Development of Integrated Measures of Ecosystem Condition to Support Biological Objectives for Riverine Wetlands

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Final Grant Deliverables Report

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Table of Contents

List of Tables

List of Figures

1. Introduction and Background

California's streams and wetlands are regulated and managed under a variety of programs by multiple State and Federal agencies. These programs share a common need for objective assessment endpoints that can be used to gauge success or compliance. Measures of physical and biological condition are increasingly preferred as assessment endpoints because they directly measure the beneficial uses or functions that are the focus of protection and management. Ecological indicators have the added advantage of integrating condition over space and time, thus providing a more comprehensive assessment than other traditional indicators.

Ultimately, management and regulatory agencies need to translate ecological indicators into criteria or objectives that can be used to assess progress toward management targets and overall program performance. Transitioning from indicators of community composition or biological/physical structure to measurable objectives poses several challenges, including: 1) ecological condition should be evaluated in comparison to an objectively defined expected state (e.g., reference sites with minimal anthropogenic disturbance), 2) multiple indicators should be developed to provide a robust measure of ecological condition, 3) ecological condition measures should transcend jurisdictional mandates, and 4) biological objectives must incorporate stressor relationships. This project addresses each of these challenges.

First, characterizing sites in reference condition provides benchmarks for comparison of sites being evaluated and serves to "anchor" biological objectives against a target at one end of a gradient of disturbance. Reference conditions provide a widely accepted mechanism for defining appropriate expectations and for accounting for this natural variability (Hughes *et al.* 1986, Barbour *et al.* 1996, Reynoldson *et al.* 1997, Karr and Chu 1999, Bailey *et al.* 2005, Stoddard et al. 2006, Hawkins et al. 2010). Furthermore, once the natural variability in biological indicators is characterized at reference sites, it can be distinguished from the variability arising from anthropogenic impacts at disturbed sites.

Second, multiple indicators exploit the different sensitivities each indicator has for different stressors. Although most biological indicators integrate impacts from multiple stressors, each indicator has its own strengths and weaknesses. For example, several studies have shown that benthic macroinvertebrates are particularly sensitive to hydrologic and habitat modification that accompanies watershed urbanization, whereas benthic algae are sensitive at different time scales to water quality impacts, such as changes in nutrients or specific conductance (Sonneman et al. 2001, Walsh *et al.* 2001, Hirst *et al.* 2002, Mazor *et al.* 2006). Using multiple indicators in tandem provides greater sensitivity to more types of impacts, and over a greater range of the disturbance gradient. In particular, incorporating the California Rapid Assessment Method (CRAM; CWMW 2013) into stream condition assessments will allow for the integration of an assessment of overall wetland condition (via CRAM) with assessment of in-stream habitat and biological condition (via indices of biotic integrity -IBIs).

Third, measures of ecological condition should focus on the scale appropriate for assessing desired endpoints and not be limited by boundaries of agency jurisdiction or mandate. Wetland and stream regulation and management in California are often compartmentalized based on statutory, rather than ecological divisions. For example, the ecological condition of streams is a function of the in-stream habitat, the adjacent wetland and riparian zone, the buffer area, and the larger landscape setting. Unfortunately, many traditional indicators focus on single aspects of the ecosystem (*e.g.,* in-stream habitat, riparian plants) because the scope of the condition assessment is limited to the extent of a specific jurisdictional area (*e.g*., below bankfull stage). A more appropriate approach is to use multiple indicators that assess ecosystem condition at multiple scales (Frissell *et al.* 1986) and then integrate these measures to provide an index of ecosystem condition.

Fourth, biological objectives must be based on an understanding of the relationship between ecosystem condition and stressors. Evaluation of condition alone can be useful in assessing status and trends, but without an understanding of how indicators are affected by stressors impacting the ecosystem, these evaluations are less useful for informing management decisions.

The goal of this project is to begin addressing the four challenges described above by developing a multi-indicator assessment approach and preliminary tools for evaluating ecosystem condition in riverine/riparian wetlands (streams) in California. This project builds on, and coordinates with existing and past projects funded by USEPA and the State of California, including the Surface Water Ambient Monitoring Program's (SWAMP) Perennial Streams Assessment (PSA) and Reference Condition Management Program (RCMP) and Southern California's Stormwater Monitoring Coalition's (SMC's) Regional Watershed Assessment and the Development of a Statewide Network of Reference Wetlands for California projects.

There are two fundamental work products associated with this grant. The first is to supplement existing stream reference site assessment by conducting CRAM at sites currently included in the State's RCMP reference network. The second is to use the data collected under this grant and the associated projects (listed above) to begin developing multi-indicator assessment and stressor tools.

2. Tasks and Products

This project consisted of four technical tasks (Task 5 is reporting). The approach findings and major conclusions of each task are summarized below. For most tasks, the work funded under this grant contributed to ongoing efforts to produce a variety of technical products designed to support assessment of condition and stress in streams. In this way, we leveraged this effort with other programs (and sources of funding). Below, we summarize results directly attributable to this grant and explain next steps associated with each component (task). In most cases, additional technical products (in the form of technical reports and/or journal articles) will be produced once the work is completed.

2.1 Task 1: Convene Technical Advisory Committee (TAC) and Develop Detailed Work Plan and Quality Assurance Project Plan (QAPP)

Work on this project is closely aligned with (and supports) the statewide bio-objectives program. Therefore, we used the existing TAC structure for that project to serve the technical review component of this project. The bioobjectives program has three advisory groups, which had a total of 20 meetings since May 2010. Dates of the past meetings are listed below. Composition of each committee, agendas, presentations, and notes from the meetings can be found at: http://www.swrcb.ca.gov/plans_policies/biological_objectives.html.

- **Scientific Advisory Group**
  - October 2010
  - April 2011
  - October 2011
  - April 2012
  - October 2012
- **Regulatory Advisory Group**
  - September 2011
  - January 2012
  - April 2012
  - May 2012
  - October 2012
  - December 2012
  - June 2013
- **Stakeholders Advisory Group**
  - May 2010
  - November 2010
  - April 2011
  - September 2011
  - January 2012
  - April 2012
  - May 2012
  - October 2012
  - December 2012
  - February 2013
  - June 2013

A QAPP for the project was completed and submitted to EPA for review in Spring 2010. The QAPP is modeled after existing, approved CRAM and bioassessment QAPPs.

2.2 Task 2: Augment Data at Existing Assessment Sites with CRAM

The scope of work anticipated completion of CRAM assessments at 60 reference sites. To date, CRAM assessments have been completed at 50 RCMP sites under this grant by SCCWRP, MLML, and CDFG-ABL field crews (Table 1). CRAM assessments have been completed at an additional 103 sites that meet RCMP reference criteria as part of the overall statewide PSA/SMC programs (Table 1). We currently have 153 riverine reference sites across all PSA regions of the State that have data for CRAM as well as the traditional bioassessment indicators. The statewide distribution of reference sites is shown in Figure 1. All CRAM data has been loaded into the statewide CRAM database. Benthic invertebrate and Physical Habitat (PHAB) data collected from the sites is in the bio-objectives database, and will eventually be accessible through the California Environmental Data Exchange Network (CEDEN).

Table 1: Summary of riverine reference sites with completed CRAM assessments.

PSA Region	This EPA Grant	Other projects	Total
Central Lahontan	4	18	22
Central_Valley	0	0	0
Coastal Chaparral	25	12	37
Deserts Modoc	1	6	7
Interior Chaparral	4	13	17
North Coast	7	19	26
Sierra West	5	17	22
South Coast-Mts.	3	11	14
South Coast-Xeric	1	7	8
TOTAL	**50**	**103**	**153**

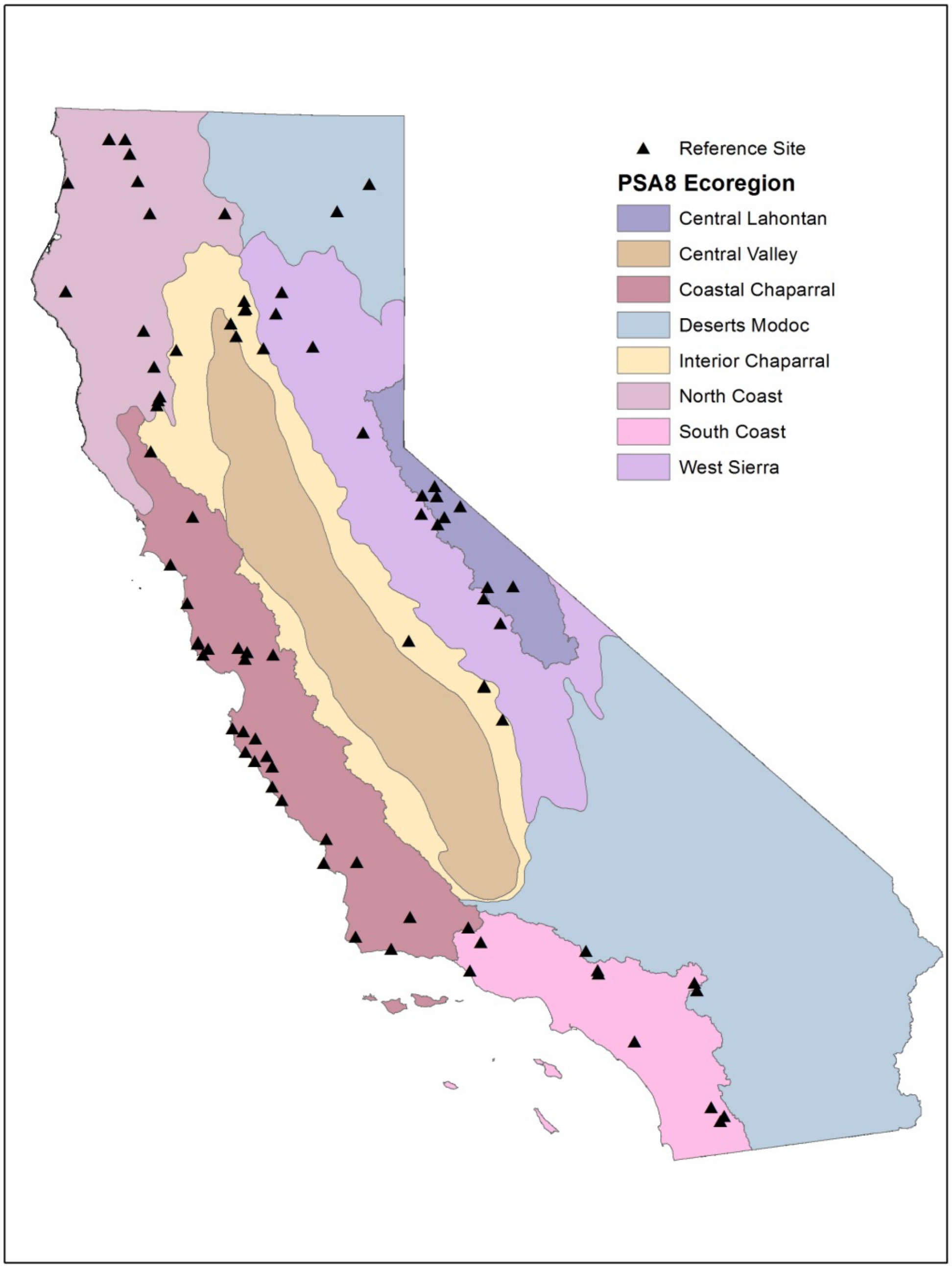

Figure 1: Locations of riverine reference sites with CRAM assessments. Reference sites were selected based on the RCMP landscape-screening criteria (Ode and Schiff 2008)

Overall CRAM score for all reference sites ranged from 59 to 99, with a mean value of 86 (Table 2). The range of conditions varied by attribute, with the Buffer and Landscape Context attribute generally showing the highest scores. Relatively low CRAM scores may occur at sites that meet reference criteria based on localized disturbances, often associated with natural variability or episodic events.

Table 2: Range of overall CRAM and attribute scores for reference sites. BLC = Buffer and Landscape Context.

	BLC Final	Hydrology	Physical	Biotic	Overall CRAM
Mean	97	84	82	77	86
Standard Error	1	1	1	1	1
Median	100	83	88	78	87
Standard Deviation	8	12	15	14	7
Range	80	70	82	80	40
Minimum	20	30	18	20	59
Maximum	100	100	100	100	99
Count	153	153	153	153	153

The range of reference scores also varied by ecoregion (Figure 2). The Coastal Chaparral and Dessert Modoc regions had the widest distribution, while the Western Sierra had the narrowest. It should be noted, that no reference sites were identified and assessed in the Central Valley. The PSA program will be conducting a more comprehensive CRAM analysis over the coming year.

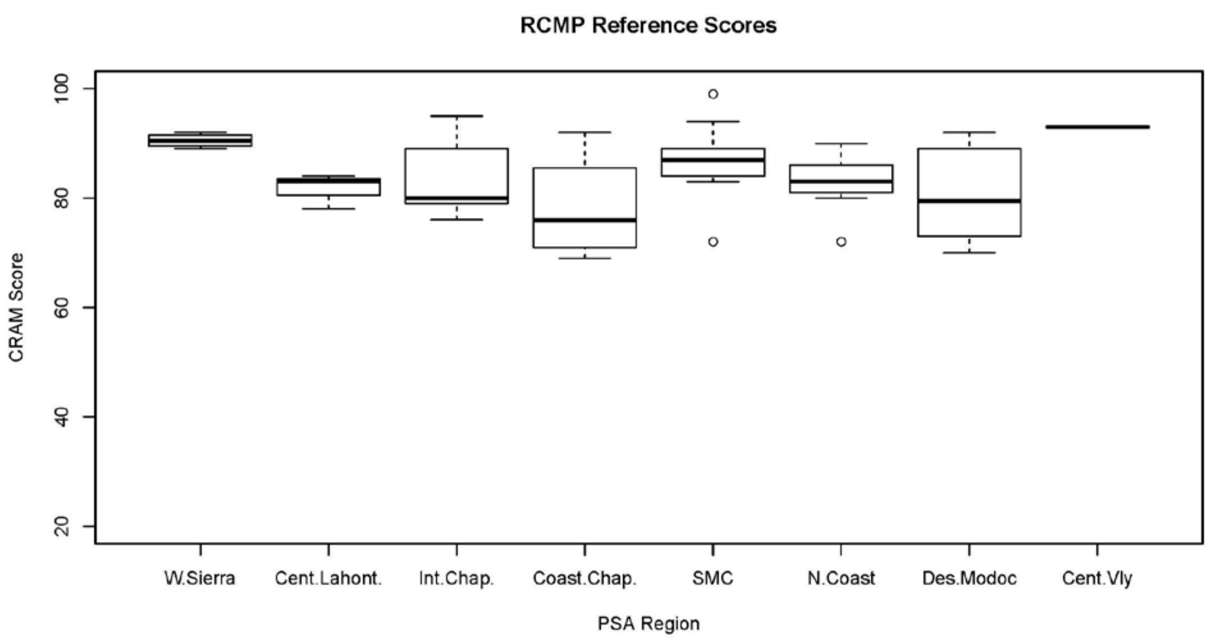

Figure 2: Distribution of CRAM scores at reference sites in each region. Possible CRAM scores range from 25 to 100.

The 153 sites identified through this and other efforts will be incorporated into a developing statewide network of RCMP reference sites (Ode and Schiff 2008, Ode et al. *in review*). This network is organized by PSA region and is intended to support the various State and Federal agency programs that require (or desire) the inclusion of reference sites for ambient assessment and project evaluation. Over time, the regional networks will provide long-term data on stream condition across gradients of natural disturbance, anthropogenic stress, and over time scales that encompass climatic (and other temporal) patterns. Similarly, reference site can support training and Quality Assurance Programs. Individual projects will be able to use the information from these reference networks to help establish project-specific targets and to interpret site-specific monitoring data.

A governance process for funding and managing the regional reference networks is needed. Because the regional reference networks are intended for use across multiple programs, they will require cooperative strategies for their long-term support and maintenance. The pooling of regional expertise, agreement on regional priorities, defining the most appropriate methodologies, data sharing, and cost sharing will be critical to this process.

It is expected that the regional networks of reference sites will grow and be dynamic over time as new reference sites are identified or former sites that no longer meet the criteria for reference condition are removed. The number of reference sites to comprise the regional reference networks that will ultimately depend on the natural variability of a particular ecoregion, the extent of which is currently unknown for most regions of California. Given this, it will be important to identify additional sites in order to capture the full range of natural variability. As more reference sites are identified and data from these sites are collected, they will be used to determine which of these gradients has the most influence on reference condition to ensure that the regional networks are representative of the most important natural gradients (Ode and Schiff 2008). Work is currently underway (funded by USEPA and the San Diego Regional Water Quality Control Board) to expand the reference network to include non-perennial and ephemeral streams.

It is recommended that this process be facilitated via the oversight of the California Wetland Monitoring Workgroup (CWMW) and/or the SWAMP program through the establishment of a reference site review panel. This panel will be the mechanism for moving sites into and/or out of the regional networks (e.g., vetting of new sites for inclusion in the network, removal of existing sites that no longer represent reference condition, etc.). Over the long-term, the California Wetlands Monitoring Workgroup (CWMW) can explore options to add to the reference network through a variety of programs including the Perennial Stream Assessment, wetland permitting programs (e.g., Section 404/401 and the State Wetlands Policy), regional or watershed based monitoring programs, or stormwater monitoring efforts. In addition, the

CWMW can serve as the venue for other agencies and programs that do not have reference condition programs (e.g., Non-point Source Monitoring, State Parks, Irrigated Lands Program, Agricultural Coalitions, etc.) to engage in and participate in the process.

Because the regional reference sites will be used for a wide range of applications and support various programs, the data gathered at these sites needs to be made available to a wide range of users. This information would consist of various type of spatial data (location, coordinates, surrounding land use), metadata (site history, access, ownership, etc.), and monitoring data (rapid assessment scores, water quality, biological monitoring, etc.). The California EcoAtlas and the California Environmental Data Exchange Network (CEDEN) provide options for a global point of entry for access to information and data on the location, extent and health of aquatic resources in California; therefore, information on the existing reference network should be made readily available via one of these databases for use by the various assessment and management programs.

As the regional networks develop, additional data on existing reference sites, as well as yet-unidentified reference sites, can be added to CEDEN or the EcoAtlas over time. It is recommended that additional information be compiled on these sites to help with interpretation of assessment data. Such factors should include land use (using existing data layers), water sources, agency districts or regions that may influence how the wetlands are managed, and wildfires, floods, or other natural phenomena which may have affected the areas assessed. Similarly, regulatory or monitoring requirements to provide reference sites can be leveraged to contribute to the overall statewide network through use of the standard reference definitions and by including data in the eCRAM database.

Related to the number of reference sites is the frequency at which these sites will be assessed. Because sites will need to be re-sampled periodically for long-term trend detection and analysis of variability, ongoing maintenance and monitoring will be necessary to take full advantage of the investment made in establishing the reference network. Sites should be monitored to ensure that they remain in reference condition or to document and understand the reasons for them becoming non-reference. The reference network can also provide a long-term sentinel sites for detecting trends in response to climate patterns or other broad-scale changes. Similarly, reference site can support training and Quality Assurance Programs. Long-term use of these sites will require ongoing tracking, monitoring, and data management.

2.3 Task 3: Identify Stressor-Response Relationships for each indicator

The objective of this task was to characterize stressors acting on perennial streams and to develop assessment tools to help rate sites in terms of relative stress. Such an assessment tool has utility for interpreting the results of condition assessments (such as CRAM and IBI scores) and to prioritizing management or restoration activities.

We initiated development of two types of tools; the first is a landscape-scale multi-metric stressor index. This tool identifies stress based on GIS data that reflects broader landscape-scale stressors. The second tool uses existing Physical Habitat (PHAB) data collected as part of routine bioassessment to develop a reach-scale index of habitat quality. This index characterizes stress at a scale that more directly affects instream biota than the landscape-scale index. Together these two tools provide additional ability to interpret monitoring results and to translate those results to recommended management actions.

Initial development of both tools was partially funded by this grant; however, neither tool is currently completed, requiring additional refinement and validation. Additional funding provided by the State Water Resources Control Board will be used to complete both these efforts.

2.3.1 Multi-metric Stressor Index

2.3.1.1 Stressor Characterization

Nine probabilistic monitoring programs, comprised of 717 sites, were compiled for evaluating stressor distributions in California's perennial wadeable streams (Table 3). A total of 688 sites remained after culling sites for redundancy (defined as < 300 m apart). These sites covered all seven Level III Ecoregions in California.

To integrate data from all nine of the probabilistic surveys compiled in this study, a common sample frame was created and used to calculate site inclusion probabilities. All probabilistic sites were registered to a common perennial wadeable stream network (i.e., NHD Plus). An initial 106 stressors were estimated for each of the sites in the database. Eighty-four were landscape-scale stressors and the remaining 22 were local-scale stressors. In order to characterize the landscape-scale stressors associated with the stream sites, watersheds were delineated for each site using 30-m digital elevation models. Sixteen spatial data sources were used to estimate landscape-scale stressors that may affect stream quality (Appendix A) such as landcover, population, transportation, hydrologic alteration, and mining. Most of these spatial data sources were from public sources (e.g., National Land Cover Dataset [NLCD]), although a few were developed specifically for this project (e.g., a custom road layer). These spatial data were overlaid with the watershed delineation information for our estimates of stressor extent. Local-scale stressor metrics were comprised of data collected "on the ground" at each of the sample sites including limited water chemistry (conductivity, total nitrogen, and total phosphorus) and physical habitat data. Human activity in the riparian zone was quantified as the W1_Hall metric from Kaufmann et al. (1999).

Table 3: Sources of data for stressor characterization.

Program	Agency	Geographic Scope	Sites
EMAP	USEPA	Statewide	169
EMAP Central Coast Supplement	USEPA	Chaparral	23
CMAP	California State Water Board	Statewide	179
PSA	California Surface Water Ambient Monitoring Program	Statewide	135
SMC	Stormwater Monitoring Coalition	South Coast	121
San Gabriel River Regional Monitoring Program	Los Angeles - San Gabriel Rivers Watershed Council	South Coast	23
Los Angeles River Watershed Monitoring Program	Los Angeles - San Gabriel Rivers Watershed Council	South Coast	10
Santa Ana River Regional Monitoring Program	Santa Ana Regional Water Quality Control Board	South Coast	51
Santa Clara Watershed Monitoring Program	Los Angeles Regional Water Quality Control Board	South Coast	6

From the initial pool of 106 stressor metrics assembled, a subset of 22 landscape- and local-scale stressors were selected for characterization and analysis (Table 4). The subset of stressors were selected based upon: 1) their completeness/coverage across the 688 sites; 2) quality of the data; and 3) lack of redundancy (e.g., using road classes 1+2+3+4, but not including data on each separate class). The distribution of local- and landscape-scale stressor data for the entire state of California and the component regions was calculated using the Horvitz-Thompson estimator (1952), which estimates the weighted average of stressor condition. Confidence intervals and standard errors were based on local neighborhood variance estimators (Stevens and Olsen 2003), which assumes that samples located close together tend to be more alike than samples that are far apart. Area-weighted estimates of stressor extent and estimates of confidence were calculated using the *spsurvey* package (Kincaid and Olsen 2009) in R v 2.11.1 (The R Foundation for Statistical Computing 2010). The extent of stress was also characterized based on the proportion of stream miles with >10% agricultural cover, >10% urban land cover, >0.5 road crossings per km, or a W1_Hall score >1.5.

Table 4: Stressors included in the stressor characterizations analysis.

Metric	Description	Unit
Census		
PopDens2000	Population density in 2000	People/km^2
Hydrology		
CANALS	% Canals or pipes at the 100 k scale	%
CanalDist	Distance to nearest canal or pipe (100 k) in watershed	km
DamDens	Density of dams	# km^{-2}
DamDist	to nearest upstream dam in catchment	km
Land Use		
Ag	% Agricultural (row crop and pasture, NLCD codes 81 and 82)	%
CODE_21	% Urban/Recreational Grass (NLCD code 21)	%
IMPERVMEAN	Imperviousness	%
PASTURE	% Natural pasture (NLCD code 81)	%
ROW_CROPS	% R ow crops (NLCD code 82)	%
URBAN	% Urban (NLCD codes 22, 23, 24)	%
GRAZING	% Allotted to grazing on USFS and BLM lands in CA	%
Mining		
GravelMinesDens	Density of gravel mines in riparian zone	mines km^{-2}
MinesDens	Density of mines (producers only)	mines km^{-2}
Transportation		
PavedRoadCross	Density of paved road crossings in riparian zone	# km^{-2}
RDDENSC123R	Road density (includes rail)	km km^{-2}
Other		
W1_HALL	Weighted human influence/riparian disturbance	None
Water Chemistry		
COND	Specific conductivity	µS/cm
NTL	Total nitrogen	µg/L
pH	pH	
PTL	Total phosphorous	µg/L

Correlation analysis illustrated a pattern where there are two broad classes of stressors; agricultural and urban development. Most often, these stressors were mutually exclusive of each other in perennial wadeable streams California. For example, stressors associated with urban development, such as % of urban landcover, % impervious surface, population density, and road density, and road crossings all had an r_s greater than 0.6. Stressors associated with agricultural development, such as agricultural landcover, nitrogen, or % of stream length as canal/pipes, all had an r_s greater than 0.3. Yet relationships between urban and agricultural stressors were generally weak and often negatively correlated. Only two stressors were well-correlated with both urban and agricultural landcover; road crossing density and W1_Hall. These two stressors are likely independent of development type.

Road crossing density and physical habitat disturbance were the most pervasive stressors in the perennial wadeable streams of California (Figure 3). Between 66% and 71% of the stream miles in California had some level of physical disturbance or road crossing in its watershed, respectively. Perennial wadeable streams in the Central Valley and South Coast ecoregions were consistently the most stressed in California, regardless of the stressor (Figure 3). In contrast, stream miles in the North Coast, Sierra, and Desert-Modoc ecoregions consistently had the least spatial extent of our representative stressors. In fact, the perennial wadeable stream miles in the North Coast and Sierra ecoregions had less than 10% urban or agricultural landcover and less than 10% of stream miles had high levels of physical disturbance.

Approximately 50% of the stream miles in California were associated with at least one of our example stressors at levels above our pre-determined thresholds. Roughly 20% of the stream miles were exposed to two or more stressors. Except for the Central Valley and South Coast ecoregions, the majority of stream miles in the remaining ecoregions were associated with only one of the representative stressors examined in this study. An estimated 38% of stream miles in the South Coast and nearly 92% of the stream miles in the Central Valley were associated with more than one stressor.

2.3.1.2 Stressor Multi-metric Index Development

There have been a number of important advances in the conceptualization and practice of how to define whether a stream is stressed or not (i.e., non-reference/reference) (e.g., Stoddard et al. 2006, Whittier et al. 2007, Angradi et al. 2009, Hawkins et al. 2010). Nevertheless, given the large number of stressors found across California (see section above) and the different spatial scales upon which they interact with streams (e.g., across a watershed, within a sub-catchment, or within the banks of the stream) producing a simple definition of how stressed a system is or how to relate all of those individual stressors to changes in habitat or biology can be challenging.

Complex biotic community structure information is routinely distilled and summarized into simple easily interpretable and comparable biotic indices (e.g., IBI). We pursued a similar approach to summarize the stressors that influence streams through development of a multi-metric stress index. We developed this index with two goals in mind: 1) to systematically synthesize the myriad of different potential stressors into a single value; and 2) to provide a relative context for the magnitude of stress acting on any one system relative to other systems.

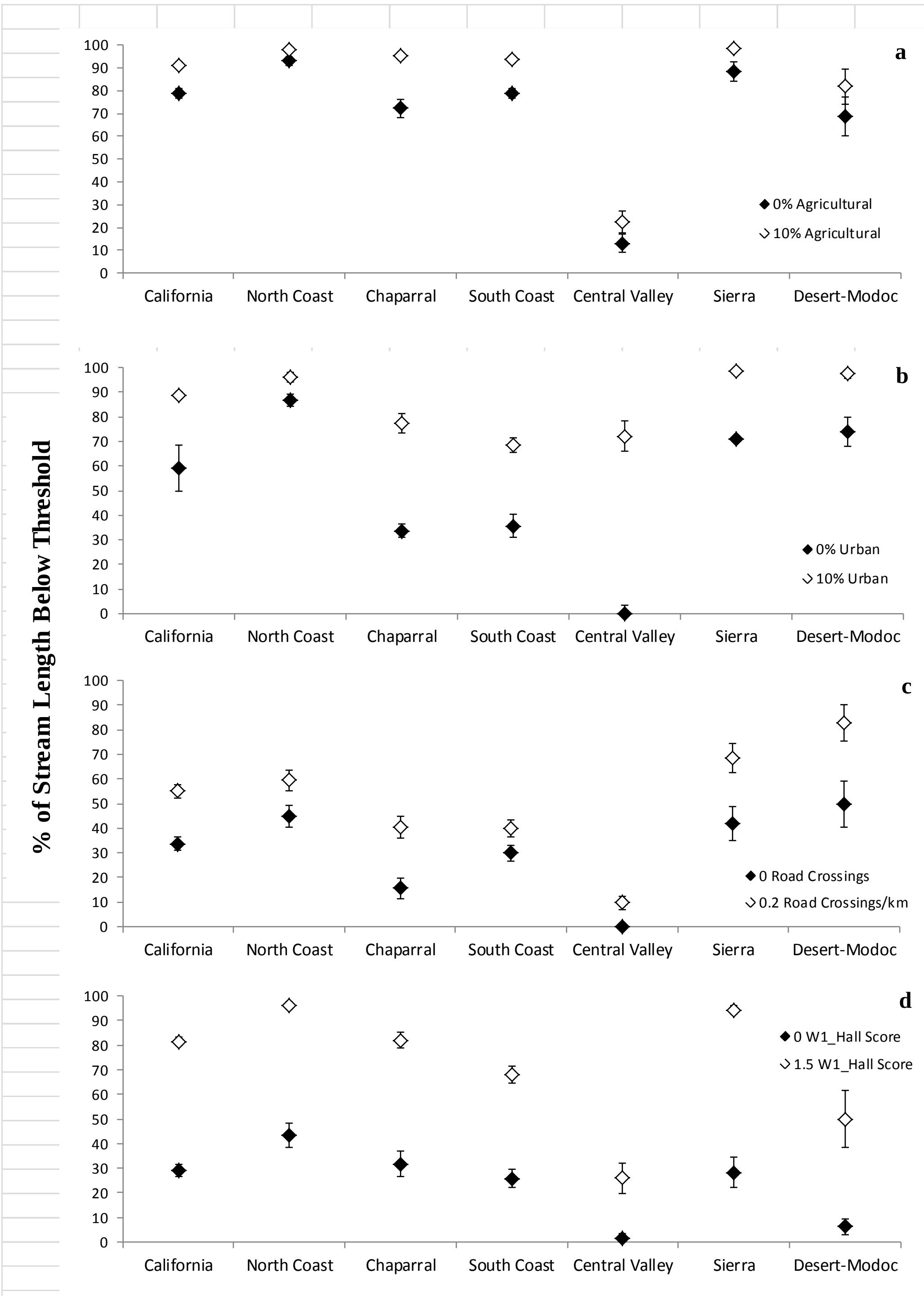

Figure 3: Proportion of stream miles below designated thresholds, statewide and by region.

We focused on the landscape-scale, pressure stressors (e.g., land cover, road density, population, etc.) that can be measured from GIS databases versus proximate, in-stream stressors (e.g., physical habitat, water chemistry) that are measured on site. Using the database compiled for the stressor characterization analysis (see above), we identified a priority set of landscape stressors to evaluate for inclusion in the ultimate index.

To gain an understanding of how the different stressor measures related to each other, 1,590 sampling sites from California's probabilistic biomonitoring programs were ordinated in multivariate space based upon a Principal Components Analysis (PCA) of the different stressor measurements (Figure 4). There was a high degree of covariance amongst the stressor measures, with most of the loading onto principle component axis 1 (PC1); with stressors related to urban development (e.g., % urban land cover, population density, road density, and road-stream crossings) along a gradient with more general stressors (e.g., dams and channelization/canals) on the opposite end. The PC2 axis explained less variation in the ordination (9%), but comprised a secondary gradient of non-urban stressors (agriculture or mining) on one end to grazing and dams and canals on the other end. As expected, measurements a single stressor at the different spatial scales (WS, 5k or 1k) typically clustered together.

Given the large number of stressor measurements and the pattern of covariance amongst them, a subset of representative stressors were selected for index development. For consistency with the State of California's reference program, the full list of 69 stressor measures was culled to match the landscape-scale stressors used to define reference condition in perennial streams for the development of statewide bio-objectives. This reduced list was then modified by aggregating three measures of landcover development (%urban + %agriculture + %Code 21[1]) so that all types of development, regardless of the land use, would be scored similarly. Road density was disaggregated into highways (road class 3) and non-highways (road class 1+2) to reflect the different levels of modification associated with each. Housing and population density from the year 2000 US Census were also added as a stressor measure. This resulted in a list of nine measures used for development of the stressor index (Table 5). Based on previous analysis, the watershed scale was used for land cover metrics and 5k or 1k sub-catchment measures were used for those stressors thought to have an increased impact on the stream with closer proximity.

[1] Code 21 is a NLCD classification covering development associated vegetation

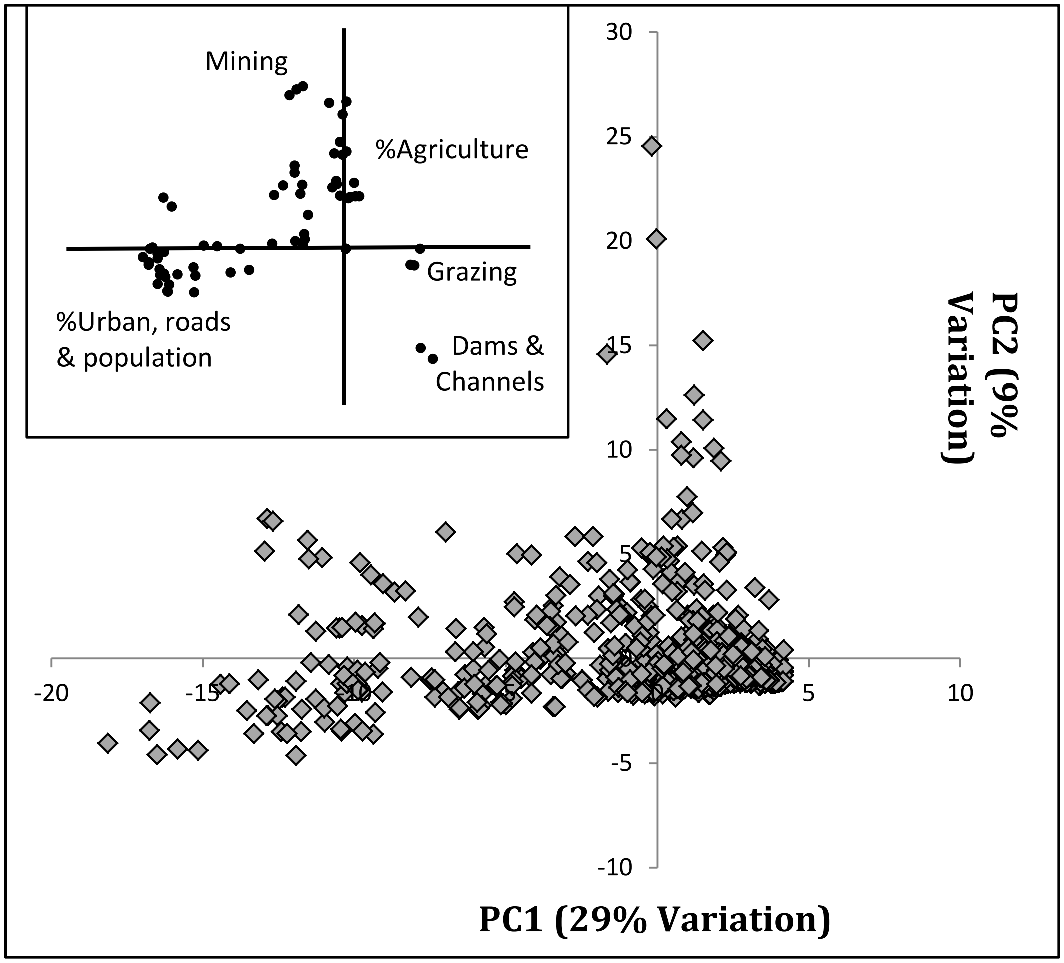

Figure 4: Principle components analysis showing distribution of stressors along gradients of urbanization, agriculture, and general land use. Inset graph shows relative loadings along major gradients of disturbance

Table 5: List of stressors used for index development and scoring thresholds.

Stressor Measure	Units	Scale	Scoring Thresholds				
			5	**4**	**3**	**2**	**1**
Agricultural + Urban + Code21 landcover	%	WS	0.0	>0.0-2.4	>2.4-4.8	>4.8-12.0	>12.0
Stream length designated as artificial	%	5k	0.0	>0.0-0.8	>0.8-1.6	>1.6-4.1	>4.1
Linear density of gravel mines	mines/km	WS	0.0				>0.0
Housing density in 2000	house/km^2	WS	0.0	>0.0-14.0	>14.0-28.0	>28.0-70.0	>70.0
Density of active mines	mines/km^2	WS	0.0	>0.00-0.01	>0.01-0.03	>0.03-0.07	>0.07
Impervious surface landcover	%	WS	0.0	>0.0-0.6	>0.6-1.3	>1.3-3.1	>3.1
Population density in 2000	people/km^2	WS	0.0	>0.0-41.2	>41.2-82.4	>82.4-205.9	>205.9
Class 1&2 road density	km/km^2	WS	0.0	>0.0-0.2	>0.2-0.5	>0.5-1.2	>1.2
Class 3 road density	km/km^2	1k	0.0	>0.0-0.09	>0.09-0.18	>0.18-0.45	>0.45

Each individual stressor measure was assigned an integer score from 1 to 5, with 5 representing the least stress and 1 the most stress. Thresholds for each measure were created as percentages of the observed 90th percentile value for each stressor across the dataset of probabilistically sampled sites: 5 = 0%, 4 = 5%, 3 = 10%, 2 = 25%, and 1 = >25% (Table 5). The 90th percentile was chosen because of the long right-handed skew of nearly all of the stressor measurements. The final index score was calculated as the arithmetic mean of the 9 individual stressor measurement scores.

The first goal of creating the stressor index was to be able to systematically synthesize a large number of stressors experienced by streams in California while still representing their general patterns. Stressor index scores were significantly correlated with principal component axes 1 (r_p= 0.74 p <0.0001) and 2 (r_p= -0.277 p <0.0001) which represents a suite of important stressors acting on streams (e.g., urban development, roads, grazing, mining, and general agriculture; see Figure 4). This confirms that the metrics selected for use in the stressor index represented the major stressors affecting streams in the state.

The second goal for the index was to capture the relative magnitude of measured stressors streams are exposed to. An analysis of variance (ANOVA) comparing stressor index score between reference and non-reference sites within the State of California's biomonitoring program (both probabilistic and targeted sites) showed significantly different scores (p <0.0001; F =917 d.f. 1, 1648). This clear distinction (Figure 5) confirms the stressor index's ability to distinguish the relative magnitude of stressor pressure experienced by streams throughout the state.

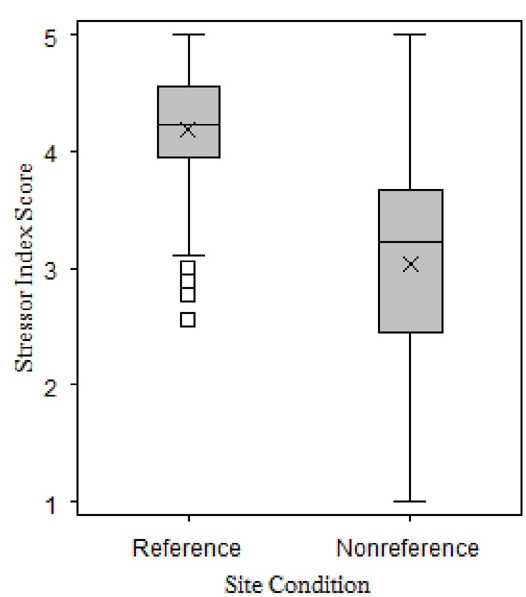

Figure 5: Comparison of reference vs. non-reference based on stressor index score.

Data from probabilistic surveys indicated that 30% of streams are under at least moderate stress (i.e., score 3 or lower), and only 2 % were under no detectable stress. This pattern suggests that, while much of the state's perennial streams experience some degree of anthropogenic influence (Figure 6). The distribution of stressor scores within the different eco-regions of California illustrates similar patterns observed in previous analysis. In the agricultural or urban Central Valley and South Coast regions of the state, more than 50-75% of steam length scored less than 3; indicating a relatively high stressor exposure. Conversely, in the relatively unpopulated, mountainous western sierra and north coast regions of California, more than 34% of the stream length scored above a stressor index score of 4.

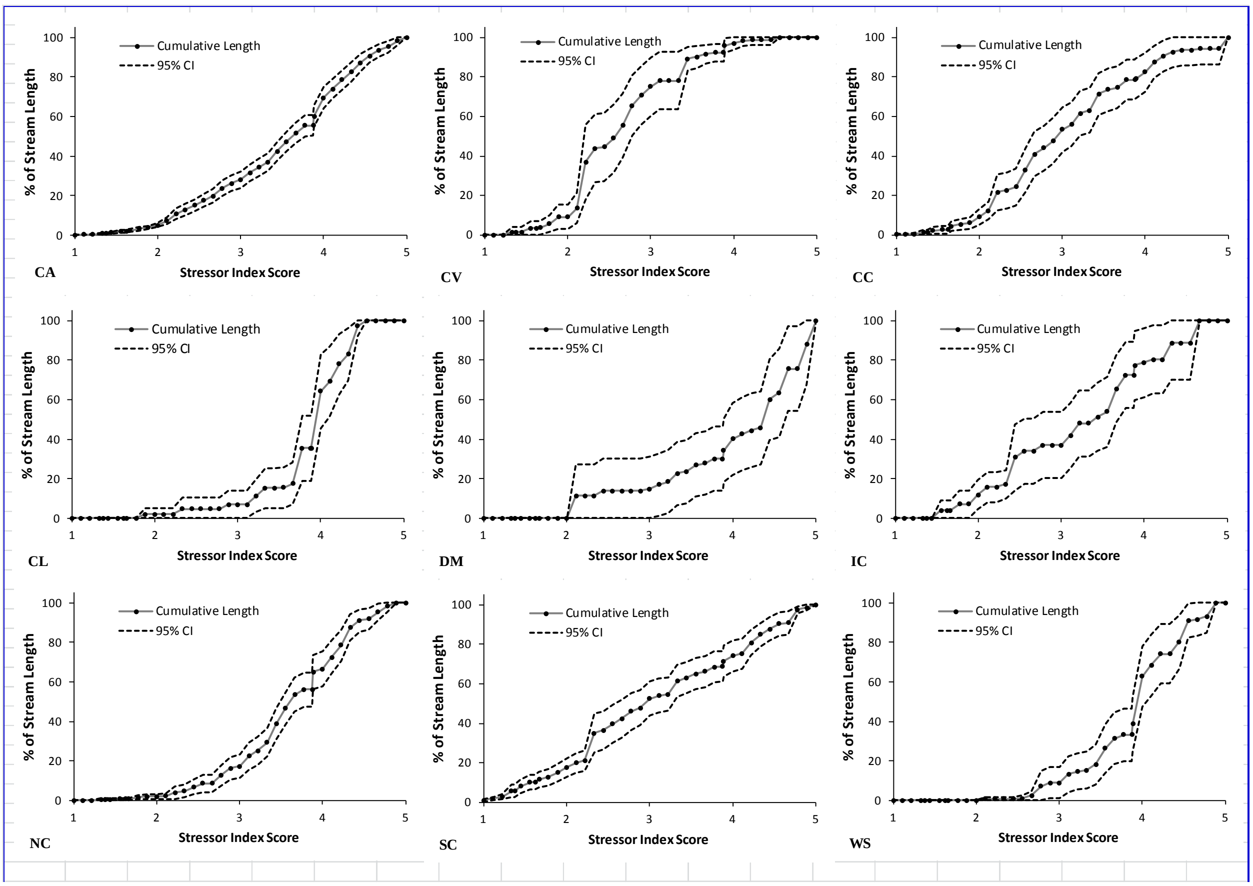

Figure 6: Distribution of stressor index values for the state as a whole and for the different ecoregions. CV=Central Valley, CC= Central Coast, CL = Central Lahonton, DM = Dessert Modoc, IC = Interior Chaparral, = NC= North Coast, SC= South Coast, and WS = Western Sierra.

The stressor index that we have created successfully achieved the goals set forward at the onset of this study: a systematic method for distilling many stressor measures into a single value and providing a relative measure of stress exposure among different streams exposed to different types of landscape-scale influences. This iteration of the index proves that a stressor index, much like more traditional biological indices, can synthesize complex information into more easily comparable numbers (e.g., Brown and Vivas 2005). Future modifications to the index should include calibrating and validating the index scores to measures of in-stream proximate stressors that represent state changes in stream ecosystems and directly influence the biotic resources of streams.

2.3.2 Physical Habitat (Reach-Scale) Multi-metric Index

The SWAMP Physical Habitat (PHAB) protocol is included in many routine bioassessment programs in California. This protocol produces data on the physical and biological structure of stream reaches over a series of 11 transects. Although much useful data is collected, interpretation of this data is challenging due to the lack of a tool (or index) to summarize the data into more readily usable scores. The goal of this task was to use existing PHAB data to identify useful habitat data endpoints. This could include developing a multi-metric index of stream physical condition and stress, or sub-indices targeted to specific components of habitat integrity. The overall process involves the following steps:

1. Develop a conceptual model for the PHAB Index
2. Compile a list of potential metrics based on literature and available data
3. Develop a cross-walk between metrics and components of conceptual model
4. Evaluate metrics based on
    a. Reference vs. non-reference
    b. Signal:noise analysis
    c. Regional differences
5. Develop a conceptual approach to index construction
6. Evaluate metric redundancy
7. Test alternative indices
8. Develop thresholds
9. Validate index with independent data

This grant supported most of Steps 1 through 4. The remaining steps will be completed over the next six months using funding from the State Water Resources Control Board.

2.3.2.1 Conceptual Approach to PHAB Index Development

A draft conceptual framework identifying thematic areas of physical habitat function was developed to guide analysis and interpretation of physical habitat metrics (Figure 7). The physical habitat at a reach is ultimately a product of catchment geology, topography, and climate. These factors determine the hydrologic and sediment regimes that dictate the reach-scale characteristics, such as slope and floodplain morphology, which in turn determine instream habitat features. Human activities can affect biota by directly or indirectly altering any of these pathways.

A stream's physical habitat supports biota in three primary ways. Structural complexity provides diverse microhabitats for attachment, growth, spawning, foraging, or finding refuge from predators or floods. Water quality and quantity create physicochemical conditions required by stream biota. The energy source of the stream, particularly the relative contributions of allochthonous or autochthonous organic matter, creates the trophic basis for the food web. Physical habitat metrics that characterize these factors and their influence on stream biota were grouped into the following thematic areas. An additional thematic area that characterizes stress from human activity was also identified:

- Channel morphology
- Hydrology
- Instream habitat – flow microhabitat complexity
- Instream habitat – Streambed substrate composition
- Instream habitat – cover types
- Riparian vegetation complexity
- Energy source – allochtonous and autochtonous
- Stress

Definitions of each of these thematic areas and the candidate metrics that relate to them are provided in Appendix B.

This framework was based on types of data generated by current protocols and therefore does not accommodate all aspects of physical habitat integrity or ecosystem function. Furthermore, the divisions among these thematic areas reflect the emphasis of current protocols, rather than an implied equal importance of each theme to physical habitat integrity.

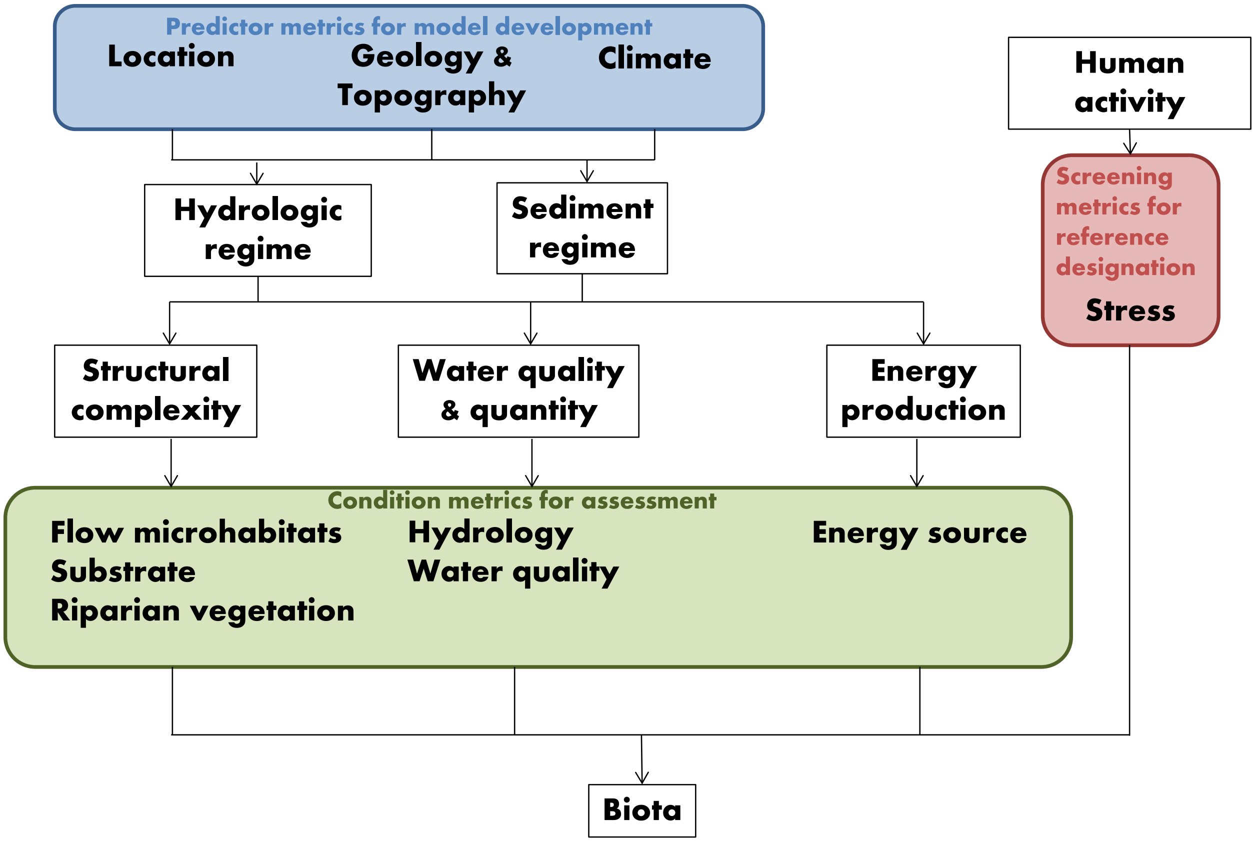

Figure 7: Conceptual framework (model) for development of PHAB Index. The red and green boxes indicate elements measured directly as part of the physical habitat protocol. The blue box indicates elements measured during landscape analysis using geographic information systems.

2.3.2.2 PHAB Index Development

A total of 776 sites with adequate physical habitat data were assigned to one of three stress classes, based on the intensity of human activity in the watershed or nearby to the site. First, catchments were delineated for each site. Land use metrics were calculated for each site at the watershed scale, as well as within 5 km or 1 km of the site. The RCMP criteria were then used to identify sites as reference, stressed, or intermediate (see Table 6). This list was then re-evaluated, and sites that were considered to be disturbed by best professional judgment but still met all reference criteria were reclassified as intermediate sites. Any sites that did not meet the criteria for either the reference or highly stressed conditions were designated as intermediate.

Table 6: Criteria used to identify reference and stressed sites. A site had to meet all reference criteria to be considered a reference site. A site had to meet any stress criteria to be considered a stressed site.

Variable	Scale	Reference Criteria	Stress Criteria
% Agriculture	1k	<3%	
	5k	<3%	
	WS	<3%	
% Urban	1k	<3%	
	5k	<3%	
	WS	<3%	
% Ag + % Urban	1k	<5%	
	5k	<5%	
% Code 21	1k	<7%	
	5k	<7%	
	WS	<10%	
Road density	1k	<2 km/km^2	
	5k	<2 km/km^2	
	WS	<2 km/km^2	
% Ag + % Urban+ % Code 21	1k		≥50%
Road crossings	1k	<5/km^2	
	5k	<10/km^2	
	WS	<50/km^2	
Dam distance	WS	>1 km	
% canals and pipelines	WS	<1%0	
Instream gravel mines	5k	<0.1/km	
Producer mines	5k	<1	
Specific conductance (if available)	site	99/1*	
W1_HALL (if available)	site	<1.5	≥5

**The 99th and 1st percentiles of predictions were used to generate site-specific thresholds for specific conductance. Because the model was observed to under-predict at higher levels of specific conductance (data not shown), a threshold of 2000 µS/cm was used as an upper bound if the prediction interval included 1000 µS/cm.*

Of the 776 sites that were screened, 352 were identified as reference, 132 as stressed, and 292 as intermediate. Eighty percent of each set was reserved for model calibration, and twenty percent for validation and performance evaluation, as described below.

Random forest models of metric values were built for each metric based on natural catchment characteristics to predict metric values under undisturbed conditions, calibrated with only reference sites. Models were based on a suite of landscape predictors thought to affect stream habitat characteristics, but not likely to be affected by human activity (summarized in the Table

7). Because these models were developed from reference sites and based on watershed characteristics resistant to disturbance, they may be used to predict metric values that would occur at test sites under low levels of disturbance.

Table 7: Predictors and their importance for random forest models of each endpoint and metric. MSE: Mean-squared error. Dashes indicate that the predictors were not used to model the metric.

Predictor	Description	Source
Location		
New_Long	Longitude	
New_Lat	Latitude	
SITE_ELEV	Elevation	A
Catchment		
LogWSA	Log watershed area	A
ELEV_RANGE	Difference in elevation between sample point and highest point in catchment	A
Climate		
TEMP_00_09	10-y (2000-2009) average tempearture	B
PPT_00_09	10-y (2000-2009) average precipitation	B
SumAve_P	Average of mean June to Sep 1971 to 2000 monthly ppt	B
Geology		
KFCT_AVE	Average soil erodibility factor (K)	C
BDH_AVE	Average bulk density	C
MgO_Mean	% MgO geology	C
Log_P_MEAN	Log % P geology	C
CaO_Mean	% CaO geology	C
PRMH_AVE	Average soil permeability	C
S_Mean	% S geology	C
PCT_SEDIM	% Sedimentary geology	C
LPREM_mean	Average log geometric mean hydraulic conductivity	C
Log_N_MEAN	Log % N geology	C

Sources: A. National Elevation Dataset (http://ned.usgs.gov/). B. PRISM climate mapping system (http://www.prism.oregonstate.edu). C: Generalized geology, minerology, and climate data from conductivity prediction model (Olson and Hawkins 2012).

To select predictors for each model, we used a recursive feature algorithm (RFE) from the R package Caret (v. 5.15-61). This algorithm builds a series of random forests models in which predictor variables were recursively removed until an optimal model was found, based on reductions in the root-mean-square-error of the model.

Model accuracy was assessed as the percent of variance (calculated as 1 – mean squared error/variance) explained by the model. If the variance explained was greater than 20%, raw metrics were not considered for further evaluation.

In order to identify responsive metrics, the distribution of residuals at reference sites were compared to those at stressed sites. Because response to stress can be bi-directional, the 5^{th} and 95^{th} percentiles of the reference calibration data set were calculated for each metric residual to identify a range defining the reference condition. If fewer than 80% of stressed sites were within this range, the metric was considered to be responsive. Metrics with a positive response to stress were identified as those where more than 10% of stressed sites had residuals above the 95^{th} percentile of reference calibration sites, and metrics with a negative response to stress were identified as those where more than 10% of stressed sites had residuals below the 5^{th} percentile; metrics meeting both of these criteria were identified as having a bidirectional response to stress. The overall strength of response was quantified as the percent of non-reference sites with residuals outside the reference range. These evaluations were performed separately for the calibration and validation data sets. Metrics were then ranked for strength of response within thematic area based on the calibration data. Metric evaluations are summarized in Appendix C.

Predictive modeling successfully explained a large proportion (>20%) of the variance in 13 metrics across thematic areas. The most successful model was for XCDENMID (% shading), which was based on six predictors (watershed area, elevation, longitude, precipitation, temperature, and bulk soil density) and explained 50% of the variance (Figure 8). Other thematic areas with successful models include channel morphology (e.g., bankfull width), instream flow microhabitats (% slow water), instream cover (filamentous algae cover), instream substrate composition (e.g., % sands and fines), and riparian vegetation (e.g., mean canopy cover). Channel morphology results suggest that reference sites have smaller bank dimensions than non-reference sites. It is unclear if these results truly represent a response to stress, or instead reflect the preponderance of stressed sites in larger systems. The high variance explained by the random forest models for bankfull width suggests that at least some of this difference reflects a true response, as some of the environmental confounding has been eliminated by using model residuals. Many metrics related to energy source showed a strong positive response to stress, perhaps reflecting eutrophication or nutrient enrichment. Metrics related to instream flow microhabitat had weak responses to stress, with only % glide showing a strong response in both calibration and validation data. However, models with strong explanatory power could not be found for many of the metrics, suggesting that the relationship to predictive variables are weak or mediated through unmeasured environmental factors.

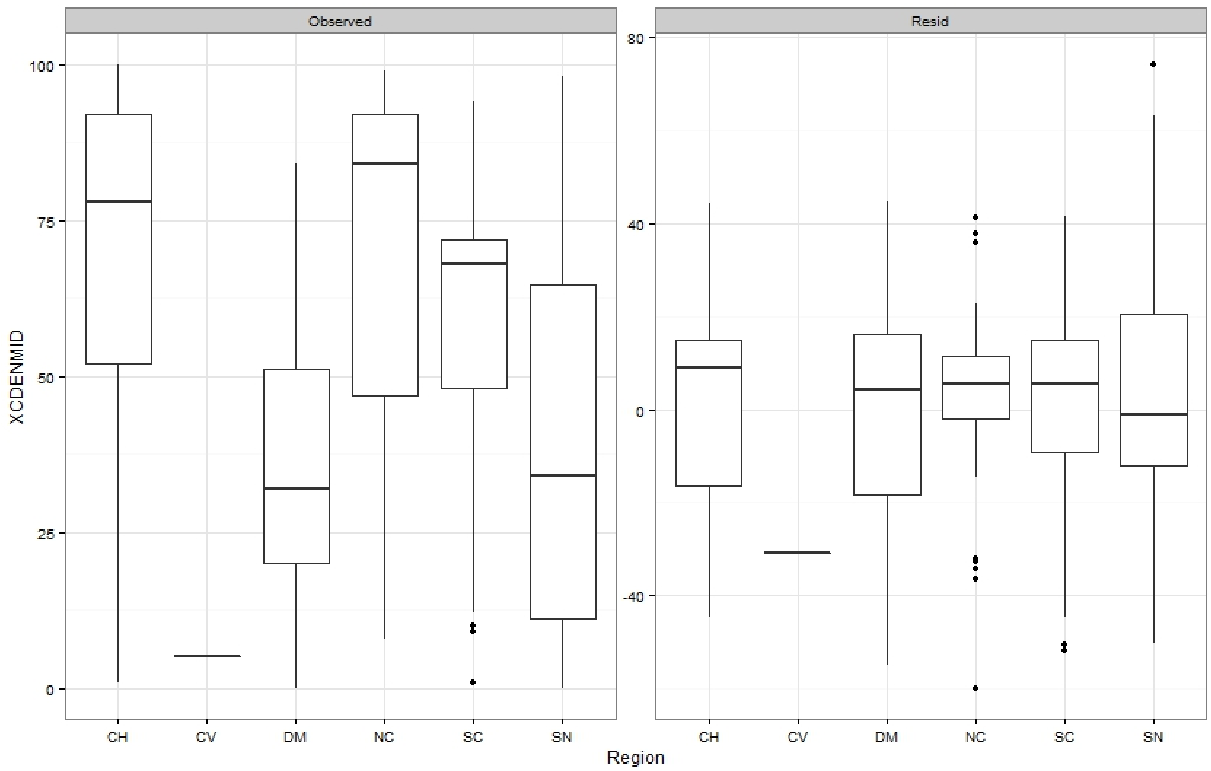

Figure 8: Boxplot plot of observed (left) and residual (right) metric scores for stream shading by region. Only reference data are plotted.

Nonetheless, several of the evaluated metrics were responsive to stress. Percent cover of thick microalgae showed the strongest response, with 44% of non-reference sites having a metric residual value outside the reference range. Natural shelter cover also showed a clear separation between stressed and non-stressed sites (Figure 9). Other responsive metrics were related to energy source (e.g., macrophyte cover), cover types (e.g., natural shelter cover), substrate (e.g., % sands and fines), flow microhabitat (% glides) and riparian vegetation (e.g., moderate riparian ground cover presence). Strong responses (i.e., >20%) were observed for metrics in all thematic areas.

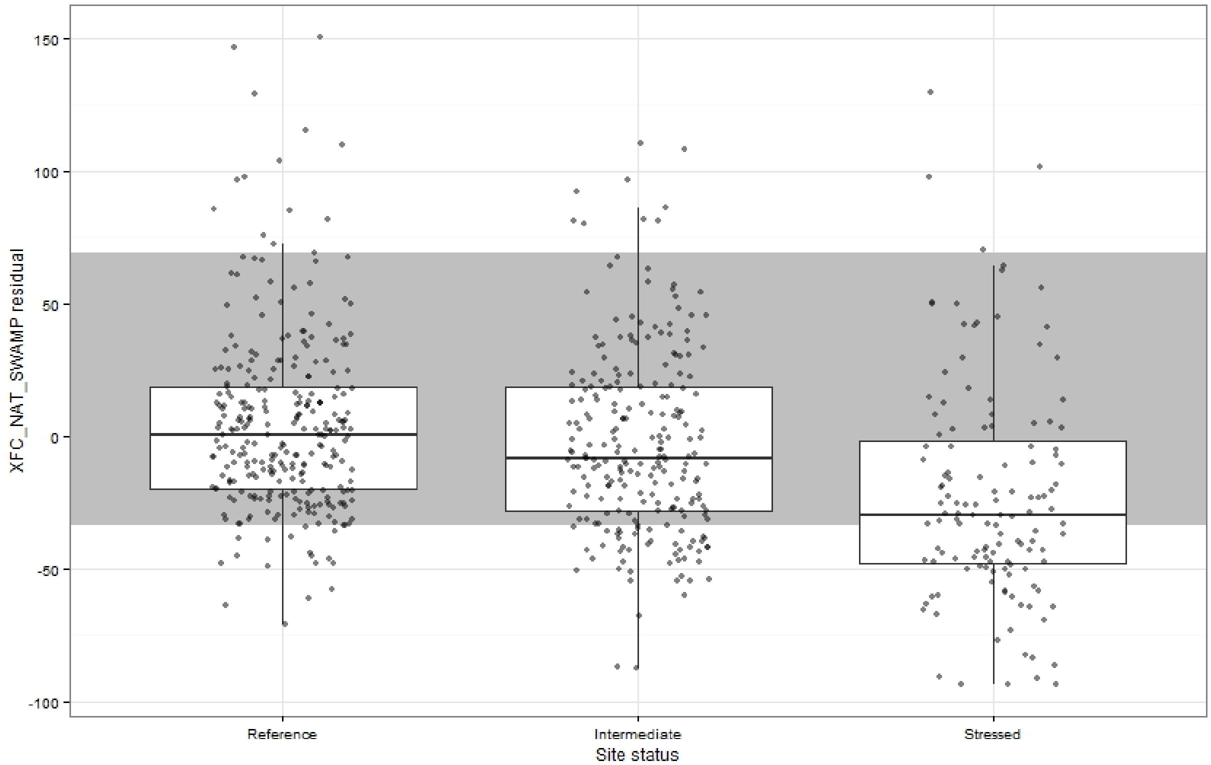

Figure 9: Distribution of residuals for the XFC_NAT_SWAMP metric, showing a negative response to stress. Each site is shown as a point overlaying a boxplot. The gray band in the background represents the range of values considered to be in reference condition based on the 5th and 95th percentiles of the reference calibration data set.

Next steps in development of the PHAB index include the following:

- Explore role of diversity metrics in index performance in more detail
- Analyze relationships between metrics and specific stressor gradients.
- Evaluate index aggregation methods.
- Validate metrics and indices with novel data.

2.4 Task 4: Development of a Framework for Integrated Indices of Wetland Ecosystem Condition

The objective of this task was to explore whether the California Rapid Assessment (CRAM) and Physical Habitat (PHAB) bioassessement protocols exhibit redundancy that could be reduced by streamlining the two methods. Because both types of data are regularly collected at several monitored locations in California, potential reduction of redundancy between the two protocols could result in saved resources. The approach to accomplishing these goals began with the development of a conceptual model to identify potential areas of redundancy. This was followed by analyses of the agreement between key CRAM and PHAB metric data to determine how similarly the two methods assess environmental conditions. Lastly, correlation analyses using field data from both protocols were used to further investigate where conclusions about environmental conditions may overlap between the two methods.

2.4.1 Conceptual Model and Approach

A conceptual model showing similarities between the ecological attributes measured via CRAM and PHAB was created to identify areas of metric redundancy. The model was developed by a team of researchers highly familiar with both protocols. The team identified which ecological attributes were represented in CRAM and PHAB protocols, and which attributes overlapped between the two assessments. The conceptual model indicated that several attributes may overlap between CRAM and PHAB (Table 8). However, it also indicated CRAM assesses some items PHAB does not, and vice versa.

CRAM data collected during 2008-2011 were obtained from the Southern California Stormwater Monitoring Coalition (SMC) monitoring program. SMC monitoring sites are all located in Southern California. Coordinated CRAM data collection through SMC began in 2008. PHAB data were obtained from the statewide database (described in previous sections). There were 295 sites with both CRAM and PHAB data. For sites where both CRAM and PHAB data were collected more than once during 2008-2011, one sampling event was randomly selected to represent each site.

To assess the similarity of PHAB and CRAM's assessment of environmental conditions, data of select components were examined for agreement. Six CRAM components were compared with conceptually corresponding PHAB metrics. Scores of each of four CRAM attributes and raw counts of patch types and stressors were used because there is a broader range of possible scores. Other CRAM metrics assign 3, 6, 9, or 12 points to observations, and the resulting variation in data is too low for this analysis.

Data sets for each CRAM or PHAB metric were divided into quartiles to evaluate agreement. For each corresponding CRAM and PHAB dataset, the numbers of samples where data existed in agreeing quartiles (1st, 2nd, 3rd, or 4th) were summed. The sum was calculated as a percent of the total samples included in each comparison.

Potential redundancy between CRAM and PHAB measurements was evaluated using Pearson's correlation. The metrics selected represented the cases of hypothesized overlap identified through the conceptual model (Table 8). Based on the hypothesized redundancies, 578 individual comparisons were examined. These involved 18 types of CRAM measurements and

91 types of PHAB measurements. All calculations and statistical analyses were performed using R x64 v12.5.3 (R Core Team 2013).

Table 8. Conceptual model of similarities and differences between ecological components evaluated by the California Rapid Assessment Method (CRAM) and Physical Habitat (PHAB) bioassessement.

System Component	Sub-component	CRAM	PHAB
Buffer/Landscape	Buffer	3 metrics (extent/width/quality)	human influence
	Watershed context	stressor checklist	Landscape setting
		none	human influence (50m) slope & sinuousity
		longitudinal continuity (riparian)	none
Hydrology	none	water source	human influence (pipes, outlets)
		channel stability	bankfull width & wetted width embeddedness bank stability deposition
		channel flood plain	bankfull width & wetted width deposition
		none	flow (velocity)
Physical	Instream	patch types	instream flow habitats (riffles, pools, etc.) instream habitat complexity particle size distribution algal cover & macrophyte cover embeddedness faunal substrate
		none	deposition
	Floodplain	topocomplexity	cross-sections
Biotic	Structure	vertical structure	riparian vegetation
		interspersion	riparian vegetation
	Composition	# plant layers	riparian vegetation macrophyte cover
		exotics codominants	none
	Productivity	none	algal cover & macrophyte cover CPOM

2.4.2 Results and Discussion

The summed agreement of key components between CRAM and PHAB metrics across quartiles ranged from 15% to 50% (Table 9). The two most highly agreeing comparisons were between CRAM Biotic Structure and PHAB Riparian Vegetation all 3 layers present (XPCMG, 45%) and CRAM Stressor Count and PHAB Combined Riparian Human Disturbance Index (W1_HALL_SWAMP, 50%; Figure 10). Both the CRAM Buffer and Landscape and Hydrology Attributes exhibited very high disagreement with W1_HALL_SWAMP (85% and 82%, respectively). The limited agreement is likely explained by the fact that CRAM evaluates overall condition of the riparian zone, while PHAB focuses more on in-stream habitat as it relates to aquatic organisms. Both methods address stressors and vegetation community, explaining why they agree in those areas. Future work will investigate the relationship between both methods and biological data.

Table 9. Key California Rapid Assessment Method (CRAM) components and Physical Habitat (PHAB) bioassessment metrics compared in the agreement analysis.

CRAM Component	PHAB Metric	n	% Agreement
Buffer and Landscape Context	W1_HALL_SWAMP	294	15
Hydrology	W1_HALL_SWAMP	294	18
Physical Structure	XFC_NAT_SWAMP	294	30
Patch Type Count	XFC_NAT_SWAMP	289	32
Biotic Structure	XPCMG	294	45
Stressor Count	W1_HALL_SWAMP	294	50

There was generally low correlation between metrics hypothesized to be similar (Appendix D). Of 578 correlations, only 10 yielded Pearson's R^2 values above 0.5 (Figure 11). The strongest correlations occurred between the PHAB Mean Bank Shade metric (XCDENBK) and CRAM Biotic Structure and Vertical Biotic Structure measurements (Pearson's R^2 = 0.784 and 0.625, respectively). Combined Riparian Human Disturbance Indices (W1_HALL_EMAP and W1_HALL_SWAMP) from PHAB and CRAM measurements influenced by human impacts or stressors (CRAM Index Score, Buffer and Landscape Context, Percent of Assessment Area with Buffer, and Stressor Checklist Count) showed fair correlation strengths (for W1_HALL_EMAP, Pearson's R^2 = 0.525, 0.528, 0.535, 0.505; for W1_HALL_SWAMP Pearson's R^2 = 0.548, 0.569, 0.571, 0.561 for comparison with CRAM Index, Buffer and Landscape, Percent of AA with Buffer, and Stressor Checklist, respectively).

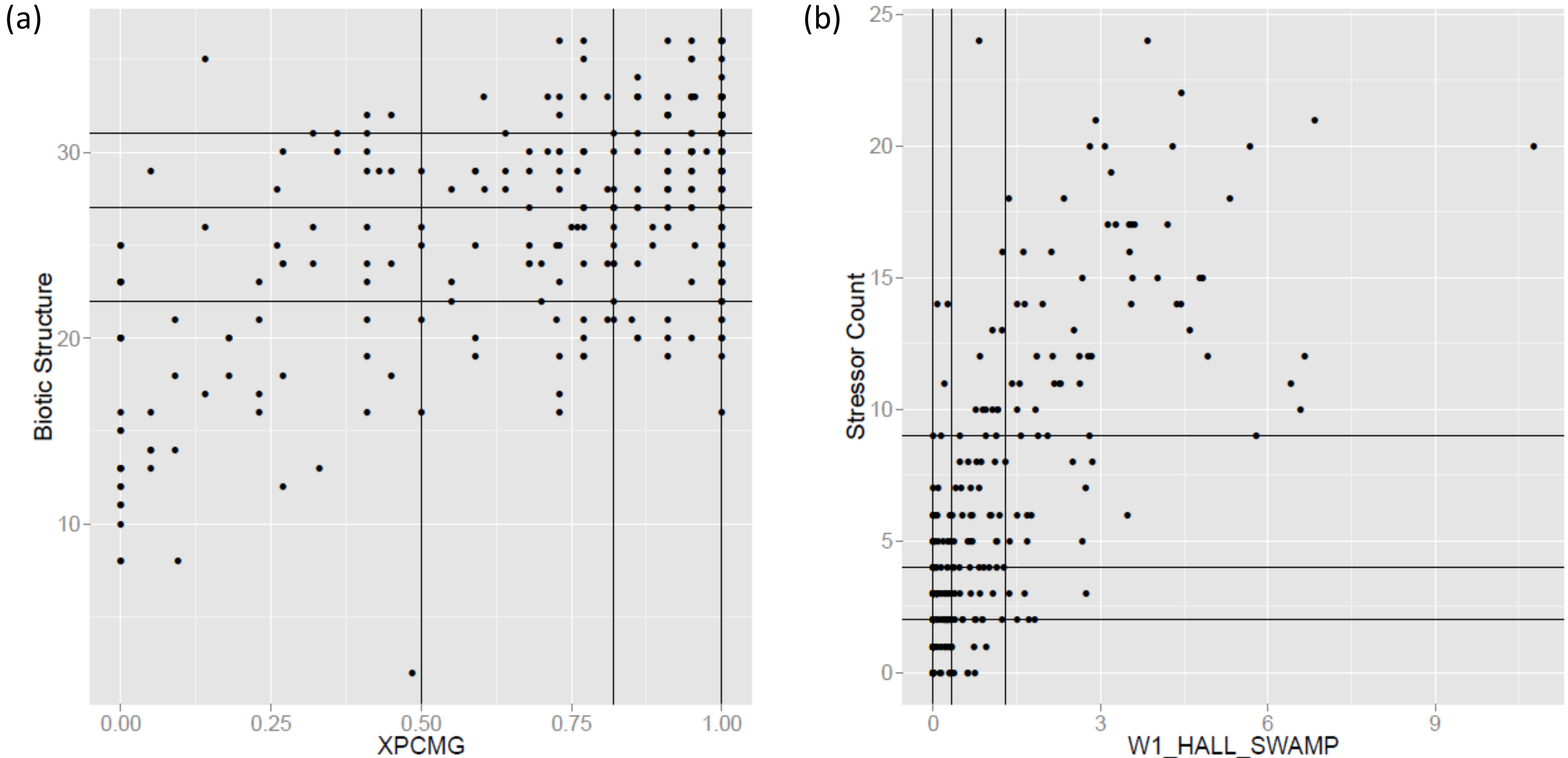

Figure 10. California Rapid Assessment Method (CRAM) and Physical Habitat (PHAB) bioassessment key metric agreement. Each point represents one sample. The lines divide the quartiles of each data type. The protocols were considered in agreement for a sample if components of both methods fell into the same quartile. Cumulative agreement in 1st – 4th quartiles between (a) CRAM Biotic Structure and PHAB XPCMG was 45%; agreement between (b) CRAM Stressor Count and PHAB W1_HALL_SWAMP (Combined Riparian Human Disturbance Index) was 50%.

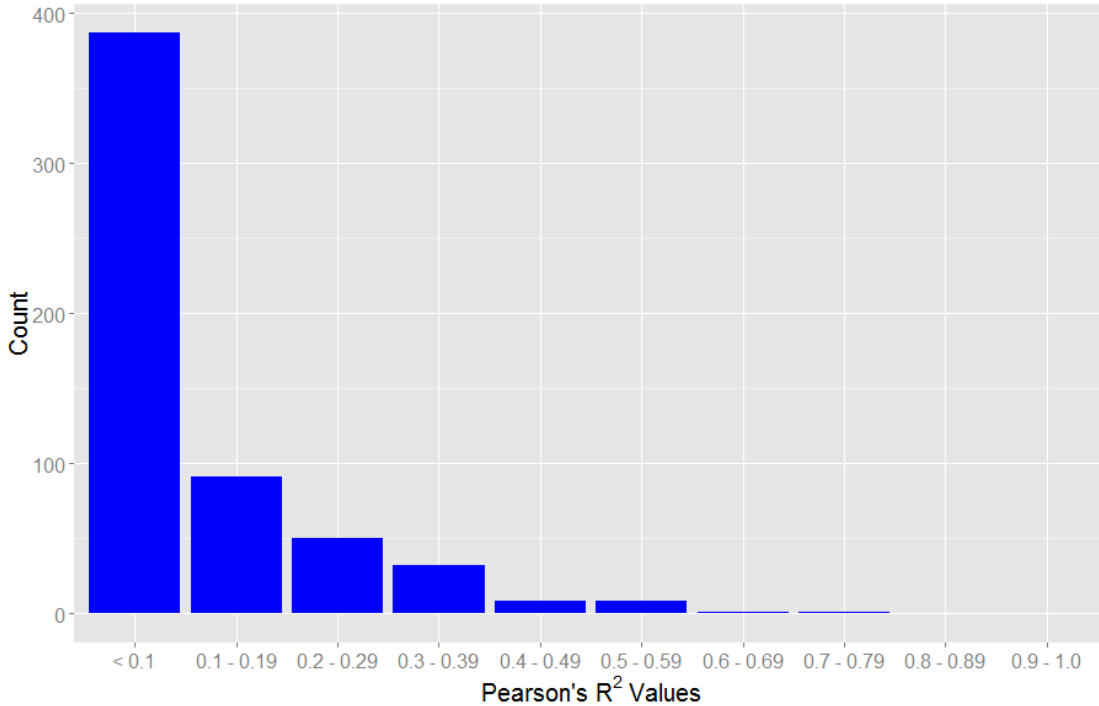

Figure 11. Distribution of Pearson's R^2 values from correlations of California Rapid Assessment Method (CRAM) components and Physical Habitat (PHAB) bioassessment metrics for which similarities were hypothesized using the conceptual model (n = 578 hypothesized similarities).

Overall, there was little redundancy between CRAM and PHAB. This is likely due to two factors. First, the two methods are focused on very different endpoints. CRAM evaluates the entire riparian ecosystem and a relatively gross scale, whereas PHAB focuses on the ability of instream habitat to support taxa of interest (e.g., benthic invertebrates, algae, and fish). Consequently, the focus of PHAB is on finer scale features within the stream than CRAM. Secondly, the two methods collect data differently, making comparisons challenging. PHAB relies on semi-quantitative data at a relatively high spatial resolution. In contrast, CRAM produces semi-qualitative data at the overall reach or site scale.

Some of the selected CRAM and PHAB metrics exhibited moderate correlation, but most displayed weak agreement. This could partially be due to fundamental differences between the metrics used for comparisons. For example, the CRAM Biotic Structure attribute integrates information about plant vertical structure and layering, horizontal interspersion, and the degree of exotic invasion throughout an entire assessment area, whereas the closest PHAB analogue in the agreement analysis, XPCMG, is based only on whether three layers of riparian vegetation are present at a finite number of study points along the stream. The conceptual similarity between these Biotic Structure and XPCMG is small, so it is logical that the metric results would disagree. Likewise, substrate diversity measures in PHAB are much more sophisticated than the analog in CRAM so these two measures also disagree.

We do not recommend additional redundancy analysis at this time because our analyses suggest the protocols are complimentary rather than redundant. Although, correlation analysis indicated similarities between a few PHAB and CRAM components, they were not strong enough to suggest high redundancy. When PHAB metric-based multi-metric indices are developed, it may be useful to search for redundancy between the new indices and CRAM data to explore their responses to environmental conditions. However, it is unlikely that redundancy between the two types of indices would lead to a reduction of one of the methods because the two methods assess environmental conditions differently. CRAM focuses on the health of the overall riparian community in terms of structure and setting, whereas PHAB focuses more on the health of in-stream habitat and its ability to support aquatic organisms.

3. Next Steps

Assessing condition of natural systems is complicated by the fact that there are multiple potential indicators and each indicator may respond to stress in different ways. Furthermore, systems are consistently affected by both natural and anthropogenic factors that interact to affect overall condition.

Comprehensive assessment requires an available suite of tools that can be used together to understand various aspects of condition and ultimately to help inform management actions to remedy stress. It has been established that some indicators are more effective in describing ecological condition than others. There are “core” indicators that can be used to characterize condition regardless of stream type and geographic domain, and “supplemental” indicators that are more effective for specific stream types or regions. Multiple indicators are needed to account for the different sensitivities each indicator has for different stressors. Although most biological indicators integrate impacts from multiple stressors, each indicator has its own strengths and weaknesses. Using multiple indicators in tandem provides greater sensitivity to more types of impacts, and over a greater range of the disturbance gradient.

The research funded by this grant moves us much closer to the ability produce integrated assessments of condition by providing tools that supplement the existing benthic invertebrate and algal based assessments.

Future steps to continue progress toward the long-term goal of integrated assessment include

- Explore the need to calibrate reference definitions by region or stream types, particularly in naturally stressed environments (e.g., arid systems) or chronically impacted systems.
- Complete the development of landscape and reach-based stressor evaluation tools that was initiated through this work.
- Compare CRAM components with PHAB MMI components once they are developed. Although specific metrics do not appear to overlap, MMI results from either protocol should exhibit similar responses to environmental conditions.
- Continue to develop a framework for using the results from multiple assessment approaches to inform management decisions. This could be in the form decision matrices, weight of evidence approaches or combination of indices.
- Expand analysis of the relationship between stressors and specific assessment endpoints. This may ultimately include manipulative studies and/or molecular approaches to stressor evaluation
- Evaluate responsiveness of CRAM and PHAB to biological indices based on benthic macroinvertebrates and algae.
- Purse development of an integrated stressor index that includes an assessment of the "restorability of the stream"
- Explore the application of this work in non-perennial systems.

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5. Appendices

Appendix A – Sources of Geospatial Data for Stressor Analysis

Type of spatial data	Source or Model	Reference
Population and housing density	US Census 2000	http://www.census.gov/
Predicted surface water conductivity	Quantile regression forest model (Meinshausen 2006)	Olson and Hawkins (in Review)
Vegetation	MODIS Satellite Imagery from Land Processes Distributed Active Archive Center	http://lpdaac.usgs.gov
Groundwater	MRI-Darcy Model (Baker et al. 2003)	Olson and Hawkins (in Review)
Waterbody location and attribute data	NHD Plus	http://www.horizon-systems.com/nhdplus/
Dam location, storage	National Inventory of Dams	http://geo.usace.army.mil/
Land cover, imperviousness	National Land Cover Dataset (2001)	http://www.epa.gov/mrlc/nlcd-2006.html
Watershed boundaries	Major watershed boundaries	http://www.ca.nrcs.usda.gov/features/calwater/
Mine location and attribute data	Mineral Resource Data System	http://tin.er.usgs.gov/mrds/
Discharge location and attribute data	California Integrated Water Quality System	http://www.swrcb.ca.gov/ciwqs/
Road location and attribute data	Custom GIS Layer	
Railroad location and attribute data	Custom GIS Layer	
Ecoregion	US EPA Level III and IV Ecoregions of the United States	http://www.epa.gov/wed/pages/ecoregions/level_iii_iv.htm
Federal Grazing Allotments	US Forest Service Grazing Allotments	http://www.fs.fed.us/r5/rsl/clearinghouse/gis-download.shtml
	BLM Grazing Allotments	http://www.blm.gov/ca/st/en/res/index/data_page.html

Appendix B – Definitions and Candidate Metrics for Development of PHAB Index

Channel Morphology

Channel morphology reflects the shape, size, and physical orientation of a stream. It is sometimes the major driver of many instream characteristics of a reach, dictating flow and sediment regimes and other processes that create instream habitat. Although many channel morphology metrics are resilient to some disturbances, they may be directly altered in engineered channels, or change in response to hydromodification. For example, channel incision may reduce the slope of a reach or destabilize banks. Certain aspects of channel morphology (such as thalweg profile or bank angle) are not characterized by current protocols.

Metric	Description
XSLOPE	Mean Slope of Reach
XBKF_H	Mean Bankfull Height
XKBF_W	Mean Bankfull Width
PBM_E	Percent Eroded Banks
PBM_S	Percent Stable Banks
PBM_V	Percent Vulnerable Banks
Slope_0	Percent 0% Slope
Slope_0_5	Percent 0.5% Slope
Slope_1	Percent 1% Slope
Slope_2	Percent 2% Slope
XBEARING	Mean Direction of Reach Flow
SINU	Sinuosity

Hydrology

Hydrologic metrics reflect the amount of water at a site. The quantity of water, interacting with channel morphology, gives rise to many of the instream habitat characteristics that are important for wildlife. Hydrologic metrics may be altered by diversions, flow regulation, groundwater withdrawals, climate change, and other human activity, as well as by natural variability in weather. Certain aspects of hydrology, such as water sources, are not characterized by current protocols.

Metric	Description
XWIDTH	Mean Width of Wetted Channel
XWDEPTH	Mean Water Depth
XWDM	Mean of Deepest Depth within Transects
XWDA	Mean Cross-Sectional Area
XWDR	Mean Wetted Width/Depth Ratio
XWV_M	Mean Water Velocity (m/s)
MWVM_M	Maximum Water Velocity (m/s)
PWVZ	Percent Zero Velocity Measurements
FL_M	Flow Discharge

Water quality

The physicochemical conditions are a product of water quantity and catchment geology, and may be modified by biological processes or by reach-scale features of a stream, such as microtopography or stream shading. Human activity can alter water quality by contributing pollutants, changing water source or quantity, modifying canopy cover, or altering biogeochemical processes. The influence of water quality on biota has long been recognized, and concern about these links prompted the earliest uses of bioassessment using benthic macroinvertebrates and diatoms.

Metric	Description
XWAK	Mean Water Alkalinity
XWDO	Mean Water Dissolved Oxygen
XWPH	Mean Water pH
XWSC	Mean Water Specific Conductivity
XWSL	Mean Water Salinity
XWTB	Mean Water Turbidity
XWTC	Mean Water Temperature (C)

Instream habitat – Flow microhabitat complexity

Flow microhabitat metrics describe the microhabitat patches created by different velocity and depth regimes, such as the abundance of riffles or pools. These microhabitats are strongly associated with the types of fauna found within a reach, with certain taxa being associated with fast- or slow-water habitats respectively. Several management activities may simplify the diversity of flow regimes observed within a reach. For example, increased sedimentation may fill pools and convert them to glides or other microhabitat types, altering the biota found therein.

Metric	Description
PCT_CF_WT	Percent Cascade/Falls of Reach Wet Habitats
PCT_GL_WT	Percent Glide of Reach Wet Habitats
PCT_POOL_WT	Percent Pool of Reach Wet Habitats
PCT_RA_WT	Percent Rapid of Reach Wet Habitats
PCT_RI_WT	Percent Riffle of Reach Wet Habitats
PCT_RN_WT	Percent Run of Reach Wet Habitats
PCT_SLOW_WT	Percent Slow Water of Reach Wet Habitats
PCT_FAST_WT	Percent Fast Water of Reach Wet Habitats

Instream habitat – Streambed substrate composition

Characterizing the composition of the streambed through pebble counts is a major emphasis of the current protocols. Streambed particle size distributions have been widely shown to have a large influence on the biota found at a site, as only certain types of particles create the type of substrate or interstitial spaces required for certain taxa. Several types of human activities can increase (e.g., unmanaged soil disturbance) or decrease (e.g., creation of upstream impoundments) the relative proportion of fine particles in a stream, and engineering may partially or completely replace the streambed with artificial substrate.

Metric	Description
PCT_FN	Percent Fines
PCT_SA	Percent Sand
PCT_GF	Percent Gravel - fine
PCT_GC	Percent Gravel - coarse
PCT_CB	Percent Cobble
PCT_SB	Percent Boulders - small
PCT_XB	Percent Boulders - large
PCT_RR	Percent Bedrock - rough
PCT_RS	Percent Bedrock - smooth
PCT_BDRK	Percent Substrate as Bedrock
PCT_RC	Percent Concrete/Asphalt
PCT_HP	Percent Hardpan
PCT_OT	Percent Other Substrate
PCT_WD	Percent Wood
PCT_SAFN	Percent Substrate Smaller than Sand (<2 mm)
PCT_SFGF	Percent Substrate Fine Gravel or Smaller (<16 mm)
PCT_BIGR	Percent Substrate Larger than Fine Gravel (>16 mm)
SB_PP_D10	Particulate Particle Size 10th (d10)
SB_PP_D25	Particulate Particle Size 25th (d25)
SB_PP_D50	Particulate Particle Size Median (d50)
SB_PP_D75	Particulate Particle Size 75th (d75)
SB_PP_D90	Particulate Particle Size 90th (d90)
XSDGM	Geometric Mean Substrate Diameter (Dgm)
XSPDGM	Geometric Mean Diameter of Particulate Substrate
XEMBED	Mean Cobble Embeddedness - channel/margin

Instream habitat – Cover types

Substrate composition alone does not characterize the types of habitat or cover a healthy stream provides. Macrophytes, woody debris, and overhanging banks may also provide refugia for biota. Several management activities modify the natural hydrologic regimes that generate some of these cover types, or directly remove them to improve flood control.

Metric	Description
CFC_ALG	Filamentous Algae Present
CFC_ALL_EMAP	Shelter Types Richness - EMAP
CFC_ALL_SWAMP	Shelter Types Richness - SWAMP
CFC_AQM	Aquatic Macrophytes/Emergent Vegetation cover present
CFC_BRS	Woody Debris <0.3m cover present
CFC_HUM	Artificial Structures cover present
CFC_LTR	Live tree Roots cover present
CFC_LWD	Woody Debris >0.3m cover present
CFC_OHV	Overhanging Vegetation cover present
CFC_RCK	Boulders cover present
CFC_UCB	Undercut Banks cover present
XFC_ALG	Mean Filamentous Algae Cover
XFC_AQM	Mean Aquatic Macrophytes/Emergent Vegetation cover
XFC_BIG	Big Shelters cover
XFC_BRS	Mean Woody Debris <0.3m cover
XFC_HUM	Mean Artificial structures cover
XFC_LTR	Mean Live tree roots cover
XFC_LWD	Mean Woody Debris >0.3m cover
XFC_NAT_EMAP	Natural Shelter cover - EMAP
XFC_NAT_SWAMP	Natural Shelter cover - SWAMP
XFC_OHV	Mean Overhanging vegetation cover
XFC_RCK	Mean Boulders cover
XFC_UCB	Mean Undercut Banks cover

Riparian vegetation complexity

Riparian vegetation both influences and is influenced by the stream. The availability of water and frequency of floods dictates the types of plants found growing in the riparian zone. In turn, riparian vegetation affects Instream biota by providing coarse particulate organic matter or obstructing light from the streambed. Streamside vegetation may provide cover from terrestrial predators, or provide vantage points for them to access fish and other stream inhabitants. Riparian vegetation may be altered by human activity through direct vegetation management, flow regulation, or introduction of invasive species.

Metric	Description
XC	Mean Upper Canopy Trees and Saplings
XCM	Mean Lower (Mid-Layer) and Upper Canopy Cover
XCMG	Riparian Cover Sum of 3 Layers
XG	Mean Vegetation Ground Cover
XGB	Mean Barren, Bare Soil/Duff Ground cover
XGH	Mean Herbs/Grasses Ground Cover
XGW	Mean Woody Shrubs Ground Cover
XM	Mean Lower (Mid-Layer) Canopy Vegetation
XM	Mean Lower (Mid-Layer) Canopy Vegetation
XMW	Mean Lower (Mid-Layer) Canopy Woody Cover
XPCAN	Upper Canopy Trees and Saplings presence
XPCM	Lower (Mid-Layer) and Upper Canopy Vegetation presence
XPCMG	Riparian Vegetation All 3 Layers presence
XPGVEG	Ground Cover Vegetation presence
XPMGVEG	Moderate Riparian Ground Cover presence
XPMID	Lower (Mid-Layer) Canopy Vegetation presence

Energy source

Two primary energy sources may form the basis of stream food webs: Autochthonous production by algae or macrophytes, and allochthonous production by organic matter contributed from terrestrial plants. Autochthonous production is typically limited by nutrients or light availability, whereas allochthonous production is dependent on the availability of riparian or upstream plants. Nutrient enrichment may increase algae production, which in turn may have many undesirable effects on stream fauna.

Metric	Description
PCT_CPOM	CPOM Presence
PCT_MAA	Percent Presence of Attached Macroalgae
PCT_MAP	Percent Presence of Macroalgae
PCT_MAU	Percent Presence of Unattached Macroalgae
PCT_MCP	Percent Presence of Macrophytes
PCT_MIAT1	Percent Presence of Thick Microalgae
PCT_MIAT1P	Percent Presence of Thick Microalgae where Microalgae Present
PCT_MIATP	Percent Presence of Microalgae
PCT_NSA	Percent Presence of Nuisance Algae
XCDENBK	Mean Bank Shade and Canopy cover
XCDENMID	Mean Mid-Channel Shade and Canopy cover
XMIAT	Mean Microalgae Thickness
XMIATP	Mean Microalgae Thickness where Microalgae Present

Stress

Several human activities may directly or indirectly affect the physical habitat of a stream, and metrics related to stress provide measurements of these activities. Under reference condition, stressors are expected to be minimal or absent. Metrics related to this thematic area may aid in quantifying disturbance and identifying reference sites, but not in evaluating condition or measuring habitat degradation.

Metric	Description
W1_HALL_EMAP	Combined Riparian Human Disturbance Index - EMAP
W1_HALL_SNARL	Combined Riparian Human Disturbance Index - SNARL
W1_HALL_SWAMP	Combined Riparian Human Disturbance Index - SWAMP
W1H_BLDG	Buildings Riparian Human Disturbance
W1H_BRDG	Bridges/Abutments Riparian Human Disturbance
W1H_CROP	Row Crops Riparian Human Disturbance
W1H_LDFL	Landfill/Trash Riparian Human Disturbance
W1H_LOG	Logging Riparian Human Disturbance
W1H_MINE	Mining Riparian Human Disturbance
W1H_ORVY	Orchards/Vineyards Riparian Human Disturbance
W1H_PARK	Park/Lawn Riparian Human Disturbance
W1H_PIPE	Pipes (Inlet/Outlet) Riparian Human Disturbance
W1H_PSTR	Pasture/Range Riparian Human Disturbance
W1H_PVMT	Pavement/Cleared Lot Riparian Human Disturbance
W1H_PWRL	Powerline Riparian Human Disturbance
W1H_ROAD	Road/Railroad Riparian Human Disturbance
W1H_TRAL	Trail Riparian Human Disturbance
W1H_VEGM	Vegetation Management Riparian Human Disturbance
W1H_WALL	Wall/Rip-Rap Riparian Human Disturbance

Appendix C - PHAB Metric Performance Summary

ftp://ftp.sccwrp.org/pub/download/TR_REVIEW/AppendixC_MetricsPerformanceSummary.xlsx

Appendix D - Comparisons of California Rapid Assessment Method Metrics and conceptually corresponding Physical Habitat Assessment Metrics with Pearson's correlation R^2 values.

CRAM Index	R^2
PBM_E	0.018
PBM_S	0.021
PBM_V	0.008
PCT_BDRK	0.104
PCT_BIGR	0.476
PCT_CB	0.279
PCT_CF	0.023
PCT_CF_WT	0.023
PCT_CPOM	0.006
PCT_DR	0.009
PCT_FN	0.188
PCT_GC	0.079
PCT_GF	0.000
PCT_GL	0.086
PCT_GL_WT	0.088
PCT_HP	0.043
PCT_POOL	0.001
PCT_POOL_WT	0.001
PCT_RA	0.037
PCT_RA_WT	0.037
PCT_RI	0.154
PCT_RI_WT	0.099
PCT_RN	0.038
PCT_RN_WT	0.039
PCT_RR	0.065
PCT_RS	0.062
PCT_SA	0.011
PCT_SAFN	0.168
PCT_SB	0.176
PCT_SFGF	0.159
PCT_WD	0.002
PCT_XB	0.114
SB_PP_D10	0.040
SB_PP_D25	0.103
SB_PP_D50	0.083
SB_PP_D75	0.086
SB_PP_D90	0.141
SB_PT_D10	0.166
SB_PT_D25	0.185
SB_PT_D50	0.103

SB_PT_D75	0.031
SB_PT_D90	0.000
SINU	0.043
W1_HALL_EMAP	0.525
W1_HALL_SWAMP	0.548
W1H_BLDG	0.318
W1H_BRDG	0.094
W1H_CROP	0.101
W1H_LDFL	0.269
W1H_LOG	0.004
W1H_MINE	0.001
W1H_ORVY	0.042
W1H_PARK	0.142
W1H_PIPE	0.217
W1H_PSTR	0.000
W1H_PVMT	0.308
W1H_ROAD	0.277
W1H_VEGM	0.146
W1H_WALL	0.359
XBKF_H	0.001
XC	0.090
XCDENBK	0.067
XCDENMID	0.062
XCM	0.152
XCMG	0.110
XFC_ALG	0.046
XFC_AQM	0.027
XFC_BIG	0.217
XFC_BRS	0.039
XFC_HUM	0.056
XFC_LTR	0.001
XFC_LWD	0.026
XFC_NAT_EMAP	0.148
XFC_NAT_SWAMP	0.064
XFC_OHV	0.002
XFC_RCK	0.237
XFC_UCB	0.000
XG	0.007
XGB	0.000
XGH	0.021
XGW	0.098
XKBF_W	0.004
XM	0.122
XPCAN	0.168
XPCM	0.190

XPCMG	0.191
XPGVEG	0.146
XPMGVEG	0.058
XPMID	0.298
XWDA	0.007
XWDEPTH	0.017
XWDM	0.006
XWDR	0.025
XWIDTH	0.009
Buffer and Landscape Context	
W1_HALL_EMAP	0.528
W1_HALL_SWAMP	0.569
W1H_BLDG	0.369
W1H_BRDG	0.120
W1H_CROP	0.054
W1H_LDFL	0.351
W1H_LOG	0.000
W1H_MINE	0.000
W1H_ORVY	0.056
W1H_PARK	0.142
W1H_PIPE	0.208
W1H_PSTR	0.007
W1H_PVMT	0.355
W1H_ROAD	0.268
W1H_VEGM	0.195
W1H_WALL	0.362
Percent of AA with Buffer	
W1_HALL_EMAP	0.535
W1_HALL_SWAMP	0.571
W1H_BLDG	0.350
W1H_BRDG	0.129
W1H_CROP	0.027
W1H_LDFL	0.420
W1H_LOG	0.001
W1H_MINE	0.005
W1H_ORVY	0.079
W1H_PARK	0.110
W1H_PIPE	0.158
W1H_PSTR	0.008
W1H_PVMT	0.336
W1H_ROAD	0.268
W1H_VEGM	0.163
W1H_WALL	0.399
Average Buffer Width	

W1_HALL_EMAP	0.452
W1_HALL_SWAMP	0.493
W1H_BLDG	0.361
W1H_BRDG	0.051
W1H_CROP	0.087
W1H_LDFL	0.372
W1H_LOG	0.001
W1H_MINE	0.001
W1H_ORVY	0.041
W1H_PARK	0.125
W1H_PIPE	0.110
W1H_PSTR	0.024
W1H_PVMT	0.263
W1H_ROAD	0.305
W1H_VEGM	0.214
W1H_WALL	0.237
Buffer Condition	
W1_HALL_EMAP	0.438
W1_HALL_SWAMP	0.476
W1H_BLDG	0.282
W1H_BRDG	0.051
W1H_CROP	0.112
W1H_LDFL	0.284
W1H_LOG	0.000
W1H_MINE	0.002
W1H_ORVY	0.055
W1H_PARK	0.120
W1H_PIPE	0.116
W1H_PSTR	0.000
W1H_PVMT	0.210
W1H_ROAD	0.270
W1H_VEGM	0.189
W1H_WALL	0.260
Hydrology	
PBM_E	0.011
PBM_S	0.012
PBM_V	0.004
PCT_BDRK	0.088
PCT_BIGR	0.325
PCT_CB	0.162
PCT_FN	0.096
PCT_GC	0.085
PCT_GF	0.000
PCT_HP	0.039

PCT_POOL	0.001
PCT_POOL_WT	0.001
PCT_RA	0.031
PCT_RA_WT	0.030
PCT_RI	0.114
PCT_RI_WT	0.075
PCT_RR	0.037
PCT_RS	0.062
PCT_SA	0.019
PCT_SAFN	0.114
PCT_SB	0.090
PCT_SFGF	0.107
PCT_WD	0.004
PCT_XB	0.060
SB_PP_D10	0.021
SB_PP_D25	0.053
SB_PP_D50	0.059
SB_PP_D75	0.042
SB_PP_D90	0.077
SB_PT_D10	0.094
SB_PT_D25	0.104
SB_PT_D50	0.070
SB_PT_D75	0.020
SB_PT_D90	0.000
W1_HALL_EMAP	0.367
W1_HALL_SWAMP	0.382
W1H_BLDG	0.239
W1H_BRDG	0.081
W1H_CROP	0.048
W1H_LDFL	0.222
W1H_LOG	0.001
W1H_MINE	0.000
W1H_ORVY	0.031
W1H_PARK	0.113
W1H_PIPE	0.137
W1H_PSTR	0.001
W1H_PVMT	0.212
W1H_ROAD	0.193
W1H_VEGM	0.094
W1H_WALL	0.263
XBKF_H	0.000
XKBF_W	0.000
XWDA	0.010
XWDEPTH	0.023
XWIDTH	0.017

Water Source	
W1_HALL_EMAP	0.345
W1_HALL_SWAMP	0.364
W1H_BLDG	0.212
W1H_BRDG	0.063
W1H_CROP	0.088
W1H_LDFL	0.251
W1H_LOG	0.003
W1H_MINE	0.004
W1H_ORVY	0.026
W1H_PARK	0.079
W1H_PIPE	0.112
W1H_PSTR	0.010
W1H_PVMT	0.209
W1H_ROAD	0.246
W1H_VEGM	0.111
W1H_WALL	0.202
Hydroperiod or Channel Stability	
PBM_E	0.026
PBM_S	0.067
PBM_V	0.042
PCT_BDRK	0.074
PCT_BIGR	0.248
PCT_CB	0.152
PCT_FN	0.028
PCT_GC	0.029
PCT_GF	0.005
PCT_HP	0.018
PCT_POOL	0.005
PCT_POOL_WT	0.005
PCT_RA	0.044
PCT_RA_WT	0.044
PCT_RI	0.063
PCT_RI_WT	0.034
PCT_RR	0.028
PCT_RS	0.053
PCT_SA	0.017
PCT_SAFN	0.049
PCT_SB	0.082
PCT_SFGF	0.057
PCT_WD	0.001
PCT_XB	0.068
SB_PP_D10	0.022
SB_PP_D25	0.056

SB_PP_D50	0.058
SB_PP_D75	0.055
SB_PP_D90	0.079
SB_PT_D10	0.128
SB_PT_D25	0.166
SB_PT_D50	0.101
SB_PT_D75	0.026
SB_PT_D90	0.000
XBKF_H	0.002
XKBF_W	0.002
XWDA	0.004
XWDEPTH	0.005
XWIDTH	0.002
Hydrologic Connectivity	
PBM_E	0.001
PBM_S	0.006
PBM_V	0.012
PCT_BDRK	0.007
PCT_BIGR	0.005
PCT_CB	0.000
PCT_FN	0.005
PCT_GC	0.012
PCT_GF	0.006
PCT_HP	0.019
PCT_POOL	0.000
PCT_POOL_WT	0.000
PCT_RA	0.000
PCT_RA_WT	0.000
PCT_RI	0.002
PCT_RI_WT	0.002
PCT_RR	0.000
PCT_RS	0.008
PCT_SA	0.006
PCT_SAFN	0.000
PCT_SB	0.000
PCT_SFGF	0.001
PCT_WD	0.000
PCT_XB	0.000
SB_PP_D10	0.000
SB_PP_D25	0.004
SB_PP_D50	0.000
SB_PP_D75	0.001
SB_PP_D90	0.000
SB_PT_D10	0.007

SB_PT_D25	0.009
SB_PT_D50	0.006
SB_PT_D75	0.008
SB_PT_D90	0.008
XBKF_H	0.000
XKBF_W	0.005
XWDA	0.011
XWDEPTH	0.015
XWIDTH	0.015
Physical Structure	
PCT_BDRK	0.097
PCT_BIGR	0.448
PCT_CB	0.233
PCT_CF	0.017
PCT_CF_WT	0.017
PCT_CPOM	0.008
PCT_DR	0.009
PCT_GC	0.054
PCT_GF	0.001
PCT_GL	0.084
PCT_GL_WT	0.085
PCT_HP	0.031
PCT_POOL	0.001
PCT_POOL_WT	0.001
PCT_RA	0.047
PCT_RA_WT	0.047
PCT_RI	0.103
PCT_RI_WT	0.062
PCT_RN	0.026
PCT_RN_WT	0.027
PCT_RR	0.079
PCT_RS	0.052
PCT_SA	0.014
PCT_SAFN	0.212
PCT_SB	0.224
PCT_SFGF	0.196
PCT_WD	0.000
PCT_XB	0.138
SB_PP_D10	0.061
SB_PP_D25	0.122
SB_PP_D50	0.085
SB_PP_D75	0.104
SB_PP_D90	0.172
SB_PT_D10	0.106

SB_PT_D25	0.124
SB_PT_D50	0.067
SB_PT_D75	0.011
SB_PT_D90	0.005
SINU	0.057
XFC_ALG	0.013
XFC_AQM	0.041
XFC_BIG	0.254
XFC_BRS	0.040
XFC_HUM	0.030
XFC_LTR	0.008
XFC_LWD	0.024
XFC_NAT_EMAP	0.152
XFC_NAT_SWAMP	0.063
XFC_OHV	0.000
XFC_RCK	0.286
XFC_UCB	0.003
XGB	0.013
XWDA	0.014
XWDEPTH	0.013
XWDM	0.002
XWDR	0.027
XWIDTH	0.014
Structural Patch Richness	
PCT_BDRK	0.068
PCT_BIGR	0.331
PCT_CB	0.148
PCT_CF	0.011
PCT_CF_WT	0.011
PCT_CPOM	0.000
PCT_DR	0.010
PCT_GC	0.057
PCT_GF	0.008
PCT_GL	0.044
PCT_GL_WT	0.045
PCT_HP	0.039
PCT_POOL	0.001
PCT_POOL_WT	0.001
PCT_RA	0.033
PCT_RA_WT	0.033
PCT_RI	0.077
PCT_RI_WT	0.032
PCT_RN	0.025
PCT_RN_WT	0.025

PCT_RR	0.058
PCT_RS	0.035
PCT_SA	0.001
PCT_SAFN	0.178
PCT_SB	0.184
PCT_SFGF	0.150
PCT_XB	0.075
SB_PP_D10	0.025
SB_PP_D25	0.040
SB_PP_D50	0.056
SB_PP_D75	0.055
SB_PP_D90	0.112
SB_PT_D10	0.060
SB_PT_D25	0.079
SB_PT_D50	0.047
SB_PT_D75	0.013
SB_PT_D90	0.004
SINU	0.044
XFC_ALG	0.003
XFC_AQM	0.029
XFC_BIG	0.214
XFC_BRS	0.058
XFC_HUM	0.025
XFC_LTR	0.017
XFC_LWD	0.026
XFC_NAT_EMAP	0.157
XFC_NAT_SWAMP	0.076
XFC_OHV	0.004
XFC_RCK	0.227
XFC_UCB	0.000
XGB	0.005
Patch Type Count	
PCT_BDRK	0.002
PCT_BIGR	0.145
PCT_CB	0.077
PCT_CF	0.000
PCT_CF_WT	0.000
PCT_CPOM	0.028
PCT_DR	0.005
PCT_GC	0.124
PCT_GF	0.028
PCT_GL	0.001
PCT_GL_WT	0.001
PCT_HP	0.031

PCT_POOL	0.000
PCT_POOL_WT	0.000
PCT_RA	0.000
PCT_RA_WT	0.000
PCT_RI	0.036
PCT_RI_WT	0.016
PCT_RN	0.054
PCT_RN_WT	0.055
PCT_RR	0.015
PCT_RS	0.000
PCT_SA	0.009
PCT_SAFN	0.054
PCT_SB	0.033
PCT_SFGF	0.030
PCT_XB	0.002
SB_PP_D10	0.000
SB_PP_D25	0.000
SB_PP_D50	0.009
SB_PP_D75	0.007
SB_PP_D90	0.011
SB_PT_D10	0.093
SB_PT_D25	0.110
SB_PT_D50	0.095
SB_PT_D75	0.080
SB_PT_D90	0.041
SINU	0.023
XFC_ALG	0.001
XFC_AQM	0.001
XFC_BIG	0.059
XFC_BRS	0.025
XFC_HUM	0.021
XFC_LTR	0.034
XFC_LWD	0.005
XFC_NAT_EMAP	0.063
XFC_NAT_SWAMP	0.051
XFC_OHV	0.011
XFC_RCK	0.052
XFC_UCB	0.011
XGB	0.000
Topographic Complexity	
PCT_CB	0.203
PCT_RA	0.037
PCT_RA_WT	0.037
PCT_RI	0.074

PCT_RI_WT	0.065
PCT_SB	0.145
PCT_WD	0.003
PCT_XB	0.140
XWDA	0.001
XWDEPTH	0.000
XWDM	0.001
XWDR	0.018
XWIDTH	0.001
Biotic Structure	
XC	0.193
XCDENBK	0.784
XCDENMID	0.194
XCM	0.319
XCMG	0.318
XFC_AQM	0.028
XFC_LTR	0.006
XFC_NAT_EMAP	0.049
XFC_NAT_SWAMP	0.015
XFC_OHV	0.001
XG	0.074
XGB	0.037
XGH	0.001
XGW	0.174
XM	0.250
XPCAN	0.324
XPCM	0.363
XPCMG	0.365
XPGVEG	0.120
XPMGVEG	0.133
XPMID	0.326
Horizontal Interspersion and Zonation	
XC	0.085
XCDENBK	0.218
XCDENMID	0.073
XCM	0.183
XCMG	0.214
XFC_AQM	0.017
XFC_LTR	0.003
XFC_NAT_EMAP	0.028
XFC_NAT_SWAMP	0.008
XFC_OHV	0.001
XG	0.073
XGB	0.047

XGH	0.000
XGW	0.128
XM	0.182
XPCAN	0.187
XPCM	0.211
XPCMG	0.211
XPGVEG	0.087
XPMGVEG	0.087
XPMID	0.270
Vertical Biotic Structure	
XC	0.268
XCDENBK	0.625
XCDENMID	0.309
XCM	0.377
XCMG	0.334
XFC_AQM	0.040
XFC_LTR	0.018
XFC_NAT_EMAP	0.045
XFC_NAT_SWAMP	0.012
XFC_OHV	0.002
XG	0.054
XGB	0.029
XGH	0.004
XGW	0.167
XM	0.249
XPCAN	0.357
XPCM	0.379
XPCMG	0.381
XPGVEG	0.067
XPMGVEG	0.116
XPMID	0.264
Number of Plant Layers Present	
XC	0.061
XCDENMID	0.049
XCM	0.139
XCMG	0.181
XFC_AQM	0.000
XFC_LTR	0.010
XFC_NAT_EMAP	0.015
XFC_NAT_SWAMP	0.012
XFC_OHV	0.004
XG	0.077
XGB	0.046
XGH	0.004

XGW	0.097
XM	0.143
XPCAN	0.158
XPCM	0.196
XPCMG	0.197
XPGVEG	0.138
XPMGVEG	0.101
XPMID	0.226
Stressor Count	
W1_HALL_EMAP	0.505
W1_HALL_SWAMP	0.561
W1H_BLDG	0.264
W1H_BRDG	0.071
W1H_CROP	0.124
W1H_LDFL	0.423
W1H_LOG	0.000
W1H_MINE	0.001
W1H_ORVY	0.065
W1H_PARK	0.124
W1H_PIPE	0.098
W1H_PSTR	0.000
W1H_PVMT	0.217
W1H_ROAD	0.355
W1H_VEGM	0.267
W1H_WALL	0.226

CRAM Index	R^2
PBM_E	0.018
PBM_S	0.021
PBM_V	0.008
PCT_BDRK	0.104
PCT_BIGR	0.476
PCT_CB	0.279
PCT_CF	0.023
PCT_CF_WT	0.023
PCT_CPOM	0.006
PCT_DR	0.009
PCT_FN	0.188
PCT_GC	0.079
PCT_GF	0.000
PCT_GL	0.086
PCT_GL_WT	0.088
PCT_HP	0.043
PCT_POOL	0.001
PCT_POOL_WT	0.001
PCT_RA	0.037
PCT_RA_WT	0.037
PCT_RI	0.154
PCT_RI_WT	0.099
PCT_RN	0.038
PCT_RN_WT	0.039
PCT_RR	0.065
PCT_RS	0.062
PCT_SA	0.011
PCT_SAFN	0.168
PCT_SB	0.176
PCT_SFGF	0.159
PCT_WD	0.002
PCT_XB	0.114
SB_PP_D10	0.040
SB_PP_D25	0.103
SB_PP_D50	0.083
SB_PP_D75	0.086
SB_PP_D90	0.141
SB_PT_D10	0.166
SB_PT_D25	0.185
SB_PT_D50	0.103
SB_PT_D75	0.031
SB_PT_D90	0.000
SINU	0.043
W1_HALL_EMAP	0.525
W1_HALL_SWAMP	0.548
W1H_BLDG	0.318
W1H_BRDG	0.094
W1H_CROP	0.101
W1H_LDFL	0.269
W1H_LOG	0.004
W1H_MINE	0.001
W1H_ORVY	0.042
W1H_PARK	0.142
W1H_PIPE	0.217
W1H_PSTR	0.000
W1H_PVMT	0.308
W1H_ROAD	0.277
W1H_VEGM	0.146
W1H_WALL	0.359
XBKF_H	0.001
XC	0.090
XCDENBK	0.067
XCDENMID	0.062
XCM	0.152
XCMG	0.110
XFC_ALG	0.046
XFC_AQM	0.027
XFC_BIG	0.217
XFC_BRS	0.039
XFC_HUM	0.056
XFC_LTR	0.001
XFC_LWD	0.026
XFC_NAT_EMAP	0.148
XFC_NAT_SWAMP	0.064
XFC_OHV	0.002
XFC_RCK	0.237
XFC_UCB	0.000
XG	0.007
XGB	0.000
XGH	0.021
XGW	0.098
XKBF_W	0.004
XM	0.122
XPCAN	0.168
XPCM	0.190

CRAM Index	R^2
PBM_E	0.018
PBM_S	0.021
PBM_V	0.008
PCT_BDRK	0.104
PCT_BIGR	0.476
PCT_CB	0.279
PCT_CF	0.023
PCT_CF_WT	0.023
PCT_CPOM	0.006
PCT_DR	0.009
PCT_FN	0.188
PCT_GC	0.079
PCT_GF	0.000
PCT_GL	0.086
PCT_GL_WT	0.088
PCT_HP	0.043
PCT_POOL	0.001
PCT_POOL_WT	0.001
PCT_RA	0.037
PCT_RA_WT	0.037
PCT_RI	0.154
PCT_RI_WT	0.099
PCT_RN	0.038
PCT_RN_WT	0.039
PCT_RR	0.065
PCT_RS	0.062
PCT_SA	0.011
PCT_SAFN	0.168
PCT_SB	0.176
PCT_SFGF	0.159
PCT_WD	0.002
PCT_XB	0.114
SB_PP_D10	0.040
SB_PP_D25	0.103
SB_PP_D50	0.083
SB_PP_D75	0.086
SB_PP_D90	0.141
SB_PT_D10	0.166
SB_PT_D25	0.185
SB_PT_D50	0.103
SB_PT_D75	0.031
SB_PT_D90	0.000
SINU	0.043
W1_HALL_EMAP	0.525
W1_HALL_SWAMP	0.548
W1H_BLDG	0.318
W1H_BRDG	0.094
W1H_CROP	0.101
W1H_LDFL	0.269
W1H_LOG	0.004
W1H_MINE	0.001
W1H_ORVY	0.042
W1H_PARK	0.142
W1H_PIPE	0.217
W1H_PSTR	0.000
W1H_PVMT	0.308
W1H_ROAD	0.277
W1H_VEGM	0.146
W1H_WALL	0.359
XBKF_H	0.001
XC	0.090
XCDENBK	0.067
XCDENMID	0.062
XCM	0.152
XCMG	0.110
XFC_ALG	0.046
XFC_AQM	0.027
XFC_BIG	0.217
XFC_BRS	0.039
XFC_HUM	0.056
XFC_LTR	0.001
XFC_LWD	0.026
XFC_NAT_EMAP	0.148
XFC_NAT_SWAMP	0.064
XFC_OHV	0.002
XFC_RCK	0.237
XFC_UCB	0.000
XG	0.007
XGB	0.000
XGH	0.021
XGW	0.098
XKBF_W	0.004
XM	0.122
XPCAN	0.168
XPCM	0.190