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PERIOD ESTIMATION OF TIME-LAPSE MICROGRAVITY MONITORING USING GAUSS THEOREM – CASE STUDY: KAMOJANG GEOTHERMAL FIELD

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ABSTRACT: Maintaining the stability and continuity of steam production in the geothermal industry is a necessity. Mass changes in the reservoir due to geothermal production need to be monitored. Time-lapse microgravity measurement can be monitoring the effect of fluid extraction and injection process in geothermal wells. Inaccuracy of the gravity monitoring period can cause bias and inaccurate depictions of fluid dynamics and mass changes that occur in geothermal reservoirs. The aim of this study is to determine the appropriate period of time-lapse microgravity monitoring. Forward modeling from the Gauss theorem can be used to estimate the magnitude of the gravitational change anomaly in a certain period. With the current measurement capabilities, the estimation of the magnitude of the gravitational changes is when the value of the changes in gravity is greater than 25 µGal between two monitoring measurement periods. In the Kamojang geothermal field, it was found that the optimal gravity monitoring period is conducted every 11-13 months to optimally describe changes in mass and fluid dynamic reservoir.

Keywords: Time-lapse microgravity, Gauss theorem, Geothermal

1. INTRODUCTION

The utilisation of geothermal energy as electrical energy is carried out through the extraction of hot fluid from the reservoir. The hot fluid drives a turbine to generate electricity which then reinjected into the reservoir. The fluid can then be filled and reheated to be used as sustainable energy.

However, the continuous extraction of geothermal mass fluid in the subsurface disrupts the operational use of geothermal energy. Some physical parameter changes can occur due to the loss of mass in the reservoir. Some of them include subsidence due to loss of pore space-filling material, thermal shock due to the rapid loss of heat-conducting fluid, and the possibility of earthquakes [1].

In the geothermal exploration and exploitation phase, gravity method is widely used to provide physical information especially density distribution in the subsurface. At the exploration stage the gravity method is widely used to search for geological structures associated with density contrast of rock [2–4]. For the exploitation phase, time-lapse microgravity monitoring is widely used to determine changes in mass that occur in the reservoir [5].

Time-lapse microgravity monitoring has been widely carried out to monitor subsidence [5–7], CO_2 storage monitoring [8–11], and mass changes that occur in geothermal fields [12–20]. Extraction and injection of geothermal fluids can cause fluid movement and redistribution of fluid mass in the subsurface. It can lead to changes in the gravity value (Δg) measured on the surface at different periods ($g_{period2}$ and $g_{period1}$) on a micro-gal scale [21]. The application of time-lapse microgravity monitoring should be able to provide information on mass changes that occur in the reservoir [22].

Equation (1) shows the value of changes in gravity difference that occur in the reservoir. The result of exploitation can be found by measuring the difference between the gravity readings in the first period and the gravity readings in the second period at the same location. Areas that have a value of $g_{period2}$ smaller than $g_{period1}$ describe a mass loss as indicated by negative Δg. Vice versa, areas with a positive Δg value indicate an increase in fluid-reservoir mass. However, the change in gravity is very small. How can we measure this small change? The description of the response to a change in gravity due to a change in mass is shown in Fig.1.

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

Fig.1 (a) and (b) show a schematic of the amount of fluid lost and moving due to production activities in the geothermal field from gravity monitoring. And Fig.1 (c) and (d) show the estimated fluid movement due to fluid injection from the reinjection well. By carrying out routine gravity monitoring in geothermal fields, it is hoped that it will be able to provide an overview of how much, how fast, and in which direction the fluid movement occurs in the reservoir due to the geothermal exploitation process [23].

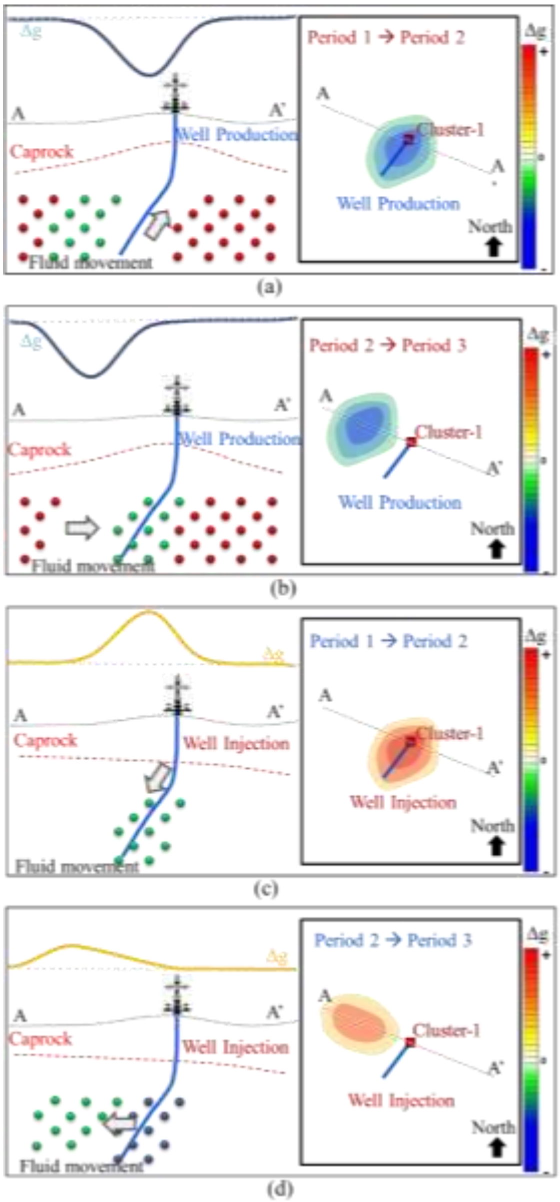

Fig.1 Schematic response of a change in gravity value due to a change in mass. (a) Mass loss occurs around the production well; (b) Mass loss occurs beside the production wells due to fluid moving to the production well; (c) Mass addition occurs around the injection well; (d) Mass addition occurs beside the injection well due to fluid moving from the injection well.

Grannell [24] explained that the main factor to be considered in conducting time-lapse microgravity monitoring is the magnitude of the anomaly changes in gravity that occur as well as the level of accuracy of the measurement tools used. The level of resolution, accuracy and minimum reading of measurement depends on the gravimeter instrument. However, the magnitude of the anomaly depends on mass changes in the subsurface. In geothermal field monitoring, mass changes in the reservoir also depend on the duration of exploitation. When the monitoring duration is too fast, the magnitude of gravity changes will be too small, and cannot be measured well. And if the duration is too long, then the subsurface fluid dynamics will not be observed. Allis [13] noted that the optimum magnitude of the anomalous magnitude that will be measured in a gravity instrument for monitoring the geothermal field has not been widely explained.

Regarding the magnitude of the gravitational-change anomaly that occurs in the geothermal field, Isherwood [25] has detected that the magnitude of the gravitational change that had occurred in the Geysers for several years reached 100 µGal. Hunt [26] also showed that during the six-year monitoring period at Wairakei, the magnitude of the measured gravitational change was approximately 500 µGal. However, regarding the magnitude of this change, further studies need to be carried out. The change in gravity is highly dependent on the production-injection activity carried out in each field. The amount of fluid extracted and injected will certainly affect the magnitude of the measured gravity change.

As was the case in the Oohaki field, 6 years gravity monitoring period was unable to answer the phenomenon that occurred from 1967 to 1974 in which there was a significant decrease in pressure in the reservoir [22]. In contrast in Salak field, from 1994 to 1998 the gravity monitoring period was carried out every year, the gravity magnitude show no changes, and after 1999 gravity monitoring was carried out every 3 years [27]. This illustrates that the determination of the monitoring period is importance to describe the dynamics of fluids reservoir.

The estimated value of the change in gravity that occurs during a certain period can be used to determine the optimal time-lapse microgravity monitoring period. Thus, it will make microgravity monitoring more effective and efficient. When the monitoring duration is too long, the dynamics of mass changes that occur in the reservoir due to the exploitation phase will certainly not be detected. Conversely, if the monitoring is carried out too quickly, the magnitude of the change in gravity that occurs is too small and cannot be read properly when the gravity data measurements are conducted.

Fig.**2** shows that determining the optimal monitoring period can describe the dynamics of fluid movement in the reservoir in each period monitoring. And conversely if the monitoring period is too long, the fluid movement cannot be detected as shown in

Fig.3. Then it is difficult to obtain an understanding of the fluid dynamics that occur in the reservoir. So this study was carried out to determine the optimal period for carrying out time-lapse gravity monitoring.

There are several examples of mass loss of fluid in geothermal reservoirs that vary and depend on the production and injection activities. For example, in Kamojang during the 2014–2016 period, it was known that the difference in the total fluid extracted and injected was about 20 MTon in an area of 21 km^2 [28]. In Wairakei, which has a reservoir area of about 15 km^2, the total extraction of geothermal fluid in the period 1952 to 1958 was about 20 MTon/year. Then there was an increase to 73 MTon/year, and in 1962 it decreased to 44 MTon/year [29]. Another example is the "US" geothermal field, which has a measurement zone of 10x10 km and during 2015 and 2016 experienced a mass deficit of 4–6 MTon annually [30]. And in the Hatchobaru geothermal field from October 1999 to October 2000, the total fluid extracted was about 3.0 MTon, and the injected fluid was about 1.7 Mton; hence, it experienced a mass deficit of about 1.3 MTon [31].

The magnitude of the total mass deficit for each period in each field can be estimated from the magnitude of the gravity change in the existing reservoir area. The areas can be known based on a study of the geoscience and drilling data. The emergence of the above changes in gravity rests on the assumption that all injection fluid re-enters the reservoir and no other fluid (natural recharge) fills the reservoir.

In this study, the average gravity anomaly from total mass changes is calculated by using the Gauss theorem. The estimation of the magnitude of the gravitational change anomaly in the Kamojang geothermal field will be discussed based on the total mass of fluids from production wells and injection wells in the 2020–2021 period. The estimated anomaly changes could be the key to resolve the time windows of time-lapse microgravity monitoring.

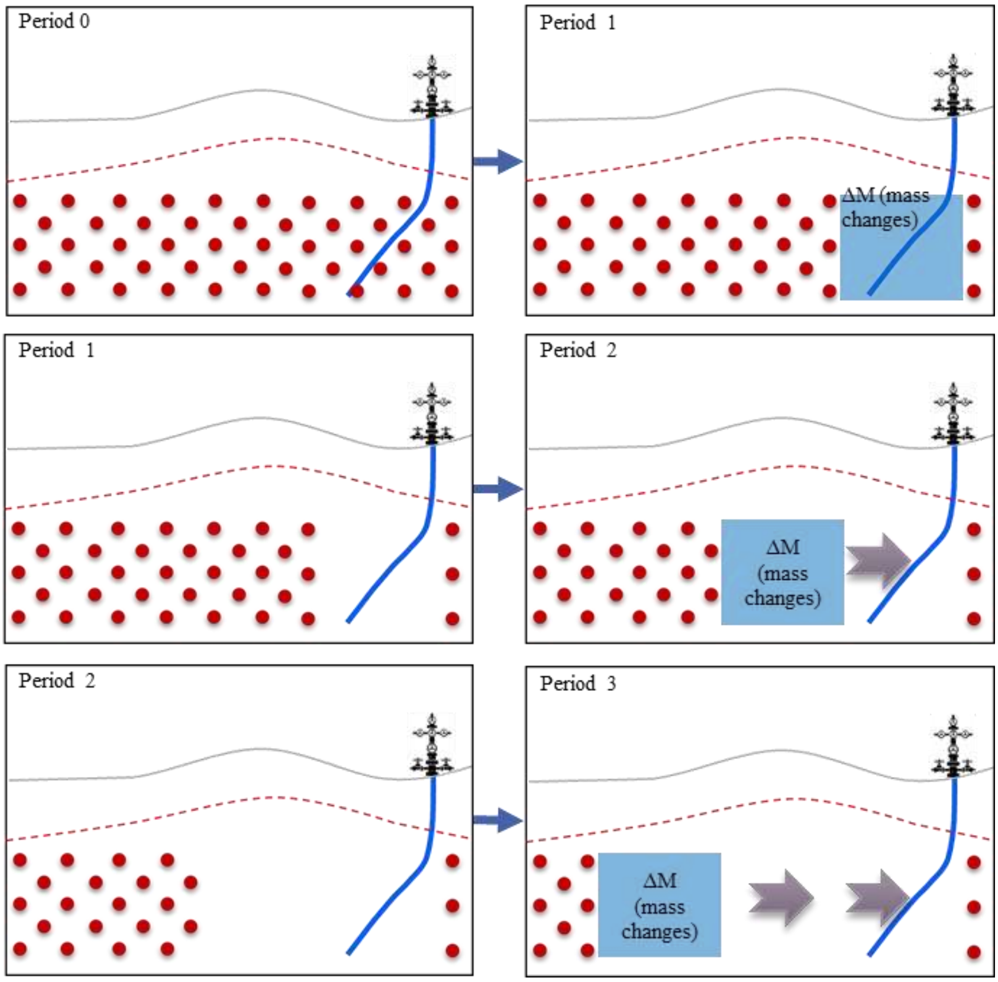

Fig.2 Schematic mass changes with optimum monitoring period.

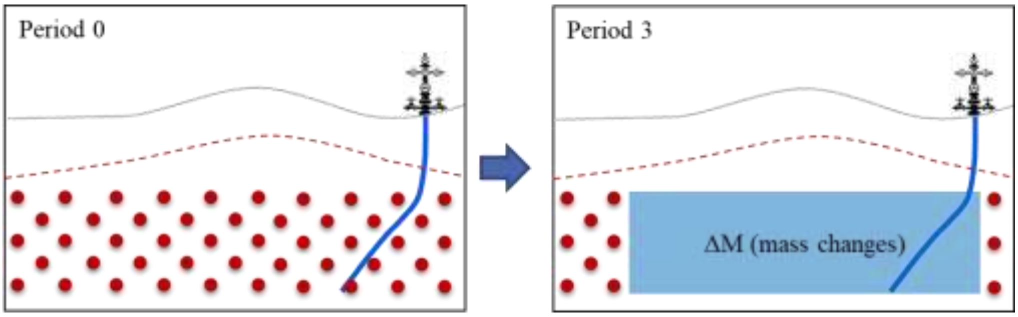

Fig.3 Schematic mass changes with too long period monitoring.

2. RESEARCH SIGNIFICANCE

Our findings will allow us to understand and estimate the magnitude of the anomalous changes in gravity over the appropriate periods. This is important for describing mass changes in geothermal reservoirs, especially in the Kamojang Geothermal Field. These results can be used for planning the development of production wells in order to maintain the continuity of geothermal industrial production.

3. METHODOLOGY

Forward modelling of the magnitude of the gravity value will be carried out in this study. The modelling is based on the total mass loss from the difference between the total extraction fluid in the production well and the fluid from the reinjection well. Forward modelling is done using the Gauss theorem, which can estimate the mass below the surface by using gravity data. By assuming the shape of the earth is a sphere, Gauss theorem states that the total flux of attractive forces on any closed surface of the earth in a gravitational field (projected in a plane and perpendicular to the field) will be equal to the area of the earth's surface multiplied by the gravitational constant and the total mass that covers the surface as written in Eq. (2). Thus, the implementation of the Gauss theorem simplifies the effect of the position of the subsurface mass anomaly on the closed area of the earth's surface [32]. The gravity anomaly is no longer a function of depth but only a function of mass and the closed area.

Hammer [33] first explained that the Gauss theorem can be used to calculate the total mass of residual gravity-anomaly data [32]. The value of gravity in a certain area on the surface can indicate, quantitatively, the value of the total mass under it by using the following equation:

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

where M is the total mass, G is the gravitational constant, S is the surface area that encloses the mass anomaly of interest and Δg is the value of the relative acceleration due to gravity. In time-lapse microgravity monitoring activities, Δg is the difference in the value of the gravity reading between the two measurement periods.

To find out the estimated magnitude of the change in gravity that will occur in a geothermal field that has been operating for a certain period and with a known area, Eq. (2) can be changed to:

$$\Delta g = \frac{2\pi G \Delta M}{S} \qquad (3)$$

The total mass loss (ΔM) in the reservoir is obtained from the difference between the fluid extracted from the production well and the fluid returned through the reinjection well. In calculating the value of ΔM it is assumed that the mass change that occurs below the surface comes only from the activity of the production and injection wells. Moreover, the value of the area S, which is taken from the extent of the proven area in the geothermal conceptual model, is generally obtained from the results of subsurface geoscience studies and data from exploration and development wells. This area can describe the approximate mass-loss zone due to the exploitation.

The estimated value of the gravitational change is expected to occur only as a result of changes in subsurface fluids due to exploitation activity. As for the additional fluid to the reservoir from natural recharge, changes in rock structure in the reservoir as well as changes in the terrain on the surface due to construction or other civil activities that change the topography significantly near the gravity monitoring location, it is assumed that these do not occur.

In terms of the accuracy of the gravimeter instrument used (the LaCoste and Romberg Model G), the uncertainty value of the gravimeter reading is about 8–10 µgal [24]. The modelling results also done by Grannell show that the change in gravity that can be monitored properly in geothermal fields (where fluid has been extracted and injected in the reservoir) needs to have a magnitude of > 50 µgal. This value is equivalent to 5–6 times the uncertainty in reading the tool that was used at that time. This value also aligns with the results of an experiment conducted by Gettings [34], which stated that the estimated minimum magnitude of the signal that can be recorded for gravity monitoring measurements is about 40 µgal.

For current conditions, the Scintrex CG-5 and CG-6 (using fused-quartz sensors with electrostatic nulling gravity-reading resolution) can reach 0.1 µgal for the CG-6 [35] and 1 µgal for the CG-5 [36]. Both the instruments have the same standard deviation of reading uncertainty, which is < 5 µgal. This is according to the results of a study conducted by Allis [13], which states that with good and careful measurement, the uncertainty of reading the current time-lapse microgravity monitoring measurement data can reach about 5 µgal. If using the same approach used by Grannell [24] using currently available gravimeter instruments, the optimal magnitude of the gravitational-change anomaly can be detected if the magnitude of the gravitational change is >25 µgal (approximately).

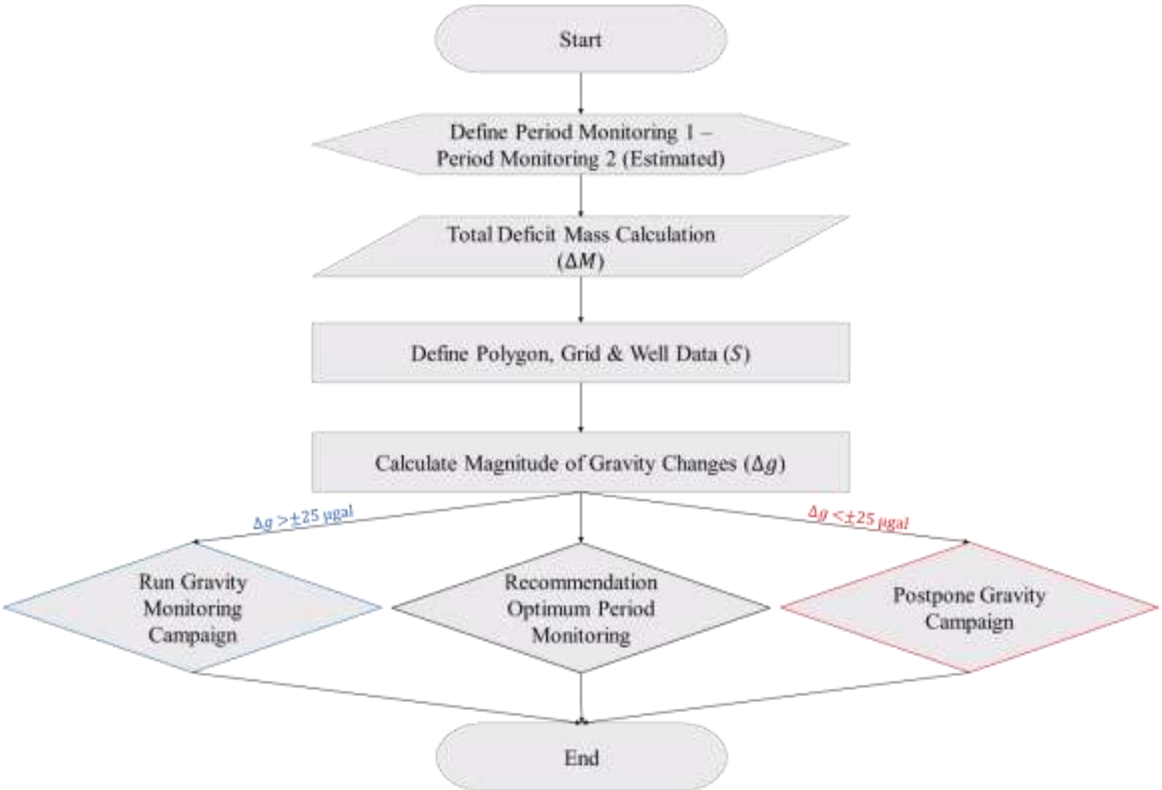

Fig.4 Flow chart for the optimum estimated period of time-lapse microgravity monitoring.

Based on several considerations that have been described previously, a flow chart of the study carried out was made as shown in Fig.4. After determining the monitoring period that will be carried out, the next step is to calculate the magnitude of the change in gravity that will occur based on the total mass lost during the monitoring period. The measurement of time-lapse microgravity monitoring must be postponed until the estimated magnitude of the gravitational change that appears (based on the calculation of the mass deficit from the production- and injection-well data) produces an anomaly estimate of > ±25 µgal.

To obtain changes in gravity that occur only from the effects of changes in mass in geothermal reservoirs, the difference in gravity readings at different periods must also be corrected (at a later time) by taking account of changes in elevation and changes in shallow groundwater levels in the same period [12-13]. By eliminating the effect of changes in gravity due to these two factors that occur near the surface, the resulting changes in gravity are expected to be able to describe changes in mass that occur in the reservoir.

4. RESULT AND DISCUSSION

The estimated magnitude of the change in gravity is found by measuring the total fluid extracted and injected from the well flow-rate data between two specific periods. From the total difference between the injected and extracted fluids, the cumulative fluid-loss value from the reservoir during that period can be known. This total mass-loss value is then estimated to occur in an area as large as the proven geothermal field being developed. Furthermore, it is estimated that the magnitude of the change in gravity that occurs is based on the forward modelling of the Gauss theorem based on Eq. (3).

This modelling is applied to the case in the Kamojang geothermal field. In this field, from October 2020 to October 2021 (13 months), there was a mass loss of 11.8 MTon in a proven area of 21 km^2. This value was obtained from the difference between all the fluid extracted from the production well and the fluid that was reinjected into the reservoir in the same period. All activities of both production and injection wells in Kamojang were assumed to have an extraction-injection zone of about 500 m^2. The polygons were made from each well with a grid size of 100 x 100 m^2 as the distribution area for mass changes that occurred due to exploitation. The cumulative total mass change that occurred in each well was then distributed to each polygon. The values in the grid that intersects between wells were accumulated to calculate the cumulative change in each grid as shown in Fig.5.

Fig.6 shows the distribution of mass loss in the Kamojang field in the 2020–2021 period. This map is based on the well flow-rate data in the each well for that period according to the grid that was made in Fig. 5. The blue colour depicts the mass loss due to fluid extraction in the surrounding wells, and the red colour shows the addition-of-mass effect from the injection well activity in the specified grid area. The production zones combined in the same main pipeline PL-401, PL-402, PL-403, PL-404, PL-405 and PL-406 experienced the higher mass loss, with the addition of mass coming from injection wells KMJ-20, KMJ-21, KMJ-35 and KMJ-39.

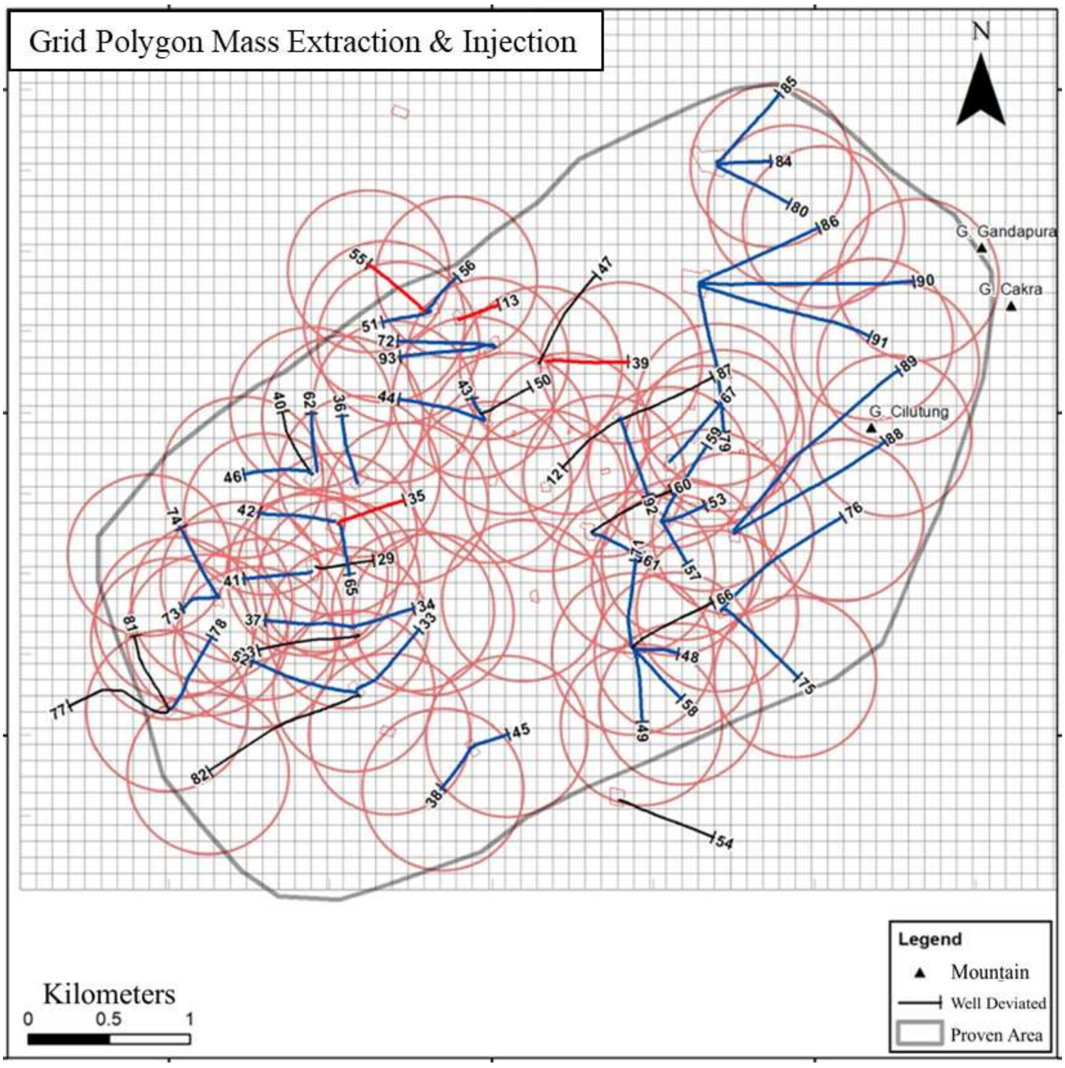

Fig.5 Polygon grid map for calculating the distribution of mass loss from production and injection wells.

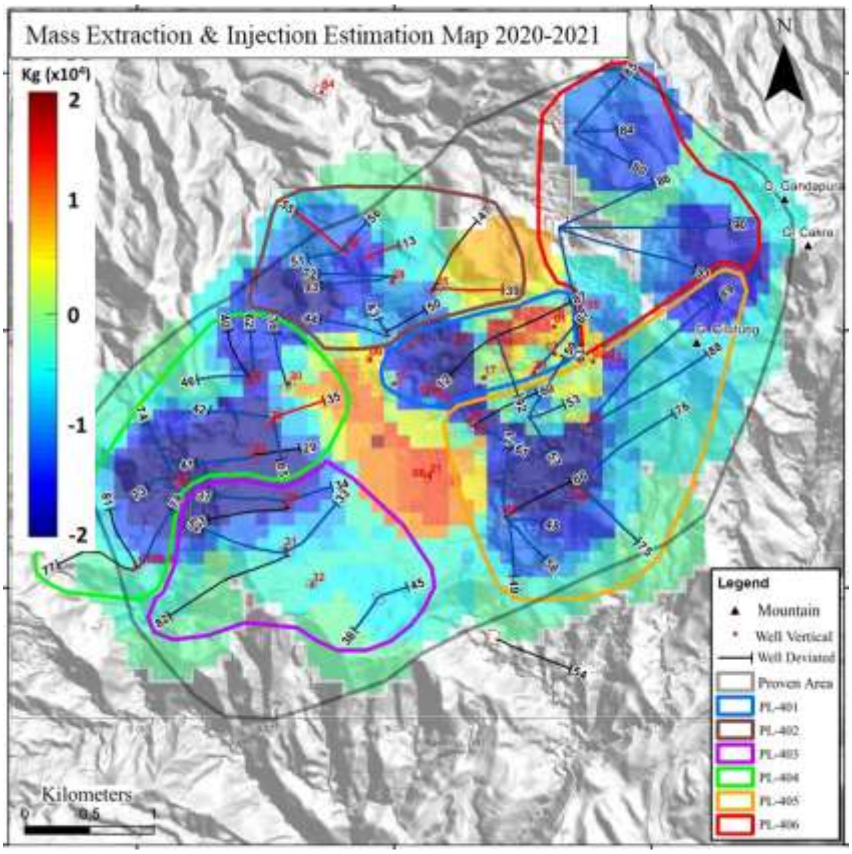

Fig.6 Kamojang deficit map based on cumulative fluid loss from well data in the 2020–2021 period.

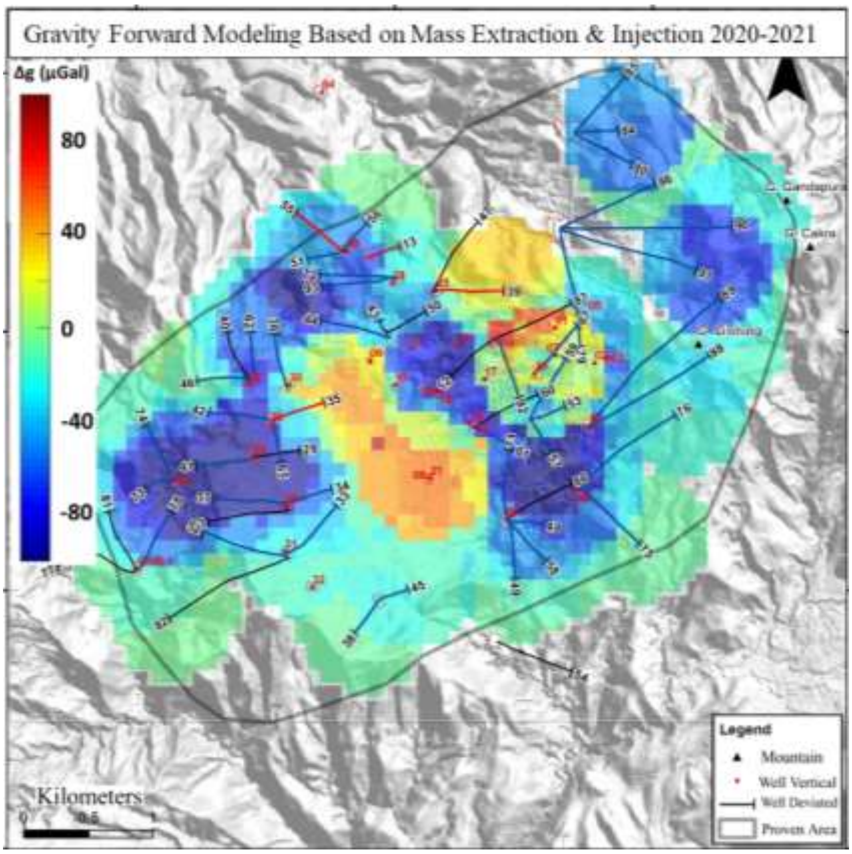

Fig.7 Gravity forward-modelling map based on mass extraction-injection of fluid from wells in Kamojang.

Based on the distribution of mass loss that occurred in each area shown in Fig. 6, forward-modelling calculations were then carried out using Eq. (3). This calculation produced an estimate of the magnitude of the gravitational change that would appear in the Kamojang area. Hence, the magnitude of time-lapse microgravity monitoring can be estimated based on the estimated mass loss on each of the grids that have been made.

Fig.7 shows the result of time-lapse microgravity forward-modelling calculations in Kamojang in 2020–2021 from each grid based on flow rate wells in Fig. 6. It was found that the variation in the magnitude of the gravitational-change anomaly ranged from −162 µGal to +87 µGal, with an average gravity-change magnitude of −29 µGal. The average value of this change in gravity was greater than the minimum magnitude of ±25 µGal (the condition for gravity monitoring to be feasible), so that gravity monitoring could be carried out in October 2021.

From these results, it can be concluded that if the flow rate of each well and the distribution of mass loss is constant, as shown in Fig.6, then gravity monitoring in Kamojang can be carried out every 11–13 months as shown in Fig.8. It is hoped that, by measuring the appropriate monitoring period in this Kamojang case study, it will be able to describe the dynamics of the fluid movement's effects from injection and the natural recharge while taking into account the magnitude of the anomaly and the capabilities of the tools used.

If the monitoring period is carried out faster than 11–13 months, it is feared that the gravity-change anomaly that is read will be smaller than allowed by the level of accuracy of the tool. So the measured value of the gravity anomaly has the potential to have a questionable level of instrument-reading accuracy. Furthermore, if the monitoring is carried out for much longer than this recommended period, then the possibility of fluid-movement dynamics from both injection fluid and natural recharge occurring in Kamojang cannot be identified more accurately due to the absence of data in a shorter period.

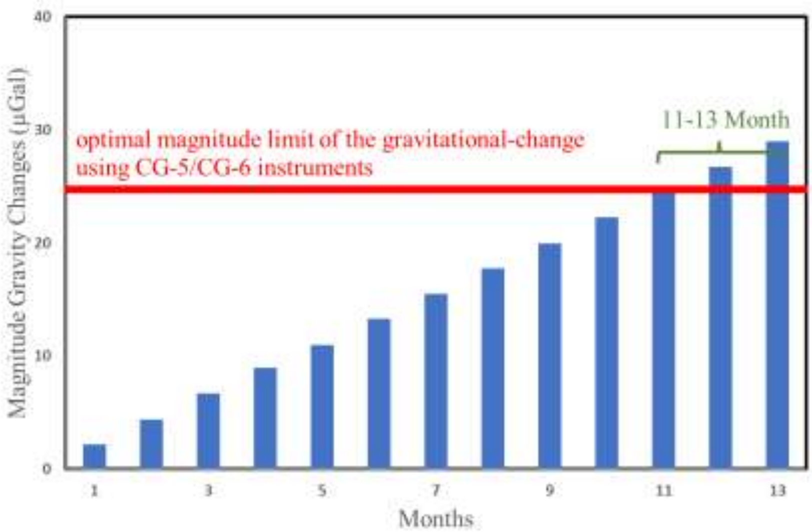

Fig.8 Estimation of optimum period time-lapse microgravity monitoring in Kamojang at 2020-2021 period.

5. CONCLUSION

Time-lapse microgravity monitoring can help provide information about the dynamics of fluid movement and mass changes that occur in geothermal reservoirs during the exploitation phase. The application of the Gauss theorem can be used to estimate the appropriate gravity-monitoring period. So that the monitoring application in the geothermal field can be carried out optimally. In the case of the Kamojang geothermal field, during the 2020–2021 exploitation period, the optimum time-lapse microgravity monitoring was carried out every 11–13 months.

The estimation of the appropriate monitoring period is expected to enable an appropriate description of the changes in mass in the exploitation phase. Therefore, the implementation of gravity monitoring can then be carried out with a monitoring strategy based on a scientific point of view that can be accounted for both in theory and application.

Optimizing the determination of the time-lapse microgravity monitoring period depends on the resolution of the gravity instrument used when monitoring is carried out. Therefore, it is necessary to update the determination of the monitoring period by considering the gravimeter instrument used in the latest conditions.

6. ACKNOWLEDGMENTS

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