Long-term change of water clarity in Lake Limboto derived from Landsat data

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Abstract. Long-term water quality data is important for supporting lake management. Performing routine in situ water quality measurement remains a challenge; thus, the available data are minimal. Long-term data archived of satellite data potentially address this data scarcity. We used Landsat TM/ETM+ images to generate a long-term water clarity or Secchi Disk Depth (SD) for Lake Limboto during 1991–2019. Pre-processing Landsat image was done before calculated SD using a selected model (i.e., removing contaminated water pixels, filtering images, and mitigating atmospheric effect). We then analyzed the long-term, temporal and spatial pattern change of SD in Lake Limboto. During the study period, linear regression showed a significant decrease in SD in Lake Limboto (R² = 0.21, p<0.001). The result showed Lake Limboto has seasonal change (peak= May, troughs= August - September). SD would positively and significantly correlate with monthly rainfall data if it shifted one-month later the rainfall period (R² = 0.46, p<0.05). Increasing population resulted in a decrease of SD during 2000 -2019 (R² = 0.81, p<0.001). The declining trend in the SD in Lake Limboto has the potential to continue under a higher future population, land cover change, and climate change. Remote sensing can be used to capture the change tendency of water clarity in Lake Limboto. Thus, useful for evaluating the implementation of a lake management plan.

1. Introduction

Water quality data is essential to support lake management. However, performing a routine water quality measurement remains a challenge related to time, labor, financial constraint. As a result, the water quality data of most Indonesian lakes are minimal.

Satellite remote sensing is often used as a supportive and powerful tool for extracting water quality data (e.g., [1-6]). The use of remote sensing techniques can thus provide opportunities to generate a water quality database for Indonesian lakes and reservoirs. Considering the longest historical data archive of Landsat TM and ETM+, these remote sensing data were selected to generate a water clarity database. A combination of high spatial resolution (30 m) and 16 days temporal resolution were considered good enough to monitor the water clarity change in Lake Limboto.

One of the vital water quality parameters is the Secchi disk depth (SD). SD is a measure of water clarity that is widely used to indicate water quality conditions [7,8]. SD is the simplest and the most often used parameter for limnological measurements because its values are easily understood [9]. Xu et al. (2016) [10] reported the use of Landsat TM/ETM+ to derived long-term water clarity data and revealed that anthropogenic activities might be driving factors for the long-term declining trend in water clarity.
Lake Limboto is a shallow lake in the north part of Sulawesi island. This lake provides essential ecological and hydrological functions, as well as a socioeconomic benefit [11]. Lake Limboto is one of 15 national priority lakes, with the shrinkage, turbidity, and siltation problem [12]. Several studies related to water quality have been done in Lake Limboto [11,13,14,15,16]. However, a long-term analysis of water quality change has never been done in this lake.

In 2019, the Indonesian Government by The Ministry of Environment and Forestry released Lake Limboto Management Plan [17]. It was stated that one of the benchmarks for lake management is the increase of SD. Therefore, the long-term SD database resulted from this study will thus provide useful data for lake managers and policymakers. Accordingly, the main objectives of this study are to [1] generate a long-term water clarity for Lake Limboto from historical Landsat TM, and ETM+ images from 1991 to 2019, [2] detect temporal water quality pattern and [3] analyze the water clarity driving factors.

2. Material and Methods

2.1. Study area

Lake Limboto is located in the North part of Sulawesi island in the Province of Gorontalo. Geographically laid between 122° 57' 40" E to 123° 02' 14" E and 0° 31' 58" N to 0° 34' 50" N, at 25 m above sea level (Figure1). The water surface is about 21 km$^2$ with the catchment area is about 890 km$^2$. Lake Limboto is a shallow lake with an average depth of 2.5 m. The ratio of the lake's watershed area to the water surface is quite large, 42.38.

2.2. In situ water clarity data

In situ Secchi Disk Depth (SD) to measured water clarity were collected from five field surveys. With three sampling sites for each campaign. A standard 20-cm-diameter Secchi disk painted in white and black quarters was used to measure the SD values. The SD values are shown in Table 1.

| Station | Investigation Month | May 2006 | Sep 2006 | May 2012 | Sep 2012 | Mar 2013 |
|---------|-------------------|----------|----------|----------|----------|----------|
| L1      |                   | 0.65     | 0.30     | 0.69     | 0.45     | 0.58     |
| L2      |                   | 0.51     | 0.38     | 0.52     | 0.50     | 0.46     |
| L3      |                   | 0.52     | 0.23     | 0.48     | 0.40     | 0.55     |
| average |                   | 0.56     | 0.30     | 0.56     | 0.45     | 0.53     |
2.3. Satellite Data Acquisition and pre-processing

A total of 309 Landsat TM/ETM+ images were downloaded from the United States Geological Survey (USGS) website [18]. However, due to the image quality and the number of lake water pixels, only 152 scenes were useful for analysis (L5: 22 scenes, L7: 130 scenes). The first image was acquired on October 26, 1991; the latest was on May 15, 2019. The number of useful Landsat images for each Year is given in Figure 2.

Preprocessing, including water pixel extraction, filtering, conversion Digital Number (DN) to radiance, atmospheric correction, and SD calculation, were performed following Setiawan et al. (2019) [19]. Water pixels were defined as Normalized Differences Water Index (NDWI) [20] and Modified Normalized Different Water Index MNDWI [21] index value > 0 (more than zero). Filtering was aimed to noise reduction following Nichol and Vohora [22]. Conversion of the DN Values to radiance referring to Chander et al. (2009) [23]. We used a two-step atmospheric correction method to avoid the requirement of ancillary data for correcting aerosol effects. In the first step, we carried out only a Rayleigh scattering correction using the 6S radiative transfer model without considering aerosol effects [24]. We selected a standard tropical atmospheric model for this correction. In the second step, we further mitigated the aerosol scattering effect pixel-by-pixel by subtracting the minimum of the Rayleigh corrected reflectance at the near-infrared (Rrc$_{4\lambda}$) and middle-infrared (Rrc$_{5\lambda}$) bands from those at the visible bands (Rrc$_{1\lambda}$):

$$Rc_{\lambda} = Rrc_{\lambda} - \min (Rrc_{4\lambda}, Rrc_{5\lambda})$$ (1)

where $Rc_{\lambda}$ is the atmospherically corrected reflectance at Landsat visible bands [19].

![Figure 2. The number of used Landsat images from 1991 – 2019.](image)

2.4. SD algorithm

Setiawan et al. [19] developed an algorithm to estimate SD using Landsat TM and ETM+ calibrated from nine Indonesian lakes, including Lake Limboto. Therefore, this paper was following and apply Setiawan et al. [19] algorithm rather than develop a new SD algorithm. The SD is calculated from atmospherically corrected reflectance of the Landsat TM/ETM+ using the following equation:

$$SD = \exp \left\{ -1.18 + 3.45(TM1/TM2) - 2.67(TM3/TM2) \right\}$$ (2)

where TM1, TM2, and TM3 are the atmospherically corrected reflectance of Landsat TM/ETM+ band 1 (Blue), band 2 (Green), and band 3 (Red) resulted from section 2.3, respectively.

2.5. Rainfall and population data

Rainfall data were obtained from TRMM 3B43 version-7 monthly data product over the period of 1998–2019 downloaded from Giovanni website ([https://giovanni.gsfc.nasa.gov/giovanni/]) [25]. The bounding box is 122.69, 0.52, 123.02, 0.79 for West, South, East, and Northbound, respectively. Population data were obtained from Gorontalo in Figure website [26].
2.6. Statistical analysis
Long-term SD data were plot using an R package named "ggplot2" [27]. We used the Locally Weighted Scatterplot Smoothing (LOESS) method to obtain long-term trends. LOESS uses Savitzky–Golay filter to get a trend line from scattered points by local polynomial regression. This method has been widely used in time-series data analyses [28,29,30]. We also calculate $R^2$ and p-value to describe the increasing or decreasing SD. Box plot diagram was selected to draw the yearly and monthly temporal change of SD and rainfall.

3. Result

3.1. Long-Term SD Changes in Lake Limboto from the Landsat TM/ETM+ Time Series
Figure 3 provides the average SD values estimated from 152 preprocessed Landsat images using eq. 2. The maximum average SD is 0.84 m, which occurred on May 27, 2006, and the minimum average SD is 0.20 m, which occurred on October 19, 2018. Overall, the average SD is 0.5 m, with a standard deviation of 0.12 m. Lehmusluoto et al. [31] reported SD of Lake Limboto in August 1993 was 0.4 m. Unfortunately, there is no image available on that date. However, this value was relatively close to our SD smoothed line. Other in situ data were plot in Figure 3 using the Red points showed a good result.

From long-term Landsat-based SD estimations, in general, the SD of Lake Limboto is continuously decreasing (shown by negative slope) despite several increasing occurred in some periods (e.g., 1995-1998, 2010-2014).

Figure 3. Long-term changes in the water transparency in Lake Limboto from 1991 to 2019. Black point: Landsat based SD. Redpoint: In situ SD. Blackline: LOESS trend analysis. Blueline: simple linear trend analysis. Gray areas: 95% confidence intervals of the trend analysis.

Figure 4 provides the averaged Landsat based SD of Lake Limboto grouped by Year (a) and month (b). We used a box plot diagram to observe the highest peaks or lowest troughs of SD that occurred. Figure 3 (a) observed that the weakest troughs happened in the Year 1994, and the maximum height happened in the Year 2006. Figure 3(b) showed a monthly change in SD in Lake Limboto. The highest average SD was in May, and the smallest SD was in August or September.

Figure 4. (a) SD of lake Limboto derived from Landsat TM/ETM+ grouped by year (b) SD of lake Limboto derived from Landsat TM/ETM+ grouped by month.
3.2. **Spatial variation of SD**

Figure 5 provides Map of SD derived from selected Landsat 5 and Landsat 7 images. Images selection based on interval time 5-year, cloud free images, acquired in April, May, or June. The chosen images were acquired on May 1995, June 2000, May 2005, April 2009, April 2015, April 2015, and May 2019. This selection aimed to analyze the SD spatial distribution visually. In general, lower SD was observed near the inflow rivers. Inflow rivers bring sediment from the large watershed and domestic waste from just the upstream of the lake. The water surface is different in each image caused by floating vegetation's dynamic existence (mostly Water Hyacinth) covering the lake surface. Using water index NDWI and MNDWI (see section 2.3), these non-water pixels were masked out from the analysis. The other factors which possibly influenced the spatial distribution in a shallow lake like Lake Limboto are wind speed and wind distribution. As the average water depth is only 2.5 m, the suspended material can be easily resuspended and redistributed.

![Figure 5](image-url)  
**Figure 5.** Map of SD derived from selected Landsat TM and Landsat ETM+ images. Landsat ETM+ images collected after May 31, 2003, have the Scan Line Corrector (SLC) failure; it made the data gaps over the lake surfaces [32]. However, the remained pixels are still useful.
3.3. Relationship of water clarity and rainfall data

Figure 6 provides the monthly rainfall data from the TRMM satellite, averaged by area of the watershed of Lake Limboto. The highest monthly rainfall was observed in 2010, while the lowest is in 2015 (Figure 6.a). It is noticeable from Figure 6.b that the lowest rainfall was statistically occurred in September, while the peak of rain occurred in May. According to Aldrian and Susanto (2003) [33], Lake Limboto is categorized in dominant rainfall region C, which has high rainfall from June to July and low rain from October to November. Comparing with Aldrian and Susanto (2003) [33] our result was slightly different; both peaks and troughs are shifted one month earlier.

![Figure 6. (a) Rainfall of lake Limboto watershed from TRMM data grouped by Year (b) Rainfall of lake Limboto watershed from TRMM data grouped by Month.](image)

**Figure 6.** (a) Rainfall of lake Limboto watershed from TRMM data grouped by Year (b) Rainfall of lake Limboto watershed from TRMM data grouped by Month.

Figure 7 provides the relationship between rainfall and SD of Lake Limboto. From Figure 7a, then SD has a positive correlation with precipitation. However, the significant value is relatively low. Considering the large watershed (890 km$^2$) compared with the water surface (21 km$^2$); ratio: 42.38, we assumed that there would be time lag (delayed) from rainfall to affect the lake's SD. Hence, we shifted SD value one month later than rains. As a result, the correlation still positive but with a higher coefficient of determination ($R^2 = 0.46$) and satisfy the significant level ($p<0.05$), as shown in Figure 7b. This result reveals that the water clarity of Lake Limboto was affected by the rainfall in the watershed one month before. However, a more detailed study on how Lake Limboto catchment responds to rain events variation using higher frequency data should be conducted.

![Figure 7. Rainfall vs SD relationship (a) same month comparison, (b) SD was set one month later than from rainfall.](image)

**Figure 7.** Rainfall vs SD relationship (a) same month comparison, (b) SD was set one month later than from rainfall.
3.4. Relationship of water clarity and population
The Lake Limboto watershed population has significant growth from 715,508 people in 1990 to 1,168,190 people in 2017 (R² = 0.988, p<0.001, Figure 8a). Linear regressions of the SD with population were conducted to evaluate the SD and anthropogenic activities relationship. When comparing the annual mean SD in Lake Limboto with the population before the year 2000 (R² = 0.988, p<0.001; Figure 8b-blue point), significant positive correlations were observed. Oppositely significant negative correlations were observed when comparing the annual mean SD in Lake Limboto with population after the Year 2000 (R² = 0.8136, p<0.0001; Figure 8b-orange point).

![Figure 8](image)

Figure 8. (a) Population data in Gorontalo province, the watershed of Lake Limboto, (b) relationship between population and SD.

4. Discussion
The use of two-band ratios (TM1/TM2 and TM3/TM3) of preprocessed atmospherically corrected reflectance of Landsat TM and ETM+ resulted in acceptable SD values for Lake Limboto, with the average value 0.5 m and the standard deviation 0.12 m. This result validates the selected SD estimation model's performance to generate a long-term SD database to monitor water transparency changes in the shallow turbid lake.

Our research recognizes the significant factors that regulate SD in Lake Limboto, including; the large ratio of the lake's watershed area to the water surface, temporal rainfall distribution, and population growth. Our result reveals that the water clarity of Lake Limboto was affected by the rainfall in the watershed from the previous month (one month delayed). This finding emphasizes that Lake Limboto has seasonal water clarity change, which is sensitive enough with the environmental change in the watershed. Water clarity of Lake Limboto shown continuously decreasing after the year 2000; it was positively related to the population reach 830.184 people. After the year 2000, as the population steadily grew, on the other hand, the SD value continuously decreasing.

5. Conclusion
This study derived temporal and spatial variations of the SD in Lake Limboto from 1991 to 2019. During the study period, the SD in Lake Limboto showed a significant decreasing trend. Monthly SD fluctuation was significantly and positively correlated to the monthly rainfall with one month delayed. After the year 2000, SD was significantly and negatively related to the human population. The declining trend in the SD in Lake Limboto may be continued under future population growth, land cover change, climate change. Remote sensing can be used to fill the water quality data gap and generate a long-term SD database to monitor water transparency changes and develop management strategies for sustainable lake use.
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