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Evaluation of Lake Toba's water level decline in Indonesia over the past six decades

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ABSTRACT

Lake Toba's water level has significantly declined during the last six decades. Unfortunately, the studies that have been conducted are only sectoral, both in terms of temporal aspects and influencing parameters. Hence, a comprehensive study has been conducted to explain the significant factor causing the Lake Toba's water level decline. Climate change and hydrological issues have become significant concerns. Change point analysis, trend tests, and Structural Equation Model (SEM) were used in this study. Since the results of the analysis show a significant decrease in the water level of Lake Toba in 1984, the discussion of the water level of Lake Toba is divided into two periods, namely Period I (1957–1983) and Period II (1984–2020). This division is also in line with the periods before and after the operation of Siruar Dam. This study revealed that climate change has occurred in the Lake Toba watershed with a significant increasing trend in temperature, evaporation, and rainfall of 0.003 °C, 1.4 mm, and 8.9 mm per year, respectively. Climate factors primarily contributed to the decline in Lake Toba's water level in Period I, whereas the use of water for hydroelectric power plants had a greater impact in Period II. However, with effective regulation of the Siruar Dam during Period II, the water level of Lake Toba has been maintained at a stable level within the predetermined threshold. The study's findings are intended to be useful to the government, stakeholders, and water users in devising mitigation and adaptation measures for the long-term management of Lake Toba's water resources.

1. Introduction

Lake water level decline has become a global issue (Wurtsbaugh et al., 2017; Yao et al., 2023). Changes in lake water levels are susceptible to climate change and human activities (Bashirian et al., 2020; Jalili et al., 2016). Changes in climate parameters such as rainfall, temperature and evaporation (Arkian et al., 2018; Tal, 2019), human activities such as regulation of dams, use of water for industry and agricultural irrigation, as well as changes in land use, have been proven to reduce the lake water level (Davraz et al., 2019; Fan et al., 2020; Minale, 2019; Yuan et al., 2015). Groundwater decline also has a great impact in lake water level (Noori et al., 2021, 2023a). Lake water resources management (Wubneh et al., 2022; Zhou et al., 2023) plays a vital role in environmental, social and economic dynamics (Fufa et al., 2024; Guo et al., 2015; Schulz et al., 2020). Therefore, an understanding of the decline in lake water levels is needed to develop, manage, and sustain lake water resources and support sustainable development goals (SDGs).

Lake Toba is the largest Quaternary caldera and has the most active seismicity in the world (Chesner, 2012; Williams, 2012). In the last sixty years, there has been a significant decline in the lake water level (Irwandi et al., 2019, 2021; Loebis, 1999; Sihotang et al., 2012), with a decreasing trend of around 2.4 cm per year (Irwandi et al., 2019). The decline in Lake Toba's water level has a significant impact on various sectors, including tourism, agriculture, plantations, fisheries, and industry (Sihotang et al., 2012; Wesli, 2017). The impact on the industrial sector is a significant concern because it is related to the national strategic industry in the form of hydroelectric power plants for aluminium

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smelting and to supply electricity in North Sumatra Province (KLH, 2014).

Many studies on the impact of climate change on lake water levels have been reported, including those on Lake Poyang in China (Wang et al., 2018), Lake Baiyangdian in China (Han and Bu, 2023), Lake Urmia in Iran (Alizadeh-Choobari et al., 2016), and Lake Qinghai in China (Zhu et al., 2023). Additionally, research on the effects of human activities on lake water levels has been conducted on Lake Burdur in Turkey (Davraz et al., 2019), Lake Victoria in Africa (Okotto-Okotto et al., 2018), Lake Sibinacocha in Peru (Bello et al., 2023), and Lake Urmia in Iran (Ghale et al., 2018). Recent research by Mahdian et al. (2024) and Mozafari et al. (2023) shows that eutrophication can worsen conditions that cause lake water levels to decline, although it is not a direct cause. These studies indicate that rising air temperatures and declining precipitation levels are indicators of the climate change. Moreover, irrigation for agriculture, changes in land use, and dam regulatory activities are the main factors of human activities.

Several previous studies have tried to explain the causes of Lake Toba's declining water levels, but there are still significant areas for improvement. Acreman et al. (1993) investigated the decline in Lake Toba's water level using the water balance method. They concluded that excessive water consumption by power plants was a significant factor contributing to the lake's decline between 1984 and 1987. Loebis (1999), Oelim (2000), and Irwandi et al. (2017) concluded that the decline in Lake Toba's water level was linked to reduced rainfall in the surrounding catchment area. Meanwhile, Tanakamaru et al. (2004) explained that maintaining the water balance of Lake Toba is largely dependent on the water usage by hydroelectric power plants. However, these studies have not been conducted over a sufficient period of time for a comprehensive analysis. The decline in Lake Toba's water level has only been analyzed for a specific period (i.e., after the operation of the Siruar Dam and hydroelectric power plants), making it difficult to determine whether the observed changes represent a decline or merely fluctuations. Furthermore, the causes of the decline in Lake Toba's water level were explained only qualitatively, without analyzing other contributing factors. As a result, the main factors behind the decline could not be precisely identified. The recent studies by Irwandi et al. (2019, 2021) indicate a decline in the water level of Lake Toba between 1957 and 2016. However, the cause of the decline remains unknown, and the distinction between the periods before and after the operation of the hydroelectric power plant has not been addressed. Meanwhile, Irwandi et al. (2023) focus solely on analyzing the impact of climate change on rainfall and temperature in the Lake Toba watershed. They have not examined the relationship between this climate change and the decline in Lake Toba's water level. Therefore, in this study, lake water level data analysis will be carried out from the beginning to the end of the observation period. This will allow the causes of the decline in water level and the dominant factors causing the decline to be explained comprehensively.

This study uses a more comprehensive approach, combining quantitative analysis with more appropriate statistical techniques, to address the shortcomings of previous research. This study conducted change point detection to show significant changes in the water level of Lake Toba so that the influence of nature (climate) and human activities can be separated. Trend analysis was used to identify the increasing or decreasing patterns in the lake level, which serve as indicators of climate change. This analysis includes the Mann–Kendall test (Kendall, 1975; Mann, 1945) and Sen's slope estimator method (Sen, 1968). They are commonly used to test trends in climate and hydrological data, because they do not require normality and are not affected by data outliers (Lima-Quispe et al., 2021; Mewded et al., 2022; Mohammed et al., 2022; Yagbasan et al., 2017) and are simple in operation (Kim et al., 2024; Noori et al., 2023b). Literature indicates that the Mann–Kendall test and Sen's slope estimator method have been used in several studies (Bashirian et al., 2020; Dubey et al., 2023; Jalili et al., 2016; Jenifer and Jha, 2021; Noori et al., 2022b; Yuan et al., 2015). Meanwhile, SEM was chosen to explore the indirect and direct influences of climate changes, hydrological, and land use variables on the connectivity of lakes (Liang et al., 2021). This approach not only provides a more comprehensive analysis but also makes new contributions. Thus, this study can explain the important and dominant factors causing the decline in the water level of Lake Toba.

This study is expected to reveal the most dominant factors influencing the decline in the water level of Lake Toba over the past 64 years. This study will analyse the impact of climate change (temperature, evaporation, and rainfall) and hydrological factors (inflow and outflow) on the decline in the water level of Lake Toba so that the results of this study can be used as input in planning and programs for climate change adaptation and mitigation of sustainable lake water resources. This is to support sustainable development goals 6 and 13. The use of Lake Toba water to operate hydroelectric power plants in supporting national strategic industries also supports sustainable development goal 7, including using renewable energy and optimizing infrastructure to support clean energy (Kementerian, 2020).

2. Study area and data

2.1. Study area

Lake Toba, the largest volcanic lake in the world, is located at 2°21′32″–2°56′28″ North Latitude and 98°26′35″–99°15′40″ East Longitude, with a lake surface area of around 1124 km^2 and a land area (the catchment area of the lake) of about 2486 km^2 (Fig. 1). Lake Toba is located in the Bukit Barisan mountains, at an elevation of 903 m.a.s.l., with an average depth of 228 m and a maximum depth of around 508 m (Lukman and Ridwansyah, 2011). Land use in the Lake Toba catchment area is dominated by agricultural land and bushes (49.7 %), followed by forests (23.4 %), open land (20.6 %), bushes and shrubs (5.1 %), swamps (0.8 %), and settlements (0.4 %) (Lukman, 2013). Lake Toba is a national priority lake for the industrial sector, primarily hydroelectric power plants, tourism, agriculture, plantations, and fisheries (Nasution and Damanik, 2009; Saragih and Sunito, 2001).

2.2. Data

2.2.1. Observation data on Lake Toba water level and outflow

The lake water level was observed in Janjimatogu Village, Porsea District, Toba Regency, North Sumatra Province (Fig. 1). PT Inalum has been observing the water level of Lake Toba for the past four decades and utilizing the water for hydroelectric power generation. Outflow observations were carried out in Siruar, 14 km from the outlet of Lake Toba in Porsea and the upstream part of the Asahan River. This study's lake water level, inflow, and outflow data are monthly from 1957 to 2020. For 1957–1980, data were obtained from Loebis (1999), while data for 1981–2020 came from PT Inalum.

2.2.2. Climate observation and climate reanalysis data

The monthly climate data utilized in this research were collected from 11 climate stations throughout the Lake Toba watershed (Fig. 1). The data from 1973 to 2020 were sourced from the BMKG North Sumatra Climatology Station. The availability of the climate observation data becomes a significant obstacle of this study because the data are generally available for <60 years. Therefore, this study combines the observed data with ERA5-Land data. ERA5-Land is an extensive dataset derived from reanalysis, incorporating both model and observational data. The ERA5-Land dataset has a spatial resolution of 9 km (Muñoz-Sabater et al., 2021). Temperature and rainfall data in this study were obtained from Irwandi et al. (2023), which used the quantile mapping method to correct bias (Piani et al., 2010). While, the mean absolute error is used to validate the model between the ERA5-Land model and the observation data. Evaporation data were also corrected and validated using the same method.

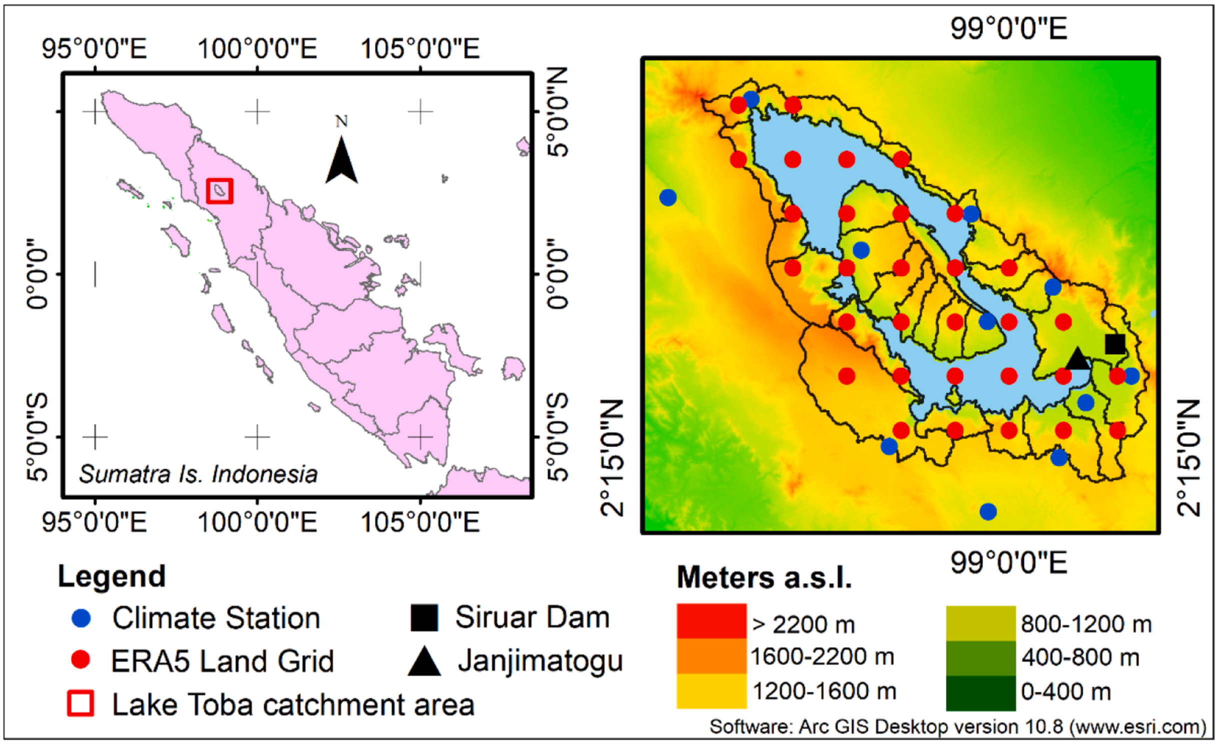

Fig. 1. Lake Toba catchment area and climate observation stations.

2.2.3. Population data

The Lake Toba catchment area is part of the territory of 7 districts in North Sumatra Province. Generally, the population distribution in the Lake Toba catchment area is in the district capital. Based on the book of Gerakan Penyelamatan Toba (KLH, 2014), the population in the Lake Toba watershed in 2010 was 2.9 % of the population of North Sumatra Province. These data were used as the basis for determining the population of the Lake Toba watershed in the period 1957–2020. Meanwhile, to determine domestic water needs, we used the number of residents, who directly use Lake Toba water, as the data. Based on research Umanda et al. (2007), only 31 % of the population in the Lake Toba catchment area directly use Lake Toba water for household needs (domestic). Based on the city category, regions that use Lake Toba water directly are included in the semi-urban category (BSN, 2015).

3. Methods

This section will explain the stages and methods used in the research. In the initial stage, Lake Toba's water level characteristics will be identified. This identification aims to analyse significant changes in the water level data of Lake Toba so that the natural factors and the influence of human activities can be separated. Trend testing is carried out to determine whether or not climate change has occurred in the Lake Toba watershed. Climate data and data on the use of Lake Toba water for domestic and non-domestic as well as industrial purposes are also analysed as significant factors in the water level of Lake Toba. Therefore, the methods used to support the above analysis are:

3.1. Quantile mapping bias correction

Bias correction is an approach based on statistical transformation that attempts to adjust the distribution of the modeled data to closely resemble the observed climate variables (Zhao et al., 2017). Currently, most bias correction methods aim to adjust a given climate variable's mean, variance, and distribution (Holthuijzen et al., 2021). The Quantile mapping method is a bias correction technique that adjusts the results of model simulations to observed data using a transfer function: $y = f(x)$ (Piani et al., 2010). This function relates the cumulative distribution (CDF) between simulated and observed data, as shown in the following equation:

$$CDF_{obs}(f(x)) = CDF_{sim}(x) \tag{1}$$

where $CDF_{obs}(f(x))$ is the observation CDF and $CDF_{sim}(x)$ is the simulation CDF.

3.2. Change point detection

Change point detection is an important process for assessing the occurrence of abrupt or abrupt changes in data distribution over time (Li et al., 2023; Militino et al., 2020). The process of identifying abrupt changes, where the change point refers to the period at which the observed behaviour changes. These changes can indicate changes in the mean or other statistical properties of the data that occur due to a variety of factors, including climate change and human activities such as deforestation or urbanization (Mahmood and Jia, 2018; Reeves et al., 2007; Rienzner and Gandolfi, 2011). This was done to determine the basic period in which natural impacts are considered to be the most dominant in the fluctuations in lake water levels (Khazaei et al., 2019; Mahmood and Jia, 2018). This study used two statistical tests to detect annual change points in the Lake Toba water level data sets. They include the Pettitt (Pettitt, 1979) and Buishand tests (Buishand, 1982).

3.2.1. Pettitt test

The Pettitt test is a nonparametric test that does not require assumptions about data distribution. This test is an adaptation of the rank-based Mann-Whitney test that identifies time shifts and detects structural changes in a data set. The goal is to identify points in time where there is a significant change in the data distribution. To calculate the statistics, the ranks $r_1 \ldots r_k$ of the $X_1 \ldots X_k$ are used (Pettitt, 1979):

$$X_k = 2\sum_{i=1}^{k} r_i - k(n+1),\ k = 1,\ \ldots,\ n, \tag{2}$$

If there is a break in year K, the statistic is maximum or minimum at the year $k = \mathrm{K}$,

$$X_\mathrm{m} = \max_{1\le k\le n} |X_k|. \tag{3}$$

3.2.2. Buishand test

The Buishand test (Buishand, 1982) can be used for variables that follow any type of distribution. This test is sensitive to breaks in the middle of the time series (Wijngaard et al., 2003),

$$S_0^* = 0;\ S_k^* = \sum_{i=1}^{k} (X_i - \overline{X}),\ k = 1,\ \ldots,\ n, \tag{4}$$

where X is the mean of time series observations $(X_1, X_2,\ \ldots,\ X_n)$ and k is the number of the observation at which a break point has occurred.

By dividing the S_k^* by the sample standard deviation we obtain the rescaled adjusted partial sums (Buishand, 1982)

$$S_k^{**} = S_k^* \,/\, D_X,\ k = 0,\ \ldots,\ n, \tag{5}$$

where

$$D_X^2 = \sum_{i=1}^{n} (X_i - \overline{X})^2 \Big/ n. \tag{6}$$

The statistic which can be used to analyze the homogeneity of data is expressed as

$$Q = \max_{0\le k\le n} \left|S_k^{**}\right| . \tag{7}$$

S_k^{**} is the cumulative normalization of deviation. At the same time, Q is the maximum cumulative deviation in the time series. The greater the Q value, the greater the possibility of a breakpoint or significant change in the data because this indicates a large deviation from the average at a point.

3.3. Mann–Kendall trend and Sen's slope estimator tests

The non-parametric Mann–Kendall test is used to identify climate change (Kendall, 1975; Mann, 1945). The World Meteorological Organization WMO recommends using this method in trend tests. The primary advantage of this approach lies in its ability to remain unaffected by the normal distribution and extreme value data, making it particularly valuable for detecting trends in climate data time series (Noori et al., 2022a). Meanwhile, Sen's slope estimator test is a non-parametric method (Sen, 1968) used to predict trend values in data. Temperature, rainfall, and evaporation data were tested using both methods to identify indications of climate change in the Lake Toba water catchment area. This test begins by calculating the S value to determine the increasing or decreasing trend in the data.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \mathrm{sgn}(x_j - x_k), \tag{8}$$

where n is the number of observations, x_j is the j^{th}observation and $\mathrm{sgn}(x_j - x_k)$ is the sign function with

$$\mathrm{sgn}(x_j - x_k) = \begin{cases} 1; & \text{if } x_j > x_k \\ 0; & \text{if } x_j = x_k \\ -1; & \text{if } x_j < x_k \end{cases}, \tag{9}$$

$$\mathrm{Var}\ (S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18}. \tag{10}$$

After calculating the variance of S by using Eq. (10), the value of the standard test statistic Z_{mk} can be calculated by using

$$Z_{mk} = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}}; & \text{if } S > 0 \\ 0; & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}}; & \text{if } S < 0 \end{cases}. \tag{11}$$

A Z_{mk}value higher (lower) than 1.96 (−1.96) indicates an increasing (decreasing) trend at the 95 % confidence level ($\alpha = 0.05$).

Non-parametric methods were used to estimate the magnitude of trends in the time series data (Sen, 1968). The slope of the data pair 'n' can be estimated in advance by using

$$b = \text{median} \left[\frac{x_j - x_k}{j - k}\right] \text{ for all } k < j \tag{12}$$

In Eq. (12), x_j and x_k represent the data values at times j and k, respectively, where j is always after k ($k < j$), and b is the slope estimator.

3.4. Domestic and non-domestic water needs

Domestic water needs are household needs calculated based on the number of residents directly using Lake Toba water. In contrast, non-domestic water needs are for social purposes (hospitals, schools, and places of worship), commercial (hospitals, tourist attractions, and public facilities), and government agencies. Non-domestic water needs are calculated based on the assumption of 35 % of domestic water needs. So, domestic water needs based on the criteria of the Lake Toba catchment area population are 90 liters/person/day (BSN, 2015).

3.5. Industrial water needs

Lake Toba water is also used for industrial processes (Loebis, 1999). With increasing number of industries, there is a corresponding increase in water consumption. In this study, the industrial use being analysed is limited to the water used for hydropower production. The use of water for hydropower production began in 1983 (Tanakamaru et al., 2004). Therefore, the outflow data for the period I (1957–1983) represents the natural hydrological conditions of Lake Toba. Meanwhile, outflow data for period II (1984–2020) represents hydrological conditions with the influence of human activities in the form of dams and the use of water for the needs of the hydroelectric power industry.

3.6. Structural equation modelling (SEM)

SEM is a multivariate statistical analysis method combining regression and factor analysis (Zhang et al., 2020). SEM can be used to describe the linear relationship between independent variables and dependent variables (Yang et al., 2021). In this study, the SEM is implemented to identify the influence of climate change, land cover and agricultural land on the water level of Lake Toba, as well as to determine the significant factors of these parameters based on research (Liang et al., 2021). Therefore, with the help of SEM, the relationship between climate, human factors and lake water levels can be clarified.

4. Results

4.1. Characteristics of the water level of Lake Toba

The water level of Lake Toba has fluctuated significantly over the past 64 years. Table 1 shows the annual change points and annual trends in the water level data of Lake Toba. The Pettitt and Buishand tests detected the year of 1984 as the change point, with maximum statistical values of 946 and 2.99, respectively. Therefore, the study examines the water level of Lake Toba in two periods: Period I (1957–1983) and

Table 1
Change points detected in the Lake Toba water level.

No	Time series	Pettitt's Test			Buishand test		
		Change point Test	Test Statistics	p-value	Change point Test	Test Statistics	p-value
1	Water level	1984	946	0.00	1984	2.99	0.00

Period II (1984–2020). In Period I, the average water level of Lake Toba was around 905.2 m.a.s.l., while in Period II, it almost reached 904.1 m. a.s.l. Fig. 2a and Table 2 show that the water level trend in Period I decreased by 22 mm per year, while in Period II decreased by 2 mm per year. However, Lake Toba's water level decreased by 26 mm per year for the entire period. Analysis of the monthly averages demonstrated a significant decrease between Periods I and II. Based on the data for these two periods, there was a consistent decline in the water level of Lake Toba for each month. It is also important to note that May had the highest water level while September had the lowest one (Fig. 2b).

Table 2
Annual trends in the water level of Lake Toba and the Climate of Lake Toba Watershed.

No	Time series	Period	Z	α	b (m)
1	Water level	1957–1983	−2.56	**	−0.022
		1984–2020	−0.34	*	−0.002
		1957–2020	−6.26	**	−0.026

* no significant trend ($0.05 < \alpha < 0.1$)
** significant trend ($0.01 < \alpha < 0.05$)

4.2. Variation of climate factors

Climate change is an important factor in changing hydrological processes. Detecting and measuring trends in climate variables is essential to assess the impact of natural changes. Table 3 shows the trend of the analyzed climate parameters, including annual mean temperature, annual evaporation, and annual rainfall. The annual mean temperature in the Lake Toba Watershed from 1957 to 2020 showed a significant increasing trend of 0.003 °C per year. The annual average temperature was 20.3 °C; the highest was 20.6 °C in 2016, and the lowest was 20.1 °C in 1999 (Fig. 3a). Annual evaporation from 1957 to 2020 showed a significant increasing trend of 1.4 mm per year. The highest annual evaporation was 1190 mm, which occurred in 2002, while the lowest annual evaporation was 978 mm, which occurred in 1976 (Fig. 3b). Annual rainfall from 1957 to 2020 reported a significant increasing trend of 8.9 mm per year. The highest annual rainfall of 2095 mm occurred in 2008, while the lowest annual rainfall of 1171 mm was recorded in 1975 (Fig. 3c).

Table 3
Annual trends in the Climate of Lake Toba Watershed.

No	Time series	Period	Z	α	b (m)
1	Temperature	1957–2020	3.52	**	0.003
2	Evaporation	1957–2020	4.68	**	1.4
3	Rainfall	1957–2020	5.41	**	8.9

* no significant trend ($0.05 < \alpha < 0.1$), ** significant trend ($0.01 < \alpha < 0.05$).

4.3. Domestic, non-domestic, and industrial needs

Along with the increasing population and the community's economy, the need for water for various sectors continues to increase. This aligns with the trend shown in Fig. 4a, where water use for annual domestic and non-domestic needs in 1957–2020 recorded a rising trend of 0.07 m^3/s per year. Lake Toba water is also used for industrial processes. In general, water use in industry is relatively constant, with variations of months or seasons. With the increasing number of industries, there is a corresponding increase in water consumption. In this study, the industrial use being analyzed is limited to the water used for hydropower production. The use of water for hydropower production began in 1983. The discharge of Lake Toba and Asahan River is utilized to support the operation of Sigura-Gura and Tangga hydroelectric power plants, and it is controlled through Siruar Dam. The average industrial water use was 100 m^3/s (Loebis, 1999). In Period I, which is the natural period of Lake Toba, Fig. 4b shows a decreasing trend in the need for Lake Toba water by 1.05 m^3/s per year. Period II is the period when Lake Toba water is used for the needs of the hydroelectric power industry. In this period, there is an increasing trend of 0.62 m^3/s per year, while the overall period shows a growing trend of 0.17 m^3/s per year.

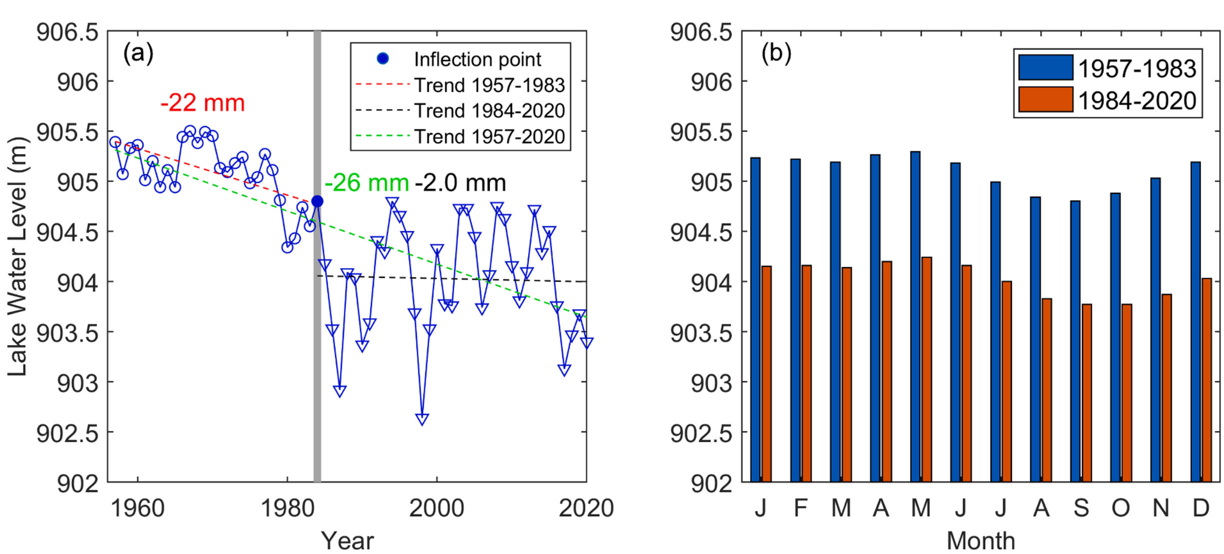

Fig. 2. (a) Annual trend of the Lake Toba water level, (b) Average monthly Lake Toba water level.

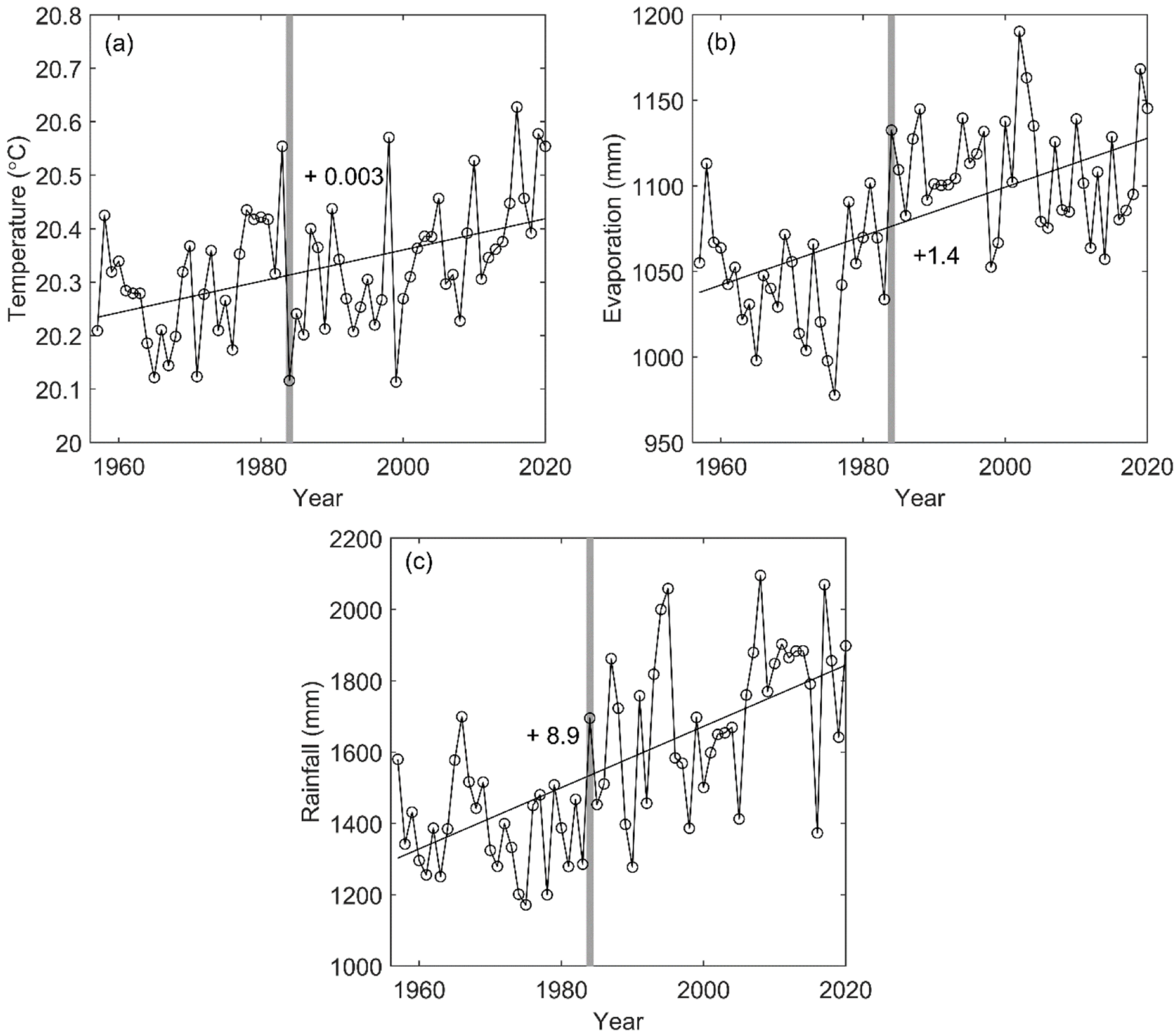

Fig. 3. Trends of (a) temperature, (b) evaporation, and (c) annual rainfall in the Lake Toba catchment area.

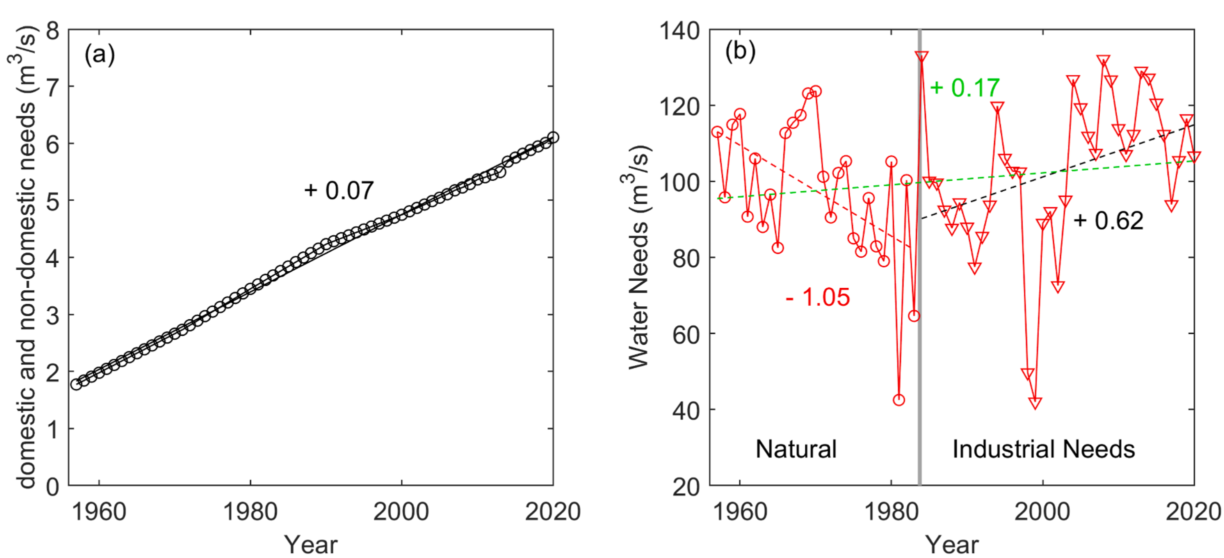

Fig. 4. (a) Domestic and non-domestic water needs sourced from Lake Toba, (b) Water demand for industry.

4.4. The impact of various important factors on inflow and water level of Lake Toba

To quantitatively explain the direct impact of climate change on the inflow factor of Lake Toba and the impact of domestic and non-domestic water demand, as well as hydrological factors (inflow and outflow) on the water level changes of Lake Toba during different periods, it was explored using SEM. As shown in Table 4, in Period I (1957–1983), inflow showed a very significant negative direct effect on air temperature ($\beta = -0.114$, $p = 0.03$), and evaporation ($\beta = -0.01$, $p = 0.05$), while rainfall showed a significant positive direct effect ($\beta = 780$, $p = 0.04$). In Period II, the inflow showed a very substantial negative direct impact on air temperature ($\beta = -0.020$, $p = 0.03$) and evaporation ($\beta = -0.045$, $p = 0.03$), while rainfall showed a significant positive direct effect ($\beta = 0.721$, $p = 0.03$). This shows that the increase in Lake Toba inflow is greatly influenced by rainfall that directly enters the lake and flows through the catchment area, while temperature and evaporation affect the reduction in inflow.

Table 5 shows that in Period I, the water level of Lake Toba had a significant positive direct effect on inflow ($\beta = 0.052$, $p = 0.01$) and a significant negative direct effect on outflow ($\beta = -0.308$, $p = 0.01$), and domestic and non-domestic needs ($\beta = -0.270$, $p = 0.04$). While in Period II the water level of Lake Toba showed a significant positive direct effect on inflow ($\beta = 0.097$, $p = 0.03$), a significant negative direct effect on outflow ($\beta = -0.505$, $p = 0.03$), and an insignificant negative on domestic and non-domestic needs ($\beta = -0.316$, $p = 0.06$). This shows that inflow, outflow, and domestic and non-domestic needs greatly influence the increase in the water level of Lake Toba during both periods. The outflow is a significant factor in the water level of Lake Toba in Periods I and II. Period I is a natural period of Lake Toba outflow, meaning that it is only influenced by climate. In Period II, the outflow is influenced by the needs of the hydroelectric power industry.

4.5. Comparison between changes in water level with climate and anthropogenic

Fig. 5 compares the water level of Lake Toba, climate, and anthropogenic (human activities) factors in two main periods. In Period I, the water level decreased by 22 mm per year, with a decrease in rainfall of 3.3 mm per year and water needs of 1.05 m^3/s. The decrease in water level is linear with the decrease in rainfall and water needs. Meanwhile, in Period II, the water level tends to be stable with an insignificant decreasing trend of 2 mm per year, although rainfall increases by 9.6 mm per year. However, anthropogenic factors also increase significantly by 0.62 m^3/s. This shows that anthropogenic have a more significant contribution compared to rainfall.

5. Discussion

5.1. Impact of dams and hydroelectric power plants on the water level of Lake Toba

The characteristics of the water level decline of Lake Toba is essential to correctly identify the leading or dominant factor causing the decline

Table 4
The direct impact of various significant factors on Lake Toba Inflow.

Period	Predictor	Direct Coefficient (β)	p-value (p)
1957–1983	Temperature	−0.114	0.03
	Evaporation	−0.011	0.05
	Rainfall	0.780	0.04
1984–2020	Temperature	−0.020	0.03
	Evaporation	−0.045	0.03
	Rainfall	0.721	0.03

Table 5
The direct impact of various significant factors on the water level of Lake Toba.

Period	Predictor	Direct Coefficient (β)	p-value (p)
1957–1983	Inflow	0.052	0.01
	Outflow (Natural)	−0.308	0.01
	Domestic and non-domestic needs	−0.270	0.04
1984–2020	Inflow	0.097	0.03
	Outflow (Industrial Needs)	−0.505	0.03
	Domestic and non-domestic needs	−0.316	0.06

(Irwandi et al., 2021). The significant decline occurred between 1983 and 1984, whereas the Siruar Dam was built in 1979–1981 and began operating in 1984. Therefore, the declining in the water level of Lake Toba is strongly related with the construction and operation of the Siruar Dam. A similar phenomenon also occurred in two lakes in China, i.e., Lake Poyang (Zhang et al., 2022) and Lake Dongting (Liang et al., 2021), where the decline in the water level was caused by human activities in the form of dam constructions. The declining in the water level of Lake Toba from 1983 to 1984 was constant, and the equilibrium point changed steadily from an average height of 905.2 to 904.1 m.a.s.l. The cause of this change is the expansion of Lake Toba's water capacity due to the construction of the Siruar Dam (Loebis, 1999). The Siruar Dam and Lake Toba are a single hydrological system of Lake Toba. The Siruar Dam is operated for hydroelectric power to meet the electricity needs of the aluminum smelter and the electricity needs of North Sumatra in general (Sihotang et al., 2012).

The constant decrease in the water level of Lake Toba can be divided into two periods, pre- and post-operation of the Siruar Dam. In Period I (1957–1983), there was a significant decrease in water level of 22 mm per year. This is due to a decrease in rainfall related to El Niño activity. The El Niño phenomenon almost occurred throughout this period, namely in 1957–1959, 1963–1966, 1969–1970, 1972–1973, and 1976–1978 (Ren et al., 2018). This is also verified by the study of Irwandi et al. (2018, 2019), which stated that the decrease in the water level of Lake Toba was due to the activity of El Niño Southern Oscillation (ENSO). In lakes such as Lake Victoria in Africa (Williams et al., 2015), the lakes on the Tibetan Plateau (Lei et al., 2019), and Lake Volta in Ghana (Boadi and Owusu, 2019), there has also been a decrease in water levels as an impact of decreased rainfall due to El Niño. In period II, the water level of Lake Toba tends to be constant and stable at an equilibrium point with an average height of 904.1 m.a.s.l. The decline rate trend in this period is only 2.0 mm per year. The stability of the water level of Lake Toba shows that the regulation of the Siruar Dam is well implemented. This regulation is carried out as a commitment to maintain the water level of Lake Toba at a safe level (above 902.4 m.a.s.l.). This was evident when there was a decrease in the water level in 1998 and 1999, electricity production decreased by 51 % (to 1,744,385 MWh) and 53 % (to 1,672,666 MWh) respectively compared to 1997. Therefore, this study refutes and corrects the results of previous studies, which stated that in the last six decades, there has been a slow but sure decline in the water level of Lake Toba (Irwandi et al., 2019, 2021; Loebis, 1999; Oelim, 2000; Sihotang et al., 2012). The Siruar Dam continuously maintains the stability of Lake Toba's water level. As a consequence, in period II, the water level of Lake Toba remains at a constant equilibrium even though, in specific years, there is a significant extreme decline in the water level.

5.2. Impact of climate change on the water level of Lake Toba

Based on the Intergovernmental Panel on Climate Change (IPCC) criteria (IPCC, 2021), climate change has occurred in the Lake Toba catchment area. There has been an increase in temperature, evaporation, and annual rainfall with an increasing trend of 0.003 °C, 1.4 mm, and 8.9 mm per year, respectively. This condition positively impacts

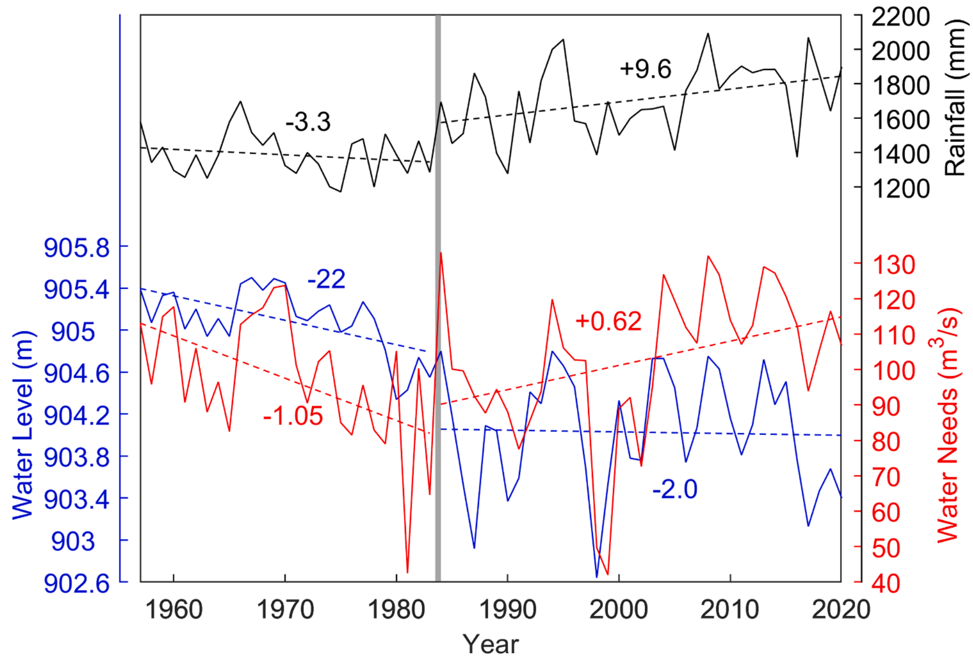

Fig. 5. Comparison between changes in water level with climate (rainfall) and anthropogenic (water needs).

Lake Toba's water level due to increased rainfall. Rainfall is a significant parameter for lake water level (Tang et al., 2018; Torabi Haghighi and Kløve, 2015; Yan and Zheng, 2015). The increase in rainfall in the Lake Toba catchment area was triggered by increased temperature and evaporation, especially in period II. This is different from several studies on other lakes where climate change causes a decreasing in rainfall due to increasing in temperature and evaporation. This has an impact on the decline in lake water levels, as in Lake Urmia in Iran, where over the past few decades, there has been a trend of increasing temperatures of 0.18 °C per decade, which has caused lake evaporation to increase at a rate of 6.2 mm per decade, while rainfall has decreased by around 9 mm per decade (Alizadeh-Choobari et al., 2016). This also happened in Lake Issyk-Kul in Kyrgyzstan (Salamat and Abuduwaili, 2015), Lake Qinghai in China (Fang et al., 2019), and Lake Chad in Africa (Mahmood et al., 2019), where the impact of climate change tends to have a negative effect on lake water levels.

5.3. *Anthropogenic impacts (domestic, non-domestic and industrial needs)*

Domestic and non-domestic needs are closely related to population. Population growth in the Lake Toba catchment area increases every year (Aziz et al., 2020). Therefore, the increase in population in the Lake Toba catchment area impacts its water needs (Wesli, 2017). According to Umanda et al. (2007), only one-third of the population in the Lake Toba catchment area uses Lake Toba water directly. Although domestic and non-domestic needs are significant parameters for Lake Toba's water level, the amount of water consumption is still relatively very small compared to the water needs of Lake Toba for the hydroelectric power generation industry. The analysis of water needs for hydroelectric power plants shows an increasing trend every year. In several studies of other lakes, it was shown that the decrease in the lake's water level was not only related to climate but also to aspects of human activities (anthropogenic) that were responsible (Davraz et al., 2019; Nsubuga et al., 2019). However, the impact of human activities showed a strengthening trend over the last decade (Wang et al., 2017). Therefore, it is essential to have mitigation in the sustainable management of Lake Toba water resources.

5.4. *Decreasing the water level of Lake Toba*

Based on the combined analysis of climate factors and SEM we may safely say that the decrease in the water level of Lake Toba in Period I was mainly caused by climate factors, where in this period there was a decrease in rainfall in the catchment area of Lake Toba. In Period II, rainfall tended to increase; this should positively impact Lake Toba's water level. However, in Period II, the factor of water uses by industry, especially hydroelectric power plants and water needs for domestic and non-domestic purposes, showed a significant influence. Therefore, it can be concluded that in Period I, climate factors were the determining factors. Conversely, in Period II, the determining factors were water use for the hydroelectric power industry and water needs for domestic and non-domestic purposes. These condition are in line with several other lakes where climate change has impacted the decline in lake water levels, while the combination of climate change and anthropogenic has impacted the decline in lake water levels in the last two decades, such as Lake Urmia in Iran (Ghale et al., 2018; Khazaei et al., 2019), Lake Chad in Africa (Mahmood and Jia, 2018), Lake Hulun in China (Huang et al., 2023), and Lake Dongting in China (Liang et al., 2021; Yuan et al., 2015). However, specifically in Lake Toba, the decrease in water level due to climate and anthropogenic influences is not significant. This is due to the regulation of the Siruar Dam, which allows the water level of Lake Toba to be controlled at a safe level so that the trend of the water level of Lake Toba tends to be constant during this period.

6. Conclusion

Lake Toba, the largest lake in Indonesia, has undergone a decline in its water level over the last six decades. In this study, we explain the changes in the lake level and analyse the origin of the decline in water level. Pettitt and Buishand's test results detected the year of 1984 as the point of change. Therefore, the water level of Lake Toba has been analysed in two different periods, i.e., Period I, which is the base period before the operation of the Siruar Dam (1957–1983), and Period II, which is the impact period after the operation of Siruar Dam (1984–2020). The trend test shows climate change has occurred in the Lake Toba catchment area. There has been an increasing trend in temperature, evaporation, and annual rainfall in the Lake Toba watershed from 1957 to 2020, with an increasing trend of 0.003 °C per year, 1.4 mm per year, and 8.9 mm per year. Climate change impacts increasing in Lake Toba's water level. A significant increase has occurred in the last four decades. So, it can be concluded that in Period I, the significant factor in the decrease in the lake water level was climate ($\beta = -0.308$, $p = 0.01$). In contrast, in Period II, was the use of water for the needs of the hydroelectric power industry ($\beta = -0.505$, $p = 0.03$). However, by regulating water use for hydroelectric power in Period II, the water level of Lake Toba can be maintained at a stable position according to the predetermined threshold (902.4–905.0 m.a.s.l.). The influence of climate change has distinct anomalies in other lakes. As a result, it is critical to conduct more specific and comprehensive studies on the future impact of climate change by developing climate projections using various climate models and scenarios. So that policymakers and stakeholders can design climate change adaptation and mitigation programs to support the sustainability and utilization of water resources and the Lake Toba ecosystem in the future.

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CRediT authorship contribution statement

Mohammad Syamsu Rosid: Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Hendri Irwandi:** Writing – original draft, Methodology, Formal analysis. **Apip:** Writing – review & editing. **Terry Mart:** Writing – review & editing, Methodology, Conceptualization. **Raden Dwi Susanto:** Writing – review & editing. **Albertus Sulaiman:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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