UDC 556.388
DOI: 10.18799/24131830/2025/8/4827
Scientific paper

Groundwater quality and health risk assessment in the area of LUSI mud volcano in Sidoarjo, East Java, Indonesia: toward clean water sustainability

I.P. Adiyaksa[1]✉, M.H. Razi[2]

[1] *Tokyo University of Agriculture and Technology, Tokyo, Japan*
[2] *Universitas Gadjah Mada, Yogyakarta, Indonesia*

✉ilhamadiyaksa@gmail.com

Abstract. ***Relevance.*** The distribution of clean water that meets acceptable standards is highly needed for public health. However, in many regions of the world, including the eastern part of Java Island (Indonesia), in the East Java province, Sidoarjo, where the world's largest mud volcano has been active since 2006, this is a significant challenge. This area has a high population density that makes a constant demand for quality drinking water. The ongoing LUSI mud volcano has greatly complicated the issue of the domestic and drinking water supply. As a result, Sidoarjo faces serious challenges, especially given that the only water treatment company – PDAM Delta Tirta Sidoarjo – can serve only 37% of the population. At the same time, the rest of the population must find reliable access to clean water independently. ***Aim.*** To analyze the physicochemical characteristics of groundwater around the LUSI mud volcano in Sidoarjo, East Java, Indonesia, and assess the associated health risks from chemical exposure. ***Methods***. Groundwater samples were analyzed for various chemical compounds, and a pollution index was calculated to classify water quality. Additionally, the method recommended by the US Environmental Protection Agency was used to assess the health risks of chemical exposure, including evaluating potential cancer risks. ***Results and conclusion***. An analysis of the groundwater conditions in the area surrounding the world's largest mud volcano, LUSI (Indonesia), was conducted using data obtained by the authors in 2024 and earlier. The authors calculated groundwater saturation concerning various minerals, water quality indices, and health risk assessments associated with water usage. The study revealed that the chemical composition of the examined groundwater is characterized as calcium chloride type, with the overall quality being classified as heavily polluted, particularly due to elevated levels of chlorides and manganese. Based on the Hazard Quotient and Hazard Index, it was determined that the high concentrations of manganese pose a non-carcinogenic health risk, especially for children. Additionally, the Cancer Risk Index analysis showed that, at present, the mercury content in the studied groundwater does not pose a significant health risk. However, ongoing monitoring and remediation of water sources in the LUSI area are highly required to improve groundwater quality as a source of clean water.

Keywords: clean water, LUSI, groundwater quality, pollutant index, health risks, cancer risk

Acknowledgment: The research was partially funded by VODAKU, a youth-led organization based in Sidoarjo, as part of its education and research initiatives.

For citation: Ilham Putra Adiyaksa, M. Haikal Razi. Groundwater quality and health risk assessment in the area of LUSI mud volcano in Sidoarjo, East Java, Indonesia: toward clean water sustainability. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, 2025, vol. 336, no. 8, pp. 7–20. DOI: 10.18799/24131830/2025/8/4827

УДК 556.388
DOI: 10.18799/24131830/2025/8/4827
Научная статья

Оценка качества грунтовых вод и риска для здоровья в районе грязевого вулкана Люси в Сидоарджо, Восточная Ява, Индонезия: на пути к устойчивому обеспечению чистой воды

И.П. Адьякса[1]✉, М.Х. Рази[2]

[1] Токийский университет сельского хозяйства и технологий, Япония, г. Токио
[2] Университет Гаджа Мада, Индонезия, г. Джокьякарта

✉ilhamadiyaksa@gmail.com

Аннотация. ***Актуальность.*** Соответствие воды, используемой для хозяйственно-питьевых целей, установленным нормативам качества является необходимым условием обеспечения здоровья населения. Однако во многих регионах мира, включая восточную часть острова Ява (Индонезия), провинция Восточная Ява, округ Сидоарджо, где с 2006 г. функционирует крупнейший в мире грязевой вулкан, это представляет собой серьёзную проблему. На этой территории высокая плотность населения, что определяет постоянную потребность в качественной питьевой воде. Но функуционирование грязевого вулкана Люси существенно усложняет проблему хозяйственно-питьевого водоснабжения. В результате округ Сидоарджо сталкивается с серьезными проблемами, особенно с учетом того, что единственная компания по водоподготовке – PDAM Delta Tirta Sidoarjo – способна охватить только 37 % населения, в то время как остальная часть населения должна самостоятельно искать надежный доступ к чистой воде. ***Цель.*** Анализ физико-химических характеристик грунтовых вод вокруг грязевого вулкана Люси в Сидоарджо, Восточная Ява, Индонезия, и оценка связанных с этим рисков для здоровья населения от химического воздействия в воде. ***Методы.*** Методы определения химического состава грунтовых вод (титриметрический, турбидиметрические и другие), статистические методы, сопоставление с индексами загрязнения, принятыми в Индонезии и США. ***Результаты и заключение.*** Проведен анализ состояния грунтовых вод в районе крупнейшего в мире грязевого вулкана Люси (Индонезия) с учетом данных, полученных авторами в 2024 г. и ранее. Выполнены расчеты насыщенности грунтовых вод относительно ряда минералов, расчеты индексов качества воды и рисков возникновения заболеваний при использовании воды и подробный анализ полученных материалов. Показано, что изученные грунтовые воды по химическому составу характеризуются как хлоридные кальциевые, а их качество оценивается как неудовлетворительное, особенно по содержаниям хлоридов и марганца. Установлено, что по величине коэффициента опасности и индекса опасности повышенные концентрации Mn представляют неканцерогенный риск для здоровья, особенно для детей. Также выполнены расчеты индекса риска рака. Анализ полученных результатов показал, что в настоящее время по содержанию ртути изученные грунтовые воды не представляют значительной опасности, но требуется постоянный мониторинг водных объектов и рекультивации земель в районе грязевого вулкана Люси для улучшения качества грунтовых вод.

Ключевые слова: чистая вода, Люси, качество грунтовых вод, индекс загрязняющих веществ, риски для здоровья, риск возникновения рака

Благодарность: Исследование было частично профинансировано VODAKU, молодежной организации, базирующейся в Сидоарджо, в рамках ее образовательных и исследовательских инициатив.

Для цитирования: Илхам Путра Адьякса, М. Хайкал Рази. Оценка качества грунтовых вод и риска для здоровья в районе грязевого вулкана Люси в Сидоарджо, Восточная Ява, Индонезия: на пути к устойчивому обеспечению чистой воды // Известия Томского политехнического университета. Инжиниринг георесурсов. – 2025. – Т. 336. – № 8. – С. 7–20. DOI: 10.18799/24131830/2025/8/4827

Introduction

Clean water is one of the key factors for maintaining human health, environmental sustainability, and even economic stability, as outlined in the 6th objective of the SDGs. It is critical for preventing a wide range of diseases by ingesting the body as drinking water, supporting agricultural practices and industrial activities, and, in general, ensuring quality of life. Many studies have been conducted to analyze the impact of water quality on human health conditions [1–3]. The current issue of population growth makes the problem of clean water increasingly urgent. Indonesia, with a population of over 280 million, still faces limited access to clean water. Environmental issues such as waste contamination in water bodies make the issue of clean water particularly relevant [4]. Inadequate access to clean water and neglecting the quality of water in general can lead to serious impacts, including increased health problems, decreased sanitation, loss of biodiversity, and hindered economic growth [5–6].

Groundwater is vital for providing clean water, especially in countries like Indonesia, where access to reliable surface water sources can be limited. A report from UNICEF Indonesia in 2022 stated that 37% of households in Indonesia, which amounts to around 100 million people, depend on self-supplied water [7]. In Sidoarjo, this self-supplied water is sourced primarily from groundwater and is financed and managed independently by each household. As the population increases and urbanization accelerates, the water demand rises. In Indonesia, with its vast archipelago and diverse geography, groundwater plays an essential role in sustaining communities, especially during dry seasons when rivers and reservoirs are depleted [8]. However, the quality and availability of groundwater are increasingly threatened by over-extraction, pollution, and environmental degradation [9].

In Sidoarjo, particularly around LUSI (abbreviation for Lumpur Sidoarjo) mud volcano, the condition of groundwater has become a significant concern due to current environmental challenges. LUSI eruption, which began on May 26th, 2006, following a drilling operation by PT Lapindo Brantas, which is believed to have triggered the event, led to widespread contamination and disruption of local water resources [10, 11]. The continuous discharge of hot mud, rich in various minerals and chemicals, contaminated water resources, degrading their quality, and making them less suitable for consumption [12]. At the same time, as the primary clean water provider in Sidoarjo, PDAM Delta Tirta Sidoarjo currently faces significant challenges in meeting the water needs of the local population. The company can only supply clean water to about 37% of the Sidoarjo population, leaving most of the population reliant on alternative water sources, such as groundwater, with quality uncertainty.

Previous research conducted in 2022 on the groundwater conditions around LUSI showed significant concerns regarding water quality [1, 10]. The study focused on areas surrounding the mud volcano, particularly in Tanggulangin and Porong, Sidoarjo, where groundwater samples were collected from wells. The analysis highlighted elevated levels of contaminants, such as a high concentration of chloride and heavy metals. The presence of elements like Fe, Mn, and Hg in concentrations exceeding safe drinking water standards raised alarms about the potential health risks to the local population, particularly for children and vulnerable groups.

Comparing this with earlier data from 2012, a similar trend of groundwater contamination was observed, although the levels of certain pollutants have fluctuated over the years [11]. The 2012 study indicated high concentrations of Na^+, Cl^-, and HCO_3^-, along with the heavy metals. These findings suggest a persistent and possibly worsening contamination of groundwater resources over the decade, underscoring the long-term environmental impact of the LUSI disaster.

This research aims to analyze groundwater physicochemical characteristics around LUSI mud volcano in Sidoarjo. By examining the levels of various chemical parameters, this study aims to assess the overall quality of groundwater using the Pollution Index (PI) method. Additionally, the research seeks to evaluate the potential health risks associated with chemical exposure, particularly for the local population who rely on this groundwater for daily use. This analysis is highly needed due to the ongoing contamination risks posed by LUSI, the lack of water management by PDAM Delta Tirta, and the ongoing issue of climate change, which continues to impact the environment and public health. Understanding these aspects is essential for developing effective strategies to mitigate the contamination, safeguard water resources, and protect the health of the residents in this heavily affected area.

Methodology

Geology and hydrogeology of the study area

Sidoarjo is located within the East Java basin, which is covered by sedimentary rocks from the Quaternary to the Miocene periods, with depths up to 6000 meters [13]. Regionally, Sidoarjo is located in the Kendeng basin as part of the Central Depression Zone of Java due to the collision between the Eurasian and Indo-Australian Plates. This collision has resulted in numerous active faults in this area, including the Watukosek one, which extends from the southwest to the northeast and is prominent in the Kendeng zone. It traverses Mojokerto, Gresik, and extends to the western part of Madura. It leads to the formation of additional faults, such as a fault that crosses Banjar Panji to Kujung [14]. Additionally, Sidoarjo is located in the delta region of the Brantas River, between its branches – the Surabaya and Porong rivers, with a flat terrain within Sidoarjo ranging from 23 to 32 meters above sea level, while the surrounding regions are mountainous.

Hydrogeochemical sampling

A total of five well samples were carefully collected from various locations within the LUSI area, with the groundwater depth ranging from 3–5 meters. The area of sampling was in Kali Tengah village, Tanggulangin, Sidoarjo, East Java.

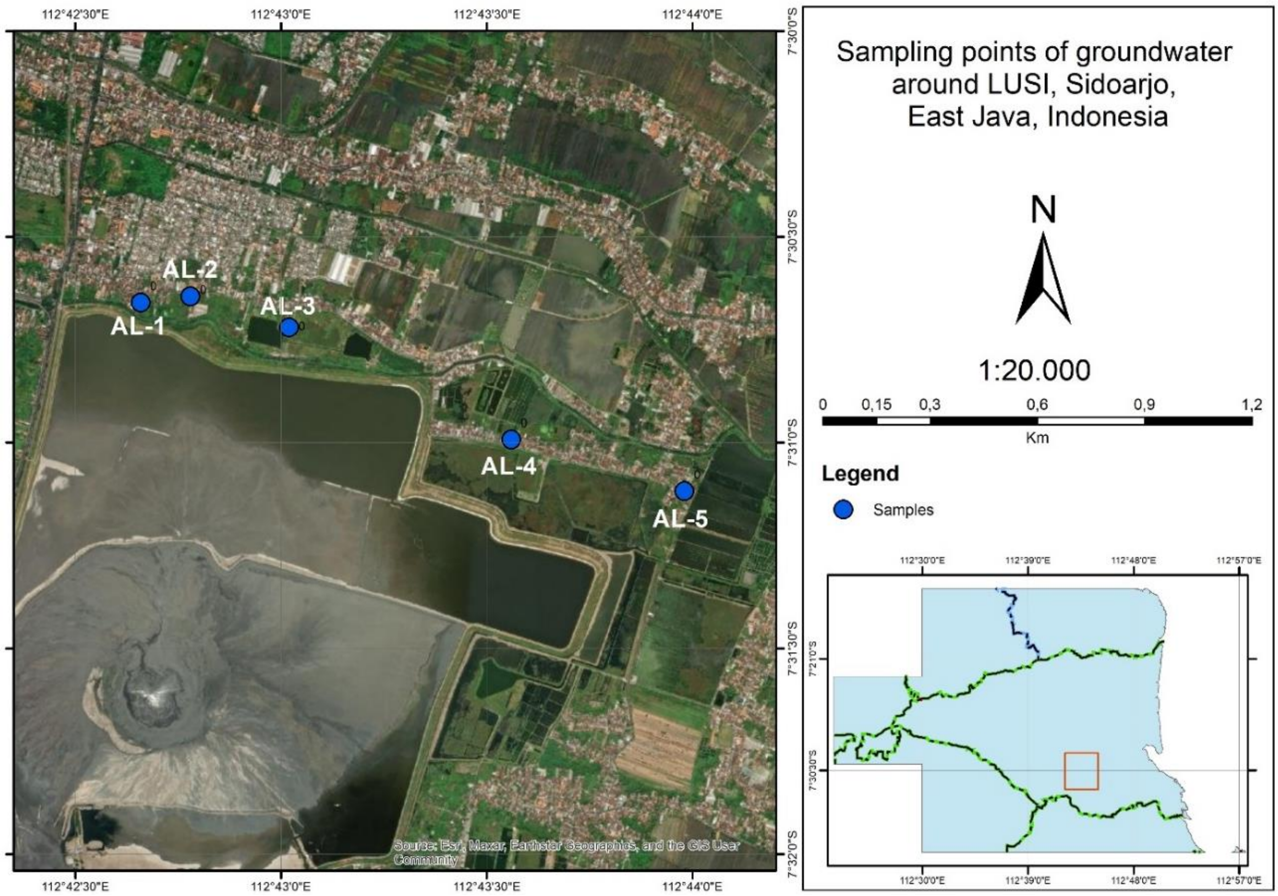

Fig. 1. *Layout of groundwater sampling points near LUSI, Sidoarjo, East Java, Indonesia in August 2024*
Рис. 1. *Схема расположения пунктов отбора грунтовых вод вблизи Люси, Сидоарджо, Восточная Ява, Индонезия, в августе 2024 г.*

The standard procedures were applied, and the water samples were collected in clean and dry polyethylene bottles with a capacity of 1.5 liters. These samples were then transported to the laboratory.

The coordinates of the samples are shown in Table 4, and the scheme is in Fig. 1. Samples were taken on August 9th, 2024, during the dry season. All wells tapped into alluvial deposits composed of clay, sand, and gravel, previously used for drinking purposes.

Table 1. *Methods used for chemical analysis of groundwater*
Таблица 1. *Методы химического анализа грунтовых вод*

Parameter/Показатель	Method/Методы
Ca^{2+}	SM APHA 23rd Ed., 3120 B, 2017
Mg^{2+}	SM APHA 23rd Ed., 3120 B, 2017
Na^{+}	SM APHA 23rd Ed., 3120 B, 2017
K^{+}	SM APHA 23rd Ed., 3120 B, 2017
HCO_3^{-}	Q1/LKA/06 (Titrimetric)
SO_4^{2-}	SNI 6989.20.2019
Cl^{-}	SNI 6989.19.2009
Fe	SM APHA 23rd Ed., 3120 B, 2017
Mn	SM APHA 23rd Ed., 3120 B, 2017
Hg	Q1/LKA/116

All groundwater samples were analyzed in the Environmental Laboratory of Jasa Tirta I, Malang, East Java. The analysis included Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}, Hg, Mn, and Fe. Methods used for the analysis are shown in Table 1. Field measurements included water temperature, pH, total dissolved solids (TDS), and salinity.

Pollutant Index (PI) calculation

Managing water quality by utilizing the PI calculation is highly recommended to inform and guide decisions aimed at addressing the decline in water quality. The PI provides a comprehensive assessment of contamination levels [15]. The calculation involves several steps as follows:

Step 1. Determine the C value for each parameter

Calculate the C value for each parameter to understand the correlation between the standard values and laboratory results. This is done using Equation (1)

$$C = \frac{C_i}{L_{ij}}, \quad (1)$$

where C is the comparison of the chemical concentration from laboratory analysis to the standard;

C_i is the chemical concentration based on laboratory results (mg/L); L_{ij} is the chemical concentration based on the standard (mg/L).

Step 2. Recalculate parameters with C values greater than 1

For parameters where C>1, recalculate C using Equation (2)

$$C_n = 1 + P \log C \,, \quad (2)$$

where C_n is the revised comparison of chemical concentration with the standard; P is the constant value of 5; C is the result from Equation (1).

Step 3. Calculate PI

Calculate the PI using Equation (3)

$$PI = \sqrt{\frac{{C_{n\,(max)}}^2 + C_{n\,(avg)}^2}{2}}\,, \quad (3)$$

where $C_{n(max)}$ is the maximum C_n value from a sample; $C_{n(avg)}$ is the average C_n value from a sample.

The PI value is an instrument for determining the extent of water contamination. Water quality is classified into four groups based on the PI value, providing a clear framework for assessing and managing water safety (Table 2).

Table 2. *Classification of water contamination based on PI value*

Таблица 2. *Классификация загрязнения воды на основе значения PI*

PI value/Значение PI	Classification/Классификация
0–1.0	Clean/Чистая
1.1–5.0	Lightly polluted/Слабо загрязненная
5.1–10	Moderately polluted/Умеренно загрязненная
>10	Heavily polluted/Сильно загрязненная

Saturation Indices

The saturation indices (SI) of groundwater for various minerals are calculated using the constants method, as outlined in [16]. The formula used for this calculation is provided in Equation (4)

$$SI = \lg PA - \lg K_{neq}, \quad (4)$$

where SI is the saturation Index; K_{neq} is the constant of non-equilibrium; PA is the product of the activities of the interacting substances, excluding the mineral series.

The SI results indicate the chemical equilibrium trends between water and minerals and describe the interaction between groundwater and rock. If the SI is negative (SI<0), it suggests that minerals are continuously dissolving into the groundwater. If the SI is positive (SI>0), it indicates that minerals are precipitating out of the water. When the SI is near zero, minerals are in a stable equilibrium state.

Health Risk Assessment due to Chemical Exposure

In this study, the evaluation of non-carcinogenic health risks was carried out by examining the daily intake of metals present in groundwater, including Hg, Mn, and Fe, around LUSI and calculating the Hazard Quotient (HQ) for various population groups. The specific groups considered in the assessment are detailed in Table 3. These groups were selected to represent typical scenarios in the Sidoarjo area near LUSI.

The parameters used for these assessments are detailed in Table 3. The health risk evaluation utilized a method recommended by the United States Environmental Protection Agency (US EPA), as described in [3]. The assessment process begins with calculating the daily intake of contaminants using Equation (5)

$$I = \frac{C\ x\ IR\ x\ FE\ x\ TE}{WT}\ x\ \frac{1}{TA}, \quad (5)$$

where I is the daily contaminant intake (mg/kg-day); C is the concentration of contaminant (mg/L), in this case concentration of Fe, Mn, and Hg; IR is the ingestion rate of water (L/day);

FE is the frequency of exposure (308 days/year); TE is the time of exposure (years); WT is the weight of the consumer (kg); TA is the time average (days).

Table 3. *Calculation of health risk parameters for several cases*

Таблица 3. *Расчет параметров риска для здоровья для нескольких случаев*

Parameters for calculation Параметры для расчета	Infants (birth) Младенцы (рождение)	Infants (3 months) Младенцы (3 месяца)	Adult male Взрослый мужчина	Adult non-pregnant female Взрослая небеременная женщина	Pregnant female (end of 1st trimester) Беременная женщина (конец 1-го триместра)
FE – frequency of exposure (days/year) частота воздействия (дней/год)	308	308	308	308	308
IR – ingestion rate of water (L/day) Объем потребления воды (л/день)	0.78	1.81	3.7	3.4	3.7
WT – Weight of consumer (kg) Вес потребителя (кг)	3.36	5.76	59	53	48.5

Source: [3]/Источник: [3].

The HQ is calculated using Equation (6)

$$HQ = \frac{I}{RfD}, \quad (6)$$

where RfD is the reference dose (mg/kg-day), for Fe is 0.7, Mn is 0.14, Hg is 0.0001, and Cl^- is 0.204.

To determine the Hazard Index (HI), the sum of the HQ values for individual metals is calculated using Equation (7)

$$HI = \Sigma\, HQ = HQ_{Fe} + HQ_{Mn} + +HQ_{Hg}, \qquad (7)$$

where HI is the Hazard Index.

HQ<1 indicates that water consumers in the study area are unlikely to experience specific adverse health effects, whereas HQ>1 suggests a potential risk of harmful effects. The HI offers a cumulative assessment of the combined HQs for all metals present, with HI>1 indicating a potential non-carcinogenic health risk, while HI<1 suggests no significant health risk.

The Cancer Risk (CR) from mercury (Hg) contamination is calculated using Equation (8):

$$CR = I \times SF, \qquad (8)$$

where SF is the oral slope factor (mg/kg-day), with values of 1 for Hg [17].

Results and discussion

Physicochemical characteristics of groundwater around LUSI

The physicochemical characteristics of groundwater refer to the physical and chemical properties that define the quality of groundwater. These characteristics are essential in assessing the suitability of groundwater for various uses, including drinking or other hygiene purposes. Table 4 shows the result of the analysis of the physicochemical characteristics of groundwater around LUSI in August 2024. The average pH of the groundwater is 6.85, which is still within the acceptable standard range. The highest pH value measured is 7.44 in AL-2, while the lowest is 6.52 in AL-4. The average electrical conductivity (EC) of groundwater in this area is 4648.4 μS/cm, with the highest value of 7850 μS/cm in AL-5 and the lowest measured of 1342 μS/cm in AL-1. The average TDS of groundwater is 2321.6 ppm, with a maximum of 3920 ppm in AL-5 and a minimum of 668 ppm in AL-1. For the major ions, the average concentrations are as follows: Ca^{2+} at 248.8 mg/L, Mg^{2+} at 34.61 mg/L, Na^{+} at 104.38 mg/L, K^{+} at 44.194 mg/L, HCO_3^{-} at 199.6 mg/L, SO_4^{2-} at 11.01 mg/L, and Cl^{-} at 1886 mg/L. Among these, chloride is the highest anion, and calcium is the highest cation. While for heavy metals, the average concentration of Mn is 0.349 mg/L, Hg is <0.00003 mg/L, and Fe is 0.0266 mg/L.

Comparing the current groundwater quality state in the area of LUSI with the results of previous researches from 2022 and 2012 shows several trends [10, 11]. The average pH has increased from 6.52 in 2022 to 6.85 in 2024. EC has risen significantly from 1.203,8 μS/cm in 2022 to 4.648,4 μS/cm in 2024. Ca^{2+} concentrations have also increased from 104.94 mg/L in 2012 to 248.8 mg/L in 2024, while Mg^{2+} has risen slightly from 31.14 mg/L in 2022 to 34.61 mg/L. In 2024, Na^{+} has decreased from 282.97 mg/L in 2012 to 104.38 mg/L, and K has risen from 27.43 mg/L in 2012 to 44.194 mg/L. HCO_3^{-} levels have dropped from 508.46 mg/L in 2012 to 199.6 mg/L, and SO_4^{2-} has decreased from 21.25 mg/L in 2012 to 11.01 mg/L in 2024. Cl^{-} has surged from 593.94 mg/L in 2012 to 1886 mg/L on average in 2024. Mn levels decreased from 1.4424 mg/L in 2022 to 0.349 mg/L in 2024. Hg levels have decreased from 0.00598 mg/L in 2022 to 0.00003 mg/L, after rising from 0.00241 mg/L in 2012. Fe has decreased from 0.452 mg/L in 2022 to 0.0266 mg/L in 2024, having increased from 0.00122 mg/L in 2012.

The changes in the physicochemical characteristics of groundwater around LUSI in Sidoarjo, East Java, Indonesia, from 2012 to 2022 and 2024 can be affected by several factors. Geographical variations among sampling points affect the concentration levels of physicochemical characteristics [18]. The elevated chloride levels are likely a result of seawater intrusion. The AL-5 site exhibits the highest Cl^{-} concentration due to its proximity to the sea, located to the east of LUSI. Moving westward, compared with 2022 research, chloride levels decrease, though they remain generally high throughout the area. Local cultural attitudes toward water quality, marked by a lack of sufficient care and awareness, also play a significant role [19]. This may contribute to the presence of heavy metals and their concentration in the water, potentially worsening the overall water quality. Additionally, the lack of adequate water and wastewater management systems exacerbates these changes. The ongoing LUSI may further affect groundwater quality [10]. Moreover, climate change contributes to variations in groundwater quality by changing precipitation patterns, increasing the frequency of weather events, and affecting water table levels, all of which can affect the concentration and distribution of contaminants in groundwater [20, 21].

Groundwater type around LUSI

The interpretation of groundwater chemistry can be approached using various methods, including the Kurlov method. The results of each groundwater chemical composition analysis are commonly represented using the Kurlov formula. This formula provides a generalized characterization of the chemical composition of a single water analysis. The main part of the formula is in the form of a fraction, where the numerator lists the percentage-equivalent concentrations of anions in descending order, and the denominator lists the cations [22]. The unit conversion of all major ions of groundwater is shown in Table 5.

In the brief water classification according to the Kurlov formula (based on ion composition), all ions with concentrations equal to or exceeding 25 percent equivalents are included. The water composition is named in ascending order, starting with ions of lower concentrations, and moving towards the dominant ions, first for anions and then for cations.

Table 4. *Physicochemical characteristics of groundwater around LUSI, Sidoarjo, East Java, Indonesia in August 2024*

Таблица 4. *Физико-химические характеристики грунтовых вод вокруг Люси, Сидоарджо, Восточная Ява, Индонезия в августе 2024 г.*

Indicator Показатель	Unit Ед. изм	Standard Стандарт	Sampling points/Точки отбора проб				
			AL-1	AL-2	AL-3	AL-4	AL-5
Sampling time Дата	–	–	09/08/2024				
Latitude Широта	◦	–	–7,510890	–7,510745	–7,512194	–7,516542	–7,518638
Longitude Долгота	◦	–	112.711	112.713	112.717	112.726	112.733
Ta	◦C	±3	28	28	28	28	28
Tw	◦C		27	27.2	27.2	27.6	27.6
pH	–	6.5–8.5	6.94	7.44	6.78	6.52	6.59
EC	μS/cm	–	1342	5890	2110	6050	7850
TDS	ppm	500	668	2950	1050	3020	3920
Salination Засоление		–	667	2970	1050	3060	3950
	%	–	0.06	0.29	0.12	0.3	0.39
Ca^{2+}	mg/L	–	116.3	311.6	173.8	334.4	307.9
Mg^{2+}		–	24.57	29.07	35.91	51.63	31.88
Na^{+}		–	129.6	84.15	86.4	90.95	130.8
K^{+}		–	25.38	42.52	27.77	57.49	67.81
HCO_3^{-}		–	201.9	145.2	159.2	249.5	242.2
SO_4^{2-}		250	6.605	6.678	15.87	8.039	17.86
Cl^{-}		250	246	2216	542	2733	3693
Mn		0.4	0.3046	0.0925	0.4214	0.8453	0.0854
Hg		0.001	<0.00003	<0.00003	<0.00003	<0.00003	<0.00003
Fe		0.3	<0.0208	0.0414	<0.0208	0.0291	<0.0208

The Standard used was from the Regulation of the Minister of Health of the Republic of Indonesia No 32, 2017 concerning Environmental Health Quality Standards and Water Health Requirements for Sanitation Hygiene Purposes, Swimming Pools, Solus per Aqua, and Public Bathing.

Использованный стандарт взят из Постановления министра здравоохранения Республики Индонезия № 32 от 2017 г. о стандартах качества окружающей среды и требованиях к качеству воды для целей санитарии и гигиены, плавательных бассейнов, Solus per Aqua и общественных купаний.

Table 5. *Unit of major ion conversion for the Kurlov formula*

Таблица 5. *Единицы перевода основного иона для формулы Курлова*

No	Unit Ед. изм	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Sum (+) Сумма (+)	HCO_3^{-}	Cl^{-}	SO_4^{2-}	Sum (–) Сумма (–)
AL-1	mg-eq/l	5.82	1.01	5.63	1.3	13.76	3.31	6.94	0.14	10.39
	%	42.25	7.35	40.94	9.46	100	31.87	66.81	1.32	100
AL-2	mg-eq/l	15.58	0.73	3.66	2.18	22.15	2.38	62.51	0.14	65.03
	%	70.35	3.28	16.52	9.85	100	3.66	96.13	0.21	100
AL-3	mg-eq/l	8.69	0.92	3.76	1.42	14.79	2.61	15.29	0.33	18.23
	%	58.75	6.23	25.4	9.63	100	14.32	83.87	1.81	100
AL-4	mg-eq/l	16.72	1.46	3.95	3.48	25.61	4.09	77.09	0.17	81.35
	%	65.29	5.69	15.44	13.58	100	5.03	94.77	0.21	100
AL-5	mg-eq/l	15.4	0.52	5.69	3.48	25.08	3.97	104.17	0.37	108.52
	%	61.38	2.08	22.67	13.86	100	3.66	96	0.34	100

Based on Table 5, the Kurlov formula for groundwater in LUSI area can be expressed as follows:

- groundwater in AL-1 is classified as $M\ 0{,}75\ \frac{Cl^{-}66{,}81\ HCO_3^{-}31{,}87}{Ca^{2+}42{,}25\ Na^{+}40{,}94} pH\ 6{,}94$ (sodium-calcium hydrocarbonate-chloride water, fresh water);
- groundwater in AL-2 is classified as $M\ 2{,}84\frac{Cl^{-}96{,}13}{Ca^{2+}70{,}35\ Na^{+}16{,}52} pH\ 7{,}44$ (sodium-calcium chloride water, slightly brackish water);
- groundwater in AL-3 is classified as $M\ 1{,}04\frac{Cl^{-}83{,}87\ HCO_3^{-}14{,}32}{Ca^{2+}58{,}75\ Na^{+}25{,}4} pH\ 6{,}78$ (magnesium-sodium-calcium chloride water, slightly brackish water);
- groundwater in AL-4 is classified as $M\ 3{,}53\frac{Cl^{-}94{,}77}{Ca^{2+}65{,}29\ Na^{+}15{,}44} pH\ 6{,}52$ (magnesium-sodium-calcium chloride water, salty water);
- groundwater in AL-5 is classified as $M\ 4{,}49\frac{Cl^{-}96}{Ca^{2+}61{,}38\ Na^{+}22{,}67} pH\ 6{,}59$ (sodium-calcium chloride water, salty water).

According to the Kurlov formula, the chemical composition of groundwater in LUSI area in Kali Tengah, Sidoarjo, East Java, as described by O.A.

Alekin [23], indicates that all sampling points are classified as calcium chloride types. In terms of mineralization, the groundwater is categorized as fresh water at one location (AL-1), slightly brackish water at two locations (AL-2 and AL-3), and salty water at two locations (AL-4 and AL-5), as detailed in Table 6. The pH levels, as reported [24], are neutral (6.5–7.5) at three locations (AL-1 to AL-3) and slightly acidic (5.0–6.5) at two locations (AL-4 and AL-5). The Piper diagram is shown in Fig 2.

The comparison between the current research on groundwater in LUSI area and the 2022 study in Sidoarjo demonstrates similarities and differences [10]. The current research classifies the groundwater as calcium chloride types, with mineralization ranging from fresh to slightly brackish and salty, and pH levels varying from neutral to slightly acidic. In contrast, the 2022 study characterizes groundwater as primarily fresh with increased mineralization, with a specific point showing a slightly brackish condition. The 2022 study also identifies different water types, including calcium bicarbonate and sodium chloride, with one point reflecting marine-like conditions. Additionally, pH levels in the 2022 study range from slightly alkaline to neutral and slightly acidic.

The differences between the current and 2022 studies can be attributed to several factors. In LUSI area, ongoing geological processes such as mudflow may have influenced groundwater chemical composition and mineralization, as well as the seawater impact on groundwater, leading to a higher classification of salty water. The current study classification might reflect more recent changes in groundwater quality due to environmental factors. The local hydrology, land use, and potential pollution sources also play a role in shaping the chemical characteristics of groundwater [25–27], thus, it is highly recommended to conduct a more comprehensive groundwater condition assessment in this area.

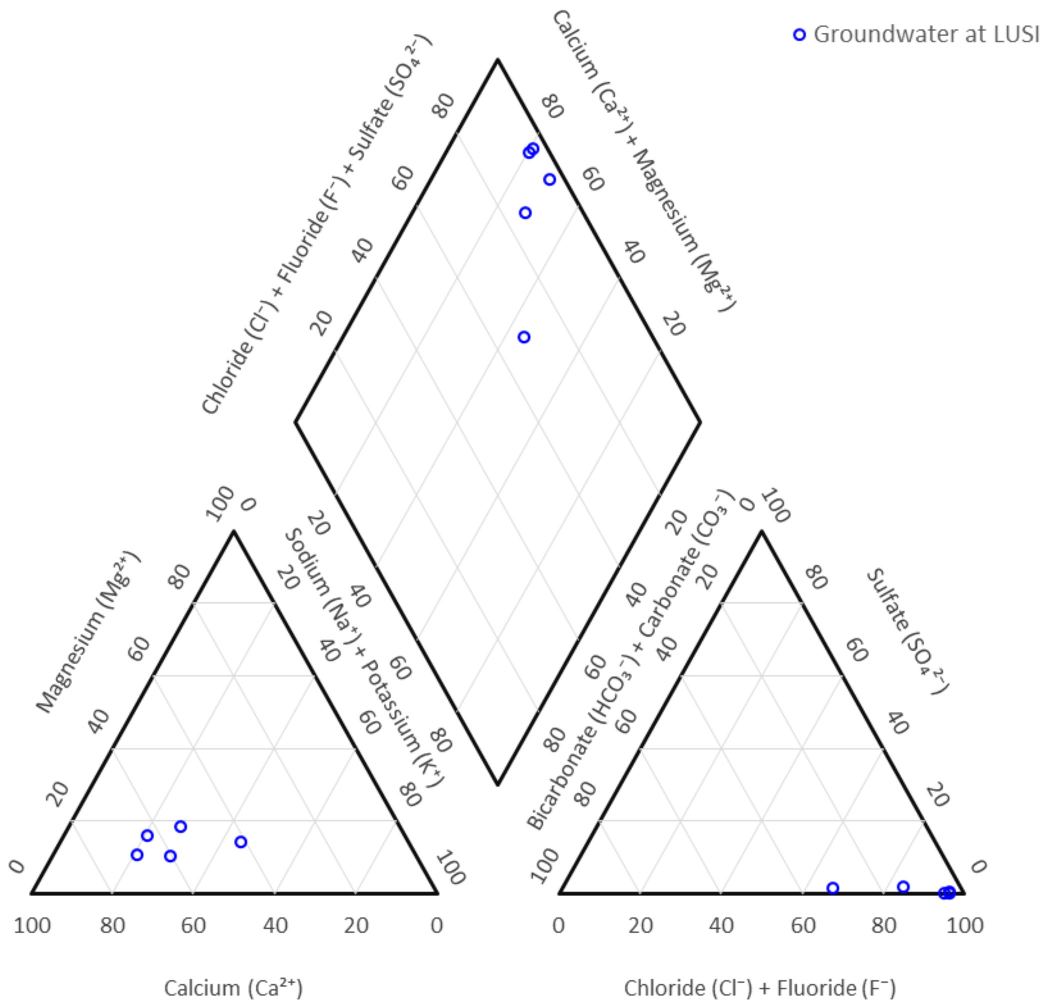

Fig 2. *Piper diagram of groundwater in LUSI area in Sidoarjo, East Java, Indonesia*
Рис. 2. *Схема трубопровода грунтовых вод в районе Люси в Сидоарджо, Восточная Ява, Индонезия*

Table 6. *Calculation of the PI for groundwater around LUSI in August 2024*

Таблица 6. *Расчет индекса загрязнения грунтовых вод вокруг Люси в августе 2024 г.*

Indicator Показатель	Unit Ед. изм	C value/Значение C					Cn value/Значение Cn				
		AL-1	AL-2	AL-3	AL-4	AL-5	AL-1	AL-2	AL-3	AL-4	AL-5
Sampling time Дата	–	09/08/2024									
Latitude Широта	◦	−7.51089	−7.510746	−7.512194	−7.516543	−7.518638	−7.51089	−7.510746	−7.512194	−7.516543	−7.518638
Longitude Долгота	◦	112.7111	112.713	112.7169	112.726	112.7327	112.7111	112.713	112.7169	112.726	112.7327
Ta	°C	–	–	–	–	–	–	–	–	–	–
Tw	°C	–	–	–	–	–	–	–	–	–	–
pH	–	0.56	0.06	0.72	0.98	0.91	0.56	0.06	0.72	0.99	0.96
EC	μS/cm	–	–	–	–	–	–	–	–	–	–
TDS	ppm	1.34	5.9	2.1	6.04	7.84	1.13	1.77	1.32	1.78	1.89
Salination Засоление	ppm	–	–	–	–	–	–	–	–	–	–
	%	–	–	–	–	–	–	–	–	–	–
Ca^{2+}	mg/L	–	–	–	–	–	–	–	–	–	–
Mg^{2+}		–	–	–	–	–	–	–	–	–	–
Na^{+}		–	–	–	–	–	–	–	–	–	–
K^{+}		–	–	–	–	–	–	–	–	–	–
HCO_3^{-}		–	–	–	–	–	–	–	–	–	–
SO_4^{2+}		0.03	0.03	0.06	0.03	0,07	0.0001	0.0001	0.0003	0.0001	0.0003
Cl^{-}		0.98	8.86	2.17	10.93	14,77	0.0039	1.95	1.34	2.04	2.17
Mn		0.76	0.23	1.05	2.11	0.21	1.9	0.58	1.02	1.32	0.53
Hg		0.03	0.03	0.03	0.03	0.03	30	30	30	30	30
Fe		0.07	0.14	0.07	0.1	0.07	0.23	0.46	0.23	0,32	0.23
Cn max/макс							30	30	30	30	30
Cn avg/срд							4.83	4.97	4.95	5.21	5.11
PI							21.49	21.5	21.5	21.53	21.52

Groundwater quality around LUSI by PI

To assess water quality, the PI can be utilized, as it offers a comprehensive approach to evaluating all types of pollutants present in the water. PI is known for its effectiveness in thoroughly assessing water quality.

Table 6 presents the PI calculations for groundwater in LUSI area, with values of 21.49, 21.52, 21.50, 21.53, and 21.52 from AL-1 to AL-5. According to the classification in Table 2, all water samples from these points are categorized as heavily polluted, as their PI values exceed 10. This high level of pollution is primarily due to elevated chloride concentrations and levels of Mn, which contribute to the high TDS.

Research in 2022 also indicated that various chemicals contaminated the groundwater in the area. Chloride was identified as one of the contaminants, along with high concentrations of Hg, Br, and I. Additionally, research from 2012 revealed a high concentration of chloride at 593.94 mg/L [10–11]. Overall, groundwater in LUSI area is affected by chemical contamination.

Saturation Indices

The calculation of mineral equilibrium can provide insights into the thermodynamic processes occurring in groundwater, as indicated by the SI values. The SI value describes groundwater saturation, where SI<0 indicates undersaturation, SI = 0 indicates equilibrium, and SI>0 indicates oversaturation. An undersaturated state implies that the mineral can continue to release ions into the groundwater. SI calculations were conducted for several minerals (Table 7). Additionally, it is noteworthy that the waters remain undersaturated concerning many minerals, which, according to previous studies [22], may be explained by the functioning of the carbonate barrier. All the analyzed waters can dissolve albite and anorthite, but they are near equilibrium or slightly oversaturated concerning quartz, calcite, dolomite, and several clay minerals (Fig. 3).

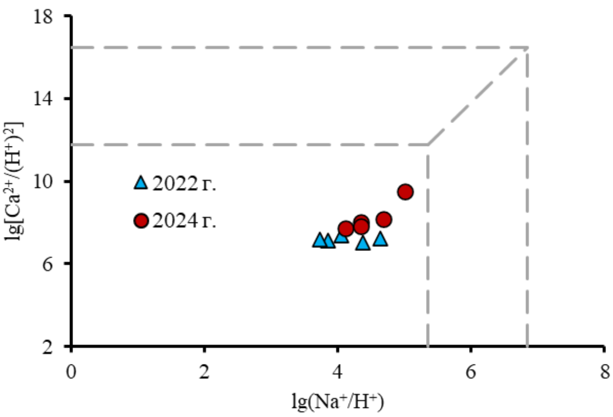

Fig. 3. *HCl-H2O-Al2O3-CO2-CaO-SiO2-Na2O system at 25°C, lg[H4SiO4]=–3.5 and P_{CO2}=101.5 Pa with drawing data of waters (Table 1 in [10])*

Рис. 3. *Система HCl-H2O-Al2O3-CO2-CaO-SiO2-Na2O при 25 °C, lg[H4SiO4]=–3,5 и P_{CO2}=101,5 Па с данными по составу вод (табл. 1 в [10])*

Table 7. *Groundwater saturation indices around LUSI in August 2024*

Таблица 7. *Индексы насыщения грунтовых вод вокруг Люси в августе 2024 г.*

Reaction/Реакция	Sampling points/Точки отбора проб				
	AL-1	AL-2	AL-3	AL-4	AL-5
$CaCO_{3(calcite)}=Ca^{2+}+CO_3^{2-}$	–0.58	–0.16	–0.73	–0.81	–0.79
$CaCO_{3(calcite)}+CO_2+H_2O=Ca^{2+}+2HCO_3^-$	–0.49	–0.01	–0.63	–0.66	–0.63
$CaMg(CO_3)_{2(dolomite)}=Ca^{2+}+Mg^{2+}+2CO_3^{2-}$	0.34	0.33	0.31	0.43	0.04
$CaMg(CO_3)_{2(dolomite)}+2\cdot CO_2+2\cdot H_2O=Ca^{2+}+Mg^{2+}+4\cdot HCO_3^-$	–0.79	–0.25	–1.1	–1.41	–1.54
$MgCO_{3(magnesite)}+CO_2+H_2O=Mg^{2+}+2\cdot HCO_3^-$	–4.07	–3.89	–4.22	–4.38	–4.53
$CaAl_2Si_2O_{8(anorthite)}+3H_2O+2CO_2=Al_2Si_2O_7\cdot 2\cdot H_2O_{(kaolinite)}+Ca^{2+}+2HCO_3^-$	–258.24	–257.13	–258.44	–258.93	–258.81
$CaAl_2Si_2O_{8(anorthite)}+2\cdot H^++H_2O=Al_2Si_2O_7\cdot 2\cdot H_2O_{(kaolinite)}+Ca^{2+}$	–23.5	–21.27	–23.9	–24.87	–24.64
$2\cdot KAl_3Si_3O_{10}OH_{2(muscovite)}+2\cdot H^++3\cdot H_2O=3\cdot Al_2Si_2O_7\cdot 2\cdot H_2O_{(kaolinite)}+2\cdot K^+$	0.82	2.21	0.56	0.61	0.89

Health Risk Assessment from Chemical Exposure

The HQ value plays a crucial role in determining the impact of chemical exposure from water on human health. It helps assess the potential risk posed by contaminants by comparing the concentration of specific chemicals to their safe exposure levels, indicating the potential for adverse health effects. The non-carcinogenic effects of potential risk from observed heavy metals exposure through consumption were calculated by summarizing the HQ values to derive the HI [2, 28].

In general, considering the measured heavy metals, including Hg, Mn, and Fe, most of the groundwater in this area is safe and does not pose a significant risk to human health. Table 8 presents the HQ and HI values for groundwater exposure to heavy metals. There are only three scenarios where the HI value exceeds 1, indicating a potential health risk. These scenarios include water from AL-4 for infants at birth and infants (3 months), and water from AL-3 for infants (3 months). The health risk is associated with the use of this water for drinking, where ingestion introduces contaminants into the body.

Table 8. *Hazard Index and Hazard Quotient of Heavy Metals Exposure*

Таблица 8. *Индекс опасности и коэффициент опасности воздействия тяжелых металлов*

Chemical content Химический состав	Consumer Потребитель	AL-1	AL-2	AL-3	AL-4	AL-5
Hg	Infants (birth)/Младенцы (рождение)	0.07	0.07	0.07	0.07	0.07
	Infants (3 months)/Младенцы (3 месяца)	0.094	0.094	0.094	0.094	0.094
	Adult male/Взрослый мужчина	0.019	0.019	0.019	0.019	0.019
	Adult non-pregnant female Взрослая небеременная женщина	0.019	0.019	0.019	0.019	0.019
	Pregnant female (end of 1st trimester) Беременная женщина (конец 1-го триместра)	0.023	0.023	0.023	0.023	0.023
Mn	Infants (birth)/Младенцы (рождение)	0.505	0.153	0.699	1.402	0.142
	Infants (3 months)/Младенцы (3 месяца)	0.684	0.208	0.946	1.897	0.192
	Adult male/Взрослый мужчина	0.136	0.041	0.189	0.379	0.038
	Adult non-pregnant female Взрослая небеременная женщина	0.14	0.042	0.193	0.387	0.039
	Pregnant female (end of 1st trimester) Беременная женщина (конец 1-го триместра)	0.166	0.05	0.23	0.461	0.047
Fe	Infants (birth)/Младенцы (рождение)	0.007	0.014	0.007	0.01	0.007
	Infants (3 months)/Младенцы (3 месяца)	0.009	0.019	0.009	0.013	0.009
	Adult male/Взрослый мужчина	0.002	0.004	0.002	0.003	0.002
	Adult non-pregnant female Взрослая небеременная женщина	0.002	0.004	0.002	0.003	0.002
	Pregnant female (end of 1st trimester) Беременная женщина (конец 1-го триместра)	0.002	0.005	0.002	0.003	0.002
HI value/Значение HI						
Σ HQ	Infants (birth)/Младенцы (рождение)	0.582	0.237	0.775	1.481	0.218
	Infants (3 months)/Младенцы (3 месяца)	0.787	0.32	1.049	2.005	0.295
	Adult male/Взрослый мужчина	0.157	0.064	0.209	0.4	0.059
	Adult non-pregnant female Взрослая небеременная женщина	0.161	0.065	0.214	0.409	0.06
	Pregnant female (end of 1st trimester) Беременная женщина (конец 1-го триместра)	0.191	0.078	0.255	0.487	0.072

Table 9. *Hazard Quotient from Cl^- exposure*

Таблица 9. *Коэффициент опасности от воздействия Cl^-*

Chemical content Химический состав	Consumer Потребитель	AL-1	AL-2	AL-3	AL-4	AL-5
Cl^-	Infants (birth)/Младенцы (рождение)	279.937	2521.709	616.772	3110.032	4202.468
	Infants (3 months)/Младенцы (3 месяца)	378.932	3413.467	834.882	4209.84	5688.598
	Adult male/Взрослый мужчина	75.623	681.223	166.617	840.155	1135.269
	Adult non-pregnant female Взрослая небеременная женщина	77.358	696.855	170.44	859.434	1161.321
	Pregnant female (end of 1st trimester) Беременная женщина (конец 1-го триместра)	91.995	828.704	202.688	1022.044	1381.049

In this study, Mn poses the greatest exposure risk. Chronic overexposure to Mn can lead to its accumulation in the basal ganglia of the brain, resulting in manganism, a condition similar to Parkinson's disease. Manganism results from nerve injuries in both cortical and subcortical brain regions, particularly affecting the basal ganglia, and can have severe neurological consequences [29, 30].

On the other hand, due to the high chloride content in this area, a specific health risk assessment for chloride exposure was conducted. Table 9 shows that all scenarios resulted in an HQ value greater than 1, indicating a significant health risk due to chloride exposure. The greatest risk is posed to infants (3 months), while the least risk is to adult males. This variation in risk is influenced by factors such as ingestion rate, frequency of exposure, duration of exposure, and the consumer's weight.

Therefore, given the high chloride levels and the presence of heavy metals, the groundwater in this area requires treatment before consumption. Although consuming water with chloride and/or sodium alone may not pose direct health risks for most people, it can affect the water taste and potentially impact individuals with kidney and heart conditions [31]. To mitigate these risks, it is strongly recommended to treat the groundwater to lower its contaminant levels, including chloride, to ensure it is safer for consumption.

The Cancer Risk Index (CRI) measures the likelihood of developing cancer due to exposure to carcinogens in water. In this research, the CRI assessment focuses solely on Hg-contaminated water. The US EPA generally considers the CRI of $1{,}0\times10^{-6}$, which translates to one case of cancer per one million people, as the threshold for assessing cancer risk [5, 32]. Values surpassing $1{,}0\times10^{-4}$, or one case of cancer per 10000 people, are deemed unacceptable.

Overall, since the groundwater in this area contains relatively low levels of mercury, the CRI value is less than $1{,}0\times10^{-4}$ (Table 10). This indicates that the groundwater does not pose a significant cancer risk to its consumers.

The 2022 health risk assessment for groundwater in the Sidoarjo mud volcano area highlighted significant concerns related to heavy metal contamination. The assessment found that several groundwater samples exhibited high HI values, indicating a notable risk to human health. Particularly Hg high concentrations were identified as a potential cancer risk, alongside elevated levels of other heavy metals such as As, Fe, Mn, and Zn [1]. Overall, the highest health risk was associated with certain samples, while others posed a lower risk.

Table 10. *Cancer risk calculation for every scenario of Hg-contaminated groundwater around LUSI, East Java, Indonesia*

Таблица 10. *Расчет риска возникновения рака для каждого сценария загрязнения грунтовых вод ртутью вокруг Люси, Восточная Ява, Индонезия*

Consumer/Потребитель	AL-1	AL-2	AL-3	AL-4	AL-5
Infants (birth) Младенцы (рождение)	6.96 E-06	6.96 E-06	6.96 E-06	6.96 E-06	6.96 E-06
Infants (3 months) Младенцы (3 месяца)	9.43 E-06	9.43 E-06	9.43 E-06	9.43 E-06	9.43 E-06
Adult male Взрослый мужчина	1.88 E-06	1.88 E-06	1.88 E-06	1.88 E-06	1.88 E-06
Adult non-pregnant female Взрослая небеременная женщина	1.92 E-06	1.92 E-06	1.92 E-06	1.92 E-06	1.92 E-06
Pregnant female (end of 1st trimester) Беременная женщина (конец 1-го триместра)	2.29 E-06	2.29 E-06	2.29 E-06	2.29 E-06	2.29 E-06

In contrast, the current assessment of groundwater in LUSI area indicates a lower cancer risk due to mercury contamination, with the CRI value falling below 1.0×10^{-4}. However, the current findings highlight that while mercury levels are lower than those observed in 2022, the groundwater still poses health risks primarily due to high chloride concentrations and the presence of other heavy metals. Specifically, the HI values for samples AL-3 and AL-4 suggest potential health risks, particularly for infants, due to both heavy metals and elevated chloride levels. This reflects a shift in focus from mercury as the primary concern to the combined impact of chloride and heavy metals on water quality and health risks.

Conclusion

The current research on groundwater quality in LUSI area of Sidoarjo, East Java, reveals significant chemical contamination, particularly due to elevated concentrations of $Cl^{-}$and Mn, which pose health risks in some cases. The high Cl^{-} concentration is likely affected by seawater intrusion, which enters from the deep horizon and impacts the groundwater. The groundwater is predominantly classified as calcium chloride type, indicating a shift in its chemical profile due to increased mineralization. The pH levels vary across sampling points, with three sites (AL-1 to AL-3) having neutral pH, while two sites (AL-4 and AL-5) show slightly acidic conditions, potentially as a result of local environmental factors. This chemical characterization highlights the need for ongoing assessment and remediation efforts to address groundwater quality issues in the region.

PI values ranging from 21.49 to 21.53 classify all sampled locations as heavily polluted, primarily due to high chloride and manganese levels. These findings align with previous research from 2022, which also identified significant contamination by chloride and heavy metals. The contamination is widespread, making the groundwater unsafe for consumption without proper treatment.

Health risk assessments indicate that infants, especially those three months old, face the highest risk from chloride exposure due to their ingestion rates and vulnerability. On the other hand, adult males are at a lower risk. Given the combination of high chloride levels and the presence of heavy metals, it is strongly recommended that the groundwater undergo treatment to reduce contaminants and mitigate health risks for all age groups toward clean water sustainability in Sidoarjo, East Java, Indonesia.

REFERENCES

1. Adiyaksa I.P., Savichev O.G., Di Martino A. Health risk assessment due to the metals exposure of groundwater in the area of Sidoarjo Mud, East Java, Indonesiаю *Journal of Environmental Engineering and Sustainable Technology*, 2023, vol. 10, no. 01. DOI: http://dx.doi.org/10.21776/ub.jeest.2023.010.01.1.
2. Emmanuel U.C., Chukwudi M.I., Monday S.S., Anthony A.I. Human health risk assessment of heavy metals in drinking water sources in three senatorial districts of Anambra State, Nigeria. *Toxicology Reports*, 2022, vol. 9, pp. 869–875. DOI: 10.1016/j.toxrep.2022.04.011.
3. Lowe C., Kurscheid J., Lal A., Sadler R., Kelly M., Stewart D., Laksono B., Amaral S., Gray D. Health risk assessment for exposure to nitrate in drinking water in Central Java, Indonesia. *IJERPH*, 2021, vol. 18, no. 5, p. 2368. DOI: 10.3390/ijerph18052368.
4. Wijaya S.M., Putri A.O., Wijaya A. Analysis and strategy for providing clean water to the surrounding community in the Muara Angke Area. *Ijaeb*, 2023, vol. 1, no. 2, pp. 736–744. DOI: 10.24912/v1i2.736-744.
5. Moradnia M., Attar H.M., Hajizadeh Y., Lundh T., Salari M., Darvishmotevalli M. Assessing the carcinogenic and non-carcinogenic health risks of metals in the drinking water of Isfahan, Iran. *Sci Rep*, 2024, vol. 14, no. 1, p. 5029. DOI: 10.1038/s41598-024-55615-3.
6. Prabowo S., Makrufan M.C.R. Impact of clean water infrastructure to income inequality, with economic growth as intervening. *International Journal of Economics, Business and Accounting Research (IJEBAR)*, 2021, vol. 5, no. 4, pp. 218–225.
7. Priadi C.R., Putri G.L. Policy brief – self-supply for safely managed water: to promote or to deter? *UNICEF*, 2022. Available at: https://www.unicef.org/indonesia/media/13706/file/Self-supply%20for%20safely%20managed%20water.pdf (accessed 1 September 2024).
8. Gradiyanto F., Parmantoro P.N., Suharyanto. Impact of climate change on Kupang River flow and hydrological extremes in Greater Pekalongan, Indonesia. *Water Science and Engineering*, 2024, p. S1674237024000462. DOI: 10.1016/j.wse.2024.03.005.
9. Putra D.P.E., Halim D., Widagdo S.S., Atmaja R.R.S. Degradation of groundwater quality due to the occurance of salty-tasted water in Bayat District, Klaten, Central Java, Indonesia. *Journal of Degraded and Mining Lands Management*, 2020, vol. 8, no. 1, pp. 2525–2536. DOI: 15243/idmlm.2020.081.2525.
10. Adiyaksa I.P., Savichev O.G., Khvasevskaya A.A. Ecological and geochemical condition of groundwater in the region of the mud volcano in Sidoarjo (East Java Province, Indonesia). *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, 2023, vol. 334, no. 3, pp. 51–60. DOI: https://doi.org/10.18799/24131830/2023/3/3978.
11. Purwaningsih E., Notosiswoyo S. Hydrochemical study of groundwater in Sidoarjo mud volcano area, East Java Indonesia. *Procedia Earth and Planetary Science*, 2013, vol. 6, pp. 234–241. DOI: 10.1016/j.proeps.2013.01.032.
12. Auvaria S.W., Munfarida I. Analysis of Environmental capacity (water pollution load) in the Porong Area, Sidoarjo Regency, ex Lapindo Mining. *J. Presipitasi*, 2020, vol. 17, no. 2, pp. 104–112. DOI: 10.14710/presipitasi.v17i2.104-112.
13. Supriyana E. Study of Subsurface Fluid Movement Based on Mass Density Analysis in Porong Sidoarjo Area. *JMEI*, 2015, vol. 05, no. 01, pp. 17–23. (In Indonesian) DOI: 10.24198/jmei.v5i01.11153.g5013.
14. Setiadi I., Darmawan A., Marjiyono. Investigation of Subsurface Geological Structure in Sidoarjo Mud Vulcano Affected Area Based on Geomagnetic Data Analysis. *Journal of Environment and Geological Hazards*, 2016, vol. 7, no. 3, pp. 125–134. (In Indonesian)
15. Sari A., Tuwo A., Rani C., Saru A. Water quality study and pollution index based on Physics-chemical parameters in the Youtefa Bay tourism area, Jayapura. *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 564, no. 1, p. 012030, Sep. 2020, DOI: 10.1088/1755-1315/564/1/012030
16. Savichev O.G., Kolokolova O.V., Zhukovskaya E.A. Composition and equilibrium of bottom sediments of Tom river with river waters. *Geoekologiya, Inzhenernaya Geologiya, Gidrogeologiya, Geokriologiya*, 2003, vol. 1, pp. 36–47.
17. Djadé P.J.O., Keuméan K.N., Traoré A., Soro G., Soro N. Assessment of health risks related to contamination of groundwater by trace metal elements (Hg, Pb, Cd, As and Fe) in the department of Zouan-Hounien (West Côte D'Ivoire). *GEP*, 2021, vol. 09, no. 08, pp. 189–210. DOI: 10.4236/gep.2021.98013.

18. Singh S., Sharma P., Mudhulkar R., Chakravorty B., Singh A., Sharma S.D. Assessment of hydrogeochemistry and arsenic contamination in groundwater of Bahraich District, Uttar Pradesh, India. *Arab J Geosci*, 2022, vol. 15, no. 1, p. 9. DOI: 10.1007/s12517-021-09222-5.
19. Muenratch P., Nguyen T.P.L. Local governance of groundwater resources through the lens of stakeholders in the context of state-led management in the Lower Mekong Region. *Water*, 2022, vol. 14, no. 19, p. 3043. DOI: 10.3390/w14193043.
20. Aladejana J.A., Kalin R.M., Sentenac P., Hassan I. Assessing the Impact of climate change on groundwater quality of the shallow coastal aquifer of Eastern Dahomey Basin, Southwestern Nigeria. *Water*, 2020, vol. 12, no. 1, p. 224. DOI: 10.3390/w12010224.
21. Davamani V. A critical review of climate change impacts on groundwater resources: a focus on the current status, future possibilities, and role of simulation models. *Atmosphere*, 2024, vol. 15, no. 1, p. 122. DOI: 10.3390/atmos15010122.
22. Shvartsev S.L. *General of Hydrogeology (Obshaya Gidrogeologiya)*. Moscow, Nedra Publ., 1996. 155 p.
23. Turekian K.K. *The Ocean, streams and atmosphere. Handbook of Geochemistry*. USA, Springer, 1969. Vol. 1, 297–323 p.
24. Romanian V.G. *Theory and methods of studying groundwater pollution*. Russia, Nauka Publ., 2020. 559 p.
25. Lerner D.N., Harris B. The relationship between land use and groundwater resources and quality. *Land Use Policy*, 2009, vol. 26, pp. S265–S273. DOI: 10.1016/j.landusepol.2009.09.005.
26. Sejati S.P., Neritarani R. The impact of land use change on groundwater depth in the groundwater transition zone of Merapi Volcano, Yogyakarta, Indonesia. *IJG*, 2024, vol. 56, no. 1, p. 96. DOI: 10.22146/ijg.88452.
27. Kusumayudha S.B., Pratiknyo P., Riswandi H., E. Hydrogeological risk assessment for groundwater conservation in the northeastern slope area of Mount Arjuno, Pasuruan Regency, East Java, Indonesia. *IJG*, 2021, vol. 53, no. 1. DOI: 10.22146/ijg.59476.
28. Goumenou M., Tsatsakis A. Proposing new approaches for the risk characterisation of single chemicals and chemical mixtures: the source related Hazard Quotient (HQS) and Hazard Index (HIS) and the adversity specific Hazard Index (HIA). *Toxicology Reports*, 2019, vol. 6, pp. 632–636. DOI: 10.1016/j.toxrep.2019.06.010.
29. Agustina U., Fitria L., Hermawati E. Environmental health risk assessment of manganese and cadmium in the ground water around Cipayung Landfill in Depok, Indonesia. *IOP Conf. Ser.: Earth Environ. Sci.*, 2020, vol. 612, no. 1, p. 012076. DOI: 10.1088/1755-1315/612/1/012076.
30. Rahman Md.A., Kumar S., Lamb D., Rahman M.M. Health risk assessment of arsenic, manganese, and iron from drinking water for high school children. *Water Air Soil Pollut*, 2021, vol. 232, no. 7, p. 269. DOI: 10.1007/s11270-021-05212-1.
31. Dippong T., Hoaghia M.-A., Mihali C., Cical E., Calugaru M. Human health risk assessment of some bottled waters from Romania. *Environmental Pollution*, 2020, vol. 267, p. 115409. DOI: 10.1016/j.envpol.2020.115409.
32. Castresana G.P., Roldán E.C., García Suastegui W.A., Morán Perales J.L., Cruz Montalvo A., Silva A.H. Evaluation of health risks due to heavy metals in a rural population exposed to Atoyac River Pollution in Puebla, Mexico. *Water*, 2019, vol. 11, no. 2, p. 277. DOI: 10.3390/w11020277.

Information about the authors

Ilham Putra Adiyaksa, PhD Student, Tokyo University of Agriculture and Technology, 3-5-8, Saiwai-cho, Fuchu, Tokyo 183-8538, Japan. ilhamadiyaksa@gmail.com; https://orcid.org/0000-0003-3182-2835
Muhammad Haikal Razi, PhD Student, Universitas Gadjah Mada, 2, Grafika street, Bulaksumur, Yogyakarta, 55281, Indonesia. muhammadhaikalrazi@mail.ugm.ac.id; https://orcid.org/0009-0006-5546-7013

Received: 12.09.2024
Revised: 20.09.2024
Accepted: 13.05.2025

СПИСОК ЛИТЕРАТУРЫ

1. Adiyaksa I.P., Savichev O.G., Di Martino A. Health risk assessment due to the metals exposure of groundwater in the area of Sidoarjo Mud, East Java, Indonesia // Journal of Environmental Engineering and Sustainable Technology. – 2023. – Vol. 10. – № 01. DOI: http://dx.doi.org/10.21776/ub.jeest.2023.010.01.1.
2. Emmanuel U.C., Chukwudi M.I., Monday S.S., Anthony A.I. Human health risk assessment of heavy metals in drinking water sources in three senatorial districts of Anambra State, Nigeria // Toxicology Reports. – 2022. – Vol. 9. – P. 869–875. DOI: 10.1016/j.toxrep.2022.04.011.
3. Lowe C., Kurscheid J., Lal A., Sadler R., Kelly M., Stewart D., Laksono B., Amaral S., Gray D. Health risk assessment for exposure to nitrate in drinking water in Central Java, Indonesia // IJERPH. – 2021. – Vol. 18. – № 5. – P. 2368. DOI: 10.3390/ijerph18052368.
4. Wijaya S.M., Putri A.O., Wijaya A. Analysis and strategy for providing clean water to the surrounding community in the Muara Angke Area // Ijaeb. – 2023. – Vol. 1. – № 2. – P. 736–744. DOI: 10.24912/v1i2.736-744.
5. Moradnia M., Attar H.M., Hajizadeh Y., Lundh T., Salari M., Darvishmotevalli M. Assessing the carcinogenic and non-carcinogenic health risks of metals in the drinking water of Isfahan, Iran // Sci Rep. – 2024. – Vol. 14. – № 1. – P. 5029. DOI: 10.1038/s41598-024-55615-3.
6. Prabowo S., Makrufan M.C.R. Impact of clean water infrastructure to income inequality, with economic growth as intervening // International Journal of Economics, Business and Accounting Research (IJEBAR). – 2021. – Vol. 5. – № 4. – P. 218–225.
7. Priadi C.R., Putri G.L. Policy brief – self-supply for safely managed water: to promote or to deter? // UNICEF. – 2022. URL: https://www.unicef.org/indonesia/media/13706/file/Self-supply%20for%20safely%20managed%20water.pdf (дата обращения: 01.09.2024).
8. Gradiyanto F., Parmantoro P.N., Suharyanto. Impact of climate change on Kupang River flow and hydrological extremes in Greater Pekalongan, Indonesia // Water Science and Engineering. – 2024. – P. S1674237024000462. DOI: 10.1016/j.wse.2024.03.005.
9. Putra D.P.E., Halim D., Widagdo S.S., Atmaja R.R.S. Degradation of groundwater quality due to the occurance of salty-tasted water in Bayat District, Klaten, Central Java, Indonesia // Journal of Degraded and Mining Lands Management. – 2020. – Vol. 8. – № 1. – P. 2525–2536. DOI: 15243/idmlm.2020.081.2525.

10. Адьякса И.П., Савичев О.Г., Хващевская А.А. Эколого-геохимическое состояние подземных вод в районе грязевого вулкана в Сидоарджо (провинция Восточная Ява, Индонезия) // Известия Томского политехнического университета. Инжиниринг георесурсов. – 2023. – Т. 334. – № 3. – Р. 51–60. DOI: https://doi.org/10.18799/24131830/2023/3/3978.
11. Purwaningsih E., Notosiswoyo S. Hydrochemical study of groundwater in Sidoarjo mud volcano area, East Java Indonesia // Procedia Earth and Planetary Science. – 2013. – Vol. 6. – P. 234–241. DOI: 10.1016/j.proeps.2013.01.032.
12. Auvaria S.W., Munfarida I. Analysis of environmental capacity (water pollution load) in the Porong Area, Sidoarjo Regency, ex Lapindo Mining // J. Presipitasi. – 2020. – Vol. 17. – № 2. – P. 104–112. DOI: 10.14710/presipitasi.v17i2.104-112.
13. Supriyana E. Study of subsurface fluid movement based on mass density analysis in Porong Sidoarjo area // JMEI. – 2015. – Vol. 05. – № 01. – P. 17–23. (In Indonesian) DOI: 10.24198/jmei.v5i01.11153.g5013.
14. Setiadi I., Darmawan A., Marjiyono. Investigation of subsurface geological structure in Sidoarjo Mud Vulcano affected area based on geomagnetic data analysis // Journal of Environment and Geological Hazards. – 2016. – Vol. 7. – № 3. – P. 125–134. (In Indonesian)
15. Sari A., Tuwo A., Rani C., and Saru A. Water quality study and pollution index based on Physics-chemical parameters in the Youtefa Bay tourism area, Jayapura // IOP Conf. Ser.: Earth Environ. Sci. Sep. – 2020. – Vol. 564. – № 1. – P. 012030. DOI: 10.1088/1755-1315/564/1/012030
16. Савичев О.Г., Колоколова О.В., Жуковская Е.А. Состав и равновесие донных отложений р. Томь с речными водами // Геоэкология. – 2003. – № 2. – С. 108–119.
17. Djadé P.J.O., Keuméan K.N., Traoré A., Soro G., Soro N. Assessment of health risks related to contamination of groundwater by trace metal elements (Hg, Pb, Cd, As and Fe) in the department of Zouan-Hounien (West Côte D'Ivoire) // GEP. – 2021. – Vol. 09. – № 08. – P. 189–210. DOI: 10.4236/gep.2021.98013.
18. Singh S., Sharma P., Mudhulkar R., Chakravorty B., Singh A., Sharma S.D. Assessment of hydrogeochemistry and arsenic contamination in groundwater of Bahraich District, Uttar Pradesh, India // Arab J Geosci. – 2022. – Vol. 15. – № 1. – P. 9. DOI: 10.1007/s12517-021-09222-5.
19. Muenratch P., Nguyen T.P.L. Local governance of groundwater resources through the lens of stakeholders in the context of state-led management in the Lower Mekong Region // Water. – 2022. – Vol. 14. – № 19. – P. 3043. DOI: 10.3390/w14193043.
20. Aladejana J.A., Kalin R.M., Sentenac P., Hassan I. Assessing the impact of climate change on groundwater quality of the shallow coastal aquifer of Eastern Dahomey Basin, Southwestern Nigeria // Water. – 2020. – Vol. 12. – № 1. – P. 224. DOI: 10.3390/w12010224.
21. Davamani V. A critical review of climate change impacts on groundwater resources: a focus on the current status, future possibilities, and role of simulation models // Atmosphere. – 2024. – Vol. 15. – № 1. – P. 122. DOI: 10.3390/atmos15010122.
22. Шварцев С.Л. Общая гидрогеология. – М.: Недра, 1996. – 155 p.
23. Turekian K.K. The Ocean, streams and atmosphere. Handbook of Geochemistry. – USA, Springer, 1969. – Vol. 1. – P. 297–323.
24. Румынин В.Г. Теории и методы изучения загрязнения подземных вод. – СПб: Наука, 2020. – 559 с.
25. Lerner D.N., Harris B. The relationship between land use and groundwater resources and quality // Land Use Policy. – 2009. – Vol. 26. – P. S265–S273. DOI: 10.1016/j.landusepol.2009.09.005.
26. Sejati S.P., Neritarani R. The impact of land use change on groundwater depth in the groundwater transition zone of Merapi Volcano, Yogyakarta, Indonesia // IJG. – 2024. – Vol. 56. – № 1. – P. 96. DOI: 10.22146/ijg.88452.
27. Kusumayudha S.B., Pratiknyo P., Riswandi H., Hydrogeological risk assessment for groundwater conservation in the northeastern slope area of Mount Arjuno, Pasuruan Regency, East Java, Indonesia // IJG. – 2021. – Vol. 53. – № 1. DOI: 10.22146/ijg.59476.
28. Goumenou M., Tsatsakis A. Proposing new approaches for the risk characterisation of single chemicals and chemical mixtures: the source related Hazard Quotient (HQS) and Hazard Index (HIS) and the adversity specific Hazard Index (HIA) // Toxicology Reports. – 2019. – Vol. 6. – P. 632–636. DOI: 10.1016/j.toxrep.2019.06.010.
29. Agustina U., Fitria L., Hermawati E. Environmental health risk assessment of manganese and cadmium in the ground water around Cipayung Landfill in Depok, Indonesia // IOP Conf. Ser.: Earth Environ. Sci. – 2020. – Vol. 612. – № 1. – P. 012076. DOI: 10.1088/1755-1315/612/1/012076.
30. Rahman Md.A., Kumar S., Lamb D., Rahman M.M. Health risk assessment of arsenic, manganese, and iron from drinking water for high school children // Water Air Soil Pollut. – 2021. – Vol. 232. – № 7. – P. 269. DOI: 10.1007/s11270-021-05212-1.
31. Dippong T., Hoaghia M.-A., Mihali C., Cical E., Calugaru M. Human health risk assessment of some bottled waters from Romania // Environmental Pollution. – 2020. – Vol. 267. – P. 115409. DOI: 10.1016/j.envpol.2020.115409.
32. Castresana G.P., Roldán E.C., García Suastegui W.A., Morán Perales J.L., Cruz Montalvo A., Silva A.H. Evaluation of health risks due to heavy metals in a rural population exposed to Atoyac River Pollution in Puebla, Mexico // Water. – 2019. – Vol. 11. – № 2. – P. 277. DOI: 10.3390/w11020277.

Информация об авторах

Илхам Путра Адьякса, аспирант, кафедра сельскохозяйственной и экологической инженерии, Объединенная высшая школа сельскохозяйственных наук, Токийский университет сельского хозяйства и технологий, Япония, Токио, 183-8538, г. Футю, 3-5-8. ilhamadiyaksa@gmail.com; https://orcid.org/0000-0003-3182-2835

Мухаммад Хайкал Рази, аспирант, кафедра геологической инженерии, Инженерный факультет, Университет Гаджа Мада, Индонезия, 55281, Джокьякарта, Булаксумур, ул. Графика, 2. muhammadhaikalrazi@mail.ugm.ac.id; https://orcid.org/0009-0006-5546-7013

Поступила в редакцию: 12.09.2024
Поступила после рецензирования: 20.09.2024
Принята к публикации: 13.05.2025