Leachate pollution management to overcome global climate change impact in Piyungan Landfill, Indonesia

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Abstract. Environmental problems associated with the landfill system are generated by domestic waste landfills, especially those with open dumping systems. In these systems, waste degrades and produces some gases, namely methane gas (CH₄) and carbon dioxide (CO₂), which can cause global climate change. This research aimed at identifying the areas that experience groundwater pollution and the spread pattern of leachate movement to the vicinity as well as to develop a leachate management model. The Electricity Resistivity Tomography (ERT) survey is deployed to assess the distribution of electrical resistivity in the polluted areas. In this study, the groundwater contamination is at a very low in the aquifer zone, i.e., 3-9 Ωm. It is caused by the downward migration of leachate to water table that raises the ion concentration of groundwater. These ions will increase the electrical conductivity (EC), i.e., up to 1,284 μhos/cm, and decrease the electrical resistivity. The leachate spreads westward and northward at a depth of 6-17 m (aquitard) with a thickness of pollution between 4 and 11 m. The recommended landfill management model involves the installation of rainwater drainage, use of cover and baseliner made of waterproof materials, and massive waste treatment.

1. Introduction

Global warming is no longer a problem of the future but a problem that the world’s population is facing today. Various studies prove that global warming and climate change affect the annual precipitation in different countries. Viglizzo et al. [1] revealed that these two phenomena increase the annual precipitation in Argentina. In line with these results is the study performed by Plummer et al. [2], which found a corresponding increase in the annual precipitation in Australia and New Zealand. On the contrary, Mason [3] reported that global warming decreases the annual precipitation in Africa. The studies carried out by Zhai et al. [4] in China and Masoudi and Afrough [5] in Iran also proved the negative correlation between climate change and precipitation.

The search in the International Disaster Database results in a considerable number of natural disasters in Java Island that occurred in the rainy season, as discovered by Naylor et al. [6]. This study concludes that in the next 40 years, global warming will cause an early end to the rainy season in Central Java. Therefore there will be a shorter-duration of the rainy season in that region. On the other hand, while declining in the dry season, the amount of precipitation in rainy season will likely tend to increase.

The quantity of the resultant leachate is significantly influenced by water input from outside; most of which comes from rainwater. At the same time, the presence of water in landfills also relies heavily

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on the operational aspects, such as the application of soil-based cover, the slope of the surface, the climatic condition, and the ability of soil and waste to retain water vapor (i.e., ‘field capacity’). When storage capacity is exceeded, gravity causes water to flow downward and out of landfills and thereby, forms leachate [7].

Having a closer look at the characteristics of the surrounding materials leachate can become a problematic phenomenon because it can flow both in lateral and vertical ways. The discharge and the quality of leachate formed in waste piles highly fluctuate depending on precipitation and the characters of the waste itself. The relationship between the amount of rainfall and leachate discharge needs to be identified before designing the capacity of leachate treatment plan. Furthermore, the pollutant load (of leachate) used in the design has to be carefully defined.

2. Methods
This research used the Electrical Resistivity Tomography (ERT), particularly the Schlumberger electrode array, to obtain a primary data from direct measurement in the field. ERT assesses the materials of the underground layers based on the nature of their resistivity [8]. The electrical resistivity ($\rho$) was calculated from electrical current ($I$) and potential difference ($V$). Both of which were measured directly in the field [9] by injecting an electrical current beneath the ground through pairs of current electrodes (C1, C2) and potential electrodes (P1, P2) [10]. The location of the geoelectrical sounding is presented in Figure 1.

2.1. Data Acquisition
The electrical current was injected through electrodes arranged in Schlumberger configuration (Figure 2). As depicted in Figure 2, it flows through a circuit in which the current electrode pairs (C1, C2) were positioned in a purposed distance than the potential electrode pairs (P1, P2). The wider distance between the current electrode pairs (AB or L) was wider to allow for measuring the electrical resistivity of deeper materials. Meanwhile, the distance between the potential electrodes (MN or a) was widened only when the potential difference becomes difficult to measure or, in other words, when the sensitivity of the measuring instrument decreases [11].
Figure 2. An electrical circuit formed by the arrangement of electrodes in Schlumberger configuration

2.2. Data Processing
The data acquisition above resulted in a set of data on electrical current (I) and potential difference (V) [12]. This research however required pseudo-electrical resistivity instead of these two data. Hence, these two data was formulated into the following equations to obtain the values of the pseudo-electrical resistivity (ρa):

\[
R = \frac{V}{I}, \quad (1)
\]
\[
\rho_a = \frac{V}{I} \cdot k, \quad (2)
\]
\[
\rho_a = R \cdot k. \quad (3)
\]

The pseudo-electrical resistivity was converted to the actual electrical resistivity using an inverse modeling technique provided by software Res2DINV.

2.3. Data Analysis Technique
The leachate pollution is indicated when the measured electrical resistivity is lower than the expected range of related materials. For instance, groundwater (freshwater) aquifer with an electrical resistivity of 10-100 Ωm will present a reading of lower than 10 Ωm if it is contaminated. Aside from depicting the distribution of resistivity value, the pseudo-section also provides the information in depth. The interpretation of the analysis results referred to the Regulation of the Ministry of Health No.492/MenKes/Per/IV/2010 on the Requisite of Drinking Water Quality.

3. Results and Discussion
The area of study involves the settlements situated in the north of the landfill. It represents the typical influence of landfill on the surrounding settlements. Although strategic, the location only left a small open space for measurement. Therefore, the maximum line for geoelectrical sounding was 121 m. Figure 1 shows the location of the geoelectrical sounding lines around Piyungan Landfill. In general, the water table of the study area was quite shallow, i.e., 3-15 m from the surface. The farther the area from the river system on the west is, the narrower the water table will be. Following those findings,
further analysis is required to discover the trend of groundwater flow pattern and the influence of river on the groundwater system around Piyungan Landfill.

The results of the geoelectrical sounding in the study area revealed that the indicator of pollution is presumably caused by the leachate of Piyungan Landfill seeping into the intermittent river system. This particular river system allows the infiltration of leachate-contaminated water into the soil. Infiltration then triggers percolation slowly, i.e., a process of fluid or liquid entering the groundwater system vertically. The contamination was indicated by the distribution of extremely low resistivity values, i.e., 3-9 $\Omega$m, in the aquifer zone. A significant decline in electrical resistivity is caused by the addition of leachate into the groundwater system that increases the ionic contents and hence, the electrical conductivity (EC) of the groundwater. Groundwater pollution in the study area was found at a depth of 6-17 m with a thickness of pollution between 4 and 11 m. The distribution and interpretation of resistivity values in this zone are presented in Figure 3.

Figure 3. The resistivity section and the interpretation results of geoelectrical sounding lines around Piyungan Landfill

The results of geoelectrical sounding discovered the pollution indications in the groundwater around Piyungan Landfill. These indications were then validated by groundwater quality analysis. The groundwater was sampled at a specified distance to the pollutant source, namely 100 m, 200m, 500m, 700 m, and 1,000 m. Pollution is observable from the presence of physical, chemical, and biological changes in the groundwater. Physically, groundwater pollution presents a change in electrical conductivity. Meanwhile, the chemical and biological changes are identifiable from the excessive presence of dissolved chemicals (i.e., nitrate) and microorganisms (i.e., pathogenic bacteria), respectively.

3.1. The description of groundwater properties in the study area is as follows:

3.1.1. Physical Properties. Based on the laboratory analysis results, the electrical conductivity in Piyungan Landfill varied between 982 and 1,284 $\mu$mhos/cm. It can be concluded that the groundwater in the study area contained many soluble and ionizable salts that increase the electrical conductivity (EC). Electrical conductivity (EC) depends on the presence of inorganic ions, valence, temperature,
and total and relative concentration. The measurement results indicated a high concentration of minerals in the groundwater. Referring to the Decree of the Indonesian Ministry of Health No.907/MENKES/SK/VII/2002, the maximum level of electrical conductivity allowed in drinking water is 1,000 µmhos/cm. Accordingly, the groundwater in some parts of the landfill does not meet the quality standard for drinking water.

\[ 2 \text{NH}_3 + 3 \text{O}_2^- \rightarrow 2 \text{NO}_2^- + 2 \text{H}^+ + 2 \text{H}_2\text{O} \]  
(4)

\[ 2 \text{NO}_2^- + \text{O}_2 \rightarrow 2 \text{NO}_3^- \]  
(5)

Based on the results of the laboratory analysis, the concentration of nitrate in Piyungan Landfill was 21.7-176 mg/L. This concentration is higher than 5 mg/L, indicating the presence of anthropogenic pollutants from human activities and animal feces. Consuming groundwater with high nitrate content reduces the oxygen-binding capacity of blood, particularly in infants younger than five months. This condition causes blue coloration of the skin (cyanosis), known as methemoglobinemia or blue baby syndrome [14]). Based on the Decree of the Indonesian Ministry of Health No.907/MENKES/SK/VII/2002, the maximum concentration of nitrate in drinking water is 50 mg/L. Therefore, the groundwater in some parts of Piyungan Landfill does not meet the quality standard for drinking water.

3.1.2. Chemical Properties. Nitrate (NO\(_3^-\)) is the main form of nitrogen in natural waters and a major nutrient for the growth of aquatic plants and algae. In addition to its stable character nitrates are highly soluble in water. This compound is produced by the perfect oxidation process of nitrogen compounds in the water. Nitrification is the oxidation of ammonia to nitrite (nitrification) by Nitrosomonas bacteria, followed by the oxidation of nitrite to nitrate (nitrification) by Nitrobacter. This aerobic process is a major step in the nitrogen cycle. These two genera of nitrifying bacteria are chemotrophs, meaning that they obtain energy from chemical processes. The reaction of nitritation is presented in chemical equation (4), while the stoichiometry of nitration is presented in equation (5) [13].

3.1.3. Biological Properties. Inspection of microbiological characteristics is necessary to assess the concentration of microorganisms in groundwater. Various types of pathogenic bacteria can be found in clean water supply system even though in low concentration. The contaminants from warm-blooded animals and human feces are highly detectable from the existence of these bacteria, which in this case function as indicator organisms. If these indicator organisms are found in water samples, there is a high possibility of water contamination by feces and pathogenic. On the contrary, the absence of indicator organisms signifies the minimum presence of feces and pathogenic bacteria. Water quality test using indicator organisms is the easiest way to determine water contamination by pathogenic bacteria routinely. Coliform, belonging to the family Enterobacteriaceae and the genus Escherichia, is a rod-shaped, gram-negative, highly motile, and non-spore forming bacterium. It is also facultatively aerobic, meaning that it can respirate oxygen in aerobic condition and switch to fermentation in an anaerobic environment.

The presence of *E. coli* in the water is harmless, but it indicates the presence of other pathogenic bacteria. Some strains of *E. coli* can cause stomachache, such as diarrhea, when ingested. The mixed acid fermentation in *E. coli* occurs in the following stages:

- The conversion of pyruvate to the end products, such as acetyl-coenzyme A (acetyl-CoA) and formate,
- The reduction of acetyl-CoA to ethanol,
- The inability to convert pyruvate to acetoin and 2,3-butanediol, and
- The conversion of formate to carbon dioxide and hydrogen only in an anaerobic condition and with the help of pyruvate formate-lyase (an enzyme) as a catalyst.

*Enterobacter aerogenes*, a non-fecal coliform, is found in soil and other environments outside of the intestinal tract of mammals and warm-blooded animals. The fermentation of this bacterium, which
distinguishes it from *E. coli*, involves the production of acetoin and 2,3-butanediol from pyruvate and the production of Succinate. Although categorized as a fecal coliform, *E. coli* is not always pathogenic. One of the dangerous strains of *E. coli* is *E. coli* O157:H7 that produces a harmful Shiga toxin. When the contaminated food is not cooked properly, this strain leads to severe digestive disorder, such as diarrhea and dysentery, as well as death if not treated immediately. The results of the laboratory analysis showed that the fecal coliform in Piyungan Landfill was around 28-1,100 MPN/100 mL. According to the Decree of the Indonesian Ministry of Health No. 907/MENKES/SK/VII/2002, the maximum concentration of fecal coliform in drinking water is 0 MPN/100 mL. As a conclusion, all groundwater in the landfill exceeds the quality standard for drinking water.

3.2. The proposed management model of waste disposal site (landfill) associated with the vulnerability of groundwater system to leachate movement is as follows:

3.2.1. Base Lining(Liner). Infilling needs a baselining system to reduce the mobility of leachate in the groundwater. An effective liner prevents pollutants from migrating into the environment, especially groundwater. However, there is empirically no 100% efficient liner system. The discharge of leachate is inevitable, indicating the need for leachate collection channel aside from liner system. Therefore, the bottom of the landfill has to be sealed with layers of liner materials to prevent leachate from seeping out of the landfill and equipped with leachate collection channel. The liner is composed of natural materials (e.g., clay and bentonite) or synthetic materials. Depending on the desired functions, it may consist of one material (single) or a combination of natural and synthetic materials, commonly referred to as geocomposite. The layer formations and the types of liner materials vary according to the characteristics of the solid waste piled onto the landfill. The recommended base lining is geosynthetic or known as flexible membrane liner (FML). The commonly used geosynthetic for baselining is composed of Geotextile (functioning as the filter), Geonet (drainage channel), and Geomembrane and geocomposite (buffer layer). Geomembrane, as an impermeable coating, is a geosynthetically made of impermeable polymer. The best polymer is high-density polyethylene (HDPE) that is resistant to chemical reactions occurring in B3 waste.

3.2.2. Leachate Collection Channel. Leachate collection system is recommended to have holed pipes placed inside the rock-coated channels. It also requires coated channels that contain hollow river stones. In general, the necessary facilities for pipe-equipped leachate collection channels are as follows:

3.2.2.1. Terraced Slope. The base of the landfill is formed into terraces with a certain slope (i.e., 1-5%), which prevents leachate from accumulating at the bottom of the landfill but flowing into the collection channels (i.e., 0.5-1%) instead. Every collection channel is equipped with holed pipes so that leachate can flows into the collection or re-circulation unit. The designs of the maximum slope and the length of the collection channels are based on the capacity of the collection channel facility. To assess this capacity, the research uses Manning’s equation.

3.2.2.2. Piped Bottom. The bottom of the landfill is divided into several rectangles with clay-based divides. The width of the divide depends on the width of the cells. Leachate collection pipes are placed parallel to the length of cells and directly on geomembrane.

3.2.3. Final Cap. The final cap of landfill consists of several sections. The upper part is mainly soil that functions as protection and plant-growing medium (topsoil). When the soil in the area does not correspond to these requisites, it needs an improvement, i.e., by mixing or replacing it with soils from other areas. The supposed thickness of the topsoil is 60 cm. The layer beneath it functions as a drainage system, which drains as much precipitation as possible so that rainwater does not seep into
the layer beneath it. The materials used for composing this layer are porous, e.g., sand, gravels, and synthetic materials like geonet. The thickness of this layer is around 30 cm. The second part is a leachate-retaining layer, which is commonly composed of geocomposite (geomembrane and compacted clay). The thickness of geomembrane is recommended to be more than 2.5 mm; while the thickness of clay is more than 50 cm. Beneath this layer is the gas ventilation system. It is a requisite for city waste treatment because most of the city waste is organic matters that decompose biologically. In aerobic condition, the resultant gas is mainly carbon dioxide and methane. Therefore, this biogas can be utilized as an alternative source of energy. The layer of gas ventilation system consists of porous media like sand/gravel or pipe system. The lowest part of the final cap is subgrade layer that functions to increase the stability of the landfill surface. Furthermore, it forms a necessary slope for accelerating lateral drainage and reducing the hydraulic level. Its thickness is 30 cm. Aside from this final cap, reducing the amount of overland flow that enters landfill involves slope arrangement, equipped with surface drainage and sowing.

3.2.4. Leachate Treatment. The leachate treatment system is divided into two levels, namely secondary and tertiary processing, as depicted in Figure 4. As for the secondary leachate processing, it is represented by the stabilization pool (facultative and anaerobic) and aeration ponds.

4. Conclusion
The analysis results of the geoelectrical sounding data proved that there are pollution indications in the groundwater around Piyungan Landfill. The pollutants were detected from the very low resistivity (i.e., 3-9Ωm) in aquifer zone. The interpretation of geoelectrical sounding data was validated using laboratory analysis of groundwater samples. The results of the laboratory analysis showed that the groundwater around Piyungan Landfill was contaminated. The electrical conductivity, as well as the concentration of nitrate and fecal coliform, have already exceeded the quality standard for drinking water according to the Decree of the Indonesian Ministry of Health No. 907/MENKES/SK/VII/2002.

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