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Assessing groundwater vulnerability in the intermountain plains of Metro Hilir watershed Malang

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Groundwater vulnerability assessment is crucial, particularly in developing regions. The Metro Hilir Watershed is located in an intermountain plain area dominated by rural agricultural land. The purpose of this study is to identify, map, and analyze the vulnerability of groundwater to pollution through the DRASTIC Landuse Model in the Metro Hilir watershed. The DRASTIC Landuse model was employed, a highly suitable approach for groundwater vulnerability assessment. Surveys on shallow dug wells were conducted to obtain depth to water table information, and well water samples were collected to determine Nitrate levels. Geoelectric tests were also used to gather aquifer information and hydraulic conductivity. Secondary data was utilized to acquire rainfall, soil media, and topography information. Google Earth Engine analysis was employed to obtain 2024 Landuse data. The DRASTIC Landuse analysis was classified to determine groundwater vulnerability classes for the aquifer. Results indicate that 91.63% of the study area falls within the moderate to high vulnerability class. Moderate vulnerability classes are distributed in the eastern and southwestern parts, while high classes are located from the northwest extending to the southern area of the study region. Model validation was conducted using water quality parameters, specifically Nitrate, and the model was deemed valid. Sensitivity analysis revealed that the Hydraulic Conductivity and Impact on the Vadose Zone parameters show sensitivity to input changes and have a substantial impact on vulnerability. The findings of this research can inform decision-making processes for groundwater quality management in the Metro Hilir Watershed.

Keywords Groundwater, Groundwater vulnerability, DRASTIC landuse, Landuse

Water is crucial for sustaining human life. Groundwater, one of the primary water sources, is even traded commercially¹. Groundwater usage is widespread due to its superior quality, greater quantity than other water sources, and extensive distribution^{2,3}. Groundwater originates from geological materials and structures capable of forming aquifers¹. Aquifer conditions, land use types, and anthropogenic activities influence groundwater vulnerability to pollution threats⁴. Lithologies such as sand, gravel, and pyroclastic materials exhibit higher vulnerability to groundwater pollution⁵. Groundwater vulnerability is associated with assessing the risk of aquifer pollution due to anthropogenic activities, which can be visualized through mapping⁶. Groundwater vulnerability becomes increasingly dynamic due to changes in land use types. Land use dominated by settlements and industries poses a more significant threat to groundwater pollution⁷. Agricultural activities and high population growth are considered to have a greater impact on pollution in developing countries compared to other activities^{8,9}. Changes in land use types, driven by high population activities and rapid urbanization, contribute to pollution risks¹⁰. Naturally, groundwater is not easily polluted due to its slow movement, which also slows down pollutant movement. However, once groundwater is polluted, recovery is difficult¹¹. Therefore, assessing groundwater vulnerability to pollution is crucial as part of groundwater pollution prevention mitigation efforts.

Previous studies have employed a wide range of methods to assess groundwater vulnerability to pollution. Groundwater vulnerability assessment can be conducted through single-criterion and multi-criteria evaluation. The single criterion method utilizes only one variable, for example, by using water quality tests. This water quality

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can be in the form of heavy metal levels, Total Dissolved Solids, and Electrical Conductivity. The advantage of this method is that it yields more accurate results, but it has drawbacks in terms of cause-and-effect analysis and gives less consideration to hydrogeological factors¹². These shortcomings necessitate the use of a multicriteria method that can address the limitations of the single criterion method. The use of various hydrogeological and GIS-Software based variables will yield better results, as they are spatially oriented. Multi-criteria methods are more widely used due to their superior ability to assess groundwater vulnerability. Common multi-criteria methods using GIS Software include SINTACS, COP, GOD, DRASTIC, GALDIT, and various modifications thereof^{10,13–15}. The SINTACS, COP, GOD and GALDIT methods can be used in various types of hydrogeological conditions. SINTACS is better suited for areas dominated by urban settings, while COP is more appropriate for karst regions^{16,17}. The GALDIT method is well-suited for coastal aquifers that have high vulnerability to seawater intrusion¹⁸. One such method is DRASTIC⁴. DRASTIC has advantages in terms of spatial analysis and is capable of explaining the influence of various hydrogeological variables used^{19,20}. DRASTIC can also be applied to various types of groundwater conditions, such as groundwater in agricultural areas²¹, urban areas²², dan hard-rock aquifers¹⁹.

Variables used in the DRASTIC method include Depth to Water, Net Recharge, Aquifer Media, Soil Media, Topography, Impact of Vadose Zone, and Hydraulic Conductivity, representing intrinsic vulnerability²³. DRASTIC can be extended by considering land use types and existing Water Quality^{5,24}. The parameters used for assessment are often modified by incorporating other parameters. One such parameter is DRASTIC Landuse. Land use represents anthropogenic activities that can complement other DRASTIC parameters^{19,22}, thus providing better results. The DRASTIC Landuse method has a weakness in terms of the subjectivity of weight assignment, and it does not directly consider pollution sources. However, this method has advantages in analyzing various factors that influence groundwater vulnerability spatially, comprehensively, and it can be used in conjunction with other data or methods. Thus, the use of DRASTIC Landuse in this study is appropriate. The weaknesses inherent in this method can be mitigated by conducting field tests, as well as validation and sensitivity analyses, so that the resulting model becomes accurate^{5,16}. The DRASTIC Landuse method is based on several key assumptions. First, it assumes that pollutants originate from the earth's surface. Second, it posits that these pollutants are transported into the soil through precipitation. Third, it operates under the assumption that the speed of pollutants corresponds to the speed of water flow. Finally, it presupposes that the affected area has a wide coverage¹⁹. Testing of the method has also been developed to enhance its effectiveness and accuracy²⁵. Testing is performed on each parameter used against the resulting vulnerability index^{16,26}.

The study area is the Metro Hilir Watershed, located in Sukun, Wagir, Pakisaji, Sumberpucung, Ngajum, and Kepanjen Districts of Greater Malang City. This area is predominantly characterized by settlements and agricultural activities²⁷. Anthropogenic activities, such as agriculture, industry, and settlements, further exacerbate groundwater vulnerability to pollution⁷. The study area is located in the Intermountain Plain of several surrounding volcanoes. This area has extensive rice agricultural land and is the largest rice-producing region in Malang Regency²⁸. Rice paddy fields are irrigated by springs and shallow wells. However, some of these springs and shallow wells also experience quality changes, namely, odor and cloudy color (Fig. 1). Figure 1a shows a spring built in 1985 in Jatisari Village, Pakisaji District. This spring is no longer in use due to decreased groundwater discharge and odorous water. In addition to springs, shallow dug wells are also found to have cloudy and odorous water in Jatirejoyoso Village, Kepanjen District. This well has a depth of 14 m to the bottom



Fig. 1. Groundwater Spring in Jatisari Village, Pakisaji Regency (a) and Shallow Dug Well in Jatirejoyoso Village, Kepanjen Regency (b).

and is no longer used by residents. Thus, it is necessary to identify zones with groundwater vulnerability to pollution in the study area.

Based on previous research, the DRASTIC Landuse method has not been widely used in volcanic areas with high rainfall and land use dominated by rural agriculture (settlements and rice farming) as in the study area^{4,19–24,29}. Identifying and analyzing groundwater vulnerability to pollution is crucial. This research is based on geospatial technology to map various factors that influence groundwater vulnerability to pollution. Utilizing a Geographic Information System (GIS) would enhance the effectiveness of this assessment⁷. Especially for the research area, the identification of groundwater vulnerability using DRASTIC Landuse has never been carried out based on literature publications. Based on this, the purpose of this study is to identify and zone the vulnerability of groundwater to pollution through DRASTIC Landuse of the Metro Hilir watershed. The spatial use of DRASTIC will assist in analyzing groundwater vulnerability zones to pollution spatially, in relation to various influencing factor⁵. This research also utilizes geoelectric sounding tests to obtain hydrogeological data, which was not employed in previous studies.

The DRASTIC-LU method in this research will be able to fill methodological and conceptual gaps in previous studies. Kumar and Jesiya conducted research using DRASTIC-LU in India. Their study heavily relied on secondary data to determine aquifer conditions and other parameters. Kumar also used Landuse data from LISS 2013, despite its publication in 2019^{19,22}. Therefore, field-survey-based research, for instance, to obtain aquifer data, will yield more representative and valid results. Furthermore, this research utilizes actual data from the Google Earth Engine (GEE) platform via cloud computing. The use of this platform has proven to offer high data accessibility and reliability, as well as being up-to-date³⁰. Landuse information can be derived using specific Classifier Algorithms on GEE. Previous research also employed GIS²², but did not specifically mention the use of current platforms like GEE. Although this research adapts the DRASTIC-LU method from Alam³¹, there are differences in the techniques used for data acquisition and processing. Many previous studies also did not perform validation and sensitivity tests^{21,31–34}, thus necessitating validation and sensitivity tests, which can enhance the robustness and credibility of research findings²³. Specific contaminant levels can be used for validation, by adjusting the estimated contaminant sources^{23,35}. The use of Nitrate as an indicator is considered more suitable for areas with abundant vegetation and agricultural zones. Nitrate is the most frequent contaminant of groundwater compared to other pollutants^{24,36,37}.

Identification of pollution risk is crucial for groundwater conservation efforts. Regulations held by the local government are more related to land for spring conservation and rules for deep groundwater aquifer utilization. In Government Regulation of the Republic of Indonesia No. 22 of 2021 concerning the Implementation of Environmental Protection and Management, there are regulations for preventing water pollution. However, these regulations primarily govern surface water and not groundwater. The Regulation of the Minister of Energy and Mineral Resources of the Republic of Indonesia No. 31 of 2018 concerning Guidelines for the Establishment of Groundwater Conservation Zones, also regulates conservation zones. Nevertheless, specific groundwater conservation zones in the research area have not yet been designated. Consequently, the normative problem from the regulatory side further increases the need for identifying groundwater vulnerability to pollution. The DRASTIC-LU method is more suitable for shallow groundwater, which has higher vulnerability to contamination. Therefore, this research will provide new information regarding areas vulnerable to groundwater pollution, which can be considered by the community and local government in groundwater conservation efforts.

Data and methods

Study area

The research area covers 76.36 square kilometers and is located in Malang District, East Java Province, Java Island, Indonesia (Fig. 2). The research area has its upstream at Kawi Volcano and flows into the Sutami Dam. Groundwater is the primary water source for rural residents and those living far from roads and piped water networks. Some residents in urban areas utilize the piped water network provided by the Local Government. Residents without access to the piped water network construct groundwater extraction wells, such as dug wells and drilled wells. Those residing near hillside springs rely on groundwater springs for their daily water needs and agricultural activities.

Data acquisitions

The research utilizes both primary and secondary data. Primary data is collected directly in the field, while secondary data is obtained from data providers, including open data and data from specific trusted institutions (Table 1). The DRASTIC Vulnerability Index (DRASTIC-Landuse) employs the following parameters: Depth to Watertable, Net Recharge, Aquifer Media, Soil Media, Topography, Impact on Vadose Zone, Hydraulic Conductivity, and Landuse (Fig. 3).

The depth to the water table (in meters) is determined through a field survey of groundwater wells owned by residents. Data on the depth to the water table is processed using interpolation points for groundwater-surface depth. The chosen interpolation method is Kriging. Previous research indicates that the Kriging method is more effective in interpolating water table depths^{38,39}. Data was collected from 30 wells. This is due to many wells being deactivated by residents, who have switched to piped water from the local government. Data was collected during the dry season in Indonesia, from June to July 2024. The net recharge parameter utilizes data from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) satellite for the year 2024 and runoff information. CHIRPS has a resolution of 0.05 degrees (5 km) and contains rainfall information (mm/year). Net recharge is the portion of rainfall that infiltrates into the soil. The equation used to obtain net recharge is Eq. 5. In this equation, net recharge considers precipitation and runoff. Soil texture data for the soil media parameter is acquired from soil maps published by the FAO World Soil program. This data is accessible online at <https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/>. The

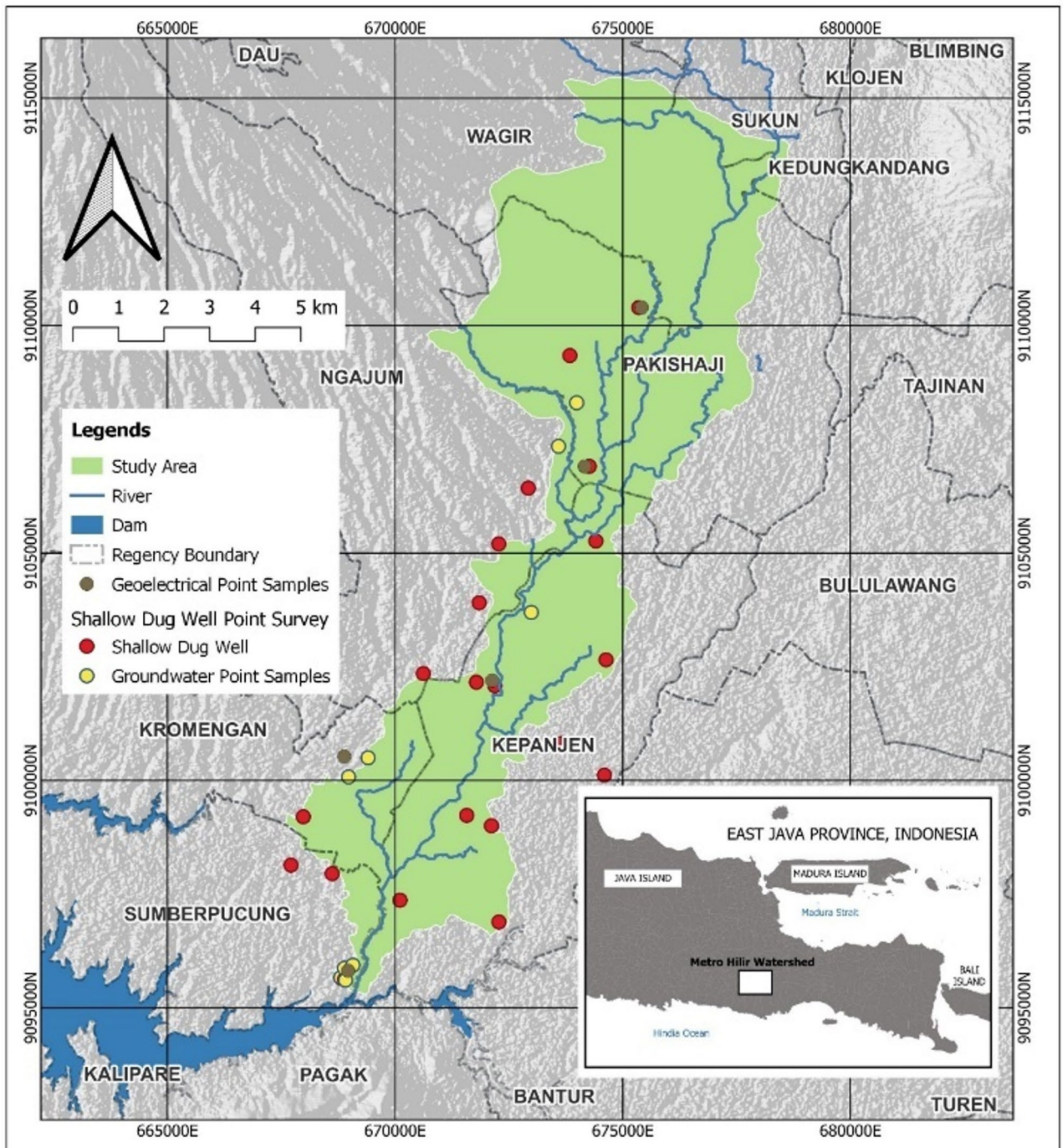


Fig. 2. Research area and sampling location.

topography parameter relies on altitude data provided by the Indonesian Geospatial Information Agency with spatial 8 m. This data is used to extract slope information relevant to the research.

This study also incorporates a field survey utilizing the Geoelectrics Method. The Geoelectrics Method is applicable for groundwater exploration up to a certain depth^{40,41}. The method used is Vertical Electrical Sounding (VES) with the Schlumberger configuration to obtain vertical interpretations. Schlumberger Configuration is applied to obtain the resistivity value of rocks. The resistivity values derived from the Geoelectrics Method can be calibrated to the rock's lithology type based on Telford et al., (1990). The geoelectric survey encompassed four trajectory points, considering the specific land conditions at each measurement site. The geoelectric survey data was subsequently analyzed to determine soil type and aquifer information at depths exceeding 20 m. Soil type is a relevant parameter for assessing the Impact on the Vadose Zone. The geoelectric estimation has indicated that the aquifer is characterized as a porous media aquifer with a specific hydraulic conductivity. The number of survey points is 5, distributed throughout the study area. Geoelectric sounding values are used to obtain aquifer

No	Data	Data sources
1	Depth to Watertable	Field survey
	Net Recharge	Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) 2024
	Aquifer Media	Field survey
	Soil Media	FAO/UNESCO Soil Map of the World 2024
	Topography	National Digital Elevation Model (DEMNAS) 2021
	Impact to Vadose Zone	Field survey
	Hydraulic Conductivity	Field survey
	Landuse	Sentinel 2 A Satellite Imagery
2	Nitrate (NO ₃)	Groundwater samples

Table 1. Data sources.

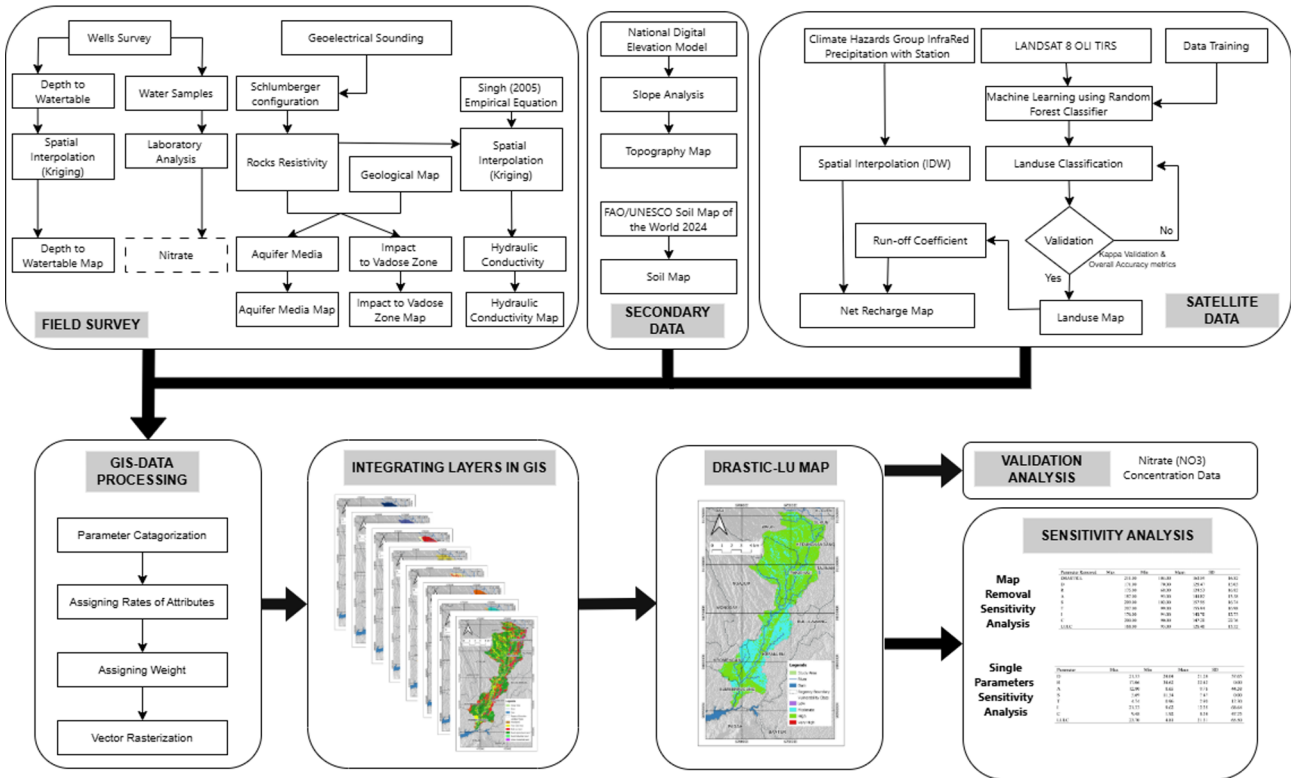


Fig. 3. Workflow research.

media information⁴¹ and to determine hydraulic conductivity^{42,43}. Equation 1 represents the empirical equation for hydraulic conductivity K (m/day) applied to weathered rocks or volcanic material, where ρ is the resistivity value (Ωm).

$$K = 1945 \times 10^{-6} e^{0.0055\rho} \tag{1}$$

The DRASTIC-Landuse parameters were determined using Sentinel 2 A Satellite Imagery provided by Google Earth Engine. The data used is LANDSAT 8 OLI TIRS satellite imagery from the year 2024. Satellite imagery is frequently employed for land use identification in groundwater studies⁴⁴. Land use identification was conducted using the Random Forest algorithm, renowned for its superior capabilities in data classification compared to other algorithms⁴⁵. The Random Forest algorithm is a part of machine learning that utilizes training data. This training data will be learned continuously (iteration) to obtain more accurate derived data⁴⁶. The identification results were validated for accuracy using Kappa Accuracy and Overall Accuracy metrics⁴⁷.

Groundwater samples were collected from 14 groundwater wells owned by residents. Groundwater sampling was conducted on sunny days during the dry season. The number of samples was determined based on well location to represent the groundwater conditions. The collected groundwater samples were subsequently analyzed in a laboratory to determine NO_3 concentration. The water quality parameters were utilized for the DRASTIC-Landuse validation test.

DRASTIC landuse data processing

The DRASTIC Landuse vulnerability index method used in this study was modified to incorporate anthropogenic impacts. Anthropogenic impacts are closely linked to land use, thus justifying the use of the DRASTIC Landuse method. This method generates a vulnerability index that quantifies the degree of groundwater vulnerability to pollution (Table 2). A higher index value indicates a higher vulnerability of groundwater to pollution.

The DRASTIC Landuse method considers the range, rating, and weighting of each parameter employed. DRASTIC Landuse utilizes Eq. 1 to determine the groundwater vulnerability zone to pollution.

$$DRASTIC - LU_{index} = D_r \cdot D_w + R_r \cdot R_w + A_r \cdot A_w + S_r \cdot S_w + T_r \cdot T_w + I_r \cdot I_w + C_r \cdot C_w + LU_r \cdot LU_w \quad (2)$$

In Eq. 2, the DRASTIC Landuse index is calculated based on the values of D, R, A, S, T, I, C, and LU, which represent the parameters used in the DRASTIC Landuse model. The value of r corresponds to the rating assigned to each component of the parameter, while w represents the weight of each parameter. The DRASTIC Landuse index is determined by summing the products of the ratings and weights for each parameter (Table 3).

Model validation and sensitivity test

The model validation and sensitivity tests ensure the validity and sensitivity of the outcome model. The sensitivity test of the model employed the Map Removal Sensitivity Index (SA) and Single Parameter Sensitivity (Sp). SA is a method used to assess the model's sensitivity by removing individual input maps^{4,5,16,26}. SA helps to ensure that the model is not overly reliant on any single input map and can be used to enhance the model's reliability and robustness. This test aids in identifying the input maps that exert the most influence on the model results. Sp is utilized to evaluate the impact of individual parameters on the overall model vulnerability.

$$SA = \frac{\left| \frac{A}{X} - \frac{B}{Y} \right|}{A} \times 100 \quad (3)$$

$$Sp = \frac{(Rp \times Rw)}{A} \times 100 \quad (4)$$

The SA in Eq. 3 represents the sensitivity analysis using the Map Removal Sensitivity Index. The values of A and B correspond to the vulnerability indices in the undisturbed and disturbed models, respectively. The X and Y values denote the number of layers implemented based on the A and B models. A higher SA value indicates that the parameter has a greater sensitivity compared to other layers. In Eq. 4, Sp represents the sensitivity analysis value, Rp is the Rating Parameter, Rw is the Rating Weight, while the A value represents the overall vulnerability index value²⁵.

The validation test compares groundwater quality parameters with the predicted groundwater vulnerability values. The water quality parameter used was Nitrate (NO₃). The validation test utilizes correlation analysis. The correlation coefficient (R²) was calculated between the predicted DRASTIC-Landuse values and the measured nitrate concentrations. The high R² value (approaching 1) suggests a strong correlation between DRASTIC and the measured water quality parameters, indicating good model validity²⁶.

Result and discussion

Hydrogeological setting

The Metro Hilir watershed is situated within the Lava of Katu Cone (Qlk), Malang Tuff Formation (Qvtm1), the Kawi-Butak Volcano Formation (Qpkb), and the Buring Volcanic Sediment Formation (Qpvb1). The Qlk formation is only found in Katu Volcano, consisting of basalt lava with a narrow distribution. The geological materials in Qpkb and Qpvb1 are lava extrusive rocks, whereas Qvtm1 comprises pyroclastic materials, sand and gravel clastic sediments, and limestone non-clastic sediment⁴⁸. Lithology exerts a significant influence on groundwater presence and accessibility⁴⁹. Additionally, lithology affects groundwater hydrogeochemistry⁵⁰ and its susceptibility to pollution risks⁵¹. The geoelectric analysis results indicate that the lithology in the study area consists of permeable basalt, alluvial sands, and sandstone (Table A1). Overall, the lithology is susceptible to groundwater pollution.

The hydrogeological map of the X sheet of Kediri illustrates the presence of several aquifer areas within the research area (Fig. 4). High-productivity aquifer zones with extensive distribution are found in Wagir District. These aquifers are composed of old quaternary volcanic rocks with low to moderate permeability, and their productivity depends on the abundance of fissures and cracks. Sukun and Pakisaji Districts also feature high aquifer productivity with wide distribution, formed from terrestrial sedimentary alluvium. Terrestrial

Vulnerability degree	DRASTIC-Landuse index
< 80	Very low
80–120	Low
120–160	Moderate
160–200	High
> 200	Very high

Table 2. Evaluation criteria of the degrees of vulnerability ³⁴.

Parameter		Range	Rating	Weight	Parameter	Range	Rating	Weight	
D	Depth to Watertable (m)	0–1.5	10	5	T	Topography (Slope %)	0–2	1	
		1.5–3	9				2–3		9
		3–4.5	8				3–4		8
		4.5–9	7				4–5		7
		9–15	5				5–6		6
		15–22.5	3				6–10		5
		22.5–30	2				10–12		4
		> 30	1				12–16		3
R	Net Recharge (mm)	> 250	9	4	I	Impact on Vadose Zone	16–18	2	5
		180–250	8				> 18	1	
		100–180	6				Karst Limestone	10	
		50–100	3				Basalt	9	
		0–50	1				Sand and Gravel	8	
A	Aquifer Media	Karst Limestone	10	3			Sand, Gravel	7	
		Basalt	9				Limestone, Gravel, Sand, Clay	6	
		Sand and Gravel	8				Sandy Silt	5	
		Massive Sandstone and Limestone	7				Metamorphic Gravel and sandstone	4	
		Bedded Sandstone and Limestone	6				Shale, Silt, and Clay	3	
		Glacial	5				Silt Clay	2	
		Weathered Metamorphic/Igneous	4				Confining layer, Granit	1	
		Metamorphic/Igneous	3				6.5E – 4	10	
		Massive Shale	2		5E – 4 – 9.5E – 4	8			
S	Soil Media	Thin or absent, Gravel	10	C	Hydraulic Conductivity (m/ day)	33E – 5 – 5E – 4	6	3	
		Sandstone and Volcanic	9			15E – 5 – 33E – 5	4		
		Peat	8			5E – 5 – 15E – 5	2		
		Aggregate Clay/Alluvium	7			1.5E – 7 – 5E – 5	1		
		Sandy loam, schist, sand, karst volcanic	6			LU	Anthropogenic Impact		Urban and Industrial Land
		Loam	5	Rural and Industrial Land	9				
		Silty Loam	4	Rural and Agricultural Land	8				
		Clay Loam	3	Built-up Land	7				
		Muckacid, granitoid	2	Coalmining Area	8				
		Non Agegrate Clay	1	Forest	3				
				Tree Clad Area	3				
				Wasteland	1				
				Waterbody	9				

Table 3. Rating and weight of DRASTIC-LU parameters ^{4,11,34}.

sedimentary alluvium is characterized by coarse to medium grains and clay. Beyond these two areas, the aquifer exhibits high productivity across a broad expanse⁵². The geoelectric results indicate that most of the aquifers in the study area are sandstone, alluvial sand, tuffs, and clays (Table A1). These findings align with the Geological Map of the research area.

DRASTIC-LU for the area study

Depth to watertable

The depth to the watertable is crucial as it relates to the depth of the material through which pollutants must pass before reaching groundwater¹⁹. This parameter provides insights into the vertical distance and the time pollutants travel when encountering the material. A deeper watertable translates to a longer travel time for pollutants, leading to reduced groundwater vulnerability^{4,19}. Depth to watertable data was acquired from residents' dug wells and drilled wells (and Fig. 5a). Areas with shallow water table depths are generally located near rivers, while areas with deep water table depths, up to more than 9 m, are located in areas with sloping topography (Table 4 and A2).

Net recharge

Groundwater recharge originates from precipitation and infiltrates into the soil. Infiltration can occur from open land, farmland, and various land use type⁵³. Net recharge is calculated based on Eq. 5⁵³.

$$R = P - (P(1 - C)) \quad (5)$$

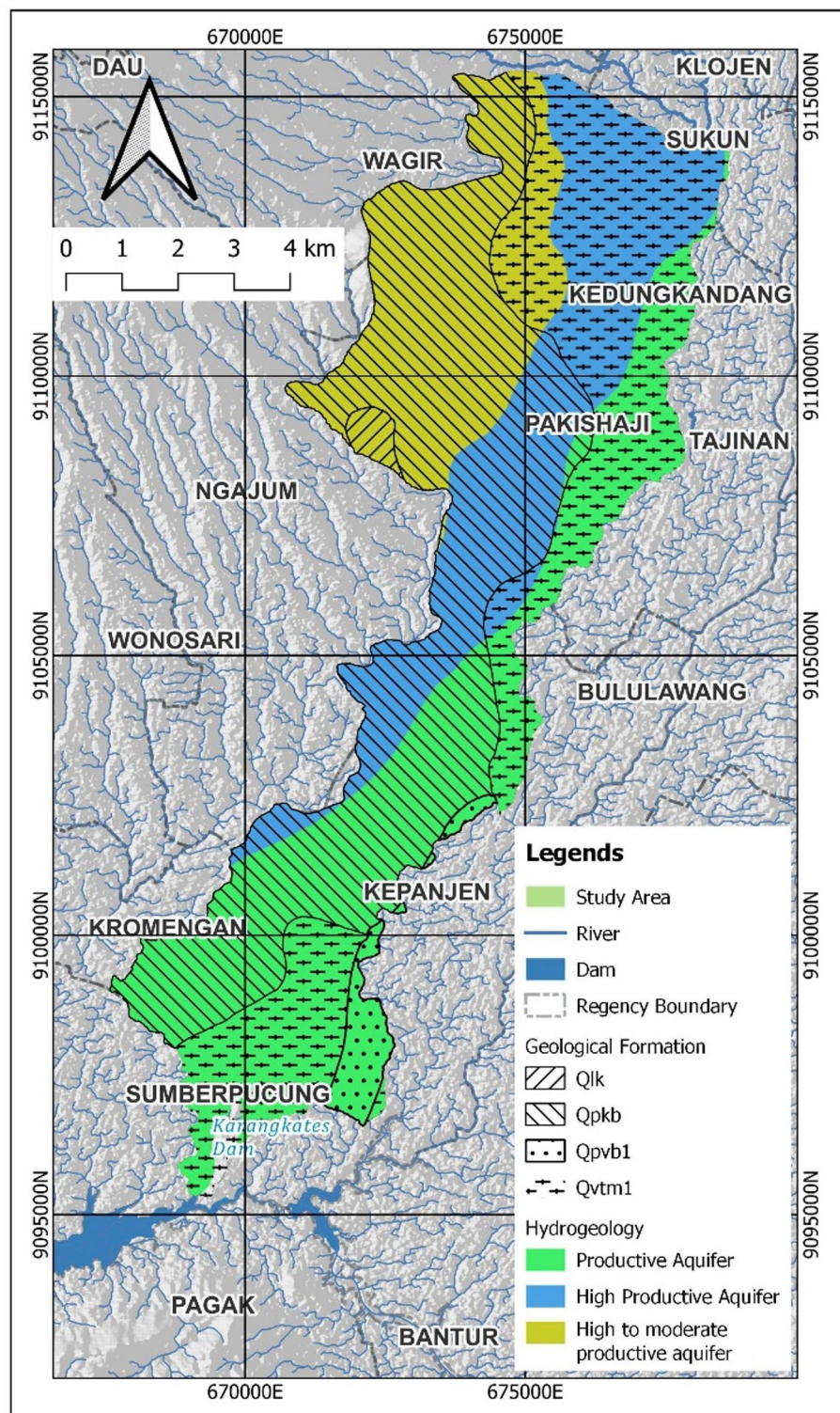


Fig. 4. Hydrogeological Map of Metro Hilir.

The R-value in Eq. 5 represents the amount of rainfall recharged, the P-value represents precipitation, and the C-value represents the runoff coefficient. Groundwater recharge refers to the addition of water through the infiltration process in various land use types⁴. Rainfall data was acquired from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) 2024. The annual rainfall depicted in the image (CH) ranges from 502 to 542 mm/month (Table 4; Fig. 5b). A range exceeding 250 mm/month corresponds to the highest rating of 9 and covers the entire study area due to the predominance of rural agricultural land, which exhibits a runoff coefficient value of 0.5⁵⁴. The runoff coefficient is a value indicating the portion of rainfall that flows above the

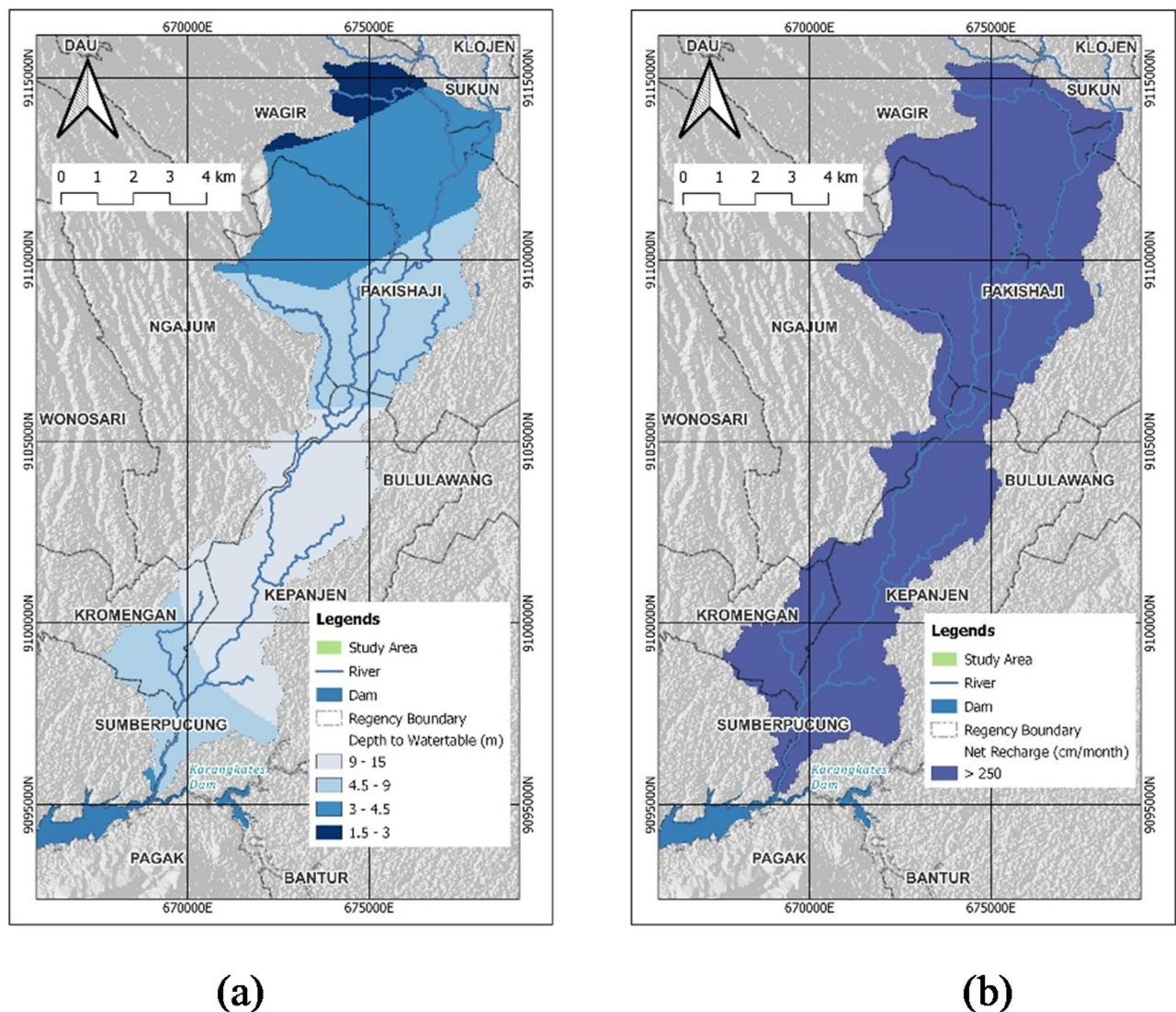


Fig. 5. Depth to watertable (a) and net recharge (b).

ground surface and the portion that infiltrates into the soil. High rainfall in areas dominated by rural agriculture leads to elevated groundwater recharge. However, increased groundwater net recharge can potentially enhance the risk of pollution²². The Net Recharge in Eq. 5 has accounted for water that does not infiltrate into the soil as runoff. The runoff in this study uses land use information from subheading 3.2.8.

Aquifer media

The aquifer media refers to specific geological formations that function as aquifers. Aquifer media typically consist of sand and gravel, fragmented or cracked rock, and unconsolidated material⁵⁵. Aquifer media plays a pivotal role in determining the direction and extent of pollutant pathways and the rate of pollutant movement within the aquifer⁵⁶. The aquifer media map was derived from field surveys and by adjusting the Geological Map provided by the Ministry of Energy and Mineral Resources. The aquifer media within the study area is predominantly composed of basalt, igneous rocks, sand, and gravel (Table 4; Fig. 6a).

The geological formation of basalt, a volcanic rock, facilitates the formation of aquifers and exhibits high permeability. Compared to crystalline silicate rocks, basalt is highly susceptible to weathering⁵⁷. Basalt lava is often characterized by a fractured structure with numerous pores and gas holes, resulting in a greater susceptibility to cracking upon solidification⁵⁸. In such media, the potential for pollution is elevated due to the increased flow rate when pollutants are introduced. The study area encompasses igneous rocks such as tuff, sand, and gravel. These rocks possess a high-water yield owing to their fine to coarse texture, enabling them to form aquifers. Tuff, sand, and gravel can potentially increase the pollutant levels within the aquifer, thereby elevating the risk of pollution⁷.

Parameter	Rating	Range	Area (Ha)	%
D—depth to watertable (m)	9	1.5–3	332.765	4
	8	3–4.5	2374.1	31
	7	4.5–9	2729.907	36
	5	9–15	2193.89	29
R—net recharge (mm)	9	> 250	7633.60	100
A—aquifer media	9	Basalt	95.51	1
	8	Sand and Gravel	3279.44	43
	3	Metamorphic/Igneous	4253.96	56
S—soil media	1	Non-Aggregate Clay	6417.052	84
	3	Clay Loam	1216.313	16
T—topography (slope %)	10	0–2	22.50	0.2
	9	2–3	188.51	2.5
	8	3–4	478.52	6.3
	7	4–5	727.79	9.5
	6	5–6	785.79	10.3
	5	6–10	2515.39	33
	4	10–12	762.29	10
	3	12–16	936.05	12.3
	2	16–18	275.52	3.6
	1	> 18	938.81	12.3
C—hydraulic conductivity (m/day)	10	> 6.5e–4	4257.339	55.76
	6	33e–5 – 5e–4	1029.26	13.49
	1	1.5e–7–5e–5	2347.312	30.75
I—impact on vadose zone	9	Basalt	95.51	1.3
	7	Sand, gravel	2250.12	29.5
	5	Sandy silt	1029.32	13.5
	2	Silt clay	4253.96	55.7
LU—land use antropogenic impact	10	Urban industrial land	142.99	1.87
	9	Rural industrial land	20.79	0.27
	9	Waterbody	693.85	9.1
	8	Rural agriculture land	3796.96	49.7
	7	Build up land	1357.21	17.78
	3	Tree clad area	1439.75	18.9
	3	Forest	18.85	0.24
	1	Wasteland	163.60	2.14

Table 4. Area of each variable.

Soil media

The soil media plays a crucial role in assessing the potential for groundwater pollution within the unsaturated zone¹⁹. Soil texture, a component of soil media, influences the level of pollutant infiltration^{55,59}. Soil map data was acquired from the FAO World Soil program, revealing that the entire study area is composed of clay loam and unconsolidated clay (Table 4; Fig. 6b). According to the FAO World Soil map data, the entire study area is characterized by clay loam and unconsolidated clay⁶⁰. A lower clay content and smaller grain size in the soil correlate with a reduced potential for pollution⁵⁶. Conversely, soils with larger grains, such as sand, allow for more efficient water passage through their pores. Soils with a loamy texture impede the free movement of water due to the presence of particles of varying sizes⁶¹.

Topography

The topography reveals variations in slope⁴. Topography influences the flow and deposition of pollutants on surfaces before they infiltrate into groundwater²⁴. Sloping areas exhibit lower vulnerability to groundwater pollution due to increased runoff and decreased infiltration. Conversely, areas with gentler slopes pose a higher risk of pollutant infiltration^{19,32}. Infiltration rates increase in flatter areas⁶². Water transports pollutants that infiltrate into groundwater. A lower topographic slope correlates with a higher vulnerability to pollution²⁰. The study area encompasses a diverse range of terrain types. Slopes exceeding 6% dominate the area, while flatter terrains are also present (Table 4; Fig. 7a).

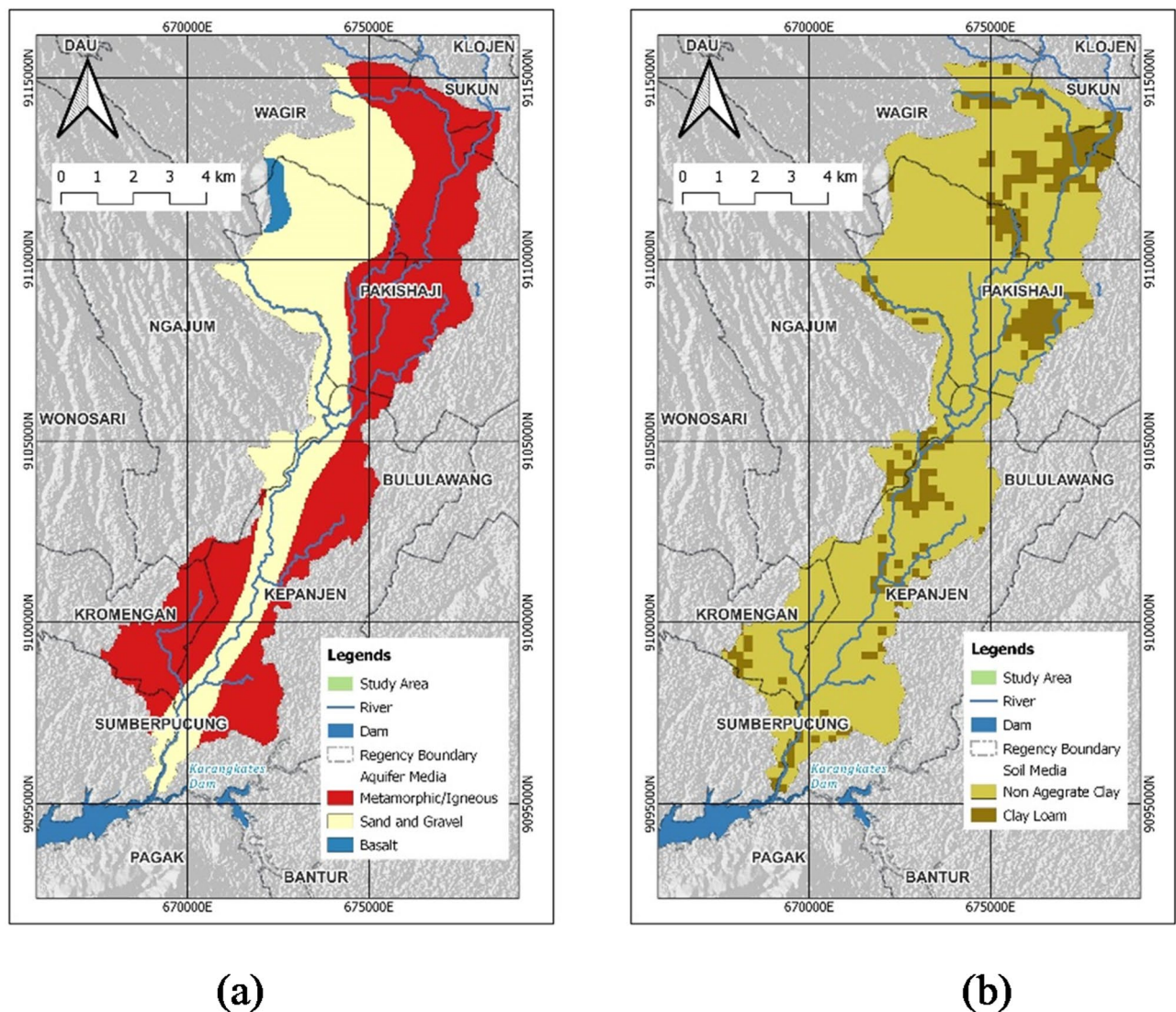


Fig. 6. Aquifer media (a) and soil media (b).

Impact on vadose zone

The vadose zone is situated beneath the ground surface and functions as a filter for pollutants present in the soil prior to their entry into the aquifer zone⁶³. The thickness of vadose zones can vary widely, ranging from less than 1 m to hundreds of meters or more, depending on the depth of the groundwater Table 3. The movement of pollutants within the vadose zone is influenced by the aquifer media and topography⁵⁵. Vadose zones composed of karst, sand, and gravel exhibit a heightened likelihood of pollutant movement reaching the aquifer¹¹. Nevertheless, the vadose zone can also act as a barrier, delaying the movement of pollutants before they reach the aquifer⁶⁴.

The vadose zone in the research area comprises basalt, sand, gravel, sandy silt, and silty clay (Table 4; Fig. 7b). Due to its fine texture, silty clay exhibits low permeability, impeding the movement of water¹¹. Sandy silt, composed of fine sand particles, can facilitate the rapid spread of pollutants. This material could be highly vulnerable to groundwater pollution if it possesses larger grains. Sand and gravel also dominate the research area. These materials exhibit high porosity and permeability, allowing for the easy passage of water and pollutants. Basalt material is exclusively found in the Mount Katu area. Basalt possesses a high pollution potential due to the possibility of pollutants entering the rock at an elevated rate⁵⁶.

Hydraulic conductivity

The type of rock formation significantly influences groundwater flow within aquifers^{65–67}. Fractures and features within the rock act as channels, directing the groundwater flow⁵⁵. Groundwater flow conditions can be assessed through hydraulic conductivity. Hydraulic conductivity is a material property that reflects the relative ease with which groundwater flows through porous media, thereby controlling the groundwater flow rate at a specific hydraulic gradient¹. Hydraulic conductivity also regulates the rate at which pollutants move from their entry

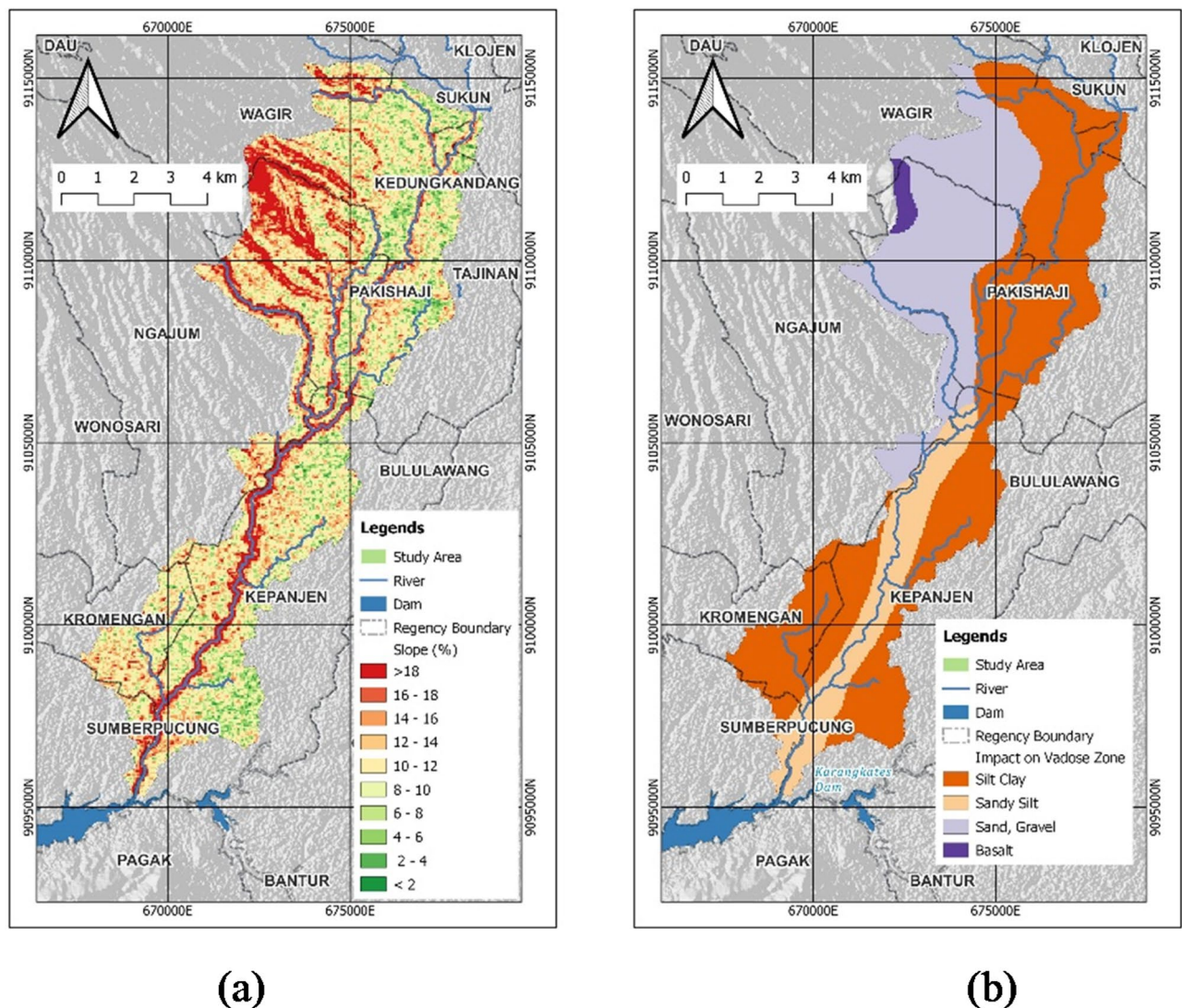


Fig. 7. Topography map (a) and impact on vadose zone (b).

point into the aquifer⁵⁶. Higher hydraulic conductivity in groundwater leads to an increased risk of pollution^{68,69}. In this study, Eq. 2 was employed to determine the hydraulic conductivity value.

The Metro Hilir watershed exhibits a diversity of material lithology, as indicated by the hydraulic conductivity values (Table 4; Fig. 8a). The Arithmetic Mean method is used to determine the hydraulic conductivity value of the aquifer⁷⁰. The materials found in the research area encompass permeable basalt, coarse sandstone, alluvium, clays, tuff, and gravel. Generally, materials with finer grain sizes, such as silt and clay, exhibit lower hydraulic conductivity and possess a greater capacity to retain pollutants, both temporarily and over extended periods⁶⁹. Overall, the hydraulic conductivity values range from 1.5×10^{-7} – 5×10^{-5} m/day. This suggests that the overall vulnerability of the area to groundwater pollution is relatively high.

Anthropogenic impact

The hydrogeochemical processes of groundwater exhibit spatial and temporal variations, influenced by geological characteristics, aquifer chemistry, and anthropogenic activity⁷¹. Anthropogenic activity can significantly alter the hydrogeochemistry of groundwater. Spatially, anthropogenic activity can be identified through land use patterns, which exert a major influence on groundwater vulnerability in most areas. The intensity of pollution can vary depending on land use patterns, including agriculture, industry, commerce, and rural-urban development⁷. Land use parameters can substantially affect hydrogeological parameters. Hydrogeological parameters can be altered by the use of pesticides, urban and industrial waste, septic tank leakage, and sewage dumps⁷². Water quality parameters indicative of pollutants from anthropogenic activities include Nitrate, Phosphate, Magnesium, suspended solids, and heavy metals³¹. Pollutants can enter groundwater through irrigation systems and infiltration from industrial areas and waste disposal^{73,74}. Urban and industrial activities can also increase the risk of pollutants entering groundwater⁶⁸.

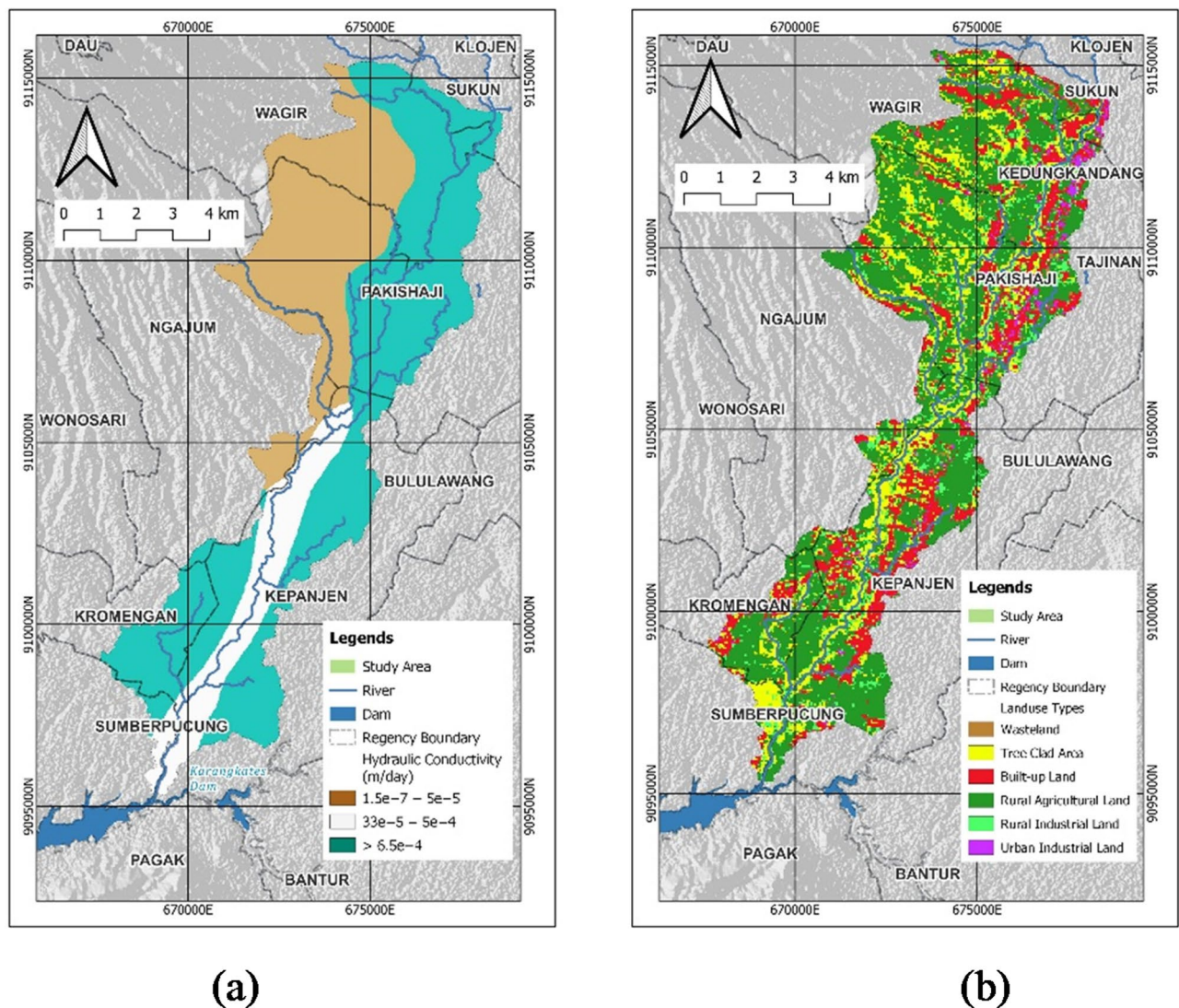


Fig. 8. Hydraulic conductivity (a) and Landuse (b).

The identification of anthropogenic impacts was achieved through the utilization of land cover maps derived from Landsat 8 OLI TIRS satellite imagery, provided by Google Earth Engine 2024. The land use types encompassed within the study area include Urban Industrial Land, Rural Industrial Land, Waterbody, Rural Agriculture Land, Built Up Land, Tree Clad Land, Forest, and Wasteland (Table 4; Fig. 8b). The validation test of the classification process yielded a kappa validation value of 0.769 and an overall accuracy of 0.801, indicating the validity of the classification results. Table 4 reveals that the most dominant land cover in the downstream region of the Metro Watershed is Rural Agriculture Land, occupying 37.97 km² or 49.74% of the total area. This land use category exhibits a high vulnerability due to associated agricultural risks.

Groundwater vulnerability to pollution/drastic landuse

The DRASTIC Landuse model offers a comprehensive assessment of the relative vulnerability of groundwater to pollution. A high DRASTIC Landuse score signifies that the location is generally situated within a sensitive or vulnerable area (Table 5). While the DRASTIC Landuse model cannot pinpoint areas where pollution has occurred, it can effectively guide prevention efforts toward regions with the highest potential for pollutant. A higher index value indicates a greater likelihood of groundwater pollution (Fig. 9). It is essential to acknowledge that the DRASTIC Landuse Index serves as a relative evaluation tool and is not intended to provide definitive answers²⁶. In this study, the DRASTIC Landuse model has been modified to incorporate land use considerations, reflecting the influence of anthropogenic impacts^{11,19}.

The DRASTIC Landuse result is derived from the calculation of all indices using Eq. 1. The Metro Hilir watershed was identified as having potential pollution in a Very High class, encompassing 0.01% of its total area. The vulnerable class is concentrated in the areas surrounding the Metro River within built-up land areas. The High vulnerability class covers 65.686% of the area, predominantly in regions with flat slope topography and rural agricultural lands. The Moderate vulnerability class dominates 34.208% of the research area, primarily found

Score	Range	Class	Area (Ha)	%
5	> 200	Very High	0.75	0.010
4	161–200	High	4934.75	65.686
3	121–160	Moderate	2569.90	34.208
2	80–120	Low	7.25	0.097
Total			7512.65	100

Table 5. DRASTIC-landuse groundwater vulnerability.

in areas with sloping topography and rural agricultural lands. The Low vulnerability class constitutes 0.097%, distributed across various land use types. This indicates that the study area, which consists of an intermountain plain and rural agricultural lands, has a high vulnerability to groundwater pollution.

Validation analysis

Validation test using Nitrate parameters. Nitrate content is one of the indicators used to suspect pollution^{75,76}. Nitrate has no natural source in groundwater systems. Its presence in groundwater systems indicates the existence of pollution, such as from agricultural and anthropogenic activities⁷³. Nitrate is a non-point pollution source, so the specific location of the pollutant source cannot be determined. Nitrate levels can be used as a basis for analyzing groundwater pollution resulting from human activities⁷⁷.

The validation test employed nitrate levels against the DRASTIC Landuse model, resulting in an R^2 value of 0.911. This value signifies a strong correlation between nitrate levels and groundwater vulnerability. While nitrate naturally occurs in the biogeochemical cycle, its elevated levels can be attributed to infiltration, which introduces nitrate pollutants into the aquifer, particularly in rural agricultural areas^{73,75}. This aligns with the conditions of the study area, which is located in a rural agricultural area.

Sensitivity analysis

The DRASTIC-Landuse results were subjected to sensitivity testing using the Map Removal Sensitivity Analysis (SA) and Single Parameter Sensitivity Analysis (Sp). Sensitivity tests are commonly employed for various models that utilize Multi-Criteria Decision Making (MCDM). These tests are valuable for comprehending the influence of each parameter on the model. This influence can be attributed to several factors, including input parameters, input inaccuracy, assigned weights and ratings, and overlay treatment²⁵.

The sensitivity test employed SA, as it is a suitable method for assessing the sensitivity of individual parameter layers²⁶. Table 6 reveals that the Hydraulic Conductivity parameter exhibits the highest SA value. A high SA value indicates that the Hydraulic Conductivity parameter exerts the most significant influence compared to other parameters within the model. In descending order, the sensitivity values of the parameters are $C > R > S > T > D > LU > I > A$. This implies that a change in the Impact on Vadose Zone value, followed sequentially by other parameters, would result in a substantial alteration of the model results^{16,25}. This can be attributed to the lithological conditions prevalent in the research area, characterized by volcanic materials such as sandstone, alluvial sand, tuffs, and clays. As further explained by Napolitano et al., (1996) the results of SA can be utilized to identify critical layers that require more detailed and accurate information. A deeper understanding of the Hydraulic Conductivity parameter is essential for producing a more refined vulnerability index.

The highest Sp value was observed for the Impact on Vadose Zone parameter (I) (Table 7). A higher value indicates that the parameter exerts a significant influence on the vulnerability index¹⁶. Sequentially, the Sp values are $I > LU > C > A > D > T > R > S$. Lower Sp values suggest that Net Recharge and Soil Media have a minor weight on the vulnerability in the research area. Overall, when compared to the Sensitivity Analysis (SA) values, the Hydraulic Conductivity and Impact on the Vadose Zone parameters show sensitivity to input changes and have a substantial impact on vulnerability.

The final result of this research is a map of groundwater vulnerability zones to pollution. This research can provide new information to reduce the risk of groundwater pollution in the study area. The information can be used by stakeholders, local government, academics, and the local community. Based on the research findings, the 'Impact on Vadose Zone' and 'Hydraulic Conductivity' factors are the most sensitive to the occurrence of pollution. Therefore, preventing the use of chemicals that are potential pollutants needs to be further considered. Efforts to disseminate information about the natural conditions in the study area can also be pursued to increase public awareness and participation in reducing the risk of groundwater pollution.

This study has limitations, namely its small scope and the use of commonly applied methods. However, this study has advantages with the use of field surveys, such as geoelectric surveys, which were not present in previous research^{4,5,19,20}. Additionally, this study includes validation tests, ensuring the reliability of its results. The study also features sensitivity tests, allowing for a clear understanding of the variables influencing vulnerability. The novelty of this research is the application of DRASTIC Landuse in an intermountain plain dominated by a rural agricultural area. The study's location in a tropical region is also a strength. The study area is located in a tropical region with high rainfall. However, based on the research results, the Net Recharge parameter, which is related to rainfall, actually has a low influence on groundwater vulnerability to pollution.

The DRASTIC-LU method, while highly relevant for groundwater vulnerability assessment, faces particular challenges in tropical environments such as the Metro Hilir Watershed, which is dominated by rural agricultural land. These limitations are often related to complex hydrological dynamics, high rainfall that can rapidly influence pollutant movement, and the extensive diversity of soil types and land use, which may not be fully represented

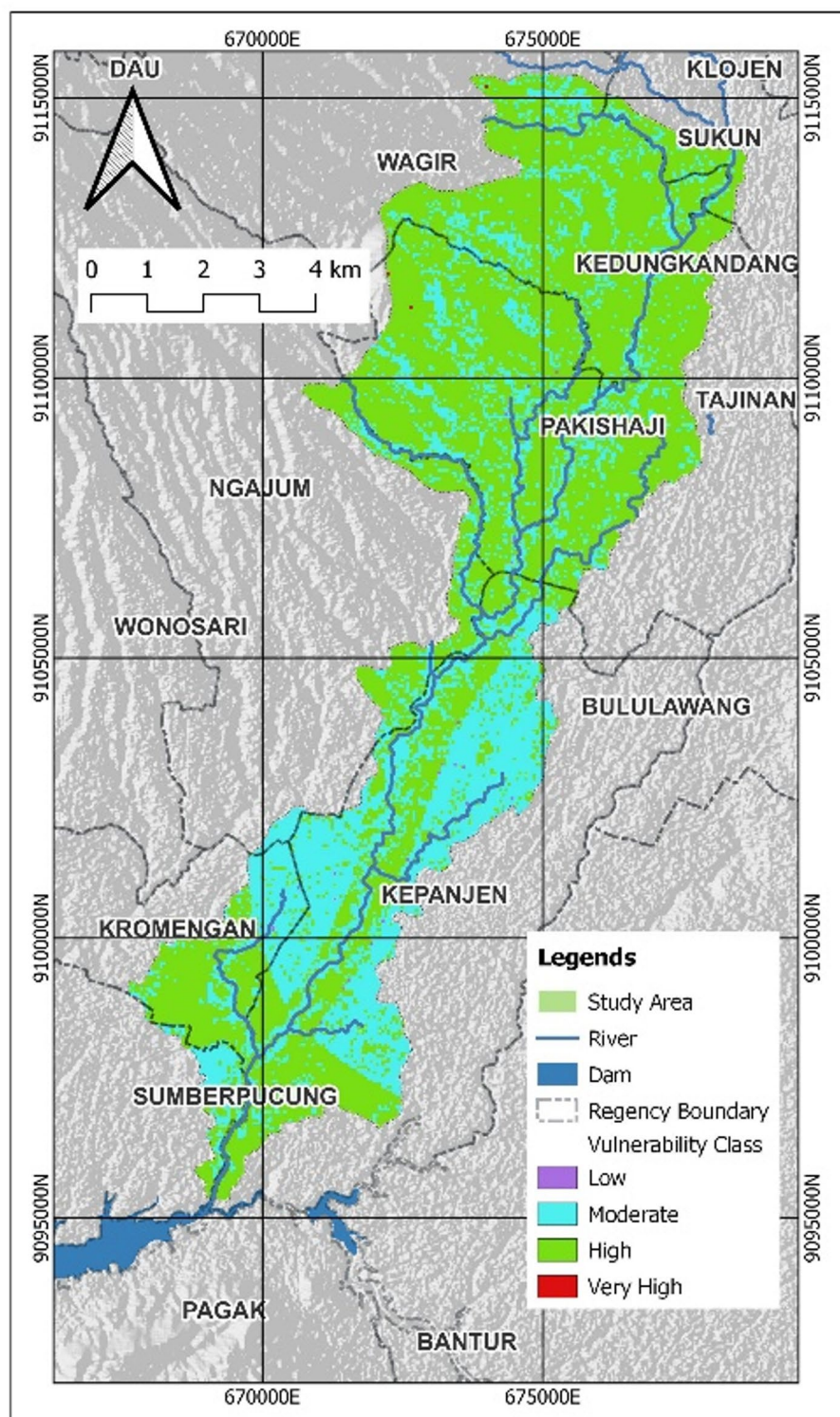


Fig. 9. DRASTIC landuse distribution.

by conventional DRASTIC parameters. Conceptually, this research contributes by applying and evaluating the DRASTIC-LU model in a tropical context, which helps highlight the need for adjustments or additions of parameters more specific to local climatic and geological conditions. Findings from this study can serve as a basis for the development of more adaptive future methodologies, possibly by integrating high-intensity rainfall data, more detailed soil characteristics, or better tropical-specific land use factors, to enhance the accuracy and relevance of groundwater vulnerability assessments in similar regions.

Parameter removed	Max	Min	Mean	SD
DRASTICL	211.00	104.00	160.59	16.82
D	171.00	70.00	126.47	15.03
R	175.00	68.00	124.53	16.82
A	187.00	95.00	144.82	13.58
S	209.00	102.00	157.95	16.74
T	207.00	99.00	155.94	16.98
I	176.00	94.00	140.70	12.73
C	200.00	90.00	147.20	22.76
LULC	168.00	95.00	126.40	13.32

Table 6. Statistical summary of rating of map removal sensitivity analysis.

Parameter	Max	Min	Mean	SD
D	21.33	24.04	21.24	37.65
R	17.06	34.62	22.42	0.00
A	12.80	8.65	9.76	44.58
S	5.69	11.54	7.47	0.00
T	4.74	0.96	2.90	12.30
I	21.33	9.62	12.35	68.64
C	9.48	1.92	8.34	47.75
LULC	23.70	4.81	21.31	65.50

Table 7. Single parameter sensitivity analysis.

Conclusion

Surface water and groundwater are interconnected. Groundwater vulnerability is influenced by surface water conditions and rainfall patterns. Rainfall infiltrates into deeper zones, forming groundwater. Groundwater vulnerability mapping is crucial for identifying pollution-prone areas. Recognizing high groundwater vulnerability zones is essential for formulating effective groundwater protection policies. The objective of this study is to map groundwater vulnerability zones to pollution in the Metro Hilir Watershed. The DRASTIC-LU analysis conducted in this study yielded a Groundwater Vulnerability Map for the Metro Hilir Watershed. This study utilizes surveys on shallow dug wells and geoelectric testing. Groundwater quality sample tests were also conducted to validate the zoning results. The vulnerability zone generated by the DRASTIC-LU Model indicates that most of the research areas fall within the moderate to high vulnerability class, encompassing 99% of the total research area. Vulnerability classes range from moderate to high. Moderate vulnerability is found in rural agricultural lands with sloping topography, while high vulnerability is found in flatter topography areas within rural agricultural lands. The validation test employed the Nitrate parameter ($R^2=0.911$), confirming the validity of the DRASTIC-Landuse model. This aligns with the characteristics of Nitrate, which is a non-point source of groundwater pollution in rural agricultural lands. Sensitivity tests were conducted to identify the most influential and heavily weighted parameters. The Map Removal Sensitivity Analysis revealed that the Hydraulic Conductivity parameter exhibits the highest sensitivity compared to other parameters. The Single Parameter Analysis further reinforces this finding, highlighting the Impact on Vadose Zone parameter as the most influential factor on vulnerability. Consequently, both parameters (Hydraulic Conductivity and Impact on the Vadose Zone) are sensitive to input changes and have a substantial impact on the vulnerability index. These parameters naturally indicate that this area has a moderate to high vulnerability. This study demonstrates that the management of rural agricultural lands located in the intermountain plain requires specific management to prevent groundwater contamination.

Depth	Rock type	Resistivity	K m/day	LN(K)	K cm/day	Ln K	Rating
Lava of Katu cone formation (Qlk)							
0–56	Tuf	3424.39	1.2867E–05	– 11.2608	0.001286733	– 6.655649122	2
56–90	Basalt	1369.98	1.0391839	0.038436	103.9183898	4.643605878	
90–100	Andesit	935.23	11.3538931	2.429561	1135.389313	7.034730878	
SUM			12.3930899	– 8.79282	1239.308989	5.022687633	
Geometric mean				– 2.93094		1.674229211	
Exp mean ln(K)				0.053347		5.334681651	
Arithmetic mean				4.13103		413.1029964	
Depth	Rock type	Resistivity	K m/day	LN(K)	K cm/hari	Ln (K)	Rating
Kawi-Butak Volcano Formation (Qpkb)							
0–45	Sand	866.15	2.46439E–06	– 12.91357	0.000246439	– 8.308397646	1
45–80	Tuf	2054.79	0.024040405	– 3.728019	2.404040534	0.877150878	
80–100	Andesit	1042.55	6.292136579	1.8393007	629.2136579	6.444470878	
SUM			6.316179449	– 14.80229	631.6179449	– 0.98677589	
Geometric Mean				– 4.934095		– 0.328925297	
Exp Mean ln(K)				0.007197		0.719696778	
Arithmetic Mean				2.1053931		210.539315	
Malang Tuff Formation (Qvtm1)							
0–42	Alluvium	172.06	755.209875	6.626995	75520.9875	11.2321658	6
42–66	Tuf	2739.59	0.00055618	– 7.494419	0.05561795	– 2.88924912	
66–78	Sand	639.01	57.9030865	4.058770	5790.30865	8.663940878	
78–100	Andesitic Fragmen	655.19	9.53728E– 05	– 13.86289	9.53728E– 05	– 9.25771764	
SUM			813.113519	– 10.67154	81311.3519	7.74913998	
Geometric Mean				– 2.667885		2.58304666	
Exp Mean ln(K)				0.0693988		13.2374067	
Arithmetic Mean				203.27838		27103.78398	
Buring Volcanic Sediment Formation (Qpvb1)							
0–42	Sand	739.25	33.36310644	3.5074507	3336.310644	8.112620878	8
42–64	Tuf	2253.25	0.001266348	– 6.671618	0.126634835	– 2.066447646	
64–85	Basalt	1093.28	4.760180995	1.5602857	476.0180995	6.165455878	
85–100	Andesit	829.65	20.29248645	3.0102507	2029.248645	7.615420878	
SUM			58.41704023	1.4063692	5841.704023	19.82704999	
Geometric Mean				0.3515923		6.609016663	
Exp Mean ln(K)				1.4213289		741.7532662	
Arithmetic Mean				14.60426		1947.234674	

Table 8. Lithological information based on geoelectrical survey.

ID	X	Y	Elevation (meter)	Types	Well depth from ground surface to bottom (m)	Depth to Watertable (m)
1	112°31'56.0" E	8°10'43.6" S	303.55	Shallow Dug Well	8	7
2	112°31'56.3" E	8°10'42.0" S	302.29	Shallow Dug Well	13	13
3	112°31'59.1" E	8°10'43.4" S	305.68	Shallow Dug Well	12.33	9.31
4	112°31'59.8" E	8°10'43.9" S	305.9	Shallow Dug Well	30	9.9
5	112°31'59.0" E	8°10'35.3" S	306.4	Shallow Dug Well	12.54	9.4
6	112°32'05.0" E	8°10'33.0" S	308.97	Shallow Dug Well	14.04	11.31
7	112°32'01.4" E	8°08'18.4" S	330.41	Shallow Dug Well	15.1	13.71
8	112°32'15.4" E	8°08'04.6" S	330.05	Shallow Dug Well	9.68	7.88
9	112°34'53.3" E	8°04'35.4" S	381.04	Shallow Dug Well	22.63	18.58
10	112°34'44.1" E	8°03'50.0" S	396.98	Shallow Dug Well	16.1	13.81
11	112°35'28.4" E	8°02'41.7" S	395.93	Shallow Dug Well	20.07	14.7
12	112°33'46.2" E	8°07'12.7" S	337.8	Shallow Dug Well	10.25	10.6
13	112°34'58.2" E	8°05'28.9" S	361.38	Shallow Dug Well	26	24
14	112°34'31.1" E	8°04'21.2" S	388	Shallow Dug Well	13.64	11.09
15	112°34'09.6" E	8°04'51.2" S	381	Shallow Dug Well	19.7	17.33
16	112°33'32.9" E	8°07'10.2" S	341.77	Shallow Dug Well	18.57	15.62
17	112°33'34.7" E	8°06'13.4" S	344.81	Shallow Dug Well	7.61	7.08
18	112°34'12.1" E	8°06'20.1" S	358.55	Shallow Dug Well	21.32	20.01
19	112°31'20.3" E	8°09'28.8" S	323.17	Shallow Dug Well	9.52	7.37
20	112°31'49.9" E	8°09'27.7" S	320.67	Shallow Dug Well	10.56	9.06
21	112°31'29.1" E	8°08'47.0" S	327.04	Shallow Dug Well	11.64	9.35
22	112°32'38.7" E	8°09'46.5" S	311.98	Shallow Dug Well	14.17	11.3
23	112°33'26.3" E	8°08'45.5" S	328.34	Shallow Dug Well	22	20.32
24	112°33'44.1" E	8°08'52.9" S	331.96	Shallow Dug Well	27	25
25	112°33'48.6" E	8°05'31.2" S	368.2	Shallow Dug Well	15.33	12.78
26	112°32'54.7" E	8°07'04.2" S	343.57	Shallow Dug Well	15.76	14.56
27	112°35'05.9" E	8°06'53.8" S	354.88	Shallow Dug Well	14.06	13.09
28	112°33'49.7" E	8°10'01.7" S	319.21	Shallow Dug Well	19.68	17.88
29	112°35'05.0" E	8°08'16.4" S	345.62	Shallow Dug Well	20.85	16.08
30	112°34'34.3" E	8°07'54.0" S	343	Shallow Dug Well	17.3	15.85

Table 9. Well survey.

Data availability

Data is available upon reasonable request by send email to ferryati.masitoh.fis@um.ac.id.

Appendix

See Tables 8 and 9.

Received: 26 February 2025; Accepted: 30 June 2025

Published online: 29 October 2025

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Acknowledgements

We gratefully acknowledge Farhan Adi, Khoirun NisaAri and Khairil Mursalin, the survey assistants from the Physical and Environmental Geography Research Group, for their valuable assistance during the field survey.

Author contributions

F.M. planned, designed the survey and analysis, and wrote the full manuscript; A.N.R. performed the data and formal analysis; F.R. supervised the project, reviewed the full manuscript and revised the format. All authors have read and agreed to the published version of the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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