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GIS and RS-Based Analysis of Water Pollution Potential Caused by Acid Mine Drainage in Samarinda, Indonesia

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ABSTRACT

Large-scale mining activity is the major environmental issue, including water pollution caused by Acid Mine Drainage (AMD). Samarinda, which is located in the province of East Kalimantan, Indonesia, has open pits and acid contributing land as a source of AMD pollutants. The potential AMD pollution can be assessed by utilizing Geographic Information System (GIS) and Remote Sensing (RS), which are considered reliable tools for measuring, mapping, monitoring, and model making for an area. The variables used in this research are void distribution, land cover, soil type, rainfall, topography, water body, and groundwater. The integration of these variables is used to analyze the potential of AMD pollution to water bodies by acid contributing land. Meanwhile, the void distribution and groundwater integration data are used to analyze the potential of AMD pollution to groundwater by voids. The overlay method is employed to analyze the potential spatial patterns of AMD pollution in the study area. The results show the high potential of AMD pollution to water bodies, specifically in the districts of Samarinda Utara, Palaran, and Sungai Kunjang. The high potential of AMD pollution to groundwater is found in the south delineation area, namely Palaran, Loa Janan Hilir, and Samarinda Seberang districts, with low and medium groundwater depth categories (20 - 70 and 50 - 150 MBGL). The spatial pattern of AMD pollution was random with the geometric arrangement of AMD pollution in the form of clusters.

1. INTRODUCTION

Acid Mine Drainage (AMD) has become a global issue due to its negative impact on the environment, specifically on water. The heavy metal contents in the AMD stream such as arsenic, cadmium, copper, silver, and zinc, are percolated from tailing wastewater and the mill process (Luo et al., 2020). Not only the metals fill the voids but also infiltrate the groundwater. Then, the AMD formed from the residual rock containing sulfide can flow into public waters such as rivers and lakes (Miller, 1997). If the metal content level exceeds the Criterion Maximum Concentration (CMC), it may cause deterioration of aquatic biotas, threat to human life, and biodiversity loss (Suryaningtyas, 2010; Ngure et al., 2014; Mulopo, 2015). The formation of AMD has an extensive impact beyond the life of the mine (Rambabu et al., 2020).

The period from 1970 to 2009 was the era of the mining boom in Indonesia. Large-scale mining using the open-pit method is one of the damaging factors with an impact on environment, including deforestation and land degradation (Subowo, 2011). Mining activities using this method also increase the pollution potential, including water contamination of AMD (Hidayat, 2017). Samarinda City in East Kalimantan Province is a city abundant in mining areas. It has several coal mining areas with a total area of 432.17 km² or equivalent to 58.5%. In this situation, Samarinda has the potential of AMD pollution to increase continuously.

In response to this problem, we aimed to analyze the potential of AMD pollution using GIS-RS. GIS-RS is considered more effective than other non-spatial mathematical models due to several advantages, including (1) the ability to simulate, predict, and describe environmental events based on space and time, (2) faster processing times, and lower costs (Jaya, 2012). Previously, the GIS-RS method was used to examine the characteristics of erosion and water sediment in watersheds (Norman et al., 2008). In 2017, the GIS-based modelling method was used to analyze mining-induced hazards by Suh et al. (2017). Then, Yucel et al. (2017) examined metal pollution levels on Etili Turkey open field using GIS-RS. GIS-RS analysis based on surface water movements in mining areas has the potential to design the placement and networks of drainage control infrastructure such as pumps, safety berms, and pipes (Song et al., 2008; Sunwoo et al., 2007). Song et al. (2008) analyzed the placement of pumping facilities for a tailing dam using the GIS method. Sunwoo et al. (2007) built the formation of a water system for an open pit mine, and they analyzed the location of the drainage line and safety berm. Therefore, data processing and modelling using GIS is an effective method to design the development of the mining area.

The spatial distribution of pollutants is very important to manage contamination (Chen et al., 2021). In order to take effective and scientific environmental protection measures, it is urgent to provide full knowledge on the pollution status and spatial distribution characteristics of the open field. By using GIS-RS, firstly, we analyze the AMD pollution potential to water bodies by acid contributing lands in Samarinda City. We present several data related to the AMD pollution potential to groundwater by inactive mine pits, the potential spatial pattern of AMD pollution in the coal mining area of Samarinda City. The GIS and RS-based environmental database will serve as a reference study for our future work.

2. THEORY AND METHODOLOGY

2.1. Study area

Samarinda City (Fig. 1) is located between 117°03'00" - 117°18'14" East Longitude and 00°19'02" - 00°42'34" South Latitude and it is bordered by Kutai Kartanegara Regency on each side (BPS Samarinda, 2019). Since 2010, Samarinda City has been divided into 10 sub-districts, namely Palaran, Samarinda Ilir, Samarinda Kota, Sambutan, Samarinda Seberang, Loa Janan Ilir, Sungai Kunjang, Samarinda Ulu, Samarinda Utara, and Sungai Pinang. The widest sub-district is Samarinda Utara with an area of 229.52 km² and the narrowest is Samarinda City with an area of 11.12 km². Besides, Samarinda City also has a coal mining area with a total area of 432.17 km² or the equivalent of 58.5% of the city's total area (BPS Samarinda, 2019). The mining work area analyzed in this study is a mining area that already has a IUP (Mining Business License) (in Indonesian: *Izin Usaha Pertambangan)* or a PKP2B (Coal Mining Concession Right Holder) (in Indonesian: *Pemegang Karya Pengusahaan Pertambangan Batubara*).

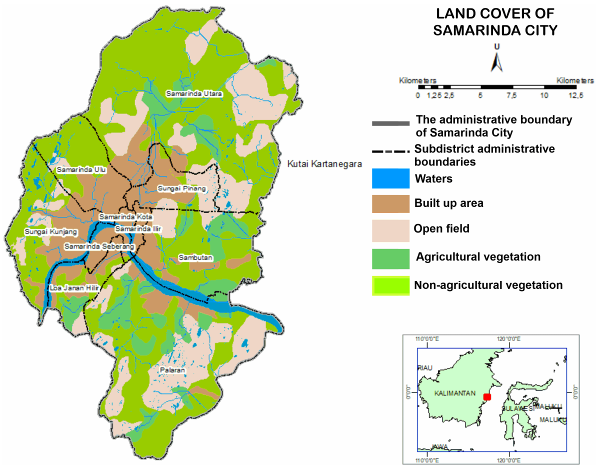

Fig. 1. Land cover map of Samarinda City.

The topography of Samarinda City has an average height of <50 MASL (Meters Above Sea Level). The high average daily rainfall in Samarinda City in 2019 was recorded in the Districts of Samarinda Kota, Samarinda Ilir, Samarinda Seberang, and parts of the Samarinda Ulu, Sungai Kunjang and Loa Janan Hilir sub-districts, with rainfall values of 7.24-7.29 mm³/day (BPS Samarinda, 2019). The Mahakam River which is the main river in Samarinda City has a dendritic pattern of river flow. In Samarinda City four types of soil are found, namely Entisol (36.59 km²), Inceptisol (488.37 km²), Oxisol (52.46 km²), and Ultisol (137 km²) (BBSDLP, 2016). The non-agricultural area covers 333.13 km². The agricultural area is of 72.38 km² and the open field extends up to 165.94 km². Meanwhile the built-up area is 130.77 km² and the water area is 36 km², being distributed in almost all districts. Open field is used to determine the distribution of acid contributing land in this study.

2.2. Methodology

Maxar Technologies satellite imagery 2018 extracted from Google Earth, was used to obtain the distribution of inactive voids, land cover classification, and field verification using the generalization method. The generalization method is used to import data by selecting the type of appearance throughout several stages, including selection, simplification, combination, and emerging and displacement (Hisanah et al., 2015; Stoter et al., 2009). SHP map (shapefile) showing licensed coal mining area (Ministry of Energy and Mineral Resources in Indonesia, 2020), Samarinda City administrative boundaries (BIGR Indonesia, 2019), and Samarinda City soil types (BBSDLP, 2016) were employed to obtain information on the distribution of voids and soil type classification. Meanwhile, soil acidity (pH), rainfall (BPS Samarinda, 2019), and GDEM data were used to examine the information of soil pH classification, surface runoff volume, watershed area, and topography.

The variables used in this study are soil type, land cover, water body, rainfall, topography, inactive mine voids, and groundwater (Fig. 2).

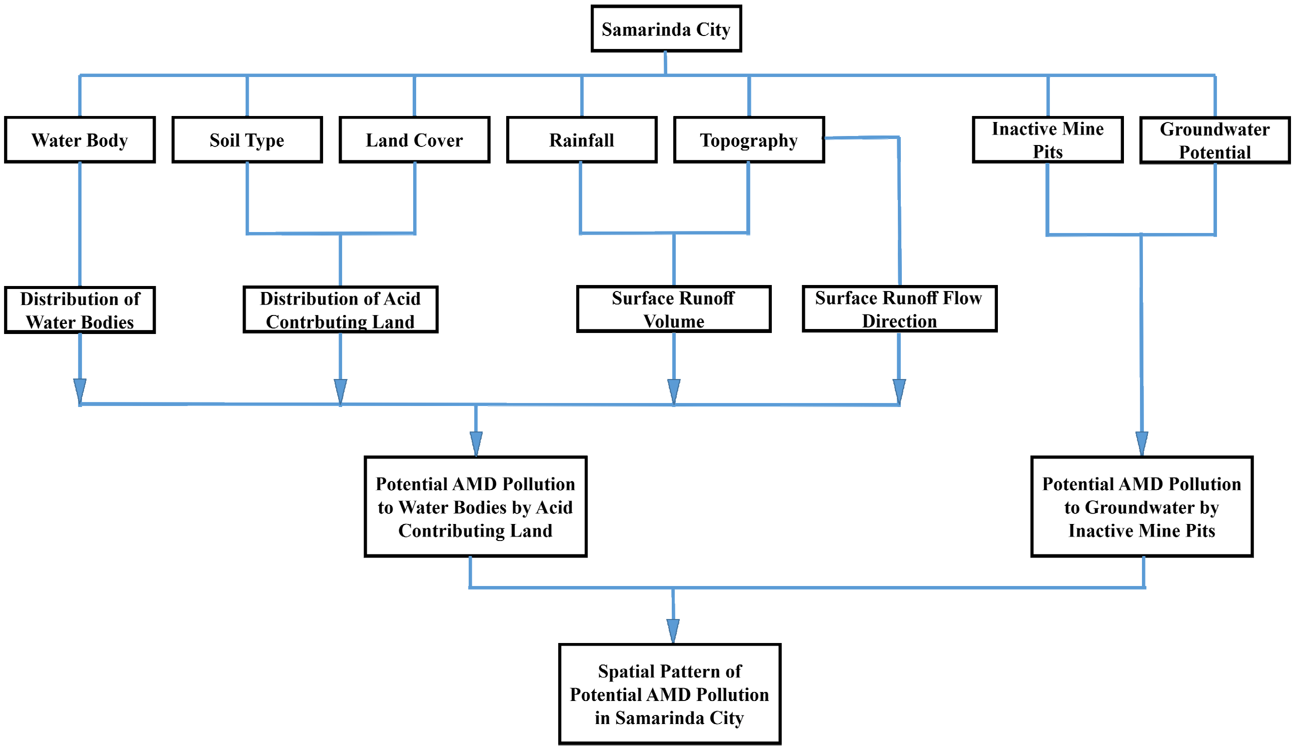

Fig. 2. Research workflow.

First, the information of soil acidity (pH) classification was obtained using the USDA (United States Department of Agriculture) soil taxonomy guideline analysis (USDA, 1999). Then, from the land cover variable, information on the distribution of open field was obtained using digitization from the Google Earth Imagery. The data layers were integrated using the overlay method to obtain the distribution information of acid contributing land. From the variable of water body, the distribution was obtained using digitization from Google Earth and DEM (Digital Elevation Model) data. From the rainfall data, the concentration and intensity of rainfall was obtained using the calculation of the rational method (Chow et al., 1998; Na and Yoo, 2018). From the topography of Samarinda City, information about the watershed area, surface runoff flow direction was obtained using hydrology tools in ArcGIS software (Vu et al., 2021). The watershed area, the concentration and intensity of rainfall were integrated to obtain the surface runoff volume using the following equation of the rational method. This equation considers the watershed area (A), the amount of rainfall intensity (I), and the runoff coefficient value (C) (Ramke, 2018).

$$Qp = 0{,}278\ C \times I \times A \qquad \text{Eq. (1)}$$

The distribution of acid contributing land, the distribution of water bodies, the surface runoff volume and direction were integrated using the overlay method to obtain the information of AMD pollution to water bodies by the acid contributing land (Vu et al., 2021).

Next, the information of potential AMD pollution to groundwater by inactive mine pits was collected by integrating the distribution of inactive mine pits and groundwater potential obtained from Maxar Technologies satellite imagery 2018. Ultimately, the information of potential AMD pollution to water bodies by acid contributing land and potential AMD pollution to groundwater by inactive mine pits was integrated to conclude the spatial pattern of Acid Mine Water (AAT) pollution in the coal mining working area of Samarinda City.

Field verification was carried out by documenting the survey object. The survey was conducted on the Samarinda Utara, Samarinda Ulu, Samarinda Kota, Samarinda Ilir, Samarinda Seberang, Kunjang, Pinang, Loa Janan Hilir, Sambutan, and Palaran Districts. The survey object of acid contributing land and mine voids are 41 and 17 sample points, revealed in Figure 3 (a-b).

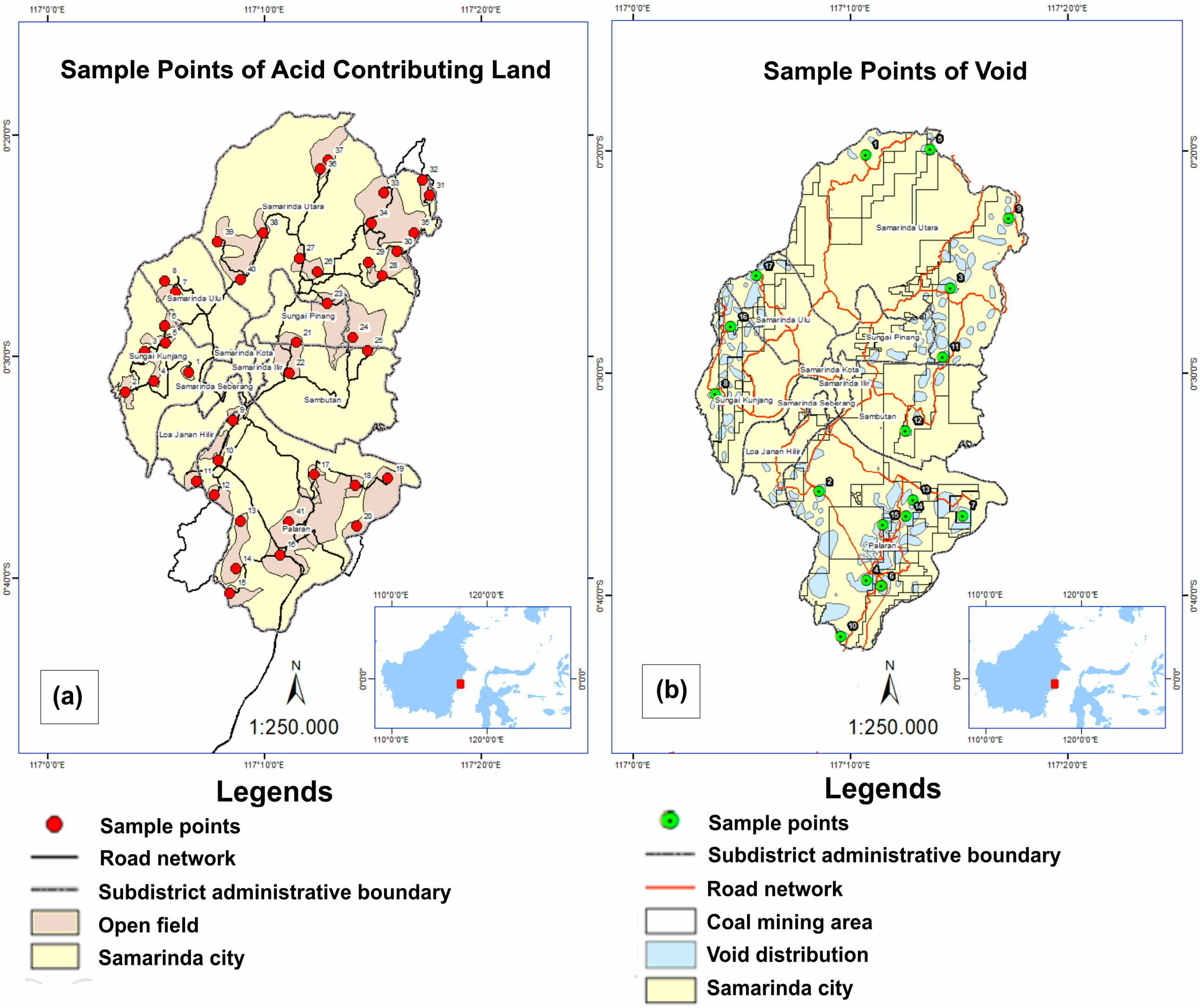

Fig. 3. The map of (a) acid contributing land and (b) void sample points in Samarinda City.

3. RESULTS AND DISCUSSION

The Information of AMD potential contamination on water bodies is expressed as the ability level of the open field to expose its acidic content (mostly iron sulfides resulting in sulfuric acid) and pollute the surrounding water bodies (Agboola et al., 2020; Iatan, 2021). The figure below (Fig. 4) is the result of the integration of acid contributing land and soil acidity classification. Based on soil type, soil acidity is divided into Ultisols (pH<5), Oxisols (pH 5 - 5.7), Inceptisols (pH 5.8-6.2), Entisols (pH 6.3 - 7), as listed in Table 1 (USDA, 1999).

Figure 4 illustrates that Samarinda City is dominated by a low acidity open field (pH 5.8 - 6.2) which is located around the sub-district covering an area of 114.94 km^2. The southern area of the Samarinda City (Palaran district) with an area of 21.93 km^2 has a pH value of 5 - 5.7.

In addition, areas with a high acidity (pH < 5) are present in the south and northwest of Samarinda City (21.15 km^2), precisely in the southern part of Palaran and Samarinda Ulu. The neutral territory extends only up to 10.24 km^2 in the southeast of Samarinda City. Therefore, Inceptisol is the main soil type in the city of Samarinda.

The overlay method is used to combine two or more pieces of information on the map to produce new information (Raghuvanshi et al., 2015). This information is obtained through data processing of acid contributing land distribution, waterbodies distribution, and surface runoff volume. The higher the surface runoff volume and the degree of acidity in the study area, the higher the potential for the surrounding water bodies to be contaminated with AMD, resulting in areas that have a low volume of surface runoff flow with a high pH, and others with a high volume of surface runoff flow with a low pH, which is in the middle level of potential contamination area.

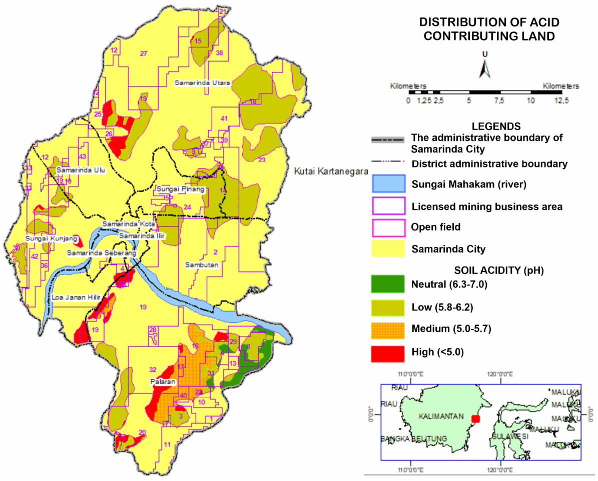

Fig. 4. Distribution of acid contributing land with acidity parameter in Samarinda City.

Table 1 reveals a classification of potential pollution based on soil acidity (pH) and surface runoff flow volume (USDA, 1999; Murtiono, 2008).

Table 1. Classification of AMD potential pollution by acid contributing land *(source: USDA, 1999; Murtiono, 2008)*.

Category	**Soil acidity (pH)**	**Surface runoff flow volume (mm^3/sec)**	**Soil type**
Neutral	6.3 – 7	<1	Entisol
Medium	5 – 6.2	1 – 3	Inceptisol
High	<5	>3	Ultisol

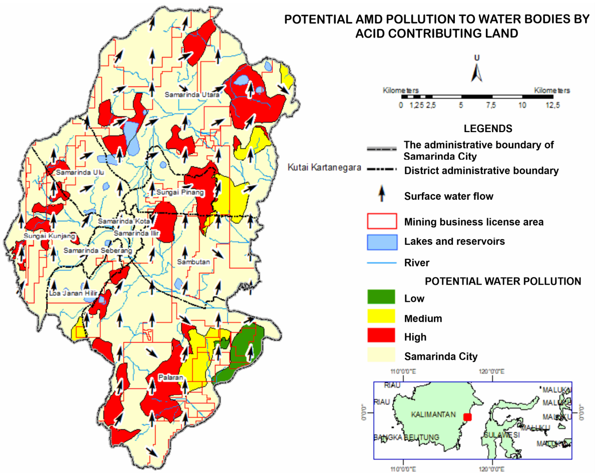

Fig. 5. Potential AMD Pollution to water bodies by acid contributing land.

Figure 5 shows the information of the potential AMD pollution to water bodies by acid contributing land. Samarinda City is dominated by areas with a high potential AMD pollution to the surrounding water bodies.

Besides, the arrow symbol indicates the flow direction of surface water containing acid from acid contributing land. Hence, the flowing water bodies become contaminated with AMD. Meanwhile, the river flow in Samarinda City has 5 river stream orders, of which Mahakam River is the largest. Flow direction affects pollution, watershed area, and rainfall (concentration and intensity) were integrated to conclude surface runoff information. The largest watershed area in Samarinda City is of 258.42 km^2 and is found in the districts of Samarinda Ulu, Samarinda Kota, Samarinda Ilir, Samarinda Seberang, Sungai Kunjang, Loa Janan Hilir, Sungai Pinang, Sambutan, and Palaran. The narrowest watershed area, of only 2.39 km^2, is found in Samarinda Utara District.

The largest daily rainfall value is in the districts of Samarinda Ulu, Samarinda Kota, Samarinda Ilir, Samarinda Seberang, Sungai Kunjang, Loa Janan Hilir, Sungai Pinang, Sambutan, and Palaran, which is 7.23 mm^3/day. The smallest daily rainfall value is in Samarinda Utara District, which is 7.06 mm^3/day.

Samarinda City is dominated by a high volume of surface runoff which has an area of 511.71 km^2. Areas with medium volume of surface runoff (83.95 km^2) were found in Samarinda Utara, Loa Janan Hilir, Sambutan, and Palaran Districts. Areas with low surface runoff volume (33.05 km^2) were found in Samarinda Utara, Sambutan, and Palaran Districts. The direction of surface runoff flow is also useful for knowing the probability of surface runoff flow with a certain volume and acidity. Thus, Figure 5 shows that the surface runoff flow direction is towards the north of Samarinda City, precisely, Samarinda Utara District. No direction of water flow was found to the south of Samarinda City. Using overlay method, The highest potential of AMD pollution was obtained in districts with a large open field distribution, namely Samarinda Utara, Palaran, and Sungai Kunjang Districts. Open-pit coal mining produces a large amount of solid waste or heavy metals ion, which enter the surface layer of the soil under the action of rainwater intrusion and erosion (Plyatsuk et al., 2019). However, the topsoil migrates under the influence of surface run-off, which leads to the accumulation of soil pollution near the mining area (Zwolak et al., 2019).

The potential AMD pollution to groundwater is expressed as the level of the void ability to infiltrate acidic content and cause pollution the surrounding groundwater (Iatan, 2021). The overlay method is used to combine some information on the map to produce new information (Vu, 2021). The potential AMD pollution to groundwater by inactive void is categorized as high, medium, and low (USDA, 1999).

Figure 6 shows that Samarinda City is dominated by low aquifer depth areas 20 – 70 MBGS

(Metres Below Ground Surface). The low aquifer depth areas are found in all districts in Samarinda City, but more concentrated in Samarinda Utara district. Medium aquifer depth areas (50 – 150 MBGS) are found in the districts of Samarinda Ulu, Sungai Kunjang, Samarinda Utara, Sambutan, and Palaran, with the largest concentration in Palaran. In addition, non aquifer areas are found in Samarinda Utara, Samarinda Ulu, Sungai Kunjang, Samarinda Seberang, and Loa Janan Hilir, with the largest concentration in Samarinda Utara District.

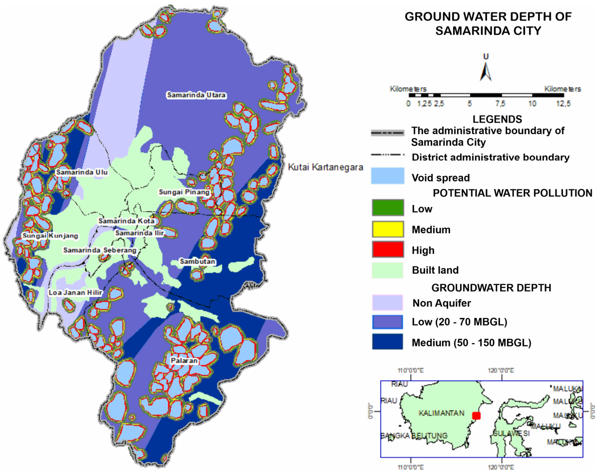

Fig. 6. Ground water depth of potential AMD pollution to groundwater by void.

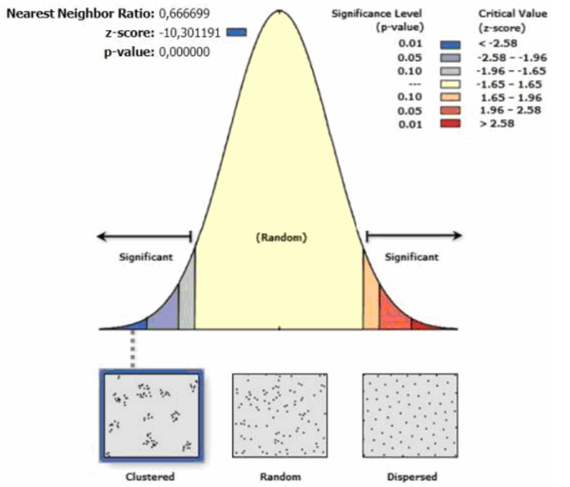

Fig. 7. Result of NNA analysis of void distribution pattern in Samarinda City.

The potential AMD pollution to groundwater is classified by the distance of AMD pollution, namely high (<100 m), medium (100 – 200 m), and low (200 – 300 m) (Sakala et al., 2018). It also shows the information of potential AMD pollution to groundwater by voids. Every void has 3 ring buffers that indicate the category of potential pollution distance to the pollutant source. The AMD surrounding the voids around Sungai Kunjang, Sungai Pinang, Samarinda Ilir, Samarinda Seberang, Loa Janan Hilir, Sambutan, and Palaran, has the potential to contaminate groundwater sources in the built-up area. The built-up areas include settlements, industrial buildings, business centres, and some space for community activities. Also, the distribution of voids in Samarinda City has a cluster pattern as shown in Figure 7, which was tested by Nearest Neighbour Analysis (NNA) (Sui and Hugill, 2002).

The delineation process of the void distribution cluster in the research area is divided into 3 delineation areas located in the west, east, and south of Samarinda City (Fig. 8).

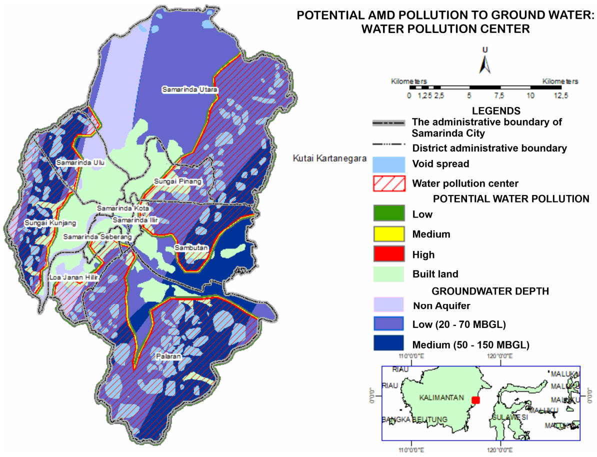

Fig. 8. Water pollution cluster map of potential AAT pollution to groundwater by void.

The figure below shows that the western delineation area covers the districts of Samarinda Ulu and Sungai Kunjang. The eastern delineation area can be observed in the districts of Samarinda Utara, Sungai Pinang, and Sambutan. The southern delineation area is noted in the Palaran and Loa Janan Hilir districts. The eastern and southern delineation areas have low groundwater depth, whilst the western delineation areas have medium groundwater depth which is opposite non aquifer areas. The western delineation area drains AMD into the low aquifer area. The built-up area in Samarinda Ulu and Sungai Kunjang sub-districts has low potential pollution because most of the area is located in non-aquifer areas. In general, the medium groundwater depth area tends to drain AMD to non aquifer areas. The research analysis also included a temporal analysis using the initial year of mining activity by assuming the voids and open field have already existed and polluted the environment. Figure 9 also explained that the coal mining work areas, which began operating in 2004 – 2008, are located in the districts of Samarinda Utara, Samarinda Ulu, Loa Janan Hilir, and Palaran. In addition, the mining areas that became active in the period 2015-2019 are spread across the districts of Sungai Pinang, Samarinda Ulu, Palaran, and Samarinda Utara.

The delineation process (Fig. 8) divides Samarinda City into 3 delineation areas located in the west, east, and south. Then, this was integrated with potential AMD pollution to water bodies by acid contributing land through the overlay method. Each delineation area is a source of pollution consisting of voids and acid contributing land, while the three-ring buffers around it indicate the distance of polluted areas. The information regarding the spatial pattern explains the geometric arrangement of AMD potential contamination (Li et al., 2018). There are three types of spatial patterns to explain the geometric arrangement of the AMD pollution, namely linear, radial or concentric pattern, along with the random pattern (Fellmann et al., 2007). The spatial pattern of AMD pollution potential in Samarinda City is random, as shown Figure 9.

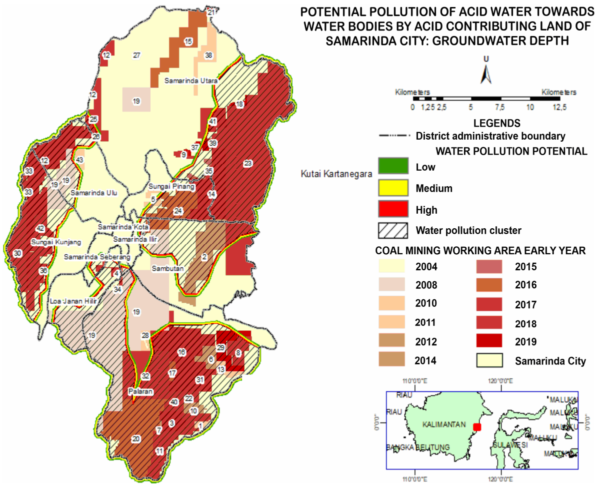

Fig. 9. The spatial pattern of AAT pollution in the coal mining area of Samarinda City.

The concept of a random spatial pattern means that the growth of an area is not influenced by conditions and the surrounding area (Lee and Wong, 2001). The spatial distribution of pollutants describe the scientific temporal variation of pollutant to formulate effective management in future research (Tezel et al., 2020). Areas with high AMD pollution potential are found in North Samarinda, Palaran, and Sungai Kunjang Districts, which represent the working area of the 31 coal mining companies. In addition, the direction of surface water flow is mostly towards the northern region, namely Samarinda Utara district. The AMD potential pollution to groundwater by voids is mostly noted in the southern delineation area of Samarinda City. The southern delineation area drains the AMD to the aquifer area, which is a source of groundwater from built-up area in the districts of Palaran, Loa Janan Hilir, and Samarinda Seberang. Spatial distribution of pollutants is related to the surface runoff and the location of potential pollution resources (Suh et al., 2017).

4. CONCLUSIONS

GIS and RS-based analysis of water pollution potential by Acid Mine Drainage in Samarinda, Indonesia, was carried out for the first time. Waterbody pollution caused by acid contributing land is found in areas with high AMD pollution potential, especially Samarinda Utara, Palaran, and Sungai Kunjang Districts, which are the working areas of 31 coal mining companies. Based on the wide distance of the pollution to the built up area, the groundwater pollution caused by voids is located in the south of Samarinda City. The southern delineation area drains the AMD into the aquifer area, which is a source of groundwater for the built-up area in the Palaran, Loa Janan Hilir, and Samarinda Seberang Districts (low and medium groundwater depth). The spatial pattern of potential AMD pollution in the coal mining area of Samarinda City is random, based on the initial year of mining activities as a benchmark. Ultimately, we offer a scientific reference for the future research to manage water pollution of Samarinda City mine area.

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