Trend of rainfall over Indonesian major lakes from tropical rainfall measuring mission data

Hidayat
Research Center for Limnology, Indonesian Institute of Sciences, Cibinong Science Center - Botanical Garden, Cibinong 16911, Indonesia
hidayat@limnologi.lipi.go.id

Abstract. Establishing patterns of natural variability of water resources in lakes is important for water management. However, the availability of reliable data often becomes obstacles, especially in ungauged regions. Rainfall products from Tropical Rainfall Measuring Mission (TRMM) potentially fill this gap. The aim of this study is to assess the trend of rainfall over Indonesian major lakes using TRMM rainfall estimates to investigate the natural variability of rainfall over the lakes. TRMM 3B43 monthly data over the period of 1998–2017 obtained from Giovanni data portal maintained by NASA were used to assess the trend of rainfall over Indonesian major lakes. Rainfall correlation with El Niño-Southern Oscillation (ENSO) variability was also investigated using Southern Oscillation Index (SOI) and Multivariate ENSO Index (MEI). Trend analysis was carried out using Mann-Kendall test. Rainfall depths over Lake Laut Tawar in Sumatra tend to gradually decline, which is confirmed by the Mann-Kendall test. Result of the test of rainfall over all other investigated lakes on Kalimantan, Sulawesi, Papua, and Java indicate no trends except for that of Lake Paniai in Papua, which indicates an increasing trend.

Keywords : ENSO, TRMM, rainfall

1. Introduction
Establishing patterns of natural variability of water resources in lakes is important for water management in the present and future time of increasing water demand and climate variability. However, the availability of reliable data including those on rainfall often becomes obstacles, especially in ungauged remote regions. The availability of satellite-based meteorological data including that of rainfall products from Tropical Rainfall Measuring Mission (TRMM) potentially fill this gap. TRMM precipitation estimates have been available since the satellite was launched in 1997. TRMM combines observations from multiple satellites, as well as gauge analyses where available with a resolution of 0.25° x 0.25° in a latitude band covering 50° N to 50° S [1]. TRMM rainfall estimates have been reported to be valuable as an alternative source of rainfall information in hydrological studies [2,3].

Indonesia has at least 840 natural lakes, 735 ponds and 162 reservoirs [3] spreading over Indonesian Archipelago, most of them are fed by rainfall as source of water. The aim of this study is to assess the trend of rainfall over Indonesian major lakes using the TRMM rainfall estimates to investigate the natural variability of rainfall over this important fresh water resources. The representative lakes on each major islands of Indonesia and their brief descriptions are given below.
1. Sumatra:
   a) Lake Laut Tawar (Aceh). Lake Laut Tawar is located in the Gayo Highland near Takengon of Central Aceh Regency. This lake has important roles for local Gayo community as source of freshwater for domestic, agriculture, industry, and fishery uses [5].
   b) Lake Toba (North Sumatra). Lake Toba is the largest lake in Indonesia that has large potentials of water resources [6]. It has been used for electricity generation through the Sigura-gura hydro-power plant with a capacity of 286 MW, for tourism, also for fishery production and source of drinking water for domestic use.
   c) Lake Maninjau (West Sumatra). Lake Maninjau, is socially important to local community for domestic uses and recreational function, economically as source of water for irrigation, fishery (both open waters and aquaculture fishery activities), tourism, and hydro-power generation with a capacity of 68 MW. Ecologically, the lake plays its role in controlling groundwater balance, as habitat for aquatic organism, as well as controlling micro-climate [7].

2. Kalimantan
   a) Sentarum Lakes complex (West Kalimantan). The Sentarum Lakes complex is an assemblage of floodplain lakes in the upper Kapuas River system of Kapuas Hulu Regency. The lakes area is declared as a Ramsar site due to its unique tropical wetland ecosystems rich in biodiversity of typical aquatic as well as terrestrial flora and fauna [2]. The Kapuas lakes are important for local communities, not only as a source of water for domestic purposes, but also to sustain the livelihoods of people, especially in the open water fishery subsector.
   b) Mahakam cascade lakes: Semayang, Melintang, Jempang Lakes (East Kalimantan). The Mahakam cascade lakes are part of the middle Mahakam River floodplain system that include some 30 shallow lakes located in the Kutai Kartanegara and Kutai Barat Regencies. The lakes are the core of inland fisheries in East Kalimantan and is considered one of the most productive freshwater fisheries in south-eastern Asia [8].

3. Sulawesi
   a) Malili lakes complex: Matano, Towuti, Mahalona Lakes (South Sulawesi). The Malili Lakes are the only hydrologically connected ancient lake system in the world located in the central eastern part of Sulawesi that include three major lakes, Matano, Mahalona, and Towuti, and two smaller lakes, Wawantoa and Masapi [9]. These tectonic lakes are biodiversity hotspots.
   b) Lake Tempe (South Sulawesi). This floodplain lake experiences hydrological variation during dry and wet seasons. Its area is highly influenced by fluctuating water level, ranging from 280–430 km² with a maximum depth of 9 m during extreme high water level to only about 10 km² remain inundated during low water period with a maximum depth of 1.5 m [10].
   c) Lake Poso (Central Sulawesi). Lake Poso is a large (323 km²; 450 m deep) tectonic lake located at about 502 m asl. The lake drains northward via the Poso River into the Gulf of Tomini.

4. Papua
   a) Lake Sentani (Papua). Lake Sentani is located on the South of the City of Sentani at about 70–90 m asl in Jayapura Regency. The lake has an area of 93.6 km² that is part of the Cyclops Nature Reserve [11]. Its source of water is from direct precipitation and from at least 14 mountain rivers debouching into the lake.
   b) Lake Paniai (Papua). It is an ancient tectonic lake (160 km² area; 54 m deep) located near the backbone of Central Papua Island mountain range at 1.742 m asl [12]. On the south of this lake, lies a smaller sister lake, Lake Tage (24 km² area; 52 m deep).

5. Java
   a) Citarum cascade dams: Saguling, Cirata, and Jatiluhur Dams (West Java). The three dams are interconnected reservoirs of the Citarum river located in West Java. Outflow from Saguling Dam goes to Cirata Dam, outflow from Cirata Dam goes to Jatiluhur Dam and
outflow from Jatiluhur is used for many purposes, including electricity generation, domestic consumption, irrigation water for agricultural uses and flushing Jakarta canals [13].

b) Gajah Mungkur Dam (Central Java). Gajah Mungkur or Wonogiri Dam is located in Wonogiri Regency, which was built with the main purpose for flood control that often occurs due to the overflowing of Bengawan Solo river in the rainy season [14]. It is also used as source of freshwater for drinking water, irrigation, and hydropower.

2. Methodology
In this contribution, TRMM 3B43 version-7 monthly data product over the period of 1998–2017 obtained from Giovanni data portal (https://giovanni.gsfc.nasa.gov/giovanni/) maintained by National Aeronautics and Space Administration were used to assess the trend of rainfall over Indonesian major lakes. Thirteen major lakes on five major Indonesian islands were selected. Table 1 shows the bounding box of the lake catchments used for the area-averaged TRMM data download.

Rainfall correlation with El Niño-Southern Oscillation (ENSO) variability was investigated using Southern Oscillation Index (SOI; http://www.cpc.ncep.noaa.gov/data/indices/soi) and Multivariate ENSO Index (MEI; http://www.esrl.noaa.gov/psd/enso/mei/mei.html). Normalized monthly precipitation (PN) was taken as 

\[ P_N = \left( \frac{P - \bar{P}}{\sigma_P} \right) \]

where \( \bar{P} \) is mean and \( \sigma_P \) is standard deviation, which were plotted along with SOI time-series. Trend analysis was carried out using Mann-Kendall test, a non-parametric monotonic trend detection [15] that test of the null hypothesis (H₀) of trend absence in the time series, against the alternative of trend (H₁). The result of the test is returned in H=0 indicates a failure to reject the null hypothesis at the α significance level. H=1 indicates a rejection of the null hypothesis at the α significance level.

| Lake Name                  | West bound | South bound | East bound | North bound |
|---------------------------|------------|-------------|------------|-------------|
| Lake Laut Tawar           | 96.82      | 4.50        | 97.03      | 4.66        |
| Lake Toba                 | 98.50      | 2.25        | 99.15      | 3.00        |
| Lake Maninjau             | 99.90      | -0.42       | 100.27     | -0.20       |
| Sentarum Lakes Complex    | 111.96     | 0.56        | 112.30     | 1.10        |
| Mahakam Cascade Lakes     | 115.50     | -0.50       | 116.70     | 0.50        |
| Malili Lakes Complex      | 121.10     | -3.01       | 121.78     | -2.92       |
| Lake Tempe                | 119.74     | -4.25       | 120.25     | -3.90       |
| Lake Poso                 | 120.39     | -2.18       | 120.75     | -1.72       |
| Lake Sentani              | 140.24     | -2.76       | 140.76     | -2.49       |
| Lake Paniai               | 136.15     | -4.15       | 136.51     | -3.74       |
| Citarum Cascade Dams      | 107.14     | -7.18       | 107.70     | -6.38       |
| Gajah Mungkur Dam         | 110.73     | -8.06       | 111.05     | -7.72       |

3. Results and discussion
Rainfall patterns in Indonesia are generally influenced by ENSO and the Indo-Pacific air-sea interaction. Twenty years of rainfall data length used in this study is actually less than the recommended data length of 30 years. However, the current analysis can be regarded as a modest proxy to rainfall characteristics over Indonesian major lakes. The analysis of rainfall trends over Indonesian major lakes are presented herein for the five Indonesian major islands.

3.1. Sumatra
Average annual rainfalls over Lake Laut Tawar, Lake Toba, and Lake Maninjau are 2600, 2745, and 2670 mm, respectively. Figure 1 a, b, c show the average TRMM 3B43 monthly rainfall estimates over Sumatran lakes plotted along with those of El-Niño (2015) and La-Niña (2000) years. The three
lakes were affected by ENSO although with different intensity. For example, during the 2015 El-Niño year, the three lake basins generally experienced below average rainfall depth except for January, June, and August for Laut Tawar and March, April, June and November for Maninjau with above average rainfall. Another example with the opposite condition was that during the La-Niña year 2000, Lake Laut Tawar experienced a highly above average rainfall for nearly the whole year followed by Lake Toba with an extremely high rainfall depth in September and Lake Maninjau with a high rainfall depth in November but with also below average rainfall depth during the first half of the year. ENSO variability affects rainfall pattern in Sumatran lake basins with varied intensity among places and times, for example, using only data in August Rainfall–SOI correlation coefficients were respectively 0.25, 0.46, and 0.29 for Lake Laut Tawar, Lake Toba, and Lake Maninjau (Fig. 1 d). MEI–rainfall depth correlation coefficients for August were respectively 0.00, -0.32, and -0.09 for Lake Laut Tawar, Lake Toba, and Lake Maninjau. Figure 2 a shows the variation of normalized monthly rainfall over Lake Toba plotted along with SOI time series from January 1998 through December 2017. During certain periods, rainfall rates over this lake perfectly follow the pattern of SOI such as those in early 1998, late 2000, and late 2016 indicating a very strong correlation, while during other periods they show no clear relation such as those in late 2005, early 2007, and early 2014.

Figure 1. Average TRMM monthly rainfall estimates along with those during an El Niño (2015)/La Niña (2000) years over Lake Laut Tawar (a) Lake Toba (b), Lake Maninjau (c), and variation of SOI–rainfall correlation values throughout the year.

Rainfall depths over the Sumatran Lake basins show a gradual decline from year to year. Figure 2 b shows the accumulated annual rainfall over the lake basins with their corresponding linear trend lines. This trend is in line with previous research [7,16]. The decline of rainfall depth over Toba Lake basin has caused the decrease of water levels in the lake [16]. Similar trend was found by other team [7] who analysed rainfall data from rain gauges in the catchment area of Lake Maninjau for the period 1994–2000. They found that rainfall depth over Maninjau Lake basin shows a decreasing trend that
needs to be anticipated in terms of the sustainability of the lake’s function for water supply, hydro-power generation, tourism, as well as its ecological function. The declining trend is also in agreement with previous research [5], who found that water levels of Lake Laut Tawar has decreased about 1 to 2 m. They reckon that this issue was due to global warming effect and deforestation in the catchment area of the lake, which in turn has caused the decline in water resources around the lake and the decrease of fishery production of about 80% during the period of 1989 through 2008. The result of the Mann-Kendall test only confirms the trend of rainfall over Lake Laut Tawar.

![Figure 2. Normalized monthly rainfall over Lake Toba plotted along with SOI (a) and Annual rainfall over Lakes Laut Tawar, Toba, and Maninjau (b)](image)

3.2. Kalimantan

Both the Sentarum Lakes complex and Mahakam Cascade Lakes are flood plain lakes. Hydrological regime is the key factor determining the ecological function and biodiversity in flood plain lake. Average annual rainfalls over Sentarum Lakes complex and Mahakam Cascade Lakes are 3680 and 2770 mm, respectively. Figure 3 a and b show the average TRMM 3B43 monthly rainfall estimates over those lakes. Using the entire 20 years data series, SOI-rainfall depth correlation coefficients were 0.14 for Sentarum and 0.25 for Mahakam Cascade Lakes, while those using only August were 0.68 for Sentarum and 0.70 for Mahakam Lakes. Figure 3 c shows SOI–rainfall correlation throughout the year. MEI–rainfall depth correlation coefficients were -0.19 for Sentarum and -0.27 for Mahakam Cascade Lakes, while those using only August were -0.54 for Sentarum and -0.65 for the Mahakam Lakes. These numbers indicate that rainfall over the Mahakam Lakes are more strongly affected by ENSO. Figure 4 a shows the time series of normalized monthly rainfall over Mahakam Lakes plotted along with SOI. Figure 4 b shows the annual rainfall over the Sentarum and Mahakam lake basins. Mann-Kendall test results indicate no trend of rainfall over the selected lake basins of Kalimantan.

3.3. Sulawesi

Average annual rainfalls over Malili lakes complex, Lake Tempe, and Lake Poso are 3010 and 2235, and 3075 mm, respectively. Figure 5 a, b, c show the average TRMM 3B43 monthly rainfall estimates over those lakes. Using the entire 20 years, SOI–rainfall depth correlation coefficients were 0.16 for Malili, 0.21 for Tempe, and 0.20 for Poso. These correlation values are varied throughout the year as shown in Figure 5 d, which also indicates that rainfall over the three Lakes are equally affected by ENSO. The highest correlation of SOI and rainfall over the catchments of lakes in Sulawesi of about 0.7 were found during the period of July through November. Using the entire data series, MEI–rainfall depth correlation coefficients were -0.08 for Malili, -0.17 for Tempe, and -0.13 for Poso. Similar pattern (opposite signs) with those of SOI (Figure 5 d) was found when MEI-rainfall analysis in monthly basis was carried out. Figure 6 a shows the variation of normalized monthly rainfall over Lake Tempe plotted along with SOI time series. Figure 6 b shows the annual rainfall over the Malili,
Tempe, and Poso lake basins. Mann-Kendall test results indicate no trend of rainfall over those lakes of Sulawesi.

3.4. Papua
Average annual rainfalls over Lake Sentani and Lake Paniai basins are 2010 and 3870 mm, respectively. Figure 7 a and b show the average TRMM 3B43 monthly rainfall estimates over those lakes. SOI–rainfall depth correlation coefficients were 0.05 and 0.11 for Lake Sentani and Lake Paniai respectively. Throughout the year, correlation between SOI and rainfall over Paniai Lake basin were generally higher than those over Lake Sentani basin with the highest value of about 0.6 for July (Figure 7 c). Using the entire dataset, MEI–rainfall depth correlation coefficients were -0.15 and -0.14 for Lake Sentani and Lake Paniai respectively, while analysis on monthly basis results in similar patterns as those of Figure 7 c except for the opposite signs. Figure 8 a shows the variation of normalized monthly rainfall over Lake Paniai plotted along with SOI time series from January 1998 through December 2017. Figure 8 b shows the annual rainfall over the Sentani and Paniai lake basins. Result of the Mann-Kendall test indicates there is a trend of rainfall over Lake Paniai basin (increasing).

Figure 3. Average TRMM monthly rainfall estimates along with those during El Niño (2015) and La Niña (2000) years over Sentarum Lakes Complex (a), Mahakam Cascade Lakes (b), and variation of SOI–rainfall correlation values throughout the year (c)

Figure 4. Normalized monthly rainfall over Mahakam Lakes plotted along with SOI (a) and annual rainfall over the Sentarum and Mahakam Lakes (b)
3.5. Java
Average annual rainfalls over Citarum Cascade Dams and Gajah Mungkur Dam basins are 2795, and 2300 mm, respectively. Figure 9 a, and b show the average TRMM 3B43 monthly rainfall estimates over the basins of those man-made lakes. Using the entire 20 years, SOI–rainfall depth correlation coefficients were 0.08 for Citarum and 0.16 for Gajah Mungkur. Throughout the year, the highest correlation of about 0.7 was found in June (Fig. 9 c). Using the entire dataset, MEI–rainfall depth correlation coefficients were -0.11 for Citarum and 0.20 for Gajah Mungkur, while results of analysis...
on monthly basis are shown in Figure 9 d. Figure 10 a shows the variation of normalized monthly rainfall over Gajah Mungkur basin plotted along with SOI time series. Figure 10 b shows the annual rainfall over the basins of Citarum Cascade Dams and Gajah Mungkur Dam. Mann-Kendall test results indicate no trend of rainfall over those dams of Java.

![Graphs](image)

**Figure 7.** Average TRMM monthly rainfall estimates along with those during an El Niño (2015) and La Niña (2000) years over Lake Sentani (a), Lake Paniai (b), and variation of SOI–rainfall correlation values throughout the year (c)

![Graphs](image)

**Figure 8.** Normalized monthly rainfall over Lake Paniai plotted along with SOI (a) and annual rainfall over the Sentani and Paniai lake basins with their corresponding linear trend lines (b)

### 4. Conclusion

Rainfalls over Indonesian major lakes are generally affected by ENSO variability with varied correlation values throughout the year. This study that based on 20 years of available TRMM data
agrees the declining trend of annual rainfall over Sumatran lakes basins (Laut Tawar, Toba, and Maninjau) found by previous site-specific respective researches. However, the Mann-Kendall test only confirms that of Laut Tawar. Result of Mann-Kendall test of rainfall over all other investigated lakes in Java, Kalimantan, Sulawesi and Papua indicate no trends except for that of Lake Paniai (Papua), which indicates an increasing trend.

Figure 9. Average TRMM monthly rainfall estimates along with those during an El Niño (2015)/La Niña (2000) years over Citarum Cascade Dams (a), Gajah Mungkur Dam (b), SOI–rainfall correlation throughout the year (c), and variation of MEI–rainfall correlation values throughout the year (d)

Figure 10. Time series of normalized monthly rainfall over Gajah Mungkur Dam plotted along with SOI (a) and annual rainfall over the Citarum Cascade Dams and Gajah Mungkur Dam basins (b)
References

[1] Huffman G J, Adler R F, Bolvin D T, Gu, G, Nelkin, E J, Bowman, K P, Yong Y, Stocker E F and Wolff D B 2007 The TRMM Multi-satellite Precipitation Analysis (TMPA): Quasi-global, multi-year, combined-sensor precipitation at fine scales J. Hydrometeor, 8 38-55

[2] Hidayat H, Teuling A J, Vermeulen B, Taufik M, Kastner K, Geertsema T J, Bol D C C, Hoekman D H, Haryani G S, Van Lanen H A J, Delinom R M, Dijksma R, Anshari G Z, Ningsih N S, Uijlenhoet R, and Hoitink A J F 2017 Hydrology of inland tropical lowlands: the Kapuas and Mahakam Wetlands Hydro. Earth Syst. Sci. 21 2579–94

[3] Su F, Hong Y and Lettenmaier, D P 2008 Evaluation of TRMM multiscale precipitation analysis (TMPA) and its utility in hydrologic prediction in the La Plata basin J. Hydrometeor. 9 622- 40

[4] Komite Nasional Pengelolaan Ekosistem Lahan Basah 2004. Strategi Nasional dan Rencana Aksi Pengelolaan Lahan Basah di Indonesia. Kementerian Lingkungan Hidup p 153 Available at http://wetlands.or.id/PDF/buku/Buku%20NSAP%202004.pdf

[5] Muchlisin Z, A, Siti Azizah M N, Rudi E and Fadli N 2009 Danau Laut Tawar and Beberapa Permasalahannya. Proc. Workshop Selamatan Danau Laut Tawar, Takengon 21-22 November 2009. Accessed on 29 Aug 2018 from internet site at: https://www.researchgate.net/publication/268309345

[6] Lukman 2013 Danau Toba: Karakteristik Limnologis dan Mitigasi Ancaman Lingkungan dari Pengembangan Karamba Jaring Apung Jakarta: LIPI Press

[7] Fakhrudin M, Wibowo H, Subehi L, and Ridwansyah I 2002 Karakterisasi Hidrologi Danau Maninjau Sumbar. Proc. Seminar Nasional Limnologi: Menuju Kesinambungan Pemanfaatan Sumberdaya Perairan, Puslit Limnologi LIPI, Bogor, 22 April 2002 65 – 75

[8] MacKinnon K, Hatta G, Halim H, and Mangalik, A 1996 The ecology of Indonesia series – The ecology of Kalimantan, Oxford University Press

[9] Vaillant J J, Haffner D G, and Cristescu M E 2011 The Ancient Lakes of Indonesia: Towards Integrated Research on Speciation Integrative and Comparative Biology 51 (4) 634–43 doi:10.1093/icb/icr101

[10] Toruan R L and Setiawan F 2017 Hydrological regimes and zooplankton ecology at Tempe Floodplains, Indonesia: preliminary study before the operation of the downstream barrage In book: Trends in Asian Water Environmental Science and Technology doi: 10.1007/978-3-319-39259-2_p 10

[11] Fauzi M, Rispiningtati and Hendrawan A P 2014 Kajian Kemampuan Maksimum Danau Sentani dalam Mere duksi Banjir di DAS Sentani J. Teknik Pengairan, 5 (1) 42–53

[12] Hehanussa P E, Haryani G S and Tjiptasumara 2005 Two ancient lakes in Paniai and Tage, the central mountains range, Papua, Indonesia Proc. 11th World Lake Conference, Kenya vol 2 253-58

[13] Boer R, Dasanto B D, Ferdinan and Mathinus D 2012 Hydrologic Balance of Citarum Watershed under Current and Future Climate in W. Leal Filho (ed.) Climate Change and the Sustainable Use of Water Resources, Climate Change Management, DOI: 10.1007/978-3-642-22266-5_3, Springer-Verlag Berlin Heidelberg

[14] Hidayani F, Sardjono Y, Fandeli C, Rukmini A R 2017 Creative Environmental Energy Technology assessment Hydroelectric Power Plant (Case Study of Wonogiri Reservoir) Indonesian Journal of Physics and Nuclear Applications 2 (3) 101-10

[15] Burkey and Jeff 2006 A non-parametric monotonic trend test computing Mann-Kendall Tau, Tau-b, and Sens Slope written in Mathworks-MATLAB implemented using matrix rotations. King County, Department of Natural Resources and Parks, Science and Technical Services section. Seattle, Washington. USA. Matlab code available at https://www.mathworks.com/matlabcentral/fileexchange/11190-mann-kendall-tau-b-with-sen-s-method-enhanced

[16] Tanakamaru H, Kato T and Takara K 2004 Water balance analysis and water level simulation of Lake Toba, Indonesia. Proc. 2nd Asia pacific Association of Hydrology and Water Resources Conf. 2 107-15