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CORAL REEF HEALTH INDEX CALCULATION FROM REMOTE SENSING DATA: A REVIEW

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Abstract

The coral reef ecosystem plays an important role as a provider of ecosystem services and has various economic benefits to the coastal community. However, the coral reefs ecosystem continues to degrade by 19% globally. This degradation caused some coastal and archipelagic countries have developed methods of calculating coral reef health index, including Indonesia. However, some literature shows that there is no common standard method for coral reef health index as the analysis depends on the data availability and the purpose of the study. Remote sensing technology that currently provides much open-source data is a potential method /tool to calculate the health index of coral reefs if the required parameters are met. This article review aims to identify remote sensing data used in the existing coral health indexes and then analyze the integration of all spatial data for coral reef health index calculation. Reference searches are sourced from the SCOPUS database combined with search engines Harzing and Mendeley. There are five coral reef health index calculation models from 25 references consisting of 19 publications and six reports out of 209 filtered references using keywords of Coral Reef Health Index. As a result, coral reef cover and algae are commonly used data obtained from remote sensing imagery. However, remote sensing technology cannot estimate other important parameters such as fish biomass. In addition, physical information of the waters, such as sea surface temperature (SST) and water clarity indicators (turbidity and diffused attenuation coefficient), are parameters contained in the five indexes that can be obtained from remote sensing data. In general, the literature review shows that coral reef health indicators (e.g. index or individual benthic cover) are significantly related to the various parameters affecting coral reef degradation such as algae cover, rubble cover, SST and river plump either as an individual or multivariate factors.

***Keywords**: Coral reef; Health Index; Remote Sensing; Open-source data*

Introduction

Coral reefs are an essential ecosystem, especially for maritime countries, as they provide ecological and economic values [1] to their surrounding environment, including coastal communities. Globally, the area of coral reefs continues to decline by 19%, where 15% of the total area was in the threatened status [2]. However, at the regional level, the trend of coral reef cover varies; for example, it shows a relatively stable condition in the East Asian Sea [3] and the Pacific [4]. On the contrary, the trend tends to decline in the Western Indian [5] and Caribbean [6]. The different trend comes from the complexity of the influencing parameters, which can be

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attributed to natural factors [7] and or anthropogenic factors [8]. Moreover, the deteriorating condition of the coral reef ecosystem can lead to reduced diversity and ecosystem services function [9].

Understanding the degradation in the coral reef ecosystem can only be achieved from time-series data analysis, which shows the dynamic change of coral reef cover. Moreover, integrating time-series data with field data like water quality can precisely represent the coral reef ecosystem's condition [10]. Previously, global monitoring data have been provided by Reef Check Program (http://data.reefcheck.us/) and Coral Watch (https://coralwatch.org/index.php/data/reefs/) for coral reef conditions. Moreover, several countries have also provided monitoring data on coral reef condition such as the Indian Ocean (CORDIO) (http://cordioea.net), the Caribbean Coastal Marine Productivity Program (CARICOMP), the Atlantic, Gulf Rapid Reef Assessment (AGRRA) Program (http://www.agrra.org), and COREMAP project in Indonesia (http://gis.oseanografi.lipi.go.id/). However, most open-public monitoring data are based on field survey activities, where they pose logistical issues (e.g. time and cost) if rapid global coral reef monitoring is needed [3].

On the other hand, remote sensing technology can be utilized to identify the degradation of the coral reef ecosystem as it can provide time-series spatial data [11] as well as cover wide reef areas enable to map and monitor in remote areas as most coral reef are. Moreover, until the 2020s satellite technology has been progressing with better sensors technology and more detailed spatial resolution such as Landsat-8, Sentinel-2, and Planet Scope. These developments also led to consistent time-series data like the Landsat image, one of the longest satellite data achieved until now [12]. In addition, the recent development of remote sensing methods such as machine learning can improve results as it allows the use of more data inputs for more complex classification methods such as by adding water quality spatial data to classify seagrass distribution [13]. Lastly, the increasing number of open-public spatial data and the development of cloud computing analysis supports the rapid and accurate extraction of spatial information such as water quality data needed to calculate the status of the coral reef ecosystem [14-15].

This article highlights the importance of reviewing methods to assess the status of the coral reef ecosystem, which would impact the ecosystem services and economic value of coral reefs. Methodologies and available open-source remote sensing data are reviewed to analyze the possibilities of calculating the status of coral reefs from remote sensing data. The status of coral reef health is assessed from the coral reef health index, which has been developed in several areas, including Indonesia [16-18]. As there is no common standard method in calculating the Coral Health Index (CHI), this paper limits the analysis only to using the currently available open-source remote sensing data. As a consequence of this effort, statistical techniques to integrate multi-source data is also assessed in this paper. The result is expected to contribute to an easy and rapid method for identifying coral reef status, allowing policymakers to devise an effective strategy for managing the coral reef ecosystem.

Review Methodology

This study used two referencing applications to obtain the most relevant references: Harzing [19] and Mendeley [20]. Harzing limits the sources only from Scopus, which is known to have complete references. Mendeley is used to complete references outside the Scopus collection. The advantage of Harzing is that it can import references into excel format more easily, which can be filtered manually based on keyword matching. The flaw of the Harzing software is that it does not provide advanced search. Therefore, searching relevant references are mainly based on keywords "*coral reef health index*" and then eliminate references that do not use spatial data in index calculations

This paper discusses the various method of calculating coral reef index commonly used as indicators of coral reef conditions. Most existing methods were developed for locations with wide coral reef areas such as the Great Barrier Reef, the Mesoamerican Reef, and the Coral Triangle, which means the coral reef health index information is very limited. Therefore, this review article is written in a narrative review without following specific and systematic protocol in reference search due to the limited available relevant references. This review focuses on the methodology of calculating coral reef health index, especially those that use parameters from remote sensing data. For this purpose, we selected a total of 209 references and by filtering them according to the keywords of Coral Reef Health Index, we got 25 references consisting of nine publications and six reports.

Review Framework

The article review explains the important value of the coral reef ecosystem, the current condition, various factors that affect the degradation, and the latest methods to calculate the coral reef health index. Each method will be analyzed to overview coral reef index calculations through spatial data that are increasingly available for free today. A spatial-based analysis is conducted to identify the parameter used in coral reef health index calculation that can be replaced with satellite data. The results then are discussed to identify the advantages and disadvantages of using spatial data, including integrating the various spatial data with different characteristics. Broadly speaking, this current content of the review article is shown in figure 1 below.

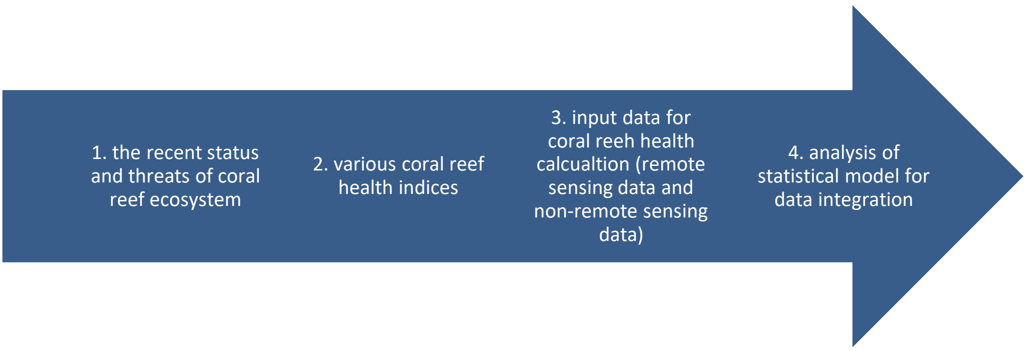

Fig. 1. Review framework

The Recent Status and threats of Coral Reef Ecosystem

Coral reefs ecosystem has degraded over recent years due to the impact of human and natural disturbances on their biodiversity and ecosystem functioning, such as reduced areas of living coral, increased algal cover, reduced species diversity, and reduced fish abundance. The degradation impacts in the coral reef ecosystem that caused by human are eutrophication [21] and sedimentation [22], while coral bleaching [23], ocean acidification, hurricanes, tropical storms, the presence of diseases, declining physiological processes can be classified as the impacts of natural disturbances. All causes have diminished the status of coral reefs, which are now considered in crisis at a global level. Based on World Research Institute (WRI) report [24], coral reef ecosystems on almost all continents have problems caused mostly due to human activities and the effects of water temperature due to climate change causing 40% of the world's coral reef areas to suffer.

Based on IUCN report in 2005, 20% of coral reefs worldwide have been destroyed, while 24% are in imminent danger and a further 26% are under longer-term danger of collapse [24] due to climate change impacts. Afterwards, the recent publication in 2021 concluded that from 1957 until 2007, the coral reef cover globally had been declined approximately by 50% [26]. Some examples from the WRI report told that 30% of reefs are threatened in Australia, and 45% of reefs are threatened in Southeast Asia due to pollution from agricultural activities, and Almost 40% of global reefs may have been affected by thermal stress. However, the trend of coral reef areas changed is different depending on the region, which means some areas get decrease like in Western Indian [7] and the Caribbean [9, 27]; and remain are relatively stable like in the East Asian Sea [28] and the Pacific [5-6].

The different condition of declining coral reef cover is due to the different coverage threats classified as local and global threats based on the WRI report. The local threats are from human activities that cause direct contact with the coral reef ecosystem in a smaller and more specific area, while the global factors are caused by the changes of global temperature that caused coral bleaching, for instance. Unlike the WRI report, IUCN states that climate change is the biggest threat to the entire global ecosystem, where the coral reef ecosystem is one of the indicators [29]. The rising of Sea Surface Temperature (SST) as the impact of climate change cause coral bleaching [30-31] that occurred on islands in the Pacific [32]. On the other hand, *J.D. Hedley et. al.* [3] has classified factors that affect coral reef condition, where land-use change and increasing sea surface temperature are the most influenced factor to coral reef degradation. The list of threats to coral reef ecosystems combined with *J.D. Hedley et al.* [3] and WRI is displayed in Table 1 below.

Table 1. Threats to coral reef

Impact categorized	General threats	Detail threats	Relation
Local	Coastal development	Land-use change [24]	Changes in land use resulting in the loss of habitats and the modification of coastlines is a good proxy for the quantification of coastal development Settlements
		Population growth	Increasing more space for living, especially in the coastal area
	Pollution	Watershed-based pollution [33-34]	erosion and nutrient fertilizer runoff from massive agriculture delivered by rivers to coastal waters, which then causes erosion and sediment dispersion in river plumes
		Marine-based pollution and damage [24]	solid waste, nutrients, toxins from oil and gas installations and shipping, and physical damage from anchors and ship groundings
	Overfishing	Distance to reef-fishing settlements, accessibility	Settlements located near reefs are more likely to exploit their resources, while accessibility (number and quality of roads) improve the distribution of the catch and stimulate its increase
		Overfishing and destructive fishing [24]	unsustainable harvesting of fish or invertebrates, and damaging fishing practices such as the use of explosives or poisons
	Invasive predators	Crown of thorns (COT)	More COT more coral reef to consume, as the impact is declining coral reef cover
Global	Thermal stress	Warming Sea Surface Temperature (SST) [24]	the link between increased temperatures and mass coral bleaching [35] Thermal stress occurs when corals are exposed to prolonged above-normal temperatures, where the level of stress depends on the absolute temperature, the rate of change, and the length of exposure [36]. The only stress variable that can be directly measured using remote sensing. Proven to be useful in the forecasting of bleaching events and hindcasting of bleaching severity Together with in situ datasets can be used to model the effects of increased CO_2 concentrations in water chemistry
	Water quality	Water salinity	Indicating that low salinity is a more suitable indicator for coastal ecosystem health [37]

Impact categorized	General threats	Detail threats	Relation
		Turbidity	Seafloor reflectance in shallow waters limits the quantification of in-water constituents Direct quantification of pollutants is not feasible using remote sensing. Turbidity monitoring offers a proxy for the assessment of pollutant pathways
		Ocean acidification [24]	increased CO2 concentrations, which can reduce coral growth rates
	Algal blooms Exposure	Chlorophyll-a content	Algal blooms, often triggered by pollution enrichment, can help pinpoint polluted areas
	Physical water	Current	distribution of ocean temperature and phytoplankton
		Tides	duration exposed area at the lowest tide
		Wave exposure	the degree of wave action on an open shore or reef area drives the distribution of reef habitats [38], ecological processes such as primary productivity [39], coral growth [40], disturbance incidence [41], fish assemblage structure [42], and defines the spatial pattern of anthropogenic influences such as fishing access.
		Wind energy and bathymetry	Calculation of wave energy can be done by simple calculations or a full numerical model
		Rugosity	In coral reefs, the most important aspects of structural complexity are rugosity, hard substrate, and refuge availability [43]; the first two factors can be derived using acoustic techniques
		water attenuation (Kd)	The newer methods improve on the limitations of standard ocean color algorithms in shallow coastal
	Atmosphere	Precipitation Wind speed	increasing nutrients from land to a coastal area When wind speeds drop, reduced mixing may increase the likelihood of high temperatures and light penetration

Results and discussion

Reference search results

In the first step, 209 references were obtained through the keywords 'coral reef health index', 168 from Scopus and 41 from Mendeley. Elimination was conducted manually through the titles that were completely following keywords because not all references provide a formula to calculate the index of coral reef health. As a result, 16 references and 19 references were obtained from Scopus and Mendeley, respectively. The final step was duplication-checking from both search engines, and then we got 19 references in total that provided a method to calculate the index for coral reef health from spatial data. In addition, we also used references from the project report of reef ecosystem protection programs at certain locations such as The Great Barriers Reef, Coral Triangle, and Meso-America Reefs. Then we obtained six additional references related to the coral reef health index. Thus, the total references related to the coral reef health index used in this review article were 25 publications, which consisted of articles and reports published in 2001-2021. The details of the 25 publications can be seen in Table 2 below.

From the 25 references, the number of parameters and specific parameters that might be replaced with spatial data is identified. From Table 2, the total number of parameters used in each reference is different because it is related to data availability. Therefore it can be understood that there is no standard method to determine the health of coral reefs. In addition, most methods use data sources from field data measured directly through diving, for example, data on juvenile corals and fish biomass. So, it is very difficult to replace with image analysis data.

Table 2. The List of References on Coral Reef Health-Indices

	Title	Source	Year	Number of spatial data from total parameters	Spatial data as a parameter	Providing health index	Index methodology
1	The coral reef health index in Teluk Sebong, Bintan Island [44]	Scopus	2021	1/3	Coral cover	v	Coral Reef Health Index Indonesia (CRHI-Ind)
2	A coral reef health study and its problem in Leti, Moa and Wetar Island, Mollucas Province [45]	Mendeley	2021	2/3	Algae cover, coral cover	v	Coral Reef Health Index Indonesia (CRHI-Ind)
3	Assessment of coral reef health conditions in Juru Seberang Village, Tanjung Pandan District, Belitung Regency-Bangka-Belitung Province [46]	Mendeley	2021	2/3	Coral cover, macroalgae cover	v	Coral Reef Health Index Indonesia (CRHI-Ind)
4	The condition of the coral reef ecosystem in Natuna Island [47]	Mendeley	2021	2/3	Coral cover, dead coral	v	Coral Reef Health Index Indonesia (CRHI-Ind)
5	Testing the performance of ecosystem indices for biodiversity monitoring [48]	Scopus	2020	0/3	NA	v	Red List Index of Ecosystems (RLIE), Ecosystem Area Index (EAI), Ecosystem Health Index (EHI)
6	Assessment of coral reefs health in Nature Recreation Park (TWA=Taman Wisata Alam) Sangiang Island, Banten [49]	Mendeley	2020	2/3	Coral cover, sand cover	v	Coral Reef Health Index Indonesia (CRHI-Ind)
7	Integrative indices for health assessment in reef corals under thermal stress [50]	Scopus	2020	0/1	NA	NA	integrated biomarker response (IBR) indices
8	Practical Resilience Index for Coral Reef Assessment [51]	Scopus	2019	1/6	Coral cover	N.A.	soil community resilience index
9	Method to design a live coral cover sensitive index for multispectral satellite images [52]	Scopus	2018	2/2	Coral cover, bathymetry	N.A.	the ratio of different linear combinations (RDLC)
10	An Ecosystem Health Index for a large and variable river basin: Methodology, challenges and continuous improvement in Queensland's Fitzroy Basin [53]	Scopus	2017	0/4	NA	v	Ecosystem Health Index (EHI)
11	Indeks Kesehatan Terumbu Karang Indonesia (Indonesian Coral Reef Health Index) [54]	Research Centre for Oceanography (RCO-Indonesia)	2017	2/3	Coral cover, rubble cover	v	Coral Reef Health Index Indonesia (CRHI-Ind)
12	Coral reef health indices versus the biological, ecological, and functional diversity of fish and coral assemblages in the Caribbean Sea [55] - Healthy Reefs Initiative (HRI) - Healthy Meso- American Reef Ecosystem (HMRE) - Coral Health Index (CHI) - Kaufman et.al	Scopus	2016	1/3	Coral cover	v	two-dimensional Coral Health Index (2D-CHI)
13	The Relationship between the Health of Coral Reefs to the Damages of Jelateng Sub Watersheds in the Northern Coast of Sekotong, West Nusa Tenggara [56]	Mendeley	2016	2/3	Coral cover, turbidity/sedimentation rates	N.A.	Red Silt Index (RSI)

	Title	Source	Year	Number of spatial data from total parameters	Spatial data as a parameter	Providing health index	Index methodology
14	Coralligenous reefs state along anthropized coasts: Application and validation of the COARSE index, based on a rapid visual assessment (RVA) approach [57]	Scopus	2015	0/5	NA	NA	COralligenous Assessment (COARSE)
15	Marine Monitoring Program Inshore Water Quality and Coral Reef Monitoring Annual Report of AIMS Activities 2013 to 2014 [58]	Great Barrier Reef Marine Park Authority (GBRMPA)	2014	3/8	Coral cover, temperature, chl-a, suspended solids	v	Ecosystem Health Index (EHI)
16	Enhancing coral health detection using spectral diversity indices from worldview-2 imagery and machine learners	Scopus	2012	1/1	Coral cover	N.A.	spectral diversity indices
17	Coral Health Index (CHI): measuring coral community health. Rapport, Knowledge Division, Conservation International Arlington, VA, USA [59]	IUCN	2011	1/3	Coral cover	v	Coral Health Index (CHI)
18	Status of coral reef species at Chabahar Bay, Sistan, and Baluchistan, Iran [60]	Scopus	2010	0/3	NA	NA	Semi-Qualitative Indexes
19	Evaluation of the health status of a coastal ecosystem in southeast Mexico: Assessment of water quality, phytoplankton and submerged aquatic vegetation [61]	Scopus	2009	5/5	Salinity, temperature, chlorophyll-a, K, coral cover	N.A.	The trophic index (TRIX), Canadian index for aquatic life (CCMEWQI)
20	Ranking coral ecosystem "health and value" for the islands of the Hawaiian Archipelago	Scopus	2007	1/5	Coral cover	N.A.	scoring and ranking scheme
21	Healthy Reefs for Healthy People: A guide to indicators of reef health and social well-being in the Mesoamerican Reef Region [62]	World Bank Document	2007	12/58	Coral cover, coral diversity, fish diversity, temperature, salinity, transparency, fish abundance, focal species abundance, mangrove areal extent, coral reef areal extent, seagrass areal extent, sedimentation rate	v	reef health index from Coral Reef Ecosystem Health (RHI-HMRW)
22	Measuring coral reef ecosystem health: Integrating societal dimensions [63]	World Bank Document	2006	12/58		v	reef health index from Coral Reef Ecosystem Health (RHI-HMRW)
23	The Healthy Mesoamerican Reef Ecosystem Initiative: a conceptual framework for evaluating reef ecosystem health [64]	World Bank Document	2005	12/58		v	reef health index from Coral Reef Ecosystem Health (RHI-HMRW)
24	Deterioration Index (DI): A suggested criterion for assessing the health of coral communities [65]	Scopus	2004	0/3	NA	NA	Deterioration Index (DI)
25	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 [66]	Scopus	2001	0/6	NA	NA	Coral reef multimetric indexes of biotic integrity (IBI)

Thirteen references clearly describe methods for calculating coral reef health index. Several references use the same method and several overlapping parameters to know the essential parameter parameters because there is always a method for calculating the health index of coral reefs. Through these 13 references, it can be concluded that there are five different calculation methods related to the coral reef health index, where some of the parameters used have the potential to be obtained through satellite imagery. The five index calculation methods are RHI-HMRW, CRHI-Ind, EHI, CHI, 2D-CHI (grey rows in the table above).

The RHI-HMRW method is the most complex calculation method because it uses the most parameters related to social dimensions. The EHI index is an index for calculating ecosystem health, where the coral reef health index is one of the parameters for the EHI calculation (EHI = coral health index + water quality index). The 2D-CHI and CRHI-Ind indices use the least parameters, namely biotic (coral reefs) and fish (biomass), the reason being due to data limitations [26, 67]. Even so, parameters are always present in every model for calculating the health index of coral reefs, namely biotic information related to the area of coral reefs and macroalgae and fish biomass. In particular, information on the area of biotic cover can be obtained through satellite image processing [68].

Meanwhile, fish biomass information is calculated directly through diving. Other parameters, such as water quality, are only found in several index calculation models, where the data can also be obtained through satellite imagery [3]. Related to several parameters obtained through remote sensing technology, *S.M. Mumby et al.* [69] has made a list of parameters related to habitat information and physical information in coastal areas, including the water quality data. Thus, it can be said that remote sensing data can be used to calculate the health index of coral reefs through a spatial approach.

Remote sensing data for Coral Reef Health

The measurement of coral reef health through remote sensing technology, according to Holden and Le Drew in the 1990s, stated that there was no direct measurement technique [70]. Although other authors [71] have succeeded in mapping healthy coral cover and diseased coral cover, indicating coral reef health, this study uses costly airborne remote sensing technology in a relatively small area. Meanwhile, the currently available open-public satellite images are medium resolution images that cannot accurately distinguish healthy coral reef cover and diseased coral cover. The problem is due to the similarity of spectral values between coral reefs, seagrass beds, and algae and the complex mixture composition between the three [72]. Spatial misregistration between individual time series images and between imagery and field data, or variation between mapping methods, also limits the consistency of time series habitat maps [3].

Therefore, until now, information on Sea Surface Temperature (SST) has become an indicator in assessing the condition of coral reefs because high-temperature increases for some time can cause coral bleaching [73]. In addition, the SST data is easy to access as open public data from Ocean Color level 3 product that a result of MODIS satellite. An example product from the SST time series data analysis is an area predicted to experience coral bleaching (Bleaching Alert Area/BAA). The BAA information was analyzed from data on temperature anomalies, coral bleaching hot spots (C.B. Hot Spots), and the duration of temperature anomalies (Degree Heating Weeks/DHW) in certain areas. This BAA information can be obtained free of charge by accessing the NOAA Coral Reef Watch website (https://coralreefwatch.noaa.gov/index.php).

Another problem in calculating coral reef health is time series analysis of biotic data and water quality. In addition, connecting the two data with different resolutions is also a challenge until now. In addition, the acquisition of time series data on benthic habitats still requires manual image processing using simple to complex methods carried out by people with special expertise [74]. The other challenge is how to relate the spatial data with a different spatial resolution, especially the open-source data, namely, between habitat cover data and water quality data. Before discussing this, it is necessary to identify parameters related to changes in coral reef health which can refer to the index calculation methods that have been collected.

Through the five methods of calculating the health index of coral reefs, spatial data analysis is seen by the methods used, data sources, characteristics of image data. The results of identifying the calculation parameters generated from the image data can be seen in Table 4 below. Like the RHI-HMRW model, the total parameters in table 4 are grouped into two based on the factors that influence changes in coral reef conditions, namely internal factors (structure attributes) and external factors (drivers of change). Furthermore, detailed data obtained through remote sensing technology is described on each influencing factor, along with a list of coral reef health indexes being studied. The selected parameters are specific only to open-source data, where the advantages and disadvantages of data sources are also described in table 3 below.

Table 3. Reef health index parameters that are possible to obtain from remote sensing data

General parameters	Detail parameters	Reef health index (RHI) method	Data source and information
Benthic community	1. Coral cover (life coral) extent	• RHI-HMRW • CRHI-Ind • EH-Thompson • CHI-Kaufman • 2D-CHI	**Source**: Global Coral Atlas **Spatial resolution**: 3-meter spatial resolution **Parameters** provided: 1. Coral/algae 2. Seagrass 3. Microalgal Mats 4. Rock 5. Rubble 6. Sand **Data availability**: one time recorded **Flaw**: 1. Only provide single-time data 2. Potentially get misclassification between coral/algae class and microalgae Mats class, which then affects the coral-algal ratio
	2. Coral: algal ratio	• RHI-HMRW CRHI-Ind • CHI-Kaufman • 2D-CHI • EH-Thompson	
	3. Rubble cover extent	• CRHI-Ind	
	4. Seagrass extent	• RHI-HMRW	
Coastal habitat	5. Mangrove extent	• RHI-HMRW	**Source**: UN-WCMC (https://data.unep-wcmc.org/datasets/45) **Spatial resolution**: 0.8 arc seconds **data availability**: 1996-2016 **Flaw:** 1. The latest data is 2016 2. Only provide one class (mangrove cover)
water quality	6. Sea Surface Temperature (SST)	• RHI-HMRW	**Source**: 1. Annual monitoring–Level 3 products, https://oceancolor.gsfc.nasa.gov/l3/ (1985-2021) 2. Google Earth Engine - Ocean Color SMI: Standard Mapped Image MODIS Aqua Data/ Terra Data (2002-2021) - NOAA AVHRR Pathfinder Version 5.3 Collated Global 4km Sea Surface Temperature (1981-2020) - HYCOM: Hybrid Coordinate Ocean Model, Water Temperature and Salinity (1992-2021) - GCOM-C/SGLI L3 Sea Surface Temperature (V1) and (V2) (2018 - 2020) **Spatial resolution**: ≈ 5 km **Band unit value**: $^0C/^0K$ **Data availability**: 2002-07-04T00:00:00 - 2021-06-30T00:00:00 **Parameters**: sea surface temperature (SST)
	7. Chlorophyll-a	• RHI-HMR • EH-Thompson	**Source**: Google Earth Engine (GEE), GCOM-C/SGLI L3 Chlorophyll-a concentration (V1) **Spatial resolution:** 2.5 arc minutes, ≈4.6km **Band unit value:** mg/m^3, 0-4000, **Data availability**: Data from 2002 **Band unit value:** mg/m^3, 0-4000 **data avalibility**: 2018-01-01T00:00:00 - 2020-06-28T00:00:00 **Flaw**: field data is needed for validation
	8. Salinity	• RHI-HMR • EH-Thompson	**Source**: Google Earth Engine (GEE), HYCOM: Hybrid Coordinate Ocean Model, Water Temperature and Salinity **Spatial resolution:** 0.08-degree ≈8.9km **Band unit value:** salinity_0, PSU, (-20.009) – 32.767, Seawater salinity, in practical salinity units, at a depth of 0m **data availability**: 1992-10-02T00:00:00 - 2021-07-13T00:00:00
	9. River plumes map Standard Mapped Image	• RHI-HMR • EH-Thompson	**Source**: 1. MODIS true-colour imagery (Level-0), http://oceancolor.gsfc.nasa.gov (2002) 2. Google Earth Engine (GEE) - Ocean Color SMI: Standard Mapped Image MODIS Aqua Data (2002 - 2021) - Ocean Color SMI: Standard Mapped Image MODIS Terra Data (2000-2021) **Spatial resolution:** 500 m × 500 m for MODIS level-0 and ≈5 km for GEE data

General parameters	Detail parameters	Reef health index (RHI) method	Data source and information
			Parameters: Chlorophyll a concentration, Normalized fluorescence line-height, Particulate organic carbon, Sea surface temperature
	10. light coefficients (Kd (PAR))	• EH-Thompson	**Source**: Annual monitoring–Level 3 products, https://oceancolor.gsfc.nasa.gov/l3/ **Data availability**: from 2002 **Spatial resolution**: 4 km **Band unit value**: diffuse attenuation coefficient (m^{-1})
Drivers of change			
Global climate change	11. Coral bleaching index	• RHI-HMRW	**Source**: The NOAA Coral Reef Watch (CRW) – Allen Coral Atlas (interactive map server), NOAA's Coral Reef Watch program (CRW). **Spatial resolution:** 5km 7-day **Data availability**: 2 Oct 2018 – 26 July 2021 **Parameters**: 1. SST (a.k.a. CoralTemp) 2. SST Anomaly 3. Coral Bleaching HotSpot 4. coral bleaching Degree Heating Week (DHW) 5. single-day Bleaching Alert Area 6. 7-day maximum Bleaching Alert Area 7. 7-day SST Trend

*Information: RHI-HMRW: reef health index from Coral Reef Ecosystem Health, CRHI-Ind: Coral Reef Health Index Indonesia, EH-Thompson: Ecosystem Health developed by Thompson, CHI-Kaufman: Coral Health Index developed by Kaufman, 2D-CHI: two-dimensional Coral Health Index. Directly used: green

Based on the image data sources used, especially open-source data to generate the parameters in table 3, the data sources can be grouped into 2, namely high-resolution images (Planet Dove in Allen Global Coral Atlas) and low-resolution images (MODIS). The detailed image data provides information on benthic habitat cover, and low image data provides information on water quality. Although high-resolution satellite imagery has provided detailed benthic habitat cover information, the time scale is only for one recording date. Therefore, actual data be a lack of data used for the future. On the other hand, for low-spatial resolution images, although they provide excellent time-series information, field data needs are essential to creating a model for extracting water quality data such as photic depth, Colored Dissolved Organic Matter (CDOM), Total Suspended Sediment (TSS), and turbidity. That reason also why other water quality data from ocean colour level 3 (https://oceancolor.gsfc.nasa.gov/product_status/) not be listed for calculating coral reef health although several indexes used the parameter namely RHI-HMR and EH-Thompson. by using that kinds data can increase the cost, time and the needs of experts before it is used for calculating the coral reef health index.

Data can be obtained from Ocean Color level 3 image and Google Earth Engine (GEE) for low-resolution. The difference between the GEE data (https://google.earthengine.app/view/ocean) provides more data choices with a longer period related to water quality but requires knowledge related to programming languages to run the web applications. While Ocean Color level 3 data only provides data, especially from the MODIS satellite recorded since 2002. In addition, preprocessing data is needed using special software provided by web ocean colour. Cloud computing technology, especially GEE, can be a solution to calculate the health index of coral reefs in the future. According to literature data [75], the availability of multi-source, multi-resolution, multi-characteristic big data is needed to get maximum results in identifying the condition of coral reef.

Non-Remote sensing data for coral reef health index

Although most of the important parameters can be obtained from the image, some other important data are still needed to calculate the coral reef health index; namely, the ratio of algae cover related to the rate of coral reef health and fish biomass. It is still difficult to map from the image for algae cover because of the similarity of the spectra values to coral reefs and seagrass beds [76]. However, *P.J. Mumby et al.* [65] stated in his publication that future time series data analysis could distinguish coral reef objects covered in algae. On the other hand, fish biomass requires direct measurement in the field through diving, and there is no method for remote sensing-based [77] for biomass estimation. One option to complete that data is by using the secondary data from monitoring activity. For instance, in Indonesia, the COREMAP CTI program (http://crmis.oseanografi.lipi.go.id/crmis) that actively conduct annual monitoring provides the field includes the percentage of algae cover and fish biomass for public use, even though the lack of data is only available in certain years and certain areas in Indonesia.

Regarding the water quality parameters in table 7, *M.J. Devlin et al.* [23] simplify the variation of water quality information excluding SST through the results of the MODIS true color level 3 data classification. Plume variation associated with the content of chlorophyll-a, CDOM, and TSS. So, by adopting the method developed by Devlin, the need for water quality information related to coral reef health can be replaced with OCEAN COLOR level 3 images which are also open-source data that are easily obtained. However, other things are still required for manual ocean color level 3 image processing in the supervised classification of multispectral images. Therefore, the need for water quality data for reef health index calculation can be simplified into the figure below.

Data Analysis Techniques and indicators to Assess Coral Reef Health

Based on the literature study, there are at least three analysis techniques and indicators to assess the health status of coral reefs, namely: 1) single indicators, 2) the application of scoring and weighting techniques on indices and statistical analysis to relate coral reef health indicators to environmental parameters.

Single Indicators

Reef health has been evaluated using a range of single indicators, including total live coral cover (http://crmis.oseanografi.lipi.go.id/crmis), coral community structure, coral species richness or diversity and community structure of reef fishes. Only live coral cover and beta diversity were extracted from satellite data regarding remote sensing data [78]. The success of *D. Palandro et al.* [76] in mapping live coral cover using Landsat-5 TM and the presence of detailed field data mainly supports Landsat-7 ETM+ data, in particular, permanent historical transect at their study site. To facilitate the development of statistical models of beta diversity, *J.D. Hedley et al*. [3] used two key variables: depth and wave exposure as a proxy to calculate beta diversity. Bathymetry was mapped using the "depth of penetration" *method of Jupp* (1988). Therefore, the spatial representation of the result of their study is implemented at the pixel size of the Landsat 5 T.M. imagery.

Scoring and Weighting Technique Applied to Coral Reef Health Indices

Even though there seem to be obvious indicators of reef health, there is not an exact definition or a common consensus relying on a single indicator species, taxa, or group for assessing coral reef health due to the highly variable nature of coral reefs. A coral reef with high fish species richness, abundance, or biomass may be assessed as a healthy coral reef, but its living coral cover is very low, its overall condition may not be healthy. Therefore, the assessment of reef health then incorporates a suite of indicator variables which are combined and weighted in such a way that represents a more holistic index categorizing a coral reef as, for instance, healthy, fair, or unhealthy [24, 58, 61, 78].

Two examples are given here: Reef Health Index (RHI) [71] and Coral Health Index (CHI). Reef Health Index (RHI) combines four indicators for evaluating coral reef health: live coral coverage, fleshy macroalgae coverage, the biomass of herbivorous fish and biomass of commercial fish to derive one simplified measure of reef health. These indicators are averaged to obtain values on a range from 1 to 5, where the value of 1 is characterized as "Critical", the value of 2 as "Poor", the value of 3 as "Fair", the value of 4 as "Good" and value of 5 as "Very Good". On the other hand, the Coral Health Index (CHI) uses three indicators: benthos (including the coverage values of both encrusting coralline algae and live coral), reef fish (total biomass of fish) and microbes (concentration of Vibrio spp.). Benthos component is scored 0 (degraded) to 1 (healthy) based on the proportional cover of coral and crustose coralline algae (CCA). Reef fish metric is scored 0 (degraded) to 1 (healthy) based on a fraction of total fish biomass from a reference site. Microbial scores for CHI are inversely related to the number of Vibrios present, with more Vibrios associated with decreased health. This metric score of 0 (degraded) to 1 (healthy) is based on an inverse relation of Vibrio concentration. These indicators are then averaged to obtain five health grades in values ranging from zero to one, 0.0–0.20 (very degraded), 0.21–0.40 (degraded), 0.41–0.60 (Fair), 0.61–0.80 (healthy), 0.81–1.0 (very healthy).

Among the aforementioned coral reef health indices, very rarely remote sensing data are used for implementing the indices though it is possible to extract coral live cover from satellite data such as *D. Palandro* [76]. To date, only *K.E. Joyce and S.R. Phinn* [79] used remote sensing data to derive spatial live coral cover index for Heron Reef, Australia. However, their data source was from hyperspectral airborne image data, which prevents the implementation of their study to the wider application due to the high cost of the image used.

Statistical Techniques for Examining the Impacts of Environmental Parameters on Coral Reefs Health

The literature review results show several statistical analysis techniques to examine the relationship between coral reef health and aquatic environmental parameters. Parameters of coral reef health indicators used are normally benthic cover for various taxa and taxonomic groups. Even though various aquatic environmental parameters are used as metric predictors of coral reef health, literature shows that various environmental parameters used result primarily from three main sources, namely in-situ measurement, modelling, and remote sensing data [80].

J. Zinke et al. [80] studied how gradients of disturbance and environmental conditions shaped the coral community structure of coral reefs in the south-eastern Indian Ocean. They used nine environmental parameters as predictors for benthic cover conditions in their study area. The metrics were specifically selected for their relevance to physiological processes, productivity and stress responses in Scleractinian reef corals. Seven metrics were derived from ocean satellite observations and modelled databases, including (1) sea surface temperature (SST); (2) thermal stress metrics; (3) total suspended matter (TSM), (4) photosynthetically active radiation (PAR); (5) tidal range; (6) nutrient concentrations (chlorophyll-a); and (7) frequency of exposure to extreme winds generated by tropical cyclones. Two parameters, (8) depth and (9) physical location (latitude, longitude, isolation), were derived from in situ data. To assess the relative contribution of spatial variation in environmental metrics in explaining the spatial variability of total coral cover, life histories, and bleaching susceptibility, they used the Generalized additive mixed model (GAMM) to fit the best models. After that, the GAMM models were compared using the Akaike information criterion for small sample sizes (AICc) and AICc weight (ωi) values. The Akaike information criterion (AIC) is a mathematical method for evaluating how well a model fits the data. It is commonly used to relate the Impact of Environmental Parameters to Coral Reef Health [81]. The AIC compares different possible models and determines which one best fits the data by calculating the number of independent variables used to build the model. The best-fit model according to AIC is the one that explains the greatest amount of variation using the fewest possible independent variables. The AIC formula is 2k – 2log L.L., where k is the number of parameters estimated by the model and log L.L. is the log-likelihood for the given model. the maximum likelihood estimates of the model (how well the model reproduces the data)

To address multiple stressor effects on coral reefs ecosystems in the Red Sea [82] used 21 metric predictors derived from both in situ data (PO_4, SiO_2, NO_3, NO_2, NO_x, chlorophyll a, temperature, salinity, oxygen, distance to shore, latitude-longitude) and modelled data (wave period, wave height, wind speed, latent heat flux, evaporation, remotely sensed chlorophyll-a, rainfall, PAR, specific humidity, fishing pressure). The authors employed multivariate linear regression to model the metric predictors that contribute to the percentage cover of each of the main taxonomic groups, including hard corals, soft corals, coralline algae, turf algae and macroalgae. The stepwise regression analysis was conducted to build models from a set of candidate metric predictors by adding and removing predictors that meet the criteria for entry or removal until a stable set of variables was achieved. The model selection is based on Akaike's Information Criterion (AIC) to distil the model that best explains the data while still not fitting too many parameters

M. Teichberg et al. [82] used multivariate generalized linear models to determine whether the various environmental variables of nitrate + nitrite (NO_X), phosphorus (PO3−4), silicate (Si), in situ Chlorophyll a-like fluorescence (Chl a), dissolved organic carbon (DOC), suspended particulate matter (SPM), dissolved oxygen (D.O.), temperature, pH, salinity, and light attenuation (Kd) could be the driving factors of change in benthic assemblages in Spermode Islands, Indonesia. Two principal components (PC1 and PC2) from the PCA on environmental variables were used in the multivariate generalized linear models. Residual plot analysis was used to examine the best fits of the various models assessed. This study also assessed the relationships of individual benthic groups with the environmental Principal Component to observe which benthic groups are contributing to patterns at the community level.

Based on table 4, it is known that parameters consist of habitat information and water quality. The number of parameters can be simplified the calculation process. The first is by eliminating parameters that do not strongly correlate with changes in coral reef cover using the Akaike information criterion (AIC) statistical model. Second, by substituting some water quality parameters with the river plum distribution map. Based on the results of their research, *M.J. Devlin et al.* [23] found that Plum variation is associated with chlorophyll-a, CDOM, and TSS content. So, the water quality parameters used for calculating the health index of coral reefs consist of SST, plum variation, salinity and light coefficient.

Based on the characteristics of the spatial and non-spatial data, there are three challenges in calculating the health index of coral reefs: data standardization, determining weight, and creating the best model. Data standardization relates to the equation of spatial resolution and temporal information. Determination of weight-related to the level of influence of each biophysical parameter that affects changes in coral reef cover indicates the health of coral reef ecosystems. The last is creating a model that can be a sum of all or several parameters as done by Giyanto and Thompson.

Because several biophysical parameters affect the condition of coral reefs, as shown in table 4. On the contrary, the level of influence of each parameter is different, as stated by *J. Zinke et al.* in his study [80]. It can be done to eliminate parameters to reduce costs in collecting field data collection. The trick is to use statistical models such as AIC. The use of AIC for coral reef health studies, based on previous studies using three main data sources, namely in situ measurement, modelling and remote sensing, has been previously carried out by [58, 80, 83]. Likewise, the use of some physical water data, as presented in table 4, has also been studied for its relationship to the health condition of coral reefs conducted by [83]. The results of AIC analysis on zinc publications show that temperature and temperature anomalies affect changes in coral reef cover. Therefore, SST data obtained and processed through GEE can be used as one of the index parameters.

In addition, to the results of the study on the use of the AIC model, which can reduce most of the physical parameters of the waters, *M.J. Devlin et al.* [23] stated that the variation of the river plump could be related to the physical conditions of the waters, such as the content of chlorophyll-a, CDOM, and TSS. So that the scenario parameters used to calculate the coral reef index can consist of coral reef cover, SST and SST anomalies, and river plum (Table 1). The provisional weight determination is still based on the modification of the results of the previous study [80], where the coral reef cover component is the main component with the highest weight, and the algae cover component, ruble cover and water conditions consisting of SST, ASST and river plum as a reducing component.

Conclusions

Although there is no standard method in calculating the health index of coral reefs, there are several main parameters: coral reef cover itself, fish biomass, and water conditions, namely SST. Along with technological developments, some of these parameters can be obtained easily and processed using cloud computing technology, especially coral reef cover and water conditions. Even so, satellite imagery and cloud computing technology are only limited to providing data, where the calculation of the coral reef health index is carried out mathematically by calculating the weight values built from the required parameters. Meanwhile, a statistical analysis such as AIC can be used to find parameters that strongly correlate to changes in the condition of coral reef ecosystems. So there is no need to use all the parameters as stated in the results and discussion based on the study results on the use of AIC related to the strong relationship between water temperature and coral reef cover and the correlation of river plum with water conditions, the parameters of water conditions can be simplified into temperature, temperature anomalies and river plume. Furthermore, the water parameters will be a deduction factor in calculating the health index value of coral reefs along with information on the percentage of algae cover and the percentage of rubble cover, which indicates the potential for restoration of coral reef cover.

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