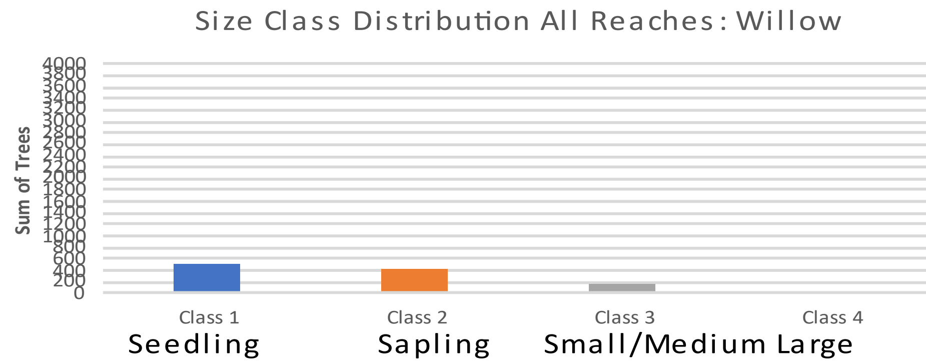
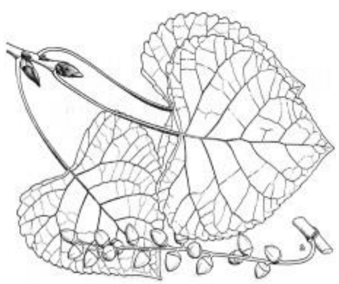


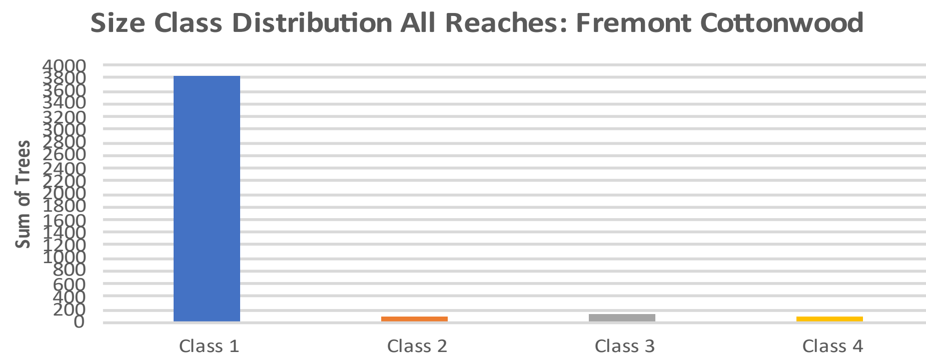
Figure 52. Biodiversity of riparian trees surveyed along Suisun Creek in August 2018.

Willow (Salix sp.)



Fremont Cottonwood (Populus fremontii)





White Alder (Alnus rhombifolia)

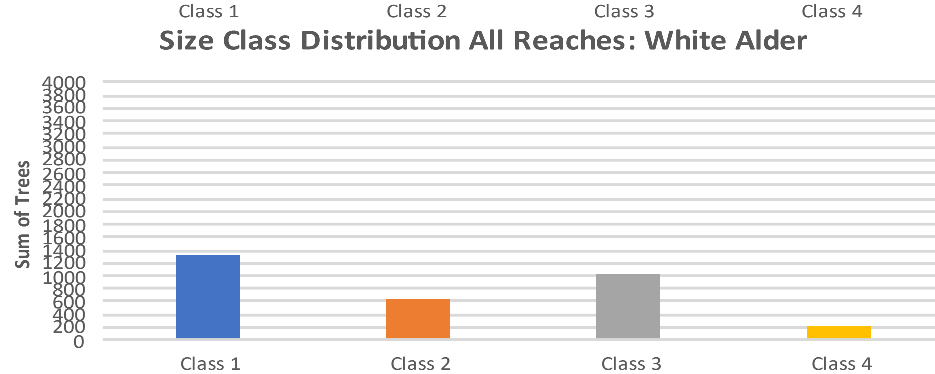
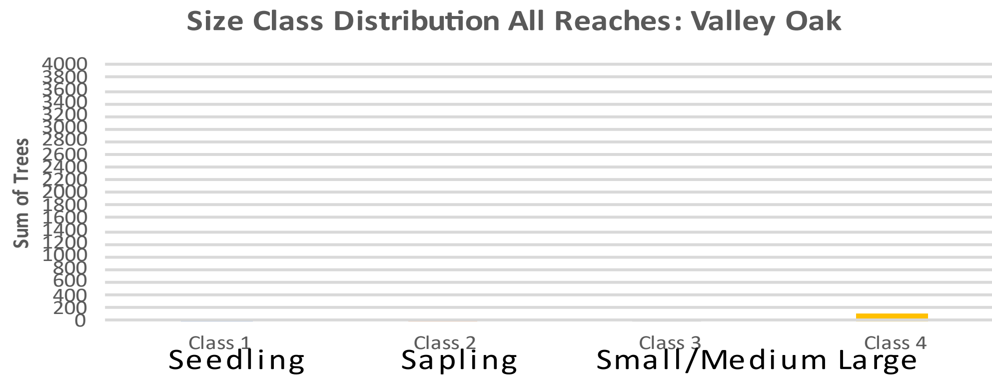
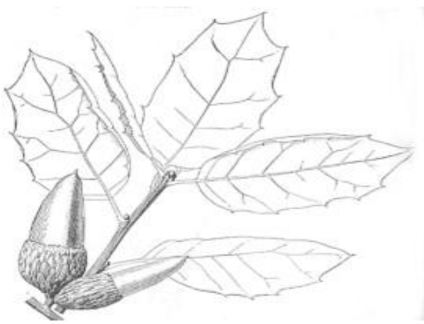


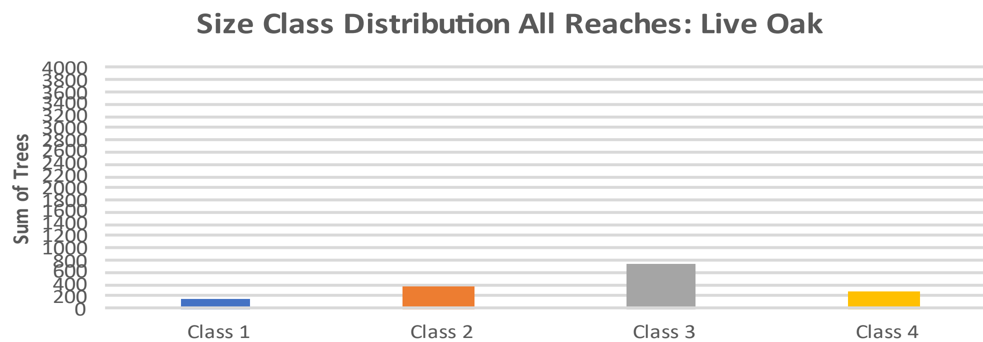
Figure 53. Size class distribution of three pioneer species recorded in riparian corridor of Suisun Creek in 2018. Fremont cottonwood and white alder are actively regenerating following the effects of drought and fire.

Valley Oak (Quercus lobata)



Live Oak (Quercus agrifolia)





California Bay Laurel (Umbellularia californica)

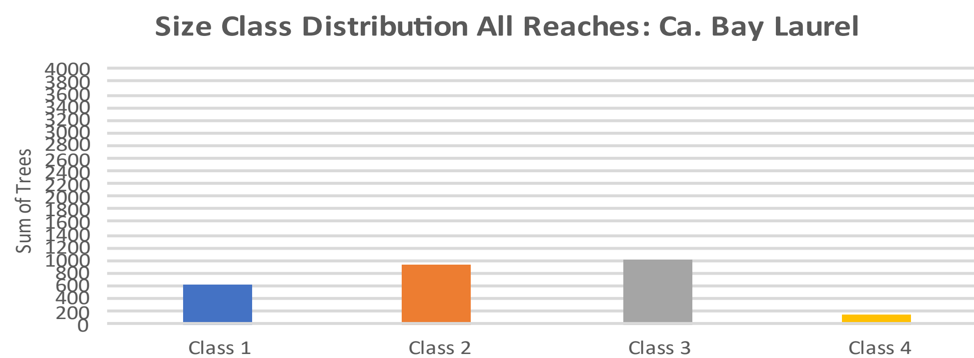


Figure 54. Size class distribution of three mid and upper streambank species recorded in riparian corridor of Suisun Creek in 2018. Both Ca. Bay laurel and live oak show a stable relationship between seedling, sapling and mature trees.

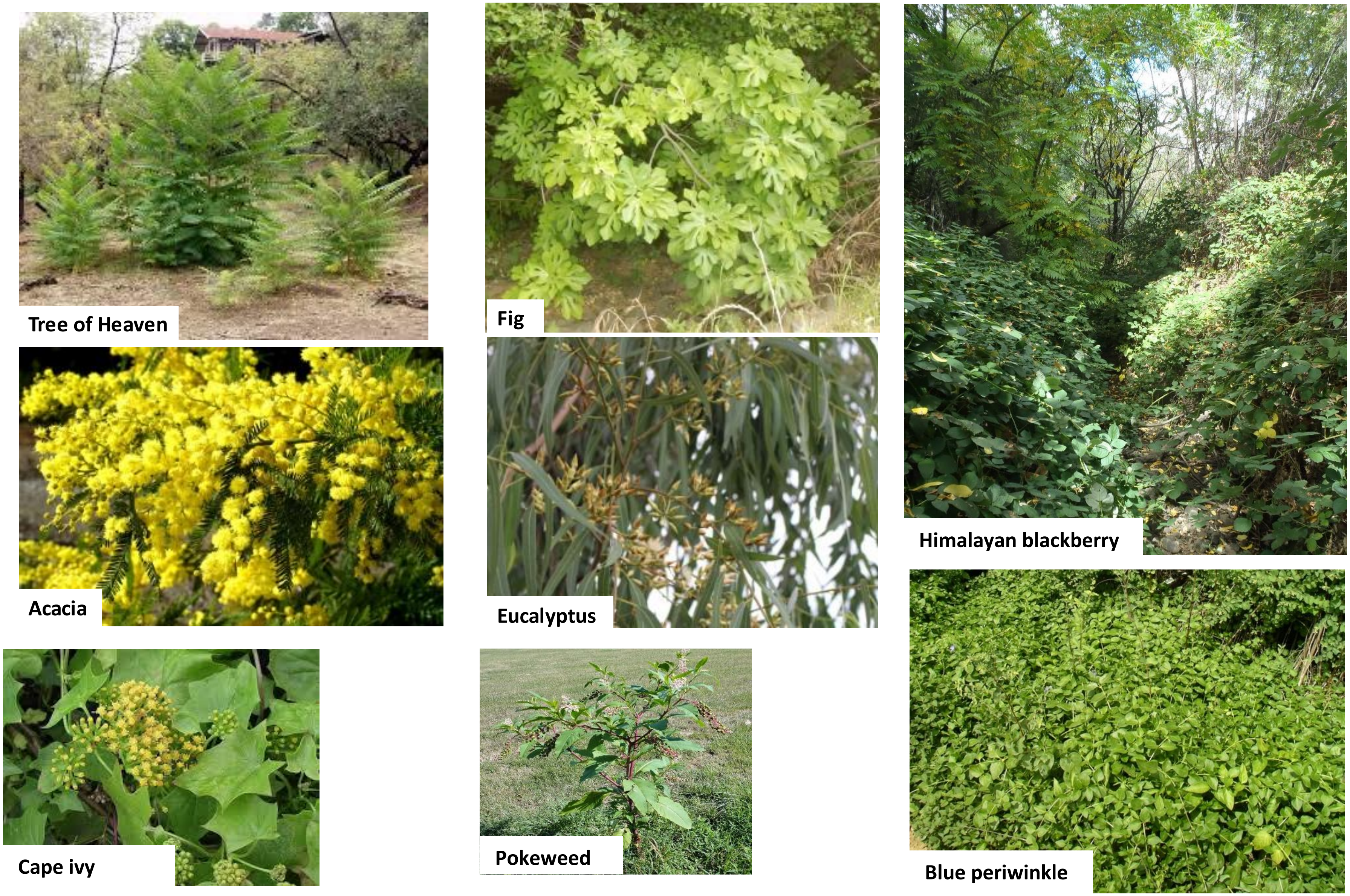


Figure 55. Invasive non-native species found in 2018 survey of Suisun Creek.

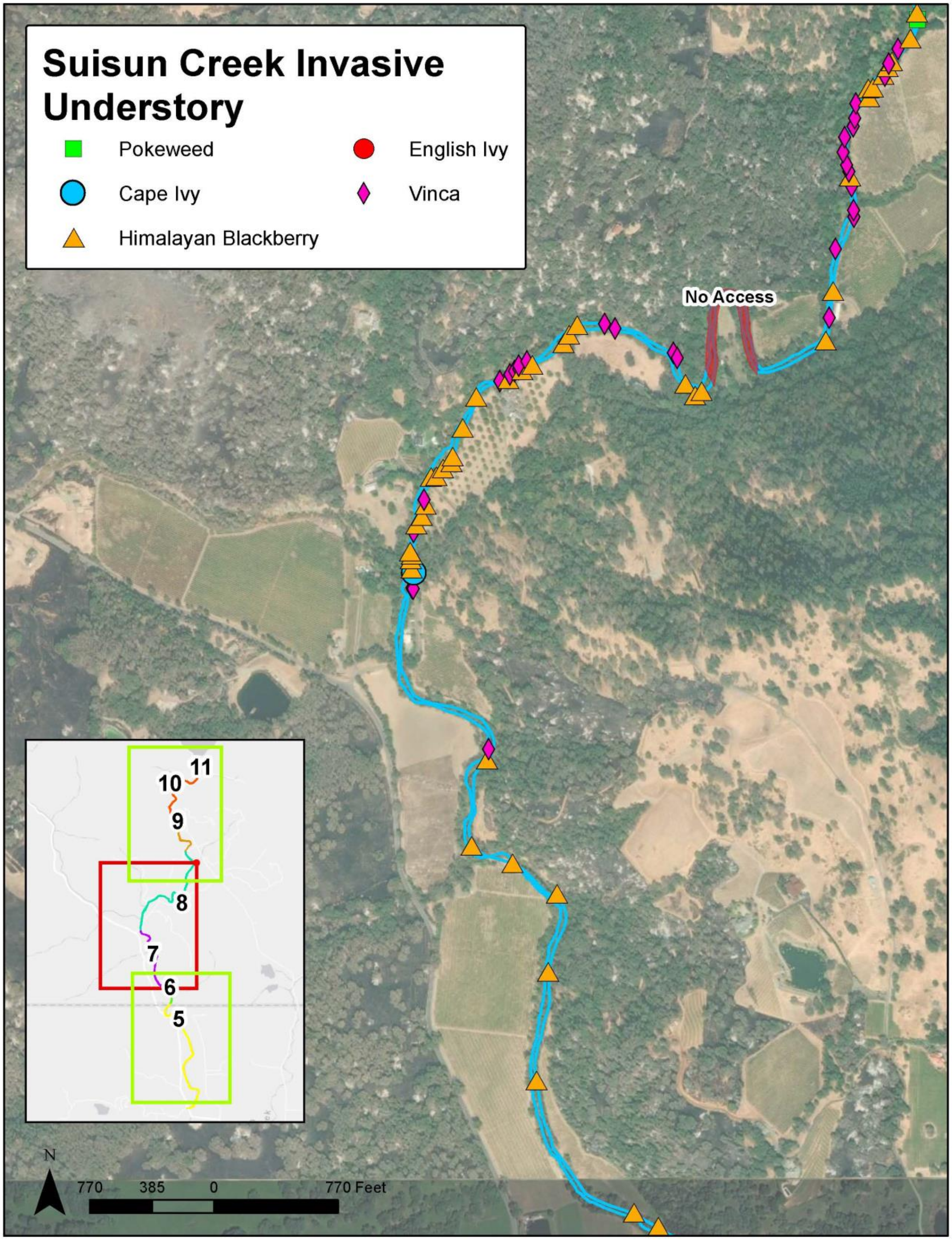


Figure 56. Example map of invasive species along Suisun Creek

FISH SURVEYS

Snorkel Surveys

Snorkel surveys were performed in 2017, 2019 and 2020 from station 10 to 5. Appendix E contains the complete results of these surveys. Snorkel surveys were conducted from Lake Curry dam downstream approximately six miles. A total of nine species were observed including Central California Coast DPS steelhead listed as threatened under the Endangered Species Act 1973 (Table 13). Survey followed guidelines described in an American Fisheries Society publication of best practices in fisheries science (Johnson et al. 2007). Steelhead were primarily found in reaches 11, 9 and 8 (Figure 1).

Table 13. Summary of Total Abundance of Each Species Identified During 2017 Suisun Creek Snorkel Surveys Between Stations 10-5.

Common & Scientific Names	Total Abundance
Bluegill Sunfish (*Lepomis macrochirus*)	1
California Roach (*Hesperoleucus symmetricus*)	8179
Inland Silverside (*Menidia beryllina*)	1
Prickly Sculpin (*Cottus asper*)	1
Sacramento Pikeminnow (*Ptychocheilus grandis*)	1736
Sacramento Sucker (*Catostomus occidentalis*)	2005
Steelhead (*Oncorhynchus mykiss*)	46

Snorkel surveys of Suisun Creek were conducted on June 7 & 8, 2018. Surveys were planned to cover stations 6.5-9.0 and 9.4-9.6). Upon reaching the creek the crew noted that the stream was dry and did not have open channel flow (Figure 57). The crew proceeded to walk the creek to determine if there were isolated pools with fish. No steelhead trout were observed during the surveys. Two known locations that had previously had steelhead trout were dry. Intermittent isolated pools occurred upstream of station 8.0. Three-spine stickleback (*Gasterosteus aculeatus*), Sacramento pikeminnow (*Ptychocheilus grandis*), Sacramento sucker (*Catostomus occidentalis)* and California roach (*Hesperoleucus symmetricus*) were observed, but they appeared to be in poor health, with significant fungus covering their scales. Appendix F contains a summary of each survey.

The June 2020 snorkel surveys found a total of 150 habitat units including pools, riffles, and flatwater; a total of 41,951 fish were observed and identified to species and additional 1,000 fish that could not be confidently identified to species were identified to family Cyprinidae and a total of 8 species were observed (Table 14).

Table 14. Total Abundance of Each Species Identified During Suisun Creek Snorkel Surveys, June 2020.

Common & Scientific Names	Total Abundance
Bluegill Sunfish (*Lepomis macrochirus*)	565
California Roach (*Hesperoleucus symmetricus*)	23,943
Prickly Sculpin (*Cottus asper*)	21
Sacramento Pikeminnow (*Ptychocheilus grandis*)	2,247
Sacramento Sucker (*Catostomus occidentalis*)	4,419
Tule Perch (*Hysterocarpus traskii*)	255
Steelhead Trout (*Oncorhynchus mykiss*)	51
Three spine Stickleback (*Gasterosteus aculeatus)*	10,450

Figure 57. In 2018 with Lake Curry releases stopped Suisun Creek is dry where steelhead were recorded the prior year.

Figure 58. Small intermittent pool upstream of station 8.0 in Suisun Creek in 2018 when no releases were made from Lake Curry.

Lifecycle model

Cramer Fish Sciences developed a life cycle model to estimate spawning and rearing habitat needed to support anadromous steelhead in Suisun Creek. The primary objective of this effort is to provide tools and information to support planning and assessment of steelhead habitat management goals that will allow stakeholders to:

- identify measurable goals that relate to federal and state laws and helps determine when “enough is enough”
- identify gaps in understanding and provide an iterative and transparent process whereby new information can fill knowledge gaps; and
- “game” habitat quantity and available water to wisely and adaptively manage flow and non-flow actions that support steelhead population targets.

The overall process to determine watershed ability to support target steelhead population assumes that a viable population goal and habitat needs can be quantified, and general relationships between potential habitat and flow can be developed. This work addresses the first steps in this process, which are to determine the minimum spawning and rearing habitat requirements needed to support a viable anadromous steelhead population in Suisun Creek using a life cycle model approach.

Information needed to parameterize the life cycle model (Figure 59) used for this analysis include the following parameters which are described in more detail later:

1. Population targets
2. Adult age, size, and sex structure
3. Adult migration and spawning timing
4. Redd size, territory requirements, and fecundity
5. Incubation timing, duration, and emergence timing and survival
6. Freshwater growth, size structure, and mortality
7. Juvenile emigration timing, duration, and production
8. Juvenile rearing territory requirements

Findings

For a minimum viable population of 833 adult steelhead spawners with no harvest goal, the model estimates that between 0.04 acres to 0.73 acres of spawning habitat area is needed with a maximum of 0.73 acres needed in April. We estimate that rearing habitat needs, for a minimum viable steelhead population, range between 75 to 118 acres throughout the year, with a peak of 118 acres required in April. These estimates do not consider habitat quality which could directly influence the required amount of habitat needed given the assumption that required habitat increases as habitat quality decreases. Appendix E includes the entire technical report on the lifecycle model. Additionally, an online interface to the model is available at https://fishsciences.shinyapps.io/Suisun_LCM/.

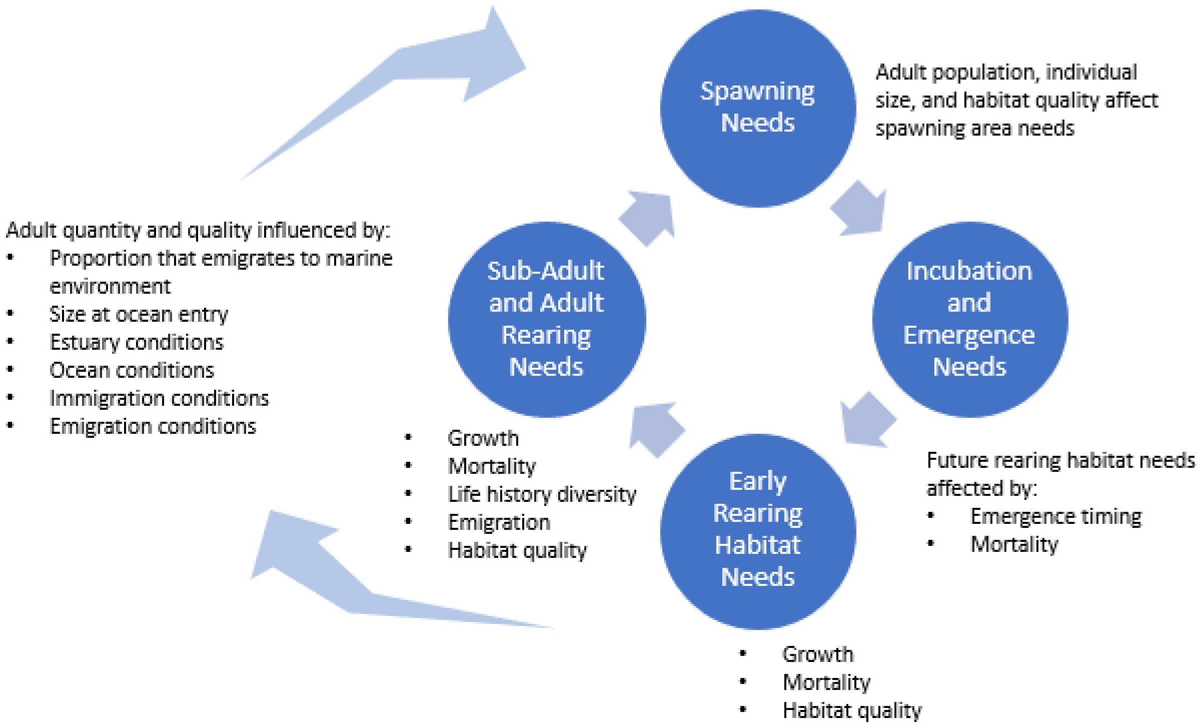


Figure 59. Conceptual diagram of the life cycle model approach used to estimate spawning and rearing habitat requirements for a target population using demographic information and relationships for key life stages.

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