Estimation of changes in the lake water level and area using remote sensing techniques (Case study: Lake Toba, North Sumatra)

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Abstract. The decline in water level that occurred in Lake Toba, North Sumatra lately has become an important issue for the local government and the community around the lake. Climate factors also have a great impact especially when the extreme conditions ENSO and IOD occurred. The purpose of this research is to look at the relationship between rainfall and the ENSO and IOD through the changing of Lake Toba’s water surface level and area. Monitoring of the dynamics of the water surface level and area of Lake Toba can be analyzed through remote sensing by using Landsat imagery to be more effective and efficient. Then the image is processed by using the MNDWI (Modified Normalized Difference Water Index) method to separate water bodies from the land. Retrieval of Landsat imagery was taken in the range of 2008 - 2017, then selected years when the conditions of ENSO and IOD occurred. The results showed in 2008, which was the La-Nina year followed by a positive IOD, the surface area of water decreased to 4.45 km$^2$ from the average area, but in 2015 when the El-Nino phase followed by positive IOD the water surface area increased to 4.7 km$^2$ from the average area. ENSO and IOD did not have much influence on rainfall in the Lake Toba region but slightly affected the water surface level and area of Lake Toba.

1. Introduction

Lake Toba supports the social, economic, political, and cultural sectors in 7 (seven) surrounding districts, such as Samosir, Toba Samosir, Simalungun, North Tapanuli, Humbang Hasundutan, Dairi, and Karo. This is because Lake Toba has various functions in meeting human needs such as tourist attractions, fisheries, agriculture, transportation, freshwater sources and especially electricity [1,4]. Asahan Hydroelectric Power Plant is one of the hydropower plants located around the Lake Toba area and is very dependent on lake water in producing electricity, but there are problems regarding the water level which is reportedly declined lately [1,10]. Based on the lake water level measurement station in the Asahan Hydroelectric Power Plant, the water level of Lake Toba ranges from 902 - 905 m.a.s.l, the minimum water level needed to produce electricity is 902 m.a.s.l [1].

Rainfall and its relation to the phenomenon of the global climate cycle such as ENSO (El-Nino Southern Oscillation) and IOD (Indian Ocean Dipole) affect rainfall in most parts of Indonesia [2]. The dry season followed by El-Nino and positive IOD can cause extreme drought, whereas when the rainy season followed by La-Nina and negative IOD can increase rainfall intensity in most parts of Indonesia [2]. The purpose of this research is to look at the relationship between rainfall and the global climate cycle phenomenon (ENSO and IOD) through the changing of Lake Toba’s water surface level and area.
The use of remote sensing techniques aims to see the dynamics of changes in height and surface area of water in Lake Toba, which is considered an effective and efficient way to provide information spatially and accurately. In this study, the images used were Landsat 5 TM, 7 ETM + and 8 OLI / TIRS in the period of years 2008 - 2017. The analysis uses MNDWI (Modified Normalized Difference Water Index) developed by [3] the method serves to distinguish clearly between water bodies and land, making it easier for processing and analyze satellite imagery.

2. Materials
Lake Toba located in North Sumatra Province is the largest lake in Indonesia and Southeast Asia, the study area in this research is in the lake water catchment area of Lake Toba that stretches from 2°01' N - 3°0' N and 98°20' E - 99°50' E with an area of about 2,486 km² and is part of a volcanic formation on the Bukit Barisan which is called Tumor Batak [4].

![Figure 1. The study area (image acquired by Landsat 8) and rainfall pattern](image)

This region has the highest rainfall in November 349 mm and the lowest in June 112 mm. The average annual rainfall is 2555 mm and has an equatorial rain pattern, where this pattern has two peaks of the rainy season which is around March-May (MAM) and October - November (ON) [5].

2.1 Data collection
2.1.1. Satellite images. This study uses satellite imagery derived from Landsat 5 Thematic Mapper (TM) for the period 2008 - 2011, Landsat 7 ETM + only in 2012 and Landsat 8 OLI / TIRS for the period 2013 - 2017. The satellite imagery can be downloaded for free by accessing the Google Earth Engine (GEE), this process aims to obtain Landsat images that are cloud-free and the process is carried out using an algorithm provided by GEE. Processed satellite imagery is an image in the annual period, this is because in the cloud masking and filling process, several images data is needed to remove clouds. Here’s an example algorithm used in this study:

```javascript
// Function to cloud mask from the pixel_qa band of Landsat SR data
// Bits 3 and 5 are cloud shadow and cloud, respectively.
var cloudShadowBitMask = 1 << 3;
var cloudsBitMask = 1 << 5;
// Get the pixel QA band.
var qa = image.select('pixel_qa');
// Both flags should be set to zero, indicating clear conditions.
var mask = qa.bitwiseAnd(cloudShadowBitMask).eq(0) .and(qa.bitwiseAnd(cloudsBitMask).eq(0));
```
2.1.2. Rainfall data. The monthly rainfall data used in this study is the monthly average of the study area with the period 2008 - 2017. This data was developed by researchers at USGS in collaboration with the University of California, Santa Barbara (UCSB) to provide precipitation data with a global scale with a spatial resolution of 5 km or 0.05° [6]. Same as obtaining satellite data, rainfall data is obtained from the GEE database using this algorithm:

```javascript
var month_mean = ee.List.sequence(0, 10*12).map(function(n) { // .sequence: number of years from starting year to present
  var start = ee.Date('2008-01-01').advance(n, 'month'); // Starting date
  var end = start.advance(1, 'month'); // Step by each iteration
  return ee.ImageCollection('UCSB-CHG/CHIRPS/DAILY').filterDate(start, end).sum().set('system:time_start', start.millis());
});
var collection = ee.ImageCollection(month_mean);
var precipitation = collection.select('precipitation');
var precipitationVis = {
  min: 1.0,
  max: 17.0,
  palette: ['001137', '0aab1e', 'e7eb05', 'ff4a2d', 'e90000'],
};
Map.addLayer(precipitation, precipitationVis, 'Precipitation');
```

2.1.3. Water surface level. Data on Lake Toba water level is obtained from the results of the annual report of PT. INALUM Asahan [10] and literature study [7] in the period 2008 - 2017 with a unit of m.a.s.l/month.

2.1.4. Nino 3.4 Index. Nino index is a value derived from the dynamics of changes in sea surface temperature (SST) in the Pacific Ocean, where this value can describe the condition of ENSO. The Nino 3.4 index is located at 5° N – 5° S and 170° W – 120° W, a positive value illustrates that the SST temperature rises, generally if the index reaches a value of 0.5°C or more than El-Nino is in the active phase, conversely if the index value is below -0.5°C or more, the condition of La-Nina in the active phase, the range of data used in this study is monthly in the period 2008 - 2017 [8,9].

2.1.5. DMI (Dipole Mode Index). DMI is an index used to describe the process of IOD which can be accessed through http://www.jamstec.go.jp/aplinfo/sintexf/DATA/dmi.monthly.txt. ENSO that occurs in the Pacific Ocean, IOD occurs in the Indian Ocean. Positive IOD will cause a decrease in rainfall intensity, whereas negative IOD increases rainfall intensity in Sumatra and Borneo [2].
3. Methods

3.1. Surface water mapping

The MNDWI method developed by [3] was used to obtain information about the value of water pixels and land. The MNDWI method is considered better in separating water bodies and land compared to NDWI and NDVI. The MNDWI calculation process is carried out using GEE, in Landsat 5 and 7 images using band 2 (green) and 5 (SWIR) while for Landsat 8 using band 3 (green) and 6 (SWIR), following the calculation algorithm MNDWI:

\[
MNDWI = \frac{\text{Green} - \text{SWIR}}{\text{Green} + \text{SWIR}}
\]

3.2 Calculate surface water area

Calculate the surface area of the lake water using ArcMap 10.3 software, then make water and land classes and after that change the raster data to polygon, so the water surface area can be calculated through the area of polygon water using the calculate geometry function.

3.3. Moving average water level, CHIRPS, NINO 3.4 and DMI data

Moving averages are performed using data analysis tools in Microsoft Excel. This aims to clarify trends in the data, in this study water level, CHIRPS and ENSO are done by five months running mean, while DMI is done by 3 months running mean [2].

4. Result and Discussion

4.1 Surface water change

The surface area of water obtained from the extraction of Landsat satellite image data has a low correlation with water level measurement data which is equal to 0.34. The effect of ENSO and IOD is quite significant when it is related to the area compared to the level of the water surface, the correlation between the water surface area and (level) with ENSO and IOD is 0.63 (0.05) and 0.53 (-0.53), respectively. Positive and negative correlation values indicate the direction of the relationship between water surface level/area and ENSO/IOD. The higher the value of ENSO, the wider and higher the lake’s water surface and vice versa. In contrast to IOD which has a negative correlation, the higher the IOD value, the wider and higher the lake's water surface (Table 1).
Table 1. Annual water level, surface area, ENSO and DMI data in the period of 2008 – 2017

| Year | Water Level (m.a.s.l/year) | Water Surface Area (km²) | NINO 3.4 (°C) | DMI (°C) |
|------|---------------------------|--------------------------|--------------|---------|
| 2008 | 904.76                    | 1123.879                 | -0.70        | 0.30    |
| 2009 | 904.63                    | 1126.936                 | 0.17         | 0.27    |
| 2010 | 904.17                    | 1124.541                 | 0.13         | 0.24    |
| 2011 | 903.81                    | 1126.039                 | -0.83        | 0.41    |
| 2012 | 904.10                    | 1124.534                 | -0.08        | 0.35    |
| 2013 | 904.73                    | 1133.390                 | -0.02        | 0.11    |
| 2014 | 904.31                    | 1133.121                 | 0.28         | 0.16    |
| 2015 | 904.50                    | 1132.937                 | 1.37         | 0.39    |
| 2016 | 903.77                    | 1131.263                 | 1.11         | 0.06    |
| 2017 | 903.09                    | 1125.662                 | 0.09         | 0.47    |
| Average | 904.20                | 1128.230                 | -            | -       |

In 2008, which was the La-Nina year followed by a positive IOD, the water surface area decreased to 4.45 km² from the average area, but in 2015 when the El-Nino phase followed by positive IOD the water surface area increased to 4.7 km² from the average area. Lake Toba has the largest water body in Indonesia so that it has quite a large local climate factor, this is because when the influence of ENSO and IOD is very low in 2013 and 2014 the lake water surface area reached 1133 km².

4.2 Identification of ENSO and IOD Years

ENSO and IOD are global climate cycles that can affect rainfall in the Indonesian region, the incidence of La-Nina followed by positive IOD can lead to such a long drought, conversely when El-Nino followed by negative IOD can provide surplus rainfall. In identifying ENSO and IOD events in the period 2008 - 2017, researchers used a combination of rainfall data (CHIRPS), ENSO and IOD, from the graph it can be concluded that in 2008, 2009 La-Nina occurred, in 2011 and 2012 La-Nina was followed by a positive IOD where conditions resulted in a decrease in lake water surface level and area, while El-Niño occurred in 2010 and 2015, only in 2015 El-Nino that was followed by a positive IOD, this resulted in an increase of the water surface level and area of the lake (Table 1 and Table 2). The rainfall is not too significant if correlated with DMI data which is equal to -0.13, while ENSO shows a greater correlation compared to DMI which is equal to -0.45. The negative relationship illustrates the higher the value of ENSO and IOD, the lower the rainfall in this region (Figure 3).

Figure 3. ENSO and CHIRPS (moving average 5 months) and IOD (moving average 3 months) in 2008 – 2017 period
Table 2. ENSO and IOD occurrence in 2008 - 2017

| Climate Condition | Year        |
|-------------------|-------------|
| El – Nino         | 2010, 2015  |
| La – Nina         | 2008, 2009, 2011, 2012 |
| Positive IOD      | 2011, 2012, 2015, 2017 |
| Negative IOD      | -           |

The decrease in water level and area can be seen through Landsat satellite imagery with MNDWI composite by taking the Mogang Port area, Palipi District, Samosir Regency. The brown color in the image depicts the land area, blue and yellow depict the water area and the red line is the coastline in 2008 when La – Nina occurred. The black line during El-Nino in 2015 where the body of water exceeds the coastline and this also happened in 2013 with the blue line when there was no effect of ENSO and IOD (Figure 4).

Figure 4. Water surface conditions when La - Nina, El - Nino and normal condition

5. Conclusion
Rainfall in the study area has a weak negative correlation with ENSO and IOD, the authors suspect that the Lake Toba region has a vast body of water so this can create local climate dynamics in this region. The negative relationship illustrates the higher the value of ENSO and IOD, the lower the rainfall intensity that occurred in this area. Unlike the case with the water surface level and area that has a negative correlation with ENSO but positive with IOD. Changes in water surface level and area are influenced by the presence of ENSO and IOD factors, both of which play a role in influencing the rainfall intensity in the Lake Toba’s catchment area. The use of remote sensing techniques has proven to be able to answer the problems regarding the change in water surface level and area in Lake Toba, this is expected to help local governments in developing the Lake Toba area and open up new scientific insights for the community.
6. References

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