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Identification of Natural Recharge Characteristics Based on Time-Lapse Microgravity Data for Sustainability Utilization at Lahendong Geothermal Field, Indonesia

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Abstract – The sustainable utilization of geothermal resources heavily relies on maintaining the fluid mass balance within the reservoir. Excessive fluid extraction without sufficient natural recharge can cause significant declines in reservoir pressure, thus threatening the long-term sustainability of geothermal energy production. This study specifically addresses the challenge of accurately characterizing natural recharge dynamics in the Lahendong Geothermal Field, where ongoing exploitation activities have led to considerable fluid mass deficits. To tackle this issue, time-lapse microgravity monitoring was conducted annually from 2015 to 2023 across 118 gravity benchmark stations strategically distributed throughout the reservoir area. The collected microgravity data were analyzed using Gauss's theorem to quantify the changes in reservoir mass balance over time. The calculated reservoir mass changes based on microgravity data were validated against mass balance estimates derived from actual well flow rate measurements. The findings indicate that natural recharge in Lahendong varies significantly, ranging from 0 to 3 M ton/year, exhibiting a clear cyclical pattern with approximately three-year intervals. On the average, natural recharge supplies approximately 1 M ton/year to the reservoir. The results validate time-lapse microgravity monitoring as a robust tool for detecting reservoir mass changes, offering critical insights into adaptive fluid injection strategies.

Keywords: sustainability, fluids, microgravity, recharge, Lahendong

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Introduction

Background

The utilization of geothermal energy for electricity in Indonesia continues to grow. Currently, the generation of electricity-based geothermal energy has only reached 2.653 MW (Figure 1) (Cariaga, 2025). The first geothermal power plant was built in Kamojang UNIT-1 in 1983 (Dwikorianto *et al*., 2021; Febriani *et al*., 2021, 2015; Hendriansyah *et al*., 2021), and by 2060 the expected generation of geothermal energy is 23 GW (EBTKE, 2023).

Electricity generation from geothermal energy is carried out by utilizing hot fluid in the reservoir to directly power the turbine (Figure 2). Hot fluid

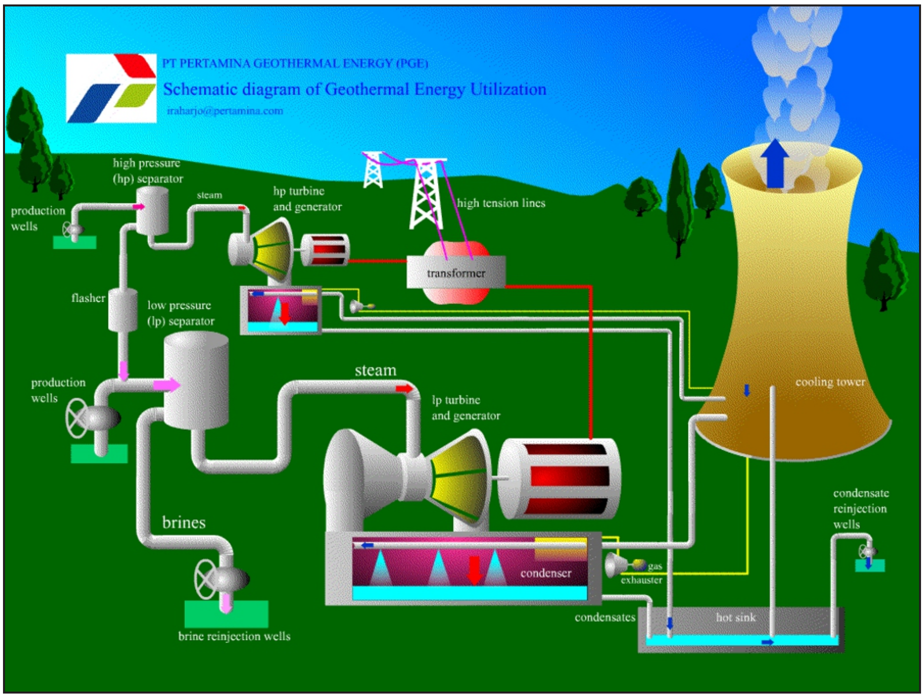

Figure 1 Geothermal generating capacity in various countries (modified from Cariaga, 2025).

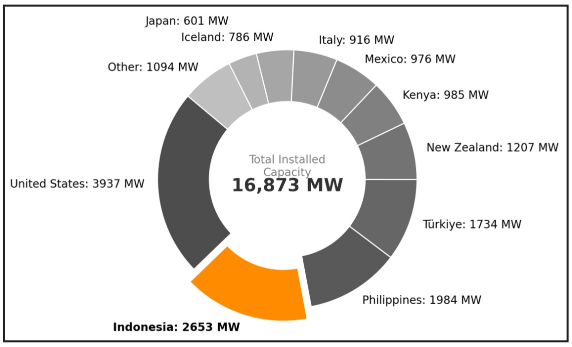

Figure 2. Schematic diagram of electricity generation from geothermal energy (P.T. Pertamina, 2005).

reservoirs produce steam or steam-water through production wells. The steam and hot water are separated, with the steam being connected to a power plant to operate one or more steam turbines and produce electrical power. Hot water separated from the separator can be used in power plants to produce additional electricity and/or put back into the reservoir via injection wells (Mburu, 2009). That is the reason geothermal energy is often referred to as a renewable, sustainable, and environmentally friendly energy source.

The term renewable energy refers to the energy resources used, while the notion of sustainability refers to how resources are utilized (Hackstein and Madlener, 2021). For geothermal resources to be sustainable, they must be renewable. Sustainability can be achieved if extraction is carried out at an equal volume or less than natural recharge (Barbier, 2002; Rybach, 2003).

There are four main components in a geothermal system: a heat source, cap rock, reservoir fluid, and natural recharge (Hochstein and Browne, 2000). If the fluid taken from the reservoir exceeds the natural recharge capacity, geothermal energy production will decrease, and in the future, it cannot be reused or is unsustainable.

The duration over which geothermal energy remains sustainable is still subject to ongoing research. Ideally, sustainable energy is one that can be utilized forever, but there are also those who consider it to be based on economic calculations of what is utilized (Rybach and Mongillo, 2006). In Iceland, the reference period considered sustainable is between a hundred and three hundred years (Axelsson *et al*., 2005). Meanwhile, in New Zealand, it has been more than a hundred years (Bromley *et al*., 2006).

The calculation of the sustainable period is related to the fluid lost during the geothermal utilization process and the amount of natural recharge. Therefore, the values and characteristics of these two parameters are important to identify.

In general, the quantity of fluid extracted and re-injected into the reservoir can be determined using surface measuring instruments. The amount of fluid that evaporates into the atmosphere from the generator after being used to power the turbine is 70 %−80 %, or only 20 %–30 % is reinjected into the reservoir (Enedy, 2014), and this value can be recorded on the surface. The problem is, How can we estimate the amount of natural recharge that enters the reservoir during the exploitation process? This is important to maintain the sustainability of geothermal energy use. Can this natural recharge compensate for the fluid loss for geothermal electricity generation?

The Lahendong Geothermal Field is situated in North Sulawesi (Figure 3), approximately 30 km south of Manado, within the Quaternary Tondano volcanic caldera. The area is surrounded by active stratovolcanoes such as Mount Soputan and Mahawu (Brehme *et al*., 2016; Utami *et al*., 2004), and is geologically characterized by basaltic-andesite lava flows, pyroclastic tuffs, volcanic breccias, and localized dioritic intrusions (Utami *et al*., 2015). A complex fault system dominated by NE–SW and NW–SE trends compartmentalizes the reservoir into northern and southern sectors (Siahaan *et al*., 2005; Sumantoro *et al*., 2015). These compartments display distinct hydrothermal behaviour: the northern zone hosts an acidic, vapour-dominated system with high gas content and intense alteration, while the southern zone contains neutral-pH, liquid-dominated fluids at higher temperatures and lower degrees of alteration (Brehme *et al*., 2016). A relatively impermeable fault separates the two compartments. High rainfall and steep terrain enhance meteoric recharge, with regional groundwater flow trending from the southwest

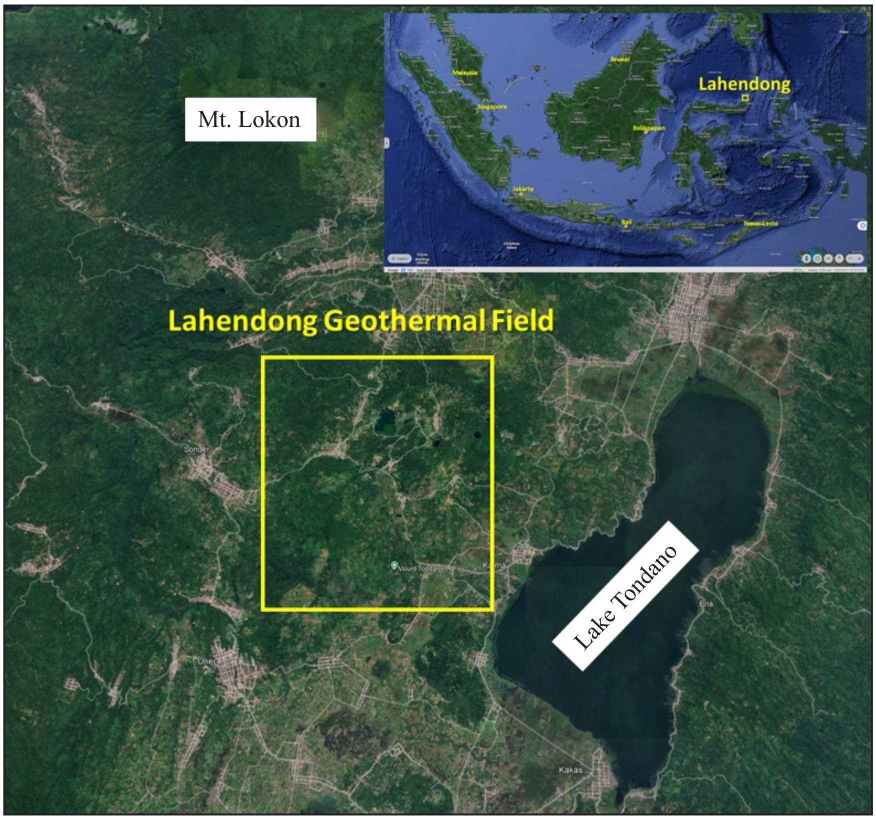

Figure 3. Location of The Lahendong Geothermal Field.

to the northeast. Thermal fluids ascend along permeable faults, and surface manifestations such as hot springs frequently occur at fault intersections, underlining the structural control on fluid migration in the field (Brehme *et al*., 2016; Utami *et al*., 2015).

Currently, the Lahendong Field has produced 80 MW of geothermal energy electricity from UNIT-1 to UNIT-4 (Table 1) through six production clusters and multiple injection wells; each powerplant generates 20 MW (Atmojo *et al*., 2015; Azka *et al*., 2015; Brehme *et al*., 2016; Firmansyah *et al.*, 2021; O'sullivan *et al*., 2023; Permana *et al*., 2015; Prasetyo *et al*., 2016; Sambodho *et al*., 2021; Sumantoro *et al*., 2015; Yani, 2022; Zahid *et al*., 2021). These four units started operating differently. UNIT-1 began operating in 2001, UNIT-2 in 2007, UNIT-3 in 2009, and UNIT-4 began in 2011 (Koestono *et al.,* 2010; Prabowo *et al., 2015;* Prasetyo *et al.*, 2016; P.T. BURSA EFEK INDONESIA, 2023; Sambodho *et al.*, 2021).

The reservoir is divided into northern and southern sectors, with the southern reservoir being drier and hotter, dominated by steam-producing wells, while the northern sector exhibits lower temperatures and higher brine production.

Table 1. Commisioning Periods of Lahendong Geothermal Power Plant

Unit	Commissioning Year	Capacity (MW)	Status
1	2001	20	Operating
2	2007	20	Operating
3	2009	20	Operating
4	2011	20	Operating

Long-term exploitation has revealed dynamic behaviour in fluid chemistry, permeability, and enthalpy distribution, reflecting reservoir compartmentalization and the influence of magmatic heat source migration over time.

A total of four units of power plants have been operated since 2011, and the difference between fluid extracted and re-injected (mass fluid loss) into the reservoir is estimated at 3.6−4.5 M ton per year (Haq *et al*., 2019; P.T. Pertamina Geothermal Energy, 2024). This shows that geothermal exploitation in Lahendong causes the mass of the reservoir to decrease every year, reaching almost 5 M ton. The loss of fluid mass could disrupt the sustainability of geothermal utilization in Lahendong.

Several studies have discussed natural recharge in the Lahendong Field (Table 2). Efendi *et al.* (2023), based on a study of the concept of surface water and fracture density in Lahendong, estimates that the water potential at the surface is around 14.1 M ton/year, and the amount of inflow surface fluid into the reservoir is around 1.1 M ton/year. However, the study was only based on surface water availability data from rainfall from August 2019 to August 2020. It is necessary to validate the linear correlation between the quantity of natural fluid recharge occurred in Lahendong and rainfall data at that time. The amount of natural fluid entering the reservoir based on the water available on the surface also needs to be validated by other data that proves that rainwater is indeed entering the reservoir.

Widagda and Jagranatha (2005) also conducted a study on recharge in Lahendong. The research method used is similar to previous studies, analyz-

Table 2. Summary of Recharge-Related Studies in Lahendong

Study	Focus	Findings	Limitation
Efendy (2023)	Surface water & fracture density	Surface water potential: 14.1 Mton/year; Estimated inflow to reservoir: 1.1 Mton/year	Based on reinfall data (Aug 2029 – Aug 2020); No validation of rainwater entering reservoir
Widagda and Jagranatha (2005)	Recharge potential based on rainfall & geological structure	Recharge potential: 10.3 Mton/ year	Does not quantify actual fluid entering reservoir
Prabowo et al., (2015)	Tracer study on fluid connectivity	Connection between LHD-7 injection and production wells (UNIT 1-4)	Describes connectivity only; does not prove reusability of injected fluid

ing potential recharge areas in Lahendong, rainfall, and geological structures that act as entry routes for surface water to the reservoir. The results show that the recharge potential in Lahendong is estimated at 10.3 M ton/year. This value only considers the potential availability of surface water that can enter the reservoir, but does not calculate the quantity of fluid entering the reservoir.

Several studies have investigated natural recharge processes using numerical modeling, and hydrochemical data (O'sullivan *et al*., 2023). Although these approaches provide valuable insights, they primarily offer qualitative or surface-based assessments. Tracer studies have also been carried out to evaluate fluid movement in the reservoir. The results of a tracer study conducted by Prabowo et al. (2015) indicate a connection between the LHD-7 injection well and the wells located in Lahendong, specifically those associated with the UNIT-1, UNIT-2, UNIT-3, and UNIT-4 plants. However, the results of this study only describe the connectivity of the movement of the injected fluid, but do not answer the purpose of re-injection, so that the fluid that has been used on the surface to produce electricity can be reheated, and can be re-used in production wells as the proof that this geothermal energy is renewable.

Considering the table above, it is important to monitor the fluid dynamics that occur in the reservoir. Maintaining the sustainability of geothermal electricity production needs to be done by paying attention to the fluid mass balance in the reservoir. However, understanding and quantifying the dynamic behaviour of natural recharge remains a significant challenge in geothermal reservoir management.

Despite several previous studies addressing natural recharge in the Lahendong Geothermal Field, most of them have relied primarily on surface-based indicators or qualitative interpretations. To date, no study has quantitatively validated the characteristics or spatial extent of natural recharge using time-lapse microgravity measurements. This gap in the literature limits the understanding of fluid mass movement at reservoir depth, particularly in relation to sustainability assessment.

This study aims to answer the following research question: Can time-lapse microgravity monitoring be used to quantitatively characterize natural recharge in an operational geothermal reservoir? The gravity was hypothesized to change over time reflect fluid mass variations associated with recharge processes, and that this approach can provide spatial and temporal insights into the dynamics of natural fluid inflow. The findings are expected to support sustainable reservoir management and improve injection strategies.

Methods and Materials

Previous studies have investigated natural recharge mechanisms in the Lahendong Geothermal Field using hydrological, hydrogeological, and geochemical approaches. Efendi (2023) estimated the availability of surface water and fracture density by analyzing rainfall data from August 2019 to August 2020, and proposed that approximately 1.1 M ton/year of surface water may enter the reservoir. Similarly, Widagda and Jagranatha (2005) examined regional recharge potential by integrating rainfall intensity, topographic configuration, and fault structures that could facilitate water infiltration. Based on their findings, the total surface water potentially available for recharge in the Lahendong region ranges from 10 to 14 M ton/year. However, these values remain estimations and were not directly validated by subsurface measurements.

Despite indicating the presence of recharge processes, these earlier studies did not provide direct quantification of the actual fluid mass entering the reservoir system. They primarily offer regional-scale assessments, lacking confirmation at the reservoir scale. Therefore, in this study, time-lapse microgravity monitoring is applied to complement those prior findings. By detecting mass changes over time, this method provides quantitative evidence of fluid accumulation in the reservoir, thus offering a reservoir-scale perspective that bridges the gap left by surface-based estimations.

Furthermore, tracer tests conducted by Prabowo *et al.* (2015) demonstrated connectivity between the LHD-7 injection well and multiple production wells in the Lahendong Field, confirming the effectiveness of reinjection strategies in supporting reservoir pressure maintenance. However, the contribution of natural recharge in compensating for fluid loss due to continuous geothermal extraction, especially in the context of long-term sustainability was not fully addressed in the tracer study. The findings from this gravity-based investigation help to highlight zones of potential fluid addition beyond reinjection influence, suggesting a possible role of natural recharge that warrants further multimethod validation. The successful application of 3-D inversion time-lapse microgravity monitoring in the Lahendong Geothermal Field (Agung *et al*., 2024) has demonstrated its ability to detect both artificial injection and natural recharge processes, emphasizing its effectiveness as a reservoir monitoring tool.

One common method to estimate the amount of natural recharge fluid entering a reservoir is time-lapse microgravity monitoring (Agung, 2022; Agung *et al*., 2018; Sofyan *et al*., 2019, 2015, 2012, 2011, 2010). The difference in gravity values between two periods of gravity measurements (Δg) in geothermal fields at two different measurement periods ($g_{period2}$ and $g_{period1}$) can describe mass changes in the reservoir due to exploitation (Hunt, 2000; Nishijima *et al*., 2015; Omollo, 2018; Omollo and Nishijima, 2024; Portier *et al*., 2022, 2021; Sofyan *et al*., 2015). In this study, the gravity monitoring method was selected as the primary approach to detect mass changes within the subsurface as a proxy for fluid movement, including natural recharge processes.

$$\Delta g = \left(g_{period2} - g_{period1}\right) \quad \text{..................(1)}$$

Gravity measurements were conducted using a Scintrex CG-5 gravimeter owned by PGE. Annual gravity monitoring has been regularly performed in Lahendong since 2015. Each gravity survey is accompanied by simultaneous measurements of elevation and shallow groundwater levels at all gravity benchmarks. These additional measurements are essential to correct gravity readings from near-surface effects, particularly changes in topography and groundwater variations, which could otherwise distort the subsurface signal.

The difference in gravity readings at two different times in a certain area can be obtained from the mass changes that occur between those times using Gauss theorem calculations (Hammer, 1945; LaFehr, 1965),

$$\Delta M = \frac{1}{2\pi G}\iint_S \Delta g dS \quad \text{................................(2)}$$

This calculation assumes that the total fluid mass loss (ΔM_{Total}) in the reservoir is all fluid extracted through production wells (ΔM_{Prod}) minus all mass reintroduced to injection wells (ΔM_{Injec}) and natural recharge (ΔM_{NR}). The difference between the mass loss obtained from Gauss theorem calculations and the mass loss results from production-injection well data can describe the value of natural recharge entering the reservoir during the monitoring period.

$$\Delta M_{Total} = \Delta M_{Prod} - \Delta M_{Injec} - \Delta M_{NR} \quad \text{........(3)}$$

$$\Delta M_{NR} = -\Delta M_{Total} + \Delta M_{Injec} - \Delta M_{Prod} \quad \text{........(4)}$$

In Lahendong, time-lapse microgravity monitoring is routinely carried out annually to measure mass changes in the reservoir. Calculating the annual mass loss from well data and comparing it with the results of Gauss theorem mass calculations is expected to provide a quantitative picture of the estimated value of natural recharge entering the Lahendong reservoir.

Since 2015, microgravity monitoring measurements in Lahendong have been annually carried out during January–February. In total, there are around 118 gravity benchmarks (BM) that are monitored each period (Figure 4). This was done because based on a study conducted by Agung *et al*. (2023), the optimum period for obtaining a picture of the fluid dynamics of a geothermal reservoir is determined based on a value of change in gravity greater than 25μ gal.

Figure 5 illustrates the spatial distribution of fluid extraction and injection mass in the Lahendong reservoir based on the activity of each pro-

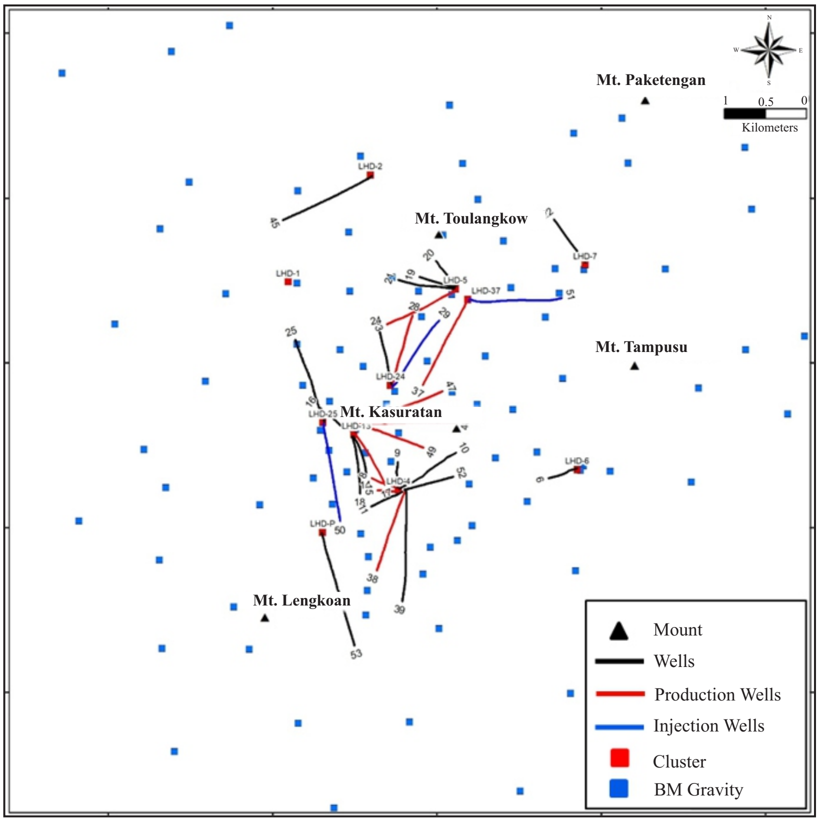

Figure 4. Lahendong Gravity Monitoring Benchmark distribution map.

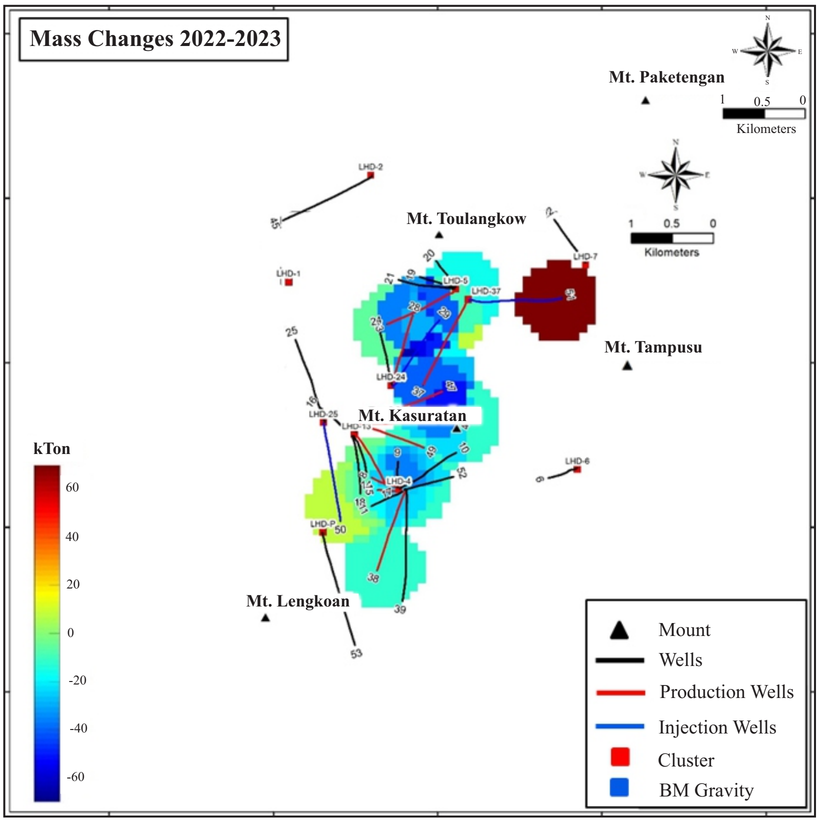

Figure 5. Changes in the mass of production and injection wells in the Lahendong geothermal field over twelve months.

duction and injection well during the 2022–2023 monitoring period. The map shows more than nine wells utilized as production wells (marked with red lines), while two wells functioned as injection wells LHD-51 located in the northern part of the field and LHD-50 in the southern section. The colour gradient on the map indicates the intensity of mass movement: areas shaded in deeper blue represent higher rates of fluid extraction, whereas red-toned areas reflect zones of greater fluid injection, typically influenced by the proximity to the nearest injection well. This spatial representation supports the interpretation of reservoir mass balance and fluid movement patterns.

The results of forward modeling using Gauss' theorem, based on mass loss data measured in flow meter measurements for each production and injection well in Lahendong, showed that the change in gravity that occurred over twelve months was 26 μ gal (Figure 5). Therefore, the optimal gravity monitoring period carried out in Lahendong is once a year, and is expected to be in the same season to avoid extreme changes in the rainy-dry season.

During each gravity monitoring period, monitoring of shallow groundwater level change and elevation change is also carried out. This aims to eliminate the effects of changes in gravity resulting from changes in elevation and changes in shallow groundwater levels (Allis *et al.*, 2000; Allis and Hunt, 1986), which occur in Lahendong. By eliminating the effect of mass changes near the surface, it is hoped that the measured changes in gravity will only be influenced by mass changes that occur in the Lahendong reservoir due to the exploitation process.

Previous studies, including tracer tests on fluid connectivity (Prabowo *et al.*, 2015), surface water availability assessments (Efendi *et al*., 2023), and recharge potential estimations based on rainfall data (Widagda and Jagranatha, 2005), were utilized as secondary references to support and validate the natural recharge estimates obtained through this time-lapse microgravity study. These complementary datasets provide independent evidence of possible recharge mechanisms and pathways, thereby strengthening the interpretation that observed gravity changes are indeed linked to subsurface fluid mass increases from natural sources. Integrating these findings helps to enhance the credibility of the gravity-based recharge assessment in the Lahendong reservoir.

Result and Analysis

Figure 6 is the result of time-lapse microgravity monitoring from 2015 to 2023, showing that the largest mass loss occurred in the production area with the largest mass extraction. However, what is interesting is that the mass loss from the results of time-lapse microgravity monitoring extends to the southern area of the production zone in the Lahendong reservoir. This shows mass flow from the south, which may be connected to the geothermal reservoir zone.

The mass flow from the southern area can be seen in Figure 7, which shows the annual microgravity changes in 2015–2016, 2016–2017, 2017–2018, 2018–2019, 2019–2020, 2020–2021, 2021–2022, and 2022–2023. In the southern part of the Lahendong production zone, in certain other periods, there is a significant increase in mass, and in certain periods, the increase in mass shows a loss. This result indicates the presence of fluid outside the reservoir entering from the south, which is thought to be natural recharge fluid in the Lahendong geothermal system. A similar gravity loss pattern in the southern part of the reservoir, indicative of natural recharge, was also observed in Lahendong using 3-D microgravity inversion (Agung *et al*., 2024), suggesting consistent mass gain due to colder fluid influx supported by PT log and temperature reversal.

Calculating the Gauss theorem, using the results of maps of gravity changes that occur in Lahendong, can estimate mass changes in the Lahendong reservoir over a certain period of time. Figure 8 shows the area where mass changes were calculated using Gauss's theorem based on the results of changes in gravity in the 2022–2023 period. The Lahendong proven res-

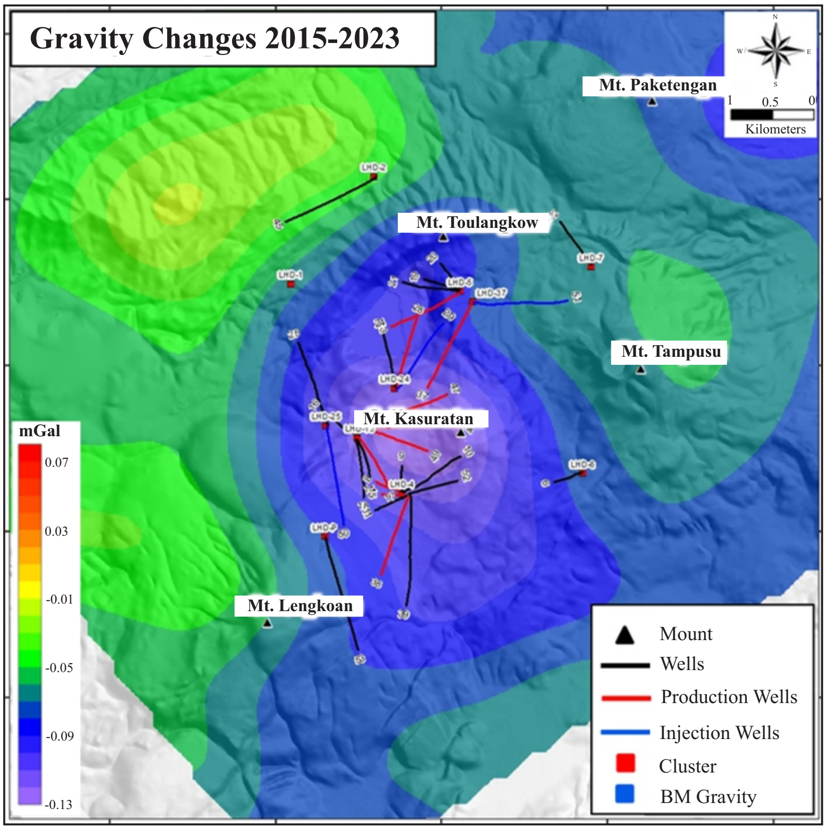

Figure 6. Total microgravity changes between the 2015–2023 period.

ervoir area of 7 km^2 is divided into a 100x100 m^2 grid. Each change in mass in the specified grid area is calculated and accumulated using the Gauss formula, resulting in a total mass change value of -0.92 M ton. Meanwhile, the difference in fluid injected and extracted in the 2022–2023 period based on the flow rate for all wells is -3.6 M ton, meaning that there is natural recharge fluid entering the Lahendong reservoir zone of around +2.68 M ton.

The calculation of the total mass deficit from Gauss theorem calculations was carried out annually from the beginning of 2015 until the latest data in 2023. Figure 9 shows the mass changes that occur in the Lahendong reservoir based on mass changes between production-injection fluid from all operating wells and mass changes based on microgravity monitoring using Gauss theorem formula.

Figure 9 shows the difference between the mass changes that occur in the reservoir based on the results of measuring the well fluid flow rate at the surface compared to the results of gravity monitoring. This shows that the fluid in the reservoir is not lost as much as measured at the surface by each well, but there is a natural increase in mass, causing the mass loss that occurs in the reservoir not to be as large as expected.

The differences in the graphical trend illustrated in Figure 9, which compares the measured mass loss across all wells with the results from gravity change monitoring, indicate that the influx of natural recharge varies from year to year. If natural recharge enters linearly, then when the difference between the fluid extracted and re-injected into the reservoir gets bigger, the change in mass measured by gravity monitoring results should get bigger too.

In the 2017–2018 monitoring period, the mass loss that occurred was calculated only based on the increase in well flow rate without data due to changes in gravity. Conversely, in the 2019–2020 period, the measured mass change in the reservoir as a result of the gravity monitoring decreased.

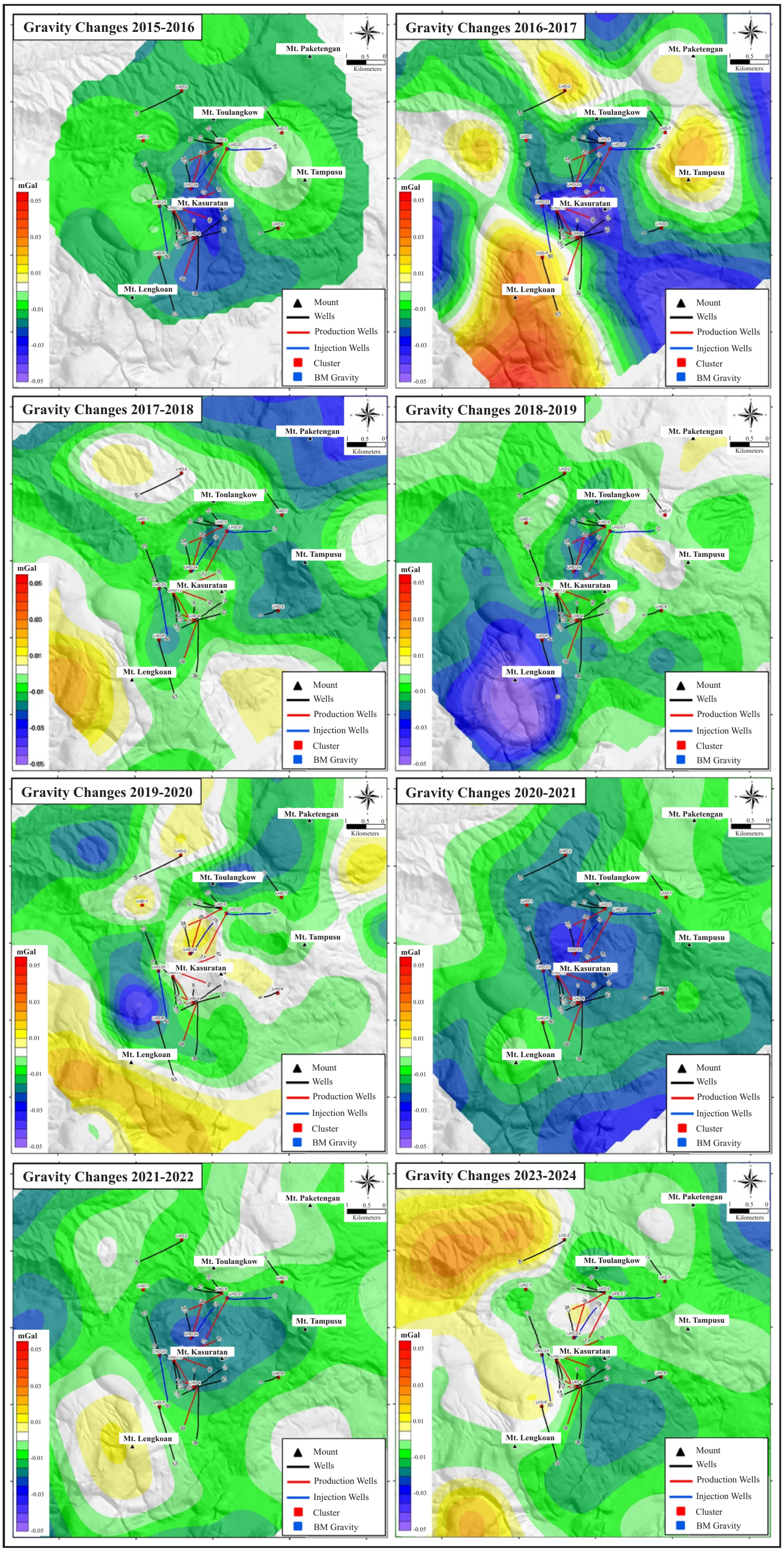

Figure 7. Annual microgravity changes from 2015 to 2023.

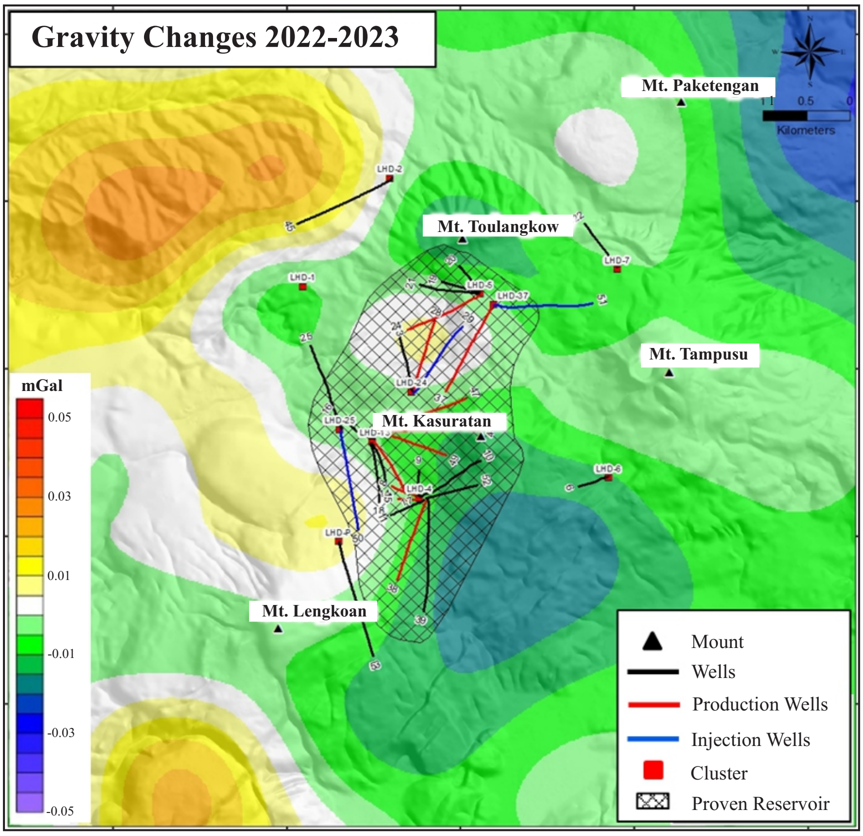

Figure 8. Calculation of mass changes in Lahendong based on microgravity monitoring results for the 2022–2023 period.

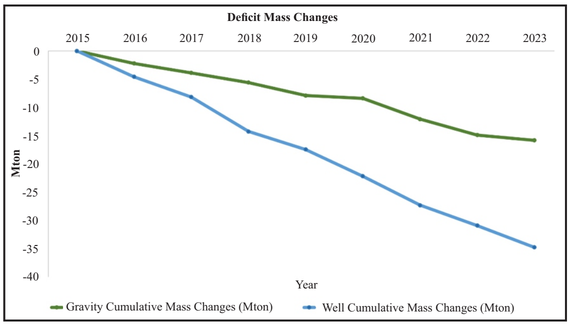

Figure 9. Cumulative mass changes in the reservoir based on production-injection well flow rate data and mass changes based on microgravity monitoring in Lahendong from 2015-2023.

However, it was reflected in the flow rate data measured from production and injection wells on the surface. Natural recharge calculations each year are carried out taking into account no changes in the scenario of operational use of production-injection wells on the surface. In 2017, there was a change in the injection well scenario, which previously used the LHD-7 well, which was changed to LHD-51. Therefore, to get an idea of the characteristics of the natural recharge fluid entering the Lahendong reservoir, calculations have been carried out since 2018 as an initial reference value.

Table 3 shows the amount of measured fluid mass lost in the Lahendong reservoir based on the flow rate throughout the well. The mass loss is based on the results of gravity monitoring using Gauss theorem, and the difference between the mass measured in the well and the mass from the

Table 3. Data on Mass Changes Based on Well Flow Rate, Changes in Gravity, And Natural Recharge

Year	Deficit Mass From Wells (Mton) A	Deficit Mass From Gravity (Mton) B	Natural Recharge (Mton) B-A
2018	0.00	0	0.00
2019	-3.60	-2.3	1.30
2020	-3.60	-0.5	3.10
2021	-3.60	-3.7	-0.10
2022	-3.60	-2.8	0.80
2023	-3.60	-0.92	2.68

results of gravity monitoring is interpreted as the amount of natural recharge fluid that entered the Lahendong reservoir during that period. The large quantity of natural recharge fluid entering each year can describe the pattern or characteristics of the dynamics of natural recharge fluid entering the Lahendong reservoir.

Figure 10 shows the natural recharge fluid flow pattern entering the Lahendong reservoir. By looking at the annual fluid flow pattern, the natural recharge fluid movement can be interpreted to repeat itself every three years (seasonality). It can be clearly seen that fluid slowly entered the reservoir in the first year (2019), and reached its peak in the following year (2020), but in 2021 period, the natural recharge fluid entering was very small. This flow pattern repeats in the 2022 period; the natural recharge fluid begins to enter again slowly, and reach a peak in 2023. Looking at this pattern, in 2024, the natural recharge fluid that can be expected to enter the Lahendong reservoir will be very small.

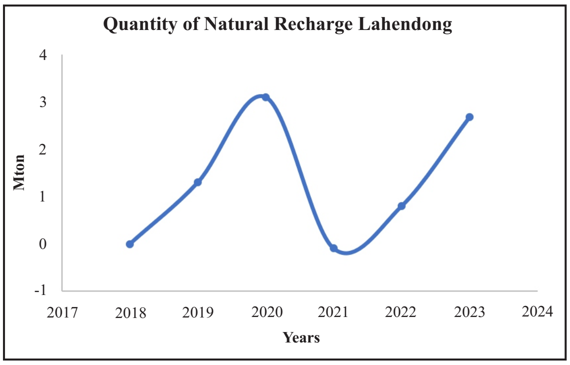

Figure 10. Fluctuations in the quantity of natural recharge in the Lahendong geothermal field for twelve months from 2018 to 2023.

Based on the characteristic pattern obtained from the results of this annual monitoring, the estimated natural recharge fluid entering the Lahendong reservoir in 2024 is around -0.6 M ton (Figure 11). In other words, there is no natural recharge fluid entering the Lahendong reservoir in that period. This calculation shows that the average natural recharge entering the Lahendong reservoir each year is around 1.03 M ton.

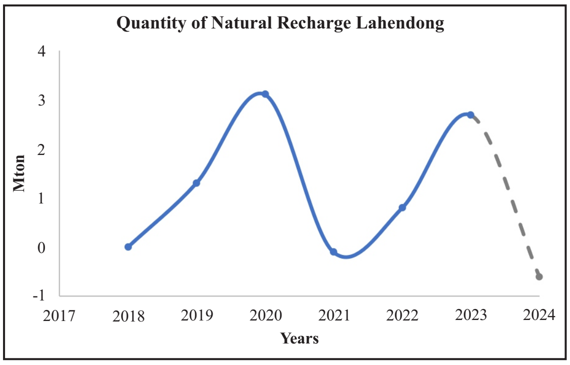

Figure 11. Estimated natural recharge fluid inflow in the 2024 period.

Discussion

The nonlinear pattern of natural recharge fluid inflow into the reservoir can be caused by many factors. The first possibility is related to the quantity of fluid that is naturally available, or it could also be related to the permeability of subsurface rocks, which makes it easy or not easy for fluid to move to other areas. However, in terms of geology, the permeability of rocks on the subsurface does not change in a short period of time (year by year), which does not create a nonlinear pattern of natural recharge flow. Therefore, the parameter of rocks permeability changes can be neglected. The permeability of the subsurface rocks is assumed to remain relatively constant over the study period.

By concept, fluids will move from areas with high pressure to locations with lower pressure (hydrostatic pressure). Hydrostatic pressure is actually influenced by two substantial parameters: rho (quantity of fluid) and location of fluid. In this scenario, quantity of fluid plays a crucial role in determining the hydrostatic pressure. This means that if natural fluid recharge is not detectable or unmeasurable enters to the reservoir, it is likely because the natural fluid pressure is not greater than the pressure in the reservoir. This is mainly due to the lower quantity of natural fluid, so the hydrostatic pressure of the natural recharge fluid is not yet able to encourage it to move and fill the reservoir zone.

The speed at which natural recharge fluid flows into the reservoir is also greatly influenced by the permeability of the rocks in the area. Large permeability will make it easier for natural recharge fluids to enter the reservoir, even in smaller quantities. Conversely, low rock permeability will make it difficult for natural recharge fluids to flow to other areas. It needs greater hydrostatic pressure to help its movement, meaning that the natural recharge fluid needs a longer time to collect and to accumulate higher pressure, so that it can move.

According to the analysis of the characteristics of Lahendong natural recharge movement, it is assumed that the permeability of rocks in the southern part is relatively large and constant. This is shown by the natural recharge, which has started to move since the first year (2019) and peaked in the second year (2020). In the third year (2021), it is possible that the "stock" of natural recharge fluid is empty. It will take time to refill it in the third year; in the fourth year (2022), it will repeat itself as in the first year; and in the fifth year (2023), it will also be similar. to the second year pattern.

The characteristics of natural recharge fluid movement can be identified by the condition that there is no change in scenario or activity on the surface, which causes differences in quantity and extraction or injection zones. The measured subsurface dynamics are naturally caused, which means that the characteristics of natural recharge fluids can be well identified.

This result of the dynamics of natural recharge movement can help provide recommendations for exploitation strategies (production and injection) in the Lahendong Geothermal Field. The study results show that the average natural recharge entering the Lahendong reservoir is 1 M ton/year, while mass loss due to exploitation activities in Lahendong is around 4.5 M ton/year, which indicates a deficit of 3.5 M ton/year that needs to be monitored to maintain the sustainability of geothermal development in Lahendong.

The relatively stable mass deficit at the surface, offset by the influx of natural recharge, which fluctuates from around 0 to 3 M ton/year, shows the potential for more optimal utilization of geothermal energy. When the natural fluid recharge is estimated at the maximum period, the fluid injection placement strategy can be relocated to areas that are known to receive less support from natural recharge. Likewise, when it is estimated that the natural fluid recharge period is at a minimum, the injection fluid allocation can be directed to relatively even areas in the Lahendong reservoir area. This strategy is expected to maintain sustainability through the more stable and long-term use of geothermal energy for human benefit.

Previous studies by Efendi (Efendi *et al.*, 2023) and Widagda and Jagranatha (2005) have qualitatively identified the presence of natural recharge in the Lahendong Geothermal Field using hydrological and hydrogeological approaches, such as rainfall data, surface water analysis, and structural pathways. However, those studies did not provide quantitative validation of how much natural recharge fluid actually enters the reservoir. This time-lapse microgravity monitoring study aims to reduce the uncertainty associated with estimating the volume of natural recharge.

By measuring gravity changes over time and combining them with surface data on fluid extraction and injection, the reservoir net mass balance can be more accurately assessed. The difference between the expected mass deficit (based on production-injection data), and the observed gravity-based mass change may indicate the magnitude of natural recharge entering the reservoir, providing a quantitative basis that complements and enhances previous qualitative assessments.

This study primarily focuses on identifying the presence and estimating the quantity of natural recharge through time-lapse microgravity monitoring. Previous investigations at Lahendong have largely addressed natural recharge qualitatively from hydrogeological, rainfall, and geochemical perspectives. While this study does not elaborate in detail on subsurface groundwater flow systems, fault compartmentalization, or reservoir boundaries, it contributes by offering a quantitative estimation based on observable mass changes. Further integration with geological and hydrogeological models is recommended in future studies to strengthen interpretations of recharge pathways and reservoir connectivity.

Conclusions

The key factor in sustainable geothermal development is to use geothermal reservoir fluids wisely and not excessively. The imbalance between the fluid extracted and injected back into the reservoir will accelerate the exhaustion of utilizable geothermal energy.

Monitoring the extracted and injected fluids is very important. Time-lapse microgravity monitoring and implementation of Gauss theorem can properly and clearly map subsurface fluid dynamics in the Lahendong Geothermal Field. Natural recharge fluid flow patterns can be well characterized. Regular annual microgravity monitoring reveals that natural recharge fluid flow in Lahendong fluctuates periodically, with a cycle of approximately three years.

The amount of natural recharge in Lahendong is between 0 and 3 M ton/year, with an average of around 1 M ton/year, which is important information for geothermal development in Lahendong. Which areas get and which do not get a supply of natural recharge fluid can be used as the evaluation material for planning geothermal utilization in Lahendong in the future. In addition, this approach demonstrates strong potential for long-term monitoring of reservoir fluid dynamics, supporting sustainable geothermal resource management.

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