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RESEARCH ARTICLE

Utilization of Gravimetric Satellite Data for Delineating of Subsurface Model of The Purwokerto-Purbalingga Groundwater Basin

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Abstract The utilization of gravimetric satellite data has been carried out to delineate the subsurface model of the Purwokerto-Purbalingga Groundwater Basin. Access and processing of satellite gravity anomalies data were carried out to obtain the residual gravity anomalies data. Modeling of the residual gravity anomalies data was conducted along the AA′, BB′, and CC′ trajectories. The modeling results show a basin model filled by alluvial deposits (1.75 g/cm^3 and 2.28 g/cm^3) with a maximum depth of about 402 m for the AA′ trajectory, 543 m for the BB′ trajectory, and 463 m for the CC′ trajectory. The modeling results show that this alluvial basin is delimited by impermeable and semi-impermeable layers, which include laharic deposits of Slamet Volcano (2.61 g/cm^3), andesite lava deposits (2.90 g/cm^3), Tapak formation rocks (2.50 g/cm^3), breccia rocks of Tapak formation (2.70 g/cm^3), and breccia rocks of Halang formation (2.80 g/cm^3). The fairly large thickness of alluvial deposits supported by dug-well water tables data and resistivity data indicates that the potential of groundwater in the Purwokerto-Purbalingga Groundwater Basin area is very large. The results of the study are expected to be a solution to overcome droughts that often occur in the Banyumas and Purbalingga regencies, as well as for the development of groundwater-based irrigation.

1. Introduction

The utilization of gravity field data from gravimetric satellites for subsurface exploration and interpretation has grown very rapidly. Various natural deposits such as coal, zinc, bauxite, and other metallic minerals that are difficult to detect using other geophysical methods due to extraordinary natural constraints, can actually be detected easily using satellite gravity methods (Motta et.al., 2019). This method is an attractive alternative because it can cover a large area, and the generated data can be accessed by all users in various countries. The satellite gravity method has been utilized to monitor changes in groundwater storage (Frappart and Ramillien, 2018) and for mapping coal mines (Xie et al., 2018). Satellite gravimetric data have also been applied in geological structures modelings, such as the great Sumatran fault in Aceh (Yanis et al., 2019), the geological model in the subsurface of Semarang (Nugraha et al., 2016), the subsurface structure of Lamongan Volcano and its surrounding areas (Suprianto et al., 2022), the major tectonic features in the South China Sea (Nhu et al., 2004), and other structures. For the study of the groundwater basin, this method was also very suitable to be applied to study the characteristics of the bedrock in the Jakarta groundwater basin (Nugraha et.al., 2020).

One of the groundwater basins in Central Java is the Purwokerto-Purbalingga, as shown in Figure 1. This basin stretches from Banyumas Regency to Banjarnegara Regency with an area of 1,318.2 km^2, an unconfined groundwater potential of 502.6 million m^3/year, and confined groundwater is 9.7 million m^3/year (Anonimous, 2017). Geophysical research related to the subsurface structure of the Purwokerto-Purbalingga groundwater basin is almost never carried out. However, these study results can support a geological study that has been conducted in this area. Geophysical modeling of groundwater basins is also useful for delineating the thickness of alluvial deposits which are difficult to reach by geological studies. Thus geophysical research using the satellite gravity method can be applied to delineate the Purwokerto-Purbalingga Groundwater Basin model, considering that this basin is very large and the study was carried out during the Covid-19 pandemic. The acquired model will show the thickness of alluvial deposits which store a lot of water in the basin. The results of this study are expected to be widely useful for developing groundwater-based irrigation and overcoming the drought, especially in the Banyumas and Purbalingga regencies.

A geological review suggests that the Purwokerto-Purbalingga Groundwater Basin has occupied a depression zone in the center of Java Island, known as the Serayu Valley. This valley is the separator between the North and the South Serayu Mountains. The Serayu Valley extends from west to east through some regencies, i.e., Majenang, Ajibarang, Purwokerto, Banjarnegara, and Wonosobo (Bammelen, 1949). The study area consists of several stratigraphic units, as shown in Figure 2 (Djuri et al., 1996; Asikin et al., 1992; Condon et al., 1996). The order of the stratigraphical units of the study area can be seen in Table 1. The alluvial deposits in this basin are estimated to come from millions of cubic meters of rocks or sediment materials carried by river flow due to erosion from the surrounding areas as the results of geomorphological processes that are dominated by exogenic processes such as climate, rainfall, temperature, and wind. Further, the materials are deposited within the basin for a long time, perhaps millions of years, resulting in thick alluvial deposits (Bammelen, 1949).

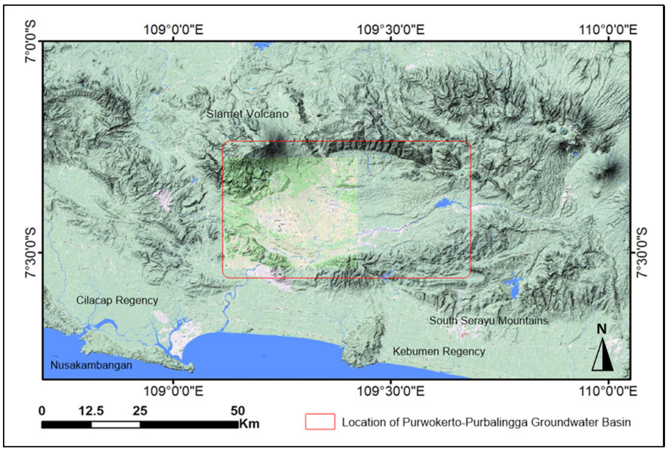
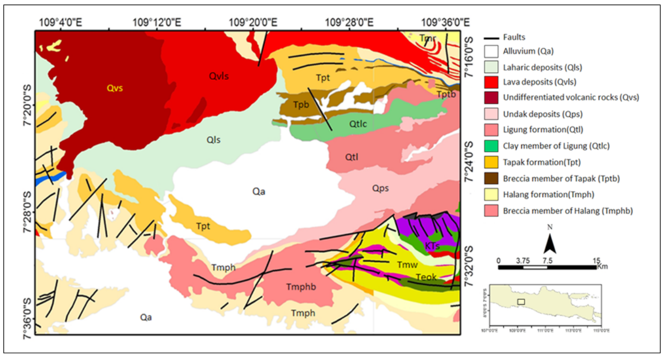


Figure 1. Terrain view of Google Earth showing the the Purwokerto-Purbalingga Groundwater Basin



Tertiary					Quaternary	
Oligocene	Miocene			Pliocene	Pleistocene	Holocene
	Early	Middle	Late			

Figure 2. Geological map of the study area (sources: the Geological Map of the Purwokerto-Tegal Sheet, Banyumas Sheet, and Pekalongan-Banjarnegara Sheet)

The advantage of gravimetric satellite data is that it does not require much correction. The satellite data do not require free-air correction because the acquisition is carried out at the same elevation datum. Latitude correction is also unnecessary because the satellite has calculated gravitational field values' effect on latitude positions' differences. In addition, by looking at the distance from the center of the earth's mass to the satellite's orbital trajectory, the difference in the gravitational acceleration value caused by the difference in latitude does not have much effect. Then, several corrections commonly applied to the gravity meter, such as equipment elevation and drift corrections, are also not required (Maulana and Prasetyo, 2019). Hence, only Bouguer and terrain corrections were employed in data processing to acquire the Complete Bouguer Anomaly (CBA) data (Holom and Oldow, 2007). The utilization of these data is also appropriate because the object of study is a regional basin (Setiadi et.al., 2021).

2. Methods

The study was carried out in March – September 2021. The satellite gravity data have been accessed from the website provided by Scripps Institution of Oceanography, University of California, San Diego, USA (Sandwell and Smith, 1997). The number of data that has been successfully accessed is 814 points spread on the geographical positions of 109.0083–109.6083° E and 7.2554°–7.6026° S. The satellite gravity anomalies data obtained from the acquisition are free-air gravity anomalies data. The data have been gridded regularly in the ASCII – XYZ format, as shown in Figure 3. The spatial resolution of grid points is 1.0 minutes; meanwhile, the accuracy of the anomalies data is 0.1 mGal, and elevation data is 1.0 m (Sandwell and Smith, 2009 and Ducet and Traon, 2000); thus, the distance between grid points is about 1.8 km.

Data processing begins with applying Bouguer correction and terrain correction on the free-air satellite gravity anomalies data to obtain Complete Bougeur Anomalies (CBA) data. Further, the CBA data that are still distributed on the topographical surface are reduced to the horizontal surface using Taylor series approximation (Blakely, 1995 and Sehah et al., 2022) and separated from regional anomalies data (Telford et al., 1990 and Kabede et al., 2020) to get residual gravity anomalies data. The residual anomaly data are assumed to come from the local anomalous sources, which are the target of the study (Quesnel et al., 2008). Two-dimensional modeling is carried out on the residual gravity anomalies data to delineate a cross-sectional model of the subsurface density of the Purwokerto-Purbalingga Groundwater Basin (Hirt, 2016). Based on the density data of the obtained objects (rocks), then an analysis is carried out to interpret the types of subsurface rocks. The

Table 1. The subsurface rock stratigraphic units of the study area (Djuri et.al., 1996)

No.	Rock Formations	Lithological Units	Age
1	Alluvium (Qa)	Clay, silt, sand, and gravel as river deposits	Holocene
2	Laharic deposits (Qls)	Lahar with a boulder of andesitic-basaltic volcanic rock of Old Slamet Volcano	Holocene
3	Lava deposits (Qvls)	Andesitic lava of Slamet Volcano; porous, and lots of cracks	Pleistocene
4	Terrace deposits (Qps)	Rock layers of tuffaceous sandstones, sands, tuffs, conglomerates, and tuffaceous breccias	Pleistocene
5	Ligung (Qtl)	Andesitic agglomerates, breccias, and grey tuffs in some places	Pleistocene
6	Clay member of Ligung (Qtlc)	Tuffaceous claystone, cross-bedded tuffaceous sandstones, and conglomerates	Pleistocene
7	Tapak (Tpt)	Greenish coarse-grained sandstones and conglomerates, locally with andesitic breccias. The upper part consists of calcareous sandstones and green marl mollusk fragments	Pliocene
8	Breccia member of Tapak (Tptb)	Volcanic breccias with tuffaceous sandstone matrix; calcite veins at some places	Pliocene
9	Halang (Tmph)	Andesitic sandstones, tuffaceous conglomerates, and marls; intercalates with sandstones	Late Miocene
10	Breccia member of Halang (Tmphb)	Polymictic breccias with andesitic, basaltic, and limestone components; intercalates with sandstones and basaltic lava	Late Miocene

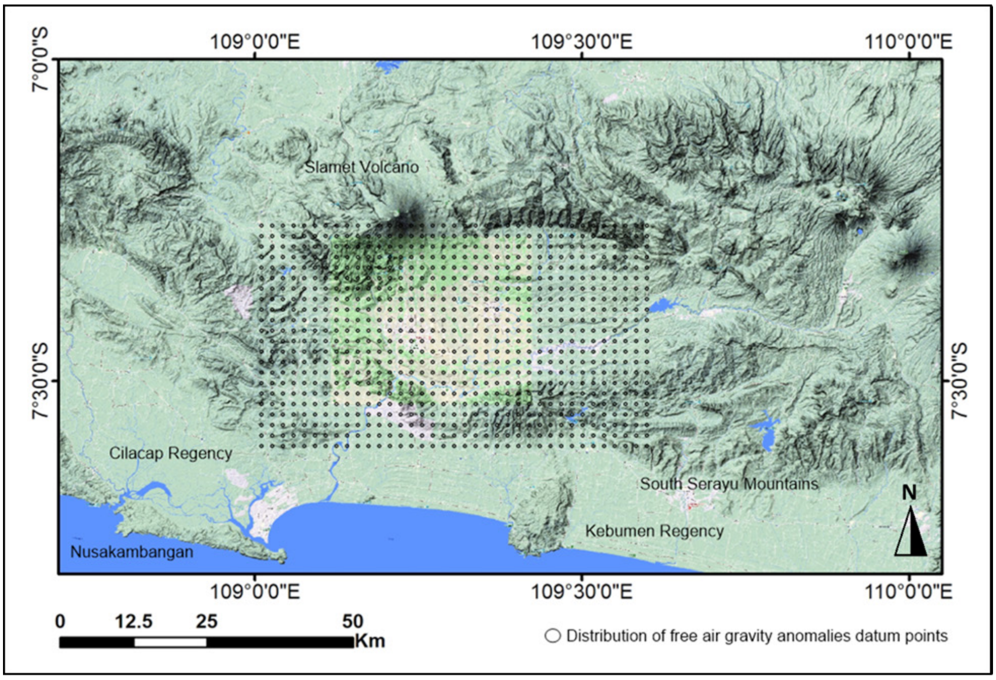


Figure 3. Distribution of datum points in the Purwokerto-Purbalingga Groundwater Basin (Background image from Google Earth)

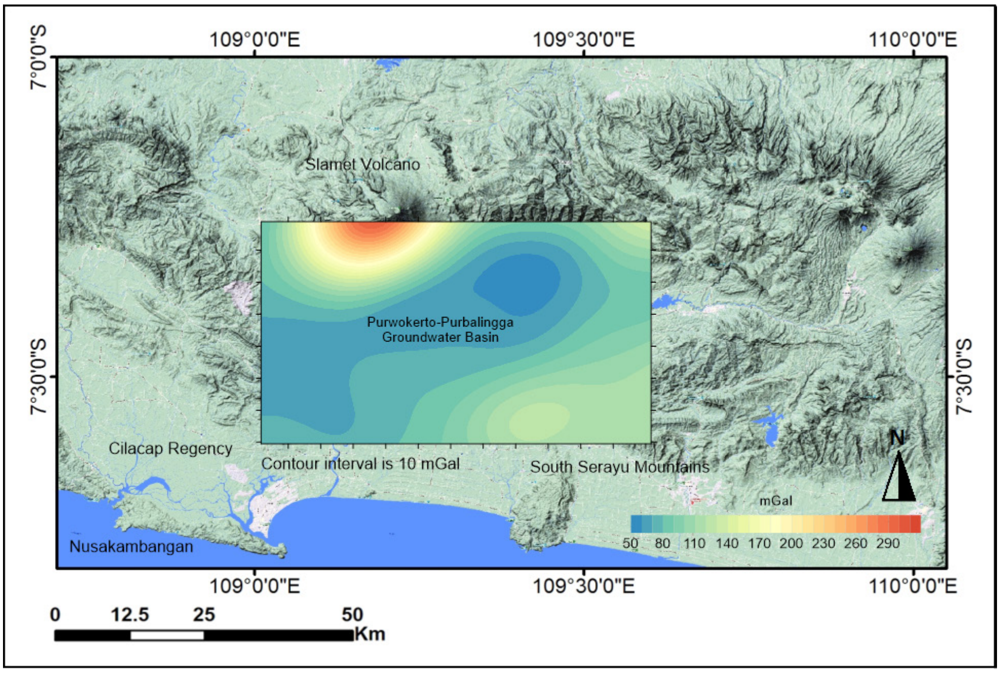


Figure 4. The free-air satellite gravity anomaly contour map of the study area.

analysis and interpretation processes are supported by geological information, well water table data, and geoelectrical data.

3. Result and Discussion

Results of The Study

The data that has been successfully accessed from the tTopex satellite are free-air gravity anomalies data with values ranging from 53.40 – 300.40 mGal. At the same time, the topographical elevation of the study area ranges from 7 – 2,495 m. A map showing the distribution of free-air satellite gravity anomaly can be seen in **Figure 4.** The contour map shows that the Purwokerto-Purbalingga Groundwater Basin area stretches from the South Serayu Mountains to the North Serayu Mountains, including the Slamet Volcano. The slopes of Slamet Volcano limit the research area in the northwest and hills in the east.

Bouguer and terrain corrections were applied, to obtain the Complete Bouguer Anomaly (CBA) data, with the value ranging from 49.66 – 152.65 mGal. Bouguer correction was carried out to reduce the rock masses effect in the earth's crust between the spheroid surface and the data point at the topographic surface (Zahorec and Patco, 2018). At the same time, terrain correction was carried out to reduce the topographic mass effects, which are relatively rough with large differences in elevation, such as mountains, hills, ravines, and valleys around the measurement point (Nowell, 1999). Further processing, the CBA data, which were still spread on the topographic, was transformed to the horizontal surface using the 3rd-order Taylor series approximation (Blakely, 1995 and Sehah et al., 2022). The flat surface chosen in the study is the average topographic elevation (i.e., 269.3 m), in order for the

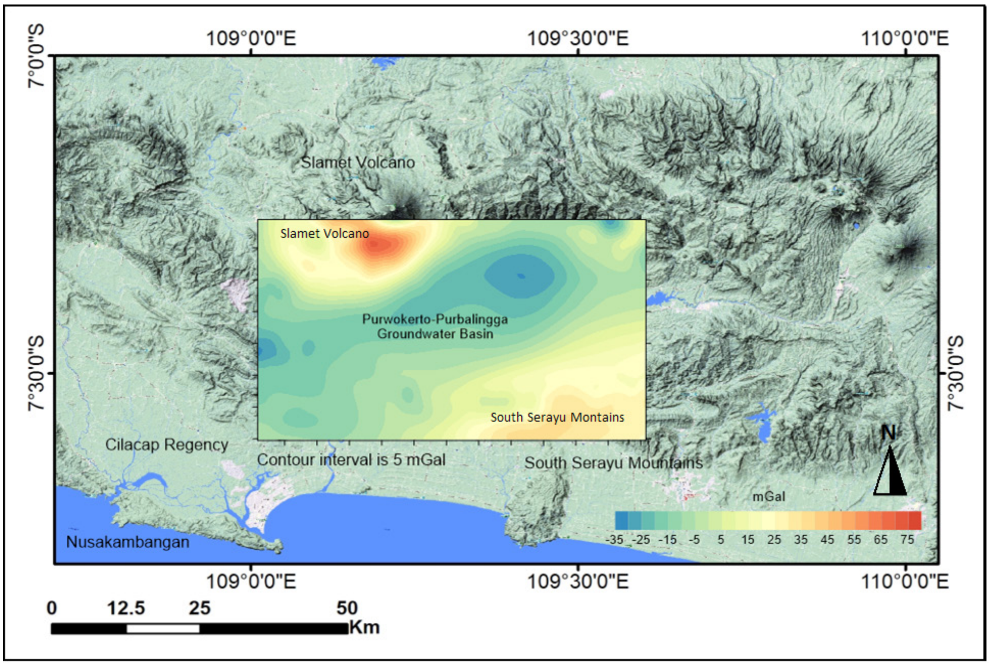
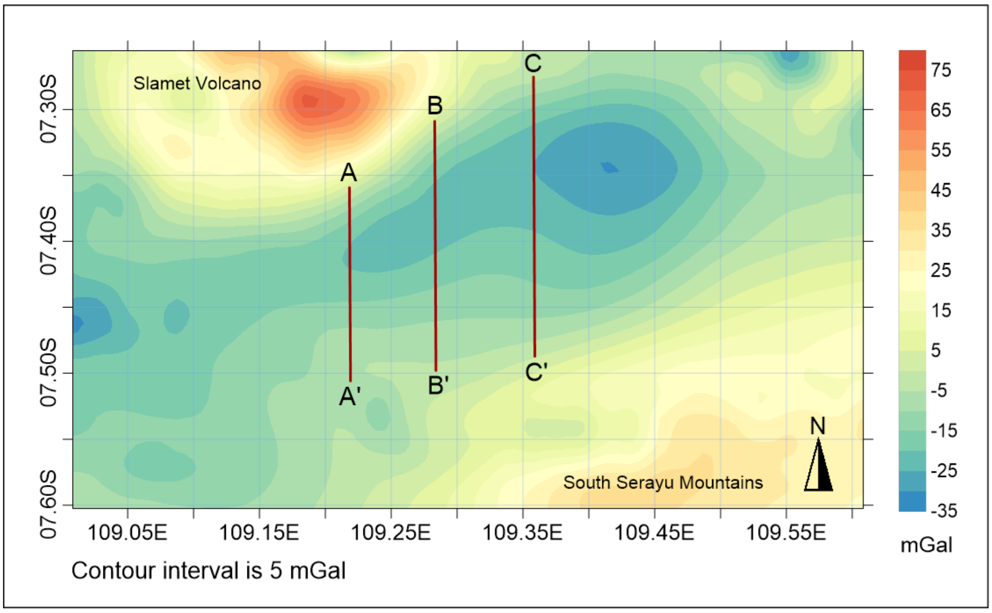


Figure 5. The satellite residual gravity anomaly contour map of the study area.



Trajectories	AA′	BB′	CC′
Position	A (7.36°S ; 109.22°E) A′ (7.51°S ; 109.22°E)	B (7.31°S ; 109.28°E) B′ (7.50°S ; 109.28°E)	C (7.27°S ; 109.36°E) C′ (7.49°S ; 109.36°E)

Figure 6. The three trajectories for modeling the residual gravity anomalies data; the placement of these trajectories was adjusted to the location of alluvial deposits based on the geological map.

interaction on the Taylor Series quickly reaches convergence (Blakely, 1995).

Furthermore, the CBA data are separated from the regional anomalies data using the upward continuation filter (Blakely, 1995; Guo et al., 2013). After the separation of regional anomalies data, the residual gravity anomalies data are obtained. The contour map showing the residual gravity anomaly pattern is shown in Figure 5, with the value ranging from -31.171 – 71.413 mGal. The acquired residual anomalies map has shown the pattern of groundwater basin in the study area. Even several natural objects such as the South Serayu Mountains and Slamet Volcano were relatively more identified than before corrections and reductions of the anomalies data were applied. This indicates that the subsurface rock density contrast on the residual gravity anomaly contour map is more clearly identified.

4. Results of Modeling and Interpretation

Geophysical modeling of the groundwater basin was carried out in two dimensions on three trajectories over the residual gravity anomaly map with the geographical position, as shown in Figure 6. The trajectories are AA′ with a length of 17,686 m, BB′ with a length of 19,830 m, and CC′ with a length of 22,387 m. The modeling of the Purwokerto-Purbalingga Groundwater Basin was based on its density values (Guglielmetti et al., 2021). The obtained sub-surface models for all trajectories are shown in Figure 7 to Figure 9, while its interpretation results are depicted in Table 2. The

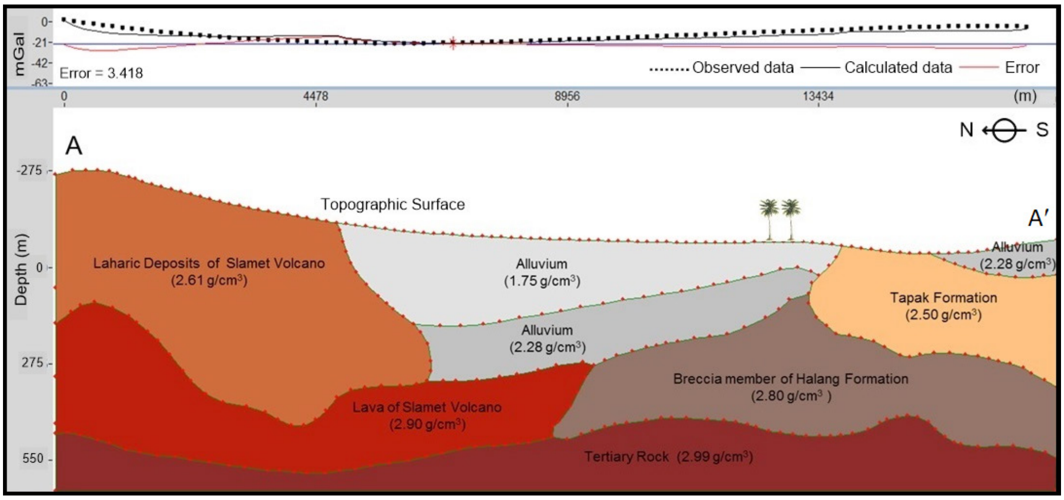


Figure 7. The result of the residual gravity anomaly modeling in the form of a rock density cross-section under the AA' trajectory

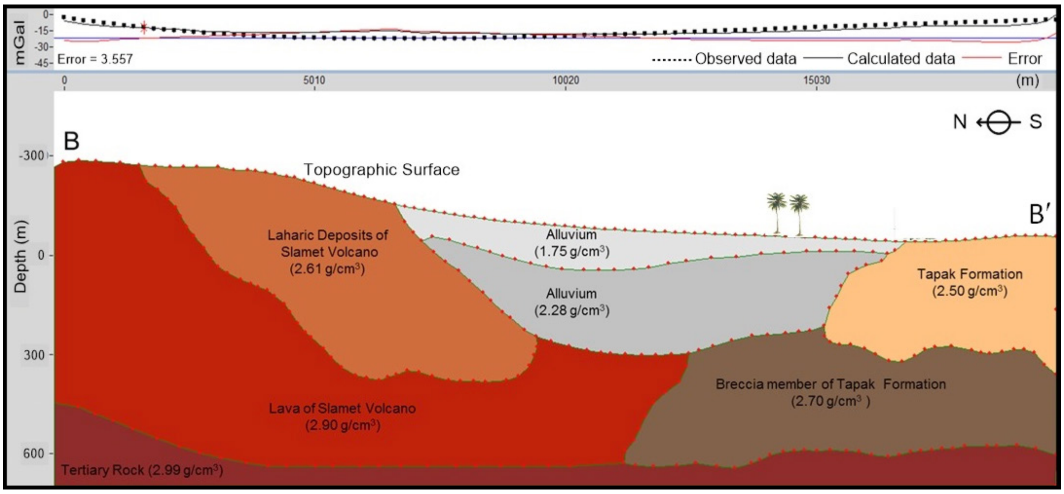


Figure 8. The result of the residual gravity anomaly modeling in the form of a rock density cross-section under the BB' trajectory.

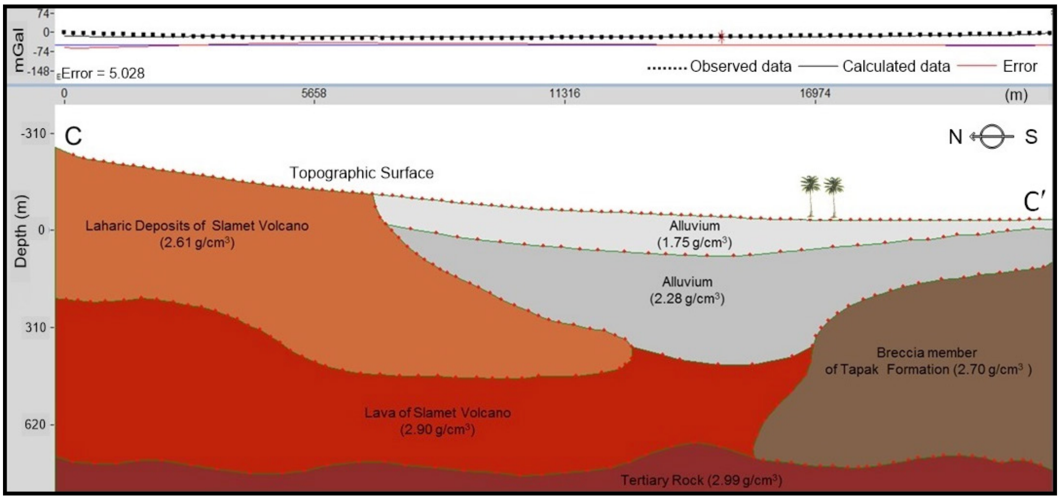


Figure 9. The result of the residual gravity anomaly modeling in the form of a rock density cross-section under the CC' trajectory

densities of all subsurface objects range from 1.73 – 2.99 g/cm^3, which are interpreted as alluvial deposits up to tertiary rocks. The modeling results show that the alluvial deposits occupy a basin-shaped zone where groundwater collects. The modeling results also show that this alluvial deposit consists of two layers, i.e., the upper alluvial (1.75 g/cm^3) and the lower alluvial (2.28 g/cm^3). The alluvial deposits, the groundwater basin's main material, are surrounded by the volcanic rocks of Slamet Volcano and the surrounding sedimentary rocks (Bammelen, 1949).

5. Discussion

The aquifer is a permeable rock formation in the form of unconsolidated material such as gravel, sand, silt, or fractured rock; which can store and drain a lot of groundwater (Darwis, 2018). The aquifer formed in the Purwokerto-Purbalingga

Table 2. The results of the lithological interpretation of the subsurface anomalous object model on the AA′, BB′, and CC′ trajectories.

No.	Density (g/cm^3)	Model Depth (m) on the trajectory of			Lithological Interpretation Results
		AA′	BB′	CC′	
1	1.75	150 – 437	122 – 328	143 – 341	Alluvium formation, composed of clay, silt, sand, and gravel deposits
2	2.28	278 – 552 194 – 299	226 – 585	257 – 686	Alluvium formation, composed of sand, gravel, and pebble deposits more compressed
3	2.61	0 – 719	12 – 662	0 – 730	Laharic deposits of Slamet volcano with boulders of andesitic-basaltic volcanic rocks
4	2.90	374 – 864	0 – 919	476 – 1.038	Lava deposits of Slamet volcano in the form of vesicular andesitic lava deposits
5	2.50	213 – 618	226 – 642		Tapak formation, composed of greenish coarse-grained sandstone and conglomerate, locally with andesitic breccia
6	2.70		497 – 924	351 –1.022	Breccia member of the Tapak formation, composed of volcanic breccia with tuffaceous sandstone matrix
7	2.80	348 – 813			Breccia member of Halang formation, composed of polimict breccias with andesitic, basalt, and limestone components, which intercalates with sandstones and basaltic lava
8	2.99	695 - 913	730 – 985	940 – 1.099	Tertiary rocks in the form of granite rocks that are part of the Sunda Arc

Groundwater Basin is a near-surface aquifer. Although this basin obtains its water supply from the recharge area on the south slopes of Slamet Volcano, the recharge process from local rainfall also occurs. All water that seeps into the soil can be stored in the alluvial layer. Based on the modeling results, the alluvial layers have an average thickness of 272.50 – 317.25 m, so the potential for water content is very large.

An aquifuge is an impermeable rock layer that does not contain water and cannot drain groundwater (Darwis, 2018). Aquifuge beds bound these alluvial deposits at the bottom which act to prevent groundwater from seeping further. These aquifuge beds consist of laharic (2.61 g/cm3) and lava (2.90 g/cm3) deposits of Slamet Volcano that are found underneath the alluvial deposits on the trajectories of AA′, BB′, and CC′. In the south of these trajectories are several rock outcrops of the Tapak formation (2.50 g/cm^3). According to Djuri et.al. (1996), this formation comprises greenish coarse-grained sandstone and conglomerates locally with andesite breccia. Below the Tapak formation, there are breccia members of the Halang formation for the trajectories of AA′ and BB′, and breccia members of the Tapak formation for the trajectory of CC′. These rock formations can act as an aquiclude, preventing groundwater in the basin from flowing further outside the basin area.

Some of the criteria of the groundwater basin are to have a recharge area and a discharge area in one groundwater formation system. Usually, the recharge area is a groundwater conservation area where groundwater should not be exploited on a large scale. In comparison, the discharge area is an area where groundwater can be utilized. Based on the information about the groundwater map index that is produced by the Department of Energy and Mineral Resources, Central Java Province (Anonimous, 2017), the location of the groundwater recharge area of the Purwokerto-Purbalingga Groundwater Basin is to be the northwest of the study area, i.e., the southeast slope of Slamet Volcano. In this area, groundwater flows through fractures and intergranular spaces in the subsurface rocks with wide distribution and high productivity (Tabrani, 1985).

The residual gravity anomaly map overlaid with the Purwokerto-Purbalingga Groundwater Basin map, as shown in Figure 10**,** shows that this recharge area has a high gravity anomaly. It is estimated to be related to the lithology of laharic deposits (Qls) and lava deposits (Qvls) (Djuri et al., 1996). The two types of volcanic rock formations are estimated to have high-density values (Sedlak et al., 2009). According to Iswahyudi et al. (2018), the lava deposits found in the Slope of Slamet Volcano area are a vesicular type with many cavities and cracks so that it can be drained by water, even several springs have sprung up in this area. The groundwater comes from the precipitation process, which collects in the rock cavities and cracks, then flows into the discharge area which has a lower elevation. The discharge area of the Purwokerto-Purbalingga Groundwater Basin is characterized by low residual gravity anomalous values. This indicates that the density of subsurface rocks also low, such as alluvial deposits that fill this basin. According to Ramadhan (2020), the groundwater recharge value in this slope can reach 2,800 mm per year, while the discharge area is only 1,200 mm per year. Therefore the south slopes of Slamet Volcano are groundwater recharge areas for highly productive aquifers (Tabrani, 1985).

The alluvial deposits in the Purwokerto-Purbalingga basin are estimated to come from millions of cubic meters of sediment materials carried by river flow due to erosion from the surrounding hills and slopes resulting from geomorphological processes, which are dominated by exogenic processes as climate, rainfall, wind, and temperature. Further, the materials are deposited into the basin for a long time, perhaps millions of years, resulting in thick alluvial deposits (Bammelen, 1949). The finer alluvial deposits are commonly localized in the basin's center, while the coarse deposits are near the mountain slopes (Anderson et al., 1992). The accumulation of the alluvial deposits was detected in the satellite residual gravity anomaly map, characterized by low anomalous values. However, considering the basin's location is close to the laharic and lava deposits of Slamet Volcano. The value of the gravity anomaly for alluvial deposits looks not too low. The lowest residual gravity anomaly value is actually seen at a position of 109.4144(E and 7.3467(S) outside the basin area (Djuri et al., 1996) and far from the laharic and lava deposits.

However, the regional gravity anomaly map shows that the location of the basin's center is per the information from the geological map. The regional anomaly map was acquired by means of an upward continuation process (Guo et.al.,

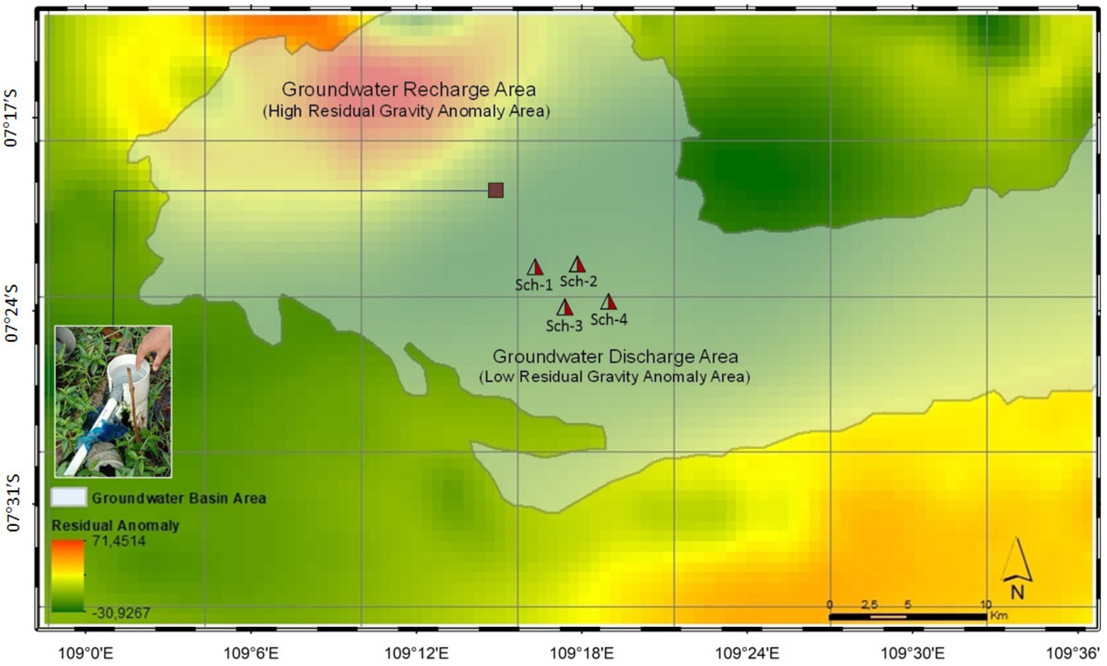


Figure 10. Residual gravity anomaly contour map that is overlaid with the Purwokerto-Purbalingga Groundwater Basin map; the picture insert shows one of the springs in the study area, and the symbols Sch-1 to Sch-4 represent the locations of the geoelectrical survey

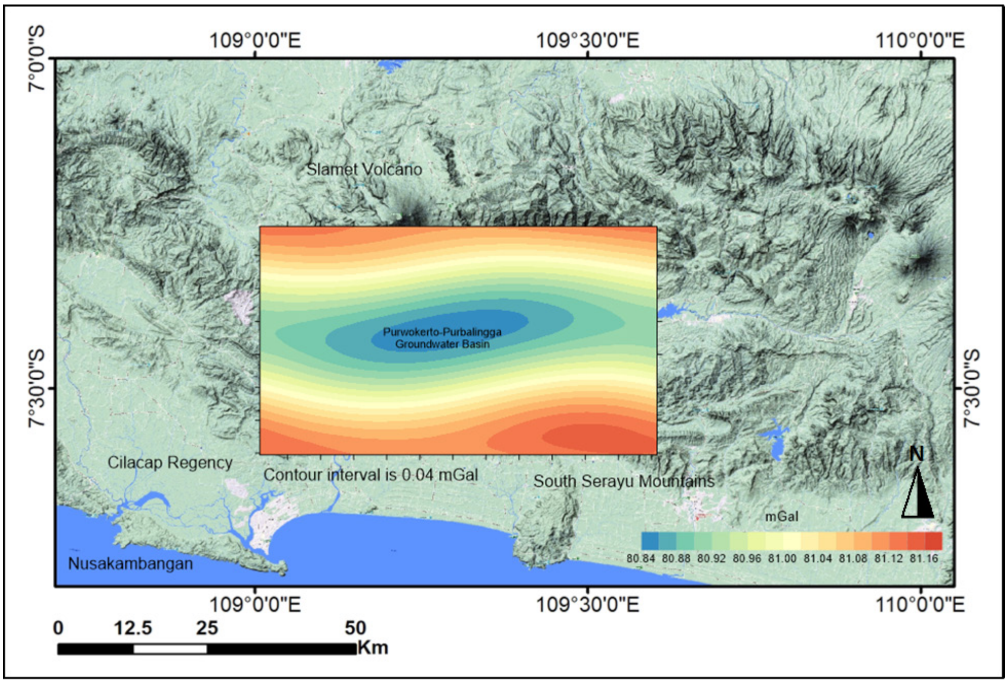


Figure 11. The satellite regional gravity anomaly contour map of the study area; the results of upward continuation up to an altitude of 40,000 m.

2013) up to a height of 40,000 m, as seen in Figure 11. This map represents a regional anomaly pattern in the study area, where the influence of the density of the laharic and lava deposits of Slamet Volcano has been removed (Sehah et al., 2021). Commonly, the regional Bouguer gravity anomaly is the longer wavelength field due to deep sources. Therefore, the lowest anomaly value on the regional anomaly map can be interpreted as the center of the Purwokerto-Purbalingga Groundwater Basin after the anomalous local closures are removed (Ekinci and Yigitbas, 2015 and Zhang et al., 2001) by an upward continuation process.

All alluvial deposits within a basin are hydraulically connected and form a single aquifer (Anderson et al., 1992). Groundwater within a basin can be unconfined because impermeable rock layers only bind it at the bottom. The modeling results show several impermeable rock layers, such as the laharic and lava deposits of Slamet Volcano, that are above the tertiary rocks (2.99 g/cm^3). Several other impermeable or semi-impermeable rock layers include breccia members of the Tapak and Halang Formation. Considering that it consists of only a single aquifer, the depth of the well water table in this groundwater basin shows the depth of the groundwater table. Based on the research results by Ramadhan (2020), the depth of the water table of 57 wells in this groundwater basin area varies, ranging from 1 – 16 m, measured from the top of the wells. The depth data of these wells also indicate that the closer to the center

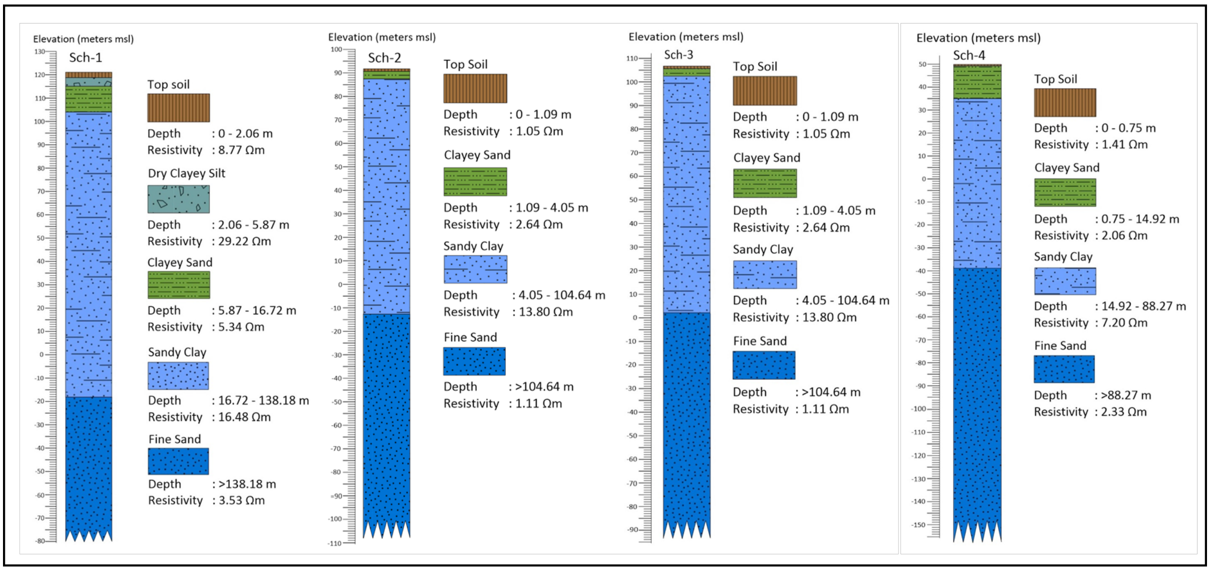


Figure 12. Resistivity logs resulting from geoelectric surveys using the VES technique at location points, as shown in Figure 10.

of the basin, the shallower the water table (Ramadhan, 2020). This indicates that the groundwater potential is estimated to be greater in the central area of the basin. This is also supported by the results of the geoelectric survey using a vertical electrical sounding (VES) technique as shown in Figure 12.

The results of the geoelectric survey using the VES technique, which was carried out in the discharge area of the Purwokerto-Purbalingga Groundwater Basin by the authors, show small resistivity values. In hydrogeology, small resistivity values are generally interpreted as alluvial deposits with high groundwater storage (Islami et al., 2018). The resistivity values in all sounding points ranged from 1.11 – 29.22 Ωm, and all types of subsurface rocks have the potential to store groundwater, considering that all of them are alluvial types (Djuri et al., 1996). However, the types of subsurface rocks that are estimated to store the most groundwater are fine sand (1.11 – 3.53 Ωm) and clayey sand (2.06 – 5.34 Ωm), as it is known that the discharge area of the Purwokerto-Purbalingga Groundwater Basin is fertile agricultural land. The areas are located around the center of the basin, i.e. groundwater discharge area. Even some villages in the areas have never experienced a drought (Anonimous, 2020). Thus, the use of the Purwokerto-Purbalingga Groundwater Basin as a source of domestic clean water and for irrigation needs to be supported. The results of this research indicate that the utilization of satellite gravimetric data for delineating the subsurface geological model of a groundwater basin has been successful.

6. Conclusion

Utilization of gravimetric satellite data has been successfully carried out for delineating the subsurface model of the Purwokerto-Purbalingga Groundwater Basin. The obtained data from the satellite are free-air gravity anomalies and geographical position data. After corrections and reductions, the residual gravity anomalies data can be obtained. The modeling has been carried out on the anomalies data along three trajectories on the residual anomaly contour map for delineating the subsurface groundwater basin model. The modeling has resulted in a basin-shaped geological model filled by alluvial deposits from the alluvium formation with a density of 1.75 g/cm^3 and 2.28 g/cm^3. The laharic deposits of Slamet Volcano bound these alluvial deposits with a density of 2.61 g/cm^3, the andesite lava deposits of Slamet Volcano with a density of 2.90 g/cm^3, the Tapak formation with a density value of 2.50 g/cm^3, breccia members of the Halang formation with the density of 2.80 g/cm^3, and breccia members of the Tapak formation with the density of 2.70 g/cm^3.

The results of the modeling show that the average depth of alluvial deposits in the Purwokerto-Purbalingga Groundwater Basin ranges from 272.50 – 317.25 m. The large thickness of alluvial deposits in this basin indicates that the groundwater potential in the basin is also large. The modeling results are supported by groundwater table data from 57 wells in the groundwater discharge area with a depth ranging from 1 – 16 m, measured from the topographic surface. In addition, the obtained resistivity data supports the modeling results, where the subsurface rock resistivity in the groundwater discharge area ranges from 1.11 – 29.22 Ωm. The range of resistivity values shows that the groundwater discharge area is filled by alluvial deposits, which have the potential to store large amounts of groundwater. The study's results on utilizing gravimetric satellite data have provided important information regarding efforts to overcome the drought that often occurs in Banyumas and Purbalingga regencies, and the development of groundwater-based irrigation.

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