INVERSION MODELING OF GRAVITY ANOMALY DATA FOR MAPPING OF SUBSURFACE ROCK DENSITY IN THE PURWOKERTO-PURBALINGGA GROUNDWATER BASIN AREA

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Abstract. The utilization of gravimetric satellite data for mapping gravity anomaly on the Earth's surface has been widely used, especially for very large areas, such as groundwater basins. This research purposes to map the density of subsurface rocks in 3D in the Purwokerto-Purbalingga Groundwater Basin area based on the inversion model of the gravity anomalies data. The research stages that have been carried out include data access, Bouguer correction, terrain correction, data reduction to a horizontal surface, separation of regional and residual anomalies data, 3D-inversion modeling, and interpretation. Gravity anomaly data have been accessed from the GGMplus 2013 website with a spatial resolution of 220 m. The results of data processing after data separation is residual gravity anomalies data. The anomaly data are distributed at the average topographical elevation of the research area (243.92 m). Inversion modeling of the residual anomalies data has been carried out, in order to obtain a 3D model of subsurface rock density with values ranging from 1.20 – 4.80 g/cm3. The modeling results show that the Purwokerto-Purbalingga Groundwater discharge area is in the form of a basin filled with alluvial deposits with density values ranging from 2.10 – 2.55 g/cm^3 and a depth of more than 4 km..

1. Introduction

Inversion modeling is a process of calculating the model data in reverse, where the model parameters are obtained directly from the data through a mathematical model [1]. Inversion modeling can be applied well for gravity anomaly data, both data from measurements in the field and data from satellites. Zuhdi et.al. (2020) have applied inverse modeling to microgravity anomaly data to identify patterns of fluid injection into the subsurface reservoir layer [2]. Jarut et.al. (2022) have applied the inversion method of satellite gravity anomaly data to model the subsurface geological structure of Anak Ranakah Volcano area in Manggarai Regency, East Nusa Tenggara, Indonesia [3]. Inversion modeling has also been successfully applied to gravity anomaly data acquired in the field to describe subsurface rocks in the Jambi sub-Basin [4]. In this article, inversion modeling is applied to obtain a density distribution model of the subsurface rock of the Purwokerto-Purbalingga Groundwater Basin. Based on the results obtained, rock complexes with small density values can be interpreted as alluvial deposits which have the potential to store large amounts of groundwater. The information is needed to support exploration and exploitation of groundwater for various purposes in the Banyumas and Purbalingga Regencies.

The authors have used satellite gravimetric data to obtain a two-dimensional subsurface geological structure model in the Purwokerto-Purbalingga Groundwater Basin area [5]. The subsurface rock model was obtained through forward modeling, so that the objectivity of the results is relatively still lacking. Power spectrum analysis of satellite gravity anomaly data has also been carried out by authors [5] to estimate the depth of sedimentary materials or alluvial deposits in the basin. The power spectrum calculation results show that the average depth between alluvial deposits and bedrock is about 470.89 m. The depth value is calculated from the topographical surface, so that the value indicates the thickness of the alluvial deposits in the basin. However, this calculation was only carried out on four tracks in the groundwater discharge area, therefore the results relatively do not represent the condition of the groundwater basin as a whole. Based on this fact, the modeling applied in this research is 3D-inversion modeling. Through this modeling, rock complexes with low density which have the potential to contain large amounts of groundwater throughout the basin area can be mapped easily.

The basic theory of the gravity method that underlies geophysical surveys is Newton's law of the force of attraction between two point masses, where the magnitude of the force between two point masses m1 and m2 which are separated by a distance r can be stated as [6]:

$$\vec{F}(\vec{r}) = -G\frac{m_1 m_2}{r^2}\hat{r} \tag{1}$$

where G is the universal gravitational constant (6,67 x 10^{-11} Nm^2/kg^2). Further Telford et.al. (1990) has described Equation (1), in order to obtain the gravitational potential at a point P outside the volume V as shown in **Figure 1** which can be expressed as [6]:

$$U_P(\vec{r}) = -\int_V \frac{G}{\left|\vec{r}^2 - \vec{r}_0^{\,2}\right|} dm = -G\int_V \frac{\rho(\vec{r}_0)}{\left|\vec{r}^2 - \vec{r}_0^{\,2}\right|} d^3\vec{r}_0 \tag{2}$$

$$\left|\vec{r}^2 - \vec{r}_0^{\,2}\right| = \sqrt{r^2 + r_0^{\,2} - 2r\,r_0\cos\gamma}$$

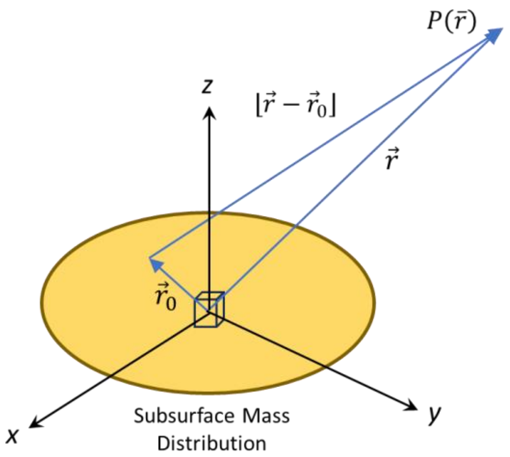

Figure 1. The gravitational potential at point P on the earth's surface due to the continuous distribution of masses in the subsurface [6].

When the volume integral in Equation (2) is taken for the all volume of the earth, then the gravity potential field strength at the earth's surface is obtained. While, the gravitational field is obtained by differentiating the gravitational potential, so that it becomes:

$$\vec{E}(\vec{r}) = \left|-\nabla U_P(\vec{r})\right| \quad (3)$$

The value of the earth's gravitational field is often referred to as the acceleration due to gravity (g). Based on equations (2) and (3), the value of the earth's gravity acceleration can be expressed by the equation [6]:

$$g(\vec{r}) = \left|-\vec{E}(\vec{r})\right| = \left|\nabla U_P(\vec{r})\right| \quad (4)$$

$$g(\vec{r}) = -G\int_V \frac{\rho(\vec{r}_0)(z_0 - z)\, d^3\vec{r}_0}{\left[(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2)\right]^{3/2}} \quad (5)$$

Equation (4) shows that the value of the gravitational field on the earth's surface varies. Variations in the earth's gravity field are influenced by longitude, latitude, elevation, and the distribution of the subsurface mass of the earth which is expressed as a function of the density of subsurface rock masses. Gravity field values measured in gravity surveys are expressed in gal units, where 1 gal is equivalent to 10-5 ms-2. However, the gravity field anomaly data measured in the field are generally very small, that is in the milligal range [7].

Geophysical data from observations in the field are expected to provide as much information as possible, not only related to the physical properties, but also the geometry and depth of the subsurface rocks. This information can be obtained if the relationship between the physical properties of the subsurface rocks and the observed data can be known. The relationship between the two is almost always in the form of a mathematical equation that is usually referred to as a mathematical model. Based on the mathematical model, rock physical parameters can be extracted from the observation data. This process is referred to as inversion modeling. Whereas, the reverse process, where we want to obtain predictive data from observations based on known physical parameters, is called forward modeling. The inversion and forward data processing flow in geophysics is shown in **Figure 2**.

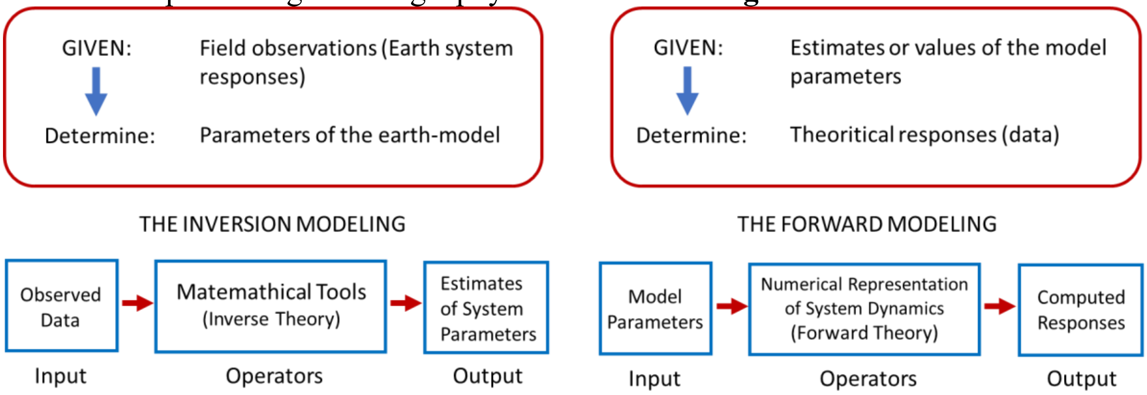

Figure 2. The flow of inversion and forward data processing in geophysics [1].

2. Methods

2.1. Location and Time

This research was carried out at the Electronics, Instrumentation and Geophysical Laboratory, Faculty of Mathematic and Natural Sciences, Jenderal Soedirman University, Purwokerto. The research data is satellite gravity anomaly data covering the Purwokerto-Purbalingga Groundwater Basin with positions of 109.0083° – 109.6083° E and 7.2554° –

7.6026° S as shown in Figure 3. The location stretch from Purwokerto City to Banjarnegara Regency, Central Java, Indonesia. The research has been carried out for 6 (six) months, i.e. March – August 2023.

2.2. Equipments and Materials

The equipment used in the research included personal computer equipped with several software and application programs, i.e.: Microsoft Excel, Fortran 77, Matlab 9.2, Gravity 900, Surfer 17, Grablox 1.7, Bloxer 1.6e, Voxler 4.0 and geological maps of the research area. All softwares are used for data processing, inversion modeling, and model interpreting. In addition, the personal computer must be connected to the internet to access gravity field anomaly data from the GGMplus 2013 website. While, the material used in the research is gravity field anomaly data from satellite which includes gravity disturbance data, quasi geoid elevation data, and geographical position data (x,y,z) for all data points in the research area. GGMplus data has a better spatial resolution (approximately 220 m) than other satellite gravity data such as TOPEX and BGI data (approximately 1,800 m), so this data can be used for good initial mapping in an area to obtain an overview of the area [8].

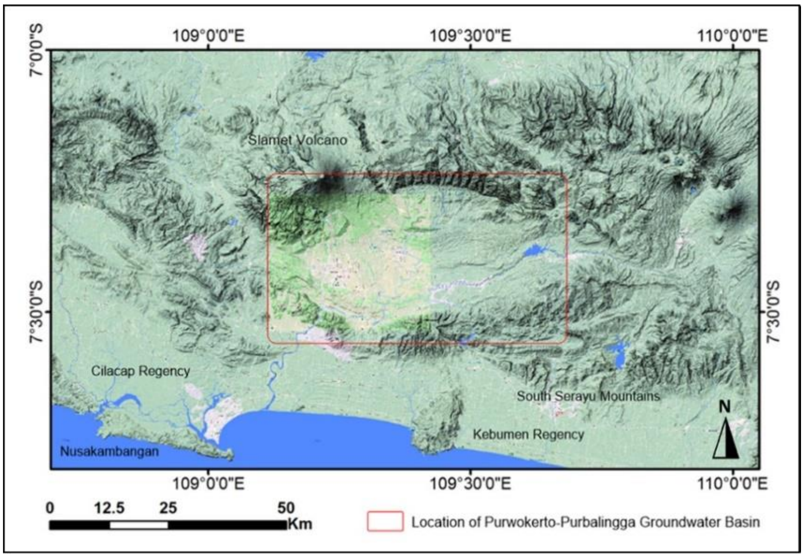

Figure 3. The research location map; the Purwokerto-Purbalingga Groundwater Basin area of Central Java, Indonesia (source: Google Earth).

2.3. Research Procedure

Accessing gravity anomalies data from GGMplus website is the first stage in the research. The data obtained consists of gravity disturbance data whose value is equivalent to free-air gravity anomalies data, geoid elevation data, and position data (x,y,z) of data points. Therefore, the data does not require free air correction, because the data acquisition process is carried out at the same elevation datum from the satellite [9]. Complete Bouguer Anomalies (CBA) data were obtained after applying the Bougeur correction and terrain correction to the gravity disturbance data [10]. Considering the CBA data are still distributed on the topographical surface, the CBA data are reduced to a horizontal surface using Taylor Series approximation technique [11][12]. Further, the CBA data are separated from regional gravity data [13]. Regional gravity anomaly data is obtained using the upward continuation technique. Continuation of CBA data is carried out step by step in order to obtain regional anomalies data at a certain height. A visual analysis is carried out on the anomalies contour patterns obtained at each upward continuation step to identify the level of regionality of the resulting contour maps [13].

Separation of regional anomaly data produces residual gravity anomaly data that are also distributed on a horizontal surface. Residual anomaly data are gravity anomaly data that have been cleared from various effects of other anomaly sources that are not the target of research and are assumed to be associated only with research targets. Residual gravity anomalies data obtained can be directly modeled. If there is still the influence of a strong local density originating from the topographical surface, then filtering can be applied to reduce the local density sources [6]. 3D-inversion modeling was performed using Grablox 1.7 and Bloxer 1.6e. Grablox and Bloxer are free software for inversion modeling and interpretation of gravity anomalies data based on 3D models consisting of minor cubes with a certain density [2]. The aim of modeling and interpreting is to determine the density contrast and the geometry of the object causing the anomaly in the Purwokerto-Purbalingga Groundwater Basin area.

3. Results And Discussion

3.1. Results of Gravity Anomaly Data Access

Satellite gravimetric data have been accessed on March 1-2, 2023 at the Laboratory of Electronics, Instrumentation, and Geophysics, Faculty of Mathematics and Natural Sciences, Jenderal Soedirman University, Purwokerto. Gravity anomalies and geographic position data have been accessed from the Bureau Gravimetrique International (BGI) website as described in the Research Methods. The amount of data which have been successfully accessed is 51,900 data spanning geographic positions from 109.0083° – 109.6083°E and 7.2554° – 7.6026°S. Accessing data have produced gravity disturbance data whose values are equivalent to free air gravity anomalies data [14]. The anomaly data obtained ranges from 57.51 – 287.06 mGal, while the elevation data ranges from -19.91 – 2606.64 m with a spatial resolution of 220 m [15]. The topography of the research area and the gravity disturbance contour maps are shown in **Figure 4**.

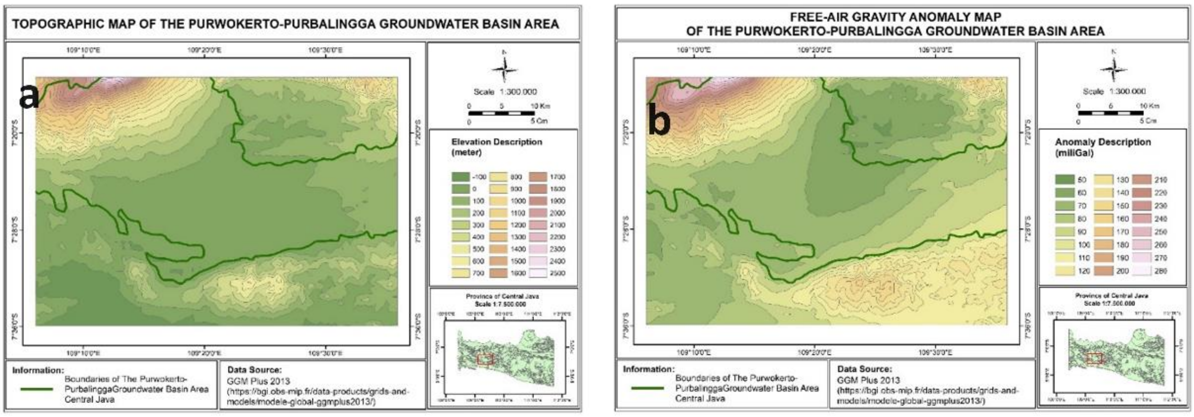

Figure 4. (a)The topographic map of the research area; Purwokerto-Purbalingga Groundwater Basin, (b) The gravity disturbance map of the research area; Purwokerto-Purbalingga Groundwater Basin

3.2. Results of Data Correction and Reduction

Corrections to the gravity disturbance data that have been carried out include Bouguer and terrain corrections to obtain Complete Bouguer Anomaly (CBA) data [12]. After corrections, CBA data can be obtained with values ranging from 59.18 – 127.85 mGal with a contour map can be seen in **Figure 5A**. The CBA data were still distributed on the topographical surface which is a function of the geographic position (longitude, latitude, elevation). Considering further data processing, the anomalies data must be distributed on a horizontal surface, so a reduction to a horizontal surface is carried out. The Taylor Series approximation method has been applied in this research to reduce the CBA data from a non-horizontal surface (as topography) to a horizontal surface (average topographic elevation, i.e. 243.92 m), so that the obtained values range from 59.69 – 127.85 mGal. This data range has shown convergence than before reduction; where this indicates that the anomalies data have been distributed on a horizontal surface [11].

3.3. Results of Separation of Regional-Residual Anomaly Data

CBA data which has been distributed on the topographical average elevation is still superposed with anomalies data originating from very deep and wide regional geological structures. Hence, the influence of the regional anomalies data must be eliminated, considering that the research target is alluvial deposits that fill the discharge area of the groundwater basin. The regional gravity anomalies data can be obtained by continuation of the CBA data (which have been distributed on the topographic average elevation) up to a certain elevation so that the variation in the data shows a relatively fixed pattern [16]. Visual analysis of the gravity anomalous contour maps after upward continuation with an elevation of 500 – 45,000 m shows that the regional anomalous contour pattern is reached at an elevation of 25,000 m. Further, the regional gravity anomaly data are then corrected to the CBA data and produce the residual gravity anomalies data, with a contour map shown in **Figure 5B**. The residual gravity anomaly data is anomaly data that is ready to be modeled and interpreted, in order to obtain a subsurface structure model of the Purwokerto-Purbalingga Groundwater Basin.

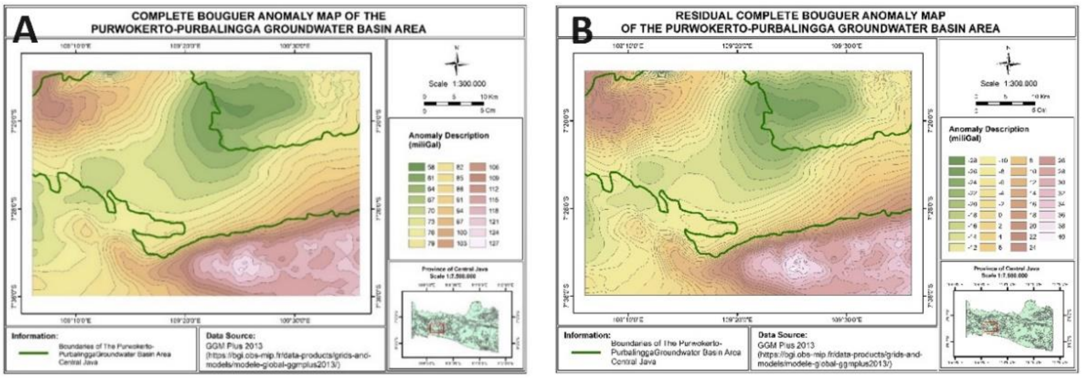

Figure 5. A. The CBA contour map of the research area; Purwokerto-Purbalingga Groundwater Basin, B. The residual CBA contour map of the research area; Purwokerto-Purbalingga Groundwater Basin

3.4. Results of Data Modeling and Interpretation

The residual gravity anomalies data have been modeled in 3D-inversion using Grablox 1.7, Bloxer 1.6e, and Voxler 4.0 to get a subsurface structure model of the Purwokerto-Purbalingga Groundwater Basin. The geographical position of the modeled residual anomalies data are adjusted to the research target as can be seen in **Figure 6a**; i.e. at longitude 303.35 – 323.75 km-UTM and latitude 9172.15 – 9188.92 km-UTM, so the anomalies data ranges from -23.38 – 3.26 mGal. Modeling which has been carried out with Grablox 1.7 divides the x-axis into 45 blocks, the y-axis into 30 blocks, and the z-axis into 7 blocks. Thus the total number of 3D-model blocks is 9,450 blocks. The dimensions of each block are 0.5 km x 0.5 km x 0.5 km. Further, the modeled residual anomalies data are calculated in inversion against the initial model. The inversion process is carried out through some optimization steps, consisting of base optimization, density optimization, and density occam. The inversion process has produced a 3D model as shown in **Figure 6b**, with density values ranging from 1.20 – 4.80 g/cm^3 and an average value of 2.61 g/cm^3. This value is smaller than the average density value of the rocks in the Earth's Crust, i.e. 2.67 g/cm3 [17].

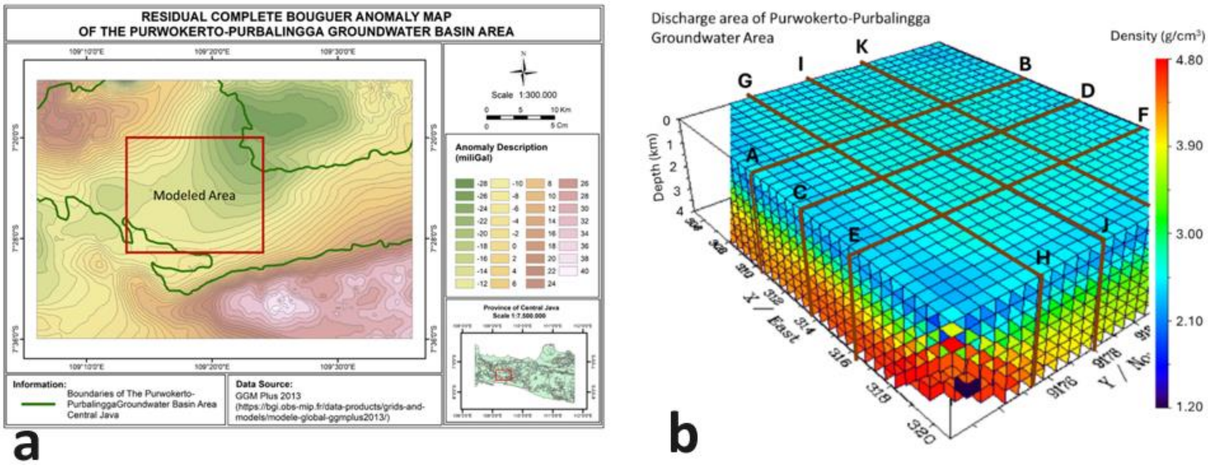

Figure 6. a: The boundaries of the modeled area for the residual gravity anomaly contour map, b: Three-dimensional model of subsurface rock density distribution in the Purwokerto-Purbalingga Groundwater Basin

Based on **Figure 6b**, the density with large values is dominated by rocks on the edge of the basin in the form of Slamet Volcano lava rocks and South Serayu Mountain sedimentary rocks [18]. Figure 9 also indicates that the discharge area of this groundwater basin is dominated by subsurface rocks with relatively low-density values. The rocks are interpreted as alluvial deposits from Alluvium formation and sedimentary materials from other formations (marked in dark to light blue). Based on the geological information, the alluvial deposits which fill the basin at the top consist of gravel, sand, silt, and clay; which are thought to originate from river material deposits [18]. The only major river flowing through the Purwokerto-Purbalingga Groundwater Basin is Serayu River. Aquifers formed in alluvial deposits along rivers are generally composed of rock or soil that is young and not yet consolidated properly, so that the rock layers can be traversed by groundwater flow, including groundwater infiltration from below to the surface. The estimation of groundwater infiltration patterns in the subsurface rock layers is presented in the density cross-section model along the trajectories of AB, CD, and EF, as well as the trajectory of GH, as shown in **Figure 7 to Figure 12** The subsurface geological model obtained indicates that the Purwokerto-Purbalingga groundwater basin has a unified aquifer system; including recharge area, impermeable rocks, and discharge area; as the general characteristics of a groundwater basin [19].

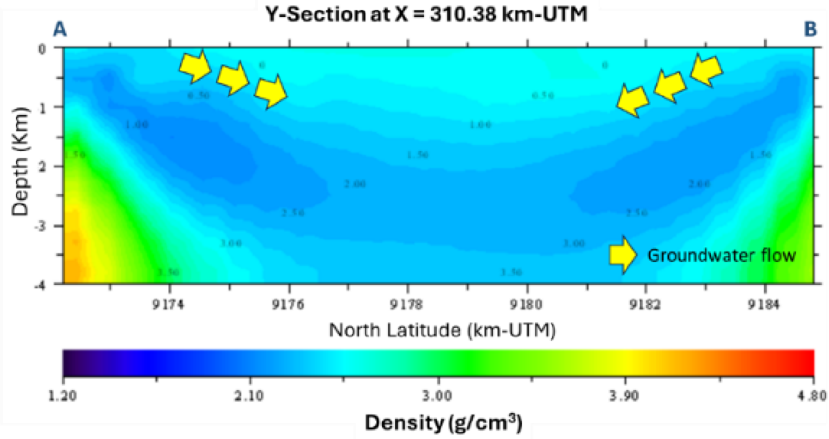

Figure 7. Cross-section of the subsurface rock density model for the Purwokerto-Purbalingga Groundwater Basin along the longitude of 310.38 km-UTM

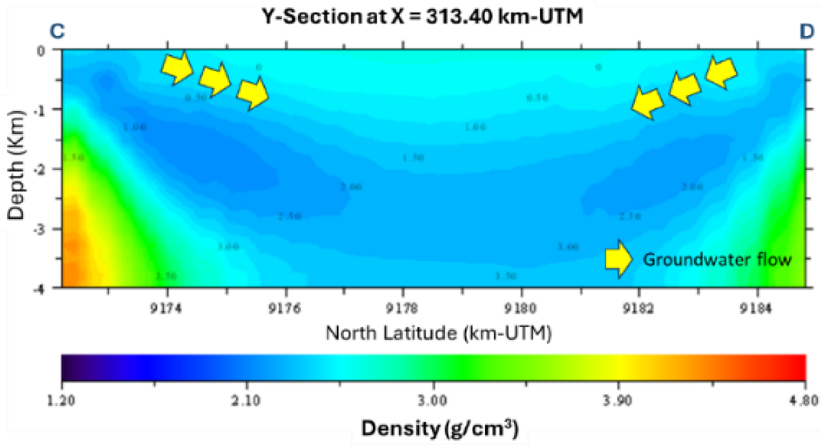

Figure 8. Cross-section of the subsurface rock density model for the Purwokerto-Purbalingga Groundwater Basin along the longitude of 313.40 km-UTM

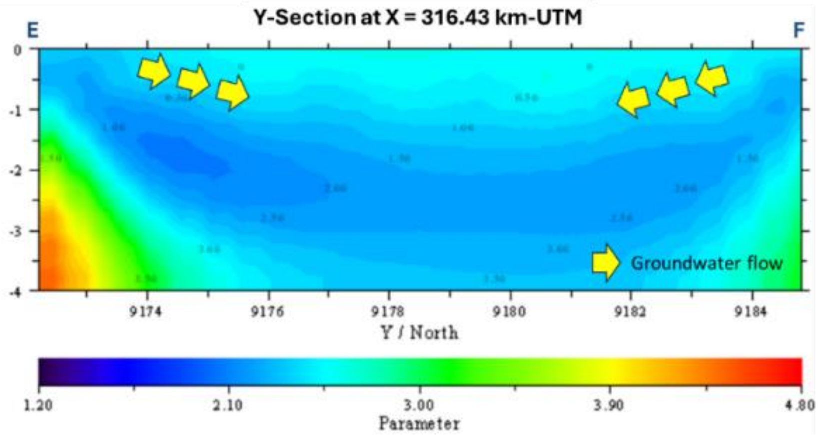

Figure 9. Cross-section of the subsurface rock density model for the Purwokerto-Purbalingga Groundwater Basin along the longitude of 316.43 km-UTM

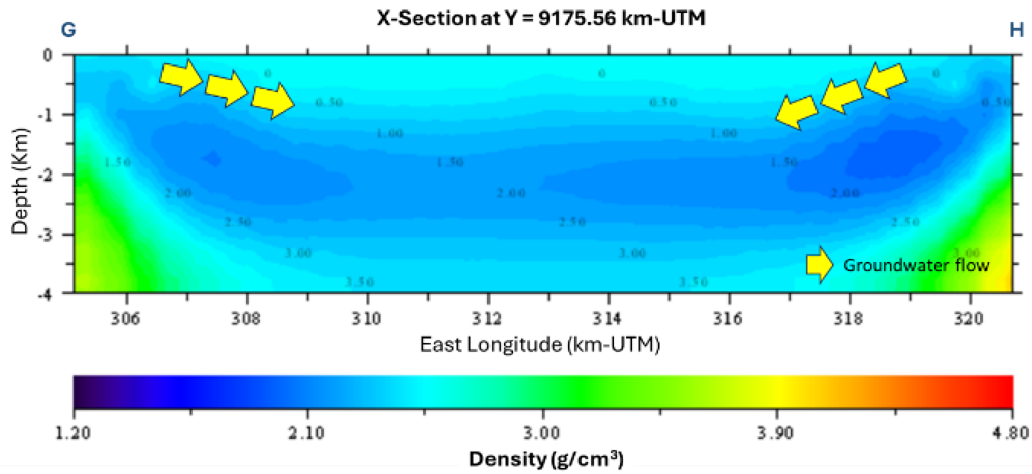

Figure 10. Cross-section of the subsurface rock density model for the Purwokerto-Purbalingga Groundwater Basin along the latitude of 9175.56 km-UTM

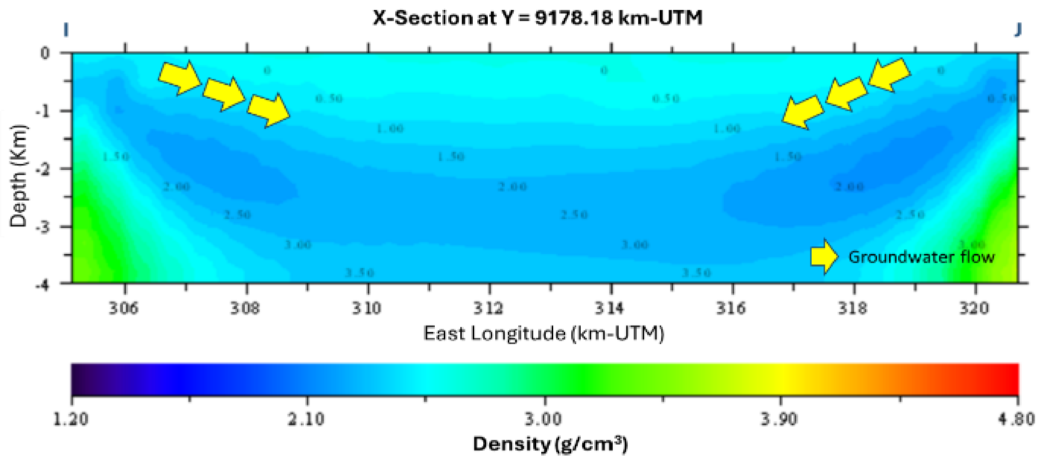

Figure 11. Cross-section of the subsurface rock density model for the Purwokerto-Purbalingga Groundwater Basin along the latitude of 9178.18 km-UTM

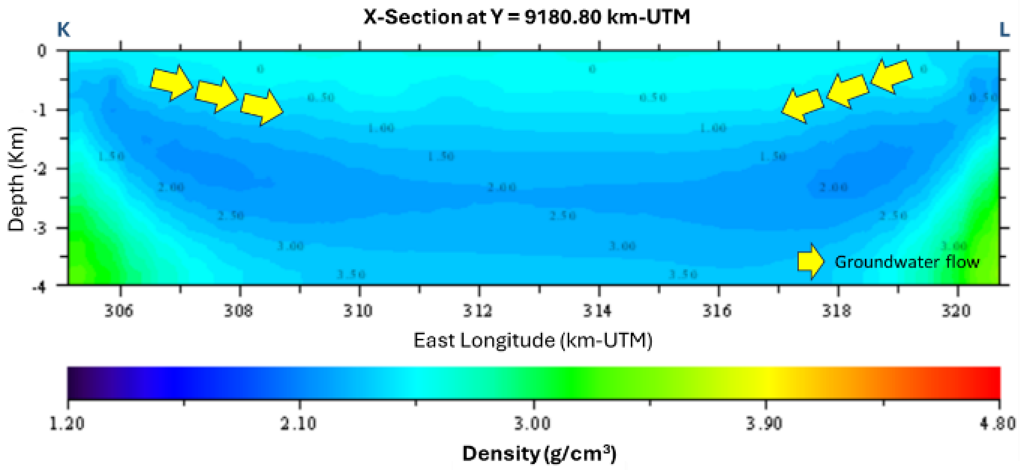

Figure 12. Cross-section of the subsurface rock density model for the Purwokerto-Purbalingga Groundwater Basin along the latitude of 9180.80 km-UTM

The creation of subsurface rock density model sections along tracks of AB, CD, EF, GH, IJ and KL purposes to obtain an overview of the groundwater infiltration pattern from the recharge area to the discharge area. Based on geological information, the Purwokerto-Purbalingga Groundwater Basin area has recharge areas on the South Slope of Slamet Volcano, as well as North and South Serayu Mountains [20]. **Figures 7** to **Figure 9** show the approximate pattern of water flow from the recharge area on the slopes of the mountains (including Slamet Volcano) to the discharge area in the middle of the groundwater basin. The value of the groundwater flow rate in the recharge area (i.e. the South Slope of Slamet Volcano) can reach 2,800 mm per year, while in the discharge area it only reaches 1,200 mm per year [21]. This shows that the South Slope of Slamet Volcano was recharge areas for highly productive aquifers [20]. Based on the results of research by Ramadhan (2020), the depth of the groundwater table in the discharge area varies according to the topographic elevation, that ranges from 0.25 – 16 m [21]. The direction of shallow groundwater flow in the research area flows from a high elevation (or high potential) to a lower elevation (or low potential), that is from the northwest and northeast to the center of the basin. This indicates that the closer to the center of the groundwater basin, the shallower the depth of the groundwater table.

The results of subsurface rock density modeling as shown in **Figure 6b** to **Figure 12** show a geological basin structure with an estimated depth of more than 4 km. The structure of this basin is characterized by rock layers with relatively low density values (estimated 2.10 – 2.55 g/cm^3). Even the subsurface rock layer at a depth of about 2 – 3 km is dominated by rock materials with lower density value. Based on geological information, alluvial deposit from alluvium formation in this groundwater basin have a depth of about 500 m [18]. Beneath this deposit is an old alluvial deposit from the Undak formation whose depth is unknown. Therefore the results of this geophysical modeling can be a new discovery (novelty) related to the subsurface geological structure of the Purwokerto-Purbalingga Groundwater Basin. The Purwokerto-Purbalingga Groundwater Basin is filled to the brim with alluvial deposits which are thought to originate from material carried by the ancient Serayu River due to erosion, weathering and other processes up to millions of cubic meters. These events are the result of geomorphological processes dominated by exogenous processes such as climate, rainfall, temperature, and wind. Further, the materials were deposited in the basin for a long time (perhaps reaching millions of years), so that it completely covered the groundwater basin [22].

4. Conclusion

The use of gravimetric satellite data to map gravity anomalies on the Earth's surface has been carried out in the Purwokerto-Purbalingga Groundwater Basin area. The gravity anomalies data used are GGMplus data which have high resolution of 220 m. The data that have been accessed are 51,900 data spanning the geographical positions from 109.0083° – 109.6083° E and 7.2554° – 7.6026° S. This research aims to map the density of subsurface rock in the Purwokerto-Purbalingga Groundwater Basin based on the residual anomalies data inversion model. Stages of research that have been carried out include data access, Bouguer and terrain corrections, reduction to a horizontal surface, separation of residual-regional anomalies data, 3D-inversion modeling, and interpretation. Modeling of the residual gravity anomalies data distributed at the topographical average elevation was done by inversion and produced a 3D-subsurface rock density model, with values ranging from 1.20 – 4.80 g/cm^3. Based on the modeling results, the area which is suspected to contain large amounts of groundwater is interpreted to be composed of alluvial deposits with density values ranging from 1.20 – 2.48 g/cm^3 and a depth of more than 4 km.

5. Acknowledgment

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