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Monitoring Biochemical Oxygen Demand (BOD) Changes During a Massive Fish Kill Using Multitemporal Landsat-8 Satellite Images in Maninjau Lake, Indonesia

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Abstract
Maninjau Lake is one of Indonesia's lakes used for hydroelectric power plants, tourism, and fish farming activities. Some activities around the lake cause pollution, leading to massive fish kills. Therefore, it is necessary to monitor water quality regularly. One of the critical water quality parameters is biochemical oxygen demand (BOD). This study aimed to analyze BOD changes using a remote sensing approach during massive fish kills in Maninjau Lake, Indonesia. Multi-temporal Landsat-8 satellite images are processed to estimate the BOD level based on Wang's Algorithm. The estimated BOD value is then validated using in situ data measurements. The results show that the average BOD concentration in Lake Maninjau was 1.85 mg/L with an R^2 of 0.8334, and the standard error was 0.076 between the estimated BOD and the in-situ data. Furthermore, the average concentration of BOD obtained on 23rd August 2017, 13th December 2017, 30th January 2018, 19th March 2018, and 7th July 2018 are 4.96 mg/L, 4.82 mg/L, 5.31 mg/L, 6.94 mg/L, and 6.60 mg/L, respectively. Increased BOD concentration in January 2018 indicates moderate pollution in the waters. BOD concentration increases after the massive fish kills due to the fish decaying across the lake.

Keywords: Biochemical Oxygen Demand, Water Quality, Massive Fish Kill.

1. Introduction

Indonesia is an archipelagic country. Its water ecosystems are larger than its terrestrial ecosystems. Indonesian waters are composed of both freshwater and marine ecosystems. Its ecosystems are estimated at 14 million hectares, consisting of lakes, reservoirs, and swamps. These freshwater ecosystems are used for clean water, fisheries, agriculture, and tourism (Soeprobowati, 2015). However, a number of activities around the freshwater ecosystems, e.g., unappropriated industry and agriculture, deforestation around the watershed, and excessive fish farming lead to eutrophication, sedimentation, and oxygen depletion (Jamaldi, 2017).

In Indonesia, there are 15 priority lakes in urgent need of conservation. One of them is Maninjau Lake (Jamaldi, 2017; Ibrahim *et al.*, 2021). Maninjau Lake has long been used for hydroelectric power, tourism, and fish farming (Putri, 2017; Subehi *et al.*, 2020). Fish farming activities around the lake cause nutrient pollution due to excessive nitrogen and phosphorus concentration (Henny *et al.*, 2016). Excessive nitrogen and phosphorus can cause eutrophication and a lack of dissolved oxygen, leading to massive fish kill (De Maisonneuve *et al.*, 2019).

The first massive fish kill occurred in Maninjau Lake in 1997, with 950 tons of dead fish due to water pollution caused by a lack of oxygen supply (LIPI, 2020; Nasution *et al.*, 2020). In 2018, 160 tons of massive fish kill and a financial loss of around IDR 3.75 billion (equivalent to USD 250 thousand). This second massive fish kill was caused by extreme weather that caused the fish's food sources to rise to the water's surface, resulting in reduced oxygen (Liputan6.com, 2018). The fish's food was forced to the surface by upwelling (Pitcher, 2021). A vicious cycle took hold. Frequent massive fish kill due to extreme weather decreased water quality (Aileen *et al.*, 2021; Kragh *et al.*, 2020). Therefore, regular water quality monitoring is needed to mitigate the causes and effects of these massive fish kills.

Water quality monitoring involves the collection and evaluation of water samples to determine the chemical, physical, and biological quality of water bodies and the causes of changes in water quality (Abdullah *et al.*, 2017; Banda *et al.*, 2020; Bozorg-Haddad *et al.*, 2021). Water quality monitoring can be undertaken using a variety of techniques. The conventional method is to analyze water samples from the field. This method can produce accurate data but takes time and effort and is not affordable (Hajigholizadeh *et al.*, 2021). Water quality monitoring has been carried out in Maninjau Lake using conventional methods. However, this approach has limitations, i.e., a challenge in data sampling. Remote sensing technology can be a solution to this problem, providing continuous monitoring of water quality parameters. Some developing countries have used remote sensing methods for water quality monitoring since the 1970s (Gholizadeh *et al.*, 2016).

Remote sensing is a potential way to use technology to continuously monitor lake water quality parameters using an empirical algorithm (Mushtaq *et al.*, 2016). Abdullah *et al.* (2017) used Landsat 8 satellite imaging to monitor and assess water quality in the lake and then compared the results with field data. The water quality parameters monitored are temperature, pH, Total Dissolved Solids (TDS), Electrical Conductivity (EC), Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Nitrate Nitrogen (NO3N), Phosphate (PO4), Total Phosphorous (TP), Temperature, Total Suspended Solid (TSS), and Turbidity. One of the most critical parameters is BOD. BOD indicates oxygen-aerobic microorganisms that are needed to decompose all suspended substances. The BOD measures the amount of oxygen needed to oxidize or degrade the polluted material contained in the water (Erfina, 2021; Tamyiz, 2015).

Remote sensing helps predict and estimate the condition causing the massive fish kill. One of the parameters that can be estimated through satellite images is temperature. Research conducted by Marti-Cardona *et al.* (2008, 2019) explained that the surface temperature map produced using MODIS satellite imagery shows that *upwelling* occurs after a wind event affects the waters, causing massive fish kills. Meanwhile, the study by Bonansea *et al.* (2019) using Landsat imagery 7 and 8 explains that low water surface temperatures could increase fungi breeding in the waters that attack the fish. Changes in surface temperature can affect dissolved oxygen levels. Low levels of dissolved oxygen can increase BOD concentrations. The higher the BOD concentration, the higher the level of pollution that occurs, reducing oxygen levels and decreasing aquatic habitats (Apelabi *et al.*, 2021; Vigiak *et al.*, 2019).

Water quality monitoring can be conducted using various parameters, including BOD. However, the remote sensing-based approach to monitor BOD in the case of fish kill is limited. Therefore, this study aimed to analyze *BOD changes* using remote sensing during massive fish kills in Maninjau Lake, Indonesia 2018. It used spectral values obtained from Landsat 8 satellite images to estimate the BOD level based on an empirical equation (Wang *et al.*, 2004, Yang *et al.*, 2022). The results have been validated using *in-situ* data from the Environment Office of Agam Regency.

2. Research Methods

The research has been undertaken in Maninjau Lake, West Sumatra, Indonesia (Figure 1). Maninjau Lake is a volcanic lake located at an altitude of 461.5 m above sea level with an area of 9,737.5 hectares and a maximum depth of 165 m (Lukman *et al.*, 2013). Lake Maninjau is used for hydroelectric power production, tourism, and fish farming in Floating Net Cages (KJA), which began in 1990 (Subehi *et al.*, 2020). The number of floating net cages (KJA) in Lake Maninjau has continued to increase from 16,380 plots in 2014 to 17,417 plots in 2021. This has caused mass fish mortality and other environmental damage.

The primary data used in this study is the Landsat 8 satellite images acquired on August 23, 2017; December 13, 2017; January 30, 2018; March 19, 2018; July 07, 2018; and October 29, 2018, obtained from the United States Geological Survey (USGS). BOD's in situ measurement data conducted on October 24, 2018, has been used for validation. This field data was obtained from six sampling locations maintained by the Environmental Service of Agam Regency with, Bayur, Batang River, Middle Lake, Tanjung Sani, Tampang River, and Muko-muko Hydroelectric Power Plant. Data from field measurements of BOD concentrations in Maninjau Lake are presented in Table 1.

In Landsat-8 image processing, digital *number* values are converted to reflectance using ToA *(Top of Atmosphere)* correction (Equation 1) and solar correction (Equation 2) (USGS, 2019). Equation 1. $\rho\lambda'$ is ToA reflectance without correction of the sun's zenith angle, MP *is the reflectance multiplicative scaling factor*, Qcal is the pixel value (*digital number*), and P is the *reflectance additive scaling factor*. In addition, $\rho\lambda$ is a ToA reflectance that corrects the sun's zenith angle, and θ_{SE} is the sun's elevation angle.

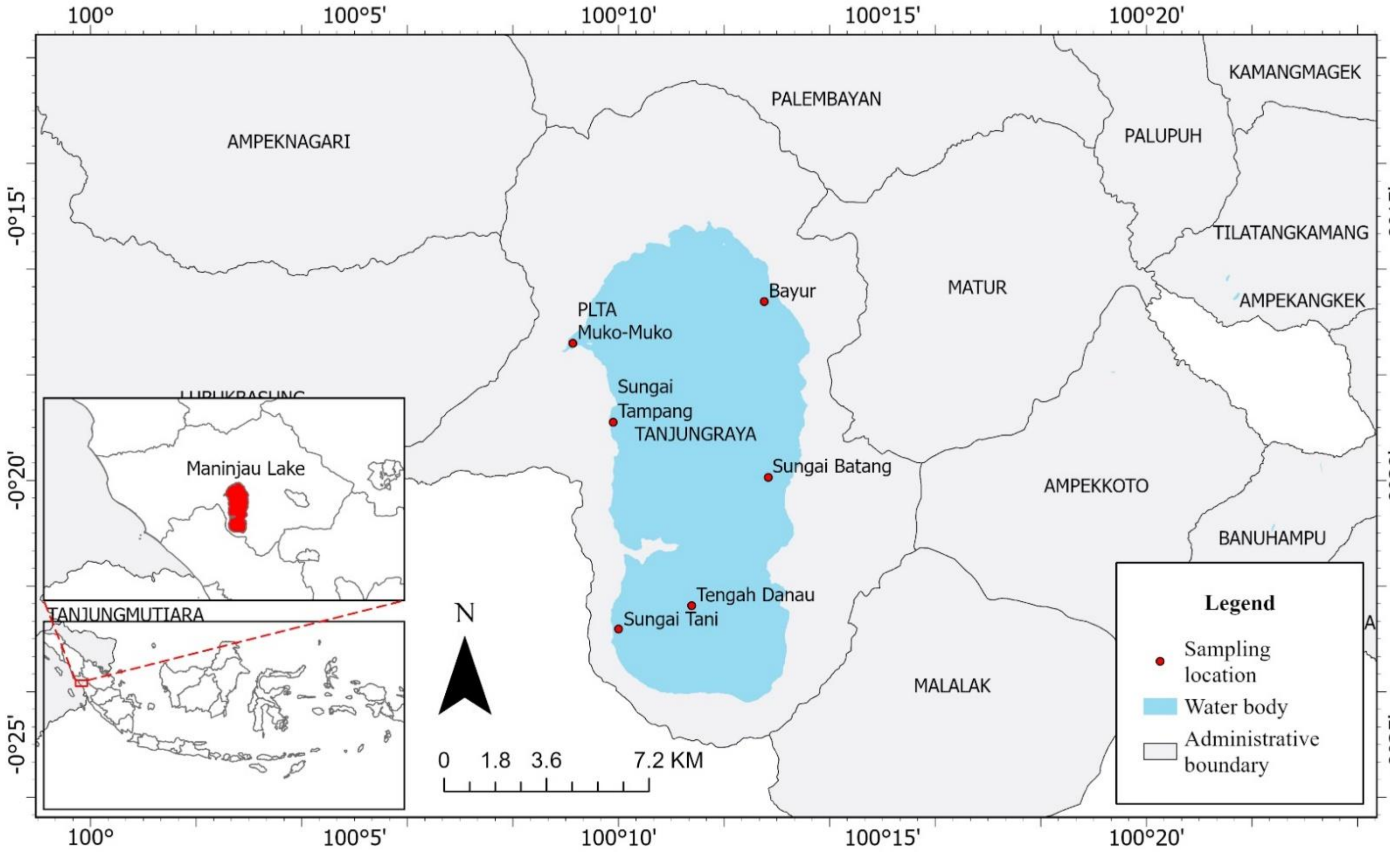

Figure 1. Research Area.

Table 1. Field Data for BOD Concentration on October 24 2018

Parameter (Unit)	Sampling Locations					
	Bayur	**Sungai Batang**	**Tengah Danau**	**Tanjung Sani**	**Sungai Tampang**	**PLTA Muko-Muko**
BOD (mg/L)	<2	<2	2.02	2.42	2.02	2.02

$$\rho\lambda' = MP.Qcal + P \tag{1}$$

$$\rho\lambda = \frac{\rho\lambda\prime}{sin(\theta_{SE})} \tag{2}$$

The BOD level is estimated using empirical equations adapted from Wang *et al.* (2004). The formula used for this estimation is shown in Equation 3. B2, B3, and B4 reflect the TOA of bands 2, 3, and 4 of Landsat-8.

$$BOD = 1.79 - 0.789 * B2 + 52.36 * B3 - 3.28 * B4 \tag{3}$$

The determination coefficient (R^2) is used to evaluate the fitness between estimated BOD and in situ data. Equation 4 is used for this validation. R^2 is the coefficient of determination, n is the number of samples, X is the independent variable, and Y is the dependent variable.

$$R^2 = \frac{((n)(\sum XY) - (\sum X)(\sum Y))^2}{(n(\sum X^2) - (\sum X)^2)(n(\sum Y^2) - (\sum Y)^2)} \tag{4}$$

3. Results and Discussion

3.1. Concentration of BOD using Remote Sensing

Using the results of the BOD level obtained using the Wang Algorithm, statistical tests were conducted between estimated BOD and in situ data, as presented in Table 2. Table 2 shows that the R^2 is 0.8334. This means that Wang's algorithm can explain BOD levels up to 83.34%, and the remaining 16.66% can be explained by other free variables not included in the study. This shows that the relationship between estimated BOD and in situ, BOD is strongly indicated by $R^2 \geq 0.8$.

Table 2. Statistical Analysis of Estimated and In Situ BOD.

Multiple R (R)	R Squared (R^2)	Adjusted R Squared (Adjusted R^2)	Standard Error (SE)	Observations (OBS)
0.912	0.833	0.791	0.076	6

On October 29, 2018, the water body recorded a maximum biochemical oxygen demand (BOD) level of 2.225 mg/L, indicating higher organic pollutants. Conversely, the lowest BOD level measured on the same date was 1.823 mg/L, indicating a comparatively cleaner condition. On average, the BOD level for that day was 1.85 mg/L, suggesting a moderate level of organic pollution in the water. The spatial BOD concentration map is presented in Figure 2.

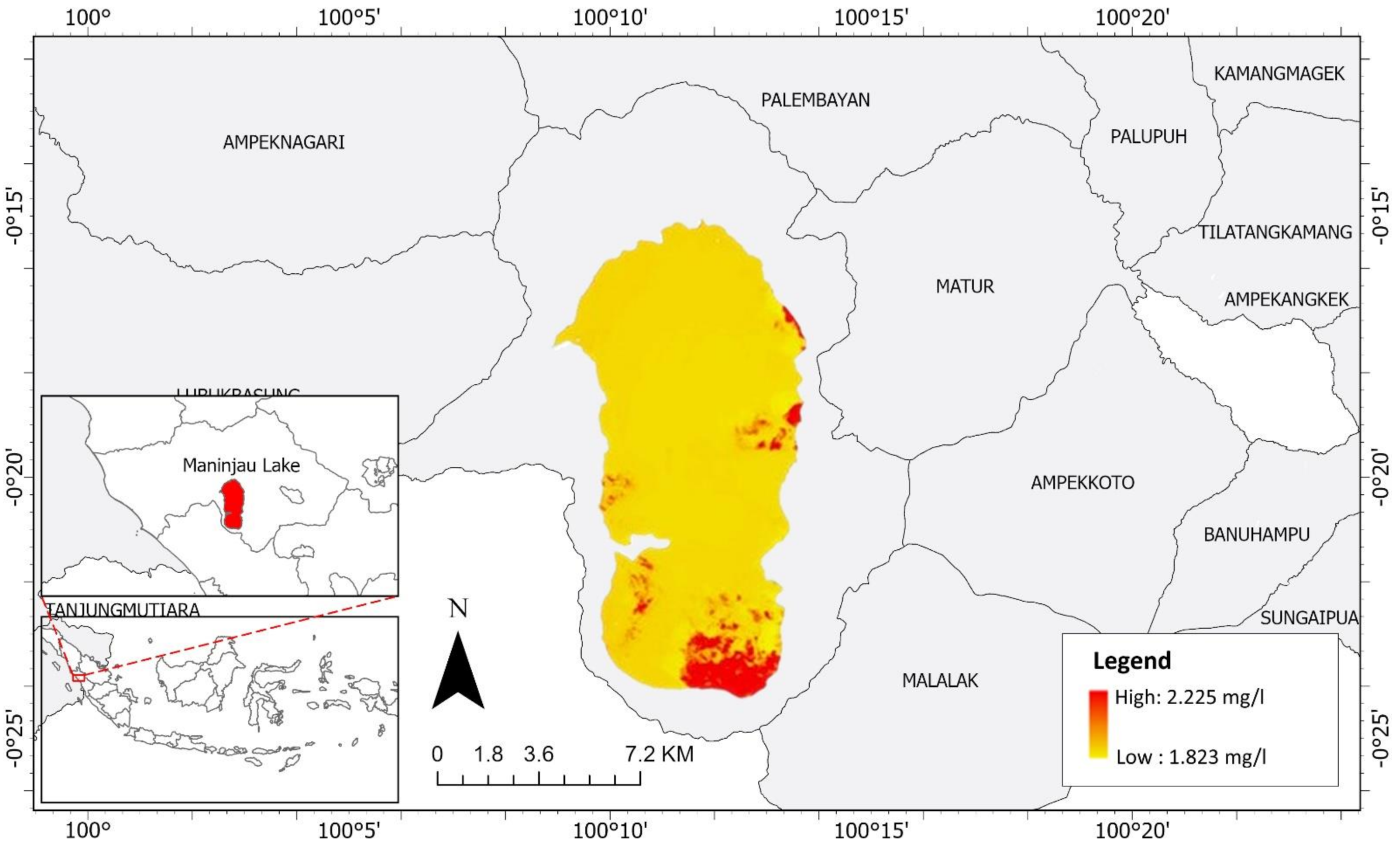

Figure 2. Map of BOD Concentration in Maninjau Lake estimated using Landsat-8 Imagery.

3.2. Monitoring BOD Changes During a Massive Fish Kill

The period of BOD changes tracking using Landsat-8 Images covered the time of a massive fish kill on February 04, 2018. The BOD level was investigated before and after the massive fish kill event. The pre-event involves two-period images, i.e., one taken on August 23, 2017, and one taken on December 13, 2017, while the post-event involves two-period images, i.e., one taken on March 19, 2018, and one taken on July 07, 2018. Figure 3 depicts spatiotemporal changes of BOD during the massive fish kill. From Fig. 3, we can observe that the BOD level on August 23, 2017, ranged from 4.159 mg/L to 22.448 mg/L with an average concentration of 4.96 mg/L. On December 13, 2017, the BOD level ranged from 4.136 mg/L to 22.678 mg/L, with 4.82 mg/L. According to the average concentration of BOD, the pollution level in Maninjau Lake before the massive fish kill is classified as mild. When the massive fish kill occurred, BOD concentrations on January 30, 2018, ranged from 4.495 to 13.409 mg/L with an average of approximately 5.31 mg/L. In this period, the average BOD level is higher than before the massive fish kill, consequently increasing the status of the pollution to moderately polluted.

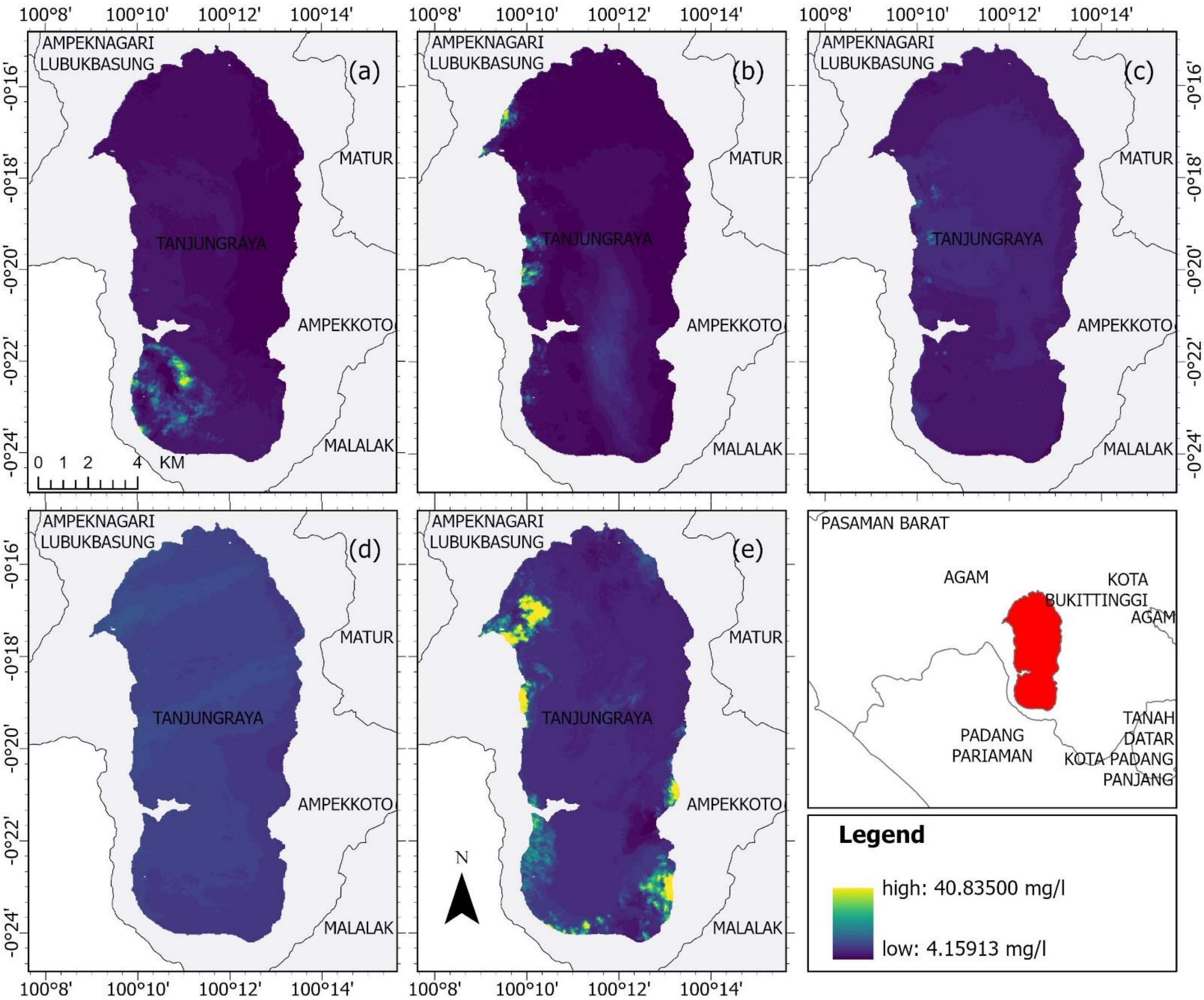

Figure 3. Spatio-temporal of BOD Changes During Massive Fish Kill in Maninjau Lake in 2018. Note: (a) August 23, 2017; (b) December 13, 2017; (c) January 30, 2018; (d) March 19, 2018; and (e) July 07, 2018.

After the massive fish kill event, the BOD concentrations on March 19, 2018, ranged from 5.479 mg/L to 10.648 mg/L with an average concentration of 6.94 mg/L. The BOD concentration on July 07, 2018, ranged from 4.382 mg/L to 40.834 mg/L with an average concentration of 6.60 mg/L. The increasing concentration of BOD in Maninjau Lake was driven by the numerous fish carcasses left after the fish kill. The decay of organic matter in the waters can cause dissolved oxygen levels to decrease (Mubarak *et al.*, 2010). A decrease in dissolved oxygen levels affects the increase in BOD concentration in the waters (Tamyiz, 2015). This finding is the same as that of several previous studies, which showed that a high BOD value indicates a low dissolved oxygen content in the waters. A high BOD value can indicate a massive fish kill due to a lack of oxygen (Daroni *et al.*, 2020). Figure 4. illustrates the trend of average BOD concentration during the massive fish kill.

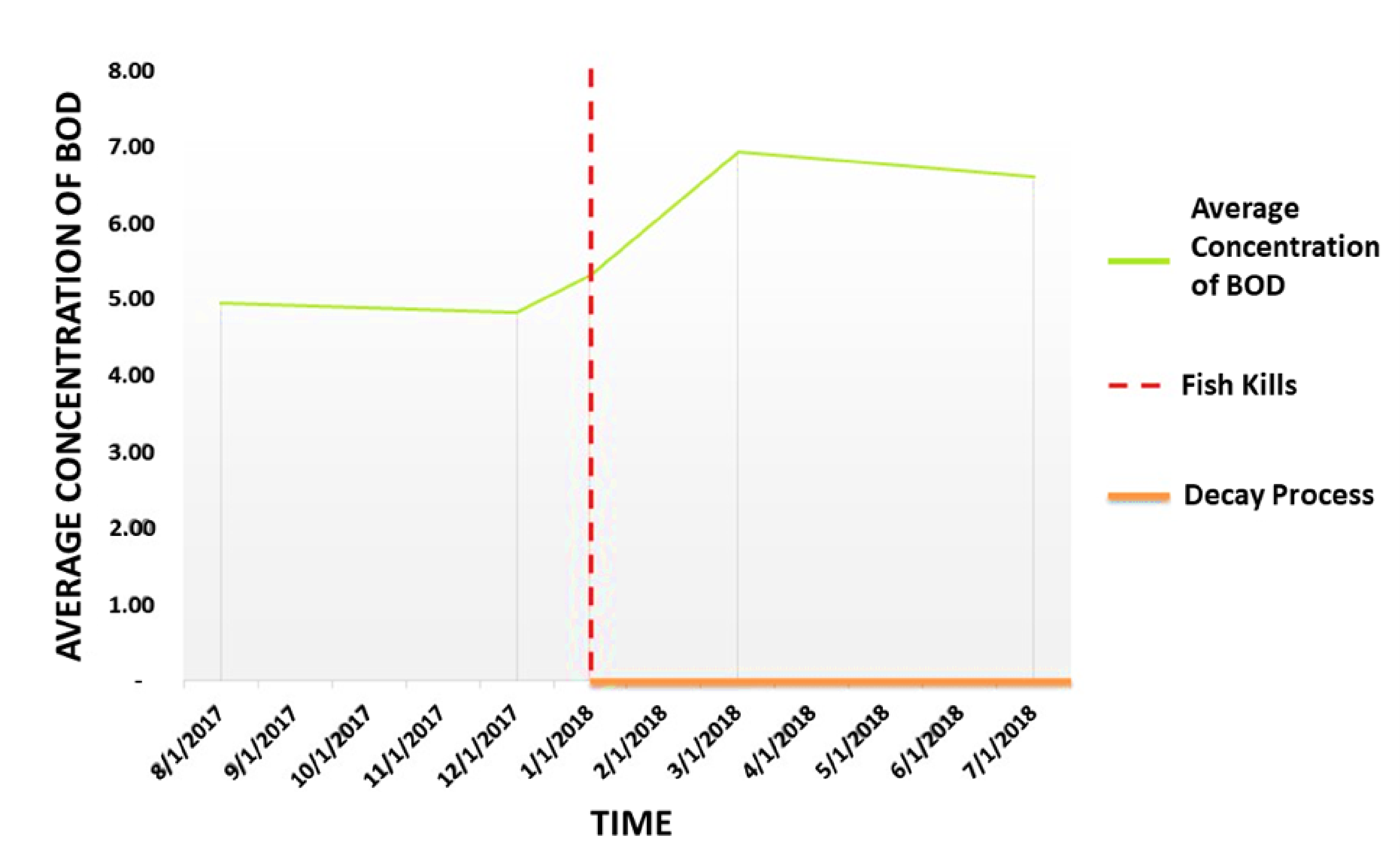

Figure 4. The trend of Average BOD Concentrations During Massive Fish Kill in Maninjau Lake.

3.3. Discussion

The BOD concentration estimated using Landsat-8 imagery shows valid data, as illustrated by R^2 reaching 0.833. Furthermore, the BOD concentration changes analysis undertaken during the massive fish kill shows that the average concentration of BOD in five-period data, i.e., August 23, 2017; December 13, 2017; January 30, 2018; March 19, 2018; and July 07, 2018, are 4.96 mg/L, 4.82 mg/L, 5.31 mg/L, 6.94 mg/L, and 6.60 mg/L. The increase in BOD before the mass fish die-off indicates light pollution in Lake Maninjau caused by various factors such as extreme weather or temperature changes and fish feed deposits. Increasing temperatures in the waters will cause an increase in BOD due to increased oxygen consumption by organisms in the waters (Daroini &; Arisandi, 2020; Putri *et al.*, 2019). At the same time, the increase in BOD due to the remnants of fish feed that settle on the bottom of the waters must be broken down by microorganisms. This decomposition process tends to produce organic substances that can increase the concentration of BOD This increase can (Ayuniar &; Hidayat, 2018). be controlled by having the right type and amount of fish feed (Salmin, 2005; Ulum *et al.*, 2020).

The mass death of fish in 2018 was caused by extreme weather, resulting in fish feed residues rising to the lake's surface and consequently reducing oxygen (Liputan6.com, 2018). Increasing temperatures in the waters will cause an increase in BOD because organisms in the waters consume increased amounts of oxygen(Daroini & Arisandi, 2020; Putri *et al.*, 2019). Increased temperatures also cause fish feed residues to rise to the surface due to upwelling. This occurs because the surface water temperature decreases and the specific gravity increases. The surface water will drop, pressing down the inner water (Maulana *et al.*, 2016). Increased loads of organic compounds and nutrients, as well as the characteristics of lakes with very high wind speeds and tropical temperatures, can affect the spread of organic compounds in lakes (Komala *et al.*, 2019). The content of organic compounds in water affects the demand for oxygen (BOD) in waters, so the higher the organic compounds, the higher the BOD value (Daroini & Arisandi, 2020). BOD concentrations increased in January 2018 after a mass fish death, indicating moderate water pollution. BOD concentrations increase after massive fish deaths because dead fish decay, lowering dissolved oxygen levels (Ndahawali, 2016; Salmin, 2005).

The spatial modeling of water quality parameters is still underutilized as a technique due to validation limitations. Validation aims to ensure that the data generated from remote sensing is accurate and trustworthy. This is done by comparing remote sensing or satellite imagery results with field data. This study used Landsat-8 satellite imagery data and field measurement data. A limited number of samples of field measurement data were used, and this sort of lack of samples can generally affect the accuracy of satellite image classifications (Danoedoro, 2015). In addition, the field data were acquired with satellite image data at different times due to the varying percentages of cloud cover in Landsat-8 satellite images. Based on the analysis of changes in BOD concentration during mass mortality of fish influenced by cloud cover, which is still contained in the results of the satellite image process. In addition, water column correction should be used in pre-processing to extract information in water areas. The correction of the water column can be done using the Lyzenga method 1978, 1981, and 2006 and the DOS (Dark Object Subtraction) method (Inamdar *et al.*, 2022; Purwanto *et al.*, 2019; Cui *et al.*, 2014; Hafizt *et al.*, 2015).

Further research can explore the utilization of remote sensing in estimating chlorophyll (Laili *et al.*, 2015; Hafeez *et al.*, 2019), temperature (Sunder *et al.*, 2020; Abdelmalik, 2018), dissolved oxygen (Wagle *et al.*, 2019), total suspended solids (Abdullah *et al.*, 2017a; Sukojo *et al.*, 2018) and other parameters. In addition, future research can use hyperspectral sensors with more channels to acquire spectral resolution. With more bands, hyperspectral sensors can be used for separation, spectral measurement, and image formatting (Ayundyahrini *et al.*, 2020). Thus, hyperspectral sensors can be used for water quality monitoring (Bresciani *et al.*, 2022) and can be integrated with UAVs(Cai *et al.*, 2022).

4. Conclusion

Lake Maninjau is one of the 15 priority lakes in Indonesia. The lake is used for hydroelectric power generation, tourism, and fish farming. Some activities around the lake cause pollution, leading to massive fish deaths. This study tried to analyze BOD changes using a remote sensing approach during the mass mortality of fish in Lake Maninjau in 2018 using Landsat-8 satellite imagery and the wang algorithm. R^2 was 0.8334, and the standard error was 0.076 between the BOD estimate using the wang algorithm and the in-situ data. Based on these results, we can conclude that there was an increase in BOD which caused the mass death of fish due to moderate water pollution. This pollution shows that Lake Maninjau requires additional attention to maintain water quality and ensure the sustainability of the ecosystem. Thus, the algorithm of this study can be used to monitor the dynamics of BOD levels that significantly affect water quality. Furthermore, in this era of geospatial research, water quality parameters should be explored using hyperspectral sensors, drone vehicles, and early warning system development based on integrating remote sensing and field data. We encourage the use of remote sensing approaches integrated with field data to support the monitoring of water quality in Indonesian territory and recommend that lakes that have a crucial role in the community have evenly- distributed water quality monitoring stations that are continuous with data accessible online so that they can be easily synchronized with satellite image data.

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Author Contributions

Conceptualization: Arif Rohman, Adam Irwansyah Fauzi; **methodology:** Arif Rohman, Adam Irwansyah Fauzi, Nesya Hafiza Ardani; **investigation:** Arif Rohman, Adam Irwansyah Fauzi; **writing—original draft preparation:** Arif Rohman, Adam Irwansyah Fauzi, Nesya Hafiza Ardani; **writing—review and editing:** Arif Rohman, Adam Irwansyah Fauzi, Nesya Hafiza Ardani, Muhammad Ulin Nuha, Redho Surya Perdana, Aynaz Lotfata; **visualization:** Arif Rohman, Nesya Hafiza Ardani, Aynaz Lotfata. . All authors have read and agreed to the published version of the manuscript.

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