Inanda *et al.* 2025, Vol. 3: 54 – 65
publishing.ssrs.or.id/ojs

SSRS Journal B: Spatial Research

Research Article Open Acces

Monitoring Model for Coral Reef Ecosystems Affected by Mining Sedimentation on the Coast of North Konawe Regency

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Abstract: Coral reefs support ocean life by providing habitats for marine life. The great potential of coral reefs has led to massive exploitation that degrades coastal ecosystems. The development of the mining industry damages coral reef ecosystems because it produces tailings from the remaining mining of valuable minerals from the mining industry. This research aims to develop an innovative model for monitoring coral reef ecosystems affected by mining sedimentation using the cloud computing-based DATAINDO InaCor platform for carbon cycle sustainability in the North Konawe Coast. This research uses the Landsat 5 satellite series with 7 TM and 4 MSS spectral bands to obtain classification data and the North Konawe coast mapping in 2000. Landsat 8 with 9 OLI-2 spectral bands and 2 TIRS-2 spectral bands was also used to obtain the same data in 2023. Through satellites, the differences in coastal conditions of North Konawe Regency between 2000 and 2023 are visible. This difference is caused by changes that occur in the form of a decrease in vegetated land to 28340.14 ha from 33776.46 ha and coral reef area from 5968.08 ha to 1388.79 ha. This was caused by the expansion of coastal mining that converted vegetated land and produced tailings that flowed into the sea, causing damage to coral reefs. High turbidity index values characterize coral reef damage, and chlorophyll index values can be seen from the analysis results through remote sensing.

Keyword: North Konawe, Coral Reef ecosystem, Mining Activity, Monitoring, Remote sensing

INTRODUCTION

Indonesia has the highest marine biodiversity in the world. Indonesia is included in the Coral Triangle region with 569 species and 83 genera of corals, representing 69% of the species and 76% of the genera of the world's coral reefs (Hadi *et al.* 2019). Indonesia's coral reefs cover 58,707 km2, of which approximately 70% are fringing reefs, 20% are barrier reefs, 2.5% are atolls and 7.5% are patch reefs (Sehatapy *et al.* 2017). Coral reefs are massive deposits of calcium carbonate produced by Cnidaria in symbiosis with zooxanthellae (Arisandi *et al.* 2018). Coral reefs are shallow marine ecosystems that have many functions and benefits for social, cultural, ecological, and economic life. Coral reefs support marine life by providing habitats for marine organisms. Coral reef ecosystems provide feeding grounds, nursery and rearing areas, spawning grounds, marine tourism, and more (Maulana *et al.* 2016). Coral reefs also indirectly protect the coast from sea waves and prevent coastal erosion (Aldilla 2014). However, the great potential of coral reefs has led to massive exploitation in coastal areas. Human extractive activities degrade coastal ecosystems and damage coral reefs.

The expansion of the mining industry, particularly in coastal areas, has resulted in the degradation of coral reef ecosystems. The mining industry generates a waste known as tailings. Tailings are the residual byproduct of the mining industry's pursuit of valuable minerals. Tailings are non-degradable waste that can accumulate in the environment more than organic matter (Napitupulu and Purwanti 2022). The potential for fine sand and clay tailings to pollute the ecosystem arises from their capacity to cover coral reef vegetation. The

closure of the coral reef vegetation will result in the loss of the symbiotic algae that are an integral part of the ecosystem. Algae (zooxanthellae) engage in photosynthesis, thereby providing carbohydrates and oxygen to coral reefs, while coral reefs offer shelter and provide the remainder of their metabolism (CO_2) to zooxanthellae (Palupi *et al.* 2016). Zooxanthellae play a pivotal role in coral reef ecosystems and the success of reef-building corals (Rifa'i *et al.* 2013). The abundance of zooxanthellae, as algae, serves as a parameter for evaluating the quality and fertility of coral reef ecosystems (Rudiyanti 2009; Afriyanti and Purwoko 2020). Therefore, it is essential to maintain the symbiotic mutualism between coral reefs and zooxanthellae.

Mining activities in coastal regions have been observed to result in the accumulation of considerable quantities of sedimentation around coral reefs. In his research, Manik (2014) stated that 11% of coral reefs worldwide had been damaged due to sedimentation. The deposition of sediment on coral reefs results in the covering of coral polyps, leading to the formation of coastal siltation. The loss of zooxanthellae due to the lack of shelter and reduced CO_2 availability caused by sedimentation from tailings will also contribute to the decline of these ecosystems. Furthermore, Palupi *et al.* (2016) have demonstrated that sedimentation impairs the growth and development of coral colonies, as they cannot effectively remove sediment from their surfaces—the loss of zooxanthellae and the inhibition of coral growth result in the bleaching of corals. In the

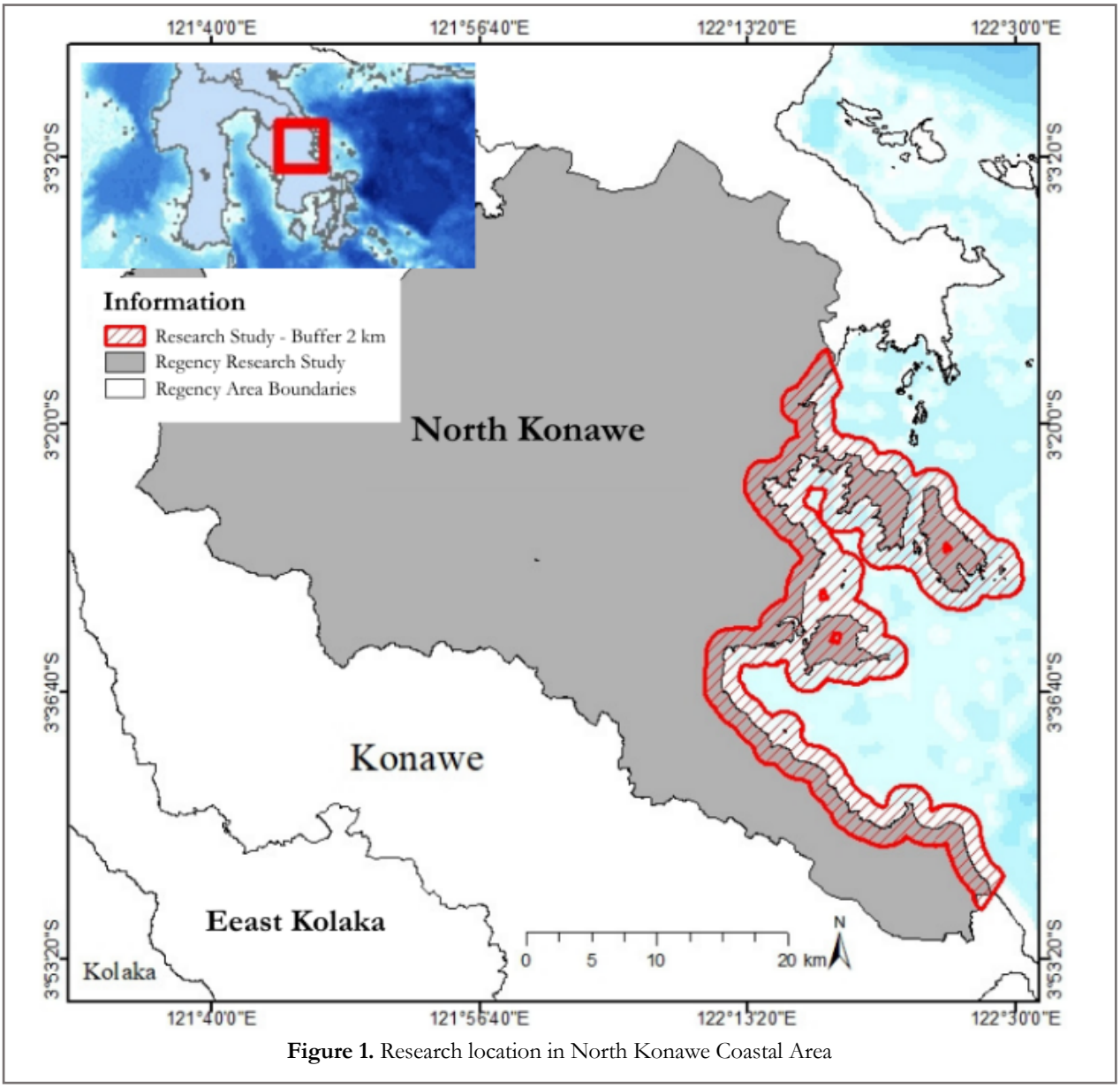


Figure 1. Research location in North Konawe Coastal Area

absence of restoration of the symbiosis between zooxanthellae and coral reefs, the continued bleaching will reduce coral populations and disrupt coastal ecosystems.

The carbon cycle is a material cycle that occurs in nature. It involves the transfer or exchange of carbon between biotic (biosphere) and abiotic reservoirs, including the ocean, atmosphere, and earth's crust. Living things that play an essential role in this cycle are groups of photosynthetic organisms on land and water (Firdaus and Wijayanti 2019). Zooxanthellae, a type of microalgae, is capable of photosynthesis, thus classifying it as an aquatic photosynthetic organism. The symbiotic mutualism between zooxanthellae and coral reefs plays a pivotal role in the sustenance of the carbon cycle, as zooxanthellae utilize the carbon captured by coral reefs and convert it into energy in the form of carbohydrates. This energy exchange process is executed precisely, ensuring no energy is dissipated or expelled from the water (Palupi *et al.* 2016).

The application of AI-based geospatial analysis for monitoring coral reef ecosystems is still in its infancy in Indonesia. Previous studies have been limited to measuring coral reef growth data using the Line Intercept Transect (LIT) method without establishing a direct link to the sustainability of the carbon cycle. This research, therefore, employs a geospatial monitoring approach to coral reefs, utilizing computational-based programming, modeling, and analysis to enhance efficiency. The objective is to utilize a range of remote sensing data resources to identify and assess mining industry activities in coastal areas, focusing on coral reefs in North Konawe.

METHODOLOGY

Study area

North Konawe Regency is administratively located in the southern part of the equator, precisely at 02°97'-03°86' N.E (Fig. 1). and 121°49' 122°49' E. with a land area of 5,101.76 km2 or about 13.38% of the area of Southeast Sulawesi Province (BPS 2021), and a sea area (including the waters of Konawe Regency and South Konawe Regency) of ± 11,960 km² or 10.87% of Southeast Sulawesi waters. The research was conducted from November to December 2023. The coastal area of North Konawe that was monitored was 793.3 km².

Research Design

The research design in writing this scientific paper uses three analyses that are included in the GIS approach and involve remote sensing data. The research design in this scientific work is shown in the flow chart (Fig. 2).

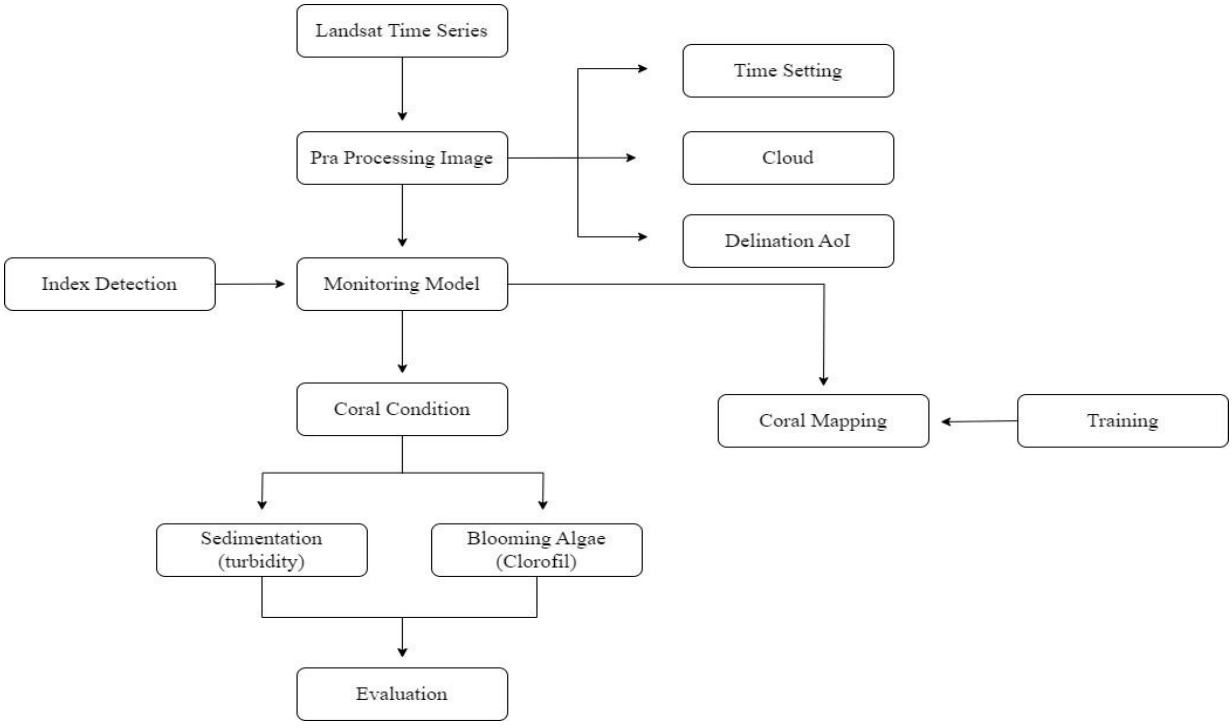


Figure 2. Research flow chart

Data

This study uses secondary data derived from the Landsat satellite time series. Landsat is the world's first high-resolution remote sensing satellite launched by NASA (National Aeronautics and Space Administration) (Edward *et al.* 2001). Landsat has been measuring reflected light waves from objects on the Earth's surface since 1972 until now so that the resulting image data can be used for mapping changes in the Earth's surface over a period of time (Hu *et al.* 2016). For 51 years, eight missions of the Landsat series have been successfully launched and continue to improve with each launch. In this study, the Landsat satellite series used is Landsat 5 with 7 TM spectral bands and 4 MSS spectral bands to obtain classification data and mapping of North Konawe coast in 2000. Landsat 5 was used for data analysis in 2000 because it was cloud-free. The most recently launched Landsat 9, with 9 OLI-2 spectral bands and 2 TIRS-2 spectral bands, was also used to obtain the same data in 2023 (NASA 2023). In addition, data from the Landsat satellite will be used to obtain land cover data from water criteria, coral reef ecosystems, vegetation, and sedimentated water. This research also uses data provided by the Ministry of Energy and Mineral Resources (ESDM) accessed through the MOMI (Minerba One Map Indonesia) portal. The data used is the distribution of mining in the North Konawe area, along with complete administrative information.

Data Analysis

The process of data analysis begins with the delineation of the Area of Interest (AoI) administrative boundaries of North Konawe Regency, followed by the specification of the monitoring area as far as ± 2 km to the sea and land from the coastal area using the uncertain buffering radius technique of the line entity (Xu *et al.* 2021). The buffering results are subsequently imported into the GEE (Google Earth Engine) platform, which is a cloud computing-based geospatial tool integrated with Landsat satellite image data sources (Kumar and Mutanga 2018). Furthermore, data analysis employed the use of Geographic Information System (GIS) processing software, specifically ArcGIS. ArcGIS is utilized for the modeling of conditions, the storage and management of geographic information, as well as the creation, editing, manipulation, mapping, analysis, and dissemination of geographic information (Maguire 2008). The mining distribution database, obtained from the MOMI portal, is digitized using Geographic

Table 1. List of indices used

Index	Formula	Sources
Normalized Difference Vegetation Index (NDVI)	NDVI = NIR - Red /NIR + Red	Rouse *et al.* (1974)
Enhanced Vegetation Index (EVI)	EVI = ((NIR - Red) / ((NIR + 6) * (Red - 7.5) * (Blue + 1))) * 2.5	Huete *et al.* (2002)
Soil Adjusted Vegetation Index (SAVI)	SAVI = ((NIR - Red) / (NIR + Red +0.5)) * (1.0+0.5)	Huete (1988)
Specific Leaf Area Vegetation Index (SLAVI)	SLAVI = NIR / (Red + SWIR2)	Lymburner *et al.* (2000)
Green Normalized Difference Vegetation Index (GNDVI)	GNDVI = (NIR - Green) / (NIR + Green)	Gitelson *et al.* (1996)
Atmospherically Resistant Vegetation Index (ARVI)	ARVI = (NIR - (Red - (1 * (Red - Blue)))) / (NIR + (Red - (1 * (Red - Blue))))	Kaufman *et al.* (1992)
Normalized Difference Water Index (NDWI)	NDWI = Green - NIR / Green + NIR	McFeeters (1996)
Augmented Normalized Difference Water Index (ANDWI)	ANDWI = (Blue + Green + Red - NIR - SWIR1 - SWIR2) / (Blue + Green + Red + NIR + SWIR1 + SWIR2)	Rad *et al.* (2021)
Index-Based Built-up Index (IBI)	IBI = NDBI − ((SAVI + MNDWI) / 2) / NDBI + ((SAVI + MNDWI) / 2)	Xu (2008)

Information: Blue: Blue band, Green: Green band, Red: Red band, RE: Red-edge, NIR: Near-infrared band, SWIR1: Shortwave-infrared band 1(1,57-1,65nm), SWIR2: Shortwave-infrared band 2 (2,11-2,29)

Information System (GIS) processing software, ArcGIS. The results of the training data are also mapped using ArcGIS. The final results of the data mapping are presented in a layout created with the same software (ArcGIS).

Analysis of coastal conditions in 2000 and 2023

The GEE platform was used to classify AoI land cover by generating training data. Classification is done by utilizing a combination of invisible and infrared multispectral bands and certain indices in the creation of classes that include water, coral reef ecosystem, vegetation, non-vegetated areas (indicative of mining), and sedimented water (USGS 2022; Taufik and Ahmad 2016). The indices were utilized for the detection of AoI conditions in 2000 and 2023, which will then be compared for changes. The list of spectral bands and indices used are summarised in the Table 1.

Sedimentation Analysis

Sedimentation analysis was conducted using remote sensing data from Landsat 5 and Landsat 9. Landsat 5 was used to detect sedimentation distribution in 2000, while Landsat 9 was used in the current year (2023). This was done to determine how much influence mining activities have on coral reef damage with the characteristics of the sedimentation content factor. Sedimentation distribution analysis was conducted by referring to the research of Ouma *et al.* (2020) and elaborated the formula Eq. (1). The sedimentation analysis process was conducted using R-Studio programming software. Remote sensing data is inputted through a series of scripts suitable for the analysis process or visualization of raster data. Then, the formula of STI will be written in the script and processed with the help of the raster package in R Programming.

$$STI = (90{,}319 \times (Bb + Gb + Rb)) - 10{,}775 \quad (1)$$

Notes:
STI : Sea Turbidity Index
Bb : Blue band
Gb : Green band
Rb : Red band

Chlorophyll analysis

Analysis of the distribution of chlorophyll-a concentrations was conducted using remote sensing data from Landsat 5 and Landsat 9. Landsat 5 was used to detect the distribution of chlorophyll-a concentration in 2000, while Landsat 9 was used for 2023 (current). Mapping in two different years was done to see the effect of land use change in North Konawe between before and after mining activities took place. The reference for the analysis of the distribution of chlorophyll-a concentration is the same research, namely Ouma *et al.* (2020), whose formula decomposition results are like Eq. (2). The chlorophyll analysis process was carried out using the s

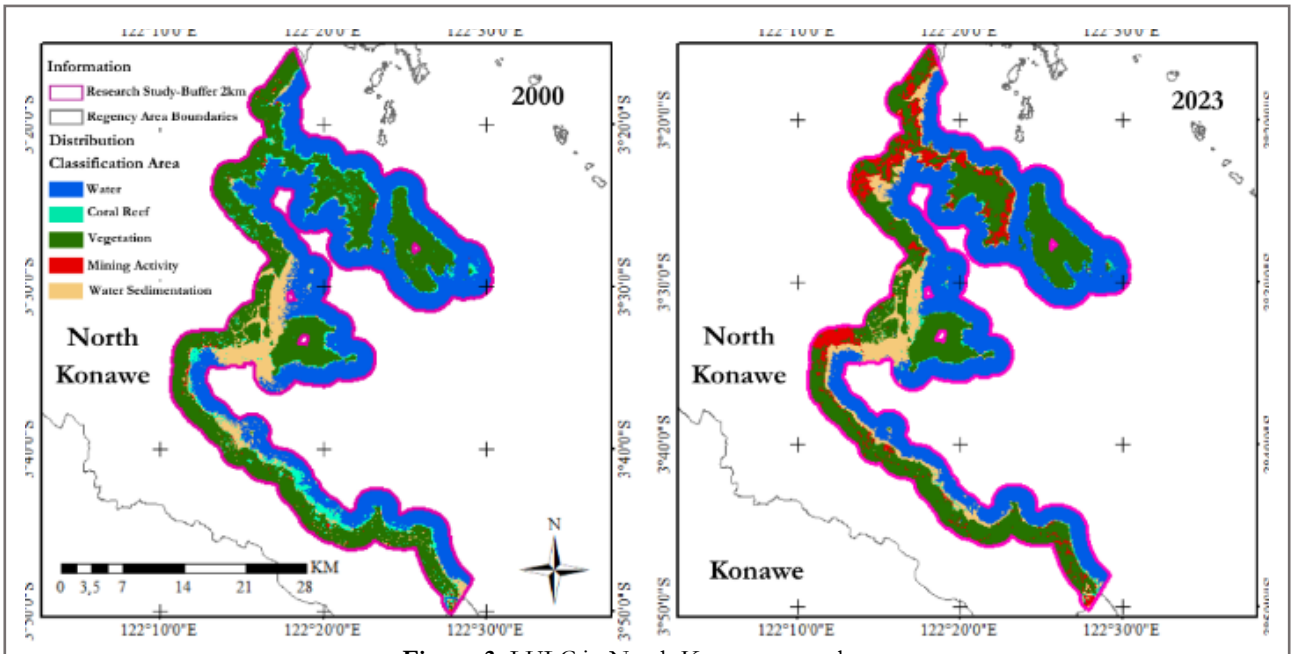


Figure 3. LULC in North Konawe coastal area

ame programming software, R-Studio, and the same mec hanism.

$$SCI = (402{,}73 \times \log(Bb + Gb)) - 888{,}88 \quad (2)$$

Notes:
SCI : Sea Chlorophyll-A Index
Bb : Blue band
Gb : Green band

Construction of Coral Reef Monitoring Platform

The results of the coastal condition data analysis produced data on the distribution of coral reefs in the 2 km buffer area, North Konawe District. The results of this data are visualised in a cloud computing-based platform, Earth Engine Apps (part of the GEE development programme) developed by the international company Google. This platform was created with a series of javascript (js) scripts with the help of the APIs (Application Programming Interface) system. All data from the previous analyses were inputted through the asset input feature and connected to the GEE script.

RESULTS AND DISCUSSION

North Konawe Coastal Condition

North Konawe is one of the districts in Southeast Sulawesi Province, located in the coastal area, and has enormous potential for coastal marine resources (Wali *et al.* 2020). The North Konawe coastal area has various human activities that can pose a risk of environmental damage. Based on the coastal condition map of North Konawe in 2000 and 2023 (Fig. 3), it is known that there are differences in conditions between the two years. The distribution of North Konawe area classification consists of 5 classifications, namely water, coral reef ecosystems, vegetation, mining activity areas, and sedimentated water. The area classification has different area values in 2000 and 2023 when viewed based on (Fig. 4), and the visualization of the difference in the area can be seen in (Fig. 3).

Conditions in 2000 showed that the coastal area was dominated by vegetated cover, which had an area of 33776.46 ha and a coral reef ecosystem of 5968.08 ha. However, in 2023, the area decreased and was replaced by an area of mining activities covering 6024.96 ha, sedimentated water covering 7188.03 ha, and waters covering 37124.01 ha, so that the area of vegetated land decreased to 28340.14 and the remaining reef area was only 1388.79 ha. Southeast Sulawesi Province, especially North Konawe Regency, has an abundance of metal elements in the world, as evidenced by the large number of nickel mining companies (Wibowo *et al.* 2020). Nickel mining is one of the largest sectors contributing to the government in North Konawe (Wali *et al.* 2020). The year 2023 shows that the mining area has expanded significantly enough to narrow the vegetated area. Not only vegetation, the existence of nickel mining activities in coastal areas will cause pollution impacts to waters so that this pollution can have a negative impact on coral reef ecosystems (damage to coral reefs) and reduce water quality by increasing the area of sedimentation.

Mine Activity

North Konawe is one of the districts in Southeast Sulawesi Province that has the potential and become a concern and special feature in the field of energy, especially nickel minerals. Many ultramafic rocks with nickel content are found exposed in North Konawe Regency (Irzon 2017). North Konawe Regency is part of the Soroako National Strategic Area (KSN) and is the Asesolo/Kendari Nickel Mining Mainstay Area, Southeast Sulawesi (Nursahan *et al.* 2013). The potential for nickel in North Konawe Regency is very large, as much as 1.8 billion metric tonnes, most of which is

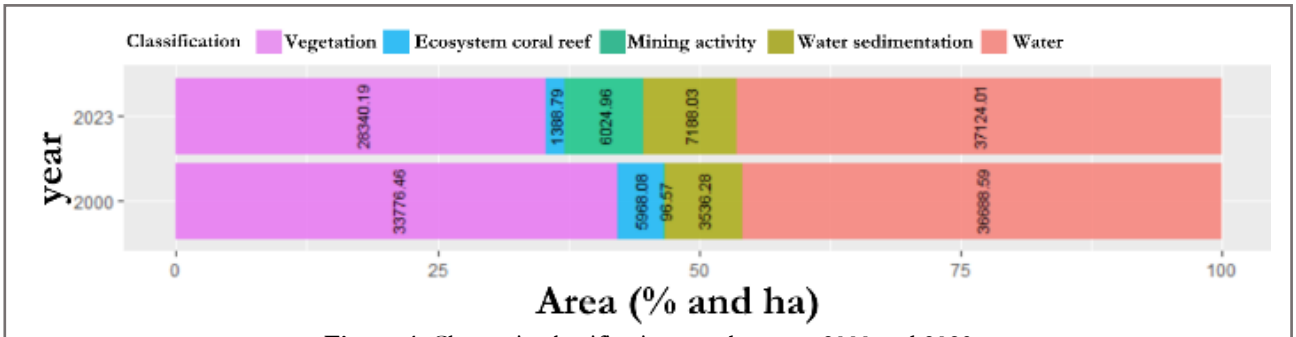


Figure 4. Change in classification area between 2000 and 2023

spread in Lasolo District. Based on data from BPS Southeast Sulawesi (2022), there are 138 nickel mining companies in Southeast Sulawesi Province, and 50 of them are nickel mining companies in North Konawe Regency. In the coastal area, there are 83 mining companies within 2 km of the recorded buffer area (Fig. 5). The large number of mining activities near the coast adversely affects the marine ecosystem. Waste from the mining industry, commonly called tailings, consists of fine sand and clay. Tailings are waste materials that are discarded after being separated from valuable ore material (Riogilang and Masloman 2009). The tailings discharge can cause the seawater to become turbid because the fine mud from the tailings is stirred up in the water column, and sedimentation is harmful to the coral reef ecosystem.

Impacts of Mining Activities on Coral Reef Ecosystems

Land, atmosphere, and oceans are all interconnected in the carbon cycle. The ocean is one of

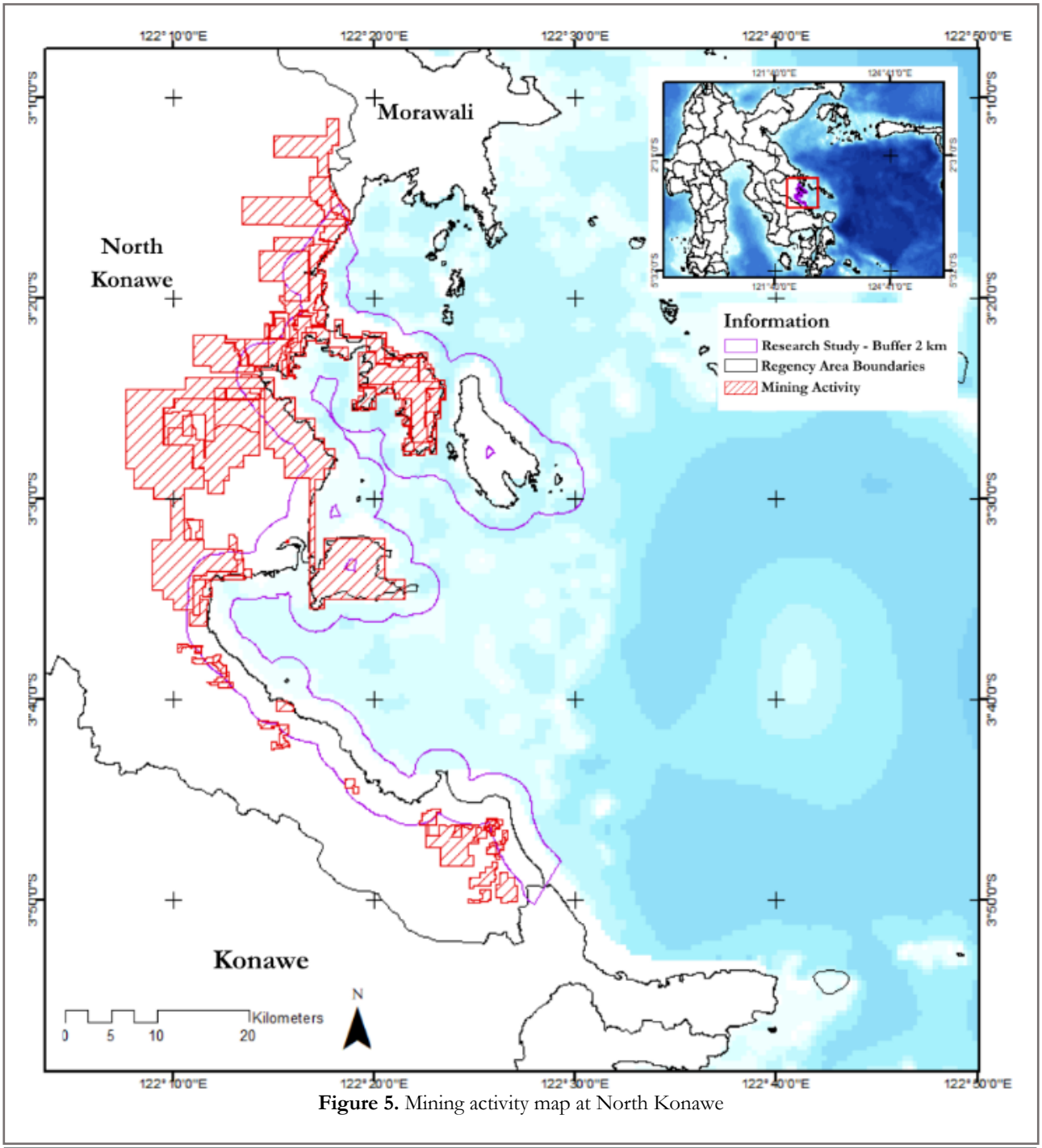


Figure 5. Mining activity map at North Konawe

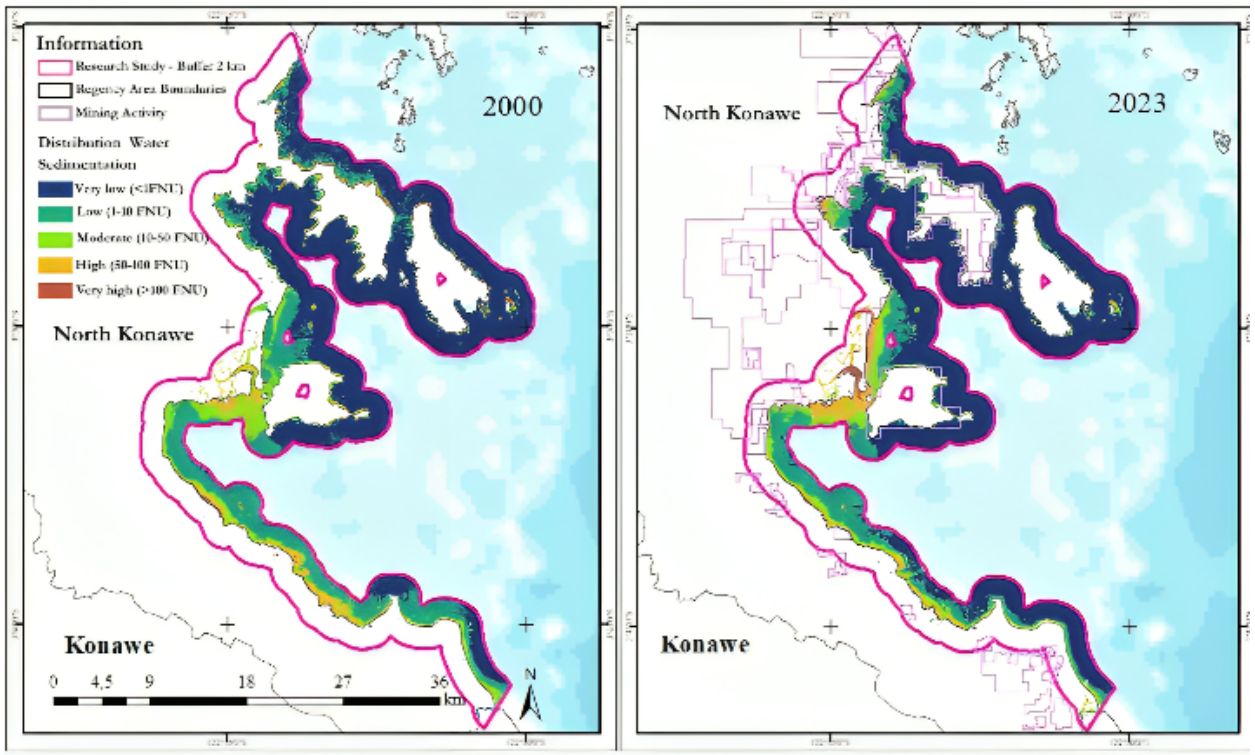


Figure 6. Coastal sedimentation distribution map

the largest carbon reservoirs that quickly absorbs CO2 from the atmosphere, thus acting as a natural control of CO2 concentrations in the atmosphere, which are increasing due to human activities that have an impact on climate change (global warming) (Albright *et al.* 2015). Due to the increase of CO2 in the atmosphere after the industrial revolution, soluble CO2 in seawater has also increased. Soluble CO2 reacts with water to form HCO3- to produce H+, which can then increase the acidity of seawater (lower pH) and can react back with CO32- available in the sea, forming more HCO3- and reducing the concentration of CO32- in water (Albright *et al.* 2015). The reduced CO32- content will result in a decrease in the calcification process (coral formation), which in turn will reduce the role of coral reefs as carbon sinks for greenhouse gases (Crisholm and Barnes 1998).

Carbon sequestration by coral reefs occurs due to the association with microalgae (zooxanthellae), which have chlorophyll and the ability to photosynthesize. In the coral reef ecosystem, phytoplankton are also present. Phytoplankton photosynthesis produces oxygen for other biota in the sea, especially those around the coral reef ecosystem. The amount of carbon that can be absorbed by 1 milligram of phytoplankton chlorophyll is equivalent to 1.6 milligrams of CO2 (Azhar 2016). Nutrients in coral reefs can be obtained by receiving translocation of photosynthetic products from zooxanthellae or feeding on zooplankton through their polyps.

Massive mining activities threaten the existence of coral reef ecosystems, which are very vulnerable to change. Waste or tailings generated from mining activities can cause damage to coral reefs. This is supported by the statement of Noviana *et al.* (2018) that coral reef damage is caused by development that changes the bay area, excessive utilization (marine tourism), fishing methods that damage the ecosystem, increased sedimentation, and pollution from industrial and domestic waste. Sedimentation of tailings downstream into the sea causes erosion of the beach and makes the water turbid. Based on the analysis results obtained in (Fig. 6), the classification class is divided into five classes, namely very low, low, medium, high, and very high. In 2023, there is a change in the turbidity index to a higher level than in 2000. The change can be seen in the Lasolo River buffer area, which is the sub-district with the largest mining activity in North Konawe Regency. If tailings fall into seawater where there is a coral reef ecosystem, sedimentation that closes coral reef cavities can hinder the activity of coral reefs in receiving nutrients due to disruption of the photosynthesis process so that the carbon cycle in the coral reef ecosystem is also disrupted. The process

of photosynthesis is disrupted due to sedimentation on the sea surface, increasing turbidity, which indirectly reduces the entry of light rays into the reef polyps or even sediment can have a direct effect on 'strangling' coral reefs by sticking to the substrate, reducing coral growth rates, and increasing coral reef vulnerability to pathogens (Haywood *et al.* 2016).

The severity of the effect of mining activities on marine ecosystem damage can also be observed in changes in chlorophyll-a concentrations. Mining activities produce waste known as Acid Mine Drainage (AMD), which is acidic and toxic to marine life in general. Disposal of mine waste that exceeds the safety tolerance limit for marine ecosystems (AMD) results in general marine biota such as fish cannot survive, but marine biota will be dominated by organisms that are resistant to these extreme conditions (acidophilic organisms) such as algae (Gomes *et al.* 2021). Each type of algae contains chlorophyll-a, while the algae species whose populations can increase during stressful seawater conditions can vary from harmless algae to harmful algae (Alharbi 2023). Harmful algae adversely affects fish spoilage and mortality due to lack of oxygen (Irawan *et al.* 2014). The theory presented previously is proven from the results of monitoring using remote sensing that there are changes in mining activities that differ significantly between 2000, where the intensity was still very small (so it was not visible on the map) and 2023, where number of mining companies (activities) increased dramatically, especially those located in coastal areas, resulting in different chlorophyll-a content detected before and after mining activities. It can be clearly seen in Fig. 7 that in the year 2000, chlorophyll-a concentrations were still expressed in dark green, symbolizing 'insignificant' concentrations, and there was no detectable level of chlorophyll content in red (very high). Whereas in 2023, it is very clear that the 'insignificant' concentration indicator no longer exists but is replaced by a higher level, and in the part close to mining activities in some areas, the level changes to the '*very high*' level..

Platform Monitoring: Data Indo InaCor

The rapid development of technology, such as internet-based data processing (cloud computing), allows monitoring of coral reef ecosystems. Monitoring is done by utilizing web-based GIS or webGIS. The existence of webGIS allows the integration of datasets and provides information to the public about coastal conditions. The development of InaCor's DATAINDO platform is used as a monitoring medium, especially the condition of coral reef ecosystems affected by sedimentation in mining areas in North Konawe Regency. This monitoring activity aims to prevent and overcome the occurrence of coral reef damage due to sedimentation from tailings that can inhibit the carbon cycle. Besides being able to monitor

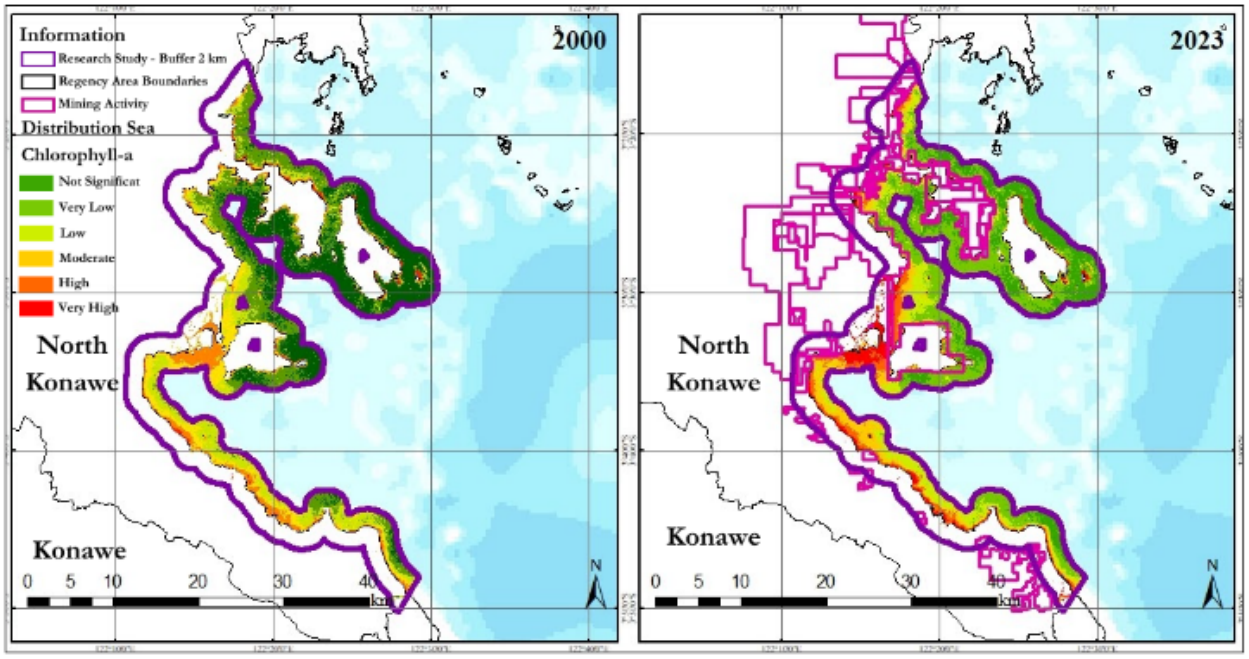


Figure 7. Chlorophyll condition map of coral reef ecosystems

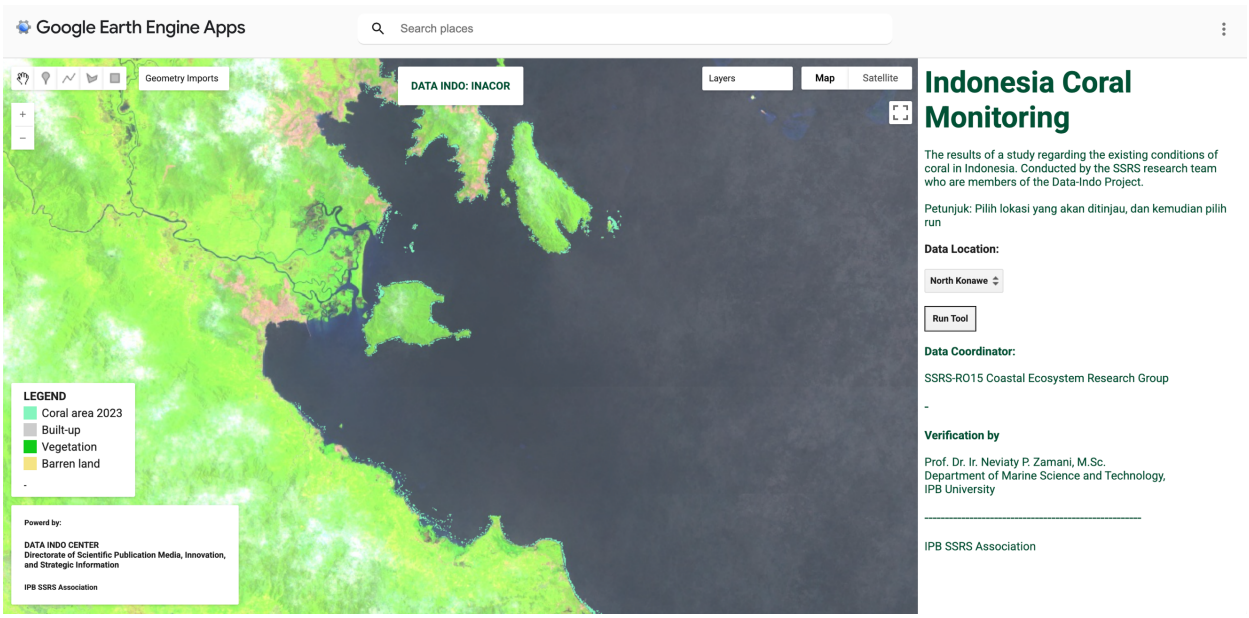


Figure 8. *Platform* InaCor

coastal areas in real-time, this platform does not require special skills to operate and does not require high costs to buy licenses from GIS applications. Evaluation of spatial and web-based information media is essential for monitoring areas prone to coral reef damage. The creation of the DATAINDO InaCor platform is a solution as a Cloud Computing-based monitoring media whose processes take place online by involving various algorithms in the form of scripts. This platform can be accessed by the public through the Earth Engine Apps website (https://ee-dataindo-ssrs.projects.earthengine.app/view/inacor). The data visualization in the coral reef monitoring platform can be seen on Fig. 8 .

CONCLUSIONS

The coastal condition of North Konawe Regency experienced a drastic change in land cover area in 2023 compared to 2000. This is due to waste from mining activities or tailings that are sedimented into the sea, which causes a buildup of sedimentation on the coast. The sedimentation pile damages the coral reef ecosystem in the shallow sea. Damage to coral reefs is characterized by high turbidity index values and chlorophyll index values that can be seen from the results of analysis through remote sensing. Coral reefs have an association relationship with microalgae (zooxanthellae) in helping the photosynthesis process. If coral reefs are damaged, then the carbon cycle in the reef is also hampered. InaCor's DATAINDO monitoring platform was created to monitor coral reef ecosystem areas in real-time and cheaply so that it is easier to use. The DATAINDO InaCor coral reef ecosystem condition data visualisation system is expected to be a consideration for policy making related to mining waste management and coral reef ecosystem conservation in various regions, and can be a reference for further research.

ACKNOWLEDGEMENTS

Thanks to the IPB Faculty of Forestry Alumni Association (HAE), SSRS Research Fund, and the Department of Soil Science and Land Resources for funding this research.

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