The Stream Condition Index: A Multi-Indicator Tool For Enhancing Environmental Management Communication

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# Methods

## General Approach

The SQI is a conceptual approach to describing stream health that is based on a stressor-response relationship between biology and in-stream stressors (Figure 1). Using these relationships, the index provides a categorical description of overall stream health to support high-level management decisions, while also providing descriptions of the biological, chemical, and physical components that establish the foundation of the index to further evaluate which factors may be driving stream health. These tiers of information represent overall stream health, biological health, and stressor condition as single, actionable categories. The underlying stressor-response relationships that define the categories are based on empirical models that quantify an expected likelihood of chemical or physical stressors impacting the separate components of biological condition. Scientists and managers can easily access different components of the SQI depending on the desired level of information within the stressor-response paradigm.

We selected water chemistry stressors that are strongly associated with biological condition in perennial streams, namesly nutrients and conductivity. Likewise, we selected physical habitat metrics that quantified flow, channel, and riparian condition observed at a site. Although physical habitat can be considered a response metric of stream health depending on the context, physical habitat herein is considered a stressor that can affect biological condition at different taxonomic levels within the stressor-response model.

## Biological response components of the SQI

### Characterizing biological condition

The stressor-response model used by the SQI uses biological endpoints as indicators of beneficial uses for wadeable streams and water chemistry and physical habitat measurements as stressors that are empirically linked to biological condition. Because biological indicators provide direct measures of aquatic life, whereas physical and chemical measures provide ancillary information about the stressors that may affect aquatic life, it was crucial to combine these indicators in a way that preserved the types of information provided by each (as opposed to treating them as equivalent lines of evidence that could be “averaged”" to assess overall condition).

We used quantitative bioassessment indices as measures of biological condition. Bioassessment indices for benthic macroinvertebrates and algal communities have been developed for California streams (Mazor et al. [2016](#ref-Mazor16); Theroux et al., [n.d.](#ref-Therouxip)) and both indices are used as complementary lines of evidence within the SQI. Analysis of multiple assemblages provides a more comprehensive indication of biological condition that can confirm overall stream health and may also provide additional diagnostic information about stressors (as different communities may respond to different characteristics of stream habitat).

Biological responses were measured as two biological indices previously developed for California wadeable streams. First, the California Stream Condition Index (CSCI, Mazor et al. ([2016](#ref-Mazor16))) is a predictive index that compares observed benethic macroinvertebrate taxa and metrics at a site to those expected under least disturbed reference conditions (sensu Stoddard et al. ([2006](#ref-Stoddard06))). Expected values at a site are based on models that estimate the likely macroinvertebrate community relative to factors that naturally influence biology (Moss et al. [1987](#ref-Moss87); Cao et al. [2007](#ref-Cao07)). Second, the Algal Stream Condition Index (ASCI, Theroux et al. ([n.d.](#ref-Therouxip))) was similarly developed as a response endpoint for lower trophic levels; the ASCI is a non-predictive multi-metric index (i.e., it uses a uniform, statewide reference expectation) that incorporates both diatoms and soft-bodied algae. Scores for both indices can range from 0 to ~ 1.4, with a score of 1 at sites in reference condtion and lower values indicating biological degradation. Both indices are used as standard assessment measures for perennial wadeable streams in California.

Index scores were compared to the distribution of scores at reference sites to assign BMI and algal samples to biological condition classes that described the likelihood of biological alteration. For both the CSCI and ASCI, the 1st, 10th, and 30th percentiles of scores at reference sites were used to categorize sites as very likely to have altered biological condition (ref 4, scores less than the 1st percentile), likely altered (ref 3, scores between the 1st and 10th percentile), possibly altered (ref 2, scores between the 10th and 30th percentiles), and likely intact (ref 1, scores greater than the 30th percentile) (Table 1). This produced four classes for each index such that each site had two categories describing separate lines of evidence of the likelihood of biological alteration in the benthic macroinvertebrate and algal communities. Both lines of evidence were jointly considered by the SQI for evaluating overall biological condition, described below.

### Integrating multiple measures of biological condition

The assigned biological condition categories for each index were combined using a ranking system to create a single numeric value that represents an overall condition reflected by both biological indices. These values were assigned based on the judgment of stakeholders, in accordance with several principles. First, the two indices should be independently applicable, so that an indication of good health in one index cannot negate indications of poor health in the other. Second, the numeric values should be sensitive to differences between sites in marginal or extreme conditions. For example, the numeric value for a sample where both indices indicate likely intact biological communities will be higher than for a sample where one index indicates likely intact and the other indicates possibly altered. This sensitivity improves detection of small changes in condition. The final numeric values ranged from -4 to +4 (Table 1). All negative values indicate impacted conditions.

## Stressor components

### Characterizing stress

Water chemistry and physical habitat measurements were used to describe stressors associated with low CSCI and ASCI scores (Mazor [2015](#ref-Mazor15); Theroux et al., [n.d.](#ref-Therouxip)) and have a conceptual relationship with both invertebrate and algal assemblages (Richards et al. [1997](#ref-Richards97); Pan et al. [2002](#ref-Pan02); Wang, Robertson, and Garrison [2007](#ref-Wang07)). The water chemistry indicators included total nitrogen (mg/L), total phosphorus (mg/L) and specific conductivity (S/cm). Nitrogen, phosphorus, and conductivity are widely measured in many regional and statewide monitoring programs and collectively act as surrogates for unmeasured or alternative water quality problems at a site (e.g., temperature, light penetration). Although other contaminants that can affect aquatic organisms are sometimes measured (e.g., metals, pesticides, pharmaceuticals), observations can be sparsely distributed in the study region (Mazor [2015](#ref-Mazor15)) and contaminants often co-occur with elevated nutrients or specific conductivity. As such, the selected indicators may be an effective proxy for other unmeasured water quality stressors in southern California.

Physical habitat conditions at a site were described using two indices of habitat condition developed for California: the Index of Physical-Habitat Integrity (IPI, Rehn, Mazor, and Ode ([2018](#ref-Rehn18))) and the California Rapid Assessment Method for riverine wetlands (Collins et al. [2007](#ref-Collins07); Solek, Stein, and Sutula [2011](#ref-Solek11)). The IPI is based on physical habitat metrics that characterize five components of in-stream habitat quality: physical habitat metrics (PHAB, (Rehn, Mazor, and Ode [2018](#ref-Rehn18))) and scores from the California Rapid Assessment Method (CRAM). The IPI is based on physical habitat metrics that characterize five components of in-stream habitat quality: percent sands, fines, or concrete (%SAFN), Shannon diversity of aquatic habitat types (H\_AqHab), Shannon diversity of natural substrate types (H\_SubNat), evenness of flow habitat types (Ev\_FlowHab), and riparian vegetation cover (XCMG). All of the metrics are positively associated with physical habitat integrity such that an increase in each was generally considered an improvement in site condition. The exception is percent sands and fines where an increase is more commonly associated with degraded physical conditions (e.g., bank instability, watershed erosion). All physical data used to calculate these metrics were collected using standard field protocols described in Ode ([2007](#ref-Ode07)), which are derived from protocols used in national assessments (USEPA (US Environmental Protection Agency) [2016](#ref-USEPA16)). As with the CSCI, the IPI is a predictive index, and values for most metrics are compared to site-specific expectations appropriate for the stream’s environmental setting. The IPI also ranges from 0 to ~1.4, with values less than 1 indicating departure from reference conditions.

In contrast to the IPI, CRAM is based on qualitative assessments of four attributes of riparian wetland function: landscape and buffer condition, hydrologic condition, physical structure, and biotic structure. Whereas the data for the IPI is derived from numerous quantitative measurements of physical habitat components collected along several transects, CRAM attributes are assessed on a whole-reach scale through visual observation. In general, CRAM characterizes larger-scale processes affecting stream condition both within and adjacent to the stream corridor, whereas the IPI focuses more narrowly on in-stream conditions. CRAM scores range from 25 to 100, with higher values indicating less degraded conditions at a site.

### Integrating multiple measures of stress

The combined impact of habitat or chemistry stressors on biological condition was evaluated by developing stress-response models that calculate the probability of observing poor biological conditions given observed levels of chemical or habitat stress. This approach eliminates the need to identify potential thresholds for identifying high levels of stress while also accounting for their combined impacts.

For both types of stress, a generalized linear model (Fox and Weisberg [2011](#ref-Fox11)) was fit to calibration data to quantify assocations for each separate water quality or physical habitat measure with binomial categories for altered or unaltered biology. Two models were developed:

where is the probability of biological alteration in equations (1) and (2) given the indicators for each chemistry or physical habitat variable. The probability of alteration is modelled using a logit link function for binomial variables, as , where defines the presence or absence of altered biology described above.

An overall likelihood of biological alteration from both chemistry and physical habitat stressors was also estimated as a multiplicative function for and :

The inverse of the likelihoods was used to represent an additive effect of both chemisty and physical habitat stressors. Equations (1), (2), and (3) provided the empirical estimates of biological alteration that were used to define the categorical outputs of the SQI, defined below.

## Combining stress and response measures into an overall Stream Quality Index (SQI)

The empirical framework for the binomial models and combined biological condition categories established a basis for the categorical descriptions from the SQI output. These descriptions linked the quantitative data to management actions such that the results were easily interpreted with an indication of biological condition and the relevant stressors which may or may not be related to condition. For the components in figure 1, categorical outputs are provided by the index for the overall SQI, the biological condition, and the stress condition (figure 2). The categorical outputs were created from a matrix combination of the respective inputs. For example, the overall SQI categories describe the four possible combinations of biology and stressors at a site from the binary categories of altered/unaltered biology and stressed/unstressed conditions: healthy and unstressed, health and resilient, impacted by unknown stress, and impacted and stressed.

Separate categorical outputs were also created for the biological condition and stressorcondition categories. The four possible outputs for the biological categories were based on the four combinations from the binary categories of high/low CSCI and high/low ASCI: healthy, impacted for CSCI, impacted for ASCI, and impacted for both. The possible stressor condition categories for a site were based on the four outcomes of the binary combinations of high/low chemistry stress and high/low physical habitat stress: low stress, stressed by chemistry, stressed by habitat, and stressed by both. A fifth stress category was also possible based on the additive combinations of low chemistry and low habitat stress if exceeded the threshold even though and did not. Thresholds for biological indices that defined high/low condition were based on the tenth percentile distribution of scores at reference sites for each index. Thresholds for high/low stress were based on the median likelihood across all sites.

## Application

All data for the SQI were from the Stormwater Monitoring Coalition (SMC) regional monitoring program in southern California (Mazor [2015](#ref-Mazor15)). This coalition represents multiple state, federal, and local agencies that have a shared mission of stormwater management for over 7000 stream kilometers in the region. The SMC initiated a regional monitoring program in 2009 to assist, in part, with the permitting process among dischargers from the member agencies. Central monitoring questions focus on assessing biological condition, identifying stressors associated with poor condition, and evaluating trends over time. This dataset represents the most comprehensive source of stream data in Southern California. Because the SQI requires synoptic biological, chemistry, and physical habitat data, the final dataset used for model calibration represents a subset of the SMC dataset where all three components were simultaneously collected. This included 266 sites, 75% of which were used for model calibration. Sampling dates ranged from 2009 to 2016 with relatively even distribution of samples between years. Most sample events occurred between May and June following standard protocols for perennial stream surveys (Ode [2007](#ref-Ode07)).

Finally, precision and sensitivity of the SQI was evaluated to describe 1) how well the underlying empirical model described the likelihood of biological alteration, and 2) sensitivity of the model output to changing thresholds that defined the categorical conditions. The first analysis evaluated precision in the validation dataset for the SQI to determine agreement between the model and actual stress and biological conditions. The second analysis evaluated the change in results for the regional database that were caused by changing the categorical thresholds that defined which categories for the SQI were assigned to each site. For example, the percentage of sites ranked as healthy and unstressed was compared by evaluating a change in the biological threshold for altered/unaltered biology, e.g., at 1%, 10%, or 30% of reference scores for each index.

# Results

Among all sites, the overall SQI categorized a majority as having altered biology under high stress conditions (impacted and stressed, 75% of sites, Table 2). Just over 5% of sites were in the opposite category of unaltered biology in low stress conditions (healthy and unstressed). For the remaining two categories of the overall SQI, nearly 20% of sites had unaltered biology but were under high stress conditions (healthy and resilient), whereas less than 1% of sites had altered biology not related to physical or chemical stressors (impacted by unkown stress). For the biological condition category, sites with altered conditions were more often altered for both CSCI and ASCI scores (47%). For sites with one low scoring index, more sites were altered for the ASCI (23%) than the CSCI (7%). Less than a quarter of all sites had unaltered biology (23%). For stress conditions, over 75% of sites were stressed by both chemistry and physical habitat stressors. More sites were stressed by habitat degradation (11%) than water chemistry (4%) if only one stressor was present. Only 6% of sites had low stress, wheres 3% of sites were impacted by the additive effect of both low chemistry and physical habitat stressors.

Spatial patterns among SQI categories in Southern California generally followed elevation and land use gradients (Figure 3). More altered biological communities and high stress conditions were observed toward coastal areas in the lower watersheds and where urbanization is highest (e.g., Los Angeles, Orange County, Ventura, San Diego). Sites with altered biological condition showed similar spatial patterns as the overall SQI, although sites altered only for the ASCI were more often observed at mid-elevation in northern and southern locations in the study area. Stress condition patterns were similar to biology although low stress conditions were confined to the extreme northeast region of the study area, whereas healthy biological conditions were observed at a wider range of locations but still generally confined to high elevation. High stress conditions were also observed across a wider elevation gradient than biological alteration, i.e., resilient biological comunities in the presence of high stress were not uncommon (Table 2).

The underlying empirical models provided insight into instream characteristics that were related to he likelihood of biological alteration (Figures 4, 5). Seventy percent of sites (n = 171) had a greater than 50% likelihood of biological alteration from water chemistry stressors and 79% (n = 187) had a greater than 50% likelihood of biological alteration from physical habitat stressors (Figure 4). Collectively, 90% of sites had a greater than 50% likelihood of biological alteration from the overall stress of both chemistry and physical habitat stressors.

Figure 5 demonstrates how the individual components for each stressor model were related to likelihood of alteration. These partial dependency plots were created by estimating the likelihood of alteration across a range of values for each predictor while holding other predictors constant. For each plot, the variables not on the x-axis were held at approximate values that were associated with low stress to better understand how biological alteration may be related to each predictor. For water chemistry stressors, all were positively associated with likelihood of alteration, particularly total phosphorus which had the steepest increase in likelihood per unit increase of nutrients. Associations of biological alteration with physical habitat predictors were more variable. The strongest relationship was observed with increases in CRAM scores, where likelihood of alteration decreased sharply with CRAM scores greater than 50. Other predictors showed expected associations with alteration but were not as strong as for CRAM, e.g., increases in substrate diversity were associated with improved biological condition. Percent sands and fines was the only physical habitat variable that showed a positive assocation with likelihood of biological alteration.

* SQI performance metrics
  + Precision
  + Any others?
* Percent So Cal stream miles or site frequency in each category
  + As a set up for the value of the categorical scoring
* Overall agreement among stressor indicators
  + As a set up for do we need multiple indicators?
* Overall agreement among response indicators
  + As a set up for do we need multiple indicators?
* SQI trends either overall or at example sites

# Figures



Figure 1 Flowchart representation of the Stream Quality Index (SQI). The overall SQI is a function of the likelihood of observing degraded biological condition given the stressors at a site. Biological condition is assessed using macroinvertebrate (California Stream Condition Index, CSCI) and algal (Algal Stream Condition Index, ASCI) indices and stressors are evaluated based on water quality measures (total nitrogen, total phosphorus, conductivity) and physical habitat (California Rapid Assessment Method or CRAM, physical habitat metrics or PHAB). Stress condition is empirically linked to bilogical condition by separate probability functions for chemistry (pCHem) and physical habitat (pHab).



Figure 2 Categorical site descriptions that are possible from the Stream Quality Index (SQI). The overall SQI is described as the possible outcomes from biological and stress conditions. The biological conditions are described by the possible outcomes from the CSCI and ASCI. The stress conditions are described by the possible outcomes from the chemistry and habitat stressors. A fifth stress category is possible because stress from both chemistry and habitat was multiplicative.

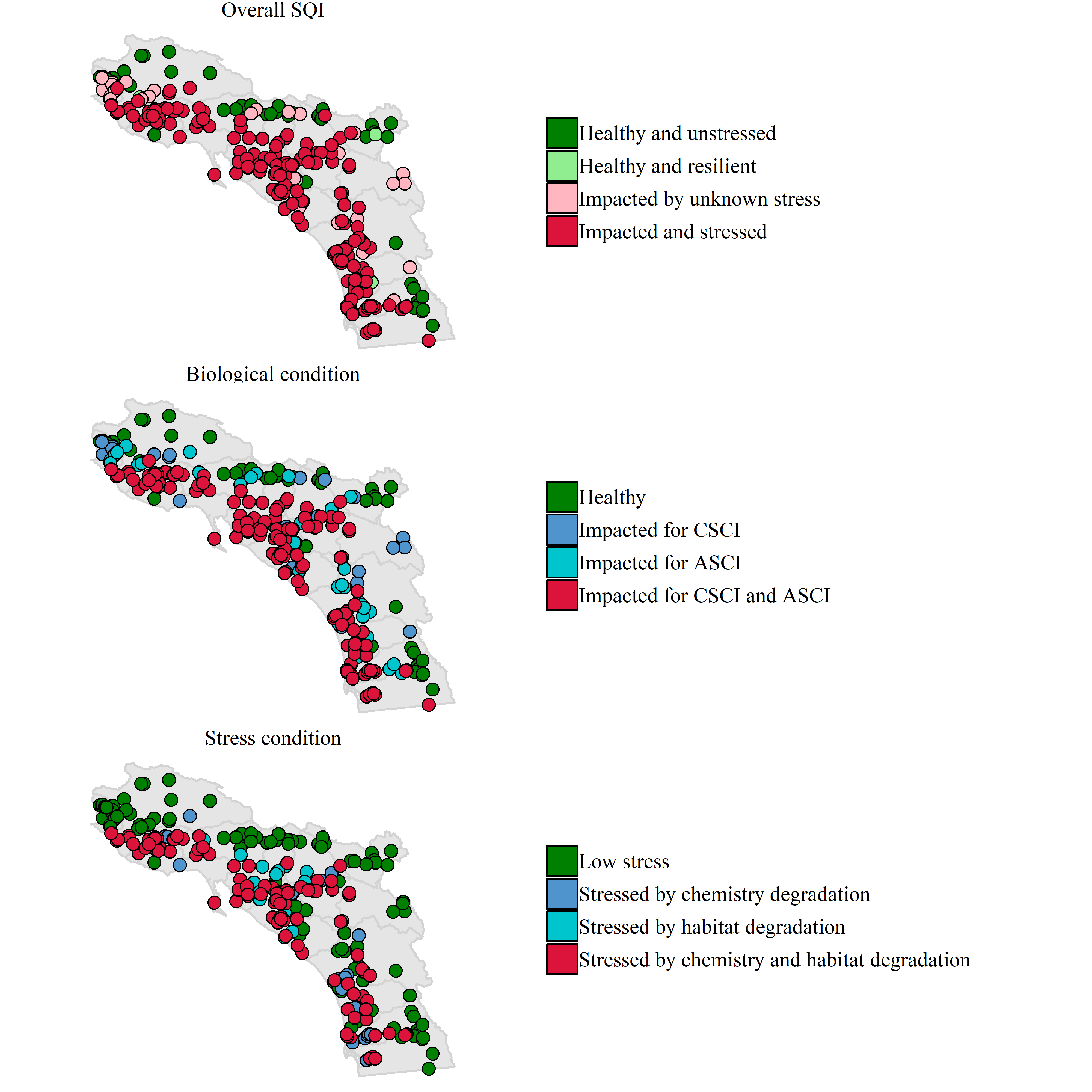


Figure 3 Categorical site descriptions for the Stream Quality Index (SQI) at monitoring sites in Southern California. The overall SQI (top) is described as the possible outcomes from biological (middle) and stress conditions (bottom). The biological conditions are described by the possible outcomes from the CSCI and ASCI. The stress conditions are described by the possible outcomes from the chemistry and habitat stressors.

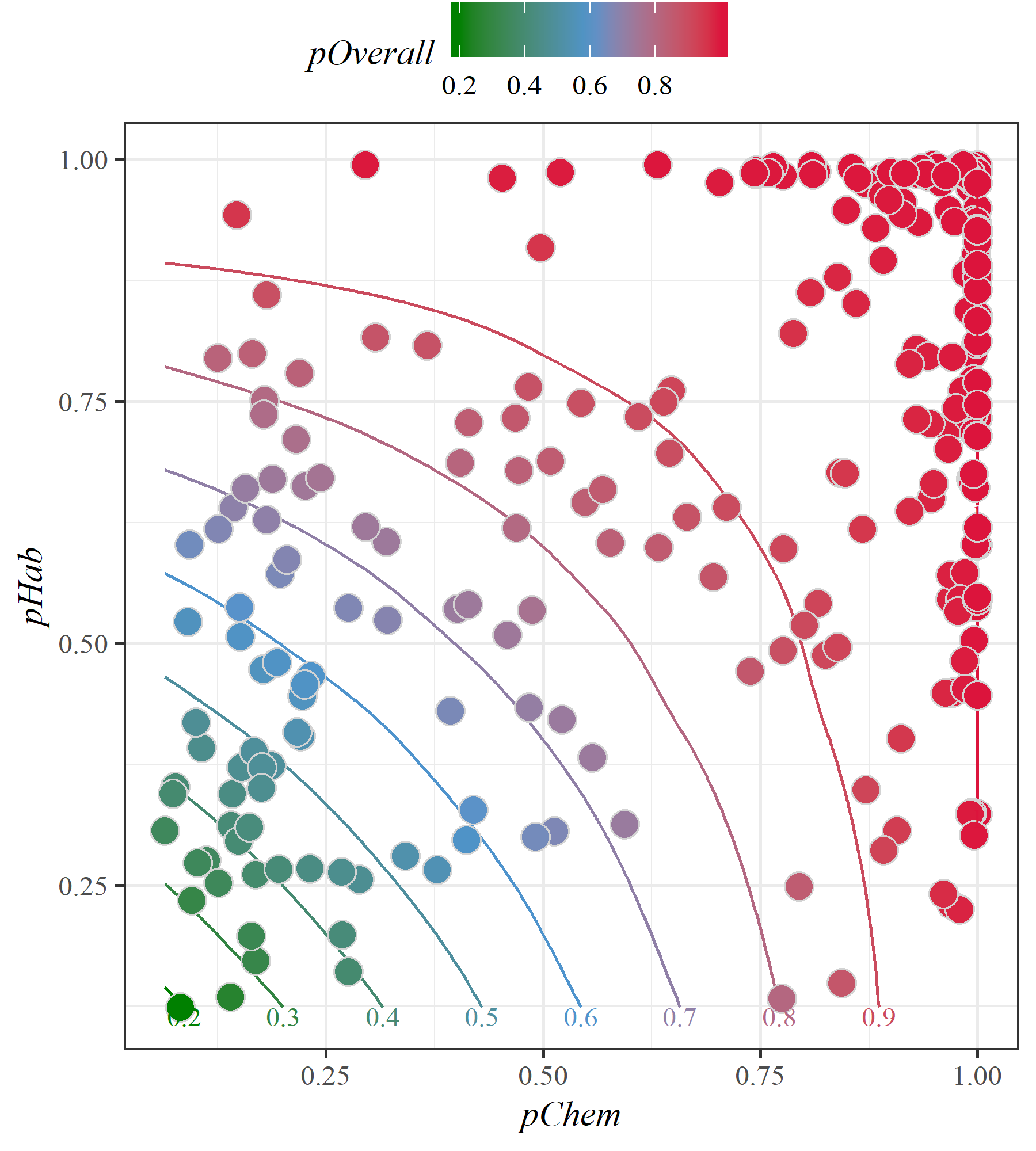


Figure 4 Relationship between stress models for water chemistry (*pChem*, eqn. (1)) and physical habitat (*pHab*, eqn. (2). Stress models for water chemistry and physical habitat were created based on the likelihood of biological alteration for the observed stress measures. The overall stress meaures (*pOverall*, eqn. (3)) is the product of both stress models. Points represent estimated stress at a single site.

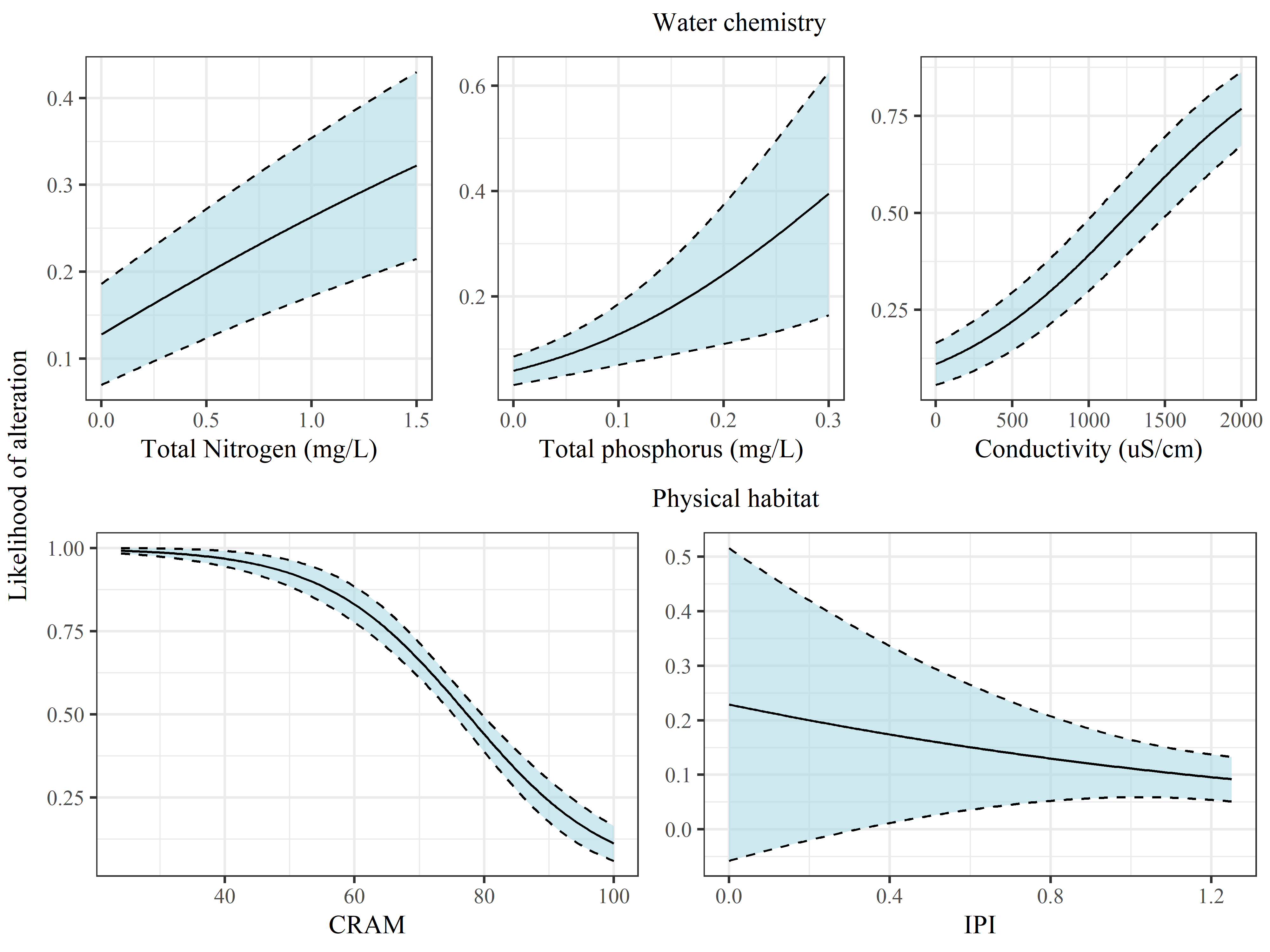


Figure 5 Modelled likelihood of biological alteration from water quality (top) and physical habitat stressors (bottom). Curves are the binomial likelihood (+/- standard error) of biological condition being altered (as measured by macroinvertebrate and algal indices) across the range of observed values for water quality and physical habitat stressors on the x-axes. The water chemistry and physical habitat stress plots are derived from equations (1) and (2). Other variables in each model not on the x-axis for each plot are held constant at values for low stress conditions.

# Tables

Table 1 Combined biological condition categories for the benthic macroinvertebrate (BMI) and algal indices. The combined categories were used to model the likelihood of biological alteration given observed physical and chemical habitat stressors. Sites with combined categories greater than zero were considered biologically healthy and those less than or equal to zero were considered biologically impacted (i.e., response variable in equations (1) and (2)). Individual biological categories for the BMI and algal indices were based on percentile distributions of scores at reference sites, i.e., 1st, 10th, and 30th percentiles. The scores associated with the percentiles for each index (CSCI, ASCI) are in parentheses.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | Algae ref 1: (ASCI > 0.93) | Algae ref 2: (ASCI 0.83 - 0.93) | Algae ref 3: (ASCI 0.70 - 0.83) | Algae ref 4: (ASCI < 0.70 |
| BMI ref 1: (CSCI > 0.92) | 4 | 1 | 0 | -1 |
| BMI ref 2: (CSCI 0.79 - 0.92) | 1 | 1 | -1 | -2 |
| BMI ref 3: (CSCI 0.63 - 0.79) | 0 | -1 | -2 | -3 |
| BMI ref 4: (CSCI < 0.63) | -1 | -2 | -3 | -4 |

Table 2 Counts of sites in each of the categorical outputs from the SQI. For every SQI output (biological condition, overall SQI, stress condition), a site is categorized as one of four possible outcomes.

|  |  |  |
| --- | --- | --- |
| SQI output | Category | Count (percent) |
| Overall SQI | Healthy and unstressed | 54 (20.3) |
|  | Healthy and resilient | 6 (2.3) |
|  | Impacted and stressed | 171 (64.3) |
|  | Impacted by unknown stress | 35 (13.2) |
| Biological condition | Healthy | 60 (22.6) |
|  | Impacted for ASCI | 43 (16.2) |
|  | Impacted for CSCI | 29 (10.9) |
|  | Impacted for CSCI and ASCI | 134 (50.4) |
| Stress condition | Low stress | 122 (45.9) |
|  | Stressed by chemistry and habitat degradation | 93 (35) |
|  | Stressed by chemistry degradation | 32 (12) |
|  | Stressed by habitat degradation | 19 (7.1) |

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