ASSESSMENT OF ENVIRONMENTAL VARIABLES AND THEIR IMPACTS ON CORAL REEFS USING REMOTE SENSING AND GIS

EXECUTIVE SUMMARY

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1. INTRODUCTION

Coral reefs are one of the important ecosystems on the earth, with high biological production and complicated environmental conditions. They can be found along the shore and off shores of islands and continents in shallow tropical waters. The majority of coral reefs are made up of stony corals, which are made up of polyps that cluster in groups. This type of corals is known as Hermatypic corals and also as Scleractinia corals, which are held together by calcium carbonate structures produced by corals (Sreekumaron and Gogate, 1972). Hermatypic corals have the zooxanthellae algae which lives in with a symbiotic relationship. In the process of symbiotic relationship, coral provides shelter to the zooxanthellae algae and in return algae provides food and nutrients to the coral by the process of photosynthesis. As this process requires the sunlight, this type of corals can survive in shallow water and in the depth up to euphotic zone. Ahermatypic corals are referred as a non-reef building corals and they are independent from the zooxanthellae. As they do not need sunlight for their survival, they can be found at higher depths of the ocean.

The Scleractinia corals are formed around 245 million years ago in Mesozoic Era (Stanley, 2003). Thus, Coral reefs are one of the world's most significant, diversified, and ancient habitats, providing a home for a variety of marine animals (Moberg and Folke, 1999). Many species dwell on the reef in a symbiotic and prey-predator interaction (Dave and Mankodi, 2009). The protection provided by corals helps in formation of associated ecosystems, which facilitates integrated food web of marine ecosystem (Moberg and Folke, 1999). Coral reefs also act as a coastal protector by protecting coastal area from storm damage, floods, tsunamis, hurricanes, coastal erosion through controlling power of waves (Parasharya, 2012). Coral reefs support local communities by generating revenue from tourism, building materials, fishing, etc. (Carte, 1996; Spalding et al., 2001; Bhattji, 2011). Thus, in comparison to other marine habitats, coral reefs are a very dynamic environment (Spalding et al., 2001).

As coral reefs are extremely sensitive to the environmental conditions, they are often used as important indicators of climate change (Chaudhury et al., 2014). In recent decades, various stressors have affected reef health negatively and as a result, coral reefs have been quickly decreasing across the world. They are primarily threatened by rising anthropogenic activity and the global climate change problem (Joshi, 2016).

Assessments to late 2000 stated that 27% of the world's reefs have been effectively lost (Almada-Villela et al., 2002) because of the massive climate-related coral bleaching event. Global warming's effects, such as an increase in the frequency and intensity of hurricanes and drastic changes in ocean temperature, have resulted in significant damage, such as coral bleaching and colony decline (Ameris et al., 2012). Temperature alone does not account for the bleaching patterns. The sources of this variation are also including environmental parameters like light, turbulence, solar radiation, water flow, and salinity. The use of these environmental variables is suitable to achieve the goal of determining the general pattern of meso-scale bleaching event, and to associate this event broadly with both long term inherent oceanographic conditions and conditions when they occur (Joseph, 2007).

Remote sensing is more practical way to monitor the change in health and coverage of the reef ecosystem covering larger area. Corals usually found in relatively shallow waters are exposed to direct sunlight with an optimum temperature of 23ºC-25ºC. However, the water column on coral reefs strongly absorbs longer wavelengths, thus the use of electromagnetic radiations is limited to visible regions (450-650nm). Also, corals have symbiotic association with zooxanthellae, discrimination of corals from algae merely based on the spectral signatures is difficult especially with data sets of broad spectral resolution (Nadoka et al., 2004). Thus, Space borne multispectral imagery demonstrates great spatial potential to accurately map coral reef habitats (Collin et al., 2016), health and resilience.

Landsat Thematic Mapper (TM) and Sentinel-2 Multispectral (MS) images offer some potential for classification of different classes of Coral reef ecosystem. Mumby et al., (1998) had tested a retrieval algorithm using the Landsat Thematic Mapper (TM), comparing the satellite-based estimates of coral reef extent against similar 1-m-resolution retrievals from an airborne imaging spectrometer; the satellite-based method yielded an overall accuracy of 75%. In one study by Prerna, et. al., (2015) on temporal change in the extent of coral reefs and mangroves patches along the Narara and Kalubhar islands using multi-temporal data of IRS LISS-III and LISS-IV from 1999 to 2010 it has been stated that only green band and red band were useful for coral identification due to their higher water penetrating capability, as opposed to NIR and SWIR bands.

Development of Spectral signature library of reef eco-system increases the understanding of controlling factors of reflection and absorption of light in reef environment. Though it is difficult to definitively determine the difference between spectral reflectance signatures of corals with algae and corals without algae in its associated reef environment, there are two documented pigments that occur only in zooxanthellae of Corals which are Peridinin and Dinoxanthin. Peridinin shows maximum absorption at 475 and 570 nm (Myers et al., 1999), whereas Dinoxanthin shows maximum absorption at 418, 442 and 470 nm (Hedley and Mumby, 2002). As per Hochberg et al., (2003), brown Corals have shown a reflectance peak near 570 nm, whereas blue corals strongly absorb in the 580 nm region. According to Joyce et al., (2013) second derivative of reflectance at 564 nm was one of the wavelength regions most sensitive to variations in live coral cover and least sensitive to variations in water depth and quality. Chaudhury, (2012) studied on the In-Situ hyperspectral signatures of eight coral targets using Analytical Spectral Devices, Field-Spec spectroradiometer at Paga and Laku Point reefs of Gulf of Kachchh to effectively understand the spectral behaviour of corals. In the visible range over 400 to 600 nm range, the live and the bleached corals are differentiated. Spectral band ratios derived from image data have been used previously in reef environments to map bottom cover (Mumby, 2000). However, when based on Landsat TM/ETM+ image data, they are restricted to clear, shallow waters, especially when utilizing the red channel (Dustan et al., 2001). Earlier Hochberg, (2003) had separated Corals, Algae and Sand by spectral band ratio based on linear discriminate function analysis using field spectrometer data, and applied them to airborne hyper spectral images, with promising results.

Using the spectral signatures, remotely sensed indices can provide a more widely applicable method for mapping and monitoring environmental parameters. Spectral indices like Normalized Difference Vegetative Index (NDVI) are among the most common data transformations for mapping vegetation's structural or physiological attributes. They are simple and relatively easy to implement from multispectral and hyper spectral datasets (Joyce et al., 2013). This type of spectral indices relies on measured absorption and scattering processes, which are strongly negatively and positively correlated to the chemical and structural properties of the object. In reef ecosystem, impact of environmental conditions may differ for different benthic features. An effective spectral index will exhibit a direct response to relatively small changes in coral cover, across a range from low to high cover levels (Joyce et al., 2013). Also, as the generation of spectral indices is not much complex process and can be applied with entry level image processing software, widely they are being used for reef environment.

Amongst the various spatial interpolation techniques, Inverse Distance Weighted (IDW) method is relatively simple and easy to calculate and also more convenient to interpret the outcomes than other techniques (Lu & Wong, 2008). In one of the studies Kumari et al., (2017) adopted the IDW interpolation method to know the spatial distribution pattern of zoanthids along the Saurashtra coast of Gujarat. Using IDW technique they found that *Palythoa mutuki* is the most common and abundant species across the Saurashtra coast and reported the highest amount of live coverage of *P. mutuki* with 60% at Dhamlej and Charra.

Coral Reefs are rich in diversity and fine-scale monitoring of these ecosystem is needed for their management and spatial planning. Remote sensing is more practical way to monitor the change in health and coverage of the reef ecosystem covering larger area. Mapping and monitoring of such large and remote ecosystem can be easily done by remote sensing and Geographic information systems (GIS) techniques. Space borne multispectral imagery demonstrates great spatial potential to accurately map coral reef habitats (Collin et al., 2016), health and resilience. Thus, coral reef mapping usually relies on remote sensing for cost effectively identifying their structural complexity, benthic composition, and regime surrogates over large areas (Goodman et al., 2013; Hedley et al., 2016).

2. REVIEW OF LITERATURE

For many years, coral reefs have helped keep the coasts and many marine species protected. But it's becoming clear that coral reefs are seriously threatened by global warming. As a result, stressed corals expel their symbiotic algae, which raises the potential for further coral ailments and mortality. This has led to coral bleaching. Over the world, both the frequency and the severity of this tendency have been rising. Over the past few decades, various researchers have used field observation data or reef environmental variables retrieved from satellite data to record regional or global coral bleaching trends and implications (Barkley *et al.,* 2018; Hughes *et al.,* 2018a). This research underscores the need of comprehending how coral bleaching is related to environmental variables. There is an urgent need for more accurate coral bleaching mapping that is both time and money efficient.

Remote sensing technologies have been demonstrated to be effective tools for coral reef monitoring so far (Mumby *et al.,* 1999; Hedley *et al.,* 2016). Remote sensing has made it possible to study the oceans in greater depth with global coverage, which has sparked a significant deal of interest in the topic of ocean remote sensing (Guerra *et al.,* 2016). In the field of ocean remote sensing, many researchers nowadays use Ocean Color (OC) to study the effects of different environmental variables on coral reefs. Since OC satellite instruments offer estimates of the light that exits a water mass and defines its color, OC is frequently referred to as spectral water-leaving radiances (Werdell *et al.,* 2018). These sensors typically measure the spectral radiation coming from the top of the atmosphere ($Lt(\lambda)$; $\mu W cm^{-2} nm^{-1} sr^{-1}$) using wavelengths at the distinct visible and near-infrared (400-1000 nm) ranges (Werdell *et al.,* 2018). Ocean Color Remote Sensing (OCRS) sensors have the potential to continuously measure physical, environmental, biological, and biogeochemical variables that are important for managing fisheries and aquaculture, managing coastal areas, assessing ecosystem health, and contextualizing behavioral changes in the context of climate change (Le Traon, 2011; Payne *et al.,* 2021).

Coral reefs mainly affects by the elevated SST, sedimentation, disease outbreak, destructive fishing practices, global warming and climate change which ultimately leads to coral bleaching and destruction of reef ecosystem. In the year 1997–98, major global coral bleaching event in connection with an El Niño event was declared. Mass Coral Bleaching (MCB) event was recorded from several coral reef countries during 1997–98, and about 16% of coral reefs were destroyed worldwide (Lough, 2000). The second world-wide confirmed MCB event was recorded in 2010, and an ENSO event is believed to trigger this and third worldwide MCB event in 2016 was the longest in record (McField, 2017). Over the last 20 years, corals have died drastically mostly due to bleaching, disease or pollution (Andréfouët et al., 2001). Different coral species has different tolerance level of thermal stress. Thus, elevated SST may affect the particular species which has low level of tolerance of thermal stress than other and might not affect the other corals with high tolerance capabilities. Warner et al., (1996) studied on zooxanthellae of different species in Discovery Bay Marine Laboratory and said that from the back-reef species of coral, Zooxanthellae of the *Siderastrea radians* tends to be more temperature-tolerant than those of Montastraea annularis and Agaricia lamarkii, coral species from fore-reef of Discovery bay, Jamaica.

Remote sensing technologies have so far proved to be significant methods for collecting information on coral reefs (Mumby *et al.,* 1999; Hedley *et al.,* 2016). Benthic habitats are easier to map in great depth and with greater accuracy using remote sensing data with high spatial and spectral resolution (Hochberg and Atkinson, 2003; Kutser *et al.,* 2020). Any given sensor's individual spectral bands are designed to cover a specific range of wavelengths. For instance, the multispectral system uses spectral bands that are 100 nm wide to cover the blue, green, red, and near-infrared regions of the electromagnetic spectrum. The hyperspectral system, in comparison, uses hundreds of spectral bands that are each 10 nm broad to cover the same wavelength range. To map coral reef benthic features at a coarse scale, multispectral methods offer widely applicable spectral reflectance characteristics. Holden *et al.,* (2001) and LeDrew *et al.,* (2004) contend that spatial statistics can be used to extract a measure of reef health from moderate spatial resolution multispectral satellite image data (such as SPOT). Landsat and SPOT are suitable for mapping geomorphological zones with low to intermediate complexity, according to prior research on benthic classification (Lyzenga, 1981; Leon and Woodroffe, 2011; Phinn *et al.,* 2012; Roelfsema *et al.,* 2013; Xu *et al.,* 2016). However, due to the variety of coral phenomena such as bleaching occurring at sizes of a few meters or less, the Copernicus Sentinel-2 mission with a special resolution of 10 m, is becoming very useful to improve coral reef remote sensing. It combines a number of excellent features for monitoring coral reefs. It contains a blue band similar to Landsat 8, but with a finer spatial resolution of 10 m and atmospheric correction, it permits the mapping of corals in shallow waters. However, due to the fact that bleached corals' reflectance resembles the sand on the reef island. Similarly, healthy corals’ spectral signatures match up with the corals covered in algae due to the mixed pixels effect and the reason is, normally corals have a symbiotic association with zooxanthellae (Chaudhury *et al.,* 2019), making discrimination of corals from algae merely based on the spectral signatures very difficult, especially with data sets of broad spectral resolution. Though, as it has been determined which wavelength ranges are absorbed by particular chemicals and processes in water bodies and coral photosystems, algorithms can be used to estimate or map these features for each pixel using reflectance signatures resolving these features.

For mapping, the structural or physiological characteristics of reefs, one of the most popular data transformations are to use spectral indices, such as the Normalized Difference Vegetative Index (NDVI). There are a variety of spatial interpolation methods that can be used to determine the pattern of diversity distribution. One of which is the Inverse Distance Weighted (IDW) interpolation approach, which was used by Kumari *et al.,* (2017) to determine the spatial distribution pattern of zoanthids along the coast of Saurashtra in Gujarat. Benthic structures on a coral reef vary from one area of the reef to another based on a variety of environmental factors, such as hydrodynamics, light quality, predation, and human influences. Hence, an effective spectral index will show a direct reaction to environmental variables with very slight variations in coral cover. Prior to now, reef ecosystems have used spectral band ratios generated from satellite imagery data to map bottom cover (Mumby, 2000; Dustan *et al.,* 2001). However, they are limited to clear, shallow waters. In their early study, Hochberg and Atkinson (2000) explored the separation of coral, algae, and sand using field spectrometry data and a linear discriminant function analysis. They then applied this to airborne hyperspectral images and saw encouraging results. Thus, when considering atmospheric attenuation, varied water depths, transparency, and circumstances at the air-sea interface, a usable coral index can be generated by spectral signatures.

2.1. AIM AND OBJECTIVE

Aim:

To assess environmental variables and its impacts on coral reefs of Gujarat using Remote Sensing and GIS data

Objectives:

1. To assess the impacts of environmental variables on coral reefs.
2. To determine stress and impact severity of environmental variables.
3. To generate the maps using remote sensing and GIS data for environmental stresses.

3. MATERIALS AND METHODS

3.1. Study area

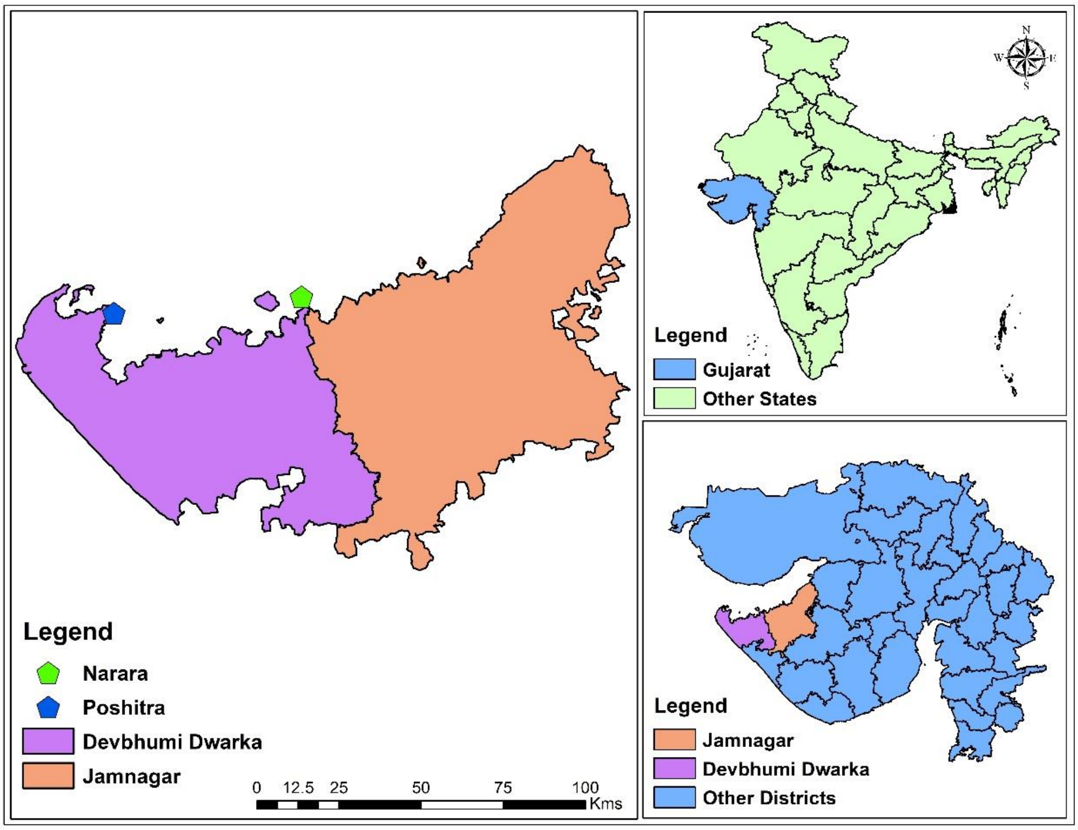

Figure 1: Selected Study sites in Gulf of Kachchh

According to Spalding et al., (2001), India contains around 2% of the world's coral reefs, with Gujarat having one of the country's four major coral reefs, mostly in the Gulf of Kachchh. The Gulf of Kachchh's coral formation is mostly limited along southern shore of Gulf. The existence of coral reef has been recorded on 42 of the 45 islands in the Gulf of Kachchh (Joshi, 2016). The majority of the islands in the Gulf of Kachchh have fringing reefs, while some of the islands in the Gulf of Kachchh have platform and patchy reefs (Dave, 2011). It covers a total area of 352.5 square kilometers with reefs (Jayaprakas and Radhakrishnan, 2014).

As it is not convenient and feasible to cover all the islands of the gulf for the study, reef areas of Dwarka and Okha for pioneer work and two islands of the Gulf of Kachchh named Narara and Poshitra have been selected to achieve the objective set for the study. Both the Narara and Poshitra comes under the protection of Marine National Park & Sanctuary (MNP & S). Many natures education camps have been conducted by MNP & S at Narara, one of the tourist destinations, to raise awareness of the importance of marine ecosystem in our lives. As there is no distinct demarcation of the mainland, Narara island has become a part of the mainland as a result of human invasion. In Narara, one can see living corals with a moderate distribution over the reef. According to Pandey et al., (2010), here the live coral cover is around 4.93 percent, and the density of recruits of various genera found on the island is 21 recruits/100 m^2. Poshitra is also known as the 'Crown of the Gulf of Kachchh' (Parasharya, 2008). Eulittoral fringing reefs are mostly found in the vicinity of Poshitra near Laku Point, on the edge of the embayment, in a 100m wide region.

3.2. In-Situ Data collection

The reefs were studied by random quadrant method for habitat characterization and sea water sample collection to assess prevailing physio-chemical environment. Each field visit was planned following the daytime low tides to study the seasonal variations in reef ecosystem.

As corals falls into the category of schedule-1 of Indian Wildlife Act 1972, required permission were taken to conduct the field survey. The reef area of Dwarka and Okha were surveyed during January 2019 to study the bleaching conditions. Reef of Narara and Poshitra islands were visited over the period of 03 months from December 2019 to March 2020 and also in June 2021 to study the seasonal variations. Collection of in-situ data for all the sites has been done by random quadrate sampling method as it is generally used for biodiversity and ecological research. Random sampling was done using $1m^2$ PVC frame. Field observations were performed to document coral bleaching and mortality by taxon using the Coral Health Chart. Therefore, during the field visit number of live corals, bleached corals and dead corals were recorded.

In the present study, in-situ data and satellite-based observations of some of the environmental variables named Sea Surface Temperature (SST), Sea Surface Salinity (SSS), Turbidity, Total Suspended Matter (TSM), and Photosynthetically Available Radiance (PAR) have been considered to evaluate their effects on corals. The most commonly observed effect on corals has been seen as coral bleaching. Thus, the ultimate goal is to identify the conditions that are less vulnerable to stress using environmental data. Here, environmental characteristics and in situ bleaching survey data are used to predict coral reefs' sensitivity to bleaching. Figure 2- presents the general conceptual paradigm that this study used. The first phase entailed choosing factors that are known to affect coral bleaching and the adaptability of coral reef ecosystems. The primary variables were then obtained after the data had been retrieved and pre-processed. Coral bleaching observation data was employed as the response variable in a statistical analysis along with the primary variables and/or their corresponding derived parameters. Anomalies of the parameters were calculated to correlate their real-time and long-term effects on corals. Multi-linear regression method was used to generate the model and coral bleaching map for the entire area was created using a regression equation. The study's findings are meant to aid in the decision-support system for marine protected zones in order to preserve biodiversity.

3.3. Computation of Coral Bleaching Index (CBI) using satellite data

During the field visits, geo locations of bleaching conditions were recorded. different level of stress conditions was recorded using CoralWatch health chart. But, to quantify the bleaching using the spectral signatures, only colonies which falls in category (4) were selected as bleached corals. Moderate and partial bleach corals have not been selected because of spatial resolution.

Along with bleached corals, geo locations of healthy corals, sedimented corals and algae were also recorded. Using this all data at once, spectral signatures for each class were generated using SNAP software. Since, the satellite images were converted into 10 m resolution pixel size, geo locations of bleached corals were also divided into $10m^2$ grids, and percentage of bleached corals in each grid out of total grids were calculated for both the sites.

To generate the spectral signatures, total 10 band of sentinel-2 were selected to see the correlation of these classes in different band. The bands selected for these calculations are band 1, band 2, band 3, band 4, band 5, band 6, band 7, band 8, band 9 and band 8A. After extracting the values from different band, regression analysis was carried out and bands with P- value < 0.1 with 90% confidence interval were selected to generate CBI.

Same as formula (8), multilinear regression of selected bands was calculated using the percentage of bleaching in each pixel as dependent variable and bands with higher correlation as independent variables.

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \cdots + \beta_p x_{ip} + e_i \quad (1)$$

Where, i = number of observations

yi = dependent variable

β_0 = constant or the y-intercept

β_p = slope coefficients

x_i = spectral reflectance of different correlated bands

e_i = random error term, also known as the residuals

Here, residuals of variables were also calculated to find the RMSE (Root Mean Square Error). The residual for each observation is the difference between the true value of the response variable (y_i) and the predicted value ($\hat{y_i}$).

$$Residual_i = y_i - \hat{y_i} \quad (2)$$

The standard deviation of the residuals is known as the root mean square error (RMSE). A lower RMSE value indicates that the regression model is more accurate.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y})^2} \quad (3)$$

As the main aim of computing CBI was to have the predicted value as near to the measured value as possible, this metric will be the one that will be concentrate on the most, using R-square and the P-value findings to better confirm the results. And using this regression model, CBI were calculated.

Following the same method, regression of different variables with CBI was calculated to find out the slope value for the generation of bleaching forecasting model.

4. RESULT AND DISCUSSION

4.1 Coastal Land-Use Classification

Mapping of different coastal land use classes from satellite data covering study area was done to map the change during the last decade. Mapping was done using open source QGIS image processing software.

From the FCC image, different coastal classes like corals on rock boulders, sparse corals, seaweeds, mangroves and algae on sand or mud bottom etc. were identified and on-screen digitization was carried out to generate the land use map of various coastal features. Landsat-5 satellite image of the year 2010 was also used to generate coastal land use map of the same year and also for the comparison with year 2022 to detect the change in reef cover area.

From the land use/ land cover maps, total area of various coastal classes was calculated to find out the area of coral reef in Narara. In the year 2022, area calculated from Land use map of coastal features of Narara is 7,984.6 ha. Amongst them, coral covers only 5% of the total reef ecosystem in Narara which is very less as compared to other reef ecosystem classes like algae, sea-weeds and mangroves.

The results indicate that area of sparse coral and corals on rock has reduced during 2022 as compared to 2010. The area of corals on rock boulders has reduced by around 32.63 hectares and corals on rock boulders, area of sparse corals has also reduced by 57.44 hectares. Whereas areas of classes like algae on sand, mangroves and seaweeds on mud have increased as compared to the year 2010. On an average, most of the area of the reef ecosystem of Narara has been covered by mud flats followed by mangroves. In past 12 years total cover of area of algae on mud flats and mangroves has shown the most increment compared to other coastal features in Narara Island.

Total area under various coastal classes was calculated to find out the total area covered by coral reef in Poshitra, from the coastal land use maps. The area estimated from the Land use map of Poshitra in the year 2022 is around 1,525.3 ha. In Poshitra Island also area covered by corals has decreased by 3% during last 12 years. Major decrease in past two decades has been noticed in mudflats of reef ecosystem amongst all coastal features. Whereas sandy area in the reef of Poshitra has increased by 3 hectares and same in the case of mangroves also, total area coverage of their diversity has been increased by approximately 5 hectares. All though Poshitra is much protected area when it comes to anthropogenic activities, decrease in the reef diversity shows environmental impacts of climate change and also increase in temperature in past 12 years in Poshitra.

The results of species diversity distribution mapping indicates that more anthropogenic and tourist activities at Narara reef have been damaging reef diversity as compared to Poshitra. The Camping and tourist activities at Narara also affects the health and growth of corals. Where as in Poshitra, these types of activities are highly restricted and the area is more protected than Narara. Thus, corals at Poshitra are much healthier and corals are found in bigger boulders. The number of species are also more at Poshitra as compared to Narara reef.

4.2 Calculation of Bleaching Response Index (BRI)

(i) Calculation of BRI for Narara

As the abundance of *Favites* and *Dipsastraea* (previously known as *Favia*) is more at Narara, maximum number of colonies were found of these genera only. Out of 278, number of coral colonies with 70-100% is 38. Out of all genera, total 39 colonies are falling into the moderately bleached. Maximum BRI for Narara in the year 2019 was calculated for the colonies of *Dipsastraea,* whereas *Platygyra Sp.* Showed the minimum bleaching with 31.09 % of BRI. However overall result of BRI indicates that, in summer months of 2019 coral colonies of all the genera in Narara were falling under the moderately bleached corals. In summer of 2020, total 189 colonies in Narara were surveyed to calculate BRI. Colonies of *Porites* showed the maximum BRI of 72.5% being highly susceptible towards bleaching. However, in comparison to 2019, colonies of *Dipsastraea* showed the less BRI with 46.21%. However, they are still under moderate threats from stress conditions. Whereas, colonies of *Lobophyllia* were resistible to the stress conditions with BRI at 27.96%. Most of all the colonies of Narara in 2021 were under the moderate threat from the stress conditions with *Porites* showing the maximum bleaching of 61.47%.

(ii) BRI calculation for Poshitra

At Poshitra, bleaching response of varies from resistible to highly susceptible amongst the coral colonies of different genera. Apart from *Pseudosiderastrea sp.* and *Goniopora sp.* most of the coral colonies are moderately susceptible to coral bleaching conditions at Poshitra. In contrast to 2019 and 2021, coral colonies of *Porites* showed very less effects of bleaching with only 7.35% of BRI. Results of BRI also shows that the corals at Poshitra are more effective to stress condition in comparison to Narara.

4.3 Coral Bleaching Model Generation Using Spectral Signatures

Throughout the course of three years, spectral responses of various coral classes were created for the Narara and Poshitra during the summer. Out of all these six sets of spectral analysis, three sets of analysis were considered for further study. One is from reflectance spectra of the summer months of 2019 in Narara and the other two are from the Poshitra for the summer season for both the years 2019 and 2021.

To check the effects of bleaching for a particular reflectance value, a number of bleached coral colonies in a 10 m^2 area was calculated. And geo-locations of these areas were also located. During this calculation, it was found that at Narara, each 10 m^2 had only one or two bleached corals with a maximum of four at some places. Thus, the spectral responses of these pixels will have less than a 1% contribution to the reflectance value of that pixel. Also, the reflectance values of healthy corals were more than the bleached coral, so it was concluded that there might be a chance of other reef features having more influence on the reflectance values apart from corals. Thus, further studies were carried out using the reflectance spectra of Poshitra. After calculating the frequency of bleached corals for both years, the spectral reflectance of these newly calculated pixels was also generated for all the bands.

Then, using multi-linear regression, P- values and R^2 were calculated to find out the bands that have the best correlation with the bleaching percentage. Following in Table (1) are the results of the regression analysis for the year 2021.

Table 1: Regression analysis of bleaching and spectral reflectance for the year 2021

Regression Statistics	
Multiple R	0.62883
R Square	0.395428
Adjusted R Square	-0.15418
Standard Error	6.777334
Observations	18

Table 2: Covariance at a different wavelength for bleaching percentage in the year 2021

	Coefficients	*P-value*
Intercept	-208.86	0.588427
443 nm	-88.2777	0.964903
492 nm	1178.458	0.55254
560 nm	-857.789	0.602553
665 nm	-109.26	0.944746
704 nm	317.7209	0.722645
741 nm	381.9181	0.894115
783 nm	-534.591	0.890126
833 nm	604.8356	0.396269
865 nm	-577.998	0.654611
945 nm	66.91881	0.719604

Since the 10 m resolution is not the best spatial resolution when it comes to coral health identification, the inaccuracy of data was kept in mind and the analysis was carried out with a 90% confidence level. But the results in table (4) show that the P-values are beyond the confidence level in all the selected wavelengths. The R^2 value for the set is 0.395, which is within an acceptable range, still, 0.395 is considered as a low correlation between variables. Thus, it is concluded that, this set of reflectance values cannot be used to generate the model and also not to predict the bleaching of the unknown area.

Regression analysis for the reflectance data of the year 2019 was also performed for each wavelength. The R^2 value for this set of data is 0.6664, which can be considered as good and significant for any multi-linear equation. Following is the table of covariance and P-values of each wavelength with the bleaching percentage data.

Table 3: Regression analysis of bleaching and spectral reflectance for the year 2019

Regression Statistics	
Multiple R	0.816345
R Square	0.666419
Adjusted R Square	0.363164
Standard Error	5.034255
Observations	22

Table 4: Covariance at a different wavelength for bleaching percentage in the year 2019

	Coefficients	*P-value*
Intercept	9.765846	0.925696
443 nm	-170.716	0.069969
492 nm	-303.167	0.753126
560 nm	622.1904	0.668974
665 nm	-327.114	0.48351
704 nm	51.08547	0.830276
741 nm	328.505	0.067289
783 nm	-354.719	0.101506
833 nm	7.179951	0.978695
865 nm	5.822632	0.974966
945 nm	31.03883	0.462389

Regression analysis of this data showed that with the 90% confidence level, bleaching severity can be calculated from the 443 nm, 741 nm, and 783 nm wavelengths with the P-values 0.0699, 0.0672, and 0.1015 respectively. Since only three variables had the P-values < 0.1, using these three variables only coefficients were again generated for accuracy in prediction Table (5).

Table 5: Coefficient of selected Bands

	Coefficients
Intercept	4.3081
442.7	-18.9758
740.5	138.5788
782.8	-123.728

Using these new coefficients, a multi-linear model was run again to calculate the bleaching percentage. These calculated values were then compared with in-situ data to see the correlation (Figure 2).

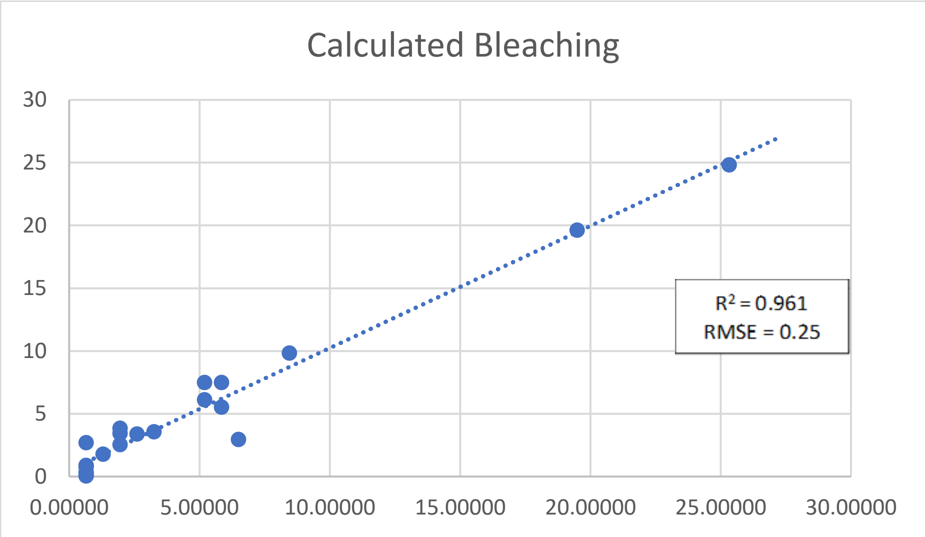

Figure 2: Model-generated bleaching (%).

With the 0.961 R^2 value and 0.25 RMSE, it can be concluded that the selected band combination was useful to calculate the bleaching. And with reference of Table 3, it is concluded that the calculated bleaching in 2019 in Poshitra was 25% which falls under the resistible category of bleaching susceptibility. And observed bleaching in 2019 was also 26.14 % falling into the same category. Thus, most of the colonies in Poshitra were resistant to environmental changes.

4.4 Assessment of Environmental Variables

Parameters calculated in table ( ) are the anomalies of that parameter apart from NDTI and salinity. Anomalies calculated here are the yearly anomalies of five years. The results of these anomalies indicate that, throughout the span of three years, SST have positive anomalies.

Table 6: Correlation of different environmental variables

	PAR (einstein m-2 day-1)	kd490 (m-1)	SST	NDTI	TSM (mg/L)	Salinity
Poshitra 2019	0.819996	1.299326	0.0244	-0.14109	0.645435	37.386
Poshitra 2020	0.444123	1.624988	0.2585	-0.19431	0.518606	35.737
Poshitra 2021	0.973097	1.890513	0.5231	-0.02087	0	36.395
Narara2019	0.732278	0.757797	0.0059	-0.14108	-0.428708	34.69
Narara2020	0.616468	-0.751977	0.3916	-0.27704	0.449409	34.176
Narara2021	1.016556	0.565175	0.5433	-0.15271	0	35.457

This also has a positive correlation with PAR. This means that bleaching recorded during the study does have effects higher than the usual intensity of solar radiation. Salinity ranges from 33 PSU in the winter season to 39 PSU in summer is normally seen at these sites. Thus, the coral colonies of these sites are used to this high level of salinity. Kd490 is also the variable of turbidity and TSM. Thus, positive anomalies of these variables indicated that both the reefs experience higher loadings of sedimentation and suspended particulate matter and turbidity which makes the reefs on GoK, one of the most stressed reefs in India.

5. CONCLUSION AND SUGGESTIONS

Coral reefs are one of the important ecosystems on the earth, with high biological production and complicated environmental conditions. Coral reefs can be found along the shore and off the shores of islands and continents in tropical waters (Buchheim, 1998). Reefs are teeming with life and are as rich as tropical rainforests in terms of diversity. They are home to a diversity of colorful exotic fish, corals, and countless other marine flora and fauna. They provide food and shelter to the many species that live in reefs (Meesters et al., 1998). Coral reefs are expected to be home to 25% of all marine species, with as many as one million unique species (Davidson, 1998). Coral reefs are one of the important ecosystems on the earth, with high biological production and complicated environmental conditions. Coral reefs can be found along the shore and off the shores of islands and continents in tropical waters (Buchheim, 1998). They can also be seen from space as spectacular color patterns tracing the borders of coastlines and spreading far out into the oceans (Spalding et al., 2001).

So far, it has been shown that remote sensing technologies are efficient tools for monitoring coral reefs (Mumby et al., 1999; Hedley et al., 2016). Ocean remote sensing has generated a great lot of interest since it has made it feasible to research the oceans in greater depth with worldwide coverage (Guerra et al., 2016). Ocean Color (OC), a technique used widely in the field of ocean remote sensing, is currently used to examine how various environmental factors affect coral reefs. Ocean Color (OC) is sometimes referred to as spectral water-leaving radiances because OC satellite instruments provide estimates of the light that exits a water mass and determines its colour (Werdell et al., 2018). These sensors commonly use wavelengths in the distinct visible and near-infrared (400-1000 nm) areas to measure the spectral radiation coming from the top of the atmosphere (Werdell et al., 2018). In order to manage fisheries and aquaculture, manage coastal areas, evaluate the health of ecosystems, and contextualise behavioural changes in the context of climate change, Ocean Color Remote Sensing (OCRS) sensors have the potential to continuously measure physical, environmental, biological, and biogeochemical variables (Le Traon, 2011; Payne et al., 2021). And identifying the bleaching effects of coral reefs using this remote sensing as tool is a main aim of this study.

Results of Bleaching Response Index (BRI) stated that in summer months of 2019 coral colonies of all the genera in Narara were falling under the moderately bleached corals. At Poshitra, bleaching response of varies from resistible to highly susceptible amongst the coral colonies of different genera. Apart from *Pseudosiderastrea sp.* and *Goniopora sp.* most of coral colonies are moderately susceptible to coral bleaching condition at Poshitra. While in the process of coral health assessment, geo-references of healthy, bleached and sedimented corals were also recorded. Using this data spectral reflectance of different classes was generated. With the intention to identify the difference between healthy and bleached corals, the spectral response of different colonies was analyzed using the SNAP software. Using this software reflectance separability between sedimentation and bleached corals was clearly visible in all the bands ranging from 440 - 940 nm wavelengths. The reflectance values of sedimented corals are also high in all the bands compared to bleached corals. However, spectral separability of healthy corals in compare to bleached corals were only visible in the spectral response results of Poshitra, using that results, Coral Bleaching Index was calculated successfully and the use of these index is to calculate the bleaching of corals without any in-situ data. The results of these anomalies indicates that, throughout the span of three years, SST have positive anomalies. This also have positive correlation with PAR. These means that bleaching recorded during the study, does have effects of higher than usual intensity of solar radiation. Salinity ranges from 33 PSU in winter season to 39 PSU in summer is normally seen at these sites. Thus, the coral colonies of these sites are used to this high level of salinity. Kd490 is also the variable of turbidity and TSM. Thus, positive anomalies of these variables indicated that both the reefs experience higher loadings of sedimentation and suspended particulate matters and turbidity which makes the reefs on GoK, one of the most stressed reefs in India.

According to Vivekanandan et al. (2009), eight out of ten bleaching episodes between 2080 and 2089 will be catastrophic events, up from zero between 2000 and 2009 and two between 2050 and 2059 in the Gulf of Kachchh. According to studies done by Done et al. in 2003, the reef cannot withstand catastrophic catastrophes more than three times per ten years. In line with this assertion, Vivekanandan et al. (2009) predicted the vulnerability of the coral reefs of Lakshadweep, Andaman and Nicobar, and the Gulf of Mannar as well as the Gulf of Kachchh. Also, studies have indicated that ocean warming is correlated with sea level rise, which causes more storms and El Ninos. These events harm the reefs by making them more susceptible to coastal erosion, sedimentation, and turbidity, which would hasten their mortality. It is challenging to predict what will happen to life that depend on the reef ecosystem and the nearby ecosystems that the reefs sustain in altered settings with reduced or no coral cover.

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