AQUATIC CONSERVATION: MARINE AND FRESHWATER ECOSYSTEMS
Aquatic Conserv: Mar. Freshw. Ecosyst. (2009)
Published online in Wiley InterScience
(www.interscience.wiley.com). DOI: 10.1002/aqc.1048

Quantifying the condition of Hawaiian coral reefs

KU'ULEI S. RODGERS[a,*], PAUL L. JOKIEL[a], CHRISTOPHER E. BIRD[a] and ERIC K. BROWN[b]
[a]*University of Hawai'i, Hawai'i Institute of Marine Biology, P.O. Box 1346, Kāne'ohe, Hawai'i 96744 USA*
[b]*National Parks Service, P.O. Box 2222, Kalaupapa, Hawai'i 96742 USA*

ABSTRACT

(1) This investigation developed and tested descriptive models designed to evaluate coral reef ecological condition based on data developed using the basic techniques most often used in coral reef surveys.

(2) Forty-three variables at 184 stations were analysed in order to identify specific factors that are useful metrics for describing reef condition.

(3) The common practice of using 'reference sites' for paired site comparisons was evaluated by developing a reference site model (RSM). This use of reference sites proved to be subjective and unreliable, especially when multiple factors and multiple sites are involved. However, in some cases the RSM is appropriate in demonstrating severe degradation based on factors such as sediment, coral cover and fish abundance.

(4) An objective ecological gradient model (EGM) was developed based on a wide range of metrics at numerous sites. A computer program was developed that allows a quantitative ranking of reef condition along a continuum and can be used to compare reefs across a wide range of conditions. Further, this approach permits the operator to alter and define criteria appropriate to a specific question.

(5) Results of this investigation provide ecological insights into the importance of natural and anthropogenic ecological factors in determining coral reef condition.

Received 3 October 2008; Revised 18 February 2009; Accepted 22 March 2009

KEY WORDS: ecological model; indicators; reference sites; rank

INTRODUCTION

Reef condition is influenced by various natural factors, but over the past century human activity has become a major driver of change on many coral reefs. Increasingly, coral reef biologists are occupied with defining degradation of reefs owing to anthropogenic impacts. In order to evaluate the condition of a reef one must be able to define the attributes of a 'normal' or 'healthy' system. A widely used method is to compare an 'affected' reef with a 'control' pristine reef or one that has not been affected by the factor of interest using various metrics. The concepts of 'biotic integrity' and 'ecosystem health' are used in terrestrial ecology (Rapport *et al*., 1998) but have not been taken advantage of by the marine science community, even though the ecological theory and concepts are broadly applicable. One exception is the report by Jameson *et al*. (2001), who described an approach designed to develop an index of biotic integrity (IBI) for coral reefs. Such approaches define the normal structure of a system, measure deviations from normal and thereby evaluate severity of impairment. This method has been effective in freshwater habitats (Green and Vascotto, 1978; Lenat, 1988; Barbour *et al*., 1992; Rosenburg and Resh, 1993). Another approach widely used in wetland systems is the hydrogeomorphic (HGM) approach (Brinson, 1993; Smith *et al*., 1995). This method measures the capacity of a wetland to perform certain functions by classification according to geomorphic setting, water source, and hydrodynamics. Reference sites are then used to establish the degree to which function has been impaired.

In 1998, the Hawai'i Coral Reef Assessment and Monitoring Program (CRAMP) (Coral Reef Assessment and Monitoring Program, 2006) began a field programme to develop techniques and compile the data required to quantitatively evaluate the condition of Hawaiian coral reefs.

CRAMP was initially implemented to describe the spatial and temporal variation in coral reef communities in relation to natural and anthropogenic forcing functions (Jokiel *et al*., 2004). The original CRAMP experimental design utilized a wide range of easily measured key variables (Brown *et al*., 2004). The present investigation utilized these key variables in the

*Correspondence to: K.S. Rodgers, University of Hawai'i, Hawai'i Institute of Marine Biology, P.O. Box 1346, Kāne'ohe, Hawai'i 96744 USA. E-mail: kuuleir@hawaii.edu

development of an ecological gradient model (EGM) that could be used to quantitatively describe coral reef condition. Unlike the HGM and IBI models which rely heavily on reference sites, these were found inappropriate for use in the EGM. Concepts that have similarity with the EGM are the HGM theory of habitat classification and the IBI premise that apply metrics to produce a ranking to evaluate the severity of impairment.

First, a database was developed that generated a matrix of variables by site. Second, factors that were shown to be reliable metrics for reef condition were identified. Third, these metrics were incorporated into descriptive models based on the various reference sites, IBI and HGM approaches. Finally, the models were tested and evaluated in terms of predictive capability.

METHODS

Development of information database

Methods used in this study were restricted to inexpensive survey techniques that have been widely used by coral reef researchers and managers for many years. Initial survey sites were selected by expert observers on the basis of degree of perceived environmental degradation, range of spatial gradients to encompass longitudinal differences, level of management protection, human population level, and extent and direction of wave exposure. These sites represent an excellent cross-section of Hawaiian coral reef communities (Figure 1). Within each site (location) a number of stations were surveyed based on time, cost and logistical availability. Stations within each site were then stratified by habitat and randomly selected within hard-bottom habitat (Coyne *et al.*, 2003). Data used in the development of the models include biological and environmental variables from 60 stations within 30 site locations from the CRAMP long-term monitoring programme and an additional 124 stations within 22 sites from fully comparable rapid assessments (RATS) (Figure 1).

Initial studies were conducted to develop an appropriate method for measuring benthic and fish communities as described in Jokiel *et al.* (2004) and Brown *et al.* (2004). To assess the characteristics of benthic communities, non-overlapping digital images (50×69 cm) were taken along each 10 m transect at a perpendicular angle from a height of 0.5 m above the substrate. The software program PhotoGrid was used to quantify percentage cover, richness and diversity of corals, algal functional groups, and substrate cover.

Fish communities were enumerated using standard visual belt transects (Brock, 1954). Scuba divers swam along four $25\,m \times 5\,m$ transects ($125\,m^2$) at each station recording species, quantity, and total fish length (Friedlander *et al.*, 2003). All fish were identified to the lowest taxon possible.

Rugosity was measured using the chain and tape method described in McCormick (1994).

Two bulk sediment samples (approximately $500\,cm^3$ each) were collected haphazardly within each study area and each mixed to assure homogeneity. Each sample was then divided into two replicate samples and from each of these two

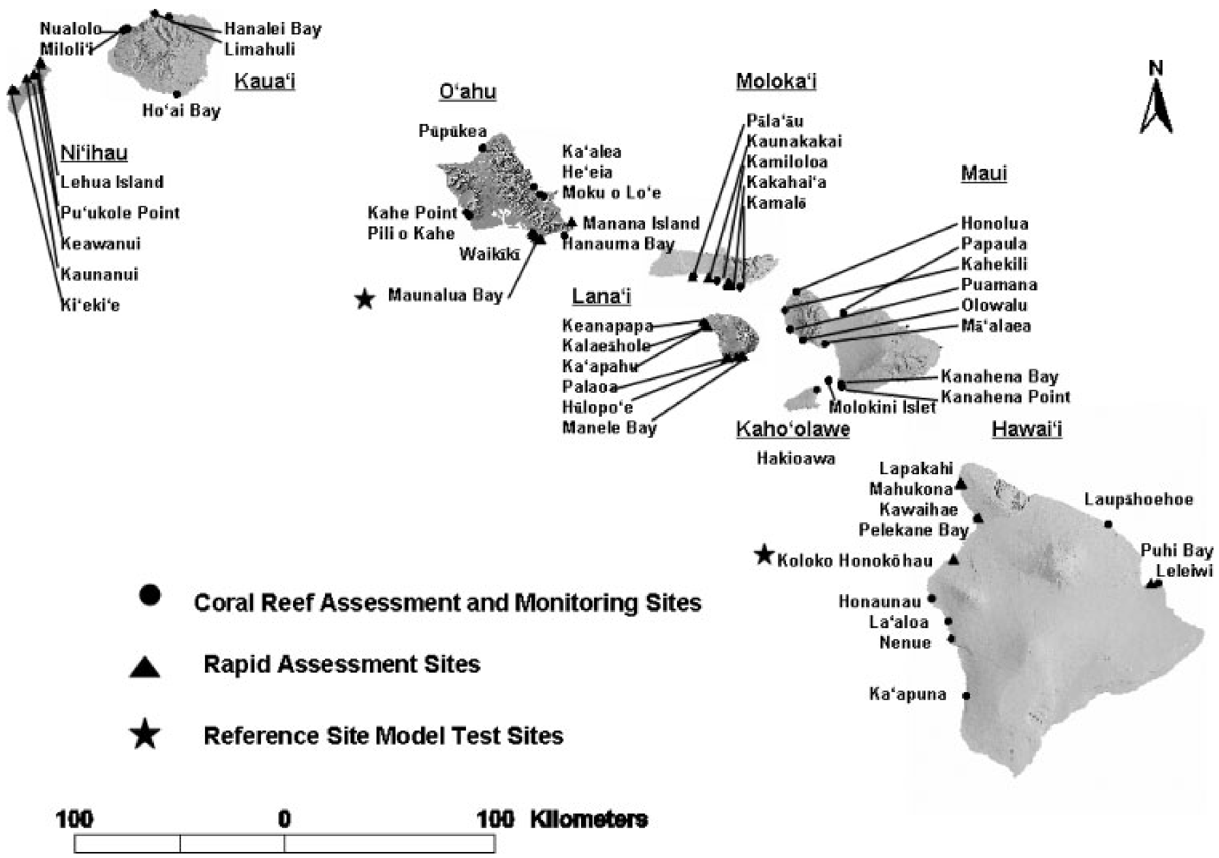


Figure 1. Main Hawaiian Islands sites ($n = 52$). Total number of stations within sites ($n = 184$). Triangles are used to show assessment sites while circles represent monitoring sites.

DOI: 10.1002/aqc

sub-samples were taken. Sediment grain sizes used were in accordance with the Wentworth scale (Folk, 1974). The sediment fraction remaining on each sieve was washed through pre-weighed filter paper (Whatman Brand 114 wet-strength, 25 micrometer) and air-dried to constant weight. The percentage weight of each grain size was determined by calculating the ratio of the various size fractions to the total sample weight.

Sediment samples to determine composition were collected and processed according to Craft *et al.* (1991). This analysis may overestimate absolute percentage values of organic material, thus only relative differences were compared among sites for this parameter. The percentage organic material and carbonate fraction was then calculated from these data. Loss on ignition (LOI_{500}) was used as an index of organic material content. The mass loss between LOI_{500} and LOI_{1000} was used as a proxy for the carbonate fraction $CaCO_3$.

Other ancillary variables derived from various sources included the following:

Anthropogenic factors

1. Total human population within 5 km of each site and within the adjacent watershed was calculated using US 2000 census data (www.census.gov/main/www/cen2000.html).
2. Mean annual rainfall (mm), total acreage of the adjacent watershed, and perennial stream lengths were derived from layers obtained for each site from the State of Hawai'i GIS website (www.state.hi.us/dbedt/gis).
3. Management status rank was included as a categorical predictor with sites pooled into three categories. A rank of three was assigned to marine protected areas (MPAs) with the highest degree of protection. These include MPAs that are designated as subsistence fishing only or fully 'no take' areas. Rank two included sites with a moderate degree of protection, for example restriction of certain fishing techniques such as gill netting and/or spearing or areas closed to taking of certain species. Rank one consisted of open access areas. These data were entered into MS Access, MS Excel and ESRI ArcView as appropriate.

Natural factors

4. Mean, minimum and maximum values for offshore significant wave height (m) along with wave direction (compass bearing) were downloaded daily from the Naval Oceanographic WAM model website (http://www.navo.navy.mil) for 2001.
5. Geologic age of the volcano underlying each site was estimated using data from Clague and Dalrymple (1994).

Analysis of the initial data (Friedlander *et al.*, 2003) indicated that a much larger spatial array of sites was desirable since the coral reefs of Hawai'i were diverse and showed high variability for many ecological parameters. Thus, the original data from the 60 monitoring stations were supplemented using a rapid assessment technique (RAT). The RAT is an abbreviated version of the CRAMP monitoring protocol, using a single 10 m transect to describe benthic cover, rugosity, and sediments along with a single 25 m transect to describe fish communities. The power to detect absolute differences in fish populations from one 25 m transect at each station was extremely low, due to high spatial variability in fish populations. However, the power to detect relative differences between sites for numerical abundance of fish was sufficient using the RAT protocol. This protocol generated the same biological data (i.e. percentage cover, species richness, diversity, fish abundances, and biomass) and environmental data (e.g. rugosity, depth, sediment composition and grain-size, etc.) as the CRAMP monitoring dataset. Multiple RAT transects were randomly selected using ARCVIEW spatial analyst. These transects were stratified on hard substrate habitats in a manner similar to the CRAMP monitoring sites but along a larger range of depths. The advantage of the RAT was that it allowed for the rapid acquisition of data suitable to describe the variation in communities and the forces controlling these distributions at a larger spatial scale. Only the first 10 m transect at each of the CRAMP monitoring stations was included to allow for comparisons on the same measurement spatial scale with the RAT data.

Identification of major factors

Parametric (multiple regression) and non-parametric analyses (principal components analysis, and non-metric multi-dimensional scaling) were used to determine which environmental factors were most important in structuring coral and fish assemblages and to narrow the field of variables used in model development.

Data were transformed as appropriate to meet the assumptions of normality, linearity, and homogeneity of variances required for some of the formal statistical tests performed. Statistical analyses were conducted using Primer© 5.0, MVSP© 3.0, and Minitab© 13.0 software to examine both univariate and multivariate aspects of the spatial data sets. The database consisted of 43 variables that were measured at 184 stations within 52 sites.

Statistics and multiple regressions were computed with Minitab 13.0. Explanatory variables were selected from among 23 environmental predictors. To avoid multicolinearity, variables that were highly correlated ($>90\%$) were dropped from the analysis without loss of information (Clarke and Gorley, 2001). Coral species richness was derived from coral cover data and included in the analysis but may not be suitable as a response variable since it is strongly dependent on sampling effort and observer variability. To determine which environmental variables best explained coral cover and species richness a general linear multiple regression model was used. Coral cover and species richness were regressed against the following environmental variables: rugosity, depth, sediment composition, grain-sizes, wave parameters, human population parameters, precipitation, distance from a perennial stream, watershed area, and geologic age of site. Legal protection rank and windward/leeward divisions were included in the model as categorical variables. Model selection was determined by a best subsets routine applying Mallows C_p and R^2. A lack of fit test was conducted to verify the model selection.

A general linear multiple regression analysis was also used to determine the best model for predicting fish biomass, numerical abundance and diversity. To obtain a parsimonious

DOI: 10.1002/aqc

model, many of the variables that made only a small contribution to explaining the variability were excluded. This facilitates ecological interpretation and management application.

Multivariate procedures in PRIMER© 5.2.9 (BIOENV and SIMPER) were used to link biological data to environmental data. The results identified spatial patterns in coral communities and determined the contribution of each species to site similarities. Results were later used in the development of the final model to determine weights for each factor.

Development of models

Reference site model (RSM)

Many previous studies of coral reef condition have been based on the use of reference sites. In general, a 'pristine' reference area or one that has not been impaired by the factor of interest is selected by experts to serve as a comparison with the 'affected' reef under study. Reference site selection is problematic due to the difficulty in determining optimal reef conditions. Sliding baselines that change over time can also make determination of pristine conditions impractical. Without historical data, this hypothetical baseline is elusive. During the present study, knowledgeable coral reef scientists in Hawai'i provided their opinion on which reef areas would serve as the best reference sites. In general, the designated reference sites were generally remote from human influence or were within marine protected areas. Reference sites used in this analysis were thus determined subjectively by experts using qualitative observations as is generally the case. This avoided a circular argument where the quantified data are used both to select and analyse the sites. Obviously selection of a 'control' reef for comparison with an 'affected' reef as done in most previous studies is a highly subjective process.

Since depth and wave exposure were found to be highly influential in determining biotic communities (Friedlander *et al*., 2003; Jokiel *et al*., 2004; Storlazzi *et al*., 2005), the first attempt at developing a model divided the reference sites into six habitat classes (three depths and two wave exposures) based on these key factors (Figure 2).

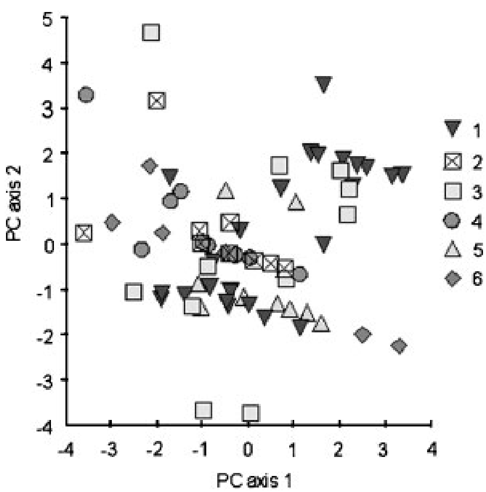


Figure 2. Principal components analysis of environmental variables of reference sites only by habitat class. Note extensive overlap between habitat types. Habitat classes shown in figure: (1) Sheltered < 5 m, (2) Exposed < 5 m, (3) Sheltered 5–10 m, (4) Exposed 5–10 m, (5) Sheltered > 10 m, (6) Exposed > 10 m.

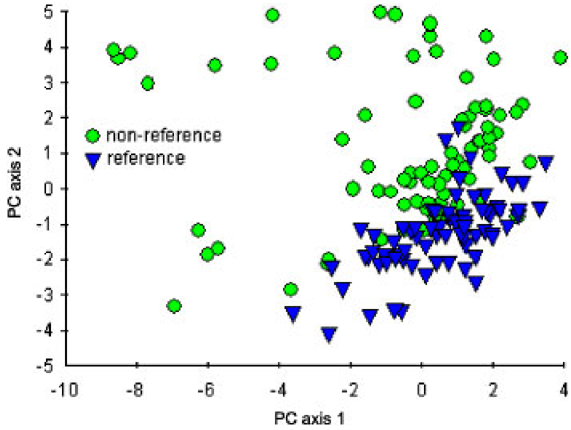


Figure 3. Principal components analysis of environmental variables of all sites (reference and non-reference sites) ($n = 184$).

Table 1. Twelve habitat classifications used in the ecological gradient model (EGM) based on depth and wave exposure

Dominant wave regime	Degree of exposure	Depth range (m)
South Pacific Swell	Exposed	< 5
South Pacific Swell	Sheltered	< 5
North Pacific Swell	Exposed	< 5
North Pacific Swell	Sheltered	< 5
South Pacific Swell	Exposed	5–10
South Pacific Swell	Sheltered	5–10
North Pacific Swell	Exposed	5–10
North Pacific Swell	Sheltered	5–10
South Pacific Swell	Exposed	> 10
South Pacific Swell	Sheltered	> 10
North Pacific Swell	Exposed	> 10
North Pacific Swell	Sheltered	> 10

Considerable overlap between reference sites and non-reference sites (Figure 3, Table 1) prompted expansion of the EGM model to 12 habitat classes (three depths and four wave exposures) to reduce the variation caused by depth and wave exposure.

Several analyses were conducted on the reference site data. First, a discriminant analysis was performed to evaluate whether the reference stations were different from the non-reference stations and to determine if the reference sites fell within their predicted habitat class. Second, a cluster analysis was also conducted to determine if the reference sites in each class grouped together. Third, a two-way analysis of variance (ANOVA) was used to determine which variables explained differences or similarities among reference sites and which specific factors were significantly different between habitat classes.

Ecological gradient model

Initial work showed that the reference site concept created difficulties because of its subjective nature so additional models were explored. A classification system based on depth, degree of wave exposure and wave regime, similar to the geomorphology and hydrodynamic characteristics used in the HGM approach (Brinson, 1993; Brinson *et al*., 1995;

DOI: 10.1002/aqc

Brinson and Rheinhardt, 1996; Magee, 1996), was implemented to define the major habitat classes. Direction of wave exposure is based on work developed by Friedlander *et al.* (2003) to evaluate the relationship of fish communities by their degree of wave exposure.

Evaluation and testing of models

Reference site model

It has been suggested that anthropogenic impacts may be identified for a site if variables within a habitat class deviate from the established ranges of their reference sites (USACE Coral Reef Functional Assessment Workshop, 2004). Two methods were employed in testing this concept.

1. Test sites

Sites not previously surveyed were compared with reference values to identify departures from reference conditions within the appropriate habitat class and to evaluate the RSM's predictive ability to detect degradation. A site perceived to have high anthropogenic impact and a site with low disturbance were selected to test the RSM. These two sites provided an additional 24 stations for use in model evaluation and testing. Kaloko/Honokōhau, Hawai'i is under federal management protection (National Parks Service) and has relatively low anthropogenic influence, while Maunalua Bay, O'ahu has open access and is perceived as impaired. Variable ranking determined that only three factors (coral cover, number of fish, and silt–clay) have ranges that are narrow enough to describe site condition. The ranges of these factors within their respective habitat classifications were used to compare the two test sites. These values were expected to fall within the reference range for their respective classification for Kaloko/Honokōhau and below reference ranges for Maunalua Bay.

2. RSM comparisons

Non-reference stations were compared against the reference ranges within the appropriate habitat class to determine if these values can indicate general disturbance and stress specificity. The same variables used for the test stations were used to compare non-reference stations. These stations were not used to develop the reference ranges, avoiding a circular argument. Stations were compared against reference standards to determine if the stations perceived as impaired could be detected by the RSM.

Ecological gradient model

The EGM was designed to rank reef condition within each of the 12 habitat classes in a large number of Hawaiian reefs. The 12 habitat classes were based on depth and wave exposure (Table 1). This method is completely objective and is based on a wide range of metrics that may be linked to specific types of disturbance. Since the values for most factors follow a continuum with high variability, all stations representing a gradient of degradation from severely affected to relatively pristine conditions were classified into one of 12 environmental groupings based on depth and wave exposure (Table 1).

A model was created in Microsoft Excel© that calculates where a quantified factor lay along the continuum of values. The operator enters a depth, wave exposure and an assessment value for a single factor or a group of factors into the main menu worksheet. A statewide percentile for a particular variable of interest is calculated to evaluate that variable relative to all others in a particular class (Figure 4). For example, the fish biomass at a 5 m station in Waikīkī, O'ahu located in the centre of prolonged, high human activity ranks in the lowest percentile (0%) of all comparable south, sheltered stations (49), between 2.5 and 7.5 m (Figure 5).

In addition to the rank percentile, an overall site index was calculated based on the number of variables input by comparing all other sites in that classification. The index is based on a scale of 0 to 10, where zero represents the most impaired site and ten corresponds to the least impaired site (Figure 5). Each individual factor is weighted based on an objective multivariate analysis of the primary factors defining reef condition. However, the option is also provided that allows the operator to change the weights to suit a particular management or ecological question or leave all factors unweighted. For example, one might wish to create an index that assigns the greatest weight to fish biomass, with little weight assigned to other factors. An index relevant to the question is thereby calculated, and a ranking of sites by fish biomass is produced.

The RSM uses only reference sites, while the EGM takes advantage of the entire suite of sites. Thus, habitat classification was expanded from six groups in the RSM (Figure 2, Table 1) to 12 groups in the EGM due to the increase in sample size. For the first tier, coastal sites were separated into groups based on major wave regime (North Pacific Swell or South Pacific Swell), degree of exposure (exposed or sheltered) and depth ranges (Table 1). The major wave regimes show quite different patterns of wave height, wave periodicity, intensity and seasonality (Jokiel, 2006). Slight differences in exposure of coral reefs along exposed coastlines have a profound impact on reef coral development (Storlazzi *et al.*, 2005).

Forty-three physical and biological variables were included in the model (Table 2). Metrics for classification within the second tier include 30 biotic measures to define 'biological integrity' and 13 environmental measures to identify signs of anthropogenic stress.

The site selected for model testing is located in Waikīkī, O'ahu in the centre of human activity at 5 m depth. This site has a long history of human activity including nitrification (Laws and Doliente, 1993), extensive shoreline modifications (Crane, 1972), beach replenishment (Marine Research Consultants, 1990), dredging (Belt Collins & Associates, 1987), and seawall and groin construction (Glenn and McMurtry, 1995). This has considerably reduced substrate and water quality. Much of the imported sands off Waikīkī have filled in low areas in the reef reducing topographical relief important to fish populations. Resuspension of these sands continues to scour the substrate inhibiting coral growth and recruitment.

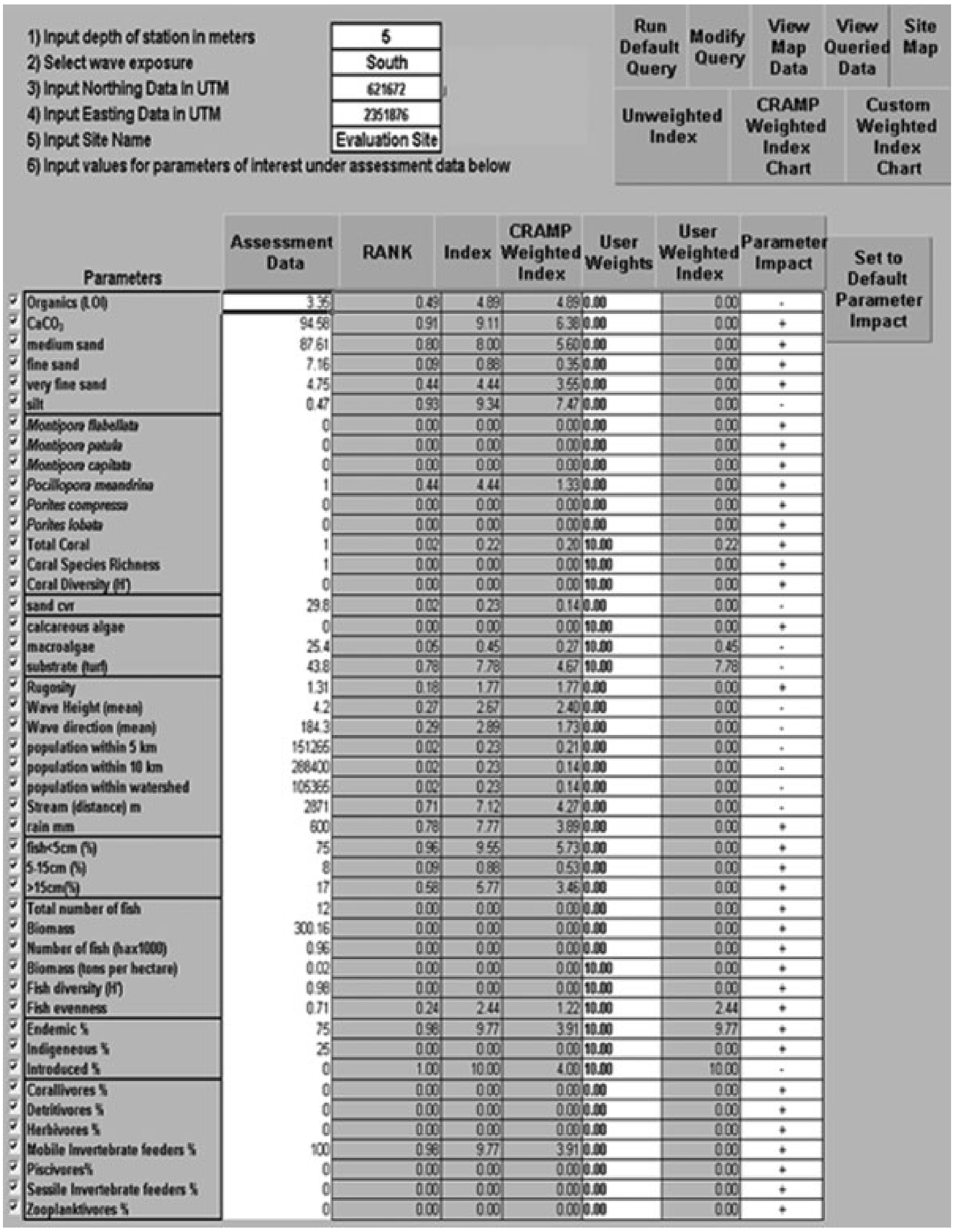
RESULTS

Identification of major factors

Both natural and anthropogenic factors were influential in structuring coral and fish communities, explaining a considerable portion of the variability (Table 3).

The most important natural factors include depth, wave regime and rugosity. Factors related to anthropogenic impact include human population, silt, and organics. Influencing factors that were

DOI: 10.1002/aqc



Parameters	Assessment Data	RANK	Index	CRAMP Weighted Index	User Weights	User Weighted Index	Parameter Impact
Organics (LOI)	3.35	0.49	4.89	4.89	0.00	0.00	-
$CaCO_3$	94.58	0.91	9.11	6.38	0.00	0.00	+
medium sand	87.61	0.80	8.00	5.60	0.00	0.00	+
fine sand	7.16	0.09	0.88	0.35	0.00	0.00	+
very fine sand	4.75	0.44	4.44	3.55	0.00	0.00	+
silt	0.47	0.93	9.34	7.47	0.00	0.00	-
Montipora flabellata	0	0.00	0.00	0.00	0.00	0.00	+
Montipora patula	0	0.00	0.00	0.00	0.00	0.00	+
Montipora capitata	0	0.00	0.00	0.00	0.00	0.00	+
Pocillopora meandrina	1	0.44	4.44	1.33	0.00	0.00	+
Porites compressa	0	0.00	0.00	0.00	0.00	0.00	+
Porites lobata	0	0.00	0.00	0.00	0.00	0.00	+
Total Coral	1	0.02	0.22	0.20	10.00	0.22	+
Coral Species Richness	1	0.00	0.00	0.00	10.00	0.00	+
Coral Diversity (H')	0	0.00	0.00	0.00	10.00	0.00	+
sand cvr	29.8	0.02	0.23	0.14	0.00	0.00	-
calcareous algae	0	0.00	0.00	0.00	10.00	0.00	+
macroalgae	25.4	0.05	0.45	0.27	10.00	0.45	-
substrate (turf)	43.8	0.78	7.78	4.67	10.00	7.78	-
Rugosity	1.31	0.18	1.77	1.77	0.00	0.00	+
Wave Height (mean)	4.2	0.27	2.67	2.40	0.00	0.00	-
Wave direction (mean)	184.3	0.29	2.89	1.73	0.00	0.00	-
population within 5 km	151266	0.02	0.23	0.21	0.00	0.00	-
population within 10 km	288400	0.02	0.23	0.14	0.00	0.00	-
population within watershed	105366	0.02	0.23	0.14	0.00	0.00	-
Stream (distance) m	2871	0.71	7.12	4.27	0.00	0.00	-
rain mm	600	0.78	7.77	3.89	0.00	0.00	+
fish<5cm (%)	75	0.96	9.56	5.73	0.00	0.00	+
5-15cm (%)	8	0.09	0.88	0.53	0.00	0.00	+
>15cm(%)	17	0.58	5.77	3.46	0.00	0.00	+
Total number of fish	12	0.00	0.00	0.00	0.00	0.00	+
Biomass	300.16	0.00	0.00	0.00	0.00	0.00	+
Number of fish (hax1000)	0.96	0.00	0.00	0.00	0.00	0.00	+
Biomass (tons per hectare)	0.02	0.00	0.00	0.00	10.00	0.00	+
Fish diversity (H')	0.98	0.00	0.00	0.00	10.00	0.00	+
Fish evenness	0.71	0.24	2.44	1.22	10.00	2.44	+
Endemic %	75	0.98	9.77	3.91	10.00	9.77	+
Indigeneous %	25	0.00	0.00	0.00	10.00	0.00	+
Introduced %	0	1.00	10.00	4.00	10.00	10.00	-
Corallivores %	0	0.00	0.00	0.00	0.00	0.00	+
Detritivores %	0	0.00	0.00	0.00	0.00	0.00	+
Herbivores %	0	0.00	0.00	0.00	0.00	0.00	+
Mobile Invertebrate feeders %	100	0.98	9.77	3.91	0.00	0.00	+
Piscivores%	0	0.00	0.00	0.00	0.00	0.00	+
Sessile Invertebrate feeders %	0	0.00	0.00	0.00	0.00	0.00	+
Zooplanktivores %	0	0.00	0.00	0.00	0.00	0.00	+

Figure 4. Main menu of ecological gradient model to enter custom data and generate ranks and index rankings using a Waikīkī station as the evaluation site.

negatively correlated with fish communities include silt, turf, coralline algae and degree of management protection (Table 3).

The variation in coral cover was best explained by rugosity, human population within 5 km, depth, distance from a perennial stream, wave direction, and maximum wave height. The variation in coral richness was best explained by sediment organic fraction, wave direction, population within 5 km, distance from a stream, and maximum wave height.

The variation in fish biomass was best explained by nine variables: sediment organic fraction, rugosity, calcareous algae, turf algae, total coral cover, coral diversity, silt, human population within 5 km, and degree of management protection. A negative relationship existed between biomass and human population within 5 km and organics, while all other variables were positively correlated with the response.

Numerical abundance of fish identified eight metrics: rugosity, organics, total coral cover, coral diversity, coralline algae, turf algae, *Montipora capitata*, and management status. All significant variables except organics and cover by the coral *M. capitata* were positively correlated with the number of fish observed.

The factors that most strongly influenced fish diversity were organics, human population, coral cover, wave direction, turf algae, sand, rugosity, and coralline algae.

Development of models

Reference site model

Based on the environmental variables (Figure 3), many of the reference stations (triangles) clustered together, although some

DOI: 10.1002/aqc

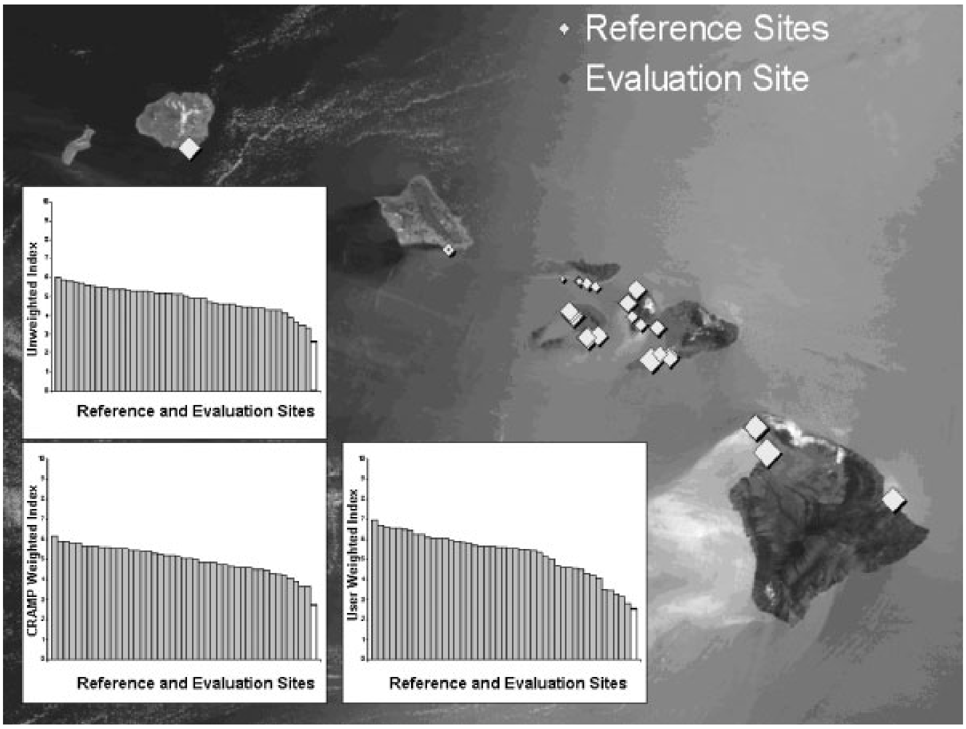


Figure 5. Ecological gradient model output depicting user evaluation (site shown as clear bar on graphs) among comparable sites. Graphs of unweighted, CRAMP weighted, and user custom weighted indices are shown. Diamonds on map depict site locations of sites with south facing exposures and sheltered from wave energy that are between 2.5 and 7.5 m in depth. Size of diamond is based on rank among other comparable sites.

Table 2. Physical and biological variables incorporated into the ecological gradient model. Subcategories italicized below variables with units in parentheses

Physical factors		Biological factors		
Other variables	Sediment variables	Coral assemblage characteristics	Fish assemblage characteristics	Algal characteristics
Rugosity (*Index*)	*Composition*	*Total coral cover* (%)	*Abundance* (no/125 m^2)	*Macroalgae* (%)
	Organics (%)		*Biomass* (mt/ha^{-1})	*Coralline* (%)
	$CaCO_3$ (%)		*Diversity (H′)*	*Turf* (%)
			Evenness (J)	
Substrate type	*Grain-sizes*	*Species*	*Trophic guild no*	
Sand (%)	Coarse sand (%)	*Porites lobata* (%)	Corallivores (no/125 m^2)	
Silt (%)	Medium sand (%)	*P. compressa* (%)	Detritivores (no/125 m^2)	
	Fine/very fine sand (%)	*Montipora capitata* (%)	Herbivores (no/125 m^2)	
		M. patula (%)	Mobile Inverts (no/125 m^2)	
	Silt/clay (%)	*M. flabellata* (%)	Sessile Inverts (no/125 m^2)	
		Pocillopora meandrina (%)	Planktivores (no/125/m^2)	
			Zooplanktivores (no/125 m^2)	
Human population		*Species richness* (no/125 m^2)	*Size classes*	
w/in 5 km (no)			<5 cm (no/125 m^2)	
w/in 10 km (no)			5–15 cm (no/125 m^2)	
Watershed (no)			>15 cm (no/125 m^2)	
Precipitation (mm h^{-1})		*Species diversity* (*H′*)	*Endemism status*	
Stream distance (km)			Endemic	
			Indigenous	
			Introduced	

exhibited considerable overlap with the non-reference stations (circles). A total of 74% of the stations were correctly classified and 26% misclassified.

Since some degree of separation occurred between reference and non-reference stations, next it was critical to determine if the reference stations in each of the six habitat classes were different from one another based on biological and environmental factors (Figure 2). To determine if the reference stations fell within the predicted classification a discriminant analysis was conducted. Of the reference stations, only 43% fell into the predicted habitat class. Similar results were obtained when all stations were included (38%). Figure 2 shows considerable overlap of reference stations with no consistent pattern between the six habitat classes.

An ANOVA determined most of the habitat classes were not statistically different from one another for the majority of

DOI: 10.1002/aqc

Table 3. Influential biological and environmental variables

Fish assemblage parameters			Coral community factors	
Biomass	Number of individuals	Diversity	Coral cover	Richness
Organics t = –4.5, P = <0.0015	Coral cover t = 5.0, P = <0.001 Diversity t = 2.7, P = <0.001	Organics t = –5.7, P = <0.001	Rugosity t = 8.4, P = <0.001	Organics t = –4.6, P = <0.001
Rugosity t = 3.5, P = 0.001	Coralline t = 4.3, P = <0.001 Turf t = 2.4, P = 0.02	Coral cover t = 3.5, P = <0.001	Human Population t = –3.4, P = 0.001	Wave direction t = –3.9, P = <0.001
Coralline t = 3.9, P = <0.001 Turf t = 2.4, P = 0.016	Rugosity t = 3.3, P = 0.001	Human Population t = –3.2, P = <0.001	Depth t = 3.0, P = 0.003	Human Population t = –3.8, P = <0.001
Coral cover t = 3.9 Diversity t = 2.2	Organics t = –2.3, P = 0.026	Wave direction t = –3.0, P = 0.024	Distance from stream t = –2.8, P = 0.006	Distance from stream t = –2.8, P = 0.006
Human Population t = –2.3, P = 0.021	Management Status t = 2.2, P = 0.033	Turf t = 2.8, P = 0.001 Coralline t = 2.0, P = 0.001	Wave direction t = –2.7, P = 0.009 Wave height t = –2.3	Wave height t = –2.3, P = 0.025
Silt t = –2.3, P = 0.023		Rugosity t = 2.2, P = 0.008		
Management Status t = 2.3, P = 0.022		Sand t = 2.0, P = 0.03		

the variables. Only nine of the 43 variables showed distinct differences between at least two of the six habitat classes. The distinguishing factors included: sand (F = 6.9, $P<0.001$), *Porites compressa* (F = 6.8, $P<0.001$), very fine sand (F = 6.7, $P<0.001$), medium grain-size (F = 4.5, $P = 0.001$), turf algae (F = 3.6, $P = 0.001$), calcareous algae (F = 2.9, $P = 0.001$), number of fishes (F = 2.6, $P = 0.03$), total coral cover (F = 2.5, $P = 0.04$) and silt (F = 2.5, $P = 0.04$).

Evaluation and testing of models

Reference site model

Test sites. As expected, all stations (17) at Kaloko/Honokōhau exhibited values within the reference ranges, while the majority of the stations (71%) were below reference ranges at Maunalua Bay.

RSM comparisons. Comparisons indicated that the majority of stations at Waikīkī had values for numerical fish abundance and coral cover that were outside the reference ranges for each station's habitat class. Coral cover was below reference levels for their respective habitat class for all 11 transects, while the number of fish was below reference values at over half of the stations. These results agreed with the established impacts from overuse (Grigg, 1995; Laws and Ziemann, 1995) and identified the specific area within the site where disturbance was occurring. In line with the lack of impact by sedimentation at the stations surveyed, silt values at Waikīkī stations were within the reference ranges.

Ninety-nine stations within 26 non-reference sites were compared with maximum reference values for silt. The sites that far exceeded the reference values included: Kakahai'a, Kamiloloa and Pālā'au, Moloka'i, Hakioawa, Kaho'olawe, Pelekane Bay, Hawai'i, and Kāne'ohe Bay, O'ahu. Sites that have silt values slightly higher than reference levels included Puamana, Maui, Laupāhoehoe, Hawai'i and Kamalō, Moloka'i. Of the nine sites that fell outside reference ranges, seven are on the 2002 EPA list of most impaired sites. The two sites detected by the reference model but missing from the 2002 EPA list are Hakioawa, Kaho'olawe and Laupāhoehoe, Hawai'i. The island of Kaho'olawe was not listed in the polluted coastal waters list, but the reefs have been subject to extreme degradation due to siltation (Cox *et al*., 1995; Te, 2001). The Laupāhoehoe site receives runoff from a large watershed and is subject to extremely high wave energy from persistent NE Trade Wind waves (EPA, 1971).

All five sites detected by the RSM as outside the reference range for fish abundance were included in the 2002 EPA polluted coastal waters list. In addition to Waikīkī, numerical fish abundance was well below reference levels at the majority of stations in Pelekane Bay, Hawai'i; Kamiloloa, Moloka'i; and at deeper stations in Kāne'ohe Bay. One station on the shallow reef flat in Hanalei Bay, Kaua'i was also outside the lower reference range of values. This is in agreement with Friedlander and Parrish (1998) who found the lowest abundance to occur on the reef flats, compared with other substrate types within Hanalei Bay.

All eight sites (Leleiwi, Puhi and Pelekane Bays, Hawai'i; Kamiloloa, Moloka'i; Waikīkī and Kāne'ohe Bay, O'ahu; and Ma'alaea and Puamana, Maui) detected by the RSM as outside reference ranges for coral cover were on the 2002 EPA polluted coastal waters list. The reference values for exposed habitats were confounded by the fact that these sites often had little or no coral cover due to the higher wave energy, thus only sheltered sites were considered in the analysis.

DOI: 10.1002/aqc

Ecological gradient model

A Waikīkī station at 5 m depth was selected as the model test site. Information on depth, wave exposure and geographic location were input into the main menu of the EGM (Figure 4). These data were used to produce an index and generate a site map of all similar sites.

The Waikīkī station was ranked the lowest of 46 comparable stations with an overall unweighted index of 2.4. Hakioawa, Kaho'olawe was ranked the highest with an unweighted index of 6.0. A rank and index for each individual factor was also generated by the model. As an example, total coral cover received a rank of 0.02 and an index of 0.2, while fish biomass ranking and index were both 0.0 indicating extremely poor conditions compared with sites within the same classification.

A site map highlighting locations of Waikīkī and all other 46 comparable sites including graphs of site index rankings was generated (Figure 5). This includes an unweighted, CRAMP weighted (based on regression analyses), and user weighted index.

The demonstration program can be downloaded at http://cramp.wcc.hawaii.edu. Additional information is also provided on this website.

DISCUSSION

Results of this investigation demonstrate that defining and quantifying the condition of a complex coral reef ecosystem is a difficult task. These communities are shaped by intricate and highly variable interrelationships between numerous ecological factors. It is unlikely that the condition of a multifaceted coral reef ecosystem can be described using measures of a single factor such as abundance of an 'indicator species' or through measurements of a physiological process. However, this investigation offers evidence that a series of key ecological metrics can be used to define the ecological status of a coral reef. The metrics used in this investigation are in wide use, easily measured at low cost, and effective in identifying natural and anthropogenic forces that influence coral reef condition. Fourteen of the 43 metrics evaluated in this investigation had a significant relationship with major reef fish and coral community characteristics.

A similar quantitative evaluation of the 'health' and 'value' of the north-western Hawaiian Islands (NWHI) in relation to the main Hawaiian Islands (MHI) has been presented by Jokiel and Rodgers (2005). Biological information for the NWHI region is very limited due to its extreme isolation, but sufficient data on five important biological indicators were developed for both the NWHI and the MHI. These included reef fish biomass, reef fish endemics, total living coral cover, population of the endangered Hawaiian monk seal *Monachus schauinslandi*, and the number of female green sea turtles *Chelonia mydas* nesting annually on each island. These diverse data sets were used in a simple integrated scoring and ranking scheme for all the islands of the archipelago. The resulting composite scoring graphically illustrates the diminished condition of reef ecosystems close to human population within the Hawaiian Archipelago. Sensitivity analysis demonstrated that even the use of a small number of well chosen parameters can provide a very useful biological index of reef ecosystem condition.

Reference site model

The RSM can detect sites that strongly deviate from reference values for selected factors in sheltered regions. While it is able to detect values that fall outside the reference ranges at highly impaired sites, it is not able to detect marginal degradation because of high variability within reference sites. The RSM based on classification of reference sites and the use of reference values to detect degradation is effective for use in the evaluation of levels of sedimentation. However, ranges suggest that only severely degraded conditions of coral and fish for specific habitat classes can be detected by this model. Possible degradation can be detected by values of coral cover outside the lower reference ranges at sites with sheltered wave regimes, but not in exposed regions that typically exhibit low coral cover. Furthermore, only strong deviations of numerical fish abundance can be detected, due to high variability. The importance of other influential factors such as sediment composition, fish biomass, fish trophic level, rugosity, and algae cannot be evaluated with this model. The RSM's usefulness and applicability on a broad scale was shown by the agreement with the 2002 EPA's 'most impaired site' listing of polluted coastal waters, showing evidence of degradation by sediments, nutrients, or bacteria. This list, revised in 2002, was based on all available water quality data at the time. The majority of listed sites are near streams with a high level of adjacent urban and agricultural activities. South Moloka'i has a long record of devegetation due to overgrazing, which has led to widespread sedimentation on the reef flats (Roberts, 2000). Kāne'ohe Bay also has an extensive history of dredging and sewage discharge with considerable urbanization in the surrounding watershed (Hunter and Evans, 1993). Both listings, however, are somewhat subjective with the 2002 EPA listing determined largely by water quality and the RSM being derived qualitatively using ecological conditions other than the 2002 EPA criteria.

Use of the reference site approach in this study is further complicated because the legal definition and interpretation of impaired waters versus unimpaired waters is continually changing. This study initially considered the 2002 list (Hawai'i State Dept. of Health, 2002) (219 stations, 143 sites) to be a valid document produced by resource managers. The list was challenged in court and determined to be inadequate. Further work by managers led to the development of a complicated report in 2006 that was eventually approved by the EPA in 2008 which included (844 stations, 590 sites) (Hawai'i Department of Health, 2008). This list continues to be contentious and will be subject to further revision. The list is growing due largely to interpretation rather than actual changes in condition of the reefs.

The selection of Kaloko-Honokōhau for a test site (reference category) was made because this is a National Historical Park located along an arid, barren-lava coastline. Subsequent events revealed another weakness of the reference site approach. The site did indeed show values within the reference ranges. However, its status as a fixed reference site might end in the near future. At the southern boundary of Kaloko-Honokōhau National Historical Park, 530 acres of public land is proposed to be developed into a mixed use development. The planned development includes a new 45 acre marina basin with a minimum of 800 additional boat slips, mixed light industrial, commercial and resort components,

DOI: 10.1002/aqc

including timeshares, hotels, and interconnected water lagoons flowing out into the existing harbour. Enlarging the harbour will lead to increased groundwater discharge onto the reef. Development is also occurring rapidly upslope to the east of the Park. At present, 13 projects are underway or proposed, as well as infrastructure improvements on water transmission lines, sewer systems and roads. A residential and golf course development is underway at the north end of the Park. Eventually the Park will be in an urban setting. The cumulative impact of these developments on the offshore reefs could be significant.

Results of this investigation show the following limitations of using a 'reference site' or a 'control reef' in determining reef condition.

1. The reference sites standard cannot distinguish degree of impairment. The extremes of 'severely impaired' and 'little or no impact' can be defined, but the high variability in range restricts the ability of reference ranges to discriminate on a finer scale.
2. Reference site values have limited power in detecting disturbance. High variability among most variables prevents identification of specific causes of disturbance. Natural heterogeneity increases reference ranges and decreases the ability of reference sites to detect impaired reef condition. For example, high wave energy environments naturally have low coral cover values that are not related to anthropogenic factors compared with degraded sites with reduced coral cover.
3. A small sample of reference sites cannot accurately describe the range of biological integrity encountered among reef communities. There is high spatial and temporal variability that cannot be encompassed by a single reference site or a small number of reference sites. When attempting to integrate a large number of reference sites, conditions can overlap substantially with non-reference sites (Figure 3).
4. Subjective selection of reference sites is flawed, even when the sites are chosen by 'experts'. The control and reference sites in most studies are chosen by researchers in order to make a point, and thus may be deliberately or unconsciously biased. No two reefs are exactly alike in all respects, and agreement on appropriateness of any 'control' or 'reference' reef cannot generally be attained, especially when litigation concerning reef damage is involved. Quantitative analysis showed poor separation between reference and non-reference sites (Figure 3). Determination of optimal reef conditions is obscured by the lack of knowledge of the anthropogenic history of a site and sliding baselines that change over time. The reference concept is defective largely because it does not embrace the diversity of unaffected reef communities.
5. When comparison of non-reference sites is made against reference sites for use in the evaluation of impairment, comparison among non-reference sites is unattainable.

Although the reference site paradigm was not found to be applicable in the Hawaiian marine environment for the purposes of identifying anything other than severely impaired reef condition because of the complexity and extreme heterogeneity of coral reef ecosystems it may be useful for other applications. The RSM approach may have utility in situations in systems that are less complex than coral reefs. For example, a reference site approach is widely employed in fresh water streams (United States Environmental Protection Agency, 2008). Coral reefs are characterized by high biotic diversity and contain orders of magnitude more species than streams. Further, coral reef habitats are diverse and characterized by extreme variation in environmental conditions. Reviews of available information emphasize the difficulties in applying the basic biocriteria concepts to coral reef communities (Jameson *et al.*, 1998, 2001). High variability among candidate reference sites should be expected on coral reefs, so it would be prudent to use more than one site as a reference for any investigation based on the reference site model. The practice of using expert opinion to select reference sites may be of use for certain purposes. For example, the RSM as used in this study was able to identify the most impaired coral reefs. Given the observed variation, it is important to use a group of reference sites rather than a single reference site. In general, however, the use of hand picked reference sites should be avoided. Our conclusions are supported by Whittier *et al.* (2006) who conducted a comparison of physical and chemical disturbance measures and biotic indices at 'handpicked reference stream sites' provided by resource agencies and at sites selected by a probability design. Most of the handpicked reference sites fell into the category of intermediately disturbed, and 12.5% were classified as most-disturbed. Thus only a small subset of the handpicked reference sites represented least-disturbed conditions. The authors concluded that all agencies using reference sites critically review such reference sites with a set of explicit criteria, using field-collected physical, chemical and biological data as well as mapped information.

Ecological gradient model

The EGM was developed to overcome the limitations noted above for the RSM. Many factors combine to influence coral reef communities, but most explain a very small portion of the variability. Both natural factors (rugosity, depth and wave energy) and anthropogenic factors (organics, human population, management protection and distance from a stream) influence biotic assemblage characteristics (Table 3). Distance from stream is a natural factor, but with an anthropogenic component. Streams are the primary agent in delivery of sediment and other materials from a human-impacted watershed to the reef. Although these factors are the most influential in explaining the observed variability in coral community structure, many other factors such as sediment composition and grain size, substrate type, water quality factors, and fishing pressure combine to varying degrees to influence biological populations.

Stratification of coral reef organisms is controlled principally by depth, topographical complexity, and wave regimes. Accretion, growth, and community structure of most coral reefs in the Hawaiian Islands are primarily under the control of wave forces (Grigg, 1998). The dominant wave regimes show quite different patterns of wave height, wave periodicity, intensity and seasonality (Jokiel, 2006) and slight differences in exposure, and have a profound impact on reef coral development (Storlazzi *et al.*, 2005). Large waves and strong currents in exposed areas flush contaminants from reefs. In general, anthropogenic impacts dominate in environments where wave forces are not the major controlling factor (Dollar and Grigg, 2004). Along open coastal sites, anthropogenic

DOI: 10.1002/aqc

effects often are undetectable relative to natural factors that affect coral community structure (Dollar and Grigg, 2004). This observation has led to the suggestion of a management framework that concentrates efforts on embayments and areas with restricted circulation (Dollar and Grigg, 2004). That is not to say that we can ignore such wave-swept communities because they are more resistant to loading of pollutants. For example, large volume of sugar mill waste dumped into the ocean along the coastline of Hamakua, Hawai'i exerted a major negative impact on this wave exposed coastline (Grigg, 1985). Upon termination of discharge strong waves and currents swept away the deposits of sediment and cane bagasse and the reefs recovered at a rapid rate (USEPA, 1971). Use of these physical factors to define the major habitat groups is similar to the HGM approach of classifying wetlands based on their geomorphic setting and hydrodynamics (Brinson, 1993; Brinson *et al.*, 1995). This approach is also equivalent to systems of terrestrial botanical zonation, which are primarily based on elevation, topography and rainfall. These oceanic, geologic, and meteorological differences created diverse habitats, supporting varied biotic distributions and abundances making selection of reference sites difficult. Unlike the attributes used to create an index of biotic integrity (IBI) for freshwater systems (Karr and Chu, 1999), most marine attributes are not composed of distinct ranges, but instead follow continuous gradients.

Multiple variables that have an influence on the biological communities follow overlapping and often dissimilar continuous gradients that confound defining of boundaries. Thus, it is advantageous to use a large number of sites within each habitat classification and rank the sites along a continuum by purely objective criteria. In this way the condition of the reef can be defined in comparison with a wide range of other reefs within its habitat classification. The EGM method continues to grow in power as the number of sites, parameters and classifications are increased.

This EGM approach provides a quantitative method for ranking coral reef condition based on extensive data, rather than depending on an arbitrary 'reference site' or a rigid set of standards. As shown by the example (Figure 4), the use of computers allows for a rapid comparison of a site under evaluation with a large range of other comparable sites. Furthermore, this approach permits the operator to alter and define criteria appropriate to a specific question. A low ranking can assist management in identifying degraded areas that may need further investigation, monitoring or restoration. A high ranking can identify sites that may be suitable for consideration as marine protected areas (MPA) or avoided for dredging or construction projects. Comparing rankings can aid in assessing compatibility of experimental and control sites for use in manipulative field experimentation. A link to specific types of disturbance may be highlighted in these rankings. For example, a high ranking of silt/clay and organics can be indicative of areas strongly affected by sedimentation. Different areas within a region can be compared to identify the range and type of impact. The EGM's quantitative assessment has the capability to be used as a valuable management tool upon which to base effective administrative decisions.

The approach taken in this study was to describe relationships between physical, anthropogenic, and biological parameters on Hawaiian coral reefs. The techniques used in this study are widely used, cost-effective, non-destructive, inexpensive, biologically meaningful and within the technical capabilities of most researchers and managers of coral reef areas. The model uses widely available software for calculations. The work was successful in identifying those coral reef metrics that are useful indicators of general reef condition. Thus physical, anthropogenic, and biological attributes were incorporated into the EGM. The next step will be to develop and test an index of biological response that relates directly to anthropogenic impact. The Index of Biotic Integrity (IBI) was developed by Karr (1981) as a means to identify and classify water pollution problems. The IBI is based solely on biological characteristics, so it is useful to contrast the EGM and IBI and discuss the design and applications of the two approaches. There is a great deal of interest in developing such an IBI for coral reefs, which has proven to be an elusive and formidable task (Jameson *et al.*, 1998, 2001). A potential coral reef IBI can be viewed as a subset of the EGM and could be derived using the biological data (e.g. coral cover, fish biomass, diversity, trophic structure, etc.) contained in the EGM. A ranking based entirely on biological data in the existing model can be achieved simply by setting all physical parameters to 0 and running the model using only the biological data. However, the weight given to each biological factor and testing the validity of the resulting indices in various habitats will require a great deal of effort in the future. The metrics of wave exposure and depth were shown to be the overriding physical factors defining the major habitats on coral reefs of Hawai'i, so a specific index must be developed within each habitat from biological data contained in the EGM habitat groupings. At the present time the environmental laws intended to protect coral reef resources from pollution in Hawai'i are based largely on water quality criteria and not biocriteria. Water quality data for reef locations throughout Hawai'i are very scanty, so a great deal of additional effort will be needed in order to link water quality criteria to the biological criteria if this work is to move forward. Likewise, data on pollutants entering the reefs by stream flow, surface runoff and groundwater is poorly documented. As such data become available, it has been suggested that the biological attributes within each physical habitat grouping of the EGM could be used as 'dependent variables' and various physical and anthropogenic factors as 'independent variables.' One could analyse such biological indices against water quality, discharge and other anthropogenic factors in order to determine which most strongly influence the biological condition. As a caution, however, it has been shown that the IBI approach is an excellent means for determining that a problem is present, but is not effective at determining the cause of the impairment, especially when multiple dischargers are present and/or the habitat has been disturbed (Seegert, 2000). The ability of the EGM to produce a relative ranking of general reef condition for a large number of sites in comparison with a particular site being evaluated is the greatest strength of the EGM at the present time that should be included in the potential development of a purely biological index.

ACKNOWLEDGEMENTS

This research was partially funded by the EPA Office of Water Quality Grant 00920, USGS Cooperative Agreement 98WRAG1030, NOS Cooperative Agreement NA170A1489,

DOI: 10.1002/aqc

and by the Hawai'i Coral Reef Initiative and the National Ocean Service MOA 2005-008/6882 Amendment No. 001, 'Research in Support of the NWHI Coral Reef Ecosystem Reserve, HIMB, SOEST, UH Mânoa' (Dr Jo-Ann Leong P.I.). We thank Fred Farrell, Kanako Uchino, Erica Muse, and Will Smith for their assistance in the field. HIMB contribution number 1349.

REFERENCES

Barbour MT, Plafkin JL, Bradley BP, Graves CG, Wisseman RW. 1992. Evaluation of EPA's rapid bioassessment benthic metrics: metric redundancy and variability among reference stream sites. *Environmental Toxicology and Chemistry* **11**: 437–449.

Belt Collins & Associates. 1987. *Environmental Assessment. Maintenance dredging and beach sand replenishment, Hawaiian Village Lagoon, Waikiki, Oahu Prepared for Hilton Hotels Corporation*. Belt Collins & Associates, Honolulu.

Brinson MM. 1993. A hydrogeomorphic classification for wetlands. Technical Report WRP-DE-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. NTIS No. AD A270 053.

Brinson MM, Rheinhardt RD. 1996. The role of reference wetlands in functional assessment and mitigation. *Ecological Applications* **16**: 69–76.

Brinson MM, Lee LC, Ainslie W, Rheinhardt RD, Hollands GG, Smith RD, Whigham DF, Nutter WB. 1995. Common misconceptions of the hydrogeomorphic approach to functional assessment of wetland ecosystems: scientific and technical issues. *Bulletin of the Society of Wetland Scientists* **17**(2): 16–21.

Brock VE. 1954. A preliminary report on a method of estimating reef fish populations. *Journal of Wildlife Management* **18**: 297–308.

Brown EK, Cox EF, Tissot B, Jokiel PL, Rodgers KS, Smith WR, Coles SL. 2004. Development of benthic sampling methods for the Coral Reef Assessment and Monitoring Program (CRAMP) in Hawai'i. *Pacific Science* **58**: 145–158.

Clague DA, Dalrymple GB. 1994. Tectonics, geochronology and origin of the Hawaiian Emperor volcanic chain. In *A Natural History of the Hawaiian Islands*, Kay EA (ed.). University of Hawai'i Press; 5–40.

Clarke KR, Gorley RN. 2001. *PRIMER v5: user manual/ Tutorial*. PRIMER-E: Plymouth, UK.

Coral Reef Assessment and Monitoring Program. Jokiel PL, Rodgers KS. 2006. www.CRAMP.wcc.hawaii.edu.

Cox EF, Jokiel PL, Te FT, Stanton FG, Naughton J, Brock RE, Bailey-Brock JH. 1995. An Evaluation of the Nearshore Coral Reef Resources of Kaho'olawe. Hawai'i Institute of Marine Biology Technical Report No. 40, Honolulu, Hawai'i. June Final Report Submitted to: The National Oceanic and Atmospheric Administration. NOAA Cooperative Agreement No. NA27OM0327.

Coyne MS, Batista TA, Anderson M, Waddell J, Smith WR, Jokiel PL, Kendall MS, Monaco ME. 2003. Benthic habitats of the main Hawaiian Islands: NOAA Technical memorandum NOS NCCOS CCMA 152, [http://ccma.nos.noaa.gov/products/biogeography/Hawaii_cd/index.htm.].

Craft CB, Seneca EB, Broome SW. 1991. Loss on ignition and Kjeldahl digestion for estimating organic carbon and total nitrogen in estuarine marsh soils: calibration with dry combustion. *Estuaries* **14**: 175–179.

Crane JK. 1972. *History of marine structures on Waikiki Beach and their effects upon the beach*. University Hawai'i, Dept. Ocean Engineering, Manoa.

Dollar SJ, Grigg RW. 2004. Anthropogenic and natural stresses on selected coral reefs in Hawai'i: a multidecade synthesis of impact and recovery. *Pacific Science* **58**: 281–304.

Folk RL. 1974. *Petrology of Sedimentary Rocks*. Hemphill Publishing Company: Austin, TX.

Friedlander AM, Parrish JD. 1998. Habitat characteristics affecting fish assemblages on a Hawaiian coral reef. *Journal of Experimental Marine Biology and Ecology* **224**: 1–30.

Friedlander AM, Brown EK, Jokiel PL, Smith WR, Rodgers KS. 2003. Effects of habitat, wave exposure, and marine protected area status on coral reef fish assemblages in the Hawaiian archipelago. *Coral Reefs* **22**: 291–305.

Glenn CR, McMurtry GM. 1995. Scientific studies and history of the Ala Wai Canal and artificial tropical estuary in Honolulu. *Pacific Science* **49**: 307–318.

Green RH, Vascotto GL. 1978. A method for the analysis of environmental factors controlling patterns of species composition in aquatic communities. *Water Resources* **12**: 583–590.

Grigg RW. 1985. Hamakua coast sugar mills revisited: an environmental impact analysis in 1983, University of Hawaii, Sea Grant Pub. No. UNIHI-SEAGRANT-TR-85-02, Honolulu.

Grigg RW. 1995. Coral reefs in an urban embayment in Hawaii: a complex case history controlled by natural and anthropogenic stress. *Coral Reefs* **14**: 253–266.

Grigg RW. 1998. Holocene coral reef accretion in Hawaii: a function of wave exposure and sea level history. *Coral Reefs* **17**: 263–272.

Hawaii Department of Health. 2008. The 2006 State of Hawaii Water Quality Monitoring and Assessment Report. Published Jan. 11, 2008, The Hawaii State Department of Health, Honolulu, Hawaii. Available for downloading at http://hawaii.gov/health/environmental/environmental/env-planning/wqm/wqm.html.

Hawai'i State Department of Health Environmental Planning Office, Henderson K, Harrigan J. 2002. List of impaired waters in Hawai'i prepared under clean water act §303(d) December 2002. Available for downloading at: http://hawaii.gov/health/environmental/env-planning/wqm/2002-303dpcfinal.pdf.

Hunter CL, Evans CW. 1993. Reefs in Kāne'ohe Bay, Hawai'i: Two centuries of western influence and two decades of data. In *Proceedings of the Colloquium on Global Aspects of Coral Reefs Health, Hazards, History*, University of Miami.

Jameson SC, Erdmann MV, Gibson Jr GR, Potts KW. 1998. Development of biological criteria for coral reef ecosystem assessment. Atoll Research Bulletin, September 1998, No. 450, Smithsonian Institution, Washington, DC, 102 pp.

Jameson SC, Erdmann MV, Karr JR, Potts KW. 2001. Charting a course toward diagnostic monitoring: a continuing review of coral reef attributes and a research strategy for creating coral reef indexes of biotic integrity. *Bulletin of Marine Science* **69**: 701–744.

Jokiel PL. 2006. Impact of storm waves and storm floods on Hawaiian reefs. *Proceedings of the Tenth International Coral Reef Symposium*; 390–398.

Jokiel PL, Rodgers KS. 2005. Ranking coral ecosystem 'health' and 'value' for the islands of the Hawaiian Archipelago. *Pacific Conservation Biology* **13**(1): 60–68.

Jokiel PL, Brown EK, Friedlander A, Rodgers KS, Smith WR. 2004. Hawai'i Coral Reef Assessment and Monitoring Program: spatial patterns and temporal dynamics in reef coral communities. *Pacific Science* **58**: 159–174.

Karr JR. 1981. Assessment of biotic integrity using fish communities. *Fisheries* **6**: 21–27.

Karr JR, Chu EW. 1999. *Restoring Life in Running Waters: Better Biological Monitoring*. Island Press: Washington, DC.

Laws EA, Doliente D. 1993. Hypereutrophication of the Ala Wai Canal, Oahu, Hawaii: prospects for cleanup. *Pacific Science* **47**(1): 59–75.

Laws EA, Ziemann DA. 1995. Effects of Sewage Discharges and Stream Runoff on Phytoplankton Communities and Water Quality in Mamala Bay Prepared for The Mamala Bay Study Commission, Honolulu, Report No. 71.

Lenat DR. 1988. Water quality assessment of streams using a qualitative collection method for benthic macroinvertebrates. *Journal of American Benthological Society* **7**: 222–233.

McCormick M. 1994. Comparison of field methods for measuring surface topography and their associations with a tropical reef fish assemblage. *Marine Ecology Progress Series* **112**: 87–96.

Magee DW. 1996. The hydrogeomorphic approach: a different perspective. *Bulletin of the Society of Wetland Scientists* **13**(2): 12–14.

Marine Research Consultants. 1990. *Waikiki Beach restoration projects: assessment of coral reef community structure at the site of sand replenishment, Waikiki, Oahu, Hawaii Prepared for O.I.* Consultants, Inc. Marine Research Consultants, Honolulu.

Rapport DJ, Gaudet C, Karr JR, Baron JS, Bohlen C, Jackson W, Jones B, Naiman RJ, Norton B, Pollock MM. 1998. Evaluating landscape health: integrating societal goals and biophysical process. *Journal of Environmental Management* **53**: 1–15.

Roberts LM. 2000. Historical land use, coastal change and sedimentation on South Molokai reefs. In *Recent Advances in Marine Science and Technology*, Saxena N (ed.). PACON International: Honolulu, Hawaii; 167–176.

Rosenburg DM, Resh VH. 1993. *Freshwater Biomonitoring and Benthic Macroinvertebrates*. Chapman and Hall: New York.

Seegert G. 2000. The development, use, and misuse of biocriteria with an emphasis on the index of biotic integrity. *Environmental Science and Policy* **3** Supplement 1: 51–58.

Smith DR, Ammann A, Bartoldus C, Brinson MM. 1995. An approach for assessing wetland functions using hydrogeomorphic classification, reference wetlands, and functional indices. Technical Report WRP-DE-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS. NTIS No. AD A307 121.

Storlazzi CD, Field ME, Jokiel PL, Rodgers KS, Brown EK, Dykes JD. 2005. A model for wave control on coral breakage and species distribution: southern Moloka'i, Hawai'i. *Coral Reefs* **24**: 43–55.

Te FT. 2001. *Response of Hawaiian Scleractinian Corals to Different Levels of Terrestrial and Carbonate Sediment. Dissertation*. Dept. of Zoology, University of Hawai'i.

United States Army Corp of Engineers (USACE). 2004. *Coral Reef Functional Assessment Workshop*, University of Hawai'i, Honolulu, Hawai'i, 31 August to 2 September.

United States Environmental Protection Agency. 1971. The Hawaii Sugar Industry Waste Study, US Environmental Protection Agency, Region IX, San Francisco, California, US Government Printing Office, Pub. 981–150.

United States Environmental Protection Agency. 2008. Best practices for identifying reference condition in Mid-Atlantic streams. Office of Environmental Information EPA-260-F-06-002, August 2006, Washington DC 20460.

Whittier TR, Stoddard JL, Larsen DP, Herlihy AT. 2006. Selecting reference sites for stream biological assessments: best professional judgment or objective criteria. *Journal of the North American Benthological Society* **26**: 349–360.

DOI: 10.1002/aqc