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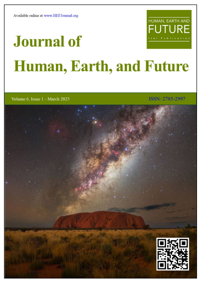

Origin and Recharge Area Determination of Springs Around a Lake for Sustainability of the Lake

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Abstract

The springs surrounding the lake may be the lake's leakage or groundwater outlets that were replenished by precipitation in the mountain. The springs' source is crucial to the lake's water balance and, thus, to its sustainability. The water level in Lake Toba has fluctuated. The water level differential between the lowest and maximum can be as much as three meters. Springs with flow rates ranging from 2 to 5 m^3/s were discovered downstream of the lake. The origin of these springs is not known yet. At one point, the locals blamed these springs for the lake's unstable water level. This study's goal is to determine if the springs came from a lake leak or from other sources, such as local groundwater. Water samples from lakes, springs, surface waters, and precipitations were taken on a regular basis. Using hydrochemical and stable isotope variations of all samples, the relationships between the springs and lake are examined. The assessment of the data showed that the lake was not the source of springs. The springs were groundwater's outlets that recharged by precipitation on Mount Simarjarungjung, which is located between 1700 and 1900 meters above sea level. These results suggest that the primary causes of lake water level fluctuation may be the reduction in groundwater flow in the lake's catchment area brought on by deforestation and changes in land use. The water flowing down the Asahan River to fuel the INALUM aluminum smelting business in the region could be the other issue.

Keywords: Water Stable Isotopes; Lake Toba; Local Meteoric Water Line; Springs; Water Bodies Interconnection.

1. Introduction

About 175 kilometers to the south of Medan, the seat of Indonesia's North Sumatera province, lies Lake Toba (Figure 1). Lake Toba is the world's largest volcanic lake. Around 74,000 years ago, the Toba caldera erupted for the fourth time, which led to the caldera's formation. Its length and width are roughly 100 km and 30 km, respectively. The highest depth of the lake is 505 meters [1–3]. The normal water level of the lake is 905 m above sea level and its estimated water volume is 2.56×10^{11} m^3 [4]. In addition to being the primary tourist destination, Lake Toba serves as the region's primary water source for household use, farming, fishing, and electric power generation [4, 5]. Together with the lake's surface area of about 1100 km^2, the total lake's catchment area is approximately 3500 km^2 [3, 6, 7]. Since the catchment and lake's surface area are only roughly 3:1, human activity in the surrounding areas has a significant impact on the lake's water quality and quantity. The lake level is directly impacted by the distribution of rainfall in the catchment area. Many researchers have noted the imbalance between inputs and outputs, particularly in the past 60 years [8, 9]. The stability of the lake's water level around its normal elevation is crucial to the region's socioeconomic activities.

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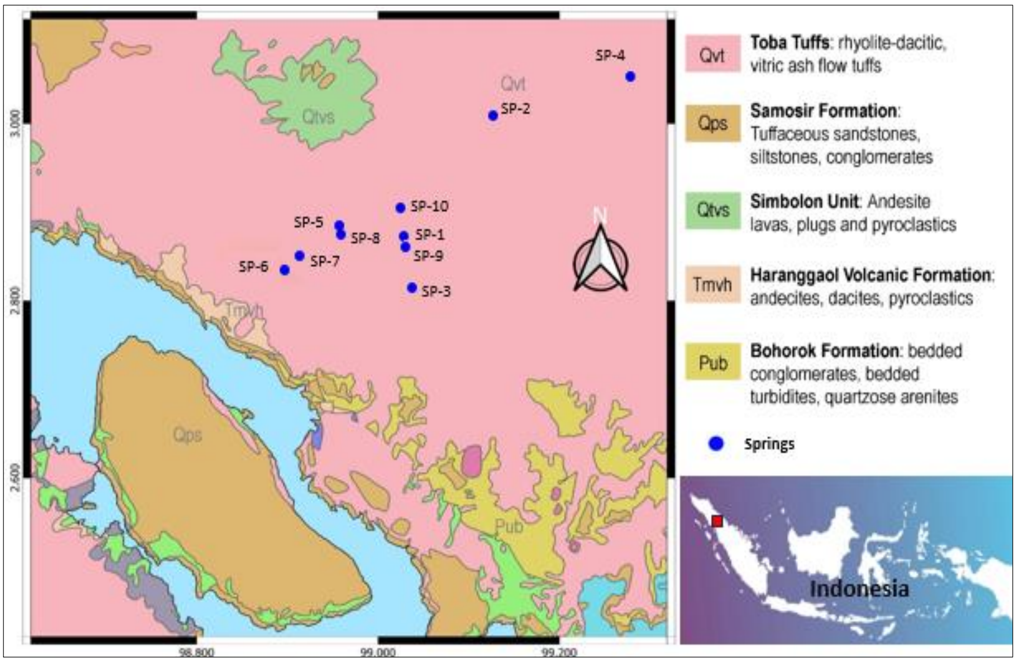


Figure 1. The location of the study and its regional geological map. Coordinates are in decimal degrees (WGS 84): Modified from [10, 11]

About 2.5 meters below the normal water level, the lowest lake water level that nearly stopped the operation of the local aluminum smelter was recorded in the middle of the 1980s [1]. Water level decline is thought to be caused by both natural and human factors, including El Nino Southern Oscillation (ENSO), climate change, catchment area deforestation (heavy land use), and water supply for home and industrial applications [3, 5, 9, 12]. However, the primary cause of the water level drop is yet unknown. Since 2009, the Indonesian government has published a national lake management program called Integrated Lakes Basin Management (ILBM), which includes Lake Toba as one of its goals [13, 14]. Numerous investigations concerning the lake's water balance have been carried out. Sihotang et al. [8] studied the water balance of Lake Toba by assuming that the output components were only the water released from the Asahan river, domestic and industrial water needs, evaporation from the lake. The lake's leak was not taken into account individually in this model; any difference between inputs and outputs was regarded as an uncategorized output. Ma'mur et al. [15] also investigated the lake's water balance, focusing just on the ENSO element, and found a direct correlation between the drop in water level and the lower rainfall during the rainy season. A different model that has been used to determine the water balance of lakes only took surface inflows and rainfall fluctuations into account [16, 17]. Water loss from seepage or leaks was not taken into account in these research studies. But according to some studies and the local water authority, there may be a substantial amount of water lost to the downstream due to seepage or leakage [8]. According to others, the presence of several springs at the downstream of the lake could be a leakage from the lake.

This study sought to ascertain whether the springs around the lake originated from the lake's leakage or from local groundwater replenished by precipitation on the mountain slope. A periodical sampling campaign was conducted involving the lake, springs, surface waters, and precipitation. The samples were subsequently analyzed for isotopic, chemical, and physical parameters. The procedures taken to accomplish the aim of this study are depicted in Figure 2. Water stable isotopes serve as primary natural tracers for characterizing hydraulic connectivity among different water bodies, including the relationship between springs and Lake Toba. Oxygen-18 ($\delta^{18}O$) and deuterium (δD), the stable isotopes of water molecule, are very conservative. Condensation, sublimation, evaporation, and interactions with other water bodies are among the processes that affect the concentrations and fluctuations of $\delta^{18}O$ and δD in water.

The contents and variations of $\delta^{18}O$ and δD have been utilized in various applications, particularly concerning the interactions among different water bodies. The contents and variations of $\delta^{18}O$ and δD have been used to identify and quantify groundwater infiltration within sewage networks [18]. This investigation demonstrated the validity and robustness of stable isotopes. Reports indicate the application of stable isotopes for assessing soil water balance and water fluxes in agricultural fields characterized by differing irrigation and tillage practices [18, 19]. Nigate et al. [20] examined the connectivity between the volcanic aquifer and springs in the Lake Tana basin of the Upper Blue Nile. The study utilized the hydrochemical and stable isotope contents of precipitation, spring water, and groundwater to assess the recharge sources of the primary springs and the hydraulic connectivity with the volcanic aquifer. The groundwater, karst spring, and potential recharge area of the Crimean Mountains were characterized through the analysis of stable water isotopes [21]. Zhang et al. [22] employed hydrochemical and stable isotope variations to investigate the relationship between surface and groundwater in the Wei River tributaries in China. The findings indicated that tributaries in the south exhibited a stronger connection to the Wei River compared to those in the north. Satrio et al. [23] employed hydrochemical and stable isotopes contents and variations of shallow groundwater samples to investigate the propagation of seawater intrusion in Cirebon, Central Java, Indonesia.

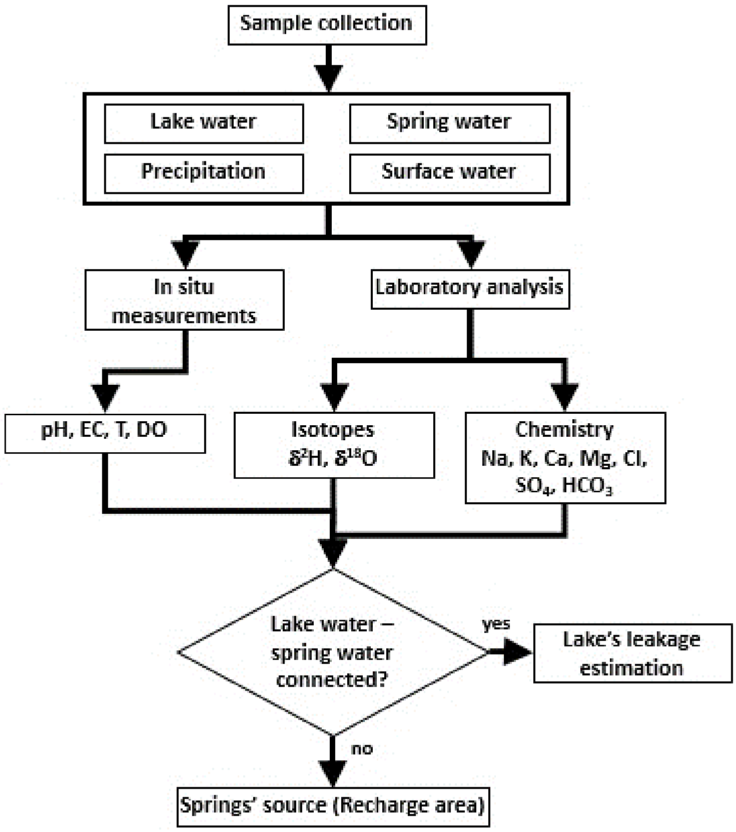


Figure 2. The flowchart of the study to achieve the goal

2. Material and Methods

2.1. Sample Collections

Around Lake Toba, there are numerous springs, some of which have incredibly high flow rates. Ten springs with water flows ranging from 1 to 5 m^3/sec (Figure 1) were included in this study. These springs are roughly 10 to 40 kilometres from the lake. Precipitation, lake water, and spring samples were collected. Every sample from every sampling location was examined for chemical, physical, and isotopic characteristics. Samples of lake water and spring water were collected in 2019 and 2021. In 2014, four rain collectors provided monthly precipitation samples for a year [13]. Generally, two different samples were collected from each sampling location: one for stable isotopes (δD and $\delta^{18}O$) and the other for hydrochemical analysis. About 20 millilitres of water samples were collected and placed in an airtight bottle for stable isotopes analysis. This is to reduce isotopic fractionation brought on by evaporation when samples are being transported or stored. 500 millilitres of water were gathered and placed in a double-capped plastic container for chemical analysis.

2.2. Water Stable Isotopes

The spatial and temporal fluctuations of δD and $\delta^{18}O$ and hydrochemical contents, along with the variations of in situ parameters, were used to study the hydraulic interconnection between the spring and the lake. According to equations 1a and 1b, δD and $\delta^{18}O$ of water molecules are the relative concentrations of $HD^{16}O$ (molecule mass 19) and $H_2{}^{18}O$ (molecule mass: 20) to $H_2{}^{16}O$ (molecule mass: 18) relative to standard mean ocean water (SMOW), repectively [13, 24–26].

$$\delta^{18}O = \left(\frac{\left[{}^{H_2{}^{18}O}/_{H_2{}^{16}O} \right]_{sample}}{\left[{}^{H_2{}^{18}O}/_{H_2{}^{16}O} \right]_{SMOW}} - 1 \right) \times 1000\ ({}^{O}/_{OO}) \tag{1a}$$

and

$$\delta D = \left(\frac{\left[{}^{HD^{16}O}/_{H_2{}^{16}O} \right]_{sample}}{\left[{}^{HD^{16}O}/_{H_2{}^{16}O} \right]_{SMOW}} - 1 \right) \times 1000\ ({}^{O}/_{OO}) \tag{1b}$$

The values, variations, and relationships of δD and $\delta^{18}O$ in water samples are important indicators of several processes that the water has, through its lifetime, such as mixing with other sources of water, evaporation, and dilution with geologic formation along its passage. Water samples' δD and $\delta^{18}O$ contents, fluctuations, and relationships provide useful information about a number of processes the water has experienced over its lifespan, including dilution with geologic formations, evaporation, and mixing with other water sources [7, 27–29]. δD and $\delta^{18}O$ are linearly related. The equation $\delta D = 8\delta^{18}O + 10$, global meteoric water line (GMWL), was first recorded in 1961 for all rain water worldwide [30–32]. Among the factors influencing the δD and $\delta^{18}O$ of meteoric water contents and fluctuations are temperature, latitude, altitude, and distance from the shore [33–35].

Compared to precipitation at lower average temperatures, precipitation at higher average temperatures often has more enriched δD and $\delta^{18}O$ values. On the other hand, precipitation will have lower δD and $\delta^{18}O$ values at higher elevations than at lower elevations [36]. The Local Meteoric Water Line (LMWL) is the linear line between δD and $\delta^{18}O$ in meteoric water in a specific location. LMWL and GMWL differ slightly. Depending on the process that the water samples have gone through, the slope of the linear line between δD and $\delta^{18}O$ will differ from 8. The following data will be interpreted in order to establish the hydraulic connectivity between the springs and the lake waters.

- In situ parameters of all samples,
- Hydrochemical contents of all samples,
- The relationship of δD and $\delta^{18}O$ of all samples
- The variations δD and $\delta^{18}O$ of rainwater samples as a function of elevation,
- The estimation of the recharge area elevations of springs.

2.3. Physical, Chemical, and Isotopic Parameters Measurements

Conductivity (C), pH, dissolved oxygen (DO), and Temperature (T) were among the physical parameters that were assessed in situ using the HORIBA multiparameter water quality tester model U-50. Metrohm Basic 883 with an auto sampler, an ion chromatography, were utilized to analyse major ions of the samples. A Metrosep A Supp 5 column was employed for the separation of anions utilizing a carbonate-bicarbonate eluent. A Metrosep C4 column was employed for cation separation with dipicolinic acid as the eluent. Alkalinity titrations were used for bicarbonate quantification. The major hydrochemical facies Ca^{2+}, Mg^{2+}, Cl^{-}, F^{-}, SO_4^{2-}, and CO_3^{2-} + $HCO3^{-}$ are illustrated in a ternary or Piper diagram to assess the water types and hydrochemical processes of each spring and lake water [37–40]. Liquid Water Isotope Analyzer (LWIA), a laser-based devise, was used to analyse stable isotopes contents (δD and $\delta^{18}O$) with the precision 0.03‰ for $\delta^{18}O$ and 0.2‰ for δD [26].

3. Results and Discussion

3.1. In Situ Parameters

The collection of samples and in situ parameter measurements of springs was carried out on two occasions, in 2016 and 2021. The measurements for both sampling periods were conducted approximately at the same period of time. Both measurements, however, showed no significant differences. The measurement shown in Table 1 is derived from the assessment carried out in 2021. The elevation of the springs varies between 100 and 900 meters above sea level. The majority of the springs observed were situated beneath the normal surface elevation of the lake. The recorded values for temperatures, conductivities, pH, and dissolved oxygen range from 24.0 to 27.5°C, 80 to 180 mS, 5.5 to 7.2, and 1.3 to 3.0 mg/L, respectively. The water parameters of Lake Toba, including temperatures, conductivities, pH, and dissolved oxygen, are observed to range from 24.5 to 26.0 °C, 165 to 180 mS, 7.0 to 8.2, and 3.0 to 8.0 mg/L, respectively [7].

Figure 3 illustrates that, overall, the temperature of spring water tends to decrease with increasing elevation. This observation suggests that the temperatures of spring water have been influenced by the ambient temperature. The conductivities of lake water tend to be significantly higher compared to spring waters. This difference may be attributed to the prolonged evaporation processes that lakes experience or the influence of human activities in the surrounding areas. The pH of the lake water is comparatively higher than that of the recharge waters. The observed phenomena may be attributed to the dissolved minerals in the lake water, resulting from human activities, including agricultural runoff and aquaculture practices in the area.

Table 1. Isotopic data and *in situ* parameters of spring waters collected from surrounding Lake Toba

No.	Code	Location	Coordinate (deg, WG84)		Elevation (m)	T (°C)	C (µS)	pH	DO (mg/L)
			North	East					
1	SP-1	Bah Tio	2.878750	99.023318	574	26.1	91	6.38	1.99
2	SP-2	Karanganyar	3.007326	99.126634	250	27.3	123	6.28	1.29
3	SP-3	Manigom	2.819443	99.038093	669	25.4	82	6.76	2.86
4	SP-4	Sungai Lobang	3.063280	99.278660	98	27.5	127	7.25	1.57
5	SP-5	Tiga Bolon	2.878236	98.965179	702	26.6	86	6.25	2.37
6	SP-6	Bah Biak	2.835018	98.895504	900	24.1	88	6.51	3.06
7	SP-7	Simatahuting	2.865993	98.919087	832	24.5	182	7.10	2.97
8	SP-8	Simodong	2.881062	98.962015	707	25.7	103	5.57	2.62
9	SP-9	Balata	2.870347	99.024985	590	26.0	112	6.25	3.00
10	SP-10	Mualgoit	2.899395	99.026707	650	26.0	-	-	-

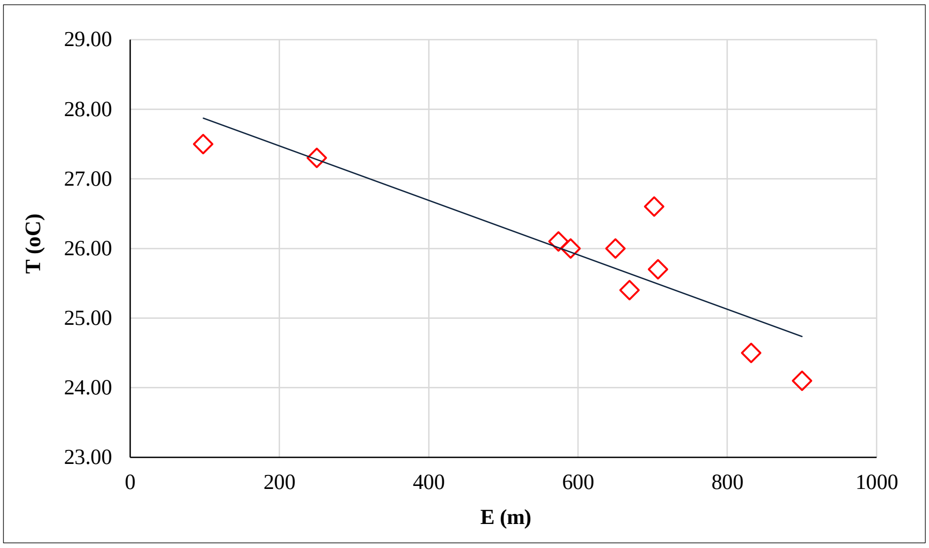


Figure 3. Temperature vs. elevation of springs

3.2. Water Chemistry

The hydrochemistry data for all spring waters, along with lake water, is presented in Table 2, and the Piper diagram illustrating the major cations and anions is shown in Figure 4. Nearly all the samples belong to a group primarily characterized by bicarbonate-carbonate facies in anions, with no clear dominant facies in cations, except for one sample that shows a dominance of sodium-potassium. Overall, all samples exhibit characteristics of weak acid water. The observation that all springs and lake samples are categorized under the same water type suggests that these samples likely traversed the same geological formation originating from the recharge area. This phenomenon was anticipated since nearly the entire study area was comprised of the same volcanic rock formation known as Young Toba Tuff [41]. The clustering of the majority of samples within the same water type presents significant challenges in examining the connectivity between the springs and the lake solely through the hydrochemical analysis of the samples.

Table 2. Major anions and cations of springs and lake

No.	Code	Na *(ppm)*	K *(ppm)*	Ca *(ppm)*	Mg *(ppm)*	Cl *(ppm)*	SO_4 *(ppm)*	HCO_3 *(ppm)*	NO_3 *(ppm)*	NO_2 *(ppm)*
1	SP-1	11.45	6.43	8.43	3.06	3.97	4.70	53.41	8.43	-
2	SP-2	6.05	5.07	5.67	2.28	2.92	1.56	38.86	2.28	-
3	SP-3	8.27	7.91	9.43	0.93	2.70	1.00	38.27	6.05	14.07
4	SP-4	7.63	6.45	7.45	0.99	1.35	1.69	42.70	6.56	-
5	SP-5	6.23	6.87	6.53	1.00	1.25	0.60	37.10	6.22	1.28
6	SP-6	6.57	4.87	8.58	1.31	0.28	0.84	43.48	8.27	-
7	SP-7	6.60	5.54	7.44	1.12	1.05	2.62	38.23	8.44	-
8	SP-8	9.61	3.02	8.63	2.47	5.04	2.24	44.03	11.99	0.65
9	SP-9	-	-	-	-	-	-	-	-	-
10	SP-10	13.13	6.24	2.57	0.24	1.00	1.93	43.92	6.08	-

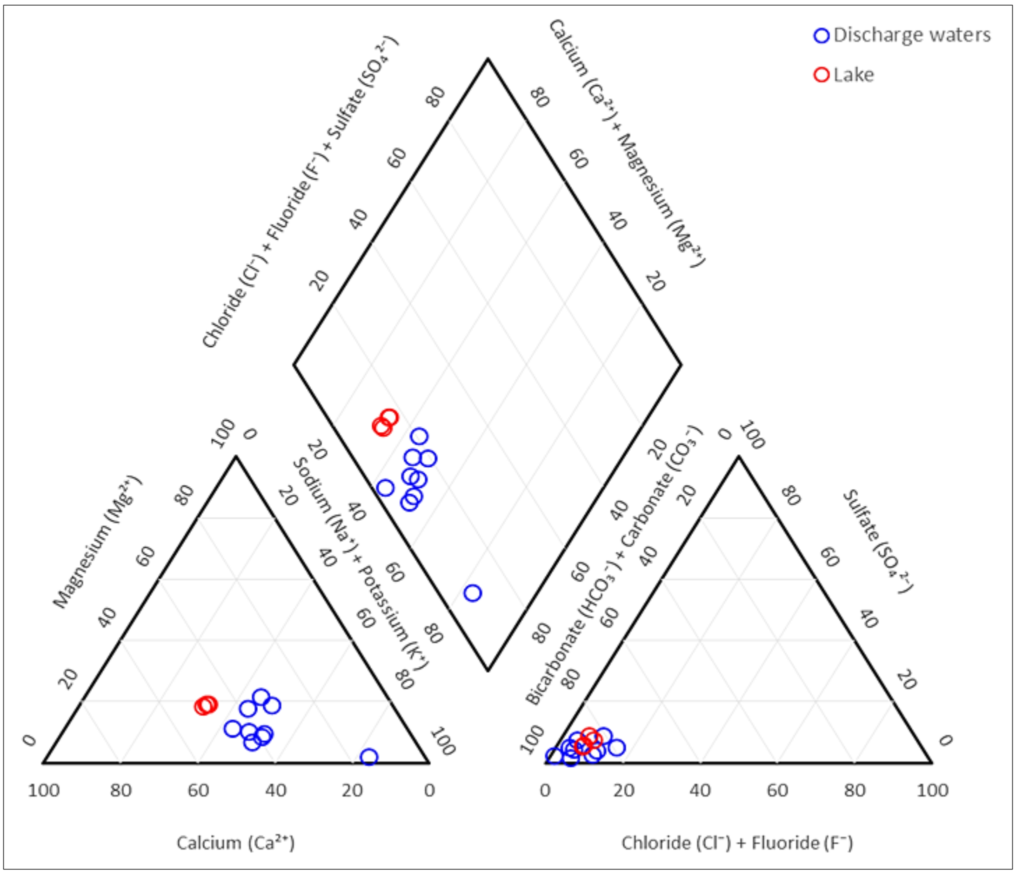


Figure 4. Piper diagram of all collected samples

3.3. Stable Isotopes

The fieldwork and sampling activities for stable isotopes took place between 2014 and 2018. Water samples were collected from the lake, Asahan River, and various surface waters surrounding Lake Toba, with some results having been disseminated in other publications [7, 26]. The average contents of stable isotopes in Lake Toba were recorded at -37.20 ‰ for δD and -4.57 ‰ for $\delta^{18}O$. Figure 5 presents the relationship between δD and $\delta^{18}O$ for the Asahan River, Lake Toba, and additional surface water sources. The graph indicates that the lake is aligned with the surface water and the output water from the Asahan River. The regression line depicted in Figure 5 has a slope of 4.89 (< 8), suggesting that all samples have experienced considerable evaporation. The prolonged residence time of the lake, coupled with the fact that the Asahan River serves as its sole outlet, results in the enrichment of δD and $\delta^{18}O$ in both Lake Toba and the Asahan River compared to other surface waters.

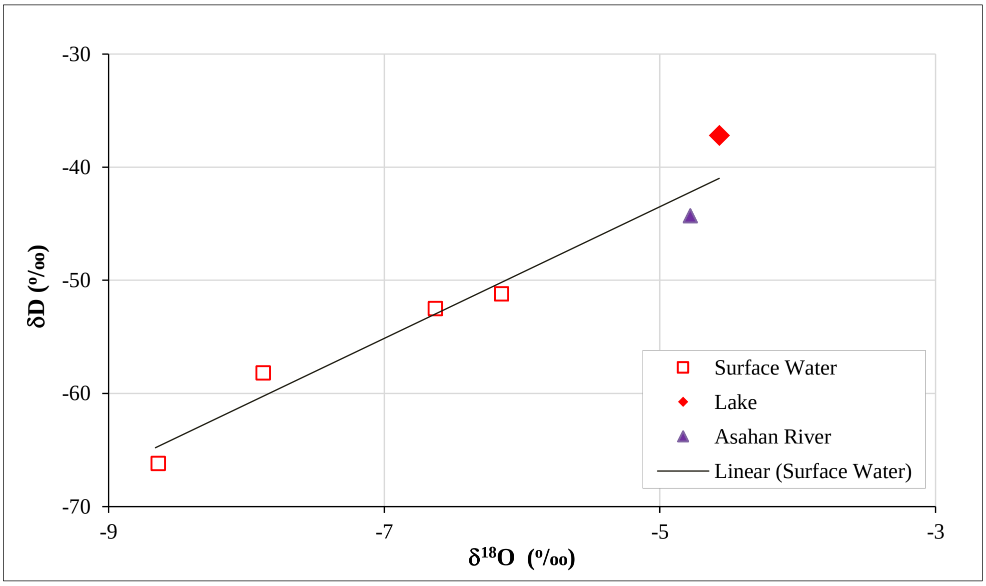


Figure 5. Graph of δD versus δ^{18}O of water samples collected from Asahan River, Lake Toba, and other surface water [26]

The stable isotopes contents of all collected spring water samples varied from -58.14 ‰ to -50.81 ‰ for δD and -8.66 ‰ to -7.63 ‰ for $\delta^{18}O$, as presented in Table 3. Overall, there was a suggestion that the δD and $\delta^{18}O$ contents exhibited a slight decrease with increasing elevation of the spring, as illustrated in Figure 6. The variations in δD and $\delta^{18}O$ contents of spring water samples may be attributed to altitude effect resulting from differences in recharge area elevation and ambient temperature. The relationship between δD and $\delta^{18}O$ is characterized by a robust linear correlation, described by the equation $\delta D = 7.70\ \delta^{18}O + 8.34$, with regression coefficient $r^2 = 0.965$. This equation closely resembles the local meteoric water line (LMWL), expressed as $\delta D = 7.74\ \delta^{18}O + 7.82$ [26]. The slope of the linear equation near 8 suggests that the spring waters have not undergone any evaporation or mixing with evaporated waters, such as surface water, during their journey from the inlet in the recharge area to the spring outlet. This information is crucial for estimating the elevation of the recharge area of the springs. The isotopic values of springs, δD and $\delta^{18}O$, can be considered similar to those of the precipitation that contributes to the spring in the recharge area. Figure 7 presents the diagram of δD versus $\delta^{18}O$ for springs, alongside surface waters and the LMWL.

Table 3. Stable isotopes contents of spring water samples

No.	Sample Code	Elevation (*E*) (m)	$\delta^{18}O$ (‰)	δD (‰)
1	SP-1	574	-7.99	-52.95
2	SP-2	250	-7.63	-50.81
3	SP-3	669	-8.05	-52.96
4	SP-4	98	-7.85	-51.54
5	SP-5	702	-8.05	-54.35
6	SP-6	900	-8.56	-57.89
7	SP-7	832	-8.66	-58.14
8	SP-8	707	-8.08	-54.41
9	SP-9	590	-8.25	-55.00
10	SP-10	650	-7.85	-52.00

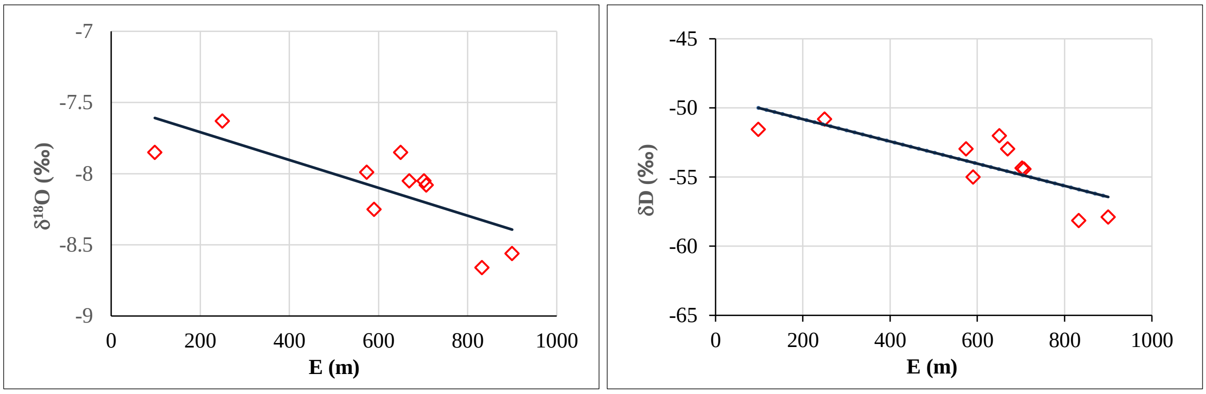


Figure 6. $\delta^{18}O$ and δD vs Elevation (*E*) diagram of spring waters

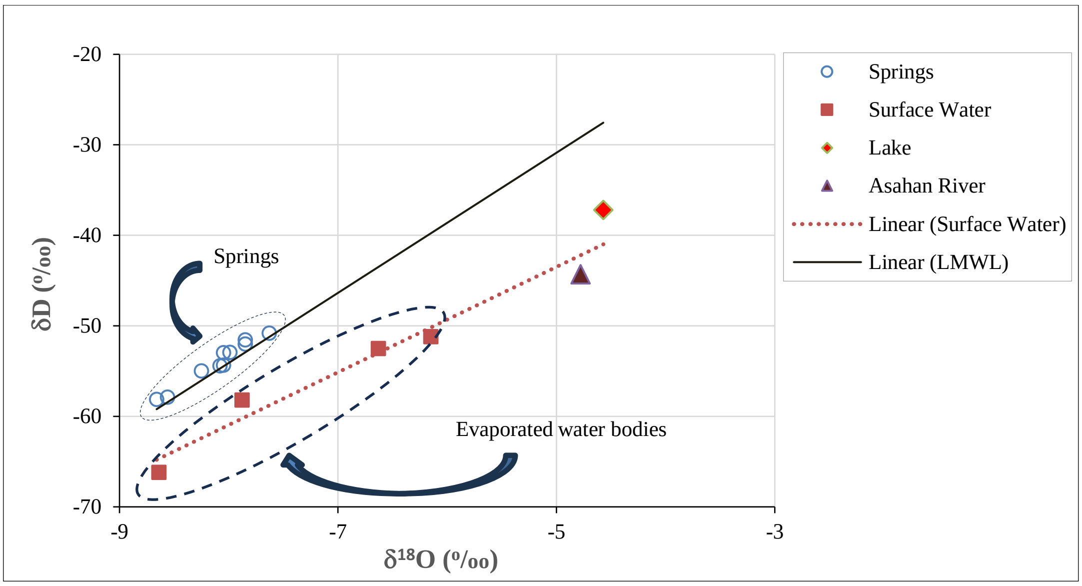


Figure 7. δD vs $\delta^{18}O$ diagram of springs, surfacewater and LMWL

Figure 7 illustrates that lake's δD and $\delta^{18}O$ contents are significantly enriched in comparison to the springs, despite the lake's relatively higher altitude than all the springs. The δD and $\delta^{18}O$ of lakes align with eveporation line where all other surface waters are positioned. The δD and $\delta^{18}O$ contents of all springs aligned with the LMWL, suggesting that the springs have not undergone any evaporation processes during their transit from the inlet in the recharge area. These facts indicate that the springs did not originate from the lake. To address the inquiry regarding the origin of the springs, the recharge area of the spring is evaluated below.

3.4. Recharge Area of Springs

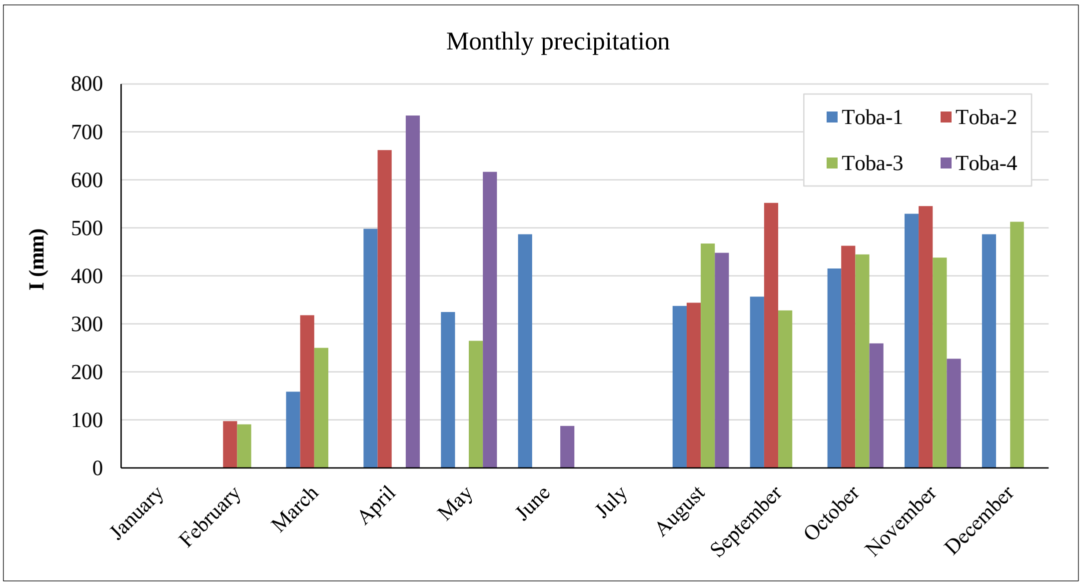
To estimate the recharge area of springs, we utilized our previous data from four rain collectors positioned at various locations and elevations within the study catchment area of Lake Toba, as presented in Table 4 [13].

Tabel 4. Elevations, locations of 4 installed rain collectors

Code	Location	Coordinate (degrees, WGS84)		Elevation (m)
		East	North	
Toba-1	Simarjarungjung-1	98.772665	2.837644	1497
Toba-2	Simarjarungjung-2	98.781882	2.816756	1350
Toba-3	Tiga Ras-1	98.777582	2.812757	1200
Toba-4	Tiga Ras-2	98.784189	2.798744	923

Tabel 5. Rain intensity and monthly cumulative isotope composition of rainwater in each rain collector

Month (2014)	Toba-1			Toba-2			Toba-3			Toba-4		
	I (mm)	δD (‰)	$\delta^{18}O$ (‰)	*I* (mm)	δD (‰)	$\delta^{18}O$ (‰)	*I* (mm)	δD (‰)	$\delta^{18}O$ (‰)	*I* (mm)	δD (‰)	$\delta^{18}O$ (‰)
January	-	-	-	-	-	-	-	-	-	-	-	-
February	-	-	-	97.4	-28.7	-6.8	90.9	-29.6	-6.1	-	-	-
March	159.1	-39.0	-7.0	318.3	-38.0	-10.1	250.1	-37.4	-6.7	-	-	-
April	498.5	-70.6	-10.0	662.5	-67.6	-9.3	-	-	-	734.0	-56.3	-9.3
May	324.8	-59.6	-8.4	-	-	-	264.7	-65.4	-7.5	617.1	-61.4	-9.4
June	487.2	-63.8	-9.4	-	-	-	-	-	-	87.7	-38.2	-5.2
July	-	-	-	-	-	-	-	-	-	-	-	-
August	337.8	-14.5	-2.6	344.3	-20.9	-2.8	467.7	-15.3	-3.1	448.2	-13.2	-2.7
September	357.2	-35.0	-5.1	552.1	-15.0	-5.3	328.0	-18.2	-3.7	-	-	-
October	415.7	-36.9	-4.8	462.8	-37.1	-5.6	444.9	-36.2	-4.9	259.8	-38.2	-5.2
November	529.4	-38.2	-5.4	545.6	-39.5	-6.8	438.4	-33.2	-4.7	227.3	-26.8	-3.7
December	487.2	-37.3	-5.2	-	-	-	513.1	-32.6	-5.7	-	-	-



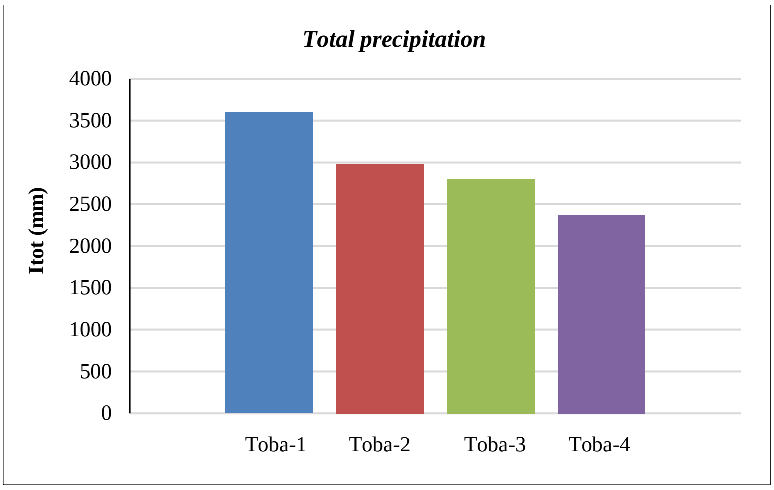


Figure 8. Monthly (*I*) and total (I_{tot}) precipitation on each rain collector station

Monthly samples were collected from each rain collector over a period of 12 months, spanning from January to December 2014. The data regarding the intensity of monthly and total rainfall for each rain collector station is presented in Table 5 and illustrated in Figure 8. The design of each rain collector allows it to retain rainwater for a duration of one month. To mitigate evaporation from the surface, paraffin oil was applied to float on top of the water. The total rainfall for the period from January to December 2014 was between 2374 and 3597 mm, with an average of approximately 2938 mm. The total rainfall exhibited a linear relationship with the altitude of the rain collector station, as illustrated in Figure 8, where the total annual rainfall rises with altitude. This incident was also in line with the Suzuki et al. study's conclusions [42]. The primary cause of this phenomenon is thought to be the rising frequency of rainfall at higher elevations. Table 5 presents the monthly rain intensity alongside the corresponding δD vs $\delta^{18}O$ values, where the dashed line (-) signifies that the sample was disregarded due to either a lack of rain, minimal rainfall, or improper handling of the sample. The calculation of the weighted average stable isotopes contents of samples ($\bar{\delta}D$ and $\bar{\delta}^{18}$O) was performed using the following formula:

$$\bar{\delta}D = \frac{\sum_i^n I_i \delta D_i}{\sum_i^n I_i} \quad (2)$$

$$\bar{\delta}\ ^{18}O = \frac{\sum_i^n I_i \delta^{18}O_i}{\sum_i^n I_i}, \quad (3)$$

The values $\overline{\delta D}$ and $\bar{\delta}\ ^{18}O$, calculated using Equations 2 and 3, are presented in Table 6. The altitude effect is clearly demonstrated in Table 6, where the stable isotope contents of water are more enriched at lower altitudes compared to those at higher altitudes. According to Equation 5, for every 100 m rise in elevation, $\delta^{18}O$ will drop by -0.47‰. These figures fall within the range of global gradient precipitation as a function of height, which is between -5‰ and -0.15‰ for every 100 meters of elevation gain [43]. Chen et al.'s [36] findings, which showed an average gradient of -0.21‰ every 100 meters gain in elevaion, are likewise consistent with these findings. The values presented in Table 6 were utilized to derive the linear regression equations for elevation in relation to the weighted average stable isotopes, as shown in Equations 4 and 5. Additionally, the corresponding graphs depicting elevation against $\bar{\delta}D$ and $\bar{\delta}^{18}$O are illustrated in Figure 9.

$$E = -26.18\ \delta D + 362.9 \quad (4)$$

$$E = -212.3\ \delta^{18}O - 123.3 \quad (5)$$

Tabel 6. Weighted average of stable isotopes of rain samples

Sample Code	Elevation (masl)	$\bar{\delta}D$ (‰)	$\bar{\delta}^{18}O$ (‰)
Toba-1	1497	-45.31	-6.53
Toba-2	1350	-32.82	-5.83
Toba-3	1200	-29.61	-4.63
Toba-4	923	-26.67	-4.10

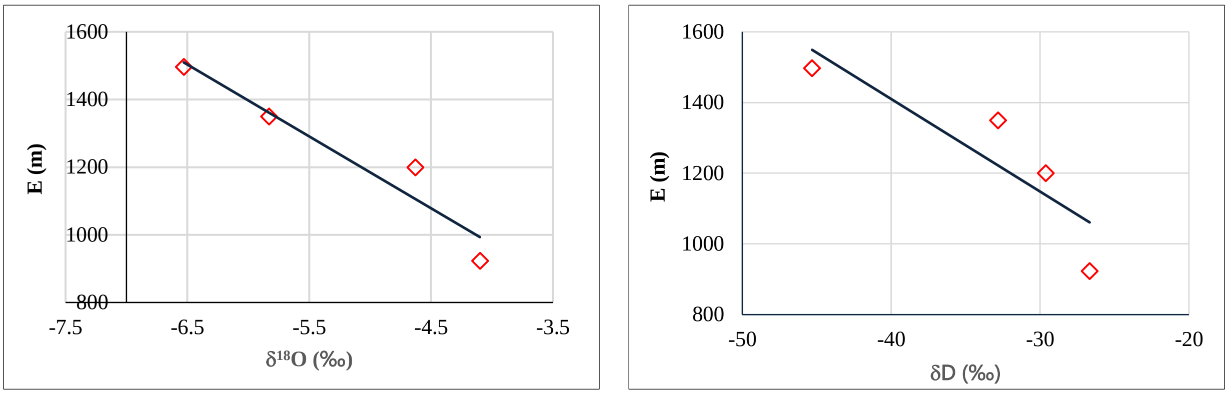


Figure 9. Elevation vs $\bar{\delta}D$ and $\bar{\delta}^{18}O$ of installed rain collectors

Given that stable isotopes of water molecules exhibit a high degree of conservativeness, it is logical to conclude that the δD and $\delta^{18}O$ values of precipitation will remain unchanged during their transit from the recharge area to the spring outlet (sampling point) [26]. This assumption is supported by the fact that the water remained isolated within the soil matrix, thereby avoiding contact with the atmosphere throughout its journey from recharge to the sampling point. The δD vs $\delta^{18}O$ diagram of all spring water, as shown in Figure 7, confirms this observation. The slope of the regression line closely aligns with the slope of the LMWL, indicating that the springs have not experienced significant evaporation or mixing with evaporated water sources throughout their existence. Based on this assumption, Equations 3 and 4 serve to predict the elevations of the recharge area of the springs, with the calculated recharge area elevations presented in Table 7. The elevations of the average recharge areas were determined to be between 1718 and 1923 meters above sea level. The average recharge elevations indicate that the recharge area is anticipated to be located in the Simarjarungjung Mount region surrounding the lake, as illustrated in Figure 10.

Table 7. Estimated recharge area estimation of spring waters

No.	Sample Code	Elevation of recharge area (m)		
		Based on δD	Based on $\delta^{18}O$	Average
1	SP-1	1749	1819	1784
2	SP-2	1693	1743	1718
3	SP-3	1749	1832	1791
4	SP-4	1712	1790	1751
5	SP-5	1786	1832	1809
6	SP-6	1878	1940	1909
7	SP-7	1885	1962	1923
8	SP-8	1787	1838	1813
9	SP-9	1803	1874	1839
10	SP-10	1724	1790	1757

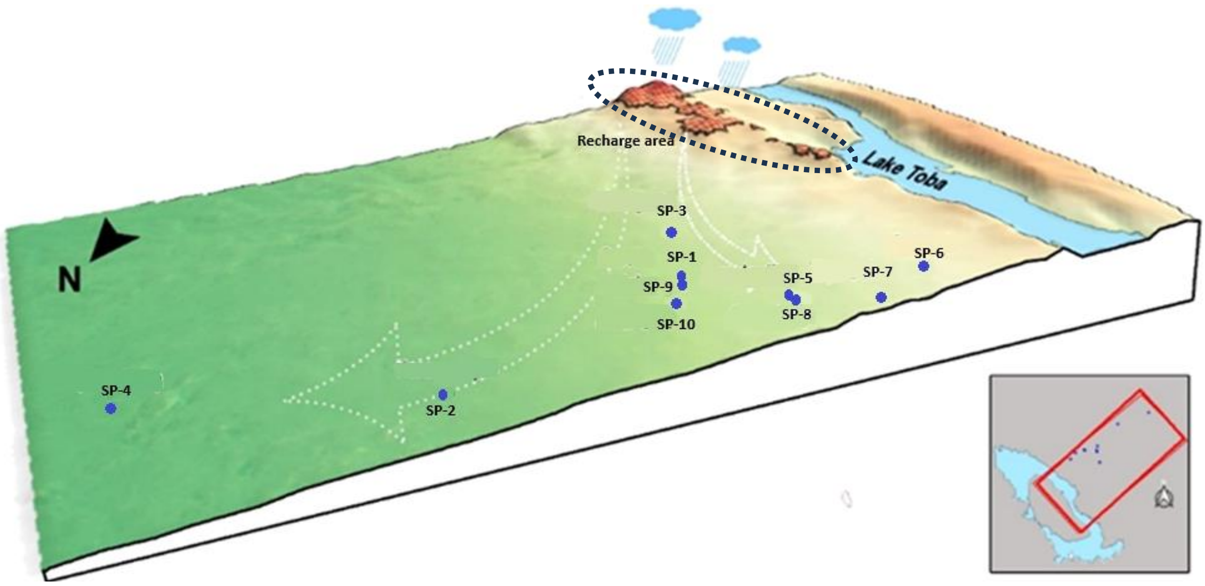


Figure 10. Recharge area of springs near Lake Toba

4. Conclusion

The grouping of springs and lake samples as the same water type (weak acid type) suggests that all samples likely originated from the same geological formation associated with their respective recharge areas. This phenomenon was anticipated since nearly the entire study area was comprised of the same volcanic rock formation known as Toba Tuff.

The temperature of spring water decreases at higher elevations, suggesting that ambient temperature influences spring water temperatures. The conductivities and pH of the lake exceed those of spring waters, likely due to an extended evaporation process the lake has experienced, along with dissolved minerals resulting from human activities like agricultural runoff and aquaculture in the area.

The regression line of δD and $\delta^{18}O$ values of spring waters closely resembles the local meteoric water line, suggesting that the spring waters have not experienced evaporation or interacted with the atmosphere or evaporated water during their transit from inlet points to the spring outlets. The δD and $\delta^{18}O$ of lakes align with the evaporation line, indicating that the lake has experienced a considerable evaporation process. These facts indicate that the springs did not originate from the lake.

The equation regression lines for $\bar{\delta}D$ or $\bar{\delta}^{18}O$ in relation to the elevation of precipitation serve to forecast the elevation of recharge areas for springs. The anticipated elevations of recharge areas for springs fall between 1700 and 1900 meters above sea level. The predicted recharge area is determined to be located at the slope of Simarjarungjung Mount, based on the estimated elevations of the recharge area. The findings suggest that the primary factors contributing to the instability of lake water levels may stem from a reduction in groundwater flow within the lake's catchment area, attributed to changes in land use and ongoing deforestation in the region. Another factor could be attributed to the necessity for a constant and continuous flow of water through the Asahan River to facilitate power generation for the INALUM aluminum smelting industry.

5. Declarations

5.1. Author Contributions

Conceptualization, P.S. and R.P.; methodology, P.S., S., and R.P.; software, P.S., R.P., and E.R.P.; validation, P.S., R.P., and S.; formal analysis, P.S., R.P., S., and E.R.P.; investigation, P.S., R.P., S., and E.R.P.; resources, P.S.; data curation, S. and E.R.P.; writing—original draft preparation, P.S.; visualization, R.P. and S.; supervision, P.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.5. Institutional Review Board Statement

Not applicable.

5.6. Informed Consent Statement

Not applicable.

5.7. Declaration of Competing Interest

The authors declare that there are no conflicts of interest concerning the publication of this manuscript. Furthermore, all ethical considerations, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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