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Research article

Two-dimensional resistivity modeling of seawater intrusion along the west flood canal, Semarang

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ABSTRACT

The northern coastal area of Semarang City has significant problems with a decrease in groundwater quality due to seawater intrusion. Increasing groundwater extraction and subsidence due to the city growth worsen the condition. It is necessary to collect information on the contaminated location to develop a strategy to decrease the spreading of seawater intrusion. This study aims to identify the presence of seawater intrusion zones in groundwater and estimate the spread distance of seawater intrusion to the land. We applied the electrical resistivity tomography method to obtain the image of the subsurface. A geo-electric survey with a dipole-dipole multi-electrode configuration was completed along the West Flood Canal. The subsurface model result indicated that the identified seawater intrusion zone is associated with a low resistivity value of less than 3 Ohm.m. The zone is about 0 - 70 meters deep near the coast and is thinning to about 2600 meters to the south. The result confirms that seawater has penetrated long distances to the land.

INTRODUCTION

Semarang is one of Indonesia's major cities with a high population increase and rapid industrial development, especially in the northern coastal area. Consequently, the large population and industrial growth in Semarang City have increased clean water consumption and resulted in the exploitation of groundwater on a large scale. Most of the clean water needs are obtained by pumping groundwater from unconfined and confined aquifers. Other sources are springs and the local government's groundwater management (PDAM) (Budiyono et al., 2020). Recently, saline and brackish groundwater have been a common problem, as reported by several studies (Ardaneswari et al., 2016; Rahmawati et al., 2013;

Supriyadi et al., 2021, 2017; Widada et al., 2018). The intrusion is an environmental problem impacting various aspects of life due to a decreased groundwater quality that is unfit for consumption. Other impacts caused by seawater intrusion include health problems, decreased soil fertility, and building damage (Erfandi and Rachman, 2011; Mabrouk et al., 2013; Supriyadi et al., 2017).

Seawater intrusion is when seawater seeps into freshwater aquifers due to hydrogeological imbalance in near-shore areas. Seawater has a lower specific resistance value than freshwater because seawater contains NaCl electrolyte conductors. Due to its greater density, it is easy for saltwater to push freshwater into the mainland. The exploitation of groundwater on a large scale can disrupt the hydrogeological balance. The emptying of aquifers due to groundwater extraction can trigger the movement of seawater into the mainland, resulting in seawater intrusion (Figure 1) (Deng et al., 2017; Mabrouk et al., 2013; Prusty and Farooq, 2020). Another factor that might cause seawater intrusion is the high rate of development resulting in land subsidence that changes the groundwater table (Rahmawati et al., 2013). In this case, Semarang experienced fast subsidence of about 1 – 15 cm/year (Sarah et al., 2011).

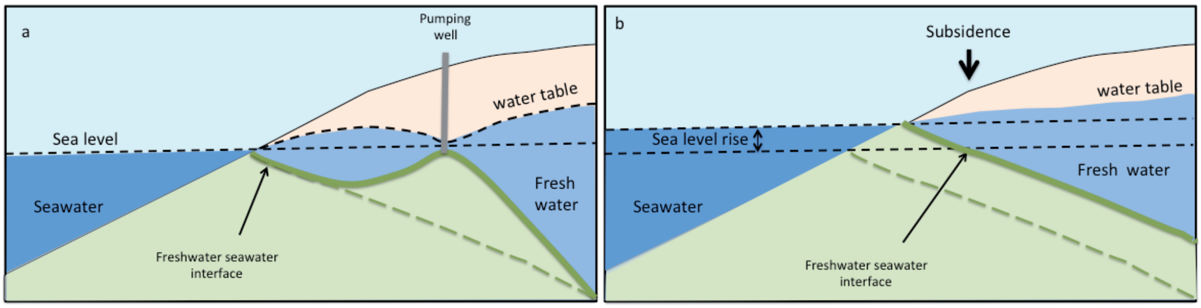

Figure 1. Schematic of the freshwater-seawater interface transformations (green dashed lines are the original position). a) uncontrolled groundwater extraction or a pumping well caused the water table to be lowered and pulled up the interface. b) subsidence and rising sea level caused the seawater to infiltrate the previously groundwater space.

The seawater intrusion in Semarang has been indicated mainly by residential and monitoring wells that have become brackish or salty and increased chloride content in the water. A pollen study has shown significant changes in the coastal environment since the 1980s (Soeprobowati et al., 2020). Hydrochemical investigations at some wells indicated high content of nitrate (Sudaryanto and Wibawa, 2013), chloride ions (Supriyadi et al., 2017), and high electrical conductivity (Widada et al., 2018). The outcome from quantitative analytical modeling for confined aquifers in Semarang indicated that seawater intrusion increases by about 0.575 km2/year (Suhartono et al., 2015). Another numerical modeling indicated the broader saline and brackish water spread in a hundred years due to the higher hydraulic area and the future sea-level rise (Rahmawati et al., 2013). Subsurface investigations based on resistivity have also been applied numerous times but locally, such as at Kaligawe (Setyawan et al., 2016), Trimulyo (Ardaneswari et al., 2016), Tanah Mas Residential (Putro et al., 2016; Supriyadi et al., 2017), and Kota Lama (Supriyadi et al., 2021).

Those previous studies indicated sporadic evidence of the saltwater intrusion problem. Accordingly, it is necessary to investigate the possible extent of seawater intrusion toward Semarang in a broader area and a deeper subsurface image. We applied electrical resistivity tomography (ERT) to study the subsurface resistivity distribution to obtain images of geological structures related to the groundwater. The resistivity method is commonly used in groundwater studies (Hussain et al., 2017; Ling et al., 2016; Nugraha et al., 2021; Thiagarajan et al., 2018). Based on the resistivity model, we can determine the distance of saltwater intrusion toward the population settlement, the depth of the current intrusion layer, and the possible extension of the intrusion.

Geology of survey area

The survey location is along the West Flood Canal on the north coast of Semarang. Alluvial deposits of the quaternary age dominate the geology of the area. Based on the regional geological map, the alluvium deposits consist of clay, silt, and sand, with a mixture of gravel due to erosion upstream (Thaden et al., 1975) (Figure 2). This sediment is not too compact, with a reasonably good groundwater potential.

The coastal area is relatively low with river mouths and tributaries, so the water will rise if there is a high tide (Suhelmi and Prihatno, 2014). The lithology of alluvial deposits, which vary from gravel to clay, also makes it easier for seawater to flow to the mainland (Rochaddi and Pratikto, 2006).

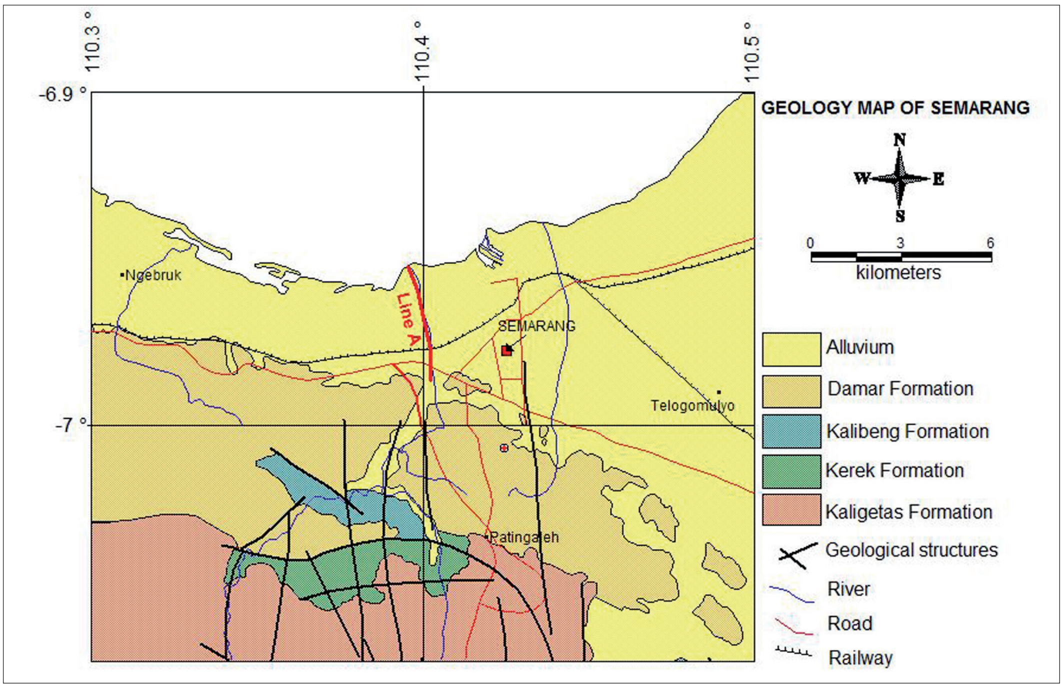

Figure 2. Geology Map of Semarang. Source: (Thaden et al., 1975). The bold red line is the survey line.

METHOD

The electrical resistivity tomography (ERT) method aims to determine subsurface resistivity distribution. Compared to other geophysical methods, the ERT provides relatively higher resolution of sub-surface images for shallow and small areas of studies. Figure 4 is the simple flow chart of the processing steps. During the survey, electrical responses on the surface are obtained by injecting an electric current into the earth. The potential difference is measured using two electrodes placed at certain distances. From the value of this potential difference and current, the apparent resistivity value below the surface of the measurement area is obtained. The difference in the measured resistivity values can reflect the subsurface variation of the earth. Specific resistance or resistivity is the ability of a material to conduct an electric current. The greater the value of the resistivity of a material, the more difficult it is for the material to conduct electricity. The nature of electrical current in rock is influenced by porosity, water trapped in rock pores, and mineral content. Briefly, it allows distinguishing between freshwater and saline, between sandy aquifers and clay rocks, or between porous aquifers and solid rocks (Kirsch, 2009). Therefore, the resistivity method is the most suitable for detecting seawater intrusion.

There are various electrode array methods used in electrical surveys. Among them are the three most commonly used: Wenner, Schlumberger, and dipole-dipole arrays. Although the Wenner and Schlumberger arrays are more popular and used, the dipole-dipole arrangement has balanced sensitivity to depth and horizontal resistivity variation (Furman et al., 2003; Okpoli, 2013). Therefore, our survey used the dipole-dipole configuration, which is particularly well suited for the shallow target of groundwater study. In a dipole-dipole array, it has the same potential and current electrode distance of 'a' and the distance between the current and potential electrodes of 'n' (Figure 3). The size of 'a' is fixed, while the factor of 'n' is increased from 1 to about 6 to increase the depth of investigation (Telford et al., 1990).

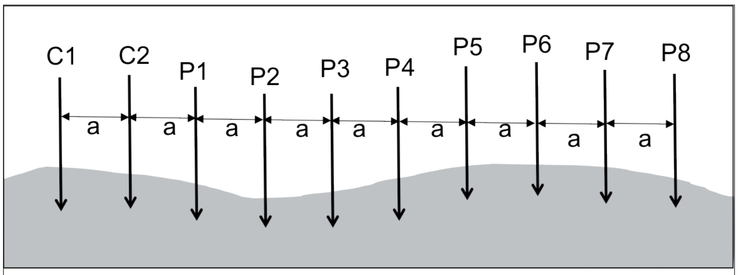

Figure 3. Configuration of Multielectrode Dipoles with 8 Channels of Receiving Electrodes.

The measurement data obtained are V/I data, apparent resistivity, output current, error, and the coordinates of each electrode. The data is in the Supersting file with the format (.stg). The Supersting data are processed with EarthImager 2D software. The result is a 2D model of the sub-surface resistivity. There are several criteria for selecting the 2D cross-sectional model. First, the general guideline in inverse modeling requires the error value should be 5% or less. Second, the convergence curve of the resistivity inversion graph should be converged as an indication that the inversion algorithm is reaching a stable solution. Third, the data distribution on the cross-plot of measured vs. predicted apparent resistivity should be approximately linear. However, the cross-plot is the most difficult to control since it depends on the heterogeneity of the subsurface geology. What we can obtain from the cross-plot is that if the data points are scattered randomly, it may indicate that the data is noisy or the sub-surface geology is complex. Moreover, an approximately linear cross-plot means that our data has little noise, or the subsurface may have simple geological conditions. Therefore, an almost linear cross-plot is always preferred.

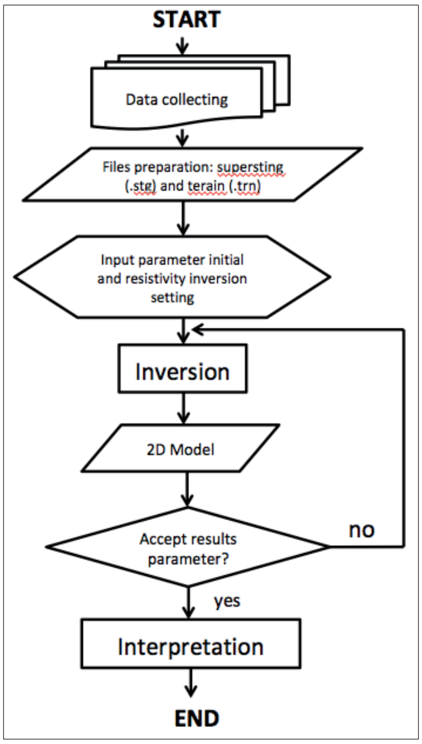

Figure 4. Flowchart of data processing and modeling.

RESULTS AND DISCUSSION

Geo-electric data acquisition was performed using the Geo-electric SuperSting model R8/IP-56 along the side of the West Flood Canal. This report presents a result from one measurement line with an electrode spacing of 25 meters. The line is perpendicular to the coastline (in Figure 2) and has a track length of 3500 meters.

Our final model has an error value of 3.81%. The convergence curve of the resistivity inversion graph converged well (Figure 5). The data distribution on the cross-plot of measured vs. predicted apparent resistivity is linear (Figure 6).

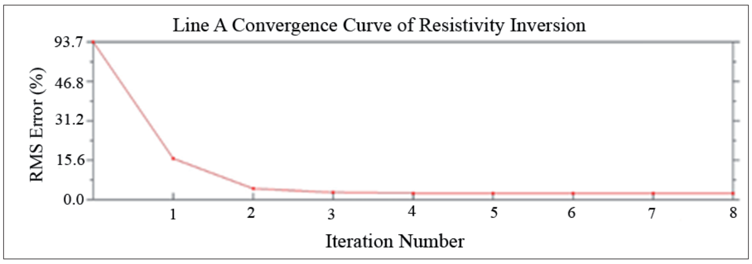

Figure 5. Convergence curve of resistivity inversion.

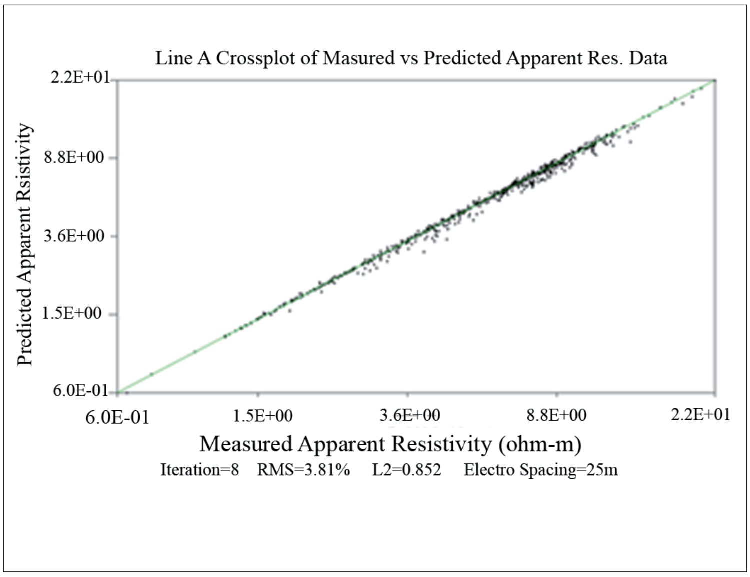

Figure 6. Crossplot of measured vs. predicted apparent resistivity.

The inversion model (Figure 7) shows a dark blue rock layer near the surface with a low resistivity value of less than 3 Ohm.m. As the geological map suggests, the surface layer is an alluvium layer and a mixture of soft clay. At the surface in the south part, the layer is bright blue with a resistivity value of between 3 and 8.5 Ohm.m, which can be associated with a layer of silt (Kirsch, 2009; Telford et al., 1990).

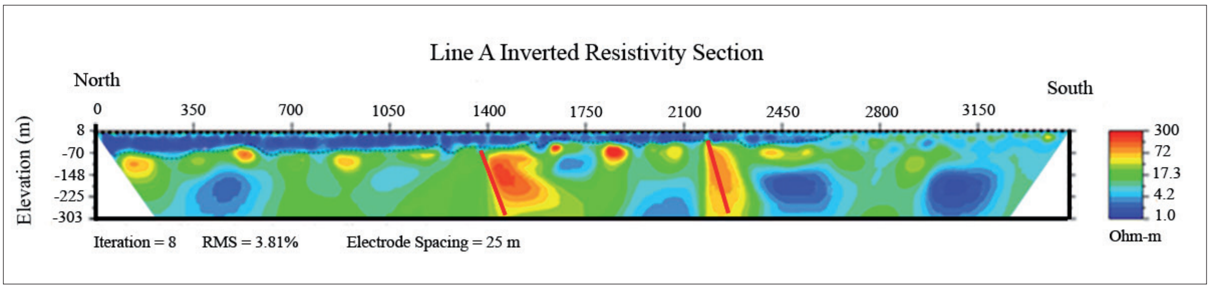

Figure 7. The 2D resistivity model of Line A. Red lines represents the structures due the high resistivity columns.

The distribution of small resistivity values near the surface (dark blue) is associated with the alluvial layer. Since seawater has a very small resistivity compared to freshwater, rocks intruded by seawater would have even smaller resistivity (Kirsch, 2009). Hence, this layer is very likely to have seawater intruded. This layer is evenly distributed at the top from point 0 to 2600 meters landward, with a maximum depth of 78 meters at the coast area and thinning to the south. Another thing to consider is the fact that the line of survey is along the side of a canal, which could be another pathway of seawater flow to landward. The extent of the area is also coincident with the intrusion reported previously.

An investigation at Kaligawe, about 1500 m from the coastline, indicated a seawater intrusion (Setyawan et al., 2016). Tanah Mas and Panggung Lor at the east side of the survey line, about 1000 m from the coastline, have seawater intrusion at a depth of less than 25 m (Ardaneswari et al., 2016; Putro et al., 2016). The intrusion was very shallow (5 – 20 m depth) at Kota Lama, about 2000 m from the coastline (Supriyadi et al., 2021).

The deeper part of the model indicates an almost uniform pattern. The green layer, which has a resistivity value of 8.5 - 50 Ohm.m, dominates the region. With such a resistivity value, the layer is considered a sandy clay layer. Such a layer is also susceptible to seawater intrusion in areas close to the coast and if there is a slight change in the fresh-saline interface. Several closures of the highest and lowest resistivity appear within this green layer. The three extensive low-resistivity closures with a depth of more than 150 meters might not related to the seawater intrusion. Nevertheless, more investigation is essential at the three locations: 500 m, 2500 m, and 3100 m from the coastline.

There are several mini closures of high resistivity value in the 50 - 100 Ohm.m (yellow-red) near the top layer, which might be composed of fine sand or sand. In addition, two columns of high resistivity appear at about 1400 and 2200 meters from the coastline. The layer with resistivity values of 100 - 300 Ohm.m could be assumed to be a sandstone column. Moreover, these columns might also indicate two faults within the Damar Formation. Even though a fault slip can temporarily increase the permeability of the fault zone (Gudmundsson, 2000), a fault usually acts as a barrier to groundwater flow or reduced permeability (Lapperre et al., 2019). A stable isotope study of groundwater recharge in Semarang indicated that the groundwater at the northern fault is not affected by groundwater from higher areas of the southern Semarang Basin (Sudaryanto and Lubis, 2011). Therefore, the fault existence is an additional factor that the northern part would be more susceptible to seawater intrusion.

Our electrical resistivity tomography results indicate the distance of seawater intrusion distribution from the coastline, which corresponds well with previous studies of seawater intrusion at some local spots. Hence, our concern is that the intrusion will spread and worsen in the future. Numerical modeling studies predicted seawater intrusion up to 4 km from the coastline at this middle part of Semarang in 2035 (Lo et al., 2021; Rahmawati et al., 2013). Recently, a hydrochemical analysis of water from the well at Mesjid Agung, about 3 km from the coastline and 1 km east of the canal, indicated high salinity (Wijatna et al., 2019). More extended subsurface investigations are recommended on the west and east sides of the canal and even further inland. The result of all subsurface studies can be applied as a foundation for further research on predicting and modeling seawater intrusion. Eventually, the acquired information should be available for future policy in city development.

CONCLUSIONS

The north coast of the Semarang area has a high occurrence of seawater intrusion due to the increasing groundwater extraction and subsidence. To obtain information on how far the intrusion influences the city, we applied electrical resistivity tomography (ERT) along the side of the West Flood Canal. Based on the ERT survey data, we acquire the subsurface resistivity distribution. Our 2D model identified a high potential for intrusion layer based on a resistivity value of less than 3 Ohm.m. The layer is extended to

2600 meters from the coastline, with a depth of 70 meters at the coastline and thinning to zero at about 2600 meters inland. In the middle of the profile, two high-resistivity columns might represent faults. The faults within the layer carrying groundwater caused the groundwater from higher ground (south) not to flow freely to the coastal area. The structure's existence might result in higher vulnerability to higher saltwater concentration in the study area.

AUTHOR CONTRIBUTIONS

Conceptualization, LH and YS; data processing and modeling, ARU and YS; analysis, LH, YS, MH, ARU; writing and editing, ARU, LH, MH. All authors have read and agreed to the published version of the manuscript.

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