Groundwater Change Detection by Gravity Measurement on Northern Coast of Java: A Case Study in Semarang City of Central Java of Indonesia

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Abstract. Northern part of Semarang city is affected by tidal flood due to land subsidence. Land subsidence is triggered by soil compaction and massive groundwater extraction. One of famous methods in analysing groundwater is gravity method. This research aim to present groundwater change in Semarang city based on gravity measurement and to analyze problems related to equipment and groundwater behaviour. Gravimeter Scintrex CG-5 was applied for gravity measurement. Geographic coordinates were measured using GNSS receiver namely TopCon HiperII. This research occupied SRTM90 Plus and regional geology map at 1:100.000 scales. Groundwater change was detected by differentiating simple Bouguer anomaly of 2014 and 2016. Data in gravity unit were then converted by coefficient of 0.012 mgal per meter. Simple Bouguer anomaly in 2014 ranged from -3.423 mgal to 19.874 mgal, while 2016 data ranged from -3.427 mgal to 19.835 mgal. Discrepancy of gravity anomaly ranged from -0.326 mgal to 0.209 mgal. The data confirmed that groundwater change ranged from -27.160 m to 17.408 m. Groundwater depletion occurred commonly on alluvial plain in northern area, while recharging could be found in some locations in southern part. This research concluded that gravity measurement had potential to be applied for groundwater detection in coastal areas.

1. Introduction
Java Island is located on the meeting plate of the Euroasia Plate with the Australian Plate. Java Island has a narrow and elongated shape that can be divided into three zones, namely the southern zone, the middle zone, and the northern zone [1]. The Southern Zone consists of folded hills and mountains stretching along the southern coast of Java. The Central Zone consists of rows of volcanoes and fluvial volcanic plain. The Northern Zone is generally dominated by the alluvial plain with a sloping topography. Major cities in the northern coast of Java region generally grow on the alluvium plain.

The alluvium plains in the region were formed from the erosion and sedimentation process by the river and coastal streams. The compositions still allow consolidation or compaction of upper soil layers [1]. On going soil compaction and groundwater extraction lead to land subsidence in northern part of the city [2]. The alluvium plain in the northern part of Semarang reaches around 40% of the area, while in the southern part it is dominated by volcanic rocks and several fault structures [3]. The thickness of the alluvium layer can reach 50 m or more [4].

Semarang City is a proper case study area to study natural and socio-economic phenomena in the northern coast of Java. The Terboyo Industrial Zone and Wijaya Kusuma Industrial Zone which are located in northern part of the city have an important role in socio-economic development, both
regionally and nationally. Contrary, the industrial activities have a strong correlation to the occurrence of land subsidence and decrease in groundwater quantity and quality [5]. Due to low capacity of regional water supply company, industries occupied deep wells for groundwater extraction. At present, there are more than 1000 registered wells operating in the city [6]. On the alluvial plain in the northern part of Semarang City, massive groundwater extraction leads to sea water intrusion.

Groundwater investigation are usually carried out by geo-electric or seismic methods. In the case of large groundwater reservoir, the gravity method may be applied [7]. The complicated problem in applying gravity method is the phenomena of land subsidence and groundwater fluctuations that affect the gravitational value recorded by gravimeter [8]. Based on the free air approach, land subsidence will give a positive impact on the value of gravity, while a decrease in the groundwater level has a negative impact on the value of gravity [9]. Another problem in groundwater research in the city of Semarang is the occurrence of seawater intrusion and tidal flood infiltration filling groundwater reservoir in the alluvial region. Another problem that must be considered in groundwater research is seasonal variations that affect groundwater level fluctuations. This study aims to detect changes in groundwater in the city of Semarang based on topographic, geomorphological, and seasonal variations as a case study for investigating groundwater change of northern coast of Java.

2. Method of research

2.1. Data collection
Groundwater changes were detected by gravity measurements on common points in two periods. The first period was September 2014, while the second period was March 2016. Both periods applied Scintrex CG-5 Gravimeter which has ± 5 μgal accuracy. Applying International System of Units, 1 μgal or 1 microgal as gravity unit is equal to 10^-8 m.s^-2 while 1 mgal or 1 milligal is equal to 10^-5 m.s^-2. Gravity measurement was carried out on 50 common points in Semarang City. Overlaying observation stations to topography map can be seen in figure 1 while figure 2 shows geological formation below the stations. The geographic positions of the gravity points were measured by TopCon HiperII GNSS receiver applying rapid static method to obtain centimeter-level accuracy [9]. This study also occupied topographic data from SRTM90 Plus and actual rock density data [10].

![Figure 1. Map of gravity data and topography in Semarang city.](image1)

![Figure 2. Map of gravity data and geology in Semarang city.](image2)
from previous interpretation of geological map and gravity data (war). Density of alluvium, volcanic rock, Damar formation, Kaligetas formation, Kalibeng formation, Kerek formation, and basement were 1.85, 2.00, 2.20, 2.30, 2.45, 2.60, and 2.85 g.cm\(^{-3}\) respectively [10].

2.2. Gravity reduction

Gravity measurements in 2014 and 2016 refered to the absolute gravity point in Department of Geophysical of Universitas Diponegoro. It is located at 7.048383836 S, 110.4424687 E and 212.707 m above the WGS84 reference ellipsoid. The absolute gravity value of the point is 978078.22865 mgal. Earth tide effect was corrected automatically inside the gravimeter using Longman formula [11].

This study implemented Bouguer anomaly to predict changes in groundwater which based on reduction of terrestrial gravity data by normal gravity in ellipsoid, free air, and Bouguer plates [12]. This study did not use terrain reduction differentiation because this study assumed that the effects of terrain changes during the study period were relatively small and could be ignored. Gravity anomaly (\(\Delta g\)) is calculated by equation (1) as follow

\[
\Delta g = g - \gamma
\]

where \(g\) is actual gravity on surface of the earth, \(\gamma\) is normal gravity on ellipsoid at measurement point. Normal gravity is computed using formula of Somigliana [13] as shown by equation (2) as follow

\[
\gamma = \left( a \gamma_a \cos^2 \varphi + b \gamma_b \sin^2 \varphi \right) \left( a^2 \cos^2 \varphi + b^2 \sin^2 \varphi \right)^{-1}
\]

where \(\gamma_a\) is normal gravity at equator, \(\gamma_b\) is normal gravity at pole, \(a\) is semi-major axis, and \(b\) is semi-minor axis. The constant of WGS84 parameter can be seen in table 1.

| Symbol | Value          | Description            |
|--------|----------------|------------------------|
| a      | 6378137 m      | Semi-major axis        |
| b      | 6356752.3142 m | Semi-minor axis        |
| \(f\)  | 1/298.257223563| Geometrical flattening |
| \(m\)  | 0.00344978650684 | Physical flattening |
| \(GM\) | 3986004.418 \(10^8\) m\(^3\).s\(^{-2}\) | Geocentric gravitational constant of the earth |
| \(M\)  | 5.9733328 \(10^{24}\) kg | Mass of the earth |
| \(\gamma_a\) | 9.7803253359 m.s\(^{-2}\) | Normal gravity at equator |
| \(\gamma_b\) | 9.8321849378 m.s\(^{-2}\) | Normal gravity at pole |

Effect of elevation on gravity data must be reduced using free air reduction [13]. Free air reduction (FA) is derived from gravity gradient against elevation change as shown by equation (3) below

\[
FA = \frac{\partial \gamma}{\partial h} = \frac{2 \gamma_a}{a} \left( 1 + f + m - 2 f \sin^2 \varphi \right) h - \frac{3 \gamma_a}{a^2} h^2
\]

where \(f\) is geometrical flattening, \(m\) is physical flattening, \(\varphi\) is geographic latitude of measurement point, \(h\) is elevation above reference plan. For this research, free air effect is computed using elevation above WGS 84 ellipsoid reference. Geometrical and physical constant of WGS 84 can be found in table 1.

Effect of mass below observation point is reduced using Bouguer reduction [13]. Formula for computing Bouguer reduction (B) can be seen in equation (4) below

\[
B = 2 \pi G \rho h
\]
where $G$ is gravitational constant of the earth, $\rho$ is rock density, $h$ is elevation or thickness of bouguer plate. Formula of simple Bouguer anomaly is shown in equation (5) below [13].

$$\Delta g_B = g - \gamma + FA - B$$  \hspace{1cm} (5)

2.3. Conversion of gravity anomaly to groundwater

Gravity measurements at the same point in different periods may give different value of gravity. In this study, changes in the value of gravity were identified due to changes in the depth of groundwater level. The effect of changes in groundwater level on gravity was calculated by modifying equation (4) into equation (6) as follow

$$\Delta B = 2\pi G \rho \alpha \Delta h$$  \hspace{1cm} (6)

Using the WGS 84 reference ellipsoid, the change effect is calculated by the following equation (7)

$$\Delta B = 0.04192769 \rho \alpha \Delta h \text{ mgal}$$  \hspace{1cm} (7)

With the assumption of rock porosity of 30% and standard density of 2.67 g.cm, the gravity response function is obtained for the following groundwater derivation in the form of equation (8)

$$\frac{\Delta B}{\Delta h} = 0.0125783069 \text{ mgal/m}$$  \hspace{1cm} (8)

3. Result and discussion

Gravity measurements in 2014 were actually carried out at 92 points in Semarang city and surroundings covering more than 400 km$^2$. Gravity measurements in 2016 consisted of 174 points covering 10000 km$^2$. For preventing bias and inaccurate results, this study only applied 50 points that both were measured in 2014 and 2016. After earth tide correction and drift correction and instrument height correction, gravity data of 2014 were ranging from 978050.505 mgal to 978119.826 mgal, while data of 2016 were ranging from 978050,544 mgal to 978119,815 mgal. The difference in gravity values from field measurements was generally smaller than 1 mgal and could not be identified visually on the map, as shown by figure 3 and figure 4. The gravity values decreased gradually from coastal area at north part of Semarang city to Ungaran Volcano at southern part of the city.

![Figure 3. Map of gravity data of 2014.](image)

![Figure 4. Map of gravity data of 2016.](image)
Trend of gravity data in figure 3 and figure 4 showed that data on earth surface have strong correlation to topography. Effect of topography were eliminated by simple Bouguer reduction to obtain gravity values on ellipsoid reference of WGS84. Gravity anomaly of 2014 were ranging from 0.023 mgal to 29.792 mgal, while gravity anomaly of 2016 was ranging from 0.017 mgal to 29.519 mgal. The differences of gravity anomaly values of 2014 and 2016 were generally smaller than 1 mgal and could not be identified visually on the map, as shown by figure 5 and figure 6.

Change in gravity anomaly were calculated by subtracting data of 2016 to 2014. Gravity anomaly change in period of 2014 and 2016 were ranging from -0.317 mgal to 0.211 mgal as shown by figure 7. Converting gravity anomaly change to groundwater change applied rock and sediment density derived from geological map, and 30% porosity assumption. Groundwater levels were declining in south part of Semarang city ranging from 10 m to 20 m as shown by figure 8. Groundwater levels were increasing at alluvial plain of Semarang city.
4. Conclusion
Gravity measurements in 2014 and 2016 were able to detect changes in gravity in the Semarang city. In this study, gravity changes in rocks and sediments with porosity of 30% were caused by changes in groundwater level that change the geological density. The decrease in groundwater generally occurred in the southern part of Semarang City, while the increase in groundwater occurred in the northern part of Semarang City. It was suspected that uplifting of groundwater level was caused by seasonal variations due to gravity measurements in September and March. For the future research, it is recommended to combine tidal flood data to groundwater analysis.

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