Simulation of Time-Lapse Microgravity in Bandung Area Using Surface and Subsurface Data

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Abstract. Utilization of excessive groundwater extraction, especially in dense urban areas can have an impact on the environment, namely the occurrence of subsidence and groundwater crisis. Non destructive monitoring using geophysics method usually applied in city area to provide information in the near surface and subsurface. The time-lapse microgravity (TLM) technique relatively simple and cheap to be conducted as monitoring method. In principle, TLM will observe changes in a gravity anomaly value at the location due to physical property in the near surface and subsurface. The conditions in the near surface and in the subsurface are considered as two main source of environmentally changes that is subsidence and groundwater level changes. In this study, a program was created to simulate TLM anomalies. The set of prism bodies are used as near surface and subsurface discretization. The program was tested using simple numerical example and then developed to accomodate real data input such as: elevation and groundwater level data in Bandung Area. We calculate the simulation of TLM in Bandung Area using data trend caused by changes in elevation using GPS geodetic survey in the period 2010-2016. We also calculate the simulation of TLM using data trend of groundwater level that occurred in 2010 until 2015. Based on the simulation in six years time-lapse, the largest subsidence produces an anomaly of about 70 μGal. Rough estimation from six years linear trend as an average estimation of one meter elevation change coresponds to TLM anomaly value of 85 μGal. The simulation results due to changes in groundwater level for five years time-lapse show the highest groundwater level rise produces an anomaly 148 μGal and the lowest groundwater level decline produces an anomaly -133 μGal.

Keywords: *computation; groundwater; time-lapse microgravity; simulation; subsidence;*

1 Introduction

At present, the development of new theories and methods for adapting classical theories to the study of objects such as size-dependent and functionally graded micro- and nanoplates, shells, and beams is still relevant. This interest is due to the potentially wide field of application of such objects.

Groundwater is an important component in urban areas. Groundwater can be used in household and industrial scale activities. Continuous and excessive extraction of groundwater has the potential to have an impact on the environment, one of which is land subsidence and groundwater crisis. So it is necessary to monitor groundwater conditions in an area to anticipate the occurrence of adverse impacts on the environment.

The time-lapse microgravity (TLM) method is one of the methods in geophysics that can be used in various monitoring in the subsurface. This method is able to observe changes in the gravitational response at a point due to changes in rock density below the surface. This principle can be used to monitor groundwater conditions in an area considering that groundwater is one of the factors that affect the density value of a rock. The TLM method also has the advantage of being non-invasive and can be done in a relatively fast time. Several study in the recent years (such as: [1]-[8]) show that TLM can be very simple and insightful for monitoring method in the subsurface.

In this study, we attempt to obtain TLM anomalies in Bandung Area using near surface data dan subsurface data. The data trend from several years will be used to create model discritization of two phenomenon, that is subsidence and groundwater level changes in the subsurface. We use the data from GPS geodetic survey to estimate subsidence and we use data trend from groundwater level changes in Bandung Area. Two sources for TLM simulation will be calculated separately, so we can get to understand the characteristic anomalies of TLM in Bandung Area (that is caused by subsidence and groundwater level).

2 Methodology

2.1 Time-lapse microgravity method

TLM is one of the developments in the gravity method with the fourth dimension being time. The principle of this method is the measurement of microgravity repeatedly in a certain time so that it can observe the possibility of changes in the density and geometry of the subsurface source as a function of *x*, *y*, *z*, and *t*. TLM microgravity can be expressed using two observation [9] between two period of times as follow:

$$\Delta g(x, y, z, \Delta t) = g(x, y, z, t_2) - g(x, y, z, t_1) \quad (1)$$

where $\Delta g(x, y, z, \Delta t)$ is the TLM anomaly in an area in the time span Δt, $g(x, y, z, t_2)$ is the response of the gravity anomaly at time t_2, and $g(x, y, z, t_1)$

is the response of the gravity anomaly at time t_1. Gravity anomaly for each observation we can calculate using forward calculation of prism body. Several study ([10]-[11]) use Plouff equation [12] for forward calculation of prism body (the formulation can be seen in equation (2)):

$$g = G\Delta\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \mu_{ijk}\left[z_k arctan \frac{x_i y_j}{z_k R_{ijk}}\right] - x_i \ln\left(R_{ijk} + y_j\right) - y_j \ln\left(R_{ijk} + x_i\right) \quad (2)$$

$$R_{ijk} = \sqrt{x_i^2 + y_j^2 + z_k^2},$$

$$\mu_{ijk} = (-1)^i(-1)^j(-1)^k,$$

$$x_i = x - \varepsilon_i\,, y_j = y - \eta_j\,, z_k = z - \zeta_k.$$

where g is the gravity anomaly, G is the gravitational constant, $\Delta\rho$ is the density contrast, x is the distance from the observation point to the edge of prism in the x-axis direction, y is the distance from the observation point to the prism edge in the y-axis direction, z is the distance from the observation point to the prism angles in the z-axis direction, and R is the resultant distance of prism to the point of observation.

2.2 Simulation of anomalies due to subsidence

Subsidence is a process of sudden subsidence of the earth's surface due to the movement of earth's groundwatererial below the surface [13]. Subsidence can be caused by human activities or by natural events. Land subsidence by human activities occurs due to various events such as fluid extraction, tunnel construction or mining [14]. Natural subsidence occurs due to loading on the sediment layer which will eventually lead to soil compaction. Subsidence caused by human activity is generally faster than natural subsidence [15]. Subsidence that occurs due to the extraction of fluids such as groundwater, oil, or gas has a large subsidence rate, reaching tens of cm/year [14]. In general, the phenomenon of subsidence occurs due to the progressive compaction process of compressible deposits such as sediment layers with high compressibility and porosity and/or high organic content (claystone, siltstone, etc.) [14]

During the subsidence process there will be a change in density which in this case is called a density redistribution. Density redistribution occurs due to subsidence in an area where this subsidence causes the volume of subsurface soil to decrease, resulting in a change in density from time t_1 (before subsidence) to time t_2 (after subsidence). The density redistribution is determined by assuming that mass conservation occurs during the subsidence event so that the mass before and after the subsidence is constant [16]. The density redistribution calculation is written in the following equation:

$$\rho_2 = \frac{v_1 \rho_1}{v_2}, \tag{3}$$

where ρ is the rock density dan v is the volume of rock. In this case it is assumed that the change in volume occurs due to changes in elevation as a result of subsidence so that equation (3) can be rewritten into equation (4) as follows:

$$\rho_2 = \frac{z_1}{z_2} \rho_1, \tag{4}$$

where ρ is the rock density and z the thickness of rock layer.

Figure 1 shows an illustration of simple computational of the TLM anomaly due to subsidence. The area is simulated to form a grid bolcks with the observation point located in the middle of the blocks. Each grid represents a prism body below the surface where the upper limit (z_1) is the elevation and the lower limit (z_2) is the lower limit of the zone experiencing density redistribution due to subsidence. The subsidence phenomenon is simulated with a decrease in elevation on a grid and an increase in density redistribution vertically. TLM anomaly simulation is done by substracting of gravity response in the final condition and in the initial condition.

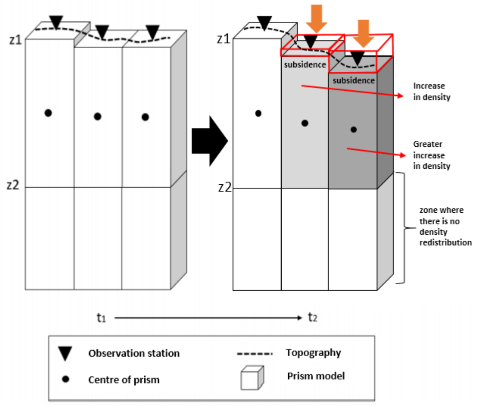

Figure 1 The illustration of subsidence proccess.

2.3 Simulation of Anomalies Due to Changes in Groundwater Level

Groundwater is one of the factors that affect the density of rocks below the surface. Groundwater fills the pores in a rock. Fluctuations in groundwater level will cause changes in rock density. The density of a rock can be calculated by considering the density of the rock matrix and the density of the fluid that fills the pores of the rock. In porous rocks, there is a decrease in density with increasing porosity and decreasing water saturation [17]. The bulk density of porous rock can be known from equation (5):

$$\rho = \rho_m(1 - \emptyset) + \rho_w\emptyset, \tag{5}$$

where ρ is the bulk density of rock, ρ_m is the density of rock groundwaterrix, $\emptyset$ is the porosity of rock, and ρ_w is the density of the fluid that fills the pores of the rock. Furthermore, to determine the value of density changes at different times due to fluctuations in the groundwater level, we can use equation (6):

$$\begin{aligned} \Delta\rho &= \rho_2 - \rho_1, \\ \Delta\rho &= \rho_m(1 - \emptyset) + \rho_{w2}\emptyset - \rho_m(1 - \emptyset) - \rho_{w1}\emptyset, \\ \Delta\rho &= (\rho_{w2} - \rho_{w1})\,\emptyset, \end{aligned} \tag{6}$$

where $\Delta\rho$ is the density change, ρ_2 is the bulk density at the final condition, ρ_1 is the bulk density at the initial conditions, ρ_m is the density of the rock matrix, ρ_{w2} is the density of the fluid that fills the rock pores at the final condition, ρ_{w1} is the density of the fluid that fills the rock pores at the initial condition, and $\emptyset$ is the porosity of rock.

The assumption used in this work is there are no changes in elevation due to subsidence caused by a decrease in groundwater level. In addition, it is also assumed that there is no change in rock volume due to changes in the composition of the constituent fluids. The scheme of the computation can be seen in Figure 2. Similiar to the previous simulation, the area will be divided into a grid with an observation point in the middle of grid block. The prism body in the subsurface shows a model of the groundwater level change. The upper and lower limits of the prism are the groundwater elevation level in the initial and final conditions. TLM anomaly simulation is done by substracting of gravity response in the final condition and in the initial condition.

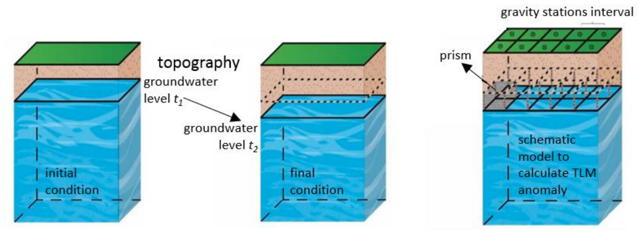

Figure 2 Illustration of ground water level change modeling scheme.

3 Simple numerical example

The simulation using simple numerical example due to subsidence was carried out on synthetic data with an area of 5 km x 5 km with observation points forming a grid with 500 meters spacing. Before the subsidence, it is illustrated that the area has a flat topography with a uniform density value of 2500 kg/m^3. Furthermore, it is assumed that a subsidence phenomenon occurs in several locations which results in a redistribution of density values and changes in the response of the resulting gravity anomaly. In order to make it easier to observe the phenomenon, a cross section is made that shows the topography, density, and gravity anomalies generated along the path before and after the subsidence. Figure 3 shows the created cross-section. Based on the cross-section, it appears that the area experiencing the subsidence phenomenon will experience a decrease in elevation. Due to a decrease in elevation, the area experiences a density redistribution so that the density value becomes higher. The response of the gravity anomaly that is caused is higher in the area that is experiencing subsidence because the density is getting bigger.

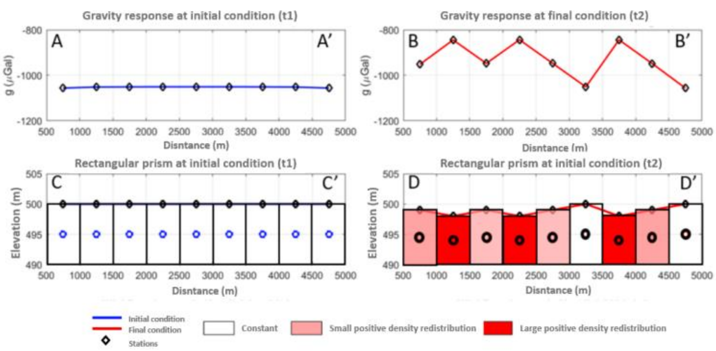

Figure 3 Simple numerical example to illustrate the elevation changes due to subsidence. Plot A-A' is gravity anomaly before subsidence, plot B-B' is gravity anomaly after subsidence, plot C-C' is density distribution before subsidence, and plot D-D' is density distribution after subsidence.

The simulation using simple numerical example due to groundwater level changes was carried out on synthetic data with an area of 5 km x 5 km with a flat topography at an elevation of 1000 meters and the observation points formed a grid with 500 meters spacing. The parameter value of the density of water used is 1000 kg/m^3 with 30% rock porosity. The rock density in the initial state is also uniform with a density value of 2300kg/m^3 at each location. The initial condition is assumed that the groundwater at a uniform level (an elevation of 950 meters). In the final state after the change in the groundwater level, it forms a pattern of distribution of the groundwater level which deepens towards the positive x axis with a range of groundwater levels from the initial conditions ranging from -20 meters to 20 meters. In order to make it easier to observe the simulation results of the groundwater level change phenomenon, a cross-section is made which can be seen in Figure 4. Based on the cross-section it appears that areas experiencing an increase in groundwater will experience an increase in density so that the TLM anomaly response generated is positive. While the area with a decrease in groundwater level will experience a decrease in density so that the TLM anomaly response generated is negative.

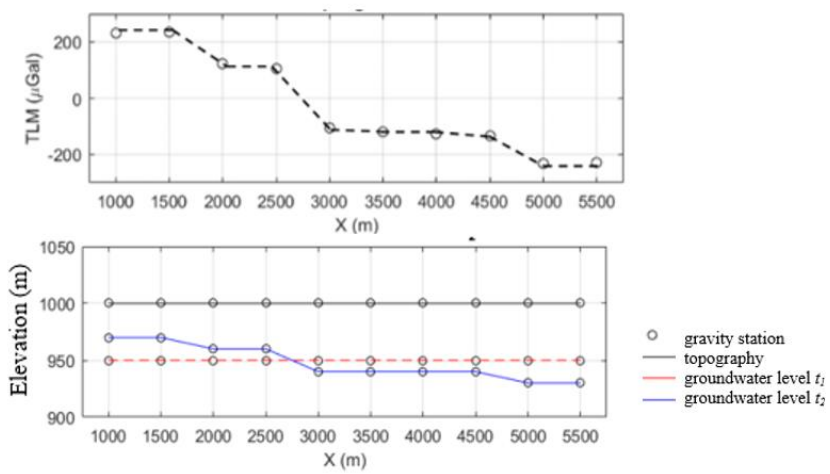

Figure 4 Line section of simple numeric example for simulation groundwater level change.

4 Simulation using data trend in Bandung Area

The application of the program to field data is carried out for the Bandung area. The simulations carried out include simulations of TLM calculations due to subsidence and simulations of TLM calculations due to changes in groundwater level. To carry out the simulation process, elevation data and groundwater level data in the Bandung area are needed in several time periods. In this study, the elevation data used came from a GPS geodetic survey from the ITB Geodetic Scientific Reasearch Group conducted in 2010-2016. Meanwhile, groundwater level data was obtained from digitizing the research map of Taufiq et al. [18] with time period of 2010 and 2015.

4.1 Simulation of subsidence data in Bandung area

The coverage area of the data that will be used to simulate the TLM due to subsidence is shown in Figure 5. The simulation process is carried out with the aim of knowing the effect of subsidence on the TLM anomaly that will be caused. So to achieve this goal, it is necessary to calculate the value of subsidence and microgravity timelapse. Calculation of subsidence is done by subtracting the elevation data at a time with the measurement data of the previous period. The time range for measuring elevation data was from 2010 to 2016. In this study, the calculation of subsidence data based on elevation data was carried out at a time that corresponded to the time of observation of gravity data that had been carried out.

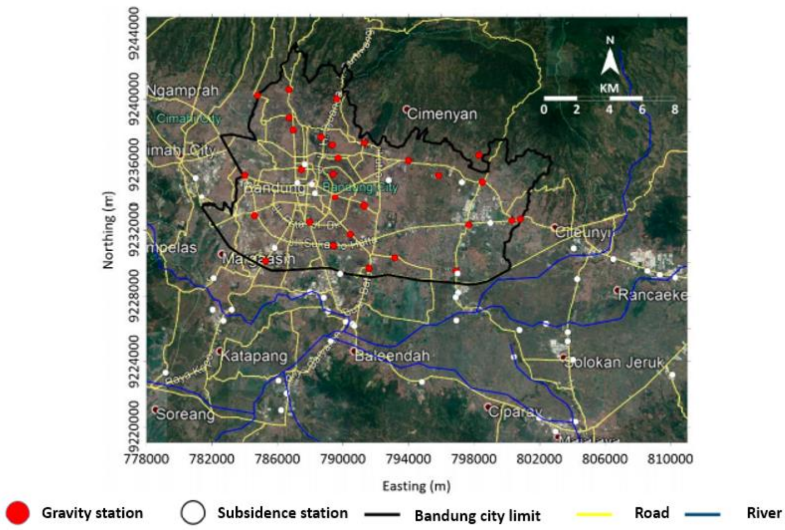

Figure 5 Map of Bandung Area overlayed with gravity observation stations and GPS geodetic observation stations.

Based on the simulation, it can be determined the average annual subsidence rate in the Bandung area in 2010-2015. Figure 6 shows a map of the average subsidence rate of the Bandung area. The highest subsidence rate on the west side forms an elongated contour to the east with the highest subsidence rate reaching 0.3 meters per year. Meanwhile, the uplift that occurs on the south and north sides has the highest rate of 0.09 meters per year.

The calculation of TLM anomaly is simulated with a time lapse that corresponds to the time range for calculating subsidence data. Based on the simulation process, it can be seen that the area experiencing subsidence has a relatively higher TLM anomaly value. The highest TLM anomaly value which reached around 70 microGal occurred for a period of six years. Meanwhile, the lowest TLM anomaly occurred in the uplifted area with the lowest anomaly value reaching -15 microGal. Illustrations related to the TLM anomaly results from the simulation results can be seen in Figure 7. In Figure 7 shows the simulation that coresponds to gravity survey in August 2010, June 2015, February 2016, and August 2016. Figure 8 shows the crossplot between elevation changes and TLM anomaly values. Based on the results of linear regression of the data, it can be seen that every 1 meter elevation change estimated roughly in the study area for an anomalous response of about 85 microGal.

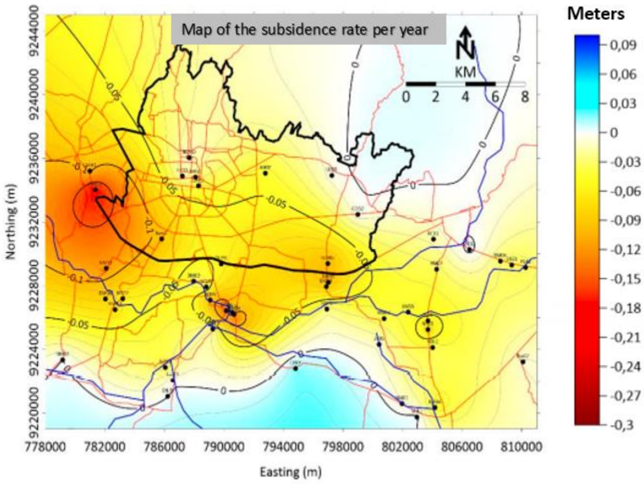

Figure 6 Map of the average annual subsidence rate for the Bandung area.

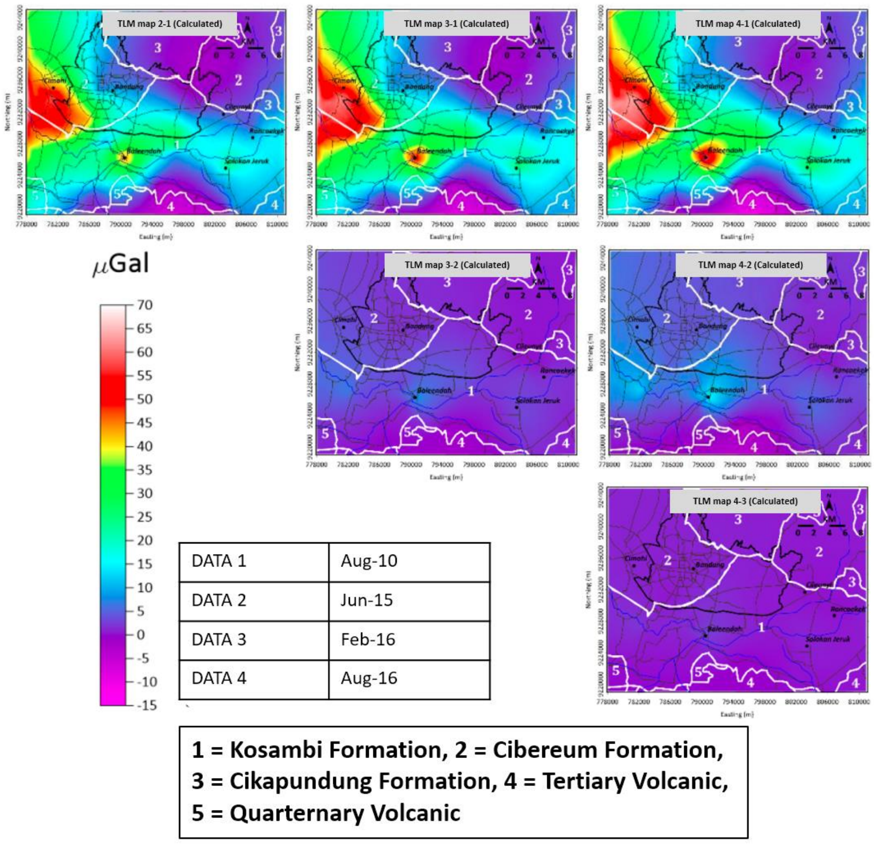

Figure 7 Map of TLM anomaly simulation results due to subsidence in the Bandung area.

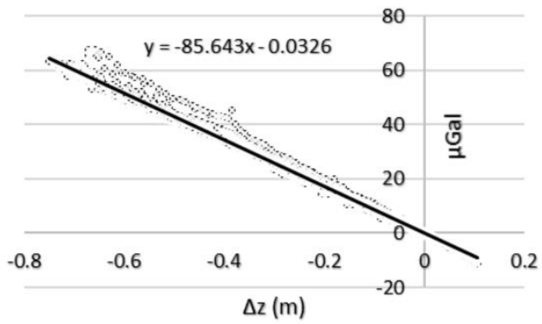

Figure 8 Regression graph between the magnitude of the subsidence and the resulting TLM anomaly.

4.2 Simulation of groundwater level changes in Bandung area

The data trend for Bandung Area for this study was digitized, so the groundwater level in 2010 and 2015 roughly estimated to provide the changes for five years of time-lapse (2010 until 2015). Figure 9 shows the groundwater level maps in 2010 and 2015. Based on the map, it can be seen that the groundwater pattern in the research area has a low level of elevation in the south and a higher elevation in the north. Based on the data, the lowest groundwater elevation is at an elevation of about 600 meters and the highest elevation is about 1000 meters.

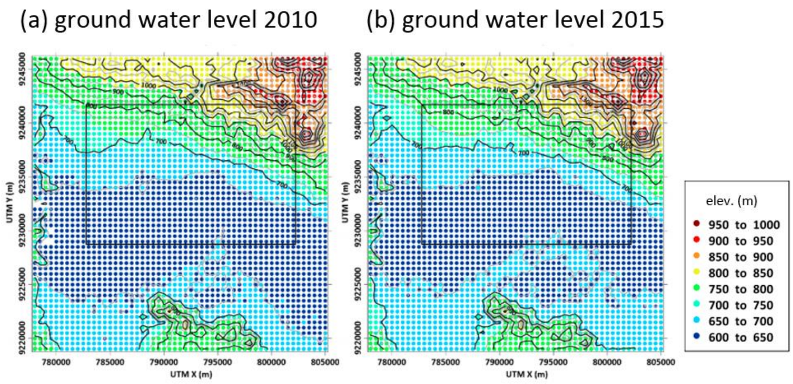

Figure 9 Groundwater level maps from digitizing the research map of Taufiq et al. [18] for (a) 2010 and (b) 2015. Black rectangular shows coverage area same as Figure 6.

Based on the digitized groundwater data, the average annual rate of change in groundwater is calculated. Figure 9 (a) shows a map of the average annual rate of change in groundwater. The increase in groundwater occurred in the southern area of the study area at a rate of up to 3 m/yr, while in the central to northern areas the study area experienced a decrease in groundwater at a rate of up to 10 meters. Meanwhile, the rate of change in the average groundwater per year is greatest in the Southwest side of the study area at a rate of about -2 m/yr.

TLM simulations are carried out based on 2015 and 2010 groundwater data from digitized data. Figure 9 (b) shows a map of the simulation results of changes in density and TLM in 2015-2010 from digitized data. Areas that experienced an increase in groundwater were simulated with a density contrast of 300 kg/m^3 while areas that experienced a decrease in groundwater were simulated with a density contrast value of -300 kg/m^3. TLM simulation results show that the area with an increase in groundwater has a positive TLM anomaly with the highest anomaly value reaching 148 μGal. While the area with decreased groundwater has a negative TLM anomaly with the value in the area of the lowest decrease in groundwater reaching -133 μGal.

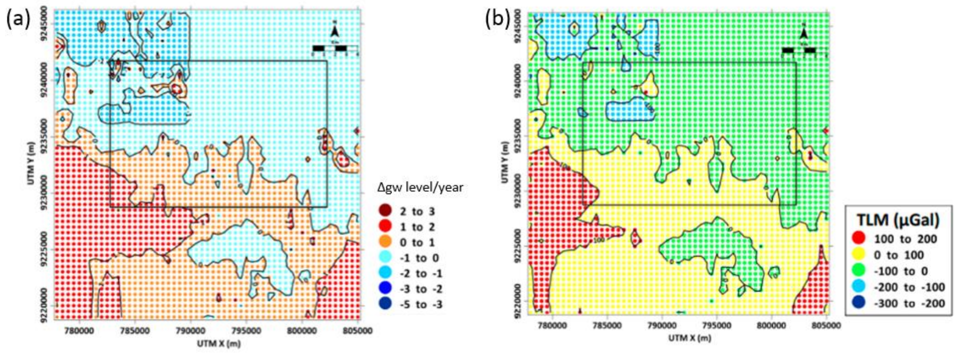

Figure 10 a) Map of the average rate of change in ground water level/year, b) Map of the TLM anomaly from the simulation. Black rectangular shows coverage area same as Figure 6.

5 Conclusion

This research has succeeded in compiling a simulation program for TLM anomaly responses caused by subsidence phenomena and changes in groundwater level. The program that has been compiled is still simulating the anomalous response due to each phenomenon separately so that there are two kinds of simulation programs.

The simulation results of the anomaly response due to the subsidence phenomenon in the city of Bandung Area indicate that positive anomalies will arise in areas that experience subsidence. In a period of 6 years, the largest subsidence produces an anomaly of about 70 μGal and the scattered uplift produces an anomaly of about -15 μGal. Based on the crossplot between the anomalous data and the magnitude of the subsidence, inforgroundwaterion is obtained that a change in elevation of 1 meter will produce an anomalous response of about 85 μGal.

The simulation results of anomaly responses due to the phenomenon of groundwater level changes in Bandung City indicate that positive anomalies will arise in areas experiencing groundwater level rise. In a period of 5 years, the largest groundwater level rise resulted in an anomaly reaching 148 μGal and the largest groundwater level decrease producing an anomaly reaching -133 μGal.

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