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A study of the effect of physical and chemical stressors on biological integrity within the San Diego hydrologic region

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Abstract Environmental agencies across the United States have searched for adequate methods to assess anthropogenic impacts on the environment. Biological assessments, which compare the taxonomic composition of an aquatic assemblage to relevant biocriteria, have surfaced as an effective method to assess the ecological integrity of US waterbodies. In this study, bioassessment data were collected and analyzed in conjunction with physical habitat and chemical stressor data for streams and rivers within the San Diego basin from 1998 through 2005. Physical stressors such as sediment loading, riparian destruction, and in-stream habitat homogenization affect many locations in the region. However, physical habitat measures alone were found to frequently overestimate the biological integrity of streams in the region. Many sites within the San Diego Basin, although unaffected by physical stressors, continue to exhibit low biological integrity scores. Sites with low biological integrity tend to possess higher specific conductance and salinity compared to sites with high biological integrity. We suggest that one possible reason for these differences is the source water used for municipal purposes.

Keywords Biological integrity · Chemical and physical stressors · SoCal B-IBI · Benthic macroinvertebrates

Introduction

Assessing the physical, chemical, and biological integrity of a waterbody is a challenging task. Water quality criteria which rely on water chemistry measures in ambient waters or effluent have not adequately addressed the effects of multiple stressors and non-point source pollutants on the biological integrity of the nation's waters. Thirty-

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seven years after the Clean Water Act was passed, a significant number of waterbodies are still listed as impaired for multiple constituents. National assessments of biological condition demonstrate a failure to fully attain aquatic life uses in as many as 41.9% of evaluated waterbodies (NRC 2001; Karr and Chu 1999; US EPA 2006). Thus, chemically focused management initiatives have not adequately protected aquatic life in the nation's waters (Copeland 2002).

Biological criteria (biocriteria), however, have shown to be an effective solution to this dilemma. Biocriteria are a collection of narrative descriptions and/or numerical values which describe the ecological qualities that a waterbody should possess to be considered fully functional (US EPA 2007). Data from biological assessments (bioassessments), direct measures of the taxonomic composition of aquatic assemblages, such as benthic algae, riparian vegetation, invertebrates, and fish, can be judged against relevant biocriteria to determine whether a waterbody is attaining its designated uses for aquatic life (US EPA 2002). Since changes in the physical and chemical integrity of a waterbody are reflected within the aquatic community over time, biological assessments encompass chemical, physical, and biological condition within one comprehensive measure (Karr and Chu 1999).

Recently, multimetric indices have become one standard for accurately developing biocriteria to assess watershed health (US EPA 2006). Multimetric indices measure the level of impairment against minimally disturbed reference sites by calibrating and scaling ecological attributes along disturbance gradients (e.g., on a scale of 1 (maximally impaired) to 10 (minimally impaired)) and then aggregating these scores into an index. Kerans and Karr (1994) pioneered using benthic macroinvertebrates (BMI) as the basis for constructing multimetric indices of biotic integrity (IBI) in the Tennessee Valley. IBIs using the BMI assemblage, similar to those developed by Kerans and Karr (1994), have several advantages including: the ubiquity of BMI in most streams, the presence of BMI in a wide diversity of in-stream habitats, the prominence of BMI in the processing of organic material, and the intermediate position of BMI between primary producers and higher trophic levels (Rosenberg and Resh 1993). Analyzing BMI communities can provide a valuable understanding of a stream's condition over time because many BMI species live in the stream throughout the year and sometimes over multiple years (Rosenberg and Resh 1993). Mebane (2001) reported the successful correlation of multimetric indices based on BMI to common stream disturbances, such as stream habitat alteration, excessive sediment, and elevated metal concentrations. Furthermore, Wang and Lyons (2003) identified that the biological response signature of BMI could be used to detect stream degradation within urbanizing watersheds.

Urbanization brings about significant degradation to the chemical, physical, and biological integrity of a watershed (Paul and Meyer 2001; Walsh et al. 2005). A waterbody's physical integrity can be compromised by such human influences as straightening, dredging, damming, and water withdrawal for agricultural, industrial, and domestic uses, while its chemical integrity can be compromised by both point source discharges and diffuse non-point source effects. Such human influences prevent a waterbody from being able to support a fully functioning complement of aquatic organisms. Thus, it is critical to link biological impairment with the anthropogenic physical and chemical stressors present in urban streams. Therefore, when bioassessment samples are taken, a visual physical habitat assessment is performed to assess "the structure of the surrounding physical habitat that influences the quality of the water resource and the condition of the resident aquatic community" (Barbour et al. 1999). The visual habitat assessment developed by Plafkin et al. (1989) and extended by Barbour and Stribling (1992, 1994) comprises ten individual metrics which are rated by those collecting the sample on a scale from 0 (low-quality habitat) to 20 (high-quality habitat). In addition, basic water chemistry measurements, such as pH, dissolved oxygen (DO), salinity, and specific conductance are also taken.

Recognizing the widespread effect of urbanization on streams in Southern California, Ode et al. (2005) developed the Southern California benthic macroinvertebrate index of biological integrity (SoCal B-IBI) as a tool for ascertaining the biological integrity of running waters in the Southern California coastal region. Bioassessment data were compiled for streams within the San Diego hydrologic region between 1998 and 2005 and compared to the SoCal B-IBI benchmarks (Viswanathan et al. 2010). To our knowledge, no comprehensive work has been undertaken to correlate physical and chemical stressors with biological integrity in the San Diego hydrologic region. This study, therefore, seeks to establish the relative impact and correlation between possible physical and chemical stressors and SoCal B-IBI scores.

Materials and methods

This research analyzed physical habitat and basic chemical stressor data that was compiled from 526 bioassessment samples within the San Diego Hydrologic Region. The samples were collected at 146 distinct sampling locations by different agencies via several sampling initiatives between 1998 and 2005. The region from which these samples were collected is located in the southwestern corner of California and occupies approximately 10,000 km^2. The hydrologic region is divided into 11 hydrologic units, each of which experiences unique water quality concerns.

The majority of the bioassessment data (285 samples) were collected by the San Diego Regional Water Quality Control Board from 1998 to 2001. Stormwater monitoring data, comprising 153 samples, were collated from municipal National Pollutant Discharge Elimination System reports from San Diego and Orange counties from 2002 to 2005. The Surface Water Ambient Monitoring Program (SWAMP), a statewide program initiated in 2000 to assess surface water conditions in California, supplied 88 samples that were taken during the 2003–2005 period. In total, the data set includes 526 bioassessment samples from the three sources. Although this study has attempted to collate all known available data, it is possible that it could have excluded some data either because the sources of that data were unknown or because they did not meet the necessary standards for taxonomic level of effort or number of organisms in the sample. The physical habitat assessment scores from 385 of the cases were collated, and basic water chemistry (pH, DO, specific conductance, and salinity) from roughly 150–225 sites was measured. An advanced geospatial decision support tool (Ecolayers 2007) was used to combine sites with different site identification codes that corresponded to the same geographic location.

The benthic macroinvertebrate samples analyzed in this study were collected by a variety of agencies using several different procedures that have been detailed in the California Stream Bioassessment Procedure (Harrington 1999), Environmental Monitoring and Assessment Program (Stoddard et al. 2005), and the SWAMP (California EPA 2011). Recent studies in California have indicated that different sampling protocols generally provide consistent measures of biological condition (Herbst and Silldorff 2006; Rehn and Ode 2007). The SoCal B-IBI (Ode et al. 2005) was then calculated for all samples (Viswanathan et al. 2010). One exception to the SoCal B-IBI classification system was to include the division of each individual metric score into similar ranges (0–1 = “very poor”; 2–3 = “poor”; 4–5 = “fair”; 6–7 = “good”; 8–10 = “very good”). Additionally, the physical habitat scores were recorded using the standard scoring ranges reported by Barbour et al. (1999). The composite scores were then converted into a similar categorization by extrapolating the midpoints between the ranges of individual measures to the composite score (0–54 = poor, 55–106 = marginal, 107–160 = suboptimal, 161–200 = optimal). The suboptimal and optimal categories were defined as having unimpaired physical habitat, while the marginal and poor categories were defined as having impaired physical habitat. Statistical analysis of data was performed using a combination of SPSS Version 15.0 and Microsoft Excel. Graphical analysis was performed using Excel, SPSS, and Ecolayers 1.0.

Results and discussion

Physical habitat metric analysis

Before analyzing the effect of physical and chemical stressors on biological integrity, the internal consistency of the physical habitat score was analyzed by exploring the answer to three main questions:

- Are the individual metrics that compose the total score redundant or unique?
- Are the scores of individual metrics in each index able to differentiate impaired sites?
- Does the analysis of individual measurements and site averages provide similar results?

The visual habitat assessment developed by Plafkin et al. (1989) and extended by Barbour and Stribling (1994) comprises ten individual metrics which are rated by those collecting the sample on a scale from 0 (low-quality habitat) to 20 (high-quality habitat): sediment deposition, channel flow status, channel alteration, embeddedness, riffle frequency, epifaunal substrate, vegetative protection, velocity depth regimes, riparian vegetative zone width, and bank stability. When looking at the pairwise correlation coefficients between component physical habitat metrics, the majority (93% for measurements; 84% for site averages) were positively correlated at $\alpha = 0.05$ level of significance. However, the majority of these correlations (75% for measurements; 62% for site averages) had a value less than 0.5. This finding indicates a lack of strong correlation on the whole even though moderate correlation exists among the component metrics. This suggests that all component metrics should be utilized to predict whether a site is physically impaired. The same conclusion was reached regardless of whether individual measurements or site averaged data were used (Pohlman and Voss 2008).

To further explore whether individual component metrics were redundant or unique, the distributions of the ten individual metrics were compared using Kendall's W, a nonparametric statistic (Legendre 2005) which is often interpreted as the level of concordance among ratings ($0 =$ no concordance, $1 =$ perfect concordance). The Kendall's W statistic was significant at the 0.05 level for the ten metrics on the measurement level (0.239) and on the site average level (0.344). Since the physical habitat condition category (i.e., optimal, suboptimal, marginal, poor) is of specific interest, the category assignment with the Kendall's W statistic was also tested. The concordance level was found to be slightly higher for measurements (Kendall's $W = 0.402$) than for site averages (Kendall's $W = 0.278$). These values indicate that there is roughly 25% to 40% concordance between the component metric ratings. The low level of concordance among component measures suggests that all of the metrics are needed to indicate physical impairment of a site.

To provide further evidence that each component metric is necessary to assign physical habitat condition, a discriminant analysis (Corder and Foreman 2009) was performed on a random sample of 70% of the measurements with physical habitat data ($N = 261$). Table 1 shows the standardized coefficients for the model built in this study. All parameters except bank stability have significant effect on classifying physical habitat impairment; sediment deposition, channel flow status, and channel alteration seem to have the most influence in physical habitat impairment classification. The model was then used to classify the remaining 30% measurements ($N = 114$) with 94% success. The fact that nine out of ten parameters have significant influence in the classification of physical habitat impairment confirms that all should be included in a summary statistic of the measure.

The analysis concerning whether individual metrics are significantly different across physical impairment status and physical habitat condition category was also performed. The significant difference in metric mean ranks was tested

Table 1 Standardized coefficients from discriminant analysis of physical habitat component parameters on physical habitat impairment classification

Parameter	Standardized coefficients
Sediment deposition	0.331
Channel flow status	0.308
Channel alteration	0.305
Embeddedness	0.229
Riffle frequency	0.220
Epifaunal substrate	0.211
Vegetative protection	0.188
Velocity depth regimes	0.154
Riparian vegetative zone width	0.137
Bank stability	0.032

using the Mann–Whitney *U* test across impairment status and the Kruskal–Wallis *H* statistic across the four physical habitat categories (Corder and Foreman 2009). Each metric showed a significantly higher score ($\alpha = 0.05$) in the less impaired categories. Although the mean differences were significantly different, whether the difference also indicated a difference in categorization (i.e., optimal, suboptimal, marginal, poor) remained unanswered. This was accomplished by associating the metric's mean rank score with an impairment category. The mean of all but two metrics (bank stability and bank vegetative protection) indicated a different category of physical habitat across impairment status (Pohlman and Voss 2008). Similar results were also seen across the four physical habitat condition categories. The analytical results obtained were similar using both measurements and site averages (Pohlman and Voss 2008). These findings provided evidence that the categorization process is consistent across all component habitat metrics and that each metric is necessary in the classification system.

Relationship between physical habitat metrics and SoCal B-IBI metrics

Having established the internal consistency and necessity of each component metric within the physical habitat score and the SoCal B-IBI (Viswanathan et al. 2010), the relationship between physical habitat stressors and biological metrics was explored. First, the extent to which physical habitat degradation and loss of biological integrity concur was investigated. Table 2 shows the relation between biological and physical impairment for individual measurements and for site averages.

The data in Table 2 clearly indicate that even though impaired physical habitat and impaired biological integrity concur, unimpaired physical habitat and unimpaired biological integrity do not concur. Although only 8% of measurements (7% of sites) with impaired physical habitat have unimpaired biological integrity, 80% of measurements (73% of sites) with unimpaired physical habitat have impaired biological integrity. Cohen's κ, a statistical measure of agreement between two raters (0 = complete disagreement and 1 = complete agreement) was calculated to determine how frequently the two measures concurred (Corder and Foreman 2009). The results indicated a value of 0.088 for individual measurements and 0.117 for the site averaged data. This discordance is likely due to both the presence of chemical pollutants and the somewhat subjective nature of the visual physical habitat assessment.

This conclusion was also confirmed by analyzing the Spearman rank correlation coefficients between the component physical habitat stressors and the SoCal B-IBI metrics (Pohlman and Voss 2008). All component physical habitat metrics were positively correlated with SoCal B-IBI except for channel alteration, bank stability, and bank vegetative protection. Conversely, all component biological metrics were positively correlated with the composite physical habitat score except for the percent collector individual score. In both cases, the correlations among the composite scores were found to be low. The results indicated that the highest correlation between the SoCal B-IBI and physical habitat metrics is $\rho = 0.437$ (Riffle frequency); the highest correlation between the composite physical habitat score and biological metrics is $\rho = 0.418$ (EPT taxa score). Furthermore, 58 (83%) of the 70 pairwise correlation coefficients were found to be weak or

Table 2 Relation between physical and biological impairment

	Measurements ($N = 385$)			Sites ($N = 105$)		
	Unimpaired physical habitat	Impaired physical habitat	Total	Unimpaired physical habitat	Impaired physical habitat	Total
Unimpaired biological integrity	50	11	61	21	2	23
Impaired biological integrity	201	123	324	57	25	82
Total	251	134	385	78	27	105

Table 3 Means of SoCal B-IBI component metrics across physical habitat impairment status

	Measurements ($N = 385$)			Sites ($N = 105$)		
	Impaired physical habitat ($N = 134$)	Unimpaired physical habitat ($N = 251$)	Significant difference?	Impaired physical habitat ($N = 27$)	Unimpaired physical habitat ($N = 78$)	Significant difference?
Coleoptera taxa score	1.29	1.91	**	0.95	2.38	**
EPT taxa score	1.41	2.37	**	1.23	2.79	**
Predator taxa score	2.02	2.51	**	1.64	2.78	**
% Collector indiv. score	2.83	3.44	–	2.74	3.65	–
% Intolerant indiv. score	0.37	0.98	**	0.5	1.52	**
% Noninsect taxa score	1.81	2.74	**	2.06	3.54	**
% Tolerant taxa score	2.36	3.93	**	2.5	4.32	**
SoCal B-IBI (100 pt)	17.28	25.54	**	16.59	29.99	**

**Difference significant according to the Mann–Whitney U test at $\alpha = 0.05$ level of significance

■ = Very poor, ▩ = Poor, ▨ = Fair, ▧ = Good, □ = Very good

absent ($0 <= \rho < 0.3$). This analysis reflects the lack of concordance between the two measures and indicates that an intervening factor such as chemical stress may be present.

This relationship was further confirmed by analyzing the means of SoCal B-IBI metrics over the range of physical habitat degradation and the means of physical habitat component metrics over the range of biological integrity. An analysis of the SoCal B-IBI metric mean ranks across physical habitat impairment (Table 3) shows statistical significance at $\alpha = 0.05$ (via Mann–Whitney U). This mean difference, although statistically significant, does not seem to improve the biological integrity category (i.e., very good, good, fair, poor, and very poor) across individual measurements. The coding scheme clearly shows that improved physical habitat, while leading to higher scores, only results in a marginal improvement of biological condition in two of the component metrics (EPT

Table 4 Means of physical habitat component metrics across biological impairment status

	Measurements ($N = 385$)			Sites ($N = 105$)		
	Impaired biological integrity ($N = 324$)	Unimpaired biological integrity ($N = 61$)	Significant difference?	Impaired biological integrity ($N = 82$)	Unimpaired biological integrity ($N = 23$)	Significant difference?
Epifaunal substrate	9.98	12.67	**	9.61	12.65	**
Embededness	8.48	10.64	**	8.38	10.91	**
Velocity depth regimes	10.48	12.51	**	10.35	12.28	**
Sediment deposition	9.02	11.03	**	9.48	12.31	**
Channel flow status	11.74	13.7	**	11.89	15.52	**
Channel alteration	15.23	17.07	**	15.67	18.26	**
Riffle frequency	10.27	14.59	**	10.85	14.71	**
Bank stability	14.52	14.9	–	14.67	15.18	–
Bank vegetative protection	13.69	13.85	–	13.72	13.8	–
Riparian vegetative zone width	13.79	16.2	**	14.29	17.38	**
Total physical habitat score	116.73	135.93	**	118.91	142.99	**

**Difference significant according to the Mann–Whitney U test at $\alpha = 0.05$ level of significance

■ = Marginal, ▧ = Suboptimal, □ = Optimal

Table 5 Stepwise regression results for SoCal B-IBI metrics using physical habitat parameters as independent variables

Data set	Dependent variable	Step 1	β_1	Step 2	β_2	Step 3	β_3	Step 4	β_4	Step 5	β_5	R^2
All	SoCal B-IBI (100 pt)	Total physical habitat	0.341									0.116
Correspond	SoCal B-IBI (100 pt)	Total physical habitat	0.779									0.607
All	SoCal B-IBI (100 pt)	Riffle frequency	0.378	Riparian vegetative zone width	0.207							0.224
Correspond	SoCal B-IBI (100 pt)	Epifaunal substrate	0.183	Riffle frequency	0.315	Riparian vegetative zone width	0.178	Sediment deposition	0.203	Velocity depth regimes	0.176	0.652
All	Coleoptera taxa score	Riffle frequency	0.303	Riparian vegetative zone width	0.207	Bank vegetative protection	−0.110					0.149
Correspond	Coleoptera taxa score	Epifaunal substrate	0.258	Riffle frequency	0.252	Riparian vegetative zone width	0.195	Bank stability	0.156	Velocity depth regimes	0.170	0.510
All	EPT taxa score	Riffle frequency	0.323	Riparian vegetative zone width	0.221	Velocity depth regimes	0.131					0.259
Correspond	EPT taxa score	Riffle frequency	0.336	Sediment deposition	0.272	Riparian vegetative zone width	0.205	Velocity depth regimes	0.205			0.590
All	Predator taxa score	Riffle frequency	0.236	Bank stability	−0.166	Riparian vegetative zone width	0.134					0.105
Correspond	Predator taxa score	Riffle frequency	0.298	Velocity depth regimes	0.283	Channel alteration	0.287	Bank vegetative protection	−0.190			0.387

Table 5 (continued)

Data set	Dependent variable	Step 1	β_1	Step 2	β_2	Step 3	β_3	Step 4	β_4	Step 5	β_5	R^2
All	% Collector indiv. score	Channel flow status	−0.231	Riffle frequency	0.158	Sediment deposition	0.112					0.068
Correspond	% Collector indiv. score	Sediment deposition	0.284	Riffle frequency	0.234							0.199
All	% Intolerant indiv. score	Riffle frequency	0.288	Riparian vegetative zone width	0.104							0.108
Correspond	% Intolerant indiv. score	Riffle frequency	0.337	Sediment deposition	0.229	Riparian vegetative zone width	0.169	Channel flow status	0.156			0.403
All	% Noninsect taxa score	Riffle frequency	0.206	Velocity depth regimes	0.195	Riparian vegetative zone width	0.286	Channel alteration	−0.165			0.170
Correspond	% Noninsect taxa score	Epifaunal substrate	0.385	Riffle frequency	0.226	Riparian vegetative zone width	0.172					0.388
All	% Tolerant taxa score	Velocity depth regimes	0.222	Riffle frequency	0.153	Riparian vegetative zone width	0.125	Bank stability	0.111			0.171
Correspond	% Tolerant taxa score	Embeddedness	0.393	Riffle frequency	0.222	Vegetative protection	0.147					0.339

Standardized coefficients significant at $\alpha = 0.05$ are shown under each step in the model building process taxa % Noninsect taxa) and the overall SoCal B-IBI score. In both cases, these increases are from very poor to poor condition.

Similarly, an analysis of the mean ranks of the component physical habitat metrics across biological condition categories (Table 4) shows statistical significance at $\alpha = 0.05$ (via Mann–Whitney U and Kruskal–Wallis H). This mean difference corresponds to an increase in physical habitat categorization in seven out of ten physical habitat metrics when looking at individual measurements (six out of ten for site averages). However, this increase does not correlate with changing the overall physical habitat score categorization since both impaired and unimpaired sites are assessed as suboptimal. A coding scheme similar to the one discussed earlier clearly shows that an increase in biological integrity, while corresponding to higher scores on physical habitat metrics, generally corresponds to the suboptimal physical habitat condition. The previously mentioned lines of evidence lead to the ultimate conclusion that physical habitat scores alone overestimate the biological condition of the stream. This suggests the necessity of assessing biological assemblages within the waterbody.

Despite this difference, the relative influence of each of the component physical habitat stressors on the SoCal B-IBI and its component metrics was analyzed. A linear regression model was used to explore the sensitivity of the SoCal B-IBI and its component metrics to the composite physical habitat score and its component measures. The results of the model building process are shown in Table 5. A simple linear regression model was used to regress the composite physical habitat score on the SoCal B-IBI using the entire suite of measurements for which both biological data and physical habitat data ($N = 385$) were available. The expected positive correlation between the two variables was observed; however, the low R^2 value indicated explanation of only 11.6% of the variance in the SoCal B-IBI (see Fig. 1). To improve the fit and remove the variability of external factors which were not included in the model (i.e., chemical stressors), the same regression procedure was performed on those cases ($N = 173$) which corresponded in their biological integrity physical habitat impairment (i.e., both unimpaired or both impaired). This significantly improved the fit of the model so that now 60.2% of the total variance was explained by the linear fit (see Fig. 2). Although this may be a simplistic way of removing the effects of chemical stressors from the analysis, it is an effective way to decompose the chemical and physical effects. Similarly, stepwise multiple regressions performed using the component physical habitat metrics on both the composite SoCal B-IBI and its individual component metrics show that riffle frequency, sediment deposition, epifaunal substrate, riparian vegetative zone width, and velocity depth regime measures

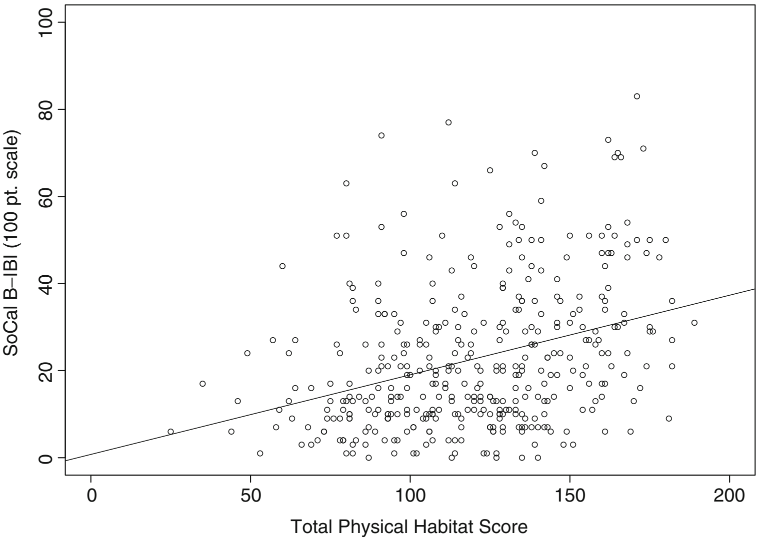

Fig. 1 Scatterplot of SoCal-IBI versus total physical habitat score with best fit linear regression line

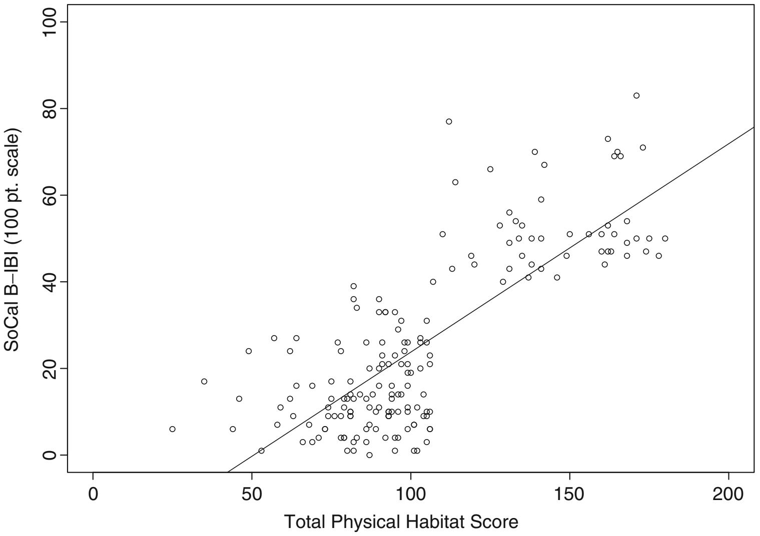

Fig. 2 Scatterplot of SoCal-IBI versus total physical habitat score with best fit linear regression line for those measurements which correspond on physical and biological impairment

explain most of the variance in the SoCal B-IBI for those sites which concur on biological and physical impairment.

To determine the relative effect of the physical habitat measures on biological impairment, a discriminant analysis (Corder and Foreman 2009) was performed on those sites that corresponded on physical habitat and biological impairment. Table 6 shows the standardized coefficients for the model built in this study. Most of the physical habitat parameters have significant effect on classifying biological impairment although the effect is not equal. Riffle frequency and riparian vegetative zone width have the most discriminating power as predictors of biological impairment. Embeddedness, vegetative protection, and channel alteration have the least discriminating power among the ten physical habitat component metrics.

Table 6 Standardized coefficients from discriminant analysis of physical habitat component parameters on biological impairment classification

Parameter	Standardized coefficients
Riffle frequency	0.514
Riparian vegetative zone width	0.383
Epifaunal substrate	0.285
Bank stability	0.273
Sediment deposition	0.266
Channel flow status	0.255
Velocity depth regimes	0.247
Embeddedness	0.100
Vegetative protection	0.082
Channel alteration	0.020

Chemical stressor analysis

Given the fact that physical impairment measures underestimate biological impairment, we conducted an introductory analysis to explore possible sources of chemical stressors that may negatively affect the biological integrity of physically unimpaired streams and rivers. To do this, the pairwise Spearman correlation coefficients between surrogates of chemical impairment (pH, dissolved oxygen, specific conductance, and salinity) and the component SoCal B-IBI metrics were examined. The results are shown in Tables 7 and 8. The results clearly indicate that an increase in specific conductance (mean ± standard deviation = 1,636 ± 959 μmho/cm, $N = 222$) and salinity (mean ± standard deviation = 0.86 ± 0.64 ppt, $N = 157$) correspond to a decrease in biological integrity scores. The trend is evident across the entire data set as well as for points that are biologically impaired but physically unimpaired.

Although a correlational analysis does not allow us to infer causation directly between specific conductance and the SoCal B-IBI scores, these measurements do provide an indication of chemical stress. First of all, we interpret specific

Table 7 Spearman rank correlation coefficients between SoCal B-IBI metrics and chemical stressors using any site with data

	pH ($N = 175$)	Dissolved oxygen ($N = 222$)	Specific conductance ($N = 222$)	Salinity ($N = 157$)
Coleoptera taxa score	0.042	−0.054	**−0.459**[a]	**−0.525**[a]
EPT taxa score	0.096	−0.009	**−0.439**[a]	**−0.526**[a]
Predator taxa score	**−0.272**[a]	−0.094	**−0.157**[a]	**−0.279**[a]
% Collector indiv. score	**−0.295**[a]	−0.048	**−0.176**[a]	**−0.207**[a]
% Intolerant indiv. score	0.011	−0.079	**−0.450**[a]	**−0.583**[a]
% Noninsect taxa score	**0.157**[a]	−0.071	**−0.382**[a]	**−0.496**[a]
% Tolerant taxa score	**0.298**[a]	0.014	**−0.304**[a]	**−0.372**[a]
SoCal IBI (100 pt)	−0.017	−0.074	**−0.453**[a]	**−0.543**[a]

[a] Significant at $\alpha = 0.05$

conductance as a surrogate for chemical stressors which were not specifically measured (e.g., organic pollutants, metal ions, nutrients, etc.) as part of the routine bioassessments from which these data were obtained (Dow and Zampella 2000). Secondly, certain aquatic insect orders (Ephemeroptera, Plecoptera, Trichoptera, and Coleoptera) included in the SoCal B-IBI have been shown to be directly sensitive to gradients in ionic strength (Kefford et al. 2011). Furthermore, two of the metrics in the SoCal B-IBI (percent intolerant individuals and percent tolerant taxa) are based specifically on tolerance scores which are scaled measures of species tolerance to organic pollution (Hilsenhoff 1987). Finally, although sediment toxicity is indeed a relevant concern for benthic macroinvertebrates (Marshall et al. 2010), the chemical parameters reported in routine bioassessment data typically do not provide sediment analyses and rely solely on water column measures. Therefore, an attempt to explore and analyze several possible causative factors at the landscape scale by combining temporal and spatial analyses of these chemical surrogates in conjunction with the SoCal B-IBI measures was undertaken.

Possible sources of chemical stressors

Fire impacts

Frequent wildfires alter soil chemistry and storm water runoff characteristics, thereby resulting in poor water quality (Gullett and Touati 2003; Meyer et al. 2004; Stein and Brown 2009). Fires increase the particulate load to streams, alter the physical habitat of the streams, and, possibly, introduce toxins as a result of the burnt litter and debris. In October 2003, San Diego experienced the largest wildfire in California since 1932. Therefore, we investigated the possibility that the 2003 wildfires had a negative effect on the SoCal B-IBI score. To determine whether this wildfire had an observable effect on the biological integrity of streams, a Mann–Whitney U test was conducted (Corder and Foreman 2009). Our data indicated that the SoCal B-IBI scores in the region were not significantly different before

Table 8 Spearman rank correlation coefficients between SoCal B-IBI metrics and chemical stressors using points with high physical habitat scores but low biological integrity

	pH ($N = 78$)	Dissolved oxygen ($N = 105$)	Specific conductance ($N = 105$)	Salinity ($N = 79$)
Coleoptera taxa score	0.123	0.031	**−0.424**[a]	**−0.479**[a]
EPT taxa score	0.116	0.052	**−0.284**[a]	**−0.395**[a]
Predator taxa score	**−0.428**[a]	0.083	0.096	0.041
% Collector indiv. score	**−0.460**[a]	−0.062	0.057	0.084
% Intolerant indiv. score	−0.082	−0.023	**−0.327**[a]	**−0.474**[a]
% Noninsect taxa score	0.201	−0.062	**−0.289**[a]	**−0.457**[a]
% Tolerant taxa score	**0.323**[a]	−0.008	**−0.245**[a]	**−0.353**[a]
SoCal IBI (100 pt)	−0.062	−0.022	**−0.316**[a]	**−0.410**[a]

[a] Significant at $\alpha = 0.05$

and after the wildfires. The seven components of the SoCal B-IBI were also tested to ascertain whether significant changes in individual scores were observed after the fires. The only metric which showed a significant difference was the percent noninsect taxa score. Due to poor SoCal B-IBI scores both before and after the wildfires in watersheds which burned, the direct impact of the fires on the biological integrity could not be confirmed.

Metropolitan Water District of Southern California service area impacts

The San Diego County Water Authority comprises a total of 24 member agencies, including six cities, five water districts, three irrigation districts, eight municipal water districts, one public utility district, and one military base. The Metropolitan Water District imports its water from Northern California and the Colorado River. The Colorado River is known for its high natural salinity which has been anthropogenically enhanced by irrigation, reservoir evaporation, and trans-basin diversions (US Department of Interior 2005). Because the water imported from the Colorado River has a much higher salinity than the water obtained from Northern California, it is blended in Lake Skinner before it is delivered to the San Diego County Water Authority.

To study the effects of imported water on the SoCal B-IBI scores within the San Diego Basin, Ecolayers 1.0 was used to classify each bioassessment station as being inside or outside the areas which receive water from the Metropolitan Water District (MWD). Although the surface water is directly unaffected by the water source, runoff from municipal use of water within the MWD would presumably possess a higher salinity than water from outside the MWD. To remove the impact that an impaired physical habitat could have on the analysis, samples with impaired physical habitat were excluded. The results are displayed in Fig. 3.

It is clear from Fig. 3 that there are differences in SoCal B-IBI scores between sites located inside and outside the MWD service area. The average SoCal B-IBI dropped from 27 (poor) for sites located outside the MWD service area to 19 (very poor) for sites located inside the MWD service area. Five of the seven metric scores were statistically lower (Mann–Whitney U, $\alpha = 0.05$) in the MWD service region. Only the percent tolerant taxa score and the percent collector individual score were not statistically different. The total physical habitat scores averaged 130 for samples both inside and outside the MWD service areas. Thus, the lower SoCal B-IBI scores do not result from different physical habitat scores, and hence we can infer that other chemical stressors may be causing these differences.

Unfortunately, chemical data were not collected at all measurement events. However, a portion of the samples did include measurements of pH, dissolved oxygen, specific conductance, and salinity. Whereas pH and DO measurements were not significantly different between sampling locations within and outside of the MWD service areas, the specific conductance and salinity measurements showed a statistically significant difference. In general, specific conductance increases from the presence of inorganic dissolved solids, as a result of industrial pollution, urban runoff, and agricultural runoff as well as the nature of the bedrock and soil of the watershed. The analysis revealed that the average specific conductance of samples taken outside the MWD service area is 910 µmho/cm while those taken inside the service area are significantly higher at 1,962 µmho/cm.

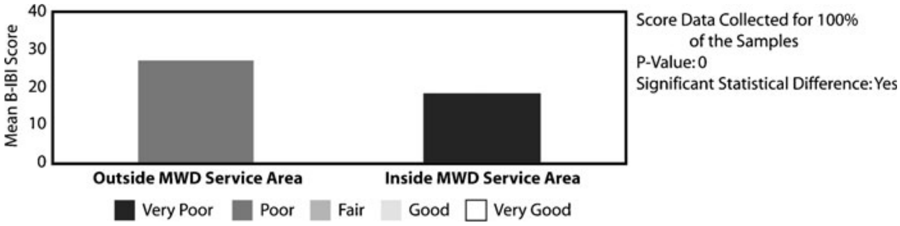

Fig. 3 Differences in SoCal B-IBI scores between sites located inside and outside the MWD service area

Salinity is an important measurement because aquatic organisms have varying abilities to survive at different salinity levels. Although tolerances to salinity vary and field intolerance may be indicative of covarying stressors (Kefford et al. 2004), many freshwater organisms exhibit intolerance to salinity above 1 ppt (Hart et al. 1991). The average salinity of surface waters outside the MWD service area (0.46 ppt) is significantly lower than the salinity inside the MWD service area (1.22 ppt). This comparison clearly indicates that even though the Colorado River water is mixed to reduce its salinity before being distributed, its use within the MWD may be contributing to higher salinities within surface waters. The difference in specific conductance and salinity in conjunction with a lower value of the SoCal B-IBI when physical habitat is unimpaired indicates that municipal use of water imported from the Colorado River may be a contributing factor to both chemical contamination and biological impairment of streams within the San Diego Basin. The surrogate nature of the specific conductance and salinity measures, however, make conclusive statements at the landscape scale of this study unwarranted. Instead, we suggest that the source of municipal water in the MWD, in combination with other localized chemical impacts in both the water column and sediment, synergistically affect biotic integrity in the region. The fact that average biological condition of streams outside the MWD service area is also poor provides further evidence for this conclusion. Detailed chemical analysis of both water column and sediment at sites with impaired biology is warranted to identify the particular chemical stressors which may prevent aquatic life from flourishing at local scales. In addition, further studies which elucidate the relative importance and synergistic nature of physical habitat and chemical stressors on biological impairment at various scales will help disentangle the complexities of the urban stream syndrome.

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