Case Study

Evaluating the feasibility and advantage of a multi-purpose submerged breakwater for harbor protection and benthic habitat enhancement at Kahului Commercial Harbor, Hawai'i: case study

Yuko Stender¹ · Michael Foley² · Ku'ulei Rodgers¹ · Paul Jokiel¹ · Amarjit Singh³

Received: 1 September 2020 / Accepted: 22 December 2020 / Published online: 21 January 2021

© The Author(s) 2021

Abstract

Construction of breakwaters provides an engineering solution for coastal protection. However, little effort has been made toward understanding the ecological impact on local coral reef ecosystems and developing engineering structures that would enhance the coral reef environment. A submerged breakwater proposed for Kahului Commercial Harbor, Hawai'i, provided an opportunity to design a multi-purpose 'reef structure' to mitigate wave impacts while providing new coral reef habitat. This design involved ecological and environmental considerations alongside engineering principles, serving as a model for environmentally sound harbor development. This field study evaluated environmental conditions and reef community composition at the proposed site in a gradient extending outward from the harbor, using in situ data with multivariate analyses. Benthic and topographic features in the area were assessed using a towed drop camera system to relate to biological factors. Results that support breakwater topography should follow the natural spur and groove and depth of the adjacent reef and orient with wave direction. A deep area characterized by unconsolidated substrata and low coral cover would be replaced with the shallow, sloping hard bottom of the breakwater, and provide an exemplary area for corals to flourish while protecting the harbor from large ocean swells. Surfaces on shallow sloping hard bottoms receive higher levels of irradiance that benefits coral growth. Optimal levels of water motion facilitate sediment removal and promote coral recruitment and growth. The design of the Kahului Harbor submerged multi-purpose structure serves as a model for design of shoreline modification that enhances, rather than degrades, the local coral reef environment.

Keywords Coral reefs · Artificial habitat · Ecological engineering · Adaptive management · Maui

1 Introduction

Coastal communities in tropical and subtropical regions face multiple consequences of global climate change [1]. Nearshore zones are hampered by intensified cyclones [2, 3], storm surges [4], and rising sea levels [5, 6]. Populated low-lying areas of many Pacific Islands are exposed to high risk of coastal erosion and flooding [7, 8], resulting in

negative impacts on their economy and livelihood from destruction of property and infrastructure, loss of agricultural products and food supplies, and drinking water contamination [7, 9]. Moreover, tropical and subtropical island ecosystems rely on coral reefs as integral components of coastal communities, providing services and goods such as coastal protection and natural resources for socioeconomic activities [10]. Nevertheless, coral reefs are made

Supplementary information The online version of this article (<https://doi.org/10.1007/s42452-020-04072-4>) contains supplementary material, which is available to authorized users.

✉ Ku'ulei Rodgers, kuuleir@hawaii.edu | ¹Hawai'i Institute of Marine Biology, P.O. Box 1346, Kane'ohe, HI 96744, USA. ²Oceanit Laboratories, Inc., 828 Fort Street Mall Ste 600, Honolulu, HI 96813, USA. ³Department of Civil Environment and Engineering, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA.

SN Applied Sciences (2021) 3:167 | <https://doi.org/10.1007/s42452-020-04072-4>

vulnerable to threats including frequent and prolonged occurrence of high temperature, decreased water quality, and habitat destruction [11]. It is critical for coastal communities to take advantage of adaptive strategies to manage coastal hazard risks while conserving coral reef ecosystems for their livelihood.

Attention is increasing from government, private sectors, and researchers to an integrative approach combining coastal hazard protection and ecosystem resilience as a potential management solution for adaptive coastal communities [12–14]. The concept of ecological engineering [15] provides a framework for such an interdisciplinary approach to achieve multiple objectives that support adaptive communities and biological conservation, benefitting both nature and society. Case studies and the efficacy of ecological engineering approaches have been evaluated for mangrove, marsh, and oyster reef systems in Asia, India, and the USA. [12]. Interest in ecological principles and the value of coastal defense structures has previously been assessed in Europe and Australia [16–19].

Despite an increase in attention to ecological engineering approaches in coastal ecosystems, integrated field studies are needed to evaluate and apply these to coral reef ecosystems. Coastal defense structures can provide substratum for the development of coral communities, providing habitat for other reef organisms [20, 21]. In contrast, others have stated that artificial structures are not natural habitat [17, 18, 21, 22], making preservation of natural habitat often more desirable and more cost-effective than creating replacement habitat [23]. Fewer studies focused on applying ecological value to coastal defense structures as multi-purpose artificial reefs [24, 25]. Although the goal of many of these coral reef projects is habitat restoration, few emphasize coastal protection [14]. One such comprehensive ecological engineering study focusing on both coastal protection and habitat restoration in coral reef ecosystems was demonstrated in Grenada Bay, Grenada [26], and Vaan Island, India [27].

Design of a coastal defense structure such as a submerged breakwater requires the understanding of many aspects of ecology and the environment. For example, water velocities of a two-layer rock armored submerged breakwater were calculated and compared to known maximum velocities that mobile and sessile invertebrates can survive, relating the structural design and wave dynamics of the structure to the tolerance of invertebrates to varying wave climates [16]. An engineering design can also incorporate natural components of macro- and microhabitats and reef characteristics such as topographic complexity, spatial orientation, materials, and texture. The design can replicate favorable biotic and abiotic drivers on neighboring natural reefs [19, 28, 29]. Artificial structures are typically characterized by

steep slopes and vertical walls which may result in lower coral cover and diversity than a natural reef [19]. Thus, it may be ecologically preferable to reduce the vertical slope. The design can include features to enhance development of coral reef communities (e.g., surface texture and composition) while minimizing the distribution of non-indigenous and/or invasive species that may displace native species.

The ecological role of a coastal defense structure is best understood through analysis of regional and site-specific knowledge of the environment and benthic communities. For example, due to Hawai'i's high endemism, the distribution of invasive organisms is one of the most central management issues [30]. The removal and prevention of invasive species is such a critical management strategy that the State of Hawai'i's Division of Aquatic Resources has created the Aquatic Invasive Species Program to control, manage, and prevent impacts to the marine environment from introduced species. Potential negative effects of introducing artificial structures include unanticipated broad-scale environmental changes and creation of habitats that enhance the dispersal of exotic species [18, 19, 22, 31]. The species composition of hermatypic corals is uniform throughout the state of Hawai'i [32], but there are great differences in relative abundance depending on local conditions [33]. Such patterns of coral community structure are controlled by physical, chemical, and biological processes that relate to geomorphic features at regional and local scales. The design needs to reflect not only features to successfully enhance coral reef communities but also to minimize its impacts on the distribution of invasive species.

In Hawai'i, a submerged breakwater has been proposed to provide increased protection for shipping operations in the Kahului Commercial Harbor on Maui [34]. The Kahului Commercial Harbor was developed on the north-facing isthmus of Kahului Bay between two volcanic mountains on Maui in the early 1900s [35]. The harbor entrance is fully exposed to prevailing northeasterly tradewind-generated seas and large northerly swells during the fall and winter. The continual tradewind waves and sporadic high-energy storm waves have serious negative impacts on shipping operations [35, 36]. Coastal protection and wave abatement are the primary objectives of the proposed submerged breakwater at Kahului, but the intended design can serve as a multi-purpose reef structure by providing necessary shallow hard substrate for symbiotic reef-building corals. The proposed submerged breakwater site is within a previously dredged reef, adjacent to the entrance of the main shipping channel. This highly disturbed reef area could be enhanced by a properly constructed engineering structure to restore some of the coral decline Maui has experienced [37].

Temporal and spatial ecological information about the area surrounding Kahului Commercial Harbor is less available relative to other regions of Maui Island. While the application of ecological engineering principles to increase value of coastal defense structures has been emerging in other regions, reports on both planned and unplanned artificial marine habitats are sparse in Hawai'i. Historical information includes compilation of primary literature from 1981 to characterize reef geomorphology and marine biota on reefs located east and west of Kahului Commercial Harbor [38]. General geomorphic features of Maui's shoreline and coastal zones have been historically surveyed and mapped in the Maui Coastal Zone Atlas [39]. More recently, the geomorphic features, biological cover, and coastal zones of the Main Hawaiian Islands were classified by the National Oceanographic and Atmospheric Administration's (NOAA) benthic habitat mapping project

[40], using high-quality satellite imagery with field accuracy assessments providing data at a minimum resolution of 0.4 hectare (Fig. 1). According to the NOAA GIS benthic habitat data, live coral cover was classified as 50% to < 90% on the spur and groove zone on the east reef of Kahului Harbor. Coral cover on pavement between the harbor breakwater and offshore spur and groove zones was broadly characterized as 10% to < 50% cover at the intermediate zone and 50% to < 90% turf at the inshore pavement zone. This level of coral cover is high when compared to the Statewide mean of 24.1% from a survey of all CRAMP main Hawaiian Island sites in 2012 [41]. Benthic habitats were also characterized and mapped with the regional prominence on inside and directly outside of Kahului Harbor to assess existing habitats and potential impacts of harbor expansion stated in the Kahului Commercial Harbor 2030 Master Plan [42].

Fig. 1 GIS map of geomorphic features, camera transect tracks (black lines) T1–T7, and in situ biological evaluation sites (white circles) including the shipping channels outside (OC), inside the channel (IC), the proposed submerged breakwater installation site (PSB),

the outer harbor breakwater (OHB), the inner harbor breakwater (IHB), and the natural vertical reef and reef flat (NRF) adjacent to the proposed site in the Kahului Bay area. Base source: NOAA NOS Biogeography Branch [40]

The distribution of non-indigenous and introduced marine organisms was documented at the CRAMP monitoring site at Papa'ula and also inside the Kahului Commercial Harbor, focusing on the pier and the breakwater [43, 44]. Environmental quality and isolation from harbor structures were discussed as predictive variables. Benthic community, nutrient pathways, and its concentrations were examined in relation to the wastewater treatment plant located on the east of Kahului Harbor [45]. However, reefs nearby Kahului Commercial Harbor have received much less attention. Existing information provides a general understanding of the reef environment in Kahului, but additional data relating to the placement and performance of the proposed submerged breakwater were needed. The present study aimed to (1) characterize benthic habitats and reef biota in the proposed area of a submerged breakwater to be installed outside Kahului Commercial Harbor and the adjacent reefs, and to (2) evaluate environmental conditions that favor the prevalence of Hawaiian reef-building corals and associated reef organisms on the submerged breakwater. We expected to find a similar level of live coral coverage and geomorphic structure as the level near the proposed installation site assessed by the NOAA benthic habitat map in 2007. Our study provides an overview of reef communities and associated habitats in the vicinity of Kahului Commercial Harbor to update the interdisciplinary approach to design and engineer a submerged breakwater for both harbor protection and habitat enhancement in Hawai'i.

2 Materials and methods

To assure a valid sampling design that would clearly distinguish differences in habitats, biota, and environmental conditions on several scales, multiple methodologies were employed. A towed video and drop camera provided a general assessment of geomorphic features and benthic cover type. Detailed visual surveys were conducted at the existing breakwater, the proposed site, the unaltered surrounding habitat, and within and outside the shipping channel in situ. Measurements of water quality were taken to describe environmental conditions. These three methods were utilized to determine the feasibility and advantages of a multi-purpose submerged breakwater at the previously determined site.

2.1 Study site

A nearshore evaluation of the benthic habitat and water quality was conducted near the Kahului Commercial Harbor entrance (20.90282°N, 156.47035°W) in May 2013. The primary survey area was located outside of the

Kahului Commercial Harbor breakwater (Fig. 1). The site was defined in accordance with results of an engineering study [46] that evaluated the best alignment and dimension of a submerged structure using numerical models. Varying designs were explored using calculations of wave transformation as base criteria for selection in accordance with [47].

2.2 Survey of geomorphic and benthic cover

Geomorphic features and biological cover types were assessed using an underwater video (Sea View, Sea View LLC) and drop camera system (GoPro Hero3). The camera system was operated from a research support vessel to cover a broad range of habitats, in the prevailing trade wind pattern, safely and efficiently. The drop camera system utilized in the present study gives comparable results to common benthic survey methods used in Hawai'i, following field sampling methods including visual estimates, photographic belt transects, video transects, systematic area estimates of a quadrat, random point estimates of a quadrat, point intercept transects, towed diver (or manta tow), and the NOAA ground truth technique used in benthic habitat map assessment [48]. Each of these benthic survey methods gives similar results for coral cover estimates in the field although some of these methods provide better taxonomic resolution than others [48]. Seven video and photographic transects were established in the general area of interest. These transects covered the proposed breakwater installation site, the ship channel, and the natural reef environment (Fig. 1). Start and end geographic positions and track of each transect were determined by Garmin GPSMAP76, providing a 95% accuracy of ± 3 m, typical when the Wide Area Augmentation System (WAAS) is enabled. Transects T1 and T2 were located on the natural reef flat (NRF), adjacent to the proposed submerged breakwater (PSB) site. Transects T3 to T5 were located at PSB site, which is a deeper area that has been disturbed by dredging and is characterized by unconsolidated substratum. Transects T6 and T7 were located on the undisturbed reef, seaward of the PSB and NRF. Depth was determined using the vessel's transducer. A lead line attached near the camera lens held the camera in a perpendicular position one meter above the bottom. The video camera was gently lowered to the sea floor at the start point of each transect and retrieved at an end point while the vessel drifted slowly from northeast to southwest. Video images were monitored as live streaming to ground truth habitat types and relative coverage of benthic classes while guiding the vessel moving over shallow reefs. Photographic data were obtained using GoPro Hero3 cameras in underwater cases mounted on the video camera system. Still images were collected at

5-s intervals. The size of each image was approximately 1.5 × 2.0 m. These photographic data were used to analyze geomorphic features and biological cover types, as well as to identify the presence of marine organisms to the lowest taxonomic level possible. To determine types and levels of benthic features, non-overlapping images were identified, color-corrected, and visually estimated for percent coverage. The geomorphic and biological cover classification system followed [40]. Six major benthic cover types were assessed (live corals, coralline algae, turf, sand, carbonate rock, and reef rubble). Percent cover was estimated and classified in the following bins: continuous (> 90%), patchy (50% to < 90%), sparse (10% to < 50%), and none (< 10%). Imagery data were analyzed to describe the relative occurrence of benthic cover types and the percent coverage for each transect.

2.3 Water quality

Water quality was measured at five sites (Fig. 1), including the shipping channel outside the harbor (OC), shipping channel inside the channel (IC), the proposed submerged breakwater installation site (PSB), the outer harbor breakwater (OHB), and the natural vertical reef and reef flat (NRF) adjacent to the proposed site in the Kahului Bay area to describe relative environmental conditions during the survey. OHB, IC, OC, and PSB are sites within artificial or human-modified habitats, while NRF represents a natural habitat. Data were collected by casting a multi-parameter water quality meter (YSI 6920 V2 SONDE) from the vessel. Water quality measurements included temperature (°C), pH, salinity (ppt), and turbidity (NTU). Measurements were taken 1.5 m off the sea floor at each sampling site. The time mark on the SONDE data allowed us to correlate geographic position using a watch synchronized with the SONDE to verify data corresponding to each station. Two water samples at each of the five dive sites were collected using a Niskin sampling bottle for nutrient analysis. Samples were kept frozen until delivery to the School of Ocean and Earth Science Technology Laboratory for Analytical Biogeochemistry at the University of Hawai'i at Mānoa. Variations of physical and chemical water quality parameters were described and examined by site. A principal component analysis (PCA) was applied to the physical water quality data to examine an environmental gradient among sites. Variables including water temperature, salinity, turbidity, depth, dissolved oxygen, and pH were assessed for linear relationships between pairs of the variables using the scatter plot matrix. The values of each variable were scaled and centered for the analysis. Data analysis was performed using R version 3.6.1 [49] with its integrated development environment, RStudio version 1.2.1335 [50] and the package 'factoextra' in R [51].

2.4 Reef biota

The reef community and neighboring habitat were visually assessed in situ at five primary sites including OC, IC, OHB, PSB, and NRF using SCUBA (Fig. 1). In addition, a visual assessment was conducted at the inner harbor breakwater (IHB) as a reference for a reef community on the artificial structure. Timed swim observations were made by a pair of experienced divers for 45 min to encompass as broad an area as possible for the proposed submerged breakwater (~ 100 m length × 15 m breadth) [52], while remaining within a representative habitat at each site. Observations were made across the depth range from subsurface to sea floor due to the vertical and rugose nature of the structures particularly at NRF, OHB, and IHB. Divers swam carefully and slowly to minimize disturbance to fishes. Presence of all species including fishes and epilithic benthos (macro-algae, hermatypic corals, and sessile and mobile macro-invertebrates) were recorded at the lowest taxonomic level possible. The in situ surveys also allowed divers to validate information obtained from the photographic data by the drop camera system, and to supplement these data with detailed field observations on reef organisms at finer taxonomic resolution. Microscopic species that require collection and infaunal species were beyond the scope of the present study. Jaccard similarity coefficient was calculated for each pair of six diving sites to determine similarity in species presence and composition among survey sites representing variety of habitats. Number of observed species was aggregated into ecological functional groups (macro-algae, hermatypic corals, macro-invertebrates, and reef fish) and analyzed using a redundancy analysis (RDA) to assess its relationship to the environment. Measured values of environmental parameters were averaged by site to relate to the number of observed species for each site. The environmental variables including depth, water temperature, salinity, pH, dissolved oxygen, depth, total nitrogen, total phosphorus, silicate, and chlorophyll *a* concentration were first examined using a PCA to select three variables with the highest proportions of contributions to avoid over-parameterization of an RDA model. An RDA model was evaluated by a permutation test of *F*-statistic for a significance of contribution by each RDA axis. Linear regression analysis was also used to examine a univariate relationship between total number of species and each of the environmental variables. Values of water temperature, turbidity, and total phosphate were log-transformed. Salinity and total nitrogen values were squared to meet the assumptions. Statistical analyses and visual representation were performed using the R packages 'vegan' [53] and 'factoextra' [51]. A species list of each of the five zones can be accessed in the supplemental information.

3 Results

3.1 Survey of geomorphic and benthic cover

The track length of the drop camera transects ranged from between 234 and 501 m (Fig. 1) covering 4682 m² of

benthic features in the study area. Figure 2a–f describes the distributions of geomorphic features and biological cover types among the seven transects. Topography of T1, T2, T6, and T7 was highly complex near the reef edge (Fig. 3a, b). The highest live coral cover was found on T7, then followed by T6 (Fig. 2a, S1 in Supplementary materials), located at the outer natural reef on the spur

Fig. 2 Relative occurrence of geomorphic features and biological cover types, **a** live coral, **b** coralline algae, **c** turf algae, **d** sand, **e** carbonate rock, and **f** reef rubble in photographic data collected dur-

ing the drop camera transects. The X-axes indicate transect IDs, and the Y-axes show relative occurrence of cover type and abundance

Fig. 3 Three-dimensional image models of geomorphic features representing **a** T6, and **b** T1 for visualization. Images were reconstructed using Metashape Professional (Agisoft, LLC) from photographic data collected during the drop camera transects

and groove zone (Fig. 1), approximately 500 m seaward from the proposed submerged breakwater installation site (PSB). About 40% and nearly 20% of images included live coral cover on T1 and T2, respectively; but the majority of images were in the category none (< 10% cover, S2) or sparse (10 to < 50% cover, S3) and a very small fraction of images included patchy (50 to < 90%) cover. No live coral was observed on T3, 4, or 5.

The most abundant live coral cover on observed transects was the genus *Montipora* (rice coral) which include *M. capitata*, *M. flabellata*, and *M. patula*. The relative abundance of *Montipora* species was high on T6 and T7, comprising nearly 70% of live corals, and about 50% on T1 and T2 where live corals were also found. *M. flabellata* (blue rice coral) was particularly abundant on T6 and T7. The genus *Porites* was common, but not as abundant as *Montipora* species, and comprised nearly 25% of live corals on transects on which live corals were found. Species included in this genus are *Porites compressa* (finger coral) and the less

dominant *P. lobata* (lobe coral). Pocilloporidae, including *Pocillopora meandrina* (cauliflower coral), were less common than the former two genera comprising < 5% of all live corals on images of T1, T6, and T7, and about 10% of live corals on T2. Zoanthids, including *Palythoa caesia* and *Protopalythoa heliodiscus*, comprised 11–16% of live colonial cnidarians on T1 and T2 and < 5% on T6 and T7. Patchy and sparse cover of coralline and turf algae was found in < 25% of transect areas on T1, T2, T6, and T7 (Fig. 2b, c).

Results of in situ observations confirmed that most areas with hard bottom, rocks, and rubble were sparsely covered by coralline or turf algae in the absence of corals and other sessile organisms. No coralline and turf algae were observed on images on T3, T4, and T5. Sand was the most frequently observed geomorphic feature in the study area. It appeared in between > 60% and 100% of images obtained from T1 through T5 (Fig. 2d). T5 consisted entirely of sand. Over 50% and 70% of images showed no substantial sand cover (< 10% cover) on T6 and T7. Sparse

carbonate rocks and reef rubble mixed with sand were observed mainly on T2, T3, and T4 (Fig. 2e, f). These rocks and rubble generally increased in coverage toward the harbor breakwater. Scattered carbonate rocks void of corals were common between the sand channel and pavement, and only hard substrate was available for epilithic organisms.

In summary, geomorphic characteristics (consolidated substrate, carbonate rock, reef rubble, and sand) shifted along a gradient of hard bottom from east to west near the entrance of the Kahului Commercial Harbor. A substantial number of images included scattered small carbonate rock and reef rubble between the shipping channel and the consolidated natural reef. The proposed submerged breakwater site fell within habitat characterized by a continuous to patchy mix of carbonate rock, reef rubble, and sand lacking in live coral coverage. A high proportion of continuous live coral occurred on the outer natural reef approximately 1 km from the harbor entrance. The occurrence and cover of live corals on the natural reef decreased near the harbor. The most abundant corals were from the genus *Montipora* that comprised a high proportion of continuous cover. *P. lobata* and *P. compressa* were common, while *P. meandrina* was least common on the natural reef observed during this evaluation. These benthic characteristics of various habitats were consistent with *in situ* observations.

3.2 Water quality characterization

Water quality measurements and sampling were conducted on May 30, 2013, between the slack outgoing tide and the incoming tide. Relatively clear weather and calm seas with an average wave height of 1.3 m (CDIP, Scripps

Institution of Oceanography, UC San Diego) [54] and wind speed of 1.6 m/s from directions ranging between 325° and 16° (Station KLIH1-1615685, NOAA National Data Buoy Center) [55] were recorded during the sampling period.

Mean temperatures were affected by depth that was related to a sampling site. Temperature was inversely related to depth, indicating that the shallower IC was warmer than the deeper sites near the bottom with sunny and less windy condition. However, this among-site variation is relatively small when compared to the difference among monthly means, which may vary by 1–2 °C within a year. At all sites, the average salinity and dissolved oxygen were within the range of observed values in coastal water exposed to open seas.

The highest turbidity occurred at IC (1.6 NTU), while relatively low at other sites (0.1–0.8 NTU) (Table 1). The coefficient of variation was high within and across site for turbidity. *In situ* horizontal visibility appeared particularly low at IC, IHB, and OHB. Stratification of turbidity was observed at OC. Excess deposition of fine-grained sediment and silt on coral and other benthic organisms was also clearly evident at IHB, although no measurements were taken at these sites.

Average nutrient concentrations were relatively low (Table 1), compared to reported nearby inshore locations in Kahului Bay in the existing literature.

Mean concentrations of all nutrients were numerically higher at OHB with greater variability than other sites. Variations in nutrient levels were particularly high for nitrate + nitrite and ammonia at sites where these were detected. Chlorophyll *a* did not exhibit an obvious association with salinity.

The first three principle components (PC1, PC2, and PC3) explained 87.3% of the total variation. Temperature

Table 1 Means of physical water quality variables, nutrients (μmol^{-1}), and chlorophyll *a* ($\mu\text{g l}^{-1}$) at five *in situ* survey sites

Variable	Site				
	IC	OC	OHB	PSB	NRF
Temp. (°C)	25.4 (0.1)	25.1 (0.3)	25.2 (0.2)	25.0 (0.1)	25.0 (0.0)
Salinity (ppt)	35.6 (0.0)	35.6 (0.0)	35.7 (0.1)	35.7 (0.0)	35.7 (0.0)
Turbidity (NTU)	1.6 (46.2)	0.8 (92.0)	<0.1 (0.0)	0.1 (180.7)	0.3 (167.3)
ODO (mg/l)	6.95 (1.0)	7.01 (0.9)	6.90 (1.0)	6.93 (0.3)	6.96 (0.4)
Depth (m)	9.1 (7.3)	11.8 (10.2)	11.7 (5.5)	13.5 (4.2)	13.0 (2.6)
Nitrate–Nitrite	0.00 (NA)	0.02 (141.4)	0.41 (141.4)	0.03 (141.4)	0.00(NA)
Ammonia	0.01(173.2)	0.07 (141.4)	0.94 (128.7)	0.15 (141.4)	0.20 (141.4)
Total nitrogen	4.91 (14.2)	3.55 (14.0)	5.04 (48.0)	4.57 (22.4)	3.37 (6.1)
Inorganic phosphate	0.11 (10.0)	0.07 (1.0)	0.07 (1.0)	0.09 (40.2)	0.05 (25.6)
Total phosphorus	0.14 (34.3)	0.13 (5.3)	0.33 (61.9)	0.25 (8.6)	0.26 (1.1)
Silicate	3.9 (23.0)	6.1 (50.5)	26.2 (126.7)	3.3 (32.1)	1.9 (21.5)
Chlorophyll <i>a</i>	0.74 (3.4)	0.79 (28.6)	0.51 (15.3)	1.00 (10.0)	1.24 (48.7)

The coefficient of variation (%) is indicated in parentheses. ODO optical dissolved oxygen. Turbidity at OHB might have the potential for interference using optical readings

and turbidity were positively correlated, while depth and salinity were negatively correlated along PC1, accounting for 46.8% of the variation (Fig. 4). The greatest contributor was water temperature followed by depth, turbidity, and salinity to PC1. Dissolved oxygen and pH were the two largest contributors that inversely correlated along PC2 accounting for 25.1% of the variation. The PCA biplot indicated that IC and OC were mainly influenced by water temperature and turbidity along PC1, and the characteristics of the physical environment were distinct from other sites for IC and OC (Fig. 4). While NRF and PSB clustered along PC1, OHB positioned between OC and correlated with PC2. OHB shared the physical water characteristics with NRF and PSB.

3.3 Reef biota

A total of 101 species, including algae (16), macro-invertebrates (37), and fishes (48), were identified among all sites during the field evaluation. A total of 13 hermatypic coral species were found among all sites (S1). The total number of observed species at each site is summarized in Table 2. Five benthic species recorded were introduced or potentially introduced, while only one introduced fish species was found throughout the observations. Five of

Table 2 Number of species observed at each site

Site	Total	Epilithic benthos (all)	Hermatypic coral	Fish
NRF	43	19	8	24
OHB	34	16	6	18
IHB	30	15	7	15
PSB	13	11	0	2
IC	1	1	0	0
OC	0	0	0	0

The number of epilithic benthos include hermatypic coral species. Site Codes: shipping channels outside (OC), inside the channel (IC), the proposed submerged breakwater installation site (PSB), the outer harbor breakwater (OHB), the inner harbor breakwater (IHB), and the natural vertical reef and reef flat (NRF) adjacent to the proposed site in the Kahului Bay area

these six species, including *Acanthophora spicifera* (spiny seaweed), *Carijoa riisei* (snowflake coral), *Mycale armata* (orange keyhole sponge), *Pennaria disticha* (Christmas tree hydroid), and *Lutjanus kasmira* (blueline snapper), are also considered invasive in Hawai'i [56].

The overall similarity in the presence of species was low, resulting in about 2–26% among sites (Table 3). A maximum of only two species were found to be common

Fig. 4 A PCA biplot of physical oceanographic parameters including water temperature, turbidity, salinity, depth, dissolved oxygen, and pH. Each ellipse corresponds to each site, representing the 0.95 probability that a random variable falls within two standard deviations of its mean when normally distributed

Table 3 Pair-wise comparison of species in common and similarity (%) in species present between two given sites

Site	Number of species	Similarity (%)
PSB-OHB	2	4.4
PSB-IHB	1	1.7
PSB-NRF	1	1.8
OHB-IHB	13	25.5
OHB-NRF	15	24.2
IHB-NRF	13	21.7

No species and only one species were observed at OC and IC, respectively; thus, these sites were excluded from the comparison. Site Codes: shipping channels outside (OC), inside the channel (IC), the proposed submerged breakwater installation site (PSB), the outer harbor breakwater (OHB), the inner harbor breakwater (IHB), and the natural vertical reef and reef flat (NRF) adjacent to the proposed site in the Kahului Bay area

between PSB and all other sites. Species at PSB were the least similar to those at NRF. Species at OHB and IHB were the most similar. Species composition observed at PSB is distinct from those observed on consolidated natural reef and the artificial habitat. Only *Thalassoma duperrey* (saddle wrasse), *Acanthurus nigrofusus* (lavender surgeonfish), *Ctenochaetus strigosus* (goldring surgeonfish), and *M.*

capitata (brown rice coral) were common to these three sites. Similarly, OHB, IHB, and NRF were predominantly influenced by fishes but not benthic species.

The RDA model was specified with total phosphorus, salinity, and turbidity as the explanatory variables according to the result of the PCA including nutrient parameters. Total phosphorus, salinity, and turbidity were the three most correlated variables with the first principle component which explained 48.2% of total variation (Fig. 5). The unconstrained ordination included a number of macroalgae, hermatypic corals, macro-invertebrates, and reef fish observed at each site as response variables, and the specified RDA model resulted in the adjusted $R^2 = 0.11$. The first redundancy axis (RDA1) accounted for 54.5% of the variance contributing to the correlations followed by 22.7% of the second RDA axis (RDA2). The three RDA axes accounted for approximately 78% of the total variance, while the unconstrained axis contributed approximately 22%. Total phosphorus and salinity were positively correlated, while turbidity was negatively correlated with RDA1 (Fig. 6). Macro-invertebrates, hermatypic corals, and reef fish were also associated with RDA1, while macroalgae was strongly associated with RDA2. Results of the *F*-statistic permutation test were not statistically significant for all three RDA axes. The best performing simple linear regression models included total phosphorus (adjusted

Fig. 5 A bar plot of variable contributions to the explained total variation along the first principle component axis when chemical parameters were included at site level

Fig. 6 A triplot of the RDA model describing the relative contributions to correlations of environmental and functional groups with RDA axis 1 and 2. Numbered yellow points indicate sites: 1 = IC, 2 = OC, 4 = PSB, and 5 = NRF. Although OHB is labeled as 3, it is not included in the triplot since it is treated as a reference level of the regression in the statistical software R

$R^2=0.63$), followed by pH (adjusted $R^2=0.63$), turbidity (adjusted $R^2=0.45$), and salinity (adjusted $R^2=0.22$) as explanatory variables for total number of species. Total phosphorus, pH, and salinity showed positive relationships with total number of species, while a negative relationship was observed with turbidity. However, the relationships between total number of species and total phosphorus, pH, turbidity, and salinity were not statistically significant.

3.4 Characterization of epilithic benthos

The highest number of epilithic species was found at NRF, followed by OHB, IHB, PSB, and IC (Table 2). The highest proportion of continuous live coral cover was also found at NRF. An abundance of multiple coral species, including *M. flabellata* found in well-circulated high wave energy zones, was present on the shallow reef top. A vertical wall that faces the shipping channel and extends to the sandy seafloor adjacent to PSB was predominantly colonized by coralline algae and *M. capitata*. These colonies of *M. capitata* were characterized with platelike morphology (S5). The observed epilithic community was dominated by non-indigenous and introduced species at PSB. These were mainly filter feeders such as sponges, tunicates, bryozoans, deposit-feeding worms as well as the invasive *Acanthophora spicifera* (spiny seaweed). However, the overall relative abundance of these organisms was low because suitable substrates, primarily carbonate rock, were scattered. *M. capitata*, *M. patula*, and *Pocillopora meandrina*

were relatively common, while *Pocillopora grandis* was rarely observed at OHB.

Live corals were sparsely distributed from 3 to 5 m depth on the breakwater at OHB. The breakwater structure was also colonized by non-indigenous species. These were mainly comprised of sponges and soft corals that were common on shaded surfaces of the breakwater. *Carijoa riisei* (snowflake coral) was documented for the first time in Hawai'i in 1972 [57] and is known for its invasive nature throughout the Hawaiian Archipelago. Zoanthids (*Palythoa caesia*), frequently observed at NRF, were also present on the breakwater. Mobile invertebrates including spiny lobster and sea cucumbers were also present. Historical colonization and growth of *M. capitata* were evident at IHB with live corals growing on dead colonies. *Pocillopora damicornis* (lace coral) and *Porites brighami* (Brigham's coral) were relatively rare during the present study and only observed at this site. *M. capitata* had poor physical conditions here compared to colonies at OHB and NRF. Many colonies of this species on the inside harbor wall exhibited a disease referred to as *Montipora* White Syndrome [58], which causes acute or chronic loss of their living tissue, often leading to partial or full mortality of a colony.

3.5 Characterization of reef fishes

Number of reef fish species was highest at NRF, followed by OHB, IHB, and PSB (Table 2). Fishes associated with natural reefs were similar in composition and relative presence to other natural reefs with similar depth ranges

in Hawai'i. Fishes were abundant at NRF on natural reefs, including small herbivores, planktivores, and corallivores such as surgeonfish, juvenile parrotfish, damsel fish, and butterfly fish. Sighting of larger carnivorous fishes was uncommon on the natural reef, but large reef fishes and mobile invertebrates, such as bluefin trevally, goatfish, and spiny lobsters, were commonly observed at OHB and IHB, frequently utilizing it as habitat both inside and outside the breakwater. Aggregations of popular fisheries species, such as convict tang and bluefin trevally, were locally common during in situ surveys on the artificial structure. The presence of reef fishes was extremely sparse in PSB, consisting of habitat with unconsolidated fine sand/mud, carbonate rock, and rubble. Observed fish species included *Chaetodon miliaris* (milletseed butterflyfish), aggregated *Lutjanus kasmira* (blue stripe snapper, an introduced invasive species), *Foa brachygramma* (bay cardinalfish, commonly seen around dead corals), sponges, and dense algae in harbors.

4 Discussion

4.1 Reef community patterns and application of a multi-purpose submerged breakwater

Although there is no lack of studies on structural engineering or coral reef habitat restoration, the absence of research on merging structural design with ecological reef enhancement to surrounding reefs is minimal. This prevented the use of similar, established methodology and required the adaptation and combination of coral reef techniques and structural engineering principles and to assess the benthic communities, environmental conditions, and topography for design of a multi-purpose reef structure.

The present field survey provided the updated information on the ecological and environmental characteristics of the varying benthic habitats inside and outside Kahului Commercial Harbor and examined ecological and engineering potentials for how a submerged breakwater at Kahului could be designed as a multi-purpose 'reef structure' for harbor protection, while replacing a deeper barren-disturbed soft-bottom area with an optimal shallow-water coral reef habitat. Our results agreed with geomorphic features and habitat characteristics classified in the NOAA benthic habitat map [40] and Kahului reef tract description [59]. Live coral cover increased and was continuously high on natural reefs with rugose (high complexity) hard substrate that was further outside and distant from Kahului Commercial Harbor. Distribution patterns of geomorphic features, live coral cover, and non-indigenous organisms were spatially distinct among transects and

survey sites and can be predominantly explained by differences in geology [59], hydrodynamic regime, substrate type, morphology, and water quality. The proposed submerged breakwater in this area would increase shallow hard bottom and water motion, which favors reef coral community development as observed on the neighboring natural reef.

The physical environment of the Kahului reef was found to be distinctly characterized by a gradient in temperature, turbidity, and salinity between habitats, with consolidated (the natural reef, NRF, and open harbor breakwall, OHB) and unconsolidated (the inside channel, IC, and outside channel, OC) substrates in addition to geomorphic and benthic features. While the substrate of the proposed submerged breakwater site (PSB) consisted mainly of reef rubble and small carbonate rock, it shared physical seawater characteristics with NRF. Such similarity in the physical environment would help facilitate the settlement and presence of reef organisms on the submerged breakwater within proximity of the natural reef. A relatively large influence of habitat types was observed regarding the presence and composition of species. Salinity, turbidity, and nutrients such as total phosphorus appeared to be influential factors on the number of reef organisms present in a given habitat in Kahului.

There are several key environmental and ecological considerations for engineering designs of the submerged breakwater in Kahului. Differences in epibenthic community compositions between artificial and natural habitats are associated with multiple factors, including human disturbance [60], the age of artificial structures and succession [61, 62], the spatial orientation and design of artificial structures [61, 63], their proximity to open-water conditions [43, 44], localized wave exposure, and environmental differences [64]. An observed gradient in composition of epibenthic communities highlighted the importance of the wave dynamics and water flow characteristics across highly complex reef topography for a formation of natural reef community. In the shallow natural reef in Kahului, the abundance of coralline algae, live coral, and low-coral morphology indicates that the dominant environmental processes were constant high-wave disturbance and prevailing open-sea-like conditions. In particular, the distribution of *Montipora flabellata* is sensitive to hydrodynamics of the reefs and commonly associated with high water motion [65, 66]. While the species ranks as the sixth most abundant species statewide [41], the relatively high abundance of *M. flabellata* on the exposed outer natural reef in Kahului was linked with a high-wave exposure and well-circulated water flow that favors this species [67]. Nevertheless, *M. flabellata* was abundant at rugose areas of the natural reef, but was absent on the outer breakwater, although the site is also exposed to constant, intense

wave energy. Preferential colonization of *M. flabellata* may be due to wave exposure and pressure as well as differences in types, directions, velocities, and turbulence of wave-driven water flow over colonizing surface, influenced by macro- and micro-habitat structures. Patterns in water flow are an influential factor for this species in optimal feeding, particle removal, competition, and niche partitioning.

A number of hermatypic corals, macro-invertebrates, and reef fishes were negatively associated with turbidity during this study. Sediment resuspension and turbidity dynamics are important factors on the design of a submerged breakwater to promote coral settlement and growth. Corals on a vertical wall adjacent to the proposed submerged breakwater installation also showed plate-like morphology [68, 69], likely responding to low light condition caused by attenuation from suspended matter, sediment, and depth. The vertical wall adjacent to soft bottom is open to sediment resuspension. Water quality data and *in situ* observations suggested that light penetration (lower turbidity) increased further from the shipping channel. Highly turbid water will reduce light available for coral photosynthesis [70–72] and reduce the energy used for competition against other opportunistic organisms, such as the non-indigenous or introduced filter feeders and deposit feeders prevalent in the harbor [43, 44]. Sediment deposition prevents coral larvae from settling on a surface and strongly impacts post-recruitment survival of corals [73, 74]. Recruitment, mortality, and growth of corals were found to be equivalent to the natural reef on the windward breakwater, while the coral community on the leeward side experienced low cover, small size, and high mortality, indicating effects of wave exposure and sedimentation [64]. A shallow and gradual sloping of hard substrate will receive higher levels of irradiance, which favors coral growth. Sediment transport and suspension would greatly differ by 'large roughness' created by canopies of corals and reef organisms, but 'large roughness' is rarely taken into account in numerical hydrodynamic models [75]. Both macro- and microstructural elements need to be reflected in a design of a submerged breakwater to facilitate optimal water flow and circulation while minimizing sediment deposition and resuspension to facilitate colonization and growth of symbiotic corals.

There is a potential for elevated nutrient levels around Kahului Commercial Harbor. High levels of fresh water and nutrients were not detected during this study but may be a long-term concern during storm events. It's been documented that heavy rains in October 2002 caused lower salinity and higher turbidity [38]. Moreover, the submerged groundwater discharge (SGD) is another pathway to introduce nitrogen in surrounding coastal waters in Kahului. The nitrogen in SGD was identified and linked

to a mix of groundwater and treated effluent water from injection wells of the Kahului Wastewater Treatment [76], which is located approximately 1400 m southeast of the proposed deployment location for the submerged breakwater. The higher mean nitrate-nitrite and ammonia values of the outer harbor breakwall site may indicate the local influence of SGD with land-based sources of nitrogen when compared to other sampling sites. Prolonged freshwater and associated high levels of nutrients with limited water circulation can favor eutrophic conditions that are detrimental to coral reef development [77]. Surfaces of the outer and inner harbor breakwater modules were noticeably covered by encrusting sponges that may indicate abundance in supply of organic matter and nutrients in the water. Invasive organisms such as *Carijoa riisei*, snowflake soft coral, and macro-algae, *Acanthophora spicifera*, can become abundant due to prolonged high nutrient levels and could potentially have negative impacts on the development of coral-dominated communities. Minimizing shady surfaces and holes favored by non-photosynthetic and/or heterotrophic invasive species (e.g., *Carijoa riisei*) is another consideration in the design of the submerged breakwater in a potential nutrient-rich environment.

It is interesting to note, however, that elevated nutrient by itself might not be a primary concern for coral health, but it is the imbalanced ratio of inorganic nitrogen to phosphate (N/P) due to a phosphate deficiency [78]. An Indo-Pacific hermatypic coral, *Euphyllia paradivisa*, maintained normal symbiont density, photosynthetic capacity, polyp size, and non-bleaching status under high nitrogen–high phosphate and low nitrogen–high phosphate conditions, while normal coral health was compromised in the high nitrogen–low phosphate environment [78]. The nutrient environment identified at NRF and PSB was nitrogen-limited, with small N/P, and total phosphorus was positively correlated with the number of species present during this study. The presence and abundance of symbiotic hermatypic corals is expected on a submerged breakwater at PSB if the N/P is small as at NRF.

Salinity of seawater is another crucial environmental factor for the presence and survival of coral reef organisms. Effects of lowered salinity due to flash floods, as is a common occurrence in Hawai'i, can be detrimental to a reef community [79, 80]. A decline in salinity can interfere with the osmotic regulation of reef organisms. In particular, corals tolerate a narrow range of salinity between 25 and 40‰ depending on the regional distribution, and salinity less than 15–20‰ over a 24-h period is lethal to most species corals [81]. However, the development and high coverage of hermatypic corals on Kahului's undisturbed natural reef suggest that low salinity due to surface runoff may not be a serious concern outside the harbor,

not limiting the potential settlement and prevalence of hermatypic corals and reef organisms. The proposed submerged breakwater deployment site faces the open ocean; thus, the seawater mixing would help maintain the salinity level that is normal for the Kahului reef.

The shading effect is another consideration in submerged breakwater designs serving as an artificial habitat. It influences the adaptation of symbiotic corals to light regimes and their photosynthetic performance. The observed difference in the composition and their phenotypic morphology of symbiotic corals inside and outside breakwall was likely a response to shading in addition to intense wave energy. The encrusting *Montipora capitata* and *M. patula* and the depressed and/or horizontally extended branching form of *Pocillopora meandrina* on the outer breakwater imply adaptation of corals to consistently high-wave disturbance and shading environments [68, 69]. While *P. meandrina* is prevalent in high surf zones on the natural reef, its morphology is normally spherical rather than depressed. Structural modules of the large harbor breakwater in Kahului [52] may create potentially strong shading effects due to its height and void among its concrete modules. However, partial shading can be a beneficial factor in coral growth and survivorship. Corals with large polyps such as *M. capitata* can absorb up to 99.9% of incident light, but less than 0.1% penetrates to the skeleton, while corals with small polyps such as *M. flabellata* can become light-saturated at very low light levels, effectively amplifying light availability for its photosynthetic algal symbionts [82–84]. Corals living in shaded conditions flourish with only 1% of surface light [85] and adapt rapidly from high light to shaded conditions with greater photosynthetic capacity [86]. Corals in high light, shallow waters have lower primary production due to light saturation than coral in low light regimes. Due to rapid light saturation, corals use only approximately 1% of available light [85] and many Hawaiian coral species become saturated by the early morning [87].

Utilization of harbor breakwaters and large pier pilings as habitat by reef fishes has been commonly observed, and these results were expected in our study. Biomass and abundance of reef fishes are greatly influenced by depth, complexity of reef topography, and interstitial space [88]. Area and volume of holes were found to be strong predictors for overall biomass and biomass of most feeding and mobility guilds, while low fish biomass was associated with habitat characterized by simple topography and minimal shelter space away from the reef edge [88]. In this study, frequent fish utilization of the breakwater is likely due to high three-dimensionality and available interstitial holes provided by the breakwater modules, while adjacent habitat is characterized by low relief with unconsolidated rubble at OHB and fine-grained sediment at IHB.

Overall, the relatively intact offshore coral communities demonstrate that water quality is sufficient to support a healthy coral reef community on the submerged breakwater insofar as the design reflects the environmental characteristics of adjacent natural reefs with similar spatial orientation and depth [25, 61]. Average salinity, dissolved oxygen, water temperatures, and nutrients would be expected to be similar between the natural reef and the submerged breakwater site outside the Kahului harbor due to a mixing by prevailing trade winds. There are engineering designs and technological considerations that can be easily combined to facilitate the development of a local reef community in Kahului reflecting the structural characteristics favored by the natural reef community on the adjacent reef. The optimal orientation, size, depth, and types of a submerged breakwater were examined by Foley [52] through numerical and physical modeling of wave dynamics focusing on harbor protection. The design can incorporate macro- and microhabitats of reef characteristics, such as topographic complexity, spatial orientation, materials, and texture mimicking natural reef components. The proposed submerged breakwater will also function as a fish habitat, adding three-dimensional complexities to the two-dimensional rubble field, likely increasing local fish density and biomass [88, 89]. The composition and morphology of the coral community that would eventually develop on the proposed submerged breakwater are expected to be similar to those observed on the outer breakwater and vertical wall of an adjacent reef. The outside harbor breakwater may be seen as an example of a transitional habitat for both native and introduced benthic organisms and reflects the potential community composition on the submerged breakwater. This would be a considerable improvement over the present situation in that area. The multi-purpose submerged breakwater will provide suitable substrate, enhance hydrodynamic conditions, increase irradiance, and provide optimal water quality for recruitment, growth, and survival of coral in the 5–7 m depth range, while minimizing colonizing space favored by non-indigenous invertebrates and algae. The existing unconsolidated mud–sand bottom will be replaced by a coral reef. A properly designed breakwater could enhance coral reef resources in the region, which would serve to offset and mitigate other impacts in Kahului.

The scope of the present study was limited to a first-hand environmental snapshot and ecological characterizations to inform the preliminary engineering design of a proposed submerged breakwater as a multi-purpose reef adjacent to Kahului Commercial Harbor. Long-term ecological studies and monitoring of surrounding natural reefs and the existing harbor breakwater would be useful to assess the development and succession of a coral reef community on the submerged breakwater if implemented.

Coral recruitment and community development on artificial reefs, engineered infrastructures, and surrounding natural reefs have been compared within other regions (e.g., the Red Sea) to assess the ecological performance of designed artificial structures [90]. However, such studies are relatively rare in Hawai'i. Spatiotemporal dynamics of the environmental quality and reef communities can be quantified to determine the performance of a submerged breakwater designed as a means of coral reef restoration in addition to coastal protection of the Kahului area. Engineering designs of submerged breakwaters can be tested using machine-aided model simulations of community dynamics, e.g., [91, 92], employing ecological, environmental, and hydrodynamic parameters derived for a candidate design. While little support was found by statistical models applied during this study, there may be additional environmental variables to be tested for model improvement. For example, many reef organisms are found in rugose hard substrates. However, structural complexity was not measured and included in the statistical model. A future study is needed to quantify and estimate ecological parameters for developing such predictive models.

4.2 Management considerations

A successful multi-purpose project must be based on the development of clear objectives, potential management approaches, and well-defined and delegated responsibilities [21]. There are several key short-term and long-term management issues that must be considered, including construction and deployment methods [93] and their impacts, changes in water quality patterns including the distribution of sediment and nutrients, the propagation of non-indigenous and harmful invasive species, recreational access, use as a de facto fish aggregation site, and hazardous scenarios for potential users in the proximity to the main shipping lane. In addition, the methods for evaluating performance of the reef structure need to be clearly defined and quantified. In the case of the submerged breakwater at Kahului, this would involve continual monitoring of the developing coral reef community on the surface of the structure. The resulting data would guide management and contribute needed information, since artificial reef programs often lack testable objectives and do not perform follow-up monitoring [21].

The following are the essential components that the authors have followed when developing a multi-purpose reef structure program in Kahului Bay and Hawai'i:

1. The objectives of building a multi-purpose submerged breakwater should be stated clearly, with a solid design and results supported by the scientific literature.
2. Stake holders, research groups, and regulatory authorities need to be identified and coordinated in a cohesive manner according to objectives, potential issues, and responsibilities during planning, implementation, and management of the proposed reef structure. Support of the community, regulatory agencies, environmentalists, and scientists is critical to the success of the undertaking.
3. The design should improve water circulation, increase irradiance, increase area of suitable hard substratum, and minimize sedimentation to produce the optimal habitat quality for corals. Such design may incorporate characteristics of adjacent natural reef by including textual and structural complexity.
4. Ecological assessment and quantitative long-term monitoring should be included in the development and management of the reef structure, to assess structural performance and determine the level of success according to management goals. Ecological monitoring of the submerged breakwater and the adjacent reference reef should be conducted before and during installation, and periodically thereafter.

5 Conclusions

The proposed Kahului project provides a valuable opportunity to demonstrate the validity of an ecological engineering approach, integrating goals for harbor protection and conservation of coral reefs in Hawai'i. This study documents and discusses what can be learned about ecological applications of artificial reefs and coastal defense structures. It is crucial to consider and implement the design of a multi-purpose reef in anticipation of different ecological consequences for the conservation and long-term management of Maui's declining coral reefs. The artificial reef can resemble the adjacent natural reef community when structural characteristics of an artificial reef are similar to those of the adjacent natural reef. There is considerable ecological information on coral reefs that supports the concept of building a suitable structure that leads to the recruitment of organisms and the development of a reef community. In Hawai'i, existing studies have focused on determining patterns of early fouling and coral communities on artificial reefs, but these study sites were not located near man-made infrastructures similar to the harbor jetty in Kahului Harbor. Explicit comparisons of the community assemblage on a coastal defense structure and an adjacent natural reef are rarely found. As impacts of sea level rise and decline of coral reefs have been widely witnessed in the Pacific, a submerged breakwater will play an important role as artificial substrate for enhancement of coral reef communities by adding to topographic and

microhabitat complexities while benefitting the coastal community with hazard protection. Results of the current study present updated habitat information and ecological insights, in relation to the design of a submerged breakwater, as a multi-purpose reef adjacent to Kahului Commercial Harbor. The data represent a vital baseline for the future planning and formal environmental assessment required prior to installation and modification of the nearshore benthic habitat. This integrative project considers combined ecological, environmental, and engineering aspects of a coastal defense structure and can serve as a guide for adaptive planning and management decisions at Kahului, and as the example for other harbor development and shoreline construction projects throughout the tropics.

Acknowledgements We acknowledge funding from the Hawai'i Department of Transportation and Federal Highway Administration, Grant # TA-2010-1R. The contents of this paper reflect the views of the writers, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of Hawai'i. The contents do not represent a policy, rule, or operating standard. We thank Darla White, State of Hawai'i Division of Aquatic Resources Maui for equipment support, Keoki Stender, Marinelifephotography.com, Jerre Hansbrough, and US Army Corps of Engineers/Civil Environment and Engineering for field and technical support; and the State of Hawai'i Department of Transportation Harbor Division for logistic support. This is the University of Hawai'i, Hawai'i Institute of Marine Biology (HIMB) contribution #1841 and School of Ocean and Earth Science and Technology (SOEST) contribution #11220.

Author contributions All authors contributed to the study conception and design. Field surveys were conducted by YS and MF. Material preparation, data collection, and analysis were performed by YS. The first draft of the manuscript was written by YS and PJ, and all authors commented on all versions of the manuscript. All authors read and approved the final manuscript.

Funding This study was funded by the Hawai'i Department of Transportation and Federal Highway Administration, Grant # TA-2010-1R.

Availability of data and materials All data and material are accessible to the public.

Code availability The statistical computation and graphics program R used in our statistical analyses is a free open source software. No custom codes were made or used.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this

article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. The Intergovernmental Panel on Climate Change (IPCC) (2014) Summary for policymakers. In: Climate Change 2014: impacts, adaptation, and vulnerability. part A: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change [Field, CB, Barros, VR, Dokken, DJ, Mach, KJ, Mastrandrea, MD, Bilir, TE, Chatterjee, M, Ebi, KL, Estrada, YO, Genova, RC, Girma, B, Kissel, ES, Levy, AN, MacCracken, S, Mastrandrea, PR, and White, LL (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1–32
2. Webster PJ, Holland GJ, Curry JA, Chang HR (2005) Changes in tropical cyclone number, duration, and intensity in a warming environment. *Science* 309:1844–1846
3. Knutson TR, McBride JL, Chan J, Emanuel K, Holland G, Landsea C, Held I, Kossin JP, Srivastava AK, Sugi M (2010) Tropical cyclones and climate change. *Nat Geosci* 3(3):157–163
4. Needham HF, Keim BD, Sathiaraj D (2015) A review of tropical cyclone-generated storm surges: global data sources, observations, and impacts. *Rev Geophys* 53(2):545–591
5. Nicholls RJ, Cazenave A (2005) Sea-level rise and its impact on coastal zones. *Science* 328:1517–1520
6. Anderson J, Milliken K, Wallace D, Rodriguez A, Simms A (2010) Coastal impact underestimated from rapid sea level rise. *Eos* 91:205–206
7. Fletcher CH, Richmond BM (2010) Climate change in the Federated States of Micronesia: food and water security, climate risk management, and adaptive strategies. University of Hawai'i Sea Grant College Program, Honolulu, Hawai'i
8. Vitousek S, Barnard PL, Fletcher CH, Frazer N, Erikson L, Storlazzi CD (2017) Doubling of coastal flooding frequency within decades due to sea-level rise. *Sci Rep* 7(1):1399
9. Fleming E, Payne J, Sweet WV, Craghan M, Haines JW, Finzi Hart J, Stiller H, Sutton-Grier A (2018) Coastal effects. In: Impacts, risks, and adaptation in the united states: forth national climate assessment, Volume II [Reidmiller D, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, Maycock TK, Stewart BC (eds.)]. U.S. Global Change Research Program, Washington, DC, U.S.A, pp 322–352. <https://doi.org/10.7930/NCA4.2018.CH8>
10. Storlazzi CD, Reguero BG, Cole AD, Lowe E, Shope JB, Gibbs AE, Nickel BA, McCall RT, van Dongeren AR, Beck MW (2019) Rigorously valuing the role of U.S. coral reefs in coastal hazard risk reduction. Open-File Report 2019–1027. <https://doi.org/10.3133/ofr20191027>
11. Hughes TP, Baird AH, Bellwood DR, Card M, Connolly SR, Folke C, Grosberg R, Hoegh-Guldberg O, Jackson JBC, Kleypas J, Lough JM, Marshall P, Nyström M, Palumbi SR, Pandolfi JM, Rosen B, Roughgarden J (2003) Climate change, human impacts, and the resilience of coral reefs. *Science* 301:929–933
12. Cheong SM, Silliman B, Wong PP, van Wesenbeeck B, Kim C, Guannel G (2013) Coastal adaptation with ecological engineering. *Nat Climate Change* 3(9):787–791
13. Ferrario F, Beck MW, Storlazzi CD, Micheli F, Shepard CC, Airolidi L (2014) The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nat Commun* 5(1):3794

14. Narayan S, Beck MW, Reguero BG, Losada JJ, van Wesenbeeck B, Pontee N, Sanchirico JN, Ingram JC, Lange G, Burks-Copes KA (2016) The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS ONE* 11(5):e0154735
15. Mitsch WJ, Jørgensen SE (2003) Ecological engineering: a field whose time has come. *Ecol Eng* 20(5):363–377
16. Kontaxi C, Memos C (2005) Submerged breakwaters as artificial habitats. In: Proceedings: 31st international association for hydro-environment engineering and research (IAHR) world congress, Seoul, Korea, September 11–16, 2005
17. Airolidi L, Abbiati M, Beck MW, Hawkins SJ, Jonsson SR, Martin D, Moschella PS, Sundelöf A, Thompson RC, Åberg P (2005) An ecological perspective on the deployment and design of low-crested and other hard coastal defense structures. *Coast Eng* 52:1073–1087
18. Bulleri F, Chapman MG (2010) The introduction of coastal infrastructure as a driver of change in marine environments. *J Appl Ecol* 47:26–35
19. Chapman MG, Underwood AJ (2011) Evaluation of ecological engineering of “armored” shorelines to improve their value as habitat. *J Exp Mar Biol Ecol* 400:302–313
20. Wen KC, Hsu CM, Chen KS, Liao MH, Chen CP, Chen CA (2007) Unexpected coral diversity on the breakwaters: potential refuges for depleting coral reefs. *Coral Reefs* 26(1):127–127
21. Burt J, Bartholomew A, Usseglio P, Bauman A, Sale PF (2009) Are artificial reefs surrogate of natural habitats for corals and fish in Dubai, United Arab Emirates? *Coral Reefs* 28(3):663–675
22. Feary DA, Burt JA, Bartholomew A (2011) Artificial marine habitats in the Arabian Gulf: review of current use, benefits and management implications. *Ocean Coast Manag* 54:742–749
23. Jokiel PL, Kolinski SP, Naughton J, Maragos JE (2006) Review of coral reef restoration and mitigation in Hawaii and the U. S.-Affiliated Pacific Islands. In: Precht WF (ed) *Coral reef restoration handbook—the rehabilitation of an ecosystem under siege*. CRC Press, Boca Raton, pp 271–290
24. Baine M (2001) Artificial reefs: a review of their design, application, management and performance. *Ocean Coast Manag* 44:241–259
25. Perkol-Finkel S, Ferrario F, Nicotera V, Airolidi L (2012) Conservation challenges in urban seascapes: promoting the growth of threatened species on coastal infrastructures. *J Appl Ecol* 49:1457–1466
26. Reguero BG, Beck MW, Agostini VN, Kramer P, Hancock B (2018) Coral reefs for coastal protection: a new methodological approach and engineering case study in Grenada. *J Environ Manag* 210:146–161
27. Jayanthi M, Patterson EJK, Malleshappa H, Gladwin GAN, Mathews G, Diraviya Raj K, Bilgi DS, Ashok Kumar TK, Sannasiraj SA (2020) Perforated trapezoidal artificial reefs can augment the benefits of restoration of an island and its marine ecosystem. *Restor Ecol* 28(1):233–243
28. Svane I, Petersen JK (2001) On the problems of epibioses, fouling and artificial reefs: a Review. *Mar Ecol* 22:169–188
29. Spieler RE, Gilliam DS, Sherman RL (2001) Artificial substrate and coral reef restoration: what do we need to know to know what we need? *Bull Mar Sci* 69:1013–1030
30. Godwin S, Rodgers KS, Jokiel PL (2006) Reducing potential impact of invasive marine species in the Northwestern Hawaiian Islands Marine National Monument. Report submitted to Northwest Hawaiian Islands Marine National Monument Administration, Honolulu, August 2006. 66 pp. Available from NTIS (<http://www.fedworld.gov/online/>) and from the Hawaii Coral Reef Assessment and Monitoring Program (CRAMP) at <http://cramp.wcc.hawaii.edu/>
31. Moschella PS, Abbiati M, Åberg P, Airolidi L, Anderson JM, Bacchiocchi F, Bulleri F, Dinesen GE, Frost M, Gacia E, Granhag L, Johsson PR, Satta MP, Sundelöf A, Thompson RC, Hawkins SJ (2005) Low-crested coastal defense structures as artificial habitats for marine life: using ecological criteria in design. *Coast Eng* 52:1053–1071
32. Grigg RW (1983) Community structure, succession and development of coral reefs in Hawai'i. *Mar Ecol Prog Ser* 11:1–14
33. Jokiel P, Brown E, Friedlander A, Rodgers SK, Smith W (2001) Coral reef assessment and monitoring program final report 1999–2000. Prepared for Hawai'i Coral Reef Initiative, University of Hawai'i, Honolulu, and National Ocean Service, National Oceanic and Atmospheric Administration, Silver Springs, Maryland. January 2001
34. Foley M, Singh A (2011) Engineered reef for shoreline and harbor protection. In: *Modern methods and advances in structural engineering and construction*, ISEC-6
35. Sargent FE, Markle DG, Grace PJ (1988) Case histories of corps breakwater and jetty structures. Technical Report REMR-CO-3, Report 4. U.S. Army Corps Engineers, Pacific Ocean Division, Vicksburg, Mississippi. <http://www.dtic.mil/cgibin/GetTRDoc?AD=ADA213589Web>. Accessed Dec 2012
36. Thompson EF, Demirbilek Z (2002) Wave climate and wave response, 2025 plan, Kahului Harbor, Maui, Hawai'i. Technical Report. Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. <http://www.dtic.mil/cgibin/GetTRDoc?AD=ADA408026Web>. Accessed Dec 2012
37. Williams ID, Sparks R, Smith C (2007) Status of Maui's Coral Reefs. Technical Report TR070404, State of Hawai'i, Department of Aquatic Resources, Honolulu. <http://hawaii.gov/dlnr/dar/pubs/MauireefDeclines.pdf>
38. Ziemann D (2003) Kahului Commercial Harbor 2025 master plan environmental assessment: water quality, marine biological and natural resources impacts assessment. Oceanic Institute, Waimanalo, Hawai'i
39. AECOS, Inc. (1979) Maui coastal zone atlas, Hawai'i coral reef inventory part C, island of Maui. AECOS Inc, Kāne'ohe
40. Battista TA, Costa BM, Anderson SM (2007) Shallow-water benthic habitats of the main Hawaiian Islands (DVD). Silver Spring
41. Rodgers KS, Jokiel PL, Brown EK, Hau S, Sparks R (2015) Hawai'i coral reef assessment and monitoring program: over a decade of change in spatial and temporal dynamics in coral reef communities. *Pac Sci* 69:1
42. Marine Research Consultants, Inc. (2007) Reconnaissance survey of the marine environment Kahului Commercial Harbor, Maui, Hawai'i: characterization of benthic habitats assessment of impacts from harbor expansion
43. Coles SL, Reath PR, Longenecker K, Bolick H, Eldredge LG (2004) Assessment of nonindigenous marine species in harbors and on nearby coral reefs on Kaua'i, Mokuoka'i, Maui, and Hawai'i. Technical Report, No. 29a. Bishop Museum, Hawai'i Biological Survey, Honolulu, Hawai'i
44. Coles SL, Kandel FLM, Reath PA, Longenecker K, Eldredge LG (2006) Rapid assessment of nonindigenous marine species on coral reefs in the Main Hawaiian Islands. *Pac Sci* 60:483–507
45. Amato DW, Bishop JM, Glenn CR, Dulai H, Smith CM (2016) Impact of submarine groundwater discharge on marine water quality and reef biota of Maui. *PLoS ONE* 11(11):e0165825
46. Singh A, Foley M, Sundar V, Sannasiraj SA (2010) Numerical model study on artificial reef at Kahului, Hawai'i, Interim Report, TA-2010-1R. Hawai'i Dept. of Transportation, Honolulu
47. Sundar V, Sannasiraj SA (2013) Kahului Harbor: numerical modeling on artificial submerged breakwater. Final Report, Department of Ocean Engineering, Indian Institute of Technology, Madras, India

48. Jokiel PL, Rodgers KR, Brown EK, Kenyon JC, Aeby G, Smith WR, Farrell F (2015) Comparison of methods used to estimate coral cover in the Hawaiian Islands. *PeerJ* 3:e954
49. R Core Team (2019) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org/>
50. RStudio Team (2020) RStudio: integrated development for R. RStudio, PBC, Boston, MA. <http://www.rstudio.com/>
51. Kassambara A, Mundt F (2020) factoextra: Extract and visualize the results of multivariate data analyses. R package version 1.0.7. <https://CRAN.R-project.org/package=factoextra>
52. Foley M (2015) Submerged breakwater modeling and coral reef ecological analyses for harbor protection. Dissertation, University of Hawai'i at Mānoa
53. Oksanen J, Guillaume Blanchet F, Friendly M, Kindt R, Legendre P, McGinn D, Minchin PR, O'Hara RB, Simpson GL, Solymos P, Henry MH, Eduard Szoecs S, Wagner H (2019) vegan: community ecology package. R package version 2.5–6. <https://CRAN.R-project.org/package=vegan>
54. The Coastal Data Information Program (CDIP). Monitoring and prediction of waves and shoreline changes. The Ocean Engineering Research Group, the Integrative Oceanography Division, Scripps Institution of Oceanography, UC San Diego, La Jolla, CA, USA. http://cdip.ucsd.edu/m/stn_table/. Accessed July 2013
55. National Data Buoy Center, National Weather Service, National Oceanic and Atmospheric Administration (NOAA), US Department of Commerce. <https://www.ndbc.noaa.gov/>. Accessed July 2013
56. Coles SL, Eldredge LG (2002) Nonindigenous species introductions on coral reefs: a need for information. *Pac Sci* 56:191–209
57. DeFelice RC, Eldredge LG, Carlton JT (2001) A guidebook of introduced marine species in Hawai'i. Technical Report No. 21. In: Eldredge LG, Smith CM (eds) Bishop Museum, Hawai'i Biological Survey, Honolulu, Hawai'i. http://www.denix.osd.mil/nr/crid/Coral_Reef_Initiative_Database/Hawaii_files/Eldredge%20%26%20Smith%20%28eds.%29,%202001.pdf. Accessed July 2013
58. Ushijima B, Smith A, Aeby GS, Callahan SM (2012) *Vibrio owenii* induces the tissue loss disease Montipora white syndrome in the Hawaiian reef coral *Montipora capitata*. *PLoS ONE* 7(10):e46717. <https://doi.org/10.1371/journal.pone.0046717>
59. Field ME, Storlazzi CD, Gibbs AE, D'Antonio NL, Cochran SA (2019) The major coral reefs of Maui Nui, Hawaii—distribution, physical characteristics, oceanographic controls, and environmental threats. U.S. Geological Survey Open-File Report 2019–2019. <https://doi.org/10.3133/ofr20191019>
60. Airolidi L, Bulleri F (2011) Anthropogenic disturbance can determine the magnitude of opportunistic species responses on marine urban Infrastructures. *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0022985>
61. Perkol-Finkel S, Benayahu Y (2005) Recruitment of benthic organisms onto a planned artificial reef: shifts in community structure one decade post-deployment. *Mar Environ Res* 59:79–99
62. Burt J, Bartholomew A, Sale PF (2011) Benthic development on large-scale engineered reefs: a comparison of communities among breakwaters of different age and natural reefs. *Ecol Eng* 37:191–198
63. Knott NA, Underwood AJ, Chapman MG, Glasby TM (2004) Epibiota on vertical and on horizontal surfaces on natural reefs and on artificial structures. *J Mar Biol Assoc UK* 84(06):1117–1130
64. Burt J, Feary D, Usseglio P, Bauman A, Sale PF (2010) The influence of wave exposure on coral community development on man-made breakwater reefs, with a comparison to a natural reef. *Bull Mar Sci* 86(4):839–859
65. Maragos J (1972) A study of the ecology of Hawaiian reef corals. Dissertation, University of Hawai'i at Mānoa
66. Jokiel PL (1978) Effects of water motion on reef corals. *J Exp Mar Biol Ecol* 35(1):87–97
67. Franklin EC, Jokiel PL, Donahue MJ (2013) Predictive modeling of coral distribution and abundance in the Hawaiian Islands. *Mar Ecol Prog Ser* 481:121–132
68. Willis BL (1985) Phenotypic plasticity versus phenotypic stability in the reef corals *Turbinaria mesenterina* and *Pavona cactus*. In: Proceedings of the fifth international coral reef congress, Tahiti, vol 4. Antenne Museum National d'Histoire Naturel, Moorea
69. Anthony KRN, Hoegh-Guldberg O (2003) Variation in coral photosynthesis, respiration and growth characteristics in contrasting light microhabitats: an analogue to plants in forest gaps and understories? *Funct Ecol* 17(2):246–259
70. Falkowski PG, Jokiel PL, Kinzie RA (1990) Irradiance and corals. In: Dubinski Z (ed) *Ecosystems of the world: coral reefs*, vol 25. Elsevier, New York, pp 89–107
71. Rogers CS (1990) Responses of coral reefs and reef organisms to sedimentation. *Mar Ecol Prog Ser* 62:185–202
72. Miller RL, Cruise JF (1995) Effects of suspended sediments on coral growth: evidence from remote sensing and hydrologic modeling. *Remote Sens Environ* 53:177–187
73. Harrison PL, Wallace CC (1990) Reproduction, dispersal and recruitment of scleractinian corals. In: Dubinski Z (ed) *Ecosystems of the world*, 25. Coral reefs. Elsevier, Amsterdam, pp 133–207
74. Babcock R, Mundy C (1996) Coral recruitment: consequences of settlement choice for early growth and survivorship in two scleractinians. *J Exp Mar Biol Ecol* 206(1–2):179–201
75. Pomeroy AW, Lowe RJ, Ghisalberti M, Storlazzi C, Symonds G, Roelvink D (2017) Sediment transport in the presence of large reef bottom roughness. *J Geophys Res Oceans* 122(2):1347–1368
76. Bishop JM, Glenn CR, Amato DW, Dulai H (2017) Effect of land use and groundwater flow path on submarine groundwater discharge nutrient flux. *J Hydrol Reg Stud* 11:194–218
77. Fabricius KE (2005) Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. *Mar Pollut Bull* 50:125–146
78. Rosset S, Wiedenmann J, Reed AJ, D'Angelo C (2017) Phosphate deficiency promotes coral bleaching and is reflected by the ultrastructure of symbiotic dinoflagellates. *Mar Pollut Bull* 118(1):180–187
79. Jokiel PL, Hunter CL, Taguchi S, Watari L (1993) Ecological impact of a fresh-water “reef kill” in Kāne'ohe Bay, O'ahu, Hawai'i. *Coral Reefs* 12:177–184
80. Bahr KD, Jokiel PL, Rodgers KS (2015) The 2014 coral bleaching and freshwater flood events in Kāne'ohe Bay, Hawai'i 3:e1136. <https://doi.org/10.7717/peerj.1136>
81. Coles SL, Jokiel PL (1992) Effects of salinity on coral reefs. In: Connell DW, Hawker DW (eds) *Pollution in tropical aquatic systems*. CRC Press, London, pp 147–166
82. Halldal P (1968) Photosynthetic capacities and photosynthetic action spectra of endozoic algae of the massive coral *Favia*. *Biol Bull* 134(3):411–424
83. Enriquez S, Méndez E, Iglesias-Prieto R (2005) Multiple scattering on coral skeletons enhances light absorption by symbiotic algae. *Limnol Oceanogr* 50:1025–1032
84. Marcelino LA, Westneat MW, Stoyneva V, Henss J, Rogers JD, Radosevich A, Tuzhitsky V, Siple M, Fang A, Swain TD, Ruby J, Backman V (2013) Modulation of light-enhancement to symbiotic algae by light-scattering in corals and evolutionary trends

- in bleaching. PLoS ONE 8:e61492. <https://doi.org/10.1371/journal.pone.0061492>
85. Chalker BE, Barnes DJ, Dunlap WC, Jokiel PL (1988) Light and reef-building corals. *Interdiscip Sci Rev* 13(3):222–237
86. Porter JW, Muscatine L, Dubinsky Z, Falkowski PG (1984) Primary production and photoadaptation in light- and shade-adapted colonies of the symbiotic coral, *Stylophora pistillata*. *Proc R Soc Lond Ser B* 222(1227):161–180
87. Richards-Donà A (2019) Investigation into the functional role of chromoproteins in the physiology and ecology of the Hawaiian Stony coral *Montipora flabellata* in Kāneʻohe Bay, Oʻahu. Dissertation, University of Hawaiʻi at Mānoa
88. Friedlander AM, Parrish JD (1998) Habitat characteristics affecting fish assemblages on a Hawaiian coral reef. *J Exp Mar Biol Ecol* 224:1–30
89. Wedding LM, Jorgensen S, Lepczyk CA, Friedlander AM (2019) Remote sensing of three-dimensional coral reef structure enhances predictive modeling of fish assemblages. *Remote Sens Ecol Conserv* 5(2):150–159
90. Perkol-Finkel S, Shashar N, Benayahu Y (2006) Can artificial reefs mimic natural reef communities? The roles of structural features and age. *Mar Environ Res* 61:121–135
91. Langmead O, Sheppard C (2004) Coral reef community dynamics and disturbance: a simulation model. *Ecol Model* 175(3):271–290
92. Kubicek A, Muhando C, Reuter H (2012) Simulations of long-term community dynamics in coral reefs—how perturbations shape trajectories. *PLoS Comput Biol* 8(11):e1002791
93. Hansbrough J, Singh A (2013) Sand-filled geotextile tubes and their application for harbor protection, Interim Report, HDOT Contract Award No. TA 2010–1R, Honolulu, August 2013

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.