# **ASSESSING THE EFFECTS OF WATERBODY TEMPERATURE ON BENTHIC COMMUNITIES IN THE SAN GABRIEL RIVER WATERSHED**

# Tech Memo– Draft May 31st, 2023

## Executive summary

The Los Angeles Regional Water Quality Control Board (LARWQCB) has recently reinterpreted the Los Angeles Region Water Quality Control Plan water quality objective for stream temperature, for warm freshwater habitat (WARM) beneficial use in the region, which has reduced the current temperature objective to 80°F. However, it is currently unknown to what extent a change in receiving water temperature will impact WARM beneficial use. To address this question, LARWQCB needs to determine whether the 80°F target is sufficient to protect beneficial uses and/or what temperature corresponds to beneficial use attainment. Beneficial use attainment can be evaluated using regional relationships between the aquatic communities in streams and stream temperature and by understanding the temperature ranges associated with healthy biological communities. However, developing these relationships requires specific questions to be answered to produce the most applicable and useful model:

1. Which biological indicator(s) are most appropriate for measuring temperature effects?
2. Which temperature metrics are most relevant, i.e., are most impactful to benthic communities?
3. How to determine key biological thresholds that indicate support of aquatic life beneficial use?

Ultimately, the regional relationships will provide an approach to determine preferred temperature ranges associated with healthy biological condition, as well as estimating the likelihood of achieving a healthy biological condition given specific stream temperatures in the San Gabriel River (SGR).

We conducted a literature review and exploratory analysis to investigate links between the stream community and stream temperature as well as establish the most useful approach to develop the regional relationships. For the exploratory analysis we used bioassessment data for Southern California streams that describe healthy biological condition through benthic communities BMI (benthic macroinvertebrates) and algae. We utilized readily available modeled temperature data that comprised minimum, maximum, mean and ranges of weekly (7-day) summary metrics and tested the influence of each on stream condition.

We found maximum and minimum weekly temperature to be the most associated benthic communities, based on their relative importance on the bioassessment indices California Stream Condition Index (CSCI) and the Algal Stream Condition Index (ASCI).

A commonly used biological threshold indicative of “healthy” stream condition for CSCI is 0.79 (0.86 for ASCI), however we found that applying a modified biological threshold, e.g., 0.6 for CSCI (0.75 for ASCI), is beneficial in regions such as SGR as it is more representative of the altered stream conditions observed in the area. We developed regional temperature-ecology response curves based on these findings. Using these curves, we found that healthy biological condition (of both CSCI and ASCI) can be supported with maximum weekly temperatures of 82 °F using standard thresholds (ASCI; 0.86, CSCI; 0.79) and 89 °F (ASCI; 0.75, CSCI; 0.6) using the thresholds for modified systems. These temperatures are based on the ASCI thresholds, chosen as a limiting factor to also support CSCI (maximum weekly temperatures of 87°F and 93°F, for standard and modified thresholds respectively).

In addition, we developed probability curves that can be used to determine the likelihood of any temperature protecting beneficial uses based on CSCI and ASCI (Figure ES 1). Using these curves, we determined that the 80°F target has a 90% probability of protecting beneficial uses based on the standard threshold and a 96% probability based on the thresholds for modified streams.

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Figure ES 1: Probability of achieving a “good“ CSCI score as a function of maximum weekly temperature for standard and modified index thresholds. Dashed blue line indicates the revised temperature objective (80F). Dashed black lines illustrate how to derive temperature limits according to probability threshold (0.95).

The next phase of this work will assess the use of these curves in the SGR to predict the ability of local stream temperatures to support beneficial uses. In addition, the regional curves will be validated using local temperature and biological condition scores.

## Background

Stream temperature is a critical determinant of stream ecological health, which can be defined in terms of aquatic life beneficial use. Most stream biota require specific temperature ranges within which they can grow, survive, and reproduce, therefore changing temperatures can drive community structure and directly impact the success of biological communities. In addition, temperature can also influence stream ecological health through indirect impacts to water quality, e.g., increased temperatures can affect concentrations of dissolved oxygen (Ficklin, Stewart, and Maurer 2013), further impairing species’ ability to survive resulting in shifts to distribution and assemblage.

Highly urbanized areas, such as the San Gabriel River (SGR) in Southern California, tend to run warmer than natural conditions due to shallow depth, channelization, limited cover from riparian vegetation, and heated discharges from water reclamation plants (WRPs) (Abdi et al. 2022; Somers et al. 2013; Caissie 2006). Accordingly, the Los Angeles Regional Water Quality Control Board (LARWQCB) reinterpreted the Los Angeles Region Water Quality Control Plan water quality objective for stream temperature, for warm freshwater habitat (WARM) beneficial use in the region, which has reduced the current temperature objective to 80°F. However, it is currently unknown to what extent a change in receiving water temperature will impact WARM beneficial use. To address this question, LARWQCB needs to determine whether the 80°F target is sufficient to protect beneficial uses and/or what temperature corresponds to beneficial use attainment.

Beneficial use attainment can be evaluated using relationships between the aquatic communities in streams and stream temperature and by understanding the temperature ranges associated with healthy biological communities. Benthic communities that comprise macroinvertebrates (BMI) and algae, are important and sensitive bioindicators of aquatic life beneficial uses. Due to their varied response to disturbance, they are commonly used as a compliance endpoint in stream management (Ode et al. 2016; Mazor et al. 2018). Benthic species vary widely in their sensitivities to stream temperature, which manifests in community composition. For example, elevated temperatures may lead to a community dominated by temperature tolerant species. This sensitivity gradient can be quantified through a variety of biological metrics that can help bridge gaps between communities and aquatic life beneficial uses.

However, developing these relationships requires that specific elements are defined in order to produce the most applicable and useful model. First, we need to establish the most relevant temperature metric and temporal resolution e.g., monthly, annual, seasonal means, maximum or minimums. Second, we need to determine the most suitable biological indicator to use as the biological response to stream temperature e.g., stream condition index (California Stream Condition Index [CSCI]), community metrics (richness, % tolerant), biological traits (fecundity, voltinism). Third, we need to ascertain an appropriate biological threshold that reflects the presence or support of aquatic life beneficial uses. These investigations can be done at a regional scale to 1) leverage past investment in developing regionally consistent and comprehensive bioassessment datasets and 2) provide a standard set of temperature-ecology relationships that can apply to all streams in the region.

The overarching goal of this study is to develop regional temperature relationships with benthic communities that can be used to help determine the degree to which temperature may be affecting aquatic life beneficial uses. Consequently, the model can provide information on whether a certain temperature threshold, i.e., 80°F, is supportive of WARM beneficial use.

Through model development we aimed to answer the following questions:

1. Which biological indicator(s) are most appropriate for measuring temperature effects?
2. Which temperature metrics are most relevant, i.e., are most impactful to benthic communities?
3. How to determine key biological thresholds that indicate support of aquatic life beneficial use?

This document describes the regional model development process and associated analysis. Ultimately, the final relationships can be applied in the San Gabriel watershed to predict the ability of local stream temperatures to support aquatic life beneficial uses as well as to validate the model with available data specific to the study area.

## Methods

### Overview of approach

The conceptual approach involved the development of regional scale relationships between benthic community composition and stream temperature. Developing regional relationships, as opposed to site-specific relationships, carry several benefits such as taking advantage of the spatially broad data that captures the biological response under varied conditions, and producing a single regional relationship that is applicable to all streams in the Southern California region, meaning that relationship development need only be completed once.

The approach produced curves that relate the probability of achieving a healthy ecological condition to stream temperature using biological relevant temperature metrics. We conducted a literature review and exploratory analysis to determine the following:

1. Biological indicators that are appropriately sensitive to changes in stream temperature
2. Biologically relevant temperature metrics and data availability
3. Most appropriate statistical approach to develop regional temperature-ecology relationships.
4. Most useful biological threshold(s) that reflect aquatic life beneficial use support.

The outcome of the literature and exploratory analysis were fundamental to the development of the regional temperature relationships; however, it is important to note that data availability was also highly influential in the feasibility of model creation. Therefore, an evaluation of available data was also undertaken and any substantial gaps in the data were recorded.

Ultimately, the regional relationships produced:

1. Preferred temperature ranges based on selected biological response variables.
2. Probability relationships based on biological thresholds that define healthy vs. unhealthy biological condition.

### Identify links between species life history and stream temperature.

We conducted a literature review to qualitatively understand broad linkages between the stream community and stream temperature. The main goal of the review was to synthesize and determine the most appropriate, or most commonly used, biological response metric and stream temperature metrics based on primary literature. We focused predominantly on rivers and the benthic communities; however, to keep the review broad we also included studies that were focused on other relevant species such as fish, as well as studies conducted in lakes and ponds, and any status of stream modification, i.e., modified, natural or combination. Studies assessing species life history traits were also compiled to relate temperature to life history attributes (e.g., voltinism, emergence synchrony), as well as traits that describe habitat preference or sensitivities (e.g., temperature tolerance, rheophilly). For the biological response indicators, we compared temperature studies that apply a variety of response variables, for example biotic indices, taxonomic measures (e.g., species richness, probability of occurrence), and biological traits (e.g., thermophily). This information guided model development by informing temperature stress sensitivities. For the temperature metrics, we collated a selection of temperature metrics documented to be informative to temperature effects studies on benthic communities and fish (e.g., 7-day means, or degree days).

Table 1: Temperature metrics commonly used in literature for macroinvertebrates and fish

|  |  |  |  |
| --- | --- | --- | --- |
| **Metrics** | **Macroinvertebrates** | **Fish** | **Citation** |
| **Daily** | Mean maximum, range, Standard deviation, Number of days above a threshold, Degree-days for each month, Diel amplitude | Degree Days, maximum 7-day mean, 7-day maximum, Mean daily water temps | Kaushal et al. (2010);Haase et al. (2019);Rivers-Moore et al. (2018);Jackson et al. (2007);Heino et al. (2003);Hawkins et al. (1997);Durance and Ormerod (2009);Vaughan and Ormerod (2014);Piggott et al. (2012);Durance and Ormerod (2007);Worthington et al. (2015);Jacobsen and Marín (2008);Filipe et al. (2013);Stewart et al. (2013);Heino et al. (2009);Chessman (2012);Sandin (2003);Burgmer et al. (2007);Vaughan and Gotelli (2019);Piggott et al. (2015), Butryn et al., 2013; Dugdale et al., 2018, Haidekker et al. 2008 |
| **Monthly** | Mean monthly | Julian Date of positive onset |
| **Annual** | Mean annual | mean, max annual, standard deviation |
| **Seasonal** | Mean winter, Residual winter, Seasonal variability, Mean and max summer | Minimum summer |
| **Other** | Min-max range, preference ranges | Hourly, first date when temp rises for 5 consecutive days |

Table 2: Biological response indicators commonly applied in temperature studies

|  |  |  |  |
| --- | --- | --- | --- |
| **Species Group** | **Response type** | **Bio Response Metrics** | **Citation** |
| Macroinvertebrate | Habitat preference | *Indicators* - prevalence, predation pressure, productivity, latitudinal shifts  *Traits -* thermal tolerance, thermophily, rheophily, | Piggott, Townsend, and Matthaei (2015); Vaughan and Gotelli (2019); Burgmer, Hillebrand, and Pfenninger (2007); Sandin (2003); LeRoy Poff (1997); Chessman (2012); Heino, Virkkala, and Toivonen (2009); Stewart et al. (2013); Filipe, Lawrence, and Bonada (2013); Jacobsen and Marín (2008); Worthington et al. (2015); Durance and Ormerod (2007); Piggott et al. (2012); Vaughan and Ormerod (2014); Durance and Ormerod (2009); Hawkins et al. (1997), Domisch et al., 2011; Chessman, 2011 |
| Community/population metrics | *Indicators:* species richness, assemblage structure, species composition, EPT richness, abundance, densities of most abundant taxa, population biomass, community homogenization, presence/absence, diversity | Domisch et al. (2011); Luhring et al. (2019); Durance and Ormerod (2007); Laurisse (2017); Chinnayakanahalli et al., 2011 and Galbraith et al., 2010; Spooner & Vaughn, 2008; Lawrence et al., 2010, Onana et al. 2019 |
| Reproduction, growth and trophic | *Indicators*: Morphology changes, phenology, hatching success, larval diet composition, growth rates, secondary productivity, respiration, development time, egg development and hatching  *Traits:* trophic guild, voltinism, fecundity | Durance and Ormerod, 2007; Glazaczow et al. 2016; Burgmer et al. 2007; Rivers-Moore et al. 2018;, Statzner and Bêche (2010); Stoks et al. (2014); Hassall and Thompson (2008); Pandolfo et al. (2010); Hester and Doyle (2011); Archambault et al. (2014); André et al. (2021); Vasseur et al. (2014); Poff et al., 2006; Diamond et al., 2011; Bonada et al., 2007; Ganser et al., 2013; Finn et al., 2022, Giebelhausen et al. 2001 |
| Fish | Trophic | competitive weight, changes in feeding behavior | Kishi et al. (2005); Campbell et al. (2020); Hughes and Grand (2000) |
| Algae/phytoplankton | Growth | growth rate, photosynthesis, biomass, size | Squires et al., 1979; Nalley et al., 2018, Bernhardt et al. 2018, Haijiang et al. 2015; Joehnk et al. 2008 |

In total, we included 57 papers that focused on stream temperature effects on benthic communities and fish. Temperature metrics (Table 1) for BMI related studies varied widely in terms of resolution (from daily to annual), summaries (mean, min, max, range, standard deviation) and data type (averages, variability, numbers of days, degree days). Metrics for fish also varied temporally, but also included weekly (7-day) summaries. These metrics mainly comprised averages, extremes (min and max) and variability (range, standard deviation).

The majority of biological response metrics (Table 2) comprised three main themes and included both indicator metrics and trait-based measures, 1) Habitat preference that includes distribution and prevalence, as well as thermal tolerance and preference, 2) Community and population metrics comprising metrics quantifying abundance and richness, which varied from whole communities to proportional subsets e.g., densities of most abundant taxa and 3) reproduction, growth and trophic, which included life history traits, development rates and diet composition.

BMI trait-based studies focused on habitat preferences (rheophily, thermophily) and life history (reproductive capabilities, body size, growth & development). Elevated temperatures were shown to impact performance of life history in the majority of trait-based studies (see Table 2 for references). We found a limited number of trait-based studies focused on algae, however growth rates and photosynthesis were the most common application.

### Quantifying the benthic community.

BMI and algae bioassessment data for the 1998-2021 time period was downloaded from the Stormwater Monitoring Coalition (SMC) regional monitoring database for the entire southern California region (*total n=1938, BMI n = 1938, Algae n = 1113,* Figure 1).The survey data included all the species data used to calculate score values and component metrics for the California Stream Condition Index (CSCI) and the Algal Stream Condition Index (ASCI). We calculated biological index scores for all samples and generated metric and index scores for the benthic macroinvertebrate CSCI (Mazor et al. 2016) and algal ASCI (Theroux et al. 2020).

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Figure 1: Map of bioassessment sites in Southern California (n=1938)

### Quantifying regional stream temperature.

Stream temperature data in the region is severely limited both spatially and temporally, hence regional monitoring efforts are of utmost importance to aid future stream temperature assessments. To understand the extent of stream temperature data available, we collated empirical data for the southern California region from various state- wide sources e.g., California Environmental Data Exchange Network (CEDEN), as well as internal databases available from previous projects and partners (Figure 2). Initially, these data would form the basis of the physical temperature element of the regional relationships. Spatially, the temperature observational data consists of sparse coverage, together with large clustering of numerous sites in several areas. Temporally, the resolution of the logged data is high but variable, ranging from 30 minutes to 12-hour intervals, and the period of record ranging from <1 year to over 30 years. However, many of the period of records do not overlap, which is essential for consistency within the model and compatibility with biological data.

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Figure 2: Map of sites with temperature data for Southern California. Sources available online: California Data Exchange Center (CDEC)[[1]](#footnote-1), California Environmental Data Exchange Network (CEDEN)[[2]](#footnote-2), all other data sourced from internal databases and partners.

Given the lack of regionally comprehensive observed temperature data, we used modelled stream temperature data available from Rogers et al., (2021) for the southern California region (Figure 2, Modelled Temp data). Here, water temperature was estimated through an empirical stream temperature model that considered air temperature, watershed elevation and area, riparian herbaceous and woody cover and baseflow index. The model produced predictions of maximum, minimum and mean weekly stream temperature (vs. a continuous temperature time series), calibrated with unaltered stream gauges. The spatiotemporal extent of the resulting temperature covers the entirety of Los Angeles and Ventura Counties (Figure 3) from 1982-2014. The data comprised temperature metrics of annual 7-day summaries (Rogers et al. 2021, Table 2) with one metric value for each year in the time series for every NHD reach (COMID *n= 5428*) in the region. In comparison to the empirical temperature observations, we determined the spatial extent and temporal scale of the modelled data most suitable for our purpose. However, we note that the modelled data are limited with the temporal resolution of the predicted temperature metrics i.e., weekly, as opposed to daily or seasonal metrics as outlined through the literature review. Therefore, we were unable to compare the usefulness of metrics that describe different time scales.

We paired the bioassessment sites to the spatiotemporal extent of the modelled temperature data through matching the COMID and year of bioassessment sampling event. This resulted in a total of 575 CSCI sites and 320 ASCI sites over 397 COMIDs.

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Figure 3: Map of temperature data modelled extent with paired bioassessment sites

#### Exploratory analysis: Temperature Metrics

The modelled temperature metrics were assessed for their influence on CSCI and ASCI scores by applying Boosted Regression Trees (BRTs). BRTs are a machine learning method commonly used in ecological applications to derive the relative importance of each predictor variable to a biological response. By determining the relative importance, we can prioritize highly influential metrics in model development. Weekly minimum and weekly maximum temperature had the highest relative influence on CSCI and ASCI in the BRT model (Figure 4). These metrics will therefore be applied in further exploratory analysis on biological response.

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Figure 4: Relative importance of temperature metrics from BRT analysis

#### Exploratory analysis: Biological thresholds

Based on information from the literature review and collated data, several models were developed as exploratory analysis of biological response to the temperature metrics. The analysis was based around the CSCI and ASCI indices that each had identified thresholds that correspond to 1) Likely altered (ASCI: 0.75, CSCI: 0.63), 2) possibly altered (ASCI: 0.86, CSCI: 0.79), and 3) likely intact (ASCI: 0.94, CSCI: 0.92), which correspond to the 1st, 10th and 30th percentile value of the index based on the distribution of reference scores (Mazor et al., 2016; Theroux et al., 2020).

Most applications of bioassessment indices use the 10th percentile threshold to demarcate the difference between possibly altered and likely unaltered conditions. However, the lower San Gabriel River is highly altered by channelization, urbanization, WRP effluent and flood control management, which tend to show lower index scores (or higher alteration). To account for this higher alteration, we derived a modified threshold using the previously developed the Stream Classification and Priority Explorer (SCAPE) tool that can be used to inform development of alternative thresholds for “modified” streams (Beck et al. 2019). SCAPE predicts a range of CSCI scores that are likely to occur given the landscape constraints of a given stream reach (e.g., road density, land use) using a statewide model.[[3]](#footnote-3) The 50th percentile of predicted scores for every stream reach in the study area were averaged to create the modified threshold. Streams in the upper watershed (mostly from San Gabriel Mountains) are largely intact and were therefore removed from calculation of the modified thresholds (**Error! Reference source not found.**). This resulted in a modified threshold score of 0.6 for CSCI (vs. the traditionally used 0.79 threshold). No equivalent predictions were available for the ASCI index, therefore we used the 1st percentile index score of 0.75 vs. the traditional used 0.86 (Theroux et al. 2020).

For the purposes on this memo, the SCAPE approach for a modified threshold was applied. However, other options for establishing a modified threshold include the approach outlined in Mazor et al (in prep). In this study, modified streams were categorized based on channel engineering, i.e., natural, hard bottom and soft bottom with 0, 1 or 2 hardened sides, and the best observed CSCI and ASCI score per category was applied as a modified threshold (Table 3).

Table 3: Best observed index scores for all modified channel categories based on Mazor et al (in prep)

|  |  |  |
| --- | --- | --- |
| Index | Channel Type | Threshold |
| CSCI | Hard Bottom | 0.67 |
|  | Soft Bottom Soft Sides | 0.78 |
|  | Soft Bottom 1 Hard Side | 1.00 |
|  | Soft Bottom 2 Hard Sides | 0.75 |
| ASCI | Hard Bottom | 0.87 |
|  | Soft Bottom Soft Sides | 0.79 |
|  | Soft Bottom 1 Hard Side | 0.86 |
|  | Soft Bottom 2 Hard Sides | 0.76 |

A close-up of a map

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Figure 5: SCAPE tool predicted ranges for each site (top) and map with subset streams (bottom). Red sites in top panel reflect reaches that are likely constrained, blue are likely unconstrained. Red square on bottom panel indicates the streams included in the modified threshold calculation.

#### Exploratory analysis: Benthic Community Metrics

We estimated a temperature range associated with “healthy” biological condition by relating the CSCI and ASCI index scores to the modeled temperature metrics. We first developed models on the raw biological metric score by applying a quadratic linear regression, which is a technique that allows for a polynomial curve with a direct relationship with the index score, so provides an intuitive method for deriving a preferred temperature range associated with level of biological response. For example, to achieve a CSCI score of 0.79, associated mean weekly maximum stream temperature should be in the range of minimum 53℉ and maximum 87 ℉ (Figure 6). To achieve a CSCI score of 0.6, associated mean weekly maximum stream temperatures should be in the range of minimum 57℉ and maximum 93 ℉.

Both CSCI and ASCI are comprised of multiple component metrics that describe the composition of the communities (e.g. taxonomic richness, percent of community intolerant). We assessed these component metrics were with the modelled temperature data in addition to the CSCI and ASCI index scores. However, there was not much variation in the separate relationships between maximum weekly temperature and the component metric scores (see appendix, Figures S1 & S2), i.e., individual curves show similar relationships. Therefore, we elected to focus our analysis on the CSCI and ASCI indices.

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Figure 6: Example quadratic linear model of Max weekly temp and CSCI score. Red dashed line represents the modified threshold (0.6), blue dashed line represents the standard threshold (0.79). Vertical grey dashed line represents the temperature objective (80℉)

#### Exploratory analysis: Probability Analysis

We estimated the likelihood of achieving a “healthy” biological condition by applying maximum weekly temperature to both CSCI and ASCI. Considering that stream temperatures in SGR run high, as well as the focus of our study being to assess stream temperature limits that constitute maximum temperatures, we focused the probability analysis solely on maximum weekly temperature due to its relevancy to the revised temperature objective. We transformed the index scores into a binary good or poor score (1,0) using the standard and modified thresholds for each index: CSCI (standard: 0.79, modified: 0.6), ASCI (standard: 0.86, modified: 0.75) (Mazor et al. 2016; Theroux et al. 2020). Using the binary variable, we applied logistic regression to both indices and temperature metrics, and maximum weekly temperature, separately (Figure 7). However, this approach could not be performed on the component metrics as there is no defined, standard thresholds available. The logistic regression approach closely follows the method previously applied to develop flow-ecology curves, outlined in Irving et al., (2022) and is beneficial as it allows flexibility in management decision making, where a level of probability, and subsequent temperature range, can be chosen depending on the management circumstances and a desired level of certainty in supporting healthy biological conditions.

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Figure 7: Probability of achieving good; a) CSCI and b) ASCI score with maximum weekly temperature using logistic regression. Each curve is derived from either the standard threshold (CSCI = 0.79, ASCI = 0.86, blue) or the modified threshold (CSCI = 0.6, ASCI = 0.75, red). Dotted blue vertical line indicates the 80℉ temperature limit.

#### Exploratory analysis: Functional traits-based approach

Functional traits analysis reflects ecological processes and species roles within the community; therefore, it is a valuable method to relate stream temperature to the diverse life history needs of the benthic community. By applying traits, we can gain further insights into the consequences of altered temperature, than from biotic indices alone. From the literature review we know that life history traits describing reproductive capabilities, such as voltinism and fecundity as well as habitat preference traits such as thermophily are useful indicators of thermal stress. Therefore, we collated trait data from EPA online trait database[[4]](#footnote-4), including categorical traits; Fecundity, Rheophily, Swimming ability, Voltinism, Thermal Indicator, Life span, Observed maximum lethal temperature, Diapause, Development speed, Maximal body size, and continuous traits; Thermal tolerance value, Thermal optima value and Body length. However, due to many data gaps we based our analysis on the few traits with sufficient data availability; Thermal tolerance value, voltinism and thermal indicator.

Using thermal tolerance of BMI, we developed a thermal trait index based on observed and expected (o/e) thermal tolerance of BMI species in each bioassessment site. Expected BMI species were estimated based on the probability of a species, i.e., capture probability, being present under reference conditions (Mazor et al. 2016). The mean thermal tolerance for both observed and expected species was computed, with weights assigned based on capture probability. The thermal tolerance index (o/e) for each bioassessment site was then determined by dividing the weighted thermal tolerance of observed species by the weighted thermal tolerance of species expected at that specific site.Unfortunately, capture probability could not be estimated for algal species (Theroux et al. 2020) successfully, therefore we were only able to complete this analysis for BMI.

Next, weekly maximum temperature was regressed against the thermal index according to taxon trait category, i.e., voltinism; 1 generation per year, <1 generation per year, >1 generation per year and thermal indicator; cold, warm. The preliminary results show that the community responds differently to stream temperature depending on their traits (Figure 8). For example, BMI species that reproduce just once, or fewer, each year show a strong positive relationship with maximum weekly temperature, whereas species that reproduce more than once a year do not respond strongly and show a slight negative trend with temperature. In addition, warm and cold indicator species show a contrasting trend with increasing temperature. However, due to limitations in the trait data, these relationships are based on a small subset of the community (23-38% of species had available trait data), therefore it was not possible to produce a representative outcome. Nonetheless, with improved data the trait-based approach could be a valuable method for evaluating temperature limits, especially with regards to seasonality and its link to species life history (Varpe 2017).

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Figure 8: Trait-based approach relating thermal tolerance index to maximum weekly temperature according to thermal indicator and voltinism traits

### Develop response models.

The literature review and exploratory analysis determined CSCI & ASCI indices as the most appropriate biological indicators, with maximum weekly temperature as the most useful temperature metric for the regional relationship curves. Through these curves, we found that, healthy biological condition (of both CSCI and ASCI) can be supported with maximum weekly temperatures of 82 °F using standard thresholds and 89 °F using the thresholds for modified systems (see Figure 6, values for CSCI & ASCI in Table 4). These temperatures are based on the ASCI thresholds, chosen as a limiting factor to also support CSCI (maximum weekly temperatures of 87°F and 93°F, for standard and modified thresholds respectively). As ASCI tended to be more sensitive to maximum temperature, we determined the ASCI temperature range to be most appropriate (Table 4). These ranges serve as a foundation for the probability analysis that enables guidance in determining most appropriate probability threshold. Importantly, the probability threshold is a management decision, however the temperature limit derived because of this decision should ideally lie within these ranges.

Table 4: Maximum weekly stream temperature range to support “good” CSCI and ASCI for standard and modified thresholds.

|  |  |  |  |
| --- | --- | --- | --- |
| Index | Threshold Value | Threshold Type | Maximum weekly temperature (°F) |
| CSCI | 0.79 | Standard | 87 |
| CSCI | 0.6 | Modified | 93 |
| ASCI | 0.86 | Standard | 82 |
| ASCI | 0.75 | Modified | 89 |

Through the probability analysis, temperature management targets can be established by choosing a probability threshold, or range of probabilities from the curve. The temperature target is based on the point where the probability threshold (on the Y axis, Figure 9) passes the curve (standard or modified) on the x axis (Figure 9). The probability threshold would be set by management, however for example, a 0.95 probability of achieving a 0.79 condition score, requires a stream temperature of 78°F or lower and a stream temperature of 81°F or lower to achieve a 0.6 condition score. In addition, we can derive the probability of achieving either the standard (0.9) or modified (0.96) condition, with a specific temperature threshold, i.e., 80°F.

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Figure 9: probability of achieving a “good“ CSCI score as a function of maximum weekly temperature for standard and modified index thresholds. Dashed blue line indicates the revised temperature objective (80F). Dashed black lines illustrate how to derive temperature limits according to probability threshold (0.95).

The model was assessed for goodness-of-fit (Table 5). Weekly maximum temperature emerged as highly significant across all models (CSCI, ASCI, Standard and Modified thresholds), indicating that stream temperature plays an important role in predicting the response of benthic communities. The R2 values show that stream temperature accounts for 14-15% of the variance in ASCI models, and 21-28% in CSCI models, with the standard CSCI model explaining the largest share of the variance. These findings affirm the importance of stream temperature in shaping benthic communities, however it is evident that the presence of other physical factors contribute to benthic community response, beyond the influence of temperature alone.

Table 5: Model goodness-of-fit metrics

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Index | Threshold | P-Value | McFaddens R2 | n |
| CSCI | Modified | <0.001 | 0.21 | 764 |
| CSCI | Standard | <0.001 | 0.28 | 764 |
| ASCI | Modified | <0.001 | 0.15 | 359 |
| ASCI | Standard | <0.001 | 0.14 | 359 |

#### Validation of the model

The validation of the probability analysis hinged on the utilization of accessible temperature data and bioassessment scores. It is important to note that spatial and temporal congruence between sites with continuous temperature data and bioassessment sites is imperative to ensure an accurate reflection of the temperature conditions encountered by the benthic community during the sampling period. In addition, sites with continuous temperature data, ideally for a full year, are necessary to enable the calculation of weekly maximum temperature metric used to develop the model.

From our compiled temperature data, only five sites met the specified spatiotemporal criteria. It's worth noting that continuous temperature data, obtained from the SMC database, was limited to the summer months (April to August). While these months align with the conditions observed during the sampling period, it's important to highlight a significant distinction: the metric used to develop the model, Weekly Maximum Temperature, is an average annual value that includes varied temperatures from other seasons, e.g., winter. Unfortunately, the average weekly maximum from the observed temperature data does not encompass winter temperatures. Consequently, this discrepancy undermines the accuracy of the comparison between the model and the observed temperature data. Furthermore, it's essential to acknowledge that the selected sites are located in mountainous regions (Figure 10), possibly characterized by more natural conditions. This geographical distinction raises concerns about the representativeness of these sites for the broader SGR study area.

Considering these details, a robust validation analysis was not possible. However, the approach and results for validation on the five selected sites is outlined in the appendix.

A map of a city

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Figure 10: Location of validation sites selected.

#### Assessing impact of elevated stream temperature on the benthic community

The model can be implemented to identify areas potentially affected by elevated stream temperature. By applying temperature management targets and adhering to the biological index thresholds detailed in Table 4, bioassessment sites in SGR were systematically classified into four distinct classes for both the modified and standard targets:

1. **No Impact**: Both the bioassessment index target and the temperature targets are successfully met
2. **Biology impact**: Bioassessment index target not achieved, but the temperature target is met. This suggests the presence of another physical factor influencing the index score
3. **Temperature impact**: Bioassessment index target is met, but the temperature target is not. In these cases, although temperature is high, it is likely not causing stress to the biological community.
4. **Both biology and temperature impacted**: Neither target is met, and low-scoring bioassessment index may be attributed to elevated temperatures.

The majority of sites in the SGR falls within the “No Impact” category (Table 6), indicating these sites to have “good” bioassessment scores and are within acceptable temperature limits. However, these sites are located in the upper SGR (Figure 11), where conditions are more natural and effluent discharge has no influence on the stream.

In the context of this study, the “Both biology and temperature impacted” (Both Impact) is of most interest, as these are the sites where stream temperature is potentially affecting the benthic community. The majority of sites in the lower SGR (Figure 11), although comprise all other categories, mostly consist of sites falling within the “Both Impact” class (Table 6). Temperatures are potentially higher here for a variety of reasons including urbanization, channelization, and effluent discharge, nonetheless it is these sites that may be the most sensitive to changes in temperature. Additionally, further downstream many of the sites are “Biology impacted” (Bio Impact), suggesting that temperature has reduced, however other physical factors are present that may be impacting bioassessment scores.

Table 6: Percentage of SGR bioassessment sites (n=124) in each impact category for modified and standard targets

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Type | No Impact (%) | Bio Impact (%) | Temp Impact (%) | Both Impact (%) |
| Modified | 69 | 16 | 6 | 10 |
| Standard | 53 | 15 | 3 | 29 |

A map of the los angeles area

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Figure 11: Bioassessment sites in SGR colour coded by impact category.

#### Recommendations

Following the literature review and exploratory analysis, we recommend the following to develop regional temperature relationships:

1. Focus on maximum weekly temperature as the primary temperature metric for assessing effects.
2. Use the overall stream condition indices CSCI and ASCI for biological response vs. the component metric values.
3. Derive standard and modified biological thresholds that are representative of the local system.
4. Use the quadratic linear regression on index score to develop preferred temperature range.
5. Use logistic regression on stream condition score to derive probability of achieving a “healthy” biological condition, with both standard and modified thresholds.
6. Implement the model to determine locations in the area potentially affected by elevated stream temperatures

#### Data limitations

The exploratory analysis revealed several challenges associated with data limitations:

1. Long term stream temperature observation data; accurately quantifying stream temperature regimes at different time scales across the region is of utmost importance to fully comprehend biological response to altered conditions. This, however, is not a trivial task as it would require a stream temperature monitoring network across the entire region, ideally spanning multiple years.
2. Spatiotemporal resolution in temperature data; limited to one value per year describing weekly summaries. Higher temporal resolution, at least to a seasonal scale, would provide understanding of the variation between winter and summer biological response. Additionally, expanding the model into other geographical areas within southern California would significantly increase data density, further improving the model and robustness of the assessment. These improvements are achievable through application of a broad-scale stream temperature model, which would utilize the available stream temperature observation data. This is a sizable task, however it could provide the necessary data much faster than with the collection of empirical observations.
3. Additional physical factors; including variables describing e.g., stream flow, channel engineering, substrate and shading would greatly improve model performance and predictive ability. Analyzing the predictive contribution of these different factors could also be helpful in recommending management actions. Regional flow and channel engineering data is available for Southern California, as well as variables related to shading. Adding these variables would require additional model development, however could be achieved in a relatively timely manner.
4. Biological traits: trait information was only available for a subset of species. Additional trait data will allow better quantification of stream temperature stress on life history needs of the benthic community, including response to seasonal and interannual changes. There are numerous benthic community studies in the primary and grey literature that measure or use life history traits related to stream temperature. A literature review would therefore be required to enhance the trait data, which could be completed in a relatively speedy manner. However, the use of traits is dependent on their transferability to the unique conditions of Southern California.

#### Conclusions

A temperature-ecology model was developed to formulate a methodology for determining stream temperature limits in relation to the benthic community. Appropriate biological indicators and stream temperature metrics were identified, as well as options for setting a modified bioassessment threshold. The model demonstrated effectiveness in explaining relationships such as identifying locations potentially impacted by elevated stream temperature. However, it may not possess sufficient strength for predictive applications necessary to determine temperature targets. Addressing the challenges posed by data limitations, especially the need for additional physical variables and enhanced spatiotemporal resolution in the modeled temperature input data, is crucial in addressing this limitation. Nevertheless, the outlined approach remains robust and intuitive, providing a valuable tool for understanding and assessing the interplay between stream temperature and the benthic community.

### Determine the sensitivity of benthic communities to varied temperature thresholds related to currently designated beneficial uses (WARM)

The sensitivity analysis will be completed once the regional relationship development has been finalized. Below describes the current workplan.

### Assess temperature impacts

The regional relationships, and biological thresholds, developed provide regional biology-focused temperature curves for benthic communities (Figure 12). The curves will be applied in the San Gabriel watershed to predict the ability of local stream temperatures to support beneficial uses. Predictions can be made using all available and appropriate temperature data within the drainage network. In addition, the regional curves will be validated using local temperature and biological conditions scores.

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Figure 12: Conceptual biological response to stream temperature under different physical conditions. The green area represents the critical temperature range needed to support the beneficial use related to the temperature threshold. The curves in this example represent different biological thresholds in the San Gabriel watershed.

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### Appendix

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Figure S1: Quadratic linear relationship between maximum weekly temperature and CSCI component metrics

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Figure S2: Quadratic linear relationship between maximum weekly temperature and ASCI component metrics

#### Validation of probability analysis method

The probability models were applied to predict the probability of attaining either the standard or modified bioassessment score based on the observed stream temperature. The continuous temperature data used were drawn from the collated dataset outlined in the main text.

Bioassessment validation sites, meeting specific criteria, were identified as follows:

1. They share the same COMID as the available temperature data.

2. They were sampled in the same year as the corresponding temperature data.

Ultimately, only five sites demonstrated a spatiotemporal match, satisfying both criteria for inclusion in the validation process.

For validation, the predicted probability was compared with the observed bioassessment score obtained from the validation sites. Probability ranges between 0 and 1, therefore, to facilitate a direct comparison the bioassessment values were standardized between 0 and 1. Here, a value of 1 represents the standard or modified threshold, e.g., 0.6 or 0.79 for CSCI. The probability was then plotted in an observed versus expected figure (Figure S3). This figure provides a visual assessment of how well the predicted probabilities align with the actual bioassessment scores, offering insights into the model's performance. Ideally, points would be close to the 45 degree line, showing the values to be similar.

The validation shows that the model predicts mixed results in terms of accuracy. However, this is likely due to several discrepancies in the observed data versus the data used to build the model (outlined in the main text). Therefore, it is suggested that additional data that adheres to the validation criteria is needed to provide a robust validation, i.e., continuous temperature for a full year that are located in the SGR or in similarly altered conditions.

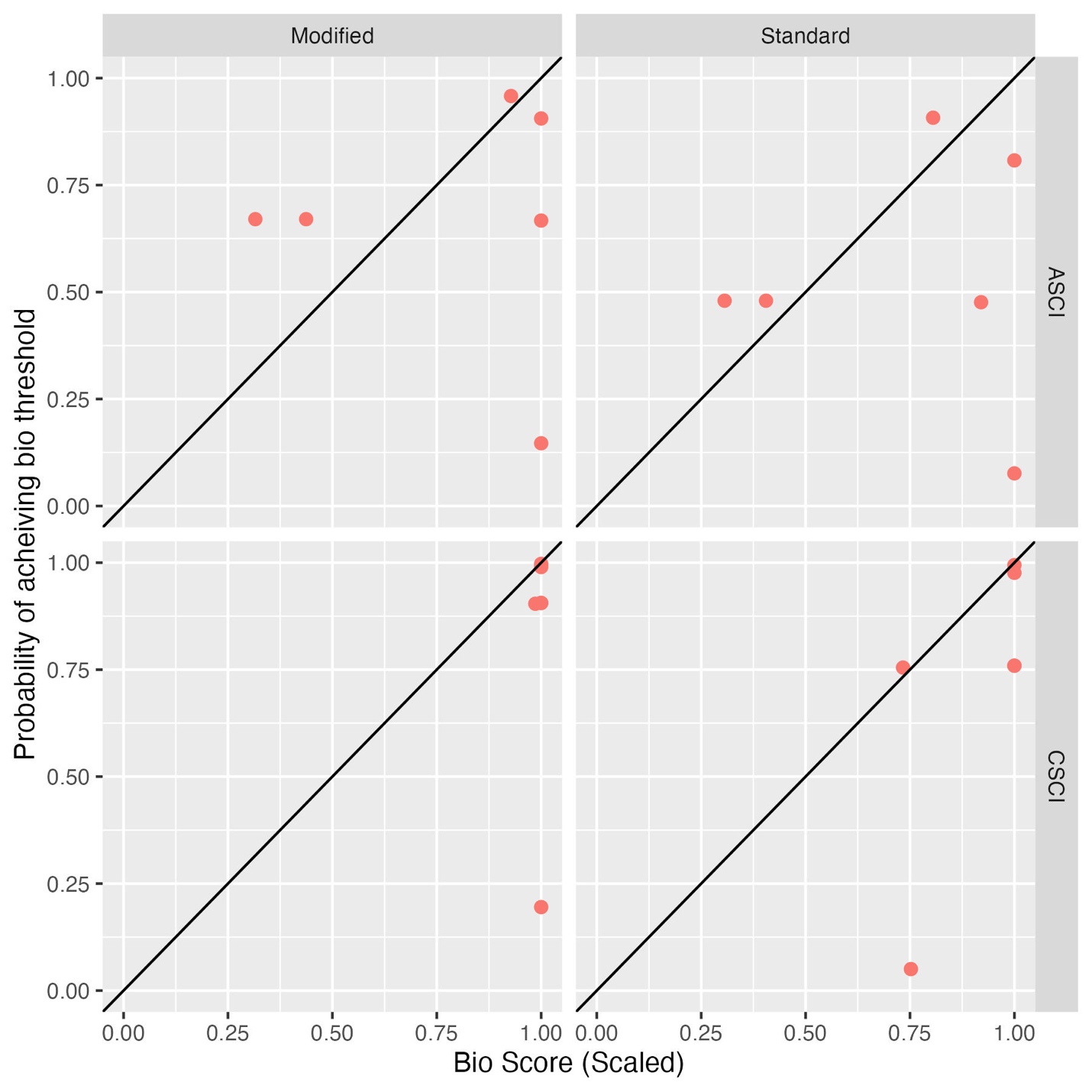


Figure S3: Validation of probability of achieving a bioassessment threshold given observed temperature data at selected validation sites (n=5)

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