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Using a Time Lapse Microgravity Model for Mapping Seawater Intrusion around Semarang

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Abstract. A modeling of time-lapse microgravity anomaly due to sea water intrusion has been conducted. It used field data of aquifer cross section, aquifer thickness and lithology of research area. Those data were then processed using Grav3D and Surfer. Modeling results indicated that the intrusion of sea water resulting in a time-lapse microgravity anomalies of 0.12 to 0.18 mGal, at soil layer density of 0.15 g/cm^3 to 0.3 g/cm^3 and at depth of 30 to 100 m. These imply that the areas experiencing seawater intrusion were Tanjung Mas, SPBE Bandarharjo, Brass, Old Market Boom and Johar as the microgravity measured there were in the range of 0.12 to 0.18 mGal and the density contrast were at 0.15 g/cm^3 to 0.28 g/cm^3. Areas that experienced fluid reduction were Puri Anjasmoro, Kenconowungu and Puspowarno with microgravity changes from -0.06 mGal to -0.18 mGal.

Keywords: time-lapse microgravity, anomaly, seawater intrusion
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INTRODUCTION

Recent studies on the relationship between changes in the value of gravity and hydrological data show that short-term changes due to rain give a correction of 10 mGal and seasonal changes provide a value of 5-10 mGal [4]. Correction of measurement results of time-lapse microgravity in Oguni geothermal area in Japan using rainfall data and water depth table show groundwater level is maximum in the rainy season and decreases along the change of seasons [5]. Microgravity measurements using superconducting gravimeter were conducted in Kyoto and Bandung to determine the effect of changes in precipitation, pressure, and ground water level on gravity. Results showed microgravity value of 9 μGal due to a 210 mm rainfall in Kyoto from 11 to 13 September 2000 gravity values of 4.2 to 4.4 μGal due to a 1 m groundwater level rise in Bandung [6]. Time lapse microgravity survey applies the following equation:

$$(g_{obs(2)} - g_{obs(1)}) = \left(G\int_0^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{\Delta\rho(\alpha,\beta,\gamma,\Delta t)(z-\gamma)}{\left[(x-\alpha)^2 + (y-\beta)^2 + (z-\gamma)^2\right]^{3/2}} \, d\alpha\beta d\gamma \right) + c_1(h_2 - h_1) \quad (1)$$

Equation (1) shows measured gravity ($g_{obs(2)}$ - $g_{obs(1)}$) caused by subsurface density changes associated with fluid dynamics and subsidence. Based on the equation, there is one source that should be reduced to obtain the desired source anomalies. This study modeled a time-lapse microgravity anomaly due to intrusion of sea water. The results obtained were compared with measurement results to determine the seawater intrusion zone at the study site. For modeling purposes this study uses Grav3D 2.0 developed by UBC Geophysical Inversion Facility, Department of Earth and Ocean Sciences, University of British Columbia. The concept of 3D gravity inversion method is

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described as follows [9]: Vertical components of the gravity field from i^{th} observation and the location r_i are expressed by equation follow:

$$F_z(r_i) = \gamma \int \frac{\rho(r)(z - z_i)}{|r - r_i|^3} \tag{2}$$

where ρ (r) is the mass distribution anomaly, γ is Newton's gravitational constant. This equation determines ρ directly from a given gravity data F_z. Errors and mismatches are given by equation the following equation:

$$\varphi_d = \left\| W_d (d - d^{obs}) \right\| \tag{3}$$

where $d^{obs.}$ is $(F_{z1},......,F_{zN})^T$ data vector, d is the data prediction, W_d is the diagonal $1/\sigma_1$ …… $1//\sigma_N$ and σ_1 is the standard deviation for i^{th} datum. Accepted model is the model that led to a fairly small φ_d. In order to obtain a model, we define the objective function of density and minimize the number of subjects to reduce errors between observed data and those generated by the model. An objective function is a function that requires a model with reference density (ρ_0) by selecting the following objective functions:

$$\varphi_m(\rho) = \alpha_s \int_v w_s \{w(z)[\rho(r) - \rho_o]\}^2 dv + \alpha_x \int_v w_x \left\{ \frac{\partial w(z)[\rho(r) - \rho_o]}{\partial x} \right\}^2 dv + \tag{4}$$

$$\alpha_y \int_v w_y \left\{ \frac{\partial w(z)[\rho(r) - \rho_o]}{\partial y} \right\}^2 dv + \alpha_z \int_v w_z \left\{ \frac{\partial w(z)[\rho(r) - \rho_o]}{\partial z} \right\}^2 dv$$

where the functions w_s, w_x, w_y, and $w_z$are functions of spatial weights α_s,α_x,α_y,α_z which themselves are coefficients that affect the relative components of different objective functions. w_z is a weighting function of depth. Equation (4) can be used to build many different models. Model reference density (ρ_0) can be estimated from previous investigations, but can also be the model of zero. w_s function controls the final model against the reference model that can be omitted should it be deemed unnecessary. The functions w_x, w_y, w_z can be designed to improve the structure of some regions in the model domain. Reference model and the four 3-D weighting functions can be `coupled with some other information such as density contrast, other geophysical survey data and geological understanding of the interpreter and its relationship with density. If this is done, the resulting models will not only has a small error but also represent a model of the earth.

Numerical solution to inversion problem is obtained by making the problem discrete. This is done by dividing the area source into multiple cells with 3-D mesh and assuming a constant density value in each cell. Forward modeling of the gravity data as defined in equation (2) can be written in the form of the following matrix equation:

$$d = \overline{G}\rho \tag{5}$$

where $\rho = (\rho_1, ... \rho_M)^T$ is the vector density cells. Matrix $\overline{G}$ has elements G_{ij} that show the contribution of the i^{th} datum of a unit density in the j^{th} cell. The model objective function in equation (4) can be rewritten as follows:

$$\varphi_m(\rho) = \left\| W_{\sim\rho}(\rho - \rho_o) \right\|^2 \tag{6}$$

where $W_{\sim\rho}$ is a weighting matrix and along with the model coefficients and the weighting function is used to define the equation (4). Inversion problem is then solved by generating a ρ model that minimizes φ_m.

METHOD

The study area is made into a model using in two steps; the initial model and the intrusion model. The initial model is made by creating a layer of rock within a mesh that is tailored for beddings in Semarang aquifer cross-section map (Fig. 1). Rock types in this model are clay, sand and sandstone. The three types of rocks are taken based on the geological map of Magelang - Semarang. The density of clay, sand and sandstone, is 1.8 g/cm^3 [10], 2.0 g/cm^3 and 2.35 g/cm^3 [11] respectively. The initial model is regarded as a model that has not experienced seawater intrusion. At a depth of 0-2 m there is a layer of clay with a density value of 1.8 g/cm^3, there is a clay layer under the sand with a density of 2.0 g/cm^3 at a depth of 2-7 m and this also evident in layers up to a depth of 78 m. There is a layer of sandstone at a depth of 78-103 m with a density of 2.35 g/cm^3.

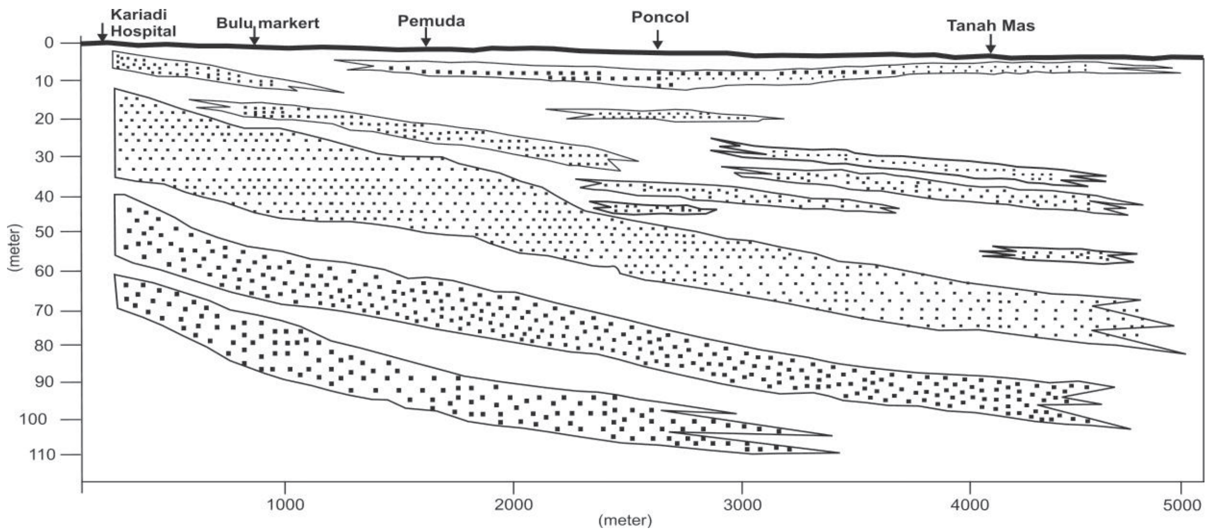


FIGURE 1. Cross-section of the North-South aquifer system in Semarang

The second model is a model of intrusion. Intrusion models are basically the same as the initial model, the difference is the presence of sea water intrusion input. Intrusion in this model is made along the 40-100 m on the x-axis at a depth of 47-103 m. The value of the density of rocks that intruded seawater is 3.4 g/cm^3, this value is assumed as a result of the addition of the density of sea water which has a density value of 1.05 g/cm^3 [11].

RESULTS AND DISCUSSION

Modeling results as mentioned consists of (1) the mesh model for the study area. The input cell size for the study area is modeled in a10,000 cells (20 x 20 x 25) mesh. The maximum depth is 100 m (Fig. 2).

Initial model shown in Figure 3a and the intrusion model in Fig. 3b. The initial model assumes no seawater intrusion. Gravity contour map of the early model had a minimum value of 1.8 mGal and a maximum value of 3.4 mGal. The intrusion model has the same value of 1.8 mGal but its maximum is 3.5 mGal. This difference of 0.1 mGal is caused by seawater intrusion. If this model is implemented to a microgravity anomaly data, a gravity anomaly due to seawater intrusion is then obtained. Therefore interpretation of field data will be easier.

Gravity anomaly values before and after seawater intrusion is the difference in gravity values at the same point. Gravity anomaly contour map before and after intrusion is shown in Fig. 4. It shows a gravity anomaly of 0.13 to 0.18 mGal caused by seawater intrusion ranging from 40 m to 100 m. This corresponds to a model where the location of intrusion is 40 m to 100 m on the x axis.

Determination of density contrast changes due to changes in the seawater intrusion is done with Grav3D. The results show that time-lapse microgravity anomaly starts at a depth of 10 m, 20, 30 m, 40 m, 50 m, 70 m, 80 m and 90 m, as shown in Fig. 5. The value density contrast caused by seawater intrusion at those depths is between 0.15 to 0.3 g/cm^3.

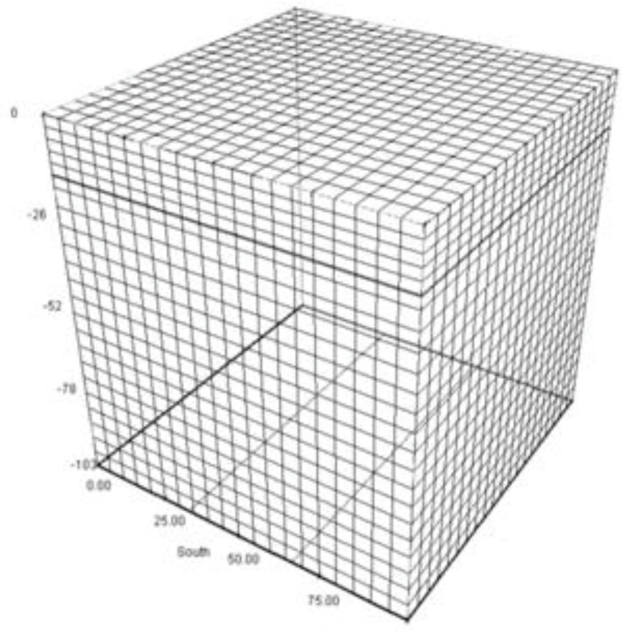
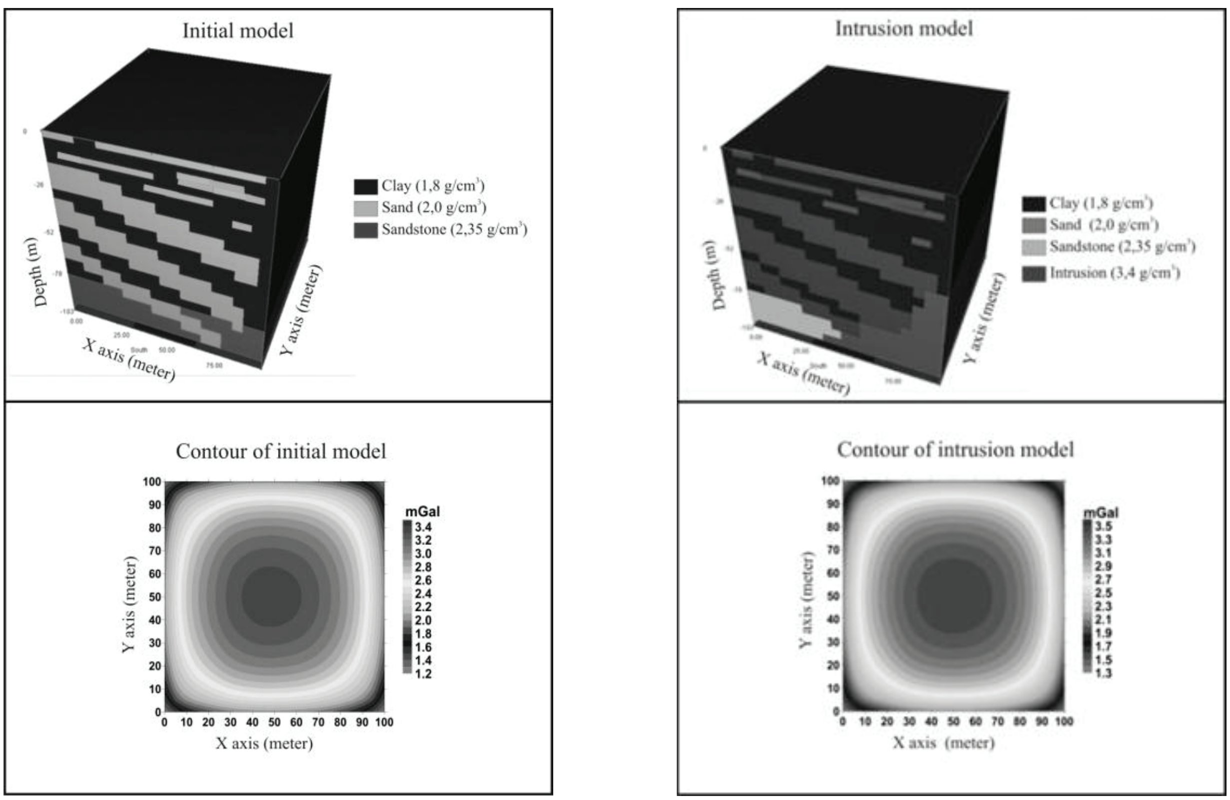


FIGURE 2. The mesh used in modeling



(a) (b)

FIGURE 3. (a) Initial model before seawater intrusion and (b) model after seawater intrusion

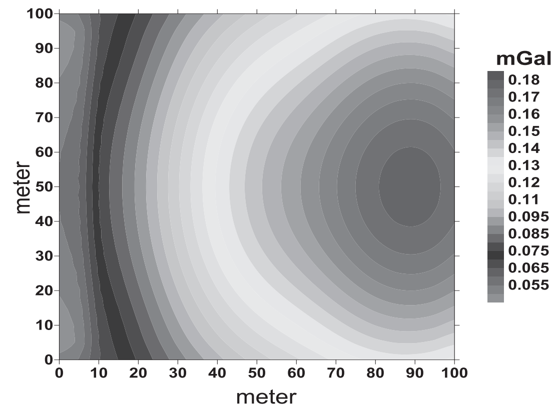


FIGURE 4. Gravity anomaly based on intrusion model

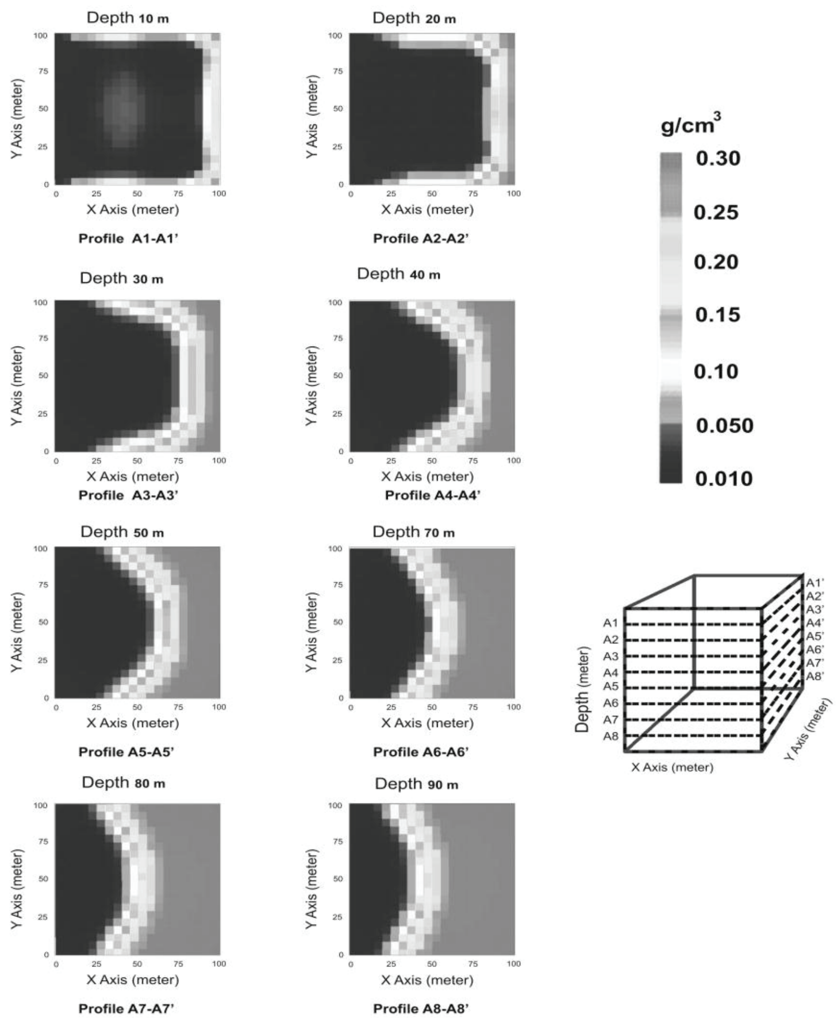
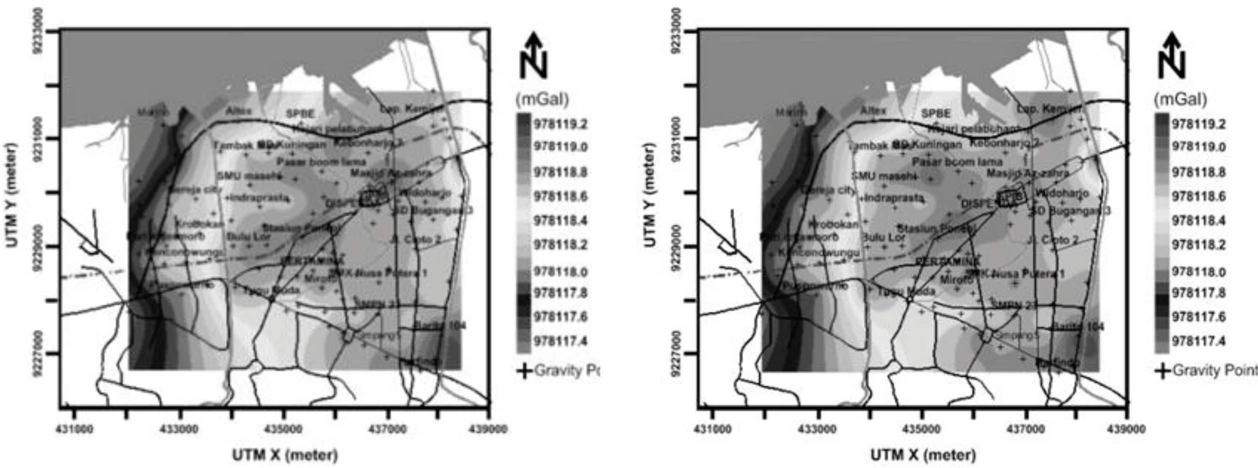


FIGURE 5. Contrast density value due to seawater intrusion at a depth of 10-90 m

Implementation of data from gravity measurements in Semarang during May and October 2013 is given in Fig. 6(a) and Fig. 6(b). Measurements were performed using a gravimeter Scintrex CG-5 Autograv. The number of measuring points is 120 in northern Semarang area. Initial corrections include drift and tidal corrections, whereas topographic correction was not done because the study area is flat.



(a) (b)

FIGURE 6. Gravity anomaly in (a) May and (b) October 2013

Results of gravity observations in May 2013 showed a maximum value of 978,119.2 mGal and a minimum value 978117.4 mGal. Research areas gravity values of 978,118.6 to 978,119.2 mGal are Kemijen, Pelabuhan Tanjung Mas, Kebonharjo, Widoharjo, Jl Cipto, SPBE Bandarharjo, Tambak Mas, Kuningan, Indraprasta, Bulu Lor, Poncol, Tugumuda, Simpang Lima, SMK Nusa Putera 1 and Jl. Barito. The areas with relatively high gravity values include Marina, Puri Anjasmoro, Kenconowungu, Puspowarno, Tanah Mas and Krobokan from 978,118.4 to 978,117.4 mGal.

Gravity data observations in October 2013 showed almost the same result as in May 2013. The maximum value of gravity observations in October 2013 is from 978,119.2 to 978,117.4 mGal. They are obtained from points in the North and East of Semarang. The western part of the study area shows the same minimum values as that of May 2013.

Microgravity anomaly is obtained by subtracting the time between observed gravity data in October 2013 to the one in May 2013 (Fig. 7). Positive anomaly values are due to subsidence, groundwater recharge and seawater intrusion, while minus anomaly values indicates a reduction in ground water level.

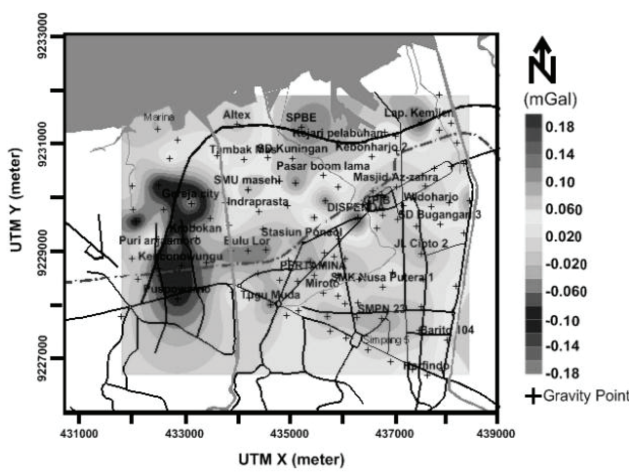


FIGURE 7. Time-lapse microgravity anomaly from May to October 2013

Figure 7 shows that (+) anomaly values of 0.02 to 0.18 mGal are observed in Bandarharjo, Kemijen, Pelabuhan Tanjung Mas, Kuningan, Bugangan, Johar and Jl Barito. This is presumably due to land subsidence and seawater intrusion. Further south, (+) anomaly values are smaller. It is presumably because of land subsidence and less intrusive waters than other areas. Minus (-) anomaly values are observed in Puri Anjasmoro, Krobokan, Kenconowungu, Bulu Lor and Puspowarno. Minus (-) anomaly values are due to a decrease in ground water level.

Figure 8 shows that at a depth of 20 to 50 m, the dominant density contrast value is between -0.007 to 0 g/cm^3. A depth of 50 m has an apparent density contrast of 0.09 g/cm^3. A depth of 60 m to 90 m has a density contrast value of 0.13 g/cm^3 to 0.28 g/cm^3. The value of 0.28 g/cm^3 was observed in Kemijen and lower density contrast was observed in its neighboring South-West area.

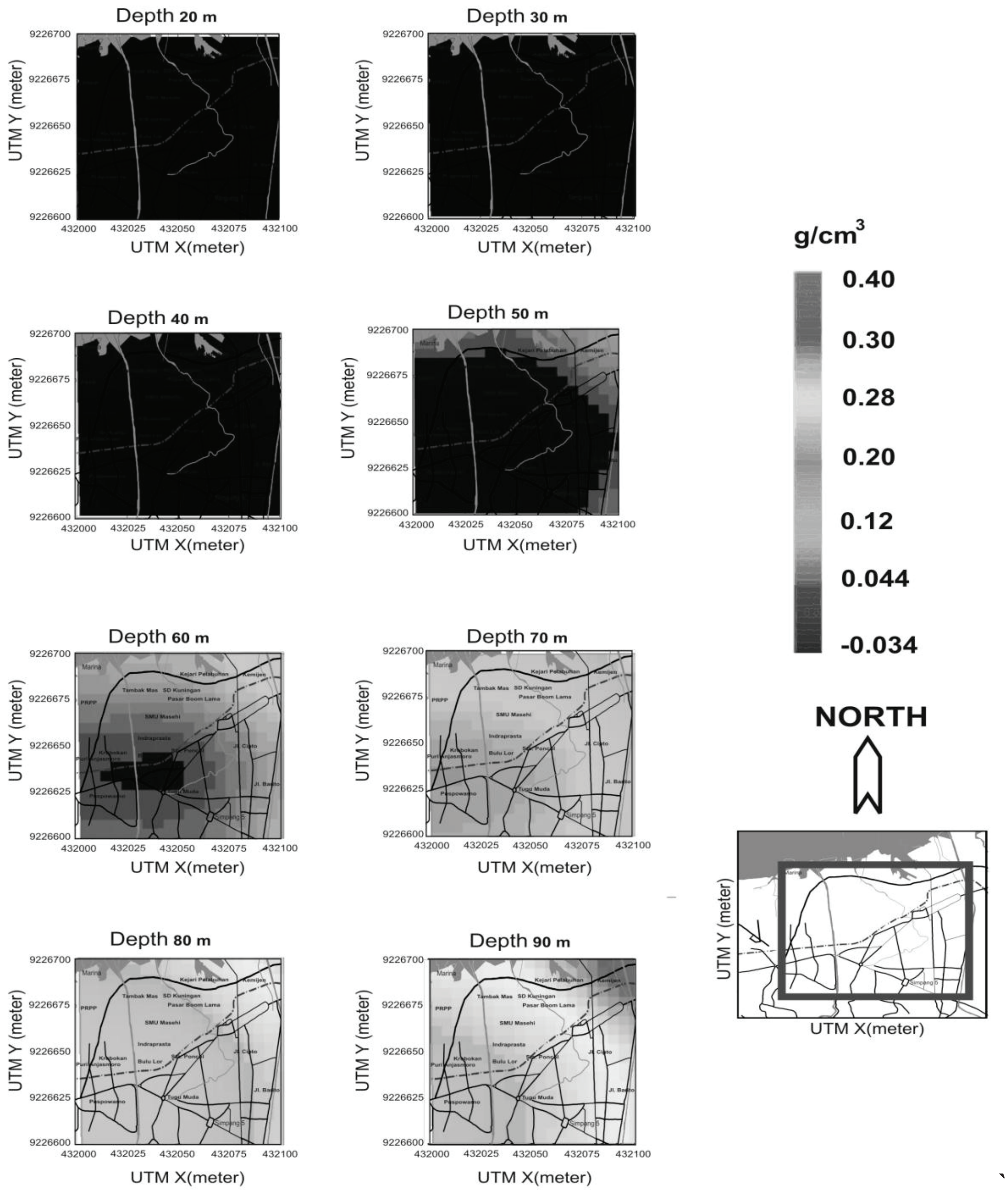


FIGURE 8. Change in density contrast at various depths

The aquifer at the study site at a depth of 60 m to 90 m has a sea water intrusion. Seawater intrusion moves from northeast to southwest. The areas located in the northeast are Kampung Laut, Kemijen and more areas southwestward. The areas in the South are Pelabuhan Tanjung Mas, SPBE Bandarharjo, Kebonharjo, Tambak Mas, Altex Tanah Mas, Kuningan and Barito. These areas experienced increased contrast density of 0.13 g/cm^3 to 0.28 g/cm^3. Those results are in line with the ones found in 2013 for areas of STM Perkapalan, PRPP, Tanjung Mas and PT. Panca Jaya. STM Perkapalan has a high chloride concentrate of 2,020.0 mg/L that exceed the safe threshold due to low ground water potential at shallow aquifer and non-aquifer structures underneath it. This is also due to population density in the area. PRPP has a high concentrate of chloride at963.0 mg/L. This is caused by population density that has increased since 2008 [12].

CONCLUSION

Forward modeling results show changes in gravity from of 0.13 mGal to 0.18 mGal and changes in density contrast from 0.15 g/cm^3 to 0.3 g/cm^3 due to sea water intrusion. Correlations of both modeling result and measured data indicate that the regions experiencing seawater intrusion include Tanjung Mas, SPBE Bandarharjo, Kuningan, Pasar Boom Lama and Johar, with observed gravity values of 0.12 to 0.18 mGal and density contrasts of 0.15 g/cm^3 to 0.28 g/cm^3. The areas experiencing ground water level reduction cover Puri Anjasmoro, Kenconowungu and Puspowarno with gravity values of -0.06 mGal to -0.18 mGal.

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