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Sustainable Geothermal Utilization Deduced from Mass Balance Estimation -A Case Study of Kamojang Geothermal Field, Indonesia-

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ABSTRACT

Geothermal energy is renewable energy, that is, the energy removed from the geothermal reservoir is continuously replaced on time scales similar to those required for energy removal. Energy supplied to the geothermal reservoir comes from natural recharge and injection. Sustainable production in the geothermal energy development is the ability of the production system applied to sustain the stable production level over long times. It is very important to manage the mass balance between production, injection and natural recharge in the geothermal reservoir during exploitation.

The Kamojang Geothermal Field in West Java is the oldest developed geothermal field in Indonesia. It is a vapor dominated system and its installed capacity is 200 MWe. More than 116.78 x 10^6 tons of steam has been exploited from KGF since 1983 to 2000. We estimated the mass balance in the geothermal reservoir based on the repeat gravity measurement. From two calculations in different times, we estimated that the rate of natural recharge is almost same, that is, 2.77 Mt/year. However the recharged energy is smaller than the produced one has influence to the decline of steam flow rate of Kamojang production wells. Increasing injection rate and/or decreasing production rate are necessary to maintain sustainable production in KGF.

1. INTRODUCTION

Renewable describes an attribute of the energy resource, i.e. the energy removed from a resource is continuously replaced by more energy on time scales similar to those required for energy removal and those typical of technological/societal systems (30-300 years), rather than geological times (Rybach L. and Mongillo M., 2006). Geothermal energy is renewable energy and the geothermal fields should be maintained to reach sustainability. Geothermal energy is renewable energy but its sustainability is not self evident. *Sustainability is the doctrine that economic growth and development must take place and be maintained for long time* (Ruckelshaus, 1989). In the case of the geothermal energy, the system applied to sustain the production level should be maintained more than 100 years. The important factors in order to achieve the sustainable development of geothermal energy are maintaining the stable production and recharge to the reservoir. It is important to determine the sustainable production level and optimum injection to the reservoir. Balancing between production and recharge rate is significant to avoid depletion. Production rates that persistently exceed the rate of recharge will eventually lead to reservoir depletion, thus stopping economic production. Sustainable development in the geothermal field will occur if production rate is same or less than recharge rate.

1.1 Kamojang Geothermal Field

1.1.1 Location

The Kamojang Geothermal Field (KGF) in the Garut region of west Java, about 40 km from the city of Bandung, is a vapor-dominated system with a reservoir depth of about 600 to 2000 m. The KGF is located on the geographical coordinate of 07°11'02" – 07°06'08" S and 107°44'36" - 107°49'30" E. The Kamojang geothermal system resulted from the complex interaction between active volcanoes and tectonic processes and it is influenced by two important faults named the Kendang fault and the Citepus fault (Sudarman et al., 1995; Kamah et al., 2005) (Figure 1). The area of the KGF is about 21 km^2 and it has altitude of about 1400 - 1800 m above sea level. The Kamojang geothermal reservoir is covered by the cap rock that consists of prophylitic altered volcanic rock of which thickness is about 500-600 m but seems to be only 200-300 m thick toward to the northern and eastern parts. The productive geothermal reservoir, which has high porosity, high permeability, high temperature, and filled with sufficient steam, is located between 600-2000 m in depth. The reservoir consists of the strongly altered andesitic rocks and some volcanic pyroclastics (Sumintadireja et al., 2000).

1.1.2 History

Geothermal exploration in the KGF has begun in the early 20th century by The Dutch. In the 1920, the shallow test wells at Kamojang were drilled successfully. The first electrical power at Kamojang was generated in 1978 when a small (mono block 250 kWe), free exhaust-type turbine was installed and then the design of the first large-scale geothermal power plant was completed in 1979 (Hochstein and Sudarman, 2008). The KGF has been exploited since 1983 and produced electricity with production capacity of about 200 MWe until 2008. There are more than 66 wells of the active production wells, injection wells and monitoring wells. Pertamina has drilled 76 wells with bottom hole temperatures ranging from 115 to 245°C (Mulyanto, 2004). The three to five deep unproductive wells, situated in the centre of the field, have been used as injection wells (see Figure 2). At first, injection wells were used for condensed steam from the power plant. To increase the efficiency of cooling in the condenser and to increase the injection rate, water from Cikaro Lake at the centre of the field is pumped to the cooling tower, and injected with the condensed water (Mulyanto, 2004).

It is very important to manage geothermal reservoir in order to realize sustainable production. The repeat gravity measurements have been conducted to monitor the change in the geothermal reservoir during exploitation.

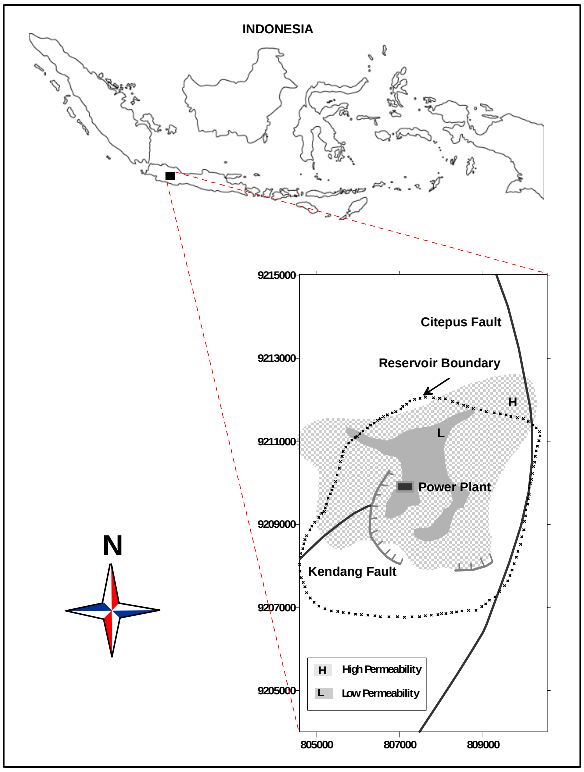

Figure 1: The reservoir boundary of the KGF from MT interpretation and direction of the Citepus and Kendang fault

2. MASS BALANCE

A mass balance or material balance is an application of the mass conservation to the analysis of physical systems. The mass balance is used to analyze and to count the mass that enters or leaves the system. The mass balance in the geothermal reservoir is regulated by the amount of production, injection and natural recharge. The mass change (Δm) is a difference of the entering mass to reservoir and the leaving mass from reservoir. The mass change rate ($\frac{\Delta m}{\Delta t}$) is result of the mass flux in ($\dot{m}_i$) and the mass flux out ($\dot{m}_j$).

$$\frac{\Delta m}{\Delta t} = \sum_{in} \dot{m}_i - \sum_{out} \dot{m}_j$$

$$\frac{\Delta m}{\Delta t} = \dot{I} + \dot{R} - \dot{P} \qquad (1)$$

$$\frac{\Delta m}{\Delta t} = Q_{in}\rho_w + Q_r\rho_w - Q_p\rho_s \qquad (2)$$

where m = mass, t = time, $\dot{I}$ = injection rate, $\dot{R}$ = recharge rate, $\dot{P}$ = production rate, Q_{in} = flow rate of the water injection, Q_r = flow rate of the water recharge, Q_p = flow rate of the steam production, ρ_w = water density, ρ_s = steam density. In the geothermal reservoir, the entering mass comes from the injection and natural recharge while the leaving mass comes from the production.

2.1 Mass Change

Mass change (dm) in the reservoir can be calculated by Gauss's theory in the repeat gravity measurement method. Gauss's theory (Hammer, 1945) explains the mass change is obtained by gravity change:

$$\Delta m = \frac{1}{2\pi G} \sum (\Delta g . \Delta A) \qquad (3)$$

where Δm = the mass change (kg), Δg = the gravity change (mgal), ΔA = Area concerned (km^2), G = the gravitational constant 6.672x10^{-11} Nm^{2}kg^{-2}.

2.1.1 Gravity Change

The Gravity changes in the KGF were measured between 1999 and 2005. Contour map of the corrected gravity change from 1999 to 2005 is shown in Figure 2 (Sofyan et al., 2008). These differences are viewed in µgal scale. The corrected repeat gravity measurement data in the KGF show gravity changes between -238 µgal to 143 µgal. The distribution of gravity change gives a picture of the mass movement in the reservoir. It is a result of exploitation and injection activity in 1999 to 2005 and natural recharge from outside of the reservoir.

The biggest negative gravity change occured around benchmark PPG-07. These big negative values have correlation with the location of high production wells such as KMJ-22, 37, 42, 65, 73 and KMJ-74 (Figure 2). The large negative gravity changes were primarily caused by net mass loss of geothermal fluids due to exploitation. Positive value of gravity change occurred near the injection wells such as KMJ-21, KMJ-55 and KMJ-46 (Figure 2). This positive gravity change can describe fluid flow from injection wells to the reservoir. The injected fluid from KMJ-55 flows to NE direction while the fluid from KMJ-21 moves to SE and KMJ-46 to SW direction. Gravity change is very clear in the high permeability zone.

2.1.2 The 1999-2005 Mass Change

The calculation of mass change refered to the equation (3) can be made by gridding the map of the corrected gravity change. The 1999-2005 corrected gravity change map of the KGF was divided into 3828 grids (Figure 3) that are indicated in the reservoir area. The area of each grid (ΔA) is 6097.114 m^2. The gravity change (Δg) for each grid as calculated below:

$$1\Delta g = \frac{dg_{i,j} + dg_{i+1,j} + dg_{i,j+1} + dg_{i+1,j+1}}{4} \qquad (4)$$

where ($dg_{i,j}, dg_{i+1,j}, dg_{i,j+1}, dg_{i+1,j+1}$) are the gravity changes at one grid square (see Figure 3). The mass change calculation of the 1999-2005 gravity change show decrease about 20.07 Mt (Million ton) for 6 years period that is about 3.34 Mt/year.

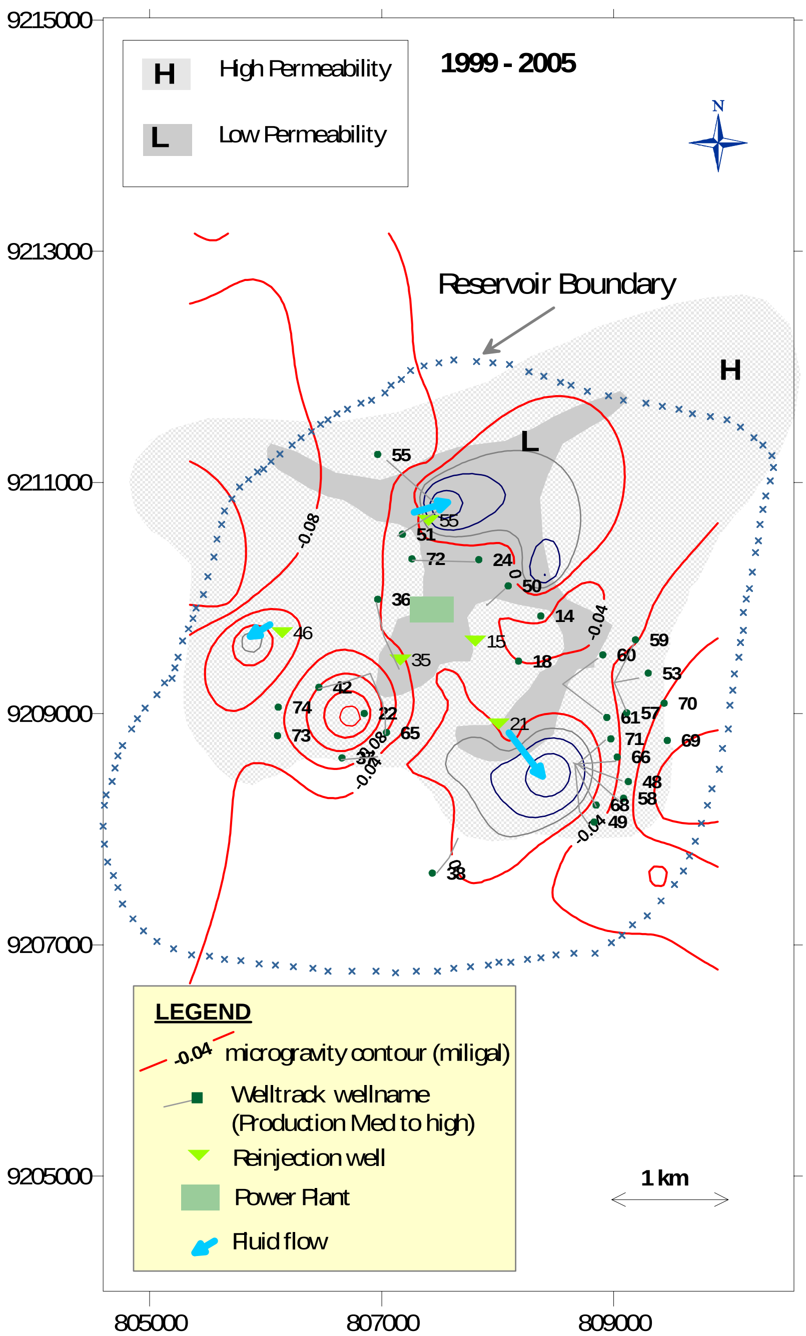

Figure 2: Distribution of the 1999-2005 gravity field change at KGF (Sofyan et al., 2008)

2.2 Mass Balance Calculated

Since 1983 to 2005, more than 160 x 10^6 tons of steam has been exploited from the KGF and more than 30 x 10^6 tons of water is injected to the KGF. The rate of the production and injection of the KGF was shown in Figure 4.

The total production and injection per year can be seen in the production and injection history (Figure 5). The average total production rate from the 1999 - 2005 is about 7.98 Mt/ year. It is bigger than the average of the 1999-2005 total injection rates of 1.87 Mt/ year. The net mass produced (total mass produced – total mass injected) at the KGF from this period is about 6.11 Mt/ year. Assuming all the injected water enters to the reservoir, the estimation of the total rate of the natural recharge to the Kamojang reservoir system is about 2.77 Mt/year. The recharge rate to the KGF of about 45% of the net mass produced has occurred from the natural flow and lateral aquifers.

This calculation result of the natural recharge rate per year is close to the previous calculation from the 1984-1999 gravity change data that is 2.71 Mt/year (Kamah et al., 2000). The natural recharge rates between 1999-2005 and 1984-1999 are almost same. This means the natural recharge rate to the reservoir in the KGF is limited.

The simple mass balance model of the 1999-2005 gravity change in the KGF is shown in Figure 6. We must balance the mass to continue the sustainable production.

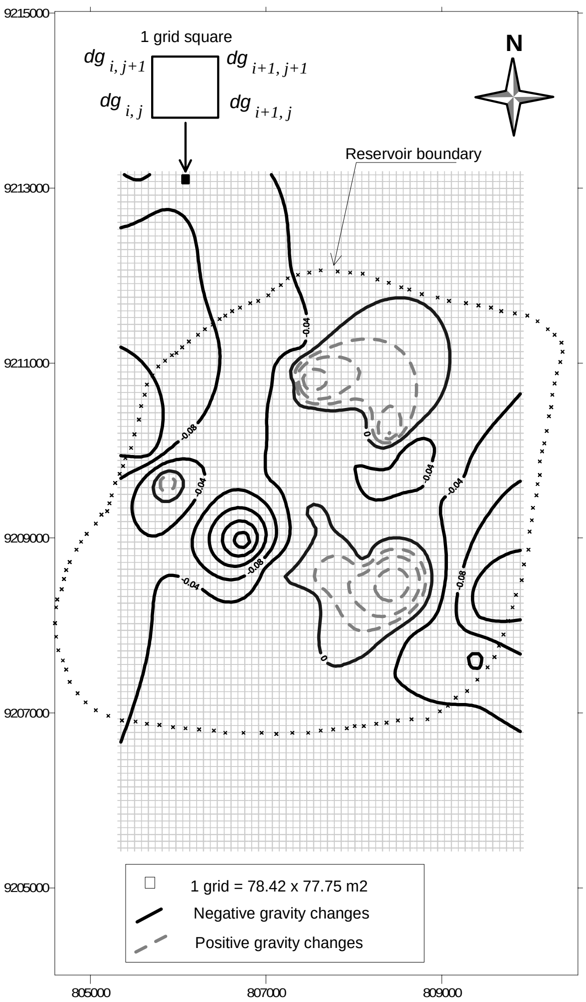

Figure 3: The gridding method of the 1999-2005 gravity field change for the mass change calculation at the KGF

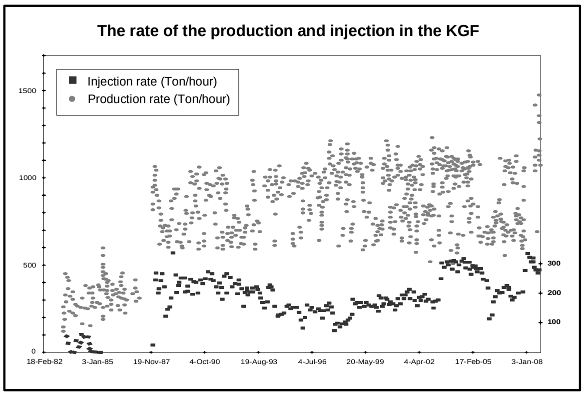

Figure 4: The rate of the production and injection (Ton/hour) at the KGF (Pertamina, 2008)

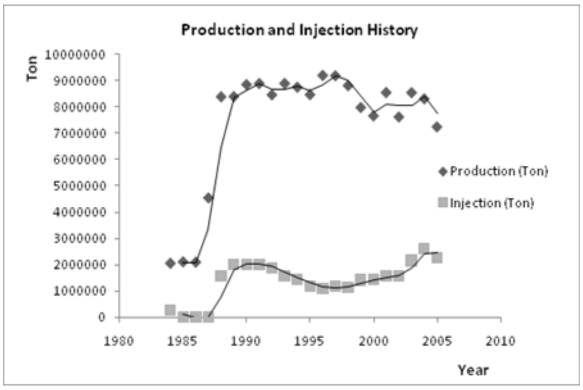

Figure 5: The 1984-2005 total production and injection per year at the KGF (Moeljanto, 2004 and Pertamina, 2008)

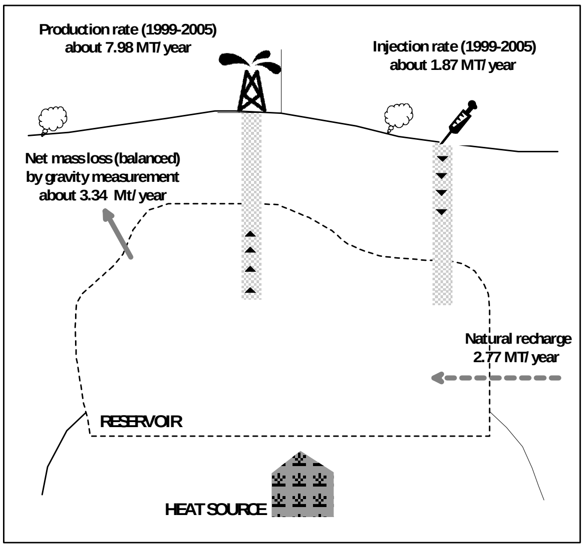

Figure 6: A 1999-2005 mass balance model at KGF showed natural recharge to the KGF reservoir is about 2.77 MT/year while net mass produced and net mass loss are about 6.11 MT/year and 3.34 MT/year (Sofyan, 2008)

3. SUSTAINABILITY

The KGF had been exploited for more than 25 years. Concerning to the evaluation of the steam production in the KGF, the decline of steam flow rate notably occurred at some production wells. Regarding to the previous research (Doddy et al., 2000) the steam production decline trend of the KGF is 7.43%/year.

We assumed that natural recharge rate at KGF is stable at a rate of about 2.77 MT/year from 1983 to 2005. If we assume that all injected fluids enter to the reservoir, the calculation of mass change will be:

$$MC = (I + R) - P \qquad (5)$$

where MC = Mass change, I = Injection rate, R = Recharge rate and P = Production rate.

We show the correlation between total production, injection and mass change during exploitation from 1988 to 1999 at the KGF in Figure 7. The changes of the produced and injected fluids amounts induce change in mass in the reservoir.

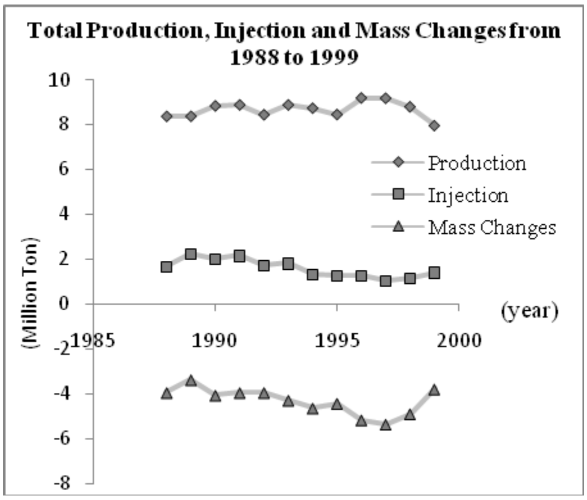

Figure 7: The total production, injection and mass change during exploitation from 1988 to 1999 at the KGF

Production rate has a negative linear correlation with mass change. Mass change will decrease with rising production rate. In this condition, from the correlation between production rate and mass change rate, the sustainability production in the KGF is less than 7 Mt/year (Figure 8). Linear correlation is:

$$P = a(MC) + P_s \qquad (6)$$

where P = Production rate, P_S = Sustainable production, a = Ratio of mass change to production. This ratio a will be negative in this equation.

The positive correlation is viewed while injection rate is correlated to mass change. Mass change will decrease when injection rate is rising. The geothermal reservoir will be sustainable with the recent production if the water injected to the reservoir is increased to about 4 Mt/year (Figure 8). Linear correlation is:

$$I = b(MC) + I_s \qquad (7)$$

where I = Injection rate, I_S = Sustainable Injection, b = Ratio of mass change to injection. This ratio b will be positive in this equation.

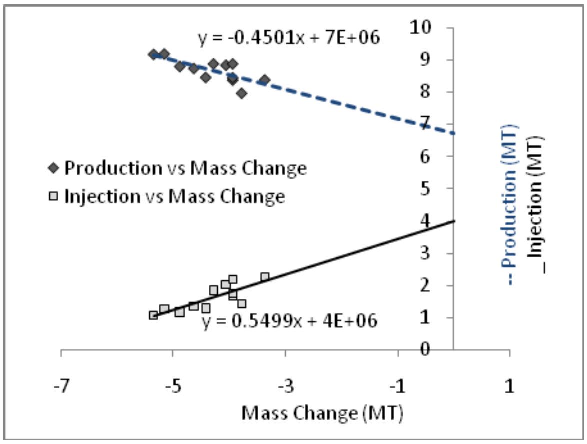

Figure 8: The correlation between production rate and mass change rate, injection rate and mass change rate during exploitation from 1988 to 1999 at the KGF

3.1 Net Production Ratio (NPR)

The net production ratio or NPR is a new term to define a comparison between the net mass produced rate and the natural recharge rate in the geothermal reservoir. The NPR is related to the term of "production ratio" or PR and the rate of PR in the geothermal field, for example 4.75 at Wairakei, can describe sustainability in the geothermal field (O'Sullivan and Mannington, 2005).

$$NPR = \frac{Net\ mass\ produced\ rate}{Natural\ recharge\ rate}$$

$$NPR = \frac{(Mass\ produced\ rate - Mass\ injected\ rate)}{Natural\ recharge\ rate}$$

$$NPR = \frac{\dot{P} - \dot{I}}{\dot{R}} \qquad (8)$$

From the equation 1:

$$\frac{dm}{dt} = \dot{I} + \dot{R} - \dot{P}$$

$$\frac{dm}{dt} = \dot{R}(1 - NPR) \qquad (9)$$

From the above equation, the sustainability of the geothermal field is influenced by the relation of the mass change, natural recharge rate and NPR.

When the NPR is more than one, the negative mass change will be resulted. The (1988-1999) NPR of the KGF can be seen in the Figure 9. The average of NPR at the KGF was about 2.56 and was resulted negative mass change.

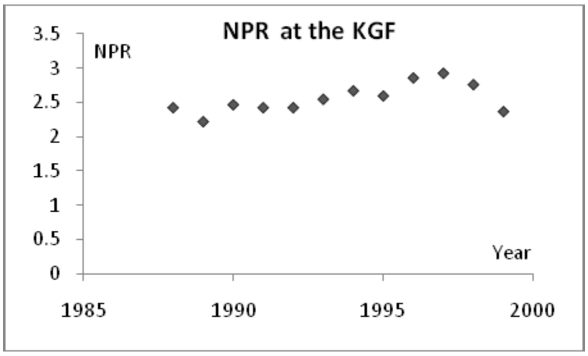

Figure 9: The NPR at the KGF

4. CONCLUSION

Interaction between production, injection and natural recharge rate resulted mass change that can be calculated by repeat gravity measurement method. The Kamojang Geothermal Field has mass decrease of about 20.07 Mt (Million ton) for 6 years or 3.34 Mt/ year. Assuming all the injected water enters to the reservoir, the total rate of the natural recharge to the Kamojang reservoir system is about 2.77 Mt/year and it is assumed almost same when is compared to the previous measurement (1984-1999). The natural recharge rate is much smaller than the net production rate.

Correlation between production rate and mass change rate is negative linear. Mass change will decrease when the production rate is rising. The (1988-1999) correlation between production rate and mass change rate resulted the sustainable production in the KGF is about 7 Mt/year if there is no the water injected adjustment. However if the (1988-1999) average production rate is exploited, about 4 Mt/year of the rate of injection water is needed in order to achieve mass balance in the KGF's reservoir. The average of NPR at the KGF was about 2.56 and resulted a negative mass change. Therefore it is recommend increasing the injection rate and or decreasing the production rate to maintain the sustainable production at KGF.

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