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Groundwater Vulnerability Analysis in the Cikao Sub-Watershed, Jatiluhur, Purwakarta: A Critical Study for Resource Management

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Abstract

An area's development leads to a rise in its population. The need for clean water also rises as a result of this population growth. The quality of groundwater, one of the community's clean water sources, is determined by subsurface conditions. The goal of the study is to determine how much the Cikao sub-watershed is impacted by the degree of groundwater vulnerability. It also seeks to ascertain its relationship to the distribution of contaminated groundwater in the same region. East of Purwakarta Regency's Jatiluhur Reservoir sits the Cikao sub-watershed. The Citarum watershed includes this sub-watershed. The quality of groundwater might deteriorate due to contamination. The DRASTIC approach was used in this investigation. Seven parameters are used in this approach. Direct measurements in main data and indirect measures in secondary data yield the seven parameters. Following processing and analysis, the measurement results are displayed as a thematic map. After that, a map of groundwater vulnerability is superimposed with the seven parameters. The Cikao sub-watershed has three categories of vulnerability, according to the findings of the DRASTIC method analysis: Medium Low (9.76%), Medium High (71.56%), and High (18.68%). The slope and the distance to the depth of the groundwater table are the main determinants of the degree of vulnerability in the Cikao Sub-watershed. According to the findings of the groundwater chemistry test, every sample examined remained within the safe threshold. The iron (Fe) and Nitrate (NO3) elements in the low medium susceptibility zone have the highest levels of content compared to the high susceptibility zone. Please pay attention to vulnerability zones for further regional development, especially the distance from the surface to the groundwater table and the slope.

Keywords: *Aquifer Media, DRASTIC Method, Groundwater Vulnerability, Susceptibility Zone, Regional Development, Indonesia.*

Introduction

The main necessity for all living things is water. Compared to the overall amount of water on Earth, clean water is comparatively scarce (Wu et al., 2018; Zhou et al., 2021). Given this rather small quantity, the storage container (medium) has a significant impact on its existence (Sprenger et al., 2019; Wang et al., 2019). The majority of Indonesian cities rely on water resources from the nearby highlands to supply their water needs (Himayoun & Roshni, 2019; Khilchevskyi & Karamushka, 2021). The main source of water supply is volcanoes (volcanic zones), much like in growing cities in West Java (As'ari et al., 2019; Luo et al., 2021).

However, the groundwater system in industrial zones is complex, and the spatial pattern is not based on water resources, particularly knowledge. Assessments and mapping of groundwater vulnerability have been created and tested globally. Process-based simulation models, overlay index models, and statistical models are the three methods used to evaluate groundwater vulnerability. The most popular technique for determining a region's groundwater vulnerability is the overlay index model (Ghouili et al., 2021). Several hydrogeological parameters are involved in the overlay index model's assessment of groundwater vulnerability, which can be modified based on data availability (Ribeiro et al., 2016). A number of approaches are available, including the SINTACS model (Civita, 1994), the GOD model (Foster, 1987), the DRASTIC model (Aller et al., 1987),the GALDIT model (Chachadi and Lobo-Ferreira, 2005) and the SI

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model (Ribeiro, 1994). 2000). The DRASTIC method (Aller et al., 1987) is commonly used, this method is a very simple and effective method for characterizing groundwater susceptibility to contamination (Breaban, 2012).

Industrialization has caused a number of environmental contamination issues in urban growth (Negi and Jain, 2008). Because of this, water issues are a common occurrence in Indonesia, even in West Javan cities. Studying groundwater resources is essential in addition to developing a region, such as Purwakarta, particularly the groundwater vulnerability surrounding the Purwakarta Industrial Estate in the Citarum river basin (Anwar et al., 2019). In accordance with the previously mentioned problem formulation, the research objectives are separated into two categories. The primary goal of the study was to ascertain how much the Cikao sub-watershed's degree of groundwater vulnerability affected the situation. The second goal, meanwhile, was to ascertain its relationship to the Cikao sub-watersheds groundwater contamination distribution.

Methodology

Research Design

The physical properties that influence groundwater hydrochemistry and vulnerability are the focus of this study. The DRASTIC technique (Aller et al., 1985) is used in this investigation. DRASTIC is a rating and weighting system for assessing groundwater risk. The acronym for the seven factors thought to have the greatest impact on groundwater risk is DRASTIC. The following describes the seven parameters of the DRASTIC method. 1. D (*Depth to water*), namely the depth of the groundwater table; 2. R (*Net Recharge)*, namely the amount of rain infiltration; 3. A (*Aquifer Media)*, namely the type of aquifer media; 4. S (*Soil Media)*, namely the variety of soil media; 5. T (*Topography)*, is the slop; 6. I (*Impact of the Vadose Zone Media)*, namely the type of vadose zone media; and 7. C (*Hydraulic Conductivity of the Aquifer)* has large hydraulic conductivity.

Direct measurements in main data and indirect measures in secondary data yield the seven parameters. After processing and analysis, the measurement results are displayed as a thematic map. Then, the seven criteria are superimposed into a groundwater vulnerability map.The DRASTIC index score, which is the total of the weights and values of the seven groundwater vulnerability factors, is the score for groundwater vulnerability. In order to determine the level of groundwater vulnerability, the DRASTIC index score is then categorized using the groundwater vulnerability level classification table based on the DRASTIC index colour code. Geospatial data processing applications and Microsoft Office were used for all data processing and analysis.

Research Stages

Groundwater vulnerability research is conducted in phases. beginning with the planning phase, followed by the data gathering, processing, and analysis phases, the mapping phase, and the reporting phase. Both primary and secondary data were gathered throughout the researchers' data gathering phase. Geological, hydrogeological, and hand-auger investigations were used to collect primary data in the study region directly. With the aid of GPS, mapping and drilling locations were positioned during primary data collection. The main information gathered includes information on the vadose zone, groundwater and soil samples, the depth of the groundwater table, and the kind of lithology found on the surface. The groundwater table depth is established by the depth of the wells in the research region (Alfarrah & Walraevens, 2018; Kolbe et al., 2019), and the distribution of surface lithology types is derived from geological mapping (Forte et al., 2019; Peters et al., 2018). In the meantime, the distribution of soil types in the study area is used to determine where the hand drill sampling point should be located.

Both before and after leaving for the research region, secondary data were gathered. In order to gather information that was not primarily available from the research area, secondary data collecting was done. Limitations in research time, such as for rainfall data, might be a barrier to obtaining primary data. The following information can be downloaded from the agency's website or acquired from connected agencies:

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1) Monthly precipitation and temperature data from BMKG Meteorology, Climatology and Geophysical Agency of Indonesia. 2) Regional Geological Map of Cianjur and Karawang, scale 1:250,000, derived from the Geological Agency Indonesia. 3) The Indonesia Hydrogeological Map II sheet Cirebon 1:250,000 scale was obtained from the Groundwater and Environmental Center in Indonesia, and 4) the DEMNAS picture was downloaded from the Indonesian government's geoportal site (Tanahair.indonesia.go.id).

Preparation of Drastic Model Data

The data processing stage is carried out to convert raw data into consistent data. This is to facilitate further analysis. Overall, the data was processed using Microsoft Excel and geospatial information. Each parameter will undergo a different processing process, although the overall data will be analyzed using geospatial information processing software. The analysis of groundwater vulnerability parameters was carried out based on the guidelines contained in the *United States Environmental Protection Agency* (US-EPA) publication entitled "*DRASTIC, A Standardized System for Evaluating Ground Water Pollution Potential Using Hydrogeological Settings*" (Aller et al., 1985).

Depth to Water

Hydrogeology mapping results are used to process primary data and determine the groundwater table's depth. In the field, the hydrogeological mapping results are compiled into a Microsoft Excel groundwater table depth table. The location, name of the observation site, and groundwater table depth are all included in the groundwater table depth information. The geospatial information processing program is then updated with the depth of the groundwater table. The observation point will automatically appear based on the coordinates once it has been entered. A well-shaped observation site is selected from among all the others in order to ascertain the depth of the groundwater level. Since it is impossible to determine the depth of the groundwater level without supporting data, the observation point in the shape of a spring point is not utilized. There are two steps involved in the analysis of the groundwater table's depth: establishing the value and defining the zoning. It is calculated by entering the groundwater depth value and the groundwater table depth in the range table.

Net Recharge

The amount of rain infiltration is calculated in Microsoft Excel using the water balance formula. Secondary data for calculating rain infiltration are rainfall data, monthly temperature, land cover, soil type, and the slope. It is necessary to carry out further rainfall processing because not all rainwater will enter the ground. Some will evaporate into evapotranspiration, and some will just flow on the surface. According to Fetter (2001), rain that falls on the earth will experience three situations: flowing on the surface, evaporating back into space, and seeping into the ground.

The amount of annual rainfall whose value is obtained from the sum of monthly rainfall measurements value of *Ev* obtained using the Thornthwaite method (Thornthwaite & Mather, 1957) with the weather data. The *Ro* is obtained from the multiplication of rainfall with the coefficient of land cover, slope, soil type, and land area. Suppose the amount of run-off has been obtained. In that case, the amount of rain infiltration calculation can then be carried out by entering the amount of rainfall, evaporation, and run-off into the water balance formula. The amount of rain infiltration is the amount of precipitation minus evaporation and run-off. After obtaining the value for rain infiltration, the rain infiltration zoning in the study area is determined based on the position of the Rainfall Measurement Station.

Type of Aquifer

The type of aquifer is obtained from the processing of regional hydrogeological maps, which are detailed with field mapping results. Processing of the source in the form of a map is to re-digitize the map with the help of geospatial information processing software. The results are re-digitized in *polygons* for each aquifer unit in the study area. Furthermore, several analyzes were carried out to obtain the value and zoning of the aquifer types in the study area. First, an analysis is carried out to determine the type of

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rock that forms the aquifer. By comparing the lithology types that comprise the aquifer on the hydrogeological map with the lithology of the mapped rock, the study was completed. Therefore, aquifer type zoning will be created based on the aquifer distribution on the regional hydrogeology map. The distribution is described in depth using a geological mapping result map. Additionally, zoning is created for every aquifer.

Type of Soil

Soil type was obtained from processing hand drill samples taken directly from the research area. Large items in the geotechnical laboratory analyzed the hand drill sample. From the grain size analysis results, it is determined the type of the soil is based on the SCS (Soil Conservation Service) classification in 1951. Processing the grain size analysis results is done with the help of Microsoft Excel, while the classification is done with the SCS classification triangle. The difficulty encountered during the analysis of soil types is determining the percentage of soil constituent material. The process must be carried out with existing tools in the engineering geology laboratory. The process must also be guided and assisted by experienced experts and requires no short time. For soil type analysis, it is carried out in the form of assessment and zoning. First, the soil type resulting from the SCS classification is entered into the table of ranges and soil type values. This analysis obtained values for each type of soil in the study area. Furthermore, the zoning of each soil type is made according to the distribution of geological units in the research area. The reason why the zoning of soil types is based on the following table

Slope

Digital Elevated Models (DEM) are used in image processing to determine the slope. The geoportal page of the Indonesian government provided the DEM picture for download. Geospatial information processing software is used to process DEM images. Slopes are then grouped according to the Range and Values table range for Topography in order to do an analysis. After that, each set of slopes is zoned. A polygon is the end product of slope zoning. The polygon is then evaluated based on the range of land slopes.

Vadose Zone Types

The slop is obtained from image processing DEM (*Digital Elevated models*). The DEM image was downloaded from the Indonesian government's geoportal page. DEM image processing is done with the help of geospatial information processing software. Next, an analysis is carried out by grouping slopes based on the Range and Values table range for Topography. Each group of slopes is then zoned. The vadose zone type is obtained from hand drill samples obtained from geotechnical mapping. First, the boundary between the soil and the vadose zone is determined from the sample. Then, for the part which is the vadose zone, a simple lithological description is carried out. Based on this simple description, one of the ranges in the Range and Values table for the Vadose Zone Effect is selected that best fits the lithology type. The type of vadose zone assessment was carried out by giving value according to the previously obtained vadose zone type. The zoning of the vadose zone, type is carried out based on the lithology distribution on the geological map of the research area, where each point of taking the vadose zone is considered to represent its geological unit.

Hydraulic Conductivity

The type of aquifer determines the hydraulic conductivity. Aquifer type is obtained from the processing of aquifer types carried out in the fourth point. To obtain the hydraulic conductivity, an estimate is made by referring to the Table of Value Ranges for Hydraulic Conductivity and Permeability. Based on the type of aquifer, the approximate range of hydraulic conductivity is obtained. The estimated results were then validated with the hydraulic conductivity of similar aquifers in other research areas. The conductivity is then assessed with a table of ranges and values for hydraulic conductivity. Furthermore, an analysis is carried out to determine the value and zoning for hydraulic conductivity. The assessment is carried out by entering the results of the estimated conductivity to obtain the value. Zoning is carried

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out like aquifer-type zoning, where the zoning boundaries follow the unit boundaries on the hydrogeological map of the research area.

Data Analysis

Groundwater vulnerability analysis was carried out after analyzing the seven parameters previously finished. Groundwater vulnerability analysis overlays *the* seven *shapefiles* software geospatial information processing. The amalgamation process adds up the multiplication results of values and weights for each parameter for groundwater vulnerability assessment. The weights for each parameter can be seen in the Weighting table for DRASTIC Parameters (Table 1).

Table 1. Weighting for DRASTIC Parameters

Parameter	**Weight**
Groundwater Depth	5
Rain Infiltration	4
Aquifer Type	3
Type of soil	2
Topography	1
Vadose Zone Types	5
Hydraulic Conductivity	3
Source: (Aller et al., 1985)	

The calculation of the groundwater vulnerability index based on the DRASTIC method is formulated as follows:

DRASTIC Index = DrDw + RrRw +ArAw+SrSw+TrTw+IrIw+CrCw

Description:

R = Score (*Rating*)

W = Weight (*Weighting*)

After obtaining the index value, zoning on the water vulnerability map, the soil can be given a colour according to the table of classification of the level of groundwater vulnerability based on the DRASTIC index colour code (Table 2). In their publication, Musálem, McDonald, Jiménez, & Laino (2015) stated that the index range DRASTIC, in addition, to provide color, can also indicate the level of vulnerability groundwater level in the area based on the interpretation studies case which produced the color-coded United States DRASTIC Index (Aller et al., 1985).

Table 2. Classification of Groundwater Vulnerability Levels Based on the Color Code Index Drastic

Index DRASTIC Range	**Color**	**Vulnerability Level**
< 79	Violet	Minimum
80 – 99	Indigo	Very Low
100 – 119	Blue	Low
120 – 139	Dark green	Medium Low
140 - 159	Light green	Medium High
160 – 179	Yellow	High
180 - 199	Orange	Very High

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>200	Red	Maximum
Source: (Aller et al., 1985)		

Results & Discussions

Parameter of DRASTIC in Cikao Sub-watershed

The seven parameters combine indirect measures derived from secondary data with direct measurements found in primary data. The measurement data is processed, analyzed, and then shown as a thematic map. The groundwater vulnerability map is then overlaid with the seven parameters.

Groundwater Depth

Groundwater depth data is obtained from direct measurements in the field using dug wells and a water level meter. The value obtained from the field is in meters, which are then converted into feet. The distribution of the groundwater level has been made by interpolation using GIS software.

The depth of groundwater table in the study area consisted of 5 classes (Figure 1).

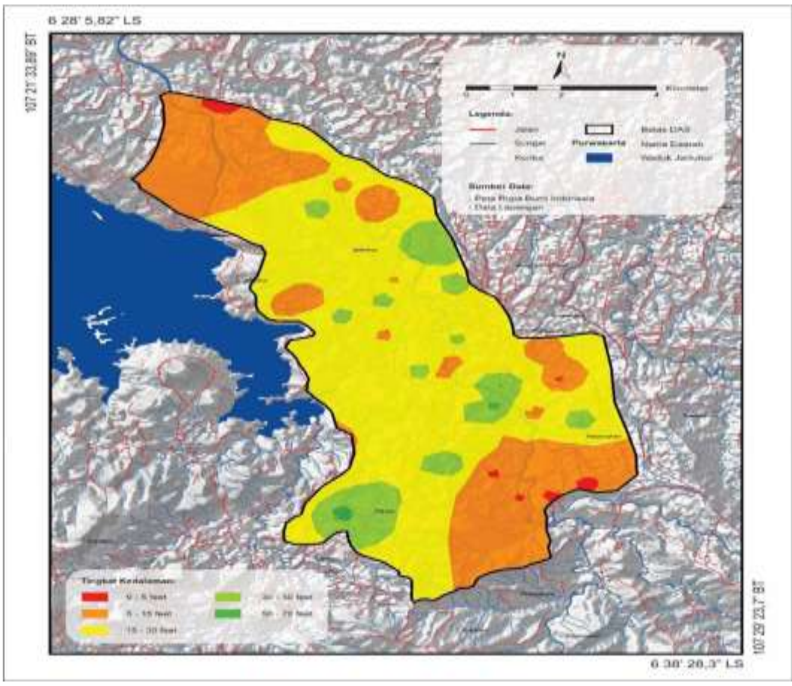

Figure 1. Map of Groundwater Depth in Cikao Sub-watershed

Rain Infiltration

This rain infiltration data is obtained from the calculation of the water balance. This parameter is calculated based on rainfall data and climate data (air temperature) obtained from the Directorate General of Water Resources, Ministry of Public Works, and Public Housing Indonesia. In addition, data on land cover types and slopes were also obtained from the Tanahair.indonesia.go.id page and soil type data from field measurements and laboratory tests to obtain run-off discharge values. From all these data, the data obtained for the amount of rain infiltration in the study area is 45.67 cm per year, or about 17.98 inches per year. This number is in the highest range, which is 10 inches per year, and gets a value of 9. This means that the potential for pollution in Cikao Sub-watershed is high.

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Aquifer Media Type

The data for this parameter refers to the results of a geoelectric survey in the form of the distribution of rock resistivity values at a certain depth according to the depth of the aquifer observed. After obtaining the resistivity distribution data, adjustments or bindings are made between the surface geological data (lithology) and the resistivity of the nearest rock from the observation station.

The aquifer observed is an unconfined aquifer with a depth of up to 30 meters with the primary lithology, namely volcanic breccia. This lithology was then compared and adjusted with the classification for the DRASTIC method (Aller et al., 1985). In this case, the researcher compares it with the Sand and Gravel class with a value range of 4-9. By considering the physical characteristics of the aquifer media, the authors chose a value for the aquifer media in the study area of 8. This value means that the aquifer media in the study area has a reasonably high pollution potential. ~~This media aquifer map weights 3.~~

Topography

The data for this parameter is obtained from the Tanahair.indonesia.go.id page. The data is then processed using ArcGis software. The data used is topographic data or elevation contours. Then the contour data is processed into slope data. The Cikao sub-watershed is divided into 5 slope classes, namely 0-2% with a value of 10, 2-6% with a value of 9, 6-12% with a value of 5, 12-18% with a value of 3, and > 18% with a value of 1. Red color with a flat-very gentle slope and green color with a steep slope. Color selection is based on the level of potential pollution. Red color with high pollution potential and green with low pollution potential. This slope map weights 1 (Figure 2)

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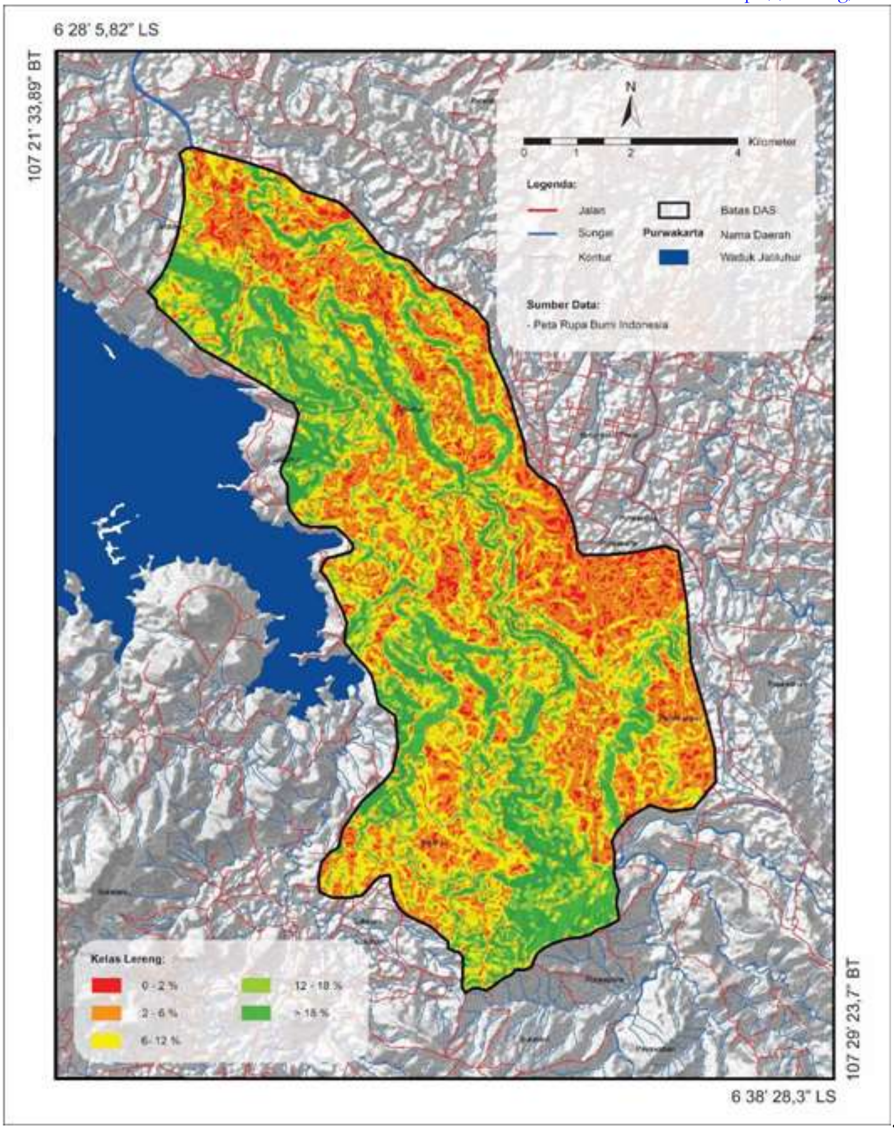

Figure 2. Slope Map in Cikao Sub-watershed

Impact of Vadose Zone

The data for this parameter is almost similar to the type of aquifer media, which refers to the interpretation of the subsurface rock's resistivity data, which is then tied to the resistivity of the rock on the .surface. From the results of subsurface modeling, it is known that the material is still similar to the aquifer media, namely volcanic breccia. In this case, volcanic breccia refer to Sand and Gravel with a value range of 6-9. Considering the characteristics of these rocks, the authors assign a value of 7 for the influence of the vadose zone media.

Conductivity Hydraulic

This hydraulic conductivity data was obtained from direct measurements in the field, namely the pumping test. This pumping test was carried out on dug wells belonging to residents in an unconfined aquifer. Using the constant discharge method. After carrying out the pumping test, the hydraulic conductivity value of the aquifer in the Cikao Sub-watershed is around 1.26×10-4 m/s or equivalent to 267.225 GDP/feet2. Compared with the classification of the DRASTIC method (Aller et al., 1985), the hydraulic conductivity value of the Cikao Sub-watershed belongs to class 100 – 300 GDP/feet2 with a value of 2.

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Groundwater Vulnerability in Cikao Sub-watershed

The groundwater vulnerability map was compiled based on 7 thematic maps that had been made previously. Then with the help of GIS software, the DRASTIC Index is calculated for each slice. The resulting figure will show the color and level of groundwater vulnerability (Figure 3). The total score of the DRASTIC Index in the Cikao Sub-watershed ranges from 125 – 169. Based on the DRASTIC Index, the Cikao Sub-watershed is divided into 3 classes, namely 120 – 139 with dark green, 140 – 159 with light green, and 160 – 179 with yellow. Dark green color indicates low or moderate vulnerability (9.76% of the study area), light green color indicates medium-high vulnerability (71.56% of the study area), and yellow color indicates high vulnerability level (18.68% of the research area).

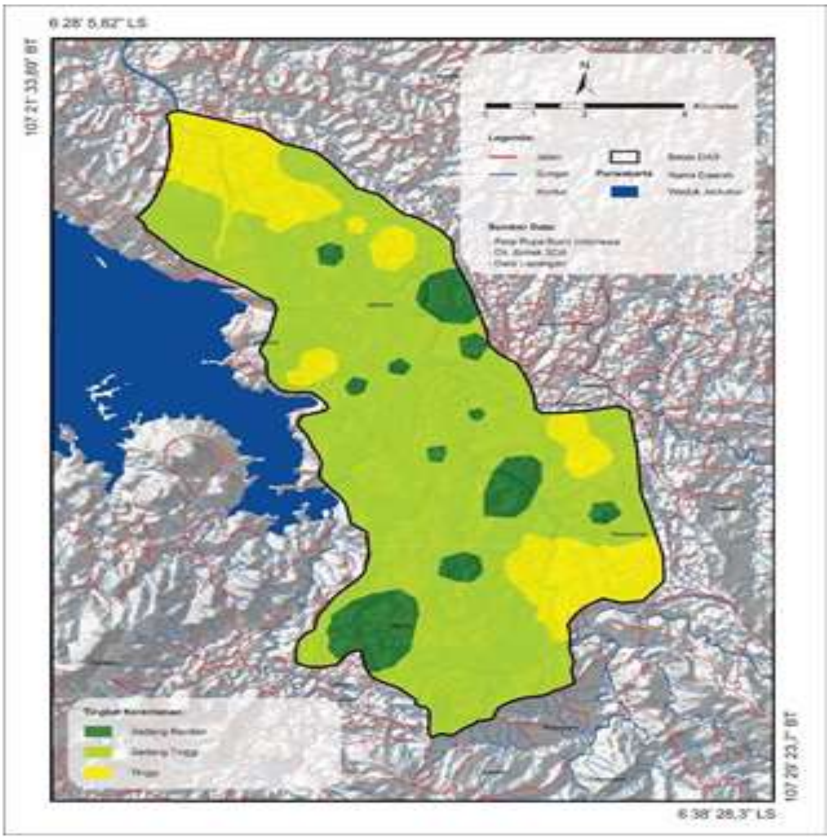

Figure 3. Map of Groundwater Vulnerability Zones in the Cikao Sub-watershed.

Medium-Low Vulnerability covers parts of Jatiluhur District, Babakan Cikao District, Purwakarta District, Pasawahan District, and Sukatani District. This area consists of areas with a groundwater level of about 9.1 – 18 meters, rainfall >254 mm, types of aquifer media in the form of sand and gravel, types of silt clay texture, topographical slopes ranging from flat to steep, types of media the vadose zone is sand and gravel and the hydraulic conductivity is 10.9 m/day.

The medium-high vulnerability covers parts of Sukasari District, Jatiluhur District, Babakan Cikao District, Purwakarta District, and Pasawahan District. This area consists of areas with a groundwater level of about 1.5 – 15.2 meters, rainfall >254 mm, types of aquifer media in the form of sand and gravel, silt clay soil texture, various topographical slopes ranging from flat to steep, the type of media in the vadose zone is sand and gravel and the hydraulic conductivity is 10.9 m/day.

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High vulnerability covers parts of Teluk Jambe Barat District, Sukasari District, Jatiluhur District, Babakan Cikao District, Purwakarta District, Pasawahan District and Sukatani District. This area consists of areas with a groundwater level of about 1.03 – 4.6 meters, rainfall >254 mm, types of aquifer media in the form of sand and gravel, silty clay texture types, topographical slopes ranging from flat to steep, the type of media in the vadose zone is sand and gravel and the hydraulic conductivity is 10.9 m/day.n From the descriptions above, it can be seen that the factors that determine the level of vulnerability in the Cikao Sub-watershed are the Depth of the Groundwater (D) and the level of Slope Slope (T). To maintain groundwater quality, areas with a high DRASTIC Index have a high priority to be protected from pollution.

Based on the results of the preparation of the groundwater vulnerability map using the DRASTIC method (Aller et al., 1985; Khosravi et al., 2018), three levels of groundwater vulnerability were found in the Cikao Sub-watershed. They were starting from the level of vulnerability of medium-low, medium-high, and high. The dominant parameters in the Cikao Sub-watershed are the groundwater table's depth and the slope. Although other parameters with a high enough value, such as the amount of rain and the influence of the vadose zone media, also have a role (Arora et al., 2019; Poulain et al., 2018) values are uniform in one watershed area.

Recommendations for further area development must pay attention to the aspect of the distance to the depth of the groundwater table and the slope (Hamidov et al., 2020; Huang et al., 2018). This is because this aspect can easily change when an area will be developed (Golkarian et al., 2018; Patra et al., 2018). Some contaminants are not always positively correlated with the groundwater vulnerability zone (Lasagna et al., 2018; Singha et al., 2019). This is because the origin of these contaminants does not come from the soil surface. Based on the results of the hydrochemical test, all test samples were still within the safe threshold.

Discussion

This research produces a groundwater vulnerability map that the local government can utilize for the benefit of developing industrial estates around the Cikao and Cilalawi sub-watersheds, mainly to avoid a water crisis in these areas. Based on the results of the preparation of the groundwater vulnerability map using the DRASTIC method (Aller et al., 1985; Khosravi et al., 2018), three levels of groundwater vulnerability were found in the Cikao Sub-watershed. They were starting from the level of vulnerability of medium-low, medium-high, and high. The dominant parameters in the Cikao Sub-watershed are the groundwater table's depth and the slope. Although other parameters with a high enough value, such as the amount of rain and the influence of the vadose zone media, also have a role (Arora et al., 2019; Poulain et al., 2018) values are uniform in one watershed area.

As mentioned before, this study uses the DRASTIC method to evaluate the level of groundwater vulnerability in the Cikao Sub-Watershed. This method involves seven main parameters, namely groundwater depth, rain infiltration, type of aquifer medium, soil type, topography, type of vadose zone media, and hydraulic conductivity. The results of the analysis show that most regions have a medium-high level of vulnerability, with small areas showing a high level of vulnerability. This approach provides a comprehensive framework for quantitatively assessing groundwater vulnerability. The vulnerability zones in the Cikao Sub-watershed are divided into three main categories, namely medium-low (9.76%), medium-high (71.56%), and high (18.68%). Zones with high vulnerability are mainly located in areas with shallow groundwater levels and flat topography. In contrast, low-vulnerability zones tend to be in areas with steep topography and greater groundwater table depths. This distribution highlights the importance of understanding local hydrological characteristics in groundwater resource management.

Groundwater table depth and slope slope emerge as dominant factors affecting vulnerability levels. Shallow groundwater table depths increase exposure to surface contamination, while flat slopes allow for slower surface water flows, increasing the likelihood of pollutant infiltration. These factors indicate the need for special protection in areas with these characteristics. Interestingly, the results of the hydrochemical test showed that all groundwater samples were still within the safe threshold even though some areas had high levels of vulnerability. This suggests that the level of vulnerability is not always directly proportional to the actual level of contamination. Sources of contamination that do not originate from surfaces or controlled human activity are likely to be factors explaining these findings. This finding has important implications for regional management in the Cikao Sub-watershed, especially in the development of industrial estates. High vulnerability zones require special attention to minimize the risk of contamination. Vulnerability map-based management strategies can help governments and other stakeholders make wiser decisions regarding land use.

Regional development, especially for industrial activities, can significantly affect vulnerability parameters such as groundwater table depth and rainfall infiltration. The addition of infrastructure, changes in land use, and increased human activity can increase the risk of contamination. Therefore, a development policy that pays attention to the results of this study is needed to ensure the sustainability of groundwater resources. If we discuss further, this study shows the importance of understanding the dynamics of groundwater systems in the Cikao Sub-Watershed. However, to complement these findings, more research is needed on the sources of contamination and the movement patterns of pollutants. This additional research can help identify more effective mitigation measures, including the use of technology to monitor groundwater quality in real-time and risk-based area planning. Some contaminants are not always positively correlated with the groundwater vulnerability zone (Lasagna et al., 2018; Singha et al., 2019). This is because the origin of these contaminants does not come from the soil surface. Based on the results of the hydrochemical test, all test samples were still within the safe threshold.

Conclusion

This study shows that the level of groundwater vulnerability in the Cikao Sub-Watershed is divided into three categories, namely medium-low, medium-high, and high vulnerability. The dominance of moderate-high vulnerability levels (71.56%) confirms that this region has a significant potential risk of groundwater contamination, especially in areas with shallow groundwater surface depths and relatively flat topography. The main factors affecting the level of vulnerability in the Cikao Sub-Watershed are the depth of the groundwater table and the slope of the slope. This parameter plays an important role in determining the level of groundwater exposure to contamination.

In addition, rain infiltration and vadose media types also contribute to susceptibility, although the values tend to be more uniform across the study area. Although areas with high levels of vulnerability have greater potential for contamination, the results of hydrochemical tests show that all groundwater samples in these areas are still within safe thresholds according to Indonesian Ministry of Health regulations. This suggests that the source of contamination does not always come from the surface, so further research is needed on the source of contamination in this area. This groundwater vulnerability mapping provides important insights for the management and development of the region, especially in protecting zones with high levels of vulnerability from human activities that can increase the risk of contamination.

The main recommendation is to pay special attention to the aspects of groundwater level depth and slope slope when planning regional development. Based on the results of the above research and discussion, the author concludes that this study emphasizes the need for preventive measures to protect groundwater resources from contamination, especially in zones with high vulnerability indexes. In addition, further research is needed to understand the dynamics of contamination, including the source and movement patterns of pollutants, so that groundwater management in the Cikao Sub-watershed area can be more sustainable.

Declaration of Conflict of Interest

There is No. conflict of interest in this work

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