Impact of Climate Change on Coral Reefs Degradation at West Lombok, Indonesia

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Abstract

Coral reefs are one of the ecosystems that provide economic and environmental benefits to coastal communities in Indonesia. However, coral reef ecosystems are also one of the ecosystems threatened by climate change at the local scale. The waters of North Sekotong, West Lombok, Indonesia, are a tropical coastal system with beautiful coral reefs and marine ecosystems. Coral reef damage has been widespread in this area due to increased water temperatures. Increased water temperature results in coral reef degradation. Field surveys were conducted on May 23-28, 2016, in collaboration with the Marine and Coastal Resources Research and Development Center, Ministry of Marine Affairs and Fisheries, and coral reef mapping using Landsat 7 and Landsat 8 during 2002 - 2016 as well as processing monthly sea surface temperature (SST) data from the AquaModis and Oi SST V2 satellites and daily SST data from the NOAA Coral Reef Watch satellite. Changes in coral cover area were compared with temperature changes due to climate change. The increase in temperature creates a hotspot phenomenon in the coral reef ecosystem, resulting in coral reef degradation. The results showed that coral reefs in this area have degraded by 17.55% or 78.21 Ha from 455.68 Ha (2002) to 367.46 Ha (2016), with a degradation rate of 2.8 Ha/year in 2002 - 2014; 8.1 Ha/year (2014 - 2014) and 36 Ha/year (2015 - 2016) caused by an increase in SST which caused a hotspot phenomenon with a high enough intensity that there was an increase in temperature in 2016 which reached 9.77°C.

Keywords: Coral reefs, sea surface temperature, hotspot, DHW, Lombok Island

INTRODUCTION

Coral reefs are among the most diverse and productive marine ecosystems on Earth. They provide economic benefits to millions of people as sources of food, employment, natural products, coastal protection, and recreation (McLeod *et al*., 2021; Woodhead *et al*., 2019). Coral reef ecosystems are also among the most threatened by human disturbance, both at local scales from overfishing and land-based pollution, and at local to global scales from climate change and ocean acidification (Tanjung *et al*., 2019). However, coastal and marine ecosystems are currently threatened by a range of human activities (Antony *et al*., 2022; Kenchington, 2018). Land use changes associated with urbanization, infrastructure, agriculture, natural resource extraction, mining, and industry have led to increased flows of sediments, nutrients, and pollutants that can affect coastal and marine ecosystems (Mollica *et al*., 2019). Coral reefs are particularly vulnerable, with more than 25% of the world's coral reef ecosystems threatened by inland water flows (Novi and Bracco, 2022). Coral reefs in Indonesia have reported 30 to 60% declines in coral species diversity because of land-derived pollutants over a 15-year period (Llovel *et al*., 2022).

This study will focus on the waters of West Sekotong located on the island of Lombok, Indonesia. This region is known for its high coral reef diversity and important economic assets (Hidayah *et al*., 2021; Lee *et al*., 2019). However, coral reefs in West Sekotong are increasingly exposed to pressures

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from both human and natural factors. Global warming and the increasing intensity and frequency of temperature anomalies have led to significant coral bleaching and mortality in many reef regions around the world (Eakin *et al*., 2019; Goreau and Hayes, 2021). Therefore, it is important to understand the status and condition of coral reef ecosystems in Western Sekotong waters affected by climate change.

This study aims to investigate the impacts of climate change on coral reefs in West Sekotong. Factors that may affect coral reef degradation in this region include changes in sea temperature, ocean acid levels, and increased sedimentation and land-based pollution. Climate change and pollution from land-based sources can damage coral reef ecosystems, causing bleaching, decreased species diversity, and physical damage to reef structures. By understanding the current condition and impacts of climate change on coral reefs in West Sekotong, this research is expected to provide important insights in coral reef conservation and management efforts in the region.

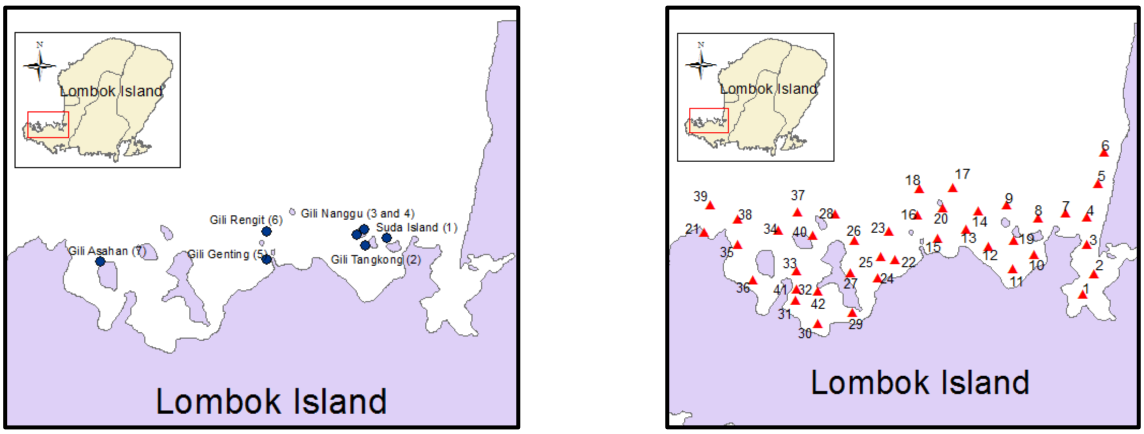
MATERIALS AND METHOD

Sekotong District is located in the west area of Lombok Island. This location was selected as a field study due to the high biodiversity of coral reefs. This research uses satellite imagery obtained by Landsat 7 ETM+ in 2002 and Landsat 8 in 2014,2015 and 2016 with the Albright algorithm (Albright and Glennie, 2020) to know the benthic habitat and calculate how much degradation that has. Satellite imagery data processing is using ER-Mapper software.z.

After using satellite imagery for mapping coral reefs, this research did ground checking on 23 - 28 May 2016 in collaboration with the Research and Development Center of Marine and Coastal Resources, Indonesia Ministry of Fisheries and Maritime Affairs by taking the coral reefs data using photo transect method with 7 stations (Figure 1A) and processed by CPCe software (Sari *et al*., 2021), after processed the data be classified using (Frade *et al*., 2018) classification method (Table 1.) Field observation (42 stations) also takes the water quality data such as salinity, sea surface temperature (SST), pH, and DO using multiparameter water quality checker, and water sample for heavy metal (Figure 1B).

Table 1. Classification of reef status according to a cover percentage (Frade *et al*., 2018).

Cover Percentage (%)	Status
0.0 - 24.9	Bad
25.0 - 49.9	Moderate
50.0 - 74.9	Good
75.0 - 100	Excellent



a b

Figure 1. a. Field station of coral reefs transect and b. water quality observation at Lombok Island.

SST was collected using the monthly SST data from satellite Aqua Modis level 3 during 2003 - 2016 and NOAA OI SST V2 during January - December 2002, other than that, daily SST data were obtained from NOAA Coral Reef Watch Satellite Monitoring which was used for calculating Degree Heat Week (DHW). The calculation of DHW is needed to see if exposure to temperature exceeds the maximum monthly limit of the climatology of the study area as an indication of coral mortality due to thermal stress or so-called coral bleaching (Sully *et al*., 2019). DHW itself is a cumulative measure of thermal stress intensity above 1°C with a duration of 12 weeks expressed in °C. This calculation was created based on the finding that temperatures exceeding 1 °C resulted in thermal stress on coral reefs (Purkis *et al*., 2019). The SST data were combined with DMI and ONI index to analyze why the SST was raised.

RESULT AND DISCUSSION

Coral reef map from 2002 and 2016 from Lansat imagery data can be seen in Figure 2 and Figure 3 in West Sekotong. From the analysis of satellite images, coral reefs can be classified into three main categories, namely live corals, dead corals, and other types such as soft corals, coral rubble, and sand. The differences in coral reef cover between 2002 and 2016 can be clearly seen in Figure 2 and Figure 3. Through these visualizations of coral reef maps, we can see that there have been significant changes in coral reef cover over time.

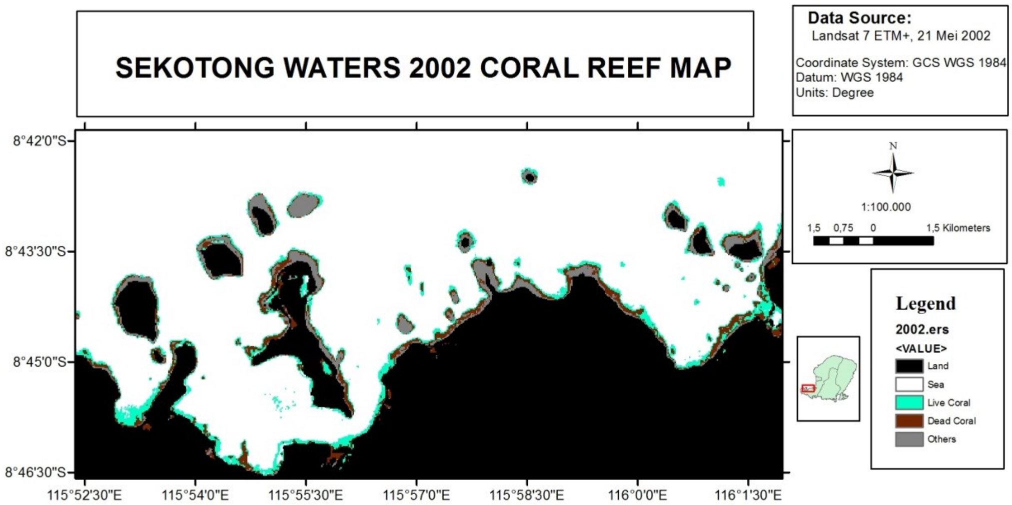


Figure 2. Coral Reef Map from satellite imagery 2002 at Sekotong waters, West Lombok.

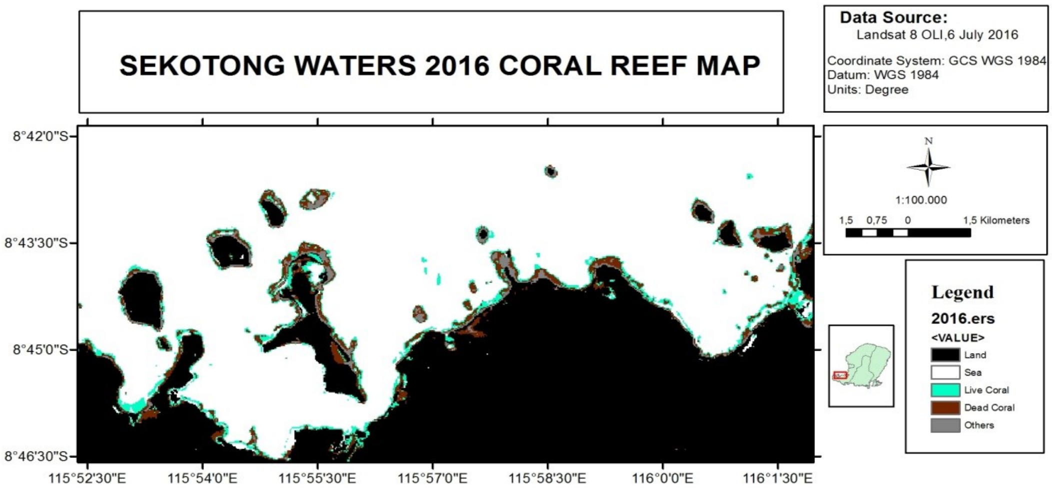


Figure 3. Coral Reef Map from satellite imagery 2016 at Sekotong waters, West Lombok.

Based on the data obtained from the coral reef map, live coral reefs have decreased significantly from 2002 to 2016. In addition, it was found that the degradation rate of coral reefs increased drastically from 2015 to 2016, with a degradation rate of 8.94% within one year. This indicates a rapid decline in the state of coral reefs in West Sekotong and demonstrates the negative impacts of climate change on coral reef ecosystems in the region. These results highlight the importance of coral reef monitoring and conservation efforts to reduce the continued rate of degradation (Reverter *et al*., 2022).

Figure 4 shows the percentage coverage of dead coral, bleached coral, dead coral with algae, soft coral, coral rubble, and sand based on field observations. The average values for all observation stations are listed in Table 4. From the observations, there are significant variations in coral reef cover in West Sekotong. Station 3 located in Gili Nanggu has the largest coral reef cover area of 58%, indicating a good condition. Meanwhile, station 6 located at Gili Rengit had the lowest coral cover, only 12% of live coral cover. There was also variation in coral bleaching across stations, with stations 2 and 6 having the greatest coral bleaching at 42% each. Station 7 on Gili Asahan had the highest amount of coral rubble, accounting for 28% of the area covered.

In addition, field observations also showed the presence of soft corals at almost every observation station except at stations 1 and 7. This indicates that the waters of West Sekotong are undergoing a recovery stage after being affected by previous coral reef damage (Brandt *et al*., 2019). However, it needs to be monitored as the presence of soft corals and hard corals living together can lead to competition, potentially inhibiting hard coral growth and ultimately leading to necrosis and mortality (Speare *et al*., 2019). Station 6, for example, had a soft coral cover of 20%. Overall, the status of coral reefs in West Sekotong Waters falls into the moderate category, with an area of live coral cover of 32.14%.

Furthermore, field observations also revealed that station 7 in Gili Asahan had a significant amount of coral rubble, reaching 28% of the cover area, indicating the use of explosives in this area (Hidayah *et al*., 2021). The use of bombs or destructive fishing methods such as these can cause physical damage to coral reefs and disrupt their ecosystems (Jawad, 2021). Therefore, protection and monitoring of human activities that harm coral reefs is essential to maintain the sustainability and health of coral reef ecosystems in West Sekotong.

Table 2. Covers the area of live and dead coral from 2002 – 2016

Year	Live Coral (m^2)	Dead Coral (m^2)
2002	4456800	3758400
2014	4115700	3836700
2015	4034700	4133600
2016	3674700	4494600

Table 3. Radiation rate of coral reef cover

Year	The degradation rate of coral reefs/per year Sekotong Water	
	m^2/year	Persen/year
2002-2014	-28400	-0.64%
2014-2015	-81000	-1.97%
2015-2016	-360000	-8.94%

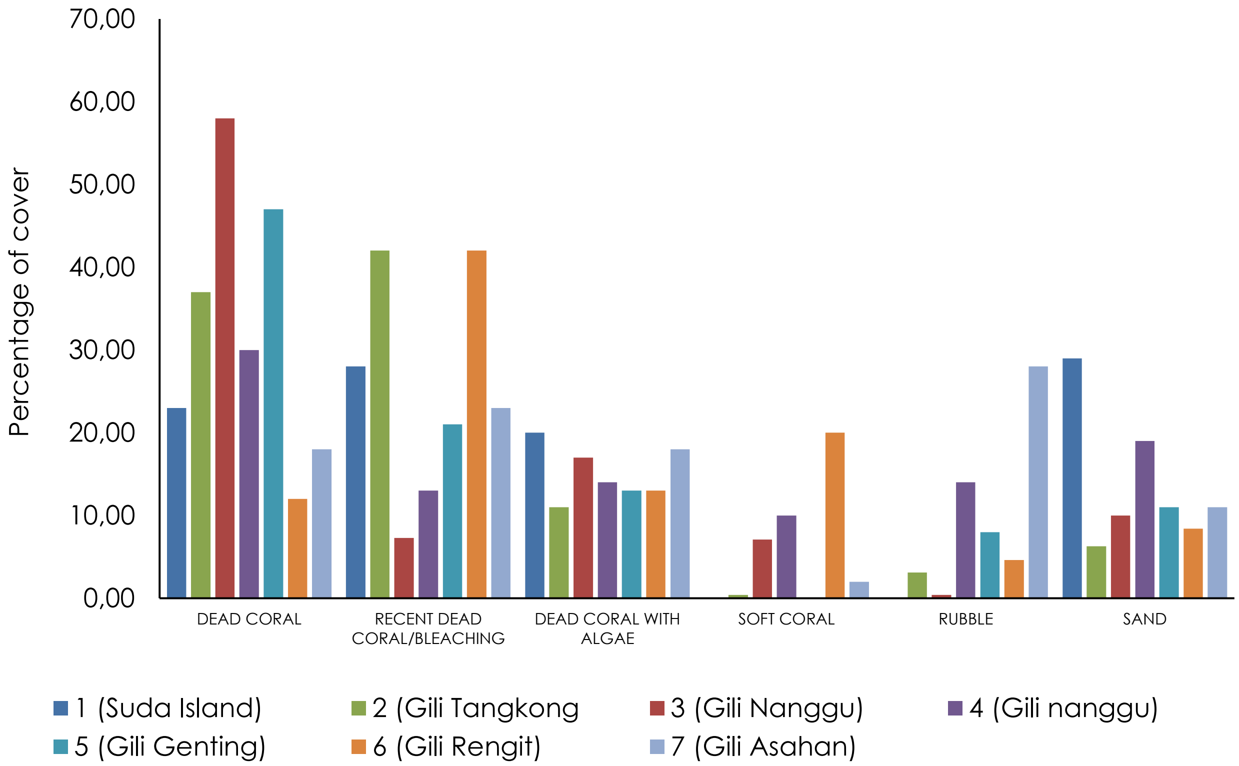


Figure 4. Percentage of the coverage area from field observation.

Table 4. Average percentage of the coverage area from all field observations

Category	Percentage of The Coverage Area (%)
Dead Coral	32
Recent Dead Coral / Bleaching	25
Dead Coral with Algae	14
Soft Coral	6
Rubble	9
Sand	14

In this study, in addition to using field data, satellite data was also used to obtain more information about SST (Figure 6). Satellite data allows the modeling and calculation of SST over a longer time span, giving us an idea of temperature changes and trends over a broader period (Rantanen *et al*., 2022). This is important because field data only provides information on current conditions, while satellite data allows us to understand changes in SST temperature from the past to the present. By combining field and satellite data, this study provides a more comprehensive understanding of the impacts of SST change on coral reef degradation in West Sekotong.

Figure 6 showing a linear increase in SST indicates the impact of global warming in Sekotong waters. Increases in SPL temperature can be caused by several factors. One of the main factors is human activities that produce greenhouse gas emissions, such as carbon dioxide (CO_2), which increases the greenhouse effect and causes an increase in global temperature. In addition, changes in atmospheric and oceanographic circulation patterns can also affect the distribution of heat in the waters, causing an increase in SST (Sauermilch *et al*., 2021).

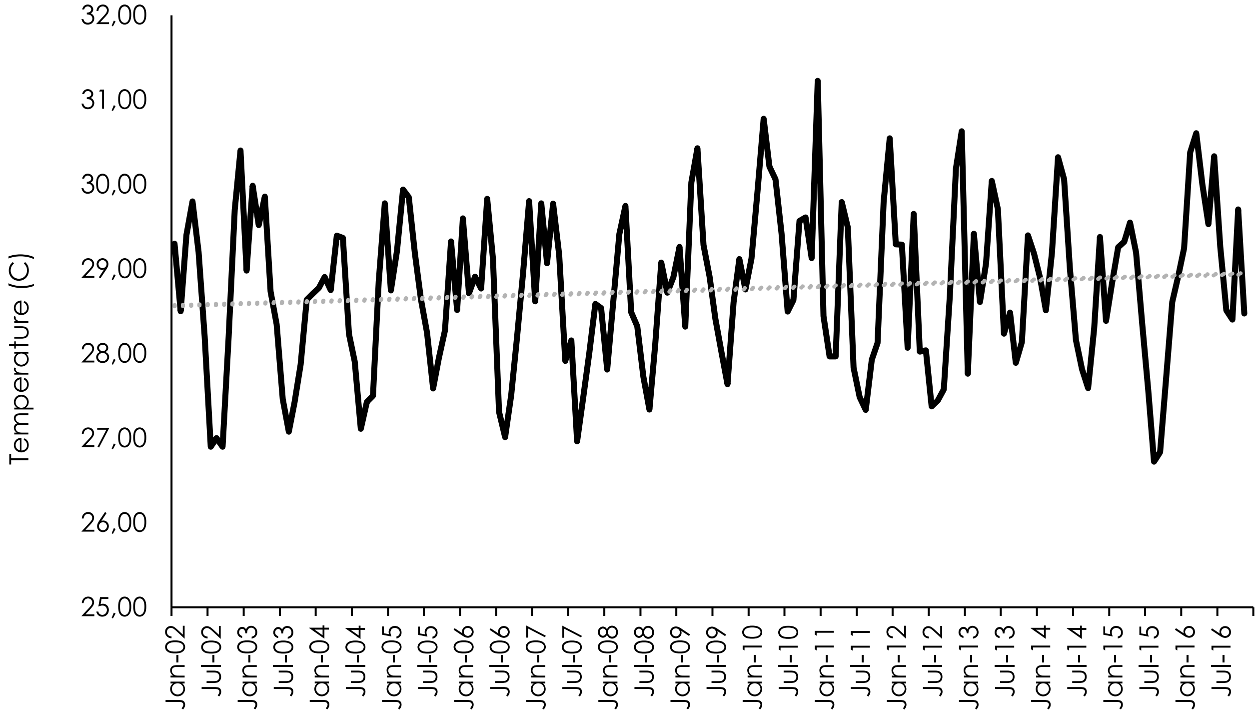


Figure 5. Graphic of monthly SST 2002 – 2016 in Sekotong waters.

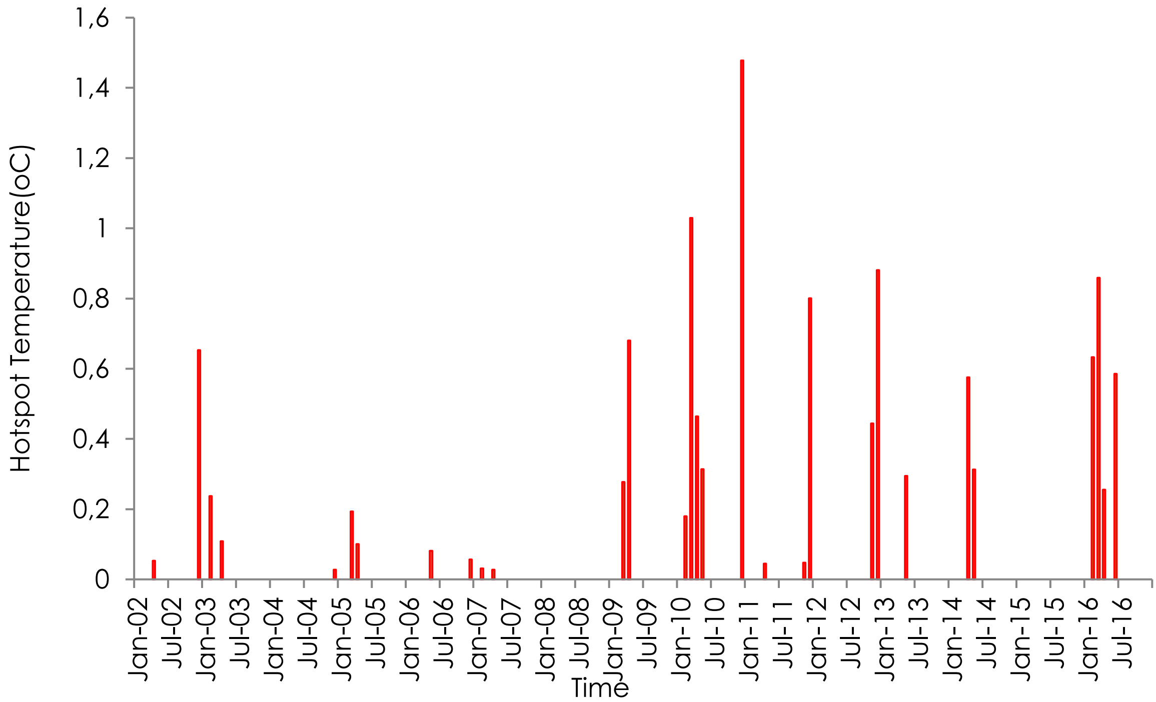


Figure 6. Monthly hotspot from January 2002 to December 2016 in Sekotong Waters.

Increasing SST has significant impacts on coral reefs. Corals are very sensitive organisms to temperature changes. When temperatures exceed a certain threshold, corals can experience bleaching, which is the loss of symbiotic algae that are essential for their survival (Evensen *et al*., 2021). Prolonged and frequent coral bleaching can lead to coral mortality and a significant reduction around live coral reef cover (Wyatt *et al*., 2023). Therefore, increasing SST is a major factor causing coral reef degradation in Sekotong waters.

Hotspots are formed due to heat exposure that exceeds the maximum monthly climatological value in an area. Corals are susceptible to bleaching when SST exceeds the normal temperature experienced by the hottest month of the waters in which area coral is alive (Hédouin *et al*., 2020). A hotspot value greater than 1.0 °C is the threshold for heat exposure that can lead to coral bleaching or mortality.

A hotspot can be indicated by a positive value of SST anomaly. Indonesia is a country experiencing two natural phenomena that can cause SST fluctuation and anomaly called Ocean Nino Index (ONI) which produces El Nino or La Nina and Dipole Mode Index (DMI) which can produce IOD+ or IOD-. El Nino causing cold waters in Indonesia and La Nina causing warm water in Indonesia (Sulaiman *et al*., 2023). IOD + gives Indonesia cold water and IOD- gives Indonesia warm water, so need to calculate of correlation between SST anomaly with ONI and DMI, where the result between ONI and SST anomaly is -0,23 and DMI - SST anomaly is -0,34 with 95% confidence interval and significance ± 0,139. ONI, DMI, and hotspot graphics of 2002 - 2016 can be viewed in Figure 7.

Natural factors such as the El Nino and La Nina phenomena and the Dipole Mode Index (IOD) can also affect SST fluctuations in Indonesia. El Nino is a phenomenon that occurs when SST in the Central and Eastern Pacific Ocean increases significantly, while La Nina is the opposite, a decrease in SST in the same region. These changes may affect SST in Sekotong waters and contribute to the observed increase in SST.

In addition to increased SST, another factor influencing coral reef degradation in Sekotong is human activities that damage coral ecosystems. Activities such as destructive fishing, selection of explosives, and pollution from land can cause physical damage to coral reefs and disrupt their ecosystems (Boakes *et al*., 2022). Sediments and nutrients carried by river water flow into the waters can increase water turbidity and cause a decrease in light needed by symbiotic algae in corals for photosynthesis. Other pollutants such as industrial and agricultural waste can also cause changes in water quality and poison corals (Varsha *et al*., 2022).

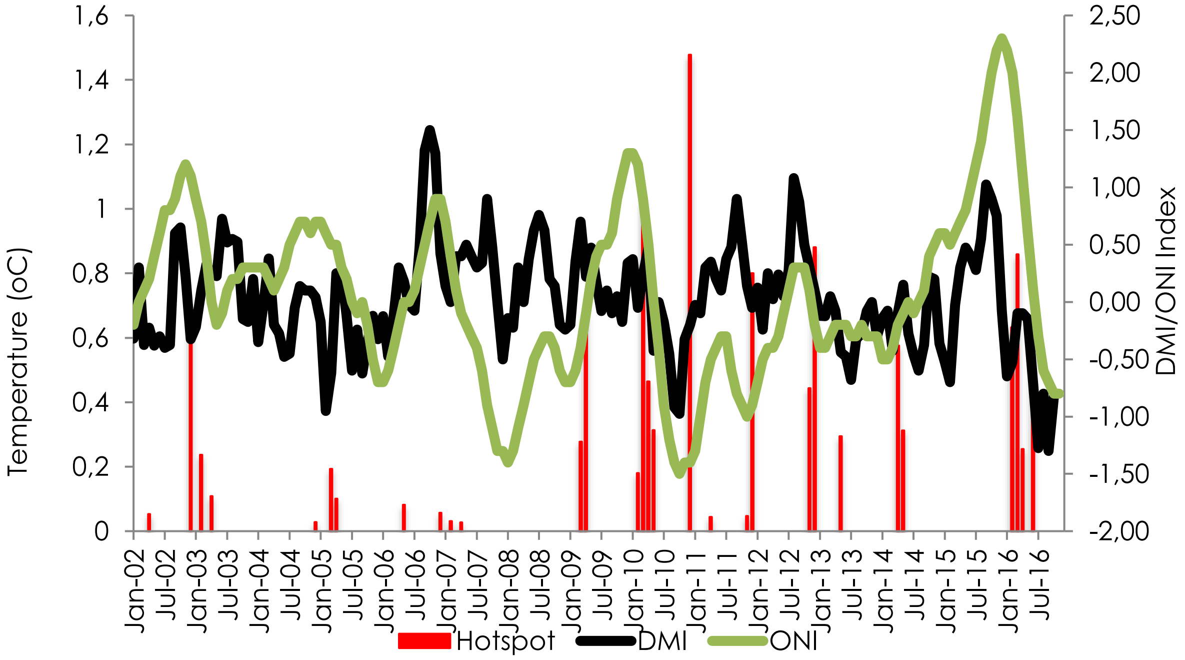


Figure 7. Graphics relation of hotspots with ONI and DMI.

From the correlation, the calculation can be seen that both have a close relationship with the condition of SST in Indonesia. The correlation between SST anomaly and DMI values is greater than the correlation between SST anomaly and ONI, indicating that DMI is more influential than ONI in Indonesia SST. ONI and DMI affected the SST anomaly directly and affect the formation of hotspots that can be formed in various ONI and DMI conditions. The list of hotspot phenomena can be seen in Table 5.

From the data processing, it was found the largest hotspot existed at the time of La-Nina with IOD-, this is because at the time of La-Nina SST in Indonesia increased due to heat transfer from east Pacific to Indonesian waters, plus IOD – a phenomenon that causing SST anomaly in the eastern Indian Ocean that including Indonesia waters with positive value. It is also found that the most common condition of the occurrence of the hotspot phenomena is during El-Nino change to La-Nina or vice versa with a total of 8 times. The condition with a maximum and minimum value of hotspots and the condition with the highest number of hotspots can be seen in Table 6.

Table 5. List of hotspot phenomena.

Phenomena							
El-Nino		El-Nino & IOD +		El Nino & IOD -		La Nina	
Date	Hotspot	Date	Hotspot	Date	Hotspot	Date	Hotspot
Apr-02	0.053	Mei-06	0.082	Mar-05	0.194	Mei-13	0.295
Des-02	0.653	Des-06	0.057	Apr-05	0.100	Apr-14	0.576
Feb-03	0.237	Feb-07	0.031	Des-04	0.028	Mei-14	0.313
Apr-03	0.109	Apr-07	0.027	-	-	-	-
Feb-10	0.180	-	-	-	-	-	-
Mar-10	1.029	-	-	-	-	-	-
Apr-10	0.464	-	-	-	-	-	-
Mei-10	0.313	-	-	-	-	-	-
Feb-16	0.632	-	-	-	-	-	-
Mar-16	0.859	-	-	-	-	-	-
Apr-16	0.255	-	-	-	-	-	-
Jun-16	0.585	-	-	-	-	-	-
Phenomena							
La Nina & IOD +		La Nina & IOD -		IOD +		IOD -	
Date	Hotspot	Date	Hotspot	Date	Hotspot	Date	Hotspot
Des-11	0.800	Des-10	1.478	Noo-12	0.444	-	-
Nop-11	0.047	Apr-11	0.044	Des-12	0.881	-	-
-	-	-	-	Mar-09	0.277	-	-
-	-	-	-	Apr-09	0.680	-	-

Table 6. Maximum, minimum, average hotspot value per condition

Phenomena	Hotspot (C)			Number of Events per Condition
	Max	Min	Average	
El-Nino	1.03	0.03	0.31	5
El-Nino & IOD +	0.47	0.08	0.28	2
El Nino & IOD -	0.87	0.19	0.54	5
La Nina	0.80	0.05	0.43	2
La Nina & IOD +	0.05	0.05	0.05	1
La Nina & IOD -	1.48	1.48	1.48	1
IOD +	0.68	0.05	0.36	3
IOD -	0.75	0.03	0.48	3
No Phenomena	0.90	0.05	0.35	8

Table 6 shows the hotspot phenomenon that occurred in Sekotong waters in 2016. According to the table, the hotspot phenomenon was observed for four months, with three consecutive months of February, March, and May. In February, there was an increase in temperature of 0.63oC, followed by a further increase of 0.83°C in March. However, hotspot intensity decreased in May with a temperature increase of 0.25 °C. It is important to note that these temperature increases indicate the presence of heat stress in these waters, which can lead to coral bleaching and possibly subsequent mortality.

Coral bleaching occurs when corals are exposed to high water temperatures for long periods of time. Increased water temperatures can disrupt the symbiotic relationship between corals and the algae (zooxanthellae) that live within the coral tissue. As a result, the coral will expel the algae, causing a loss of color and vitality, which is called "bleaching". If corals are exposed to high temperatures over a long period of time, they may not recover and may eventually die.

To further evaluate the impact of heat stress on coral reefs, a calculation called Degree Heating Weeks (DHW) is performed. DHW is an accumulative measure of the intensity and duration of heat stress above a threshold of 10 °C over a 12-week period. If the accumulated DHW exceeds a threshold of 4 °C, the likelihood of coral bleaching is high, and if it exceeds 8 °C, the likelihood of coral mortality is great. Figure 8 shows the results of the DHW calculation, which illustrates the level of heat stress experienced by coral reefs in Sekotong waters during the observed period.

The data presented in Figure 8 provides valuable information on the severity of heat stress and its potential impacts on coral reef health. This allows researchers and policy makers to evaluate the vulnerability of coral reefs in Sekotong waters and implement appropriate conservation and management strategies to mitigate the adverse impacts of increasing water temperatures and minimize coral mortality.

In March, there was an extreme increase in temperature, this can be seen through the DHV value which reached 9.77 °C. DHW is the accumulation of heat received by the waters, if the value exceeds the specified threshold, the coral reef will experience bleaching and death. In this condition, DHW has exceeded the threshold for corals to experience death with a value of 8 °C.

The results of the SST data processing showed an increase in temperature from 2002 to 2016 by 0.5 °C (Figure 9), followed by monthly hotspot monitoring and DHW calculations. Researchers concluded that apparent climate change has affected coral reefs directly through increased SST. The appearance of increasingly frequent hotspots since 2009 indicates coral mortality due to bleaching, this is due to the frequent occurrence of El-Nino and La-Nina between 2009 and 2016, with El-Nino occurring 2 times and La-Nina occurring 3 times as well as the influence of IOD+ and IOD-.

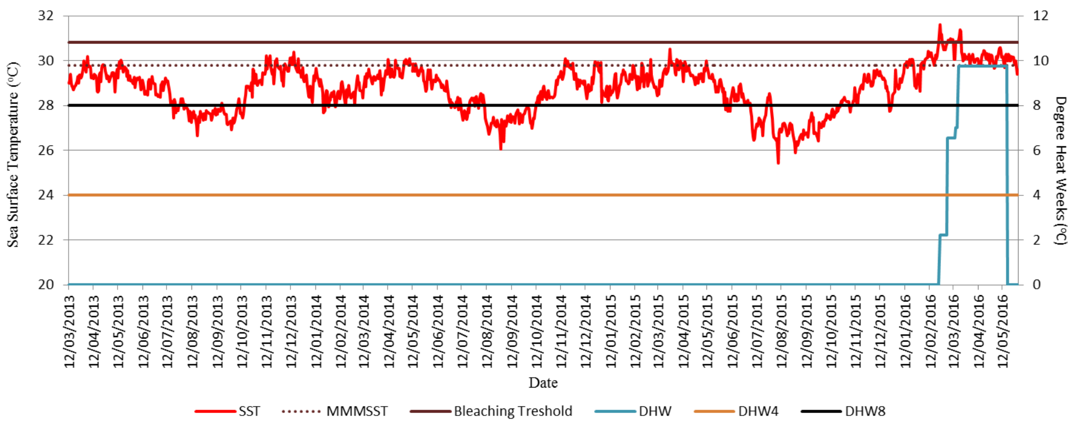


Figure 8. Result of data processing in DHW, Maret 2013 – Mei 2016 period.

These extreme SST changes and weather fluctuations are the main factors affecting coral reef degradation in Sekotong waters. The increase in SST caused by global climate change results in coral reef bleaching and death. In addition, the occurrence of unstable El-Nino, La-Nina, and IOD phenomena also worsen the condition of coral reefs. The significant increase in temperature and the frequent occurrence of hotspots within this time frame indicate that coral reefs in Sekotong waters are experiencing high heat stress and are susceptible to bleaching.

In 2016, there were 4 months of hotspot occurrences, 2 of which occurred consecutively in March and April. The largest hotspot occurred in March with a SST of 0.08, in which the DHW value exceeded the coral reef threshold of 9.77 DHW. Field survey results showed that as much as 25.18% of coral reefs experienced bleaching that could lead to death. The increase in temperature in 2016 was likely caused by a combination of IOD- and El-Nino phenomena. El-Nino causes warm water in Indonesia but can also cause fluctuations in water temperature. From the calculations, IOD has a greater influence on Indonesia, so IOD should provide increased water temperatures and impact coral reefs.

In addition, heavy metals contained in Sekotong waters have exceeded the threshold. Heavy metal accumulation affects coral soft tissues, and corals have a high sensitivity, especially zooxanthellae to environmental changes. There was a decrease in zooxanthellae density in corals exposed to heavy metals compared to control corals. Heavy metals also affected the mitotic index of zooxanthellae. The effect of heavy metals on coral reefs is also evident from the initial reaction of tentacle withdrawal into the caralite and the removal of mucus around the coral.

These two factors, increased SST and heavy metal accumulation, are important factors contributing to coral reef degradation in Sekotong waters. Increased SST caused by global climate change and natural phenomena such as El-Nino and IOD can trigger coral reef bleaching. Meanwhile, heavy metals dissolved in water can damage coral tissues and organisms, affecting their reproduction and growth. Therefore, the protection of coral reefs and the reduction of heavy metal pollution need to be a major concern in coral reef conservation and management efforts in Sekotong waters.

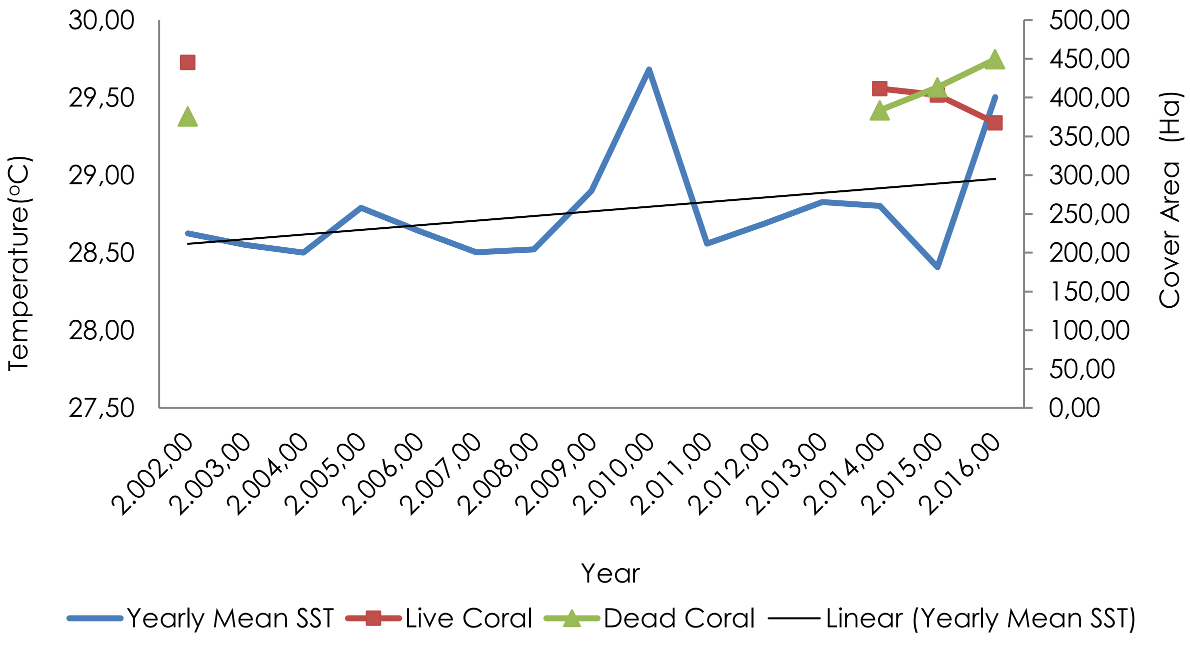


Figure 9. Coral reef area change graphic with SST rise in 2002 – 2016.

CONCLUSION

Based on the data and information presented previously, it can be concluded that coral reefs in Sekotong waters have decreased. From satellite images in 2002, 2014, 2015, and 2016, coral reefs living in Sekotong waters have decreased every year. There was a degradation of 7.65% (34.11 Ha) from 2002 to 2014, 1.97% (8.1 Ha) from 2014 to 2015, and 8.94% (36 Ha) from 2015 to 2016. In total, there was a 17.55% degradation from 2002 to 2016, equivalent to 78.21 Ha. One of the main causes of this decline is coral mortality and bleaching caused by increasing sea surface temperature (SST). This can be seen from the emergence of hotspots and DHW values, especially in 2016 when DHW values reached 9.77 oC which is likely to cause coral reef death. This phenomenon shows the direct impact of SST changes on coral reefs in Sekotong waters. In 2016, there were four months of hotspot occurrence, three of which occurred in March and April respectively. March was the month with the largest hotspot, with SST reaching 0.08 °C. In that month, the DHW value exceeded the threshold that can cause coral reefs to bleach and potentially die. Field survey results showed that as many as 25.18% of coral reefs experienced bleaching that could lead to death. In addition, the increase in SST that occurred from 2002 to 2016 by 0.5 °C can also be a factor that causes the decline of coral reefs. This temperature increase is thought to be caused by the IOD- and El-Nino phenomena. El-Nino causes an increase in water temperature in Indonesia, while IOD- also has a significant influence on SST. The combination of these two phenomena can result in increased water temperatures that negatively impact coral reefs. In addition to the SST factor, this study also showed that there was an increase in heavy metal concentrations in Sekotong waters. The accumulation of heavy metals can affect the soft tissues of coral reefs, especially zooxanthellae which have a high sensitivity to environmental changes. This can affect the health and sustainability of coral reefs and cause a decrease in zooxanthellae density.

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