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Research Article

Land use changes and their impact on groundwater vulnerability's spatio-temporal conditions

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Abstract

Bantul Regency, located on Java Island, is one of the areas in Indonesia with abundant groundwater sources, thus experiencing rapid urban growth. The hazard of groundwater vulnerability in this area has increased due to urban expansion that coevals with changes in land use and human population growth. The objective of this study was to analyze how groundwater vulnerability has changed due to land use conditions and what impact those changes have had. Because of the various variables associated with urban growth, the sub-districts of Bantul and Bambanglipuro were explicitly chosen as research areas. This study compared groundwater vulnerability and land use between 2009 and 2021 in a spatiotemporal manner. The vulnerability determination method used is the Susceptibility Index (SI), which consists of the parameters depth of groundwater table, groundwater recharge, aquifer media, topography, and land use. Each parameter is processed into an index of groundwater vulnerability by scoring and weighting methods. Techniques for descriptive comparative analysis are employed to ascertain how changes in land use will affect the degree of groundwater vulnerability. The results of the land use classification show that the agroforestry area has decreased while the semi-urban area has increased in 2009 and 2021. The sub-district of Bambanglipuro underwent numerous changes. On the other hand, it is known that medium and high vulnerability levels dominate groundwater vulnerability. In this instance, it is concluded that variations in land use have impacted how groundwater vulnerability levels are distributed.

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Introduction

At least until the mid-21st century, human population growth will continue and decline by 2100 (Vollset et al., 2020; O'Sullivan, 2023). As a result of this population growth, the environment is often subjected to various problems. The situation logically occurs because human population growth correlates with their needs. As a result, there has been a change in land use over the past few decades, coupled with pressure on natural resources to meet human needs, which effectively reduces their availability in nature (Mhawish and Saba, 2016). Land use changes in various parts of the world have transformed land cover into agricultural land, industrial land, residential areas, and urban centres, at the expense of natural vegetation (Winkler et al., 2021). These changes lead to deforestation, biodiversity loss, and land degradation (Matano et al., 2015; Kgaphola et al., 2023).

One of the resources that can be negatively affected is water resources, especially groundwater resources. Water quality declines as a result of land degradation brought on by extensive land use, according to Lestariningsih et al. (2018). In addition, Muchtar et al. (2023) highlighted that land degradation within a watershed has a significant impact on the quality of water resources. Carrard et al. (2019) mentioned that groundwater resources have a massive role in human life because they are the primary drinking water source. Therefore, carrying out the protection management of groundwater resources is necessary. One of the management "tools" that can be used is the zoning assessment of groundwater vulnerability to the contamination that occurs in an area. Groundwater vulnerability assessment is a term used to describe the level of resilience of a groundwater system under natural conditions, i.e., according to its hydrogeological factors, to contamination from natural impacts and human activities (Harter et al., 2002). Groundwater vulnerability studies are divided into intrinsic and specific groundwater vulnerability. Among these, it is recognized that specific groundwater vulnerability studies are considered more developed and capable of describing the condition of groundwater vulnerability at the study site than intrinsic groundwater vulnerability, as they consider the impact of increasing human activities (Neshat et al., 2015). Due to its vast groundwater sources, rapid urban expansion occurs in Bantul Regency, Java Island. Groundwater vulnerability in this area is rising due to urbanization, land use changes, and population growth. Bantul and Bambanglipuro Sub-districts (Figure 1) were chosen for investigation due to urban growth characteristics. Snguon et al. (2010) and Brontowiyono et al. (2022) explained that land use changes have degraded Bambanglipuro Sub-district water quality. In addition, due to increased settlement activity, residential waste has polluted various urban areas in Bantul Sub-district (Wijayanti et al., 2018).

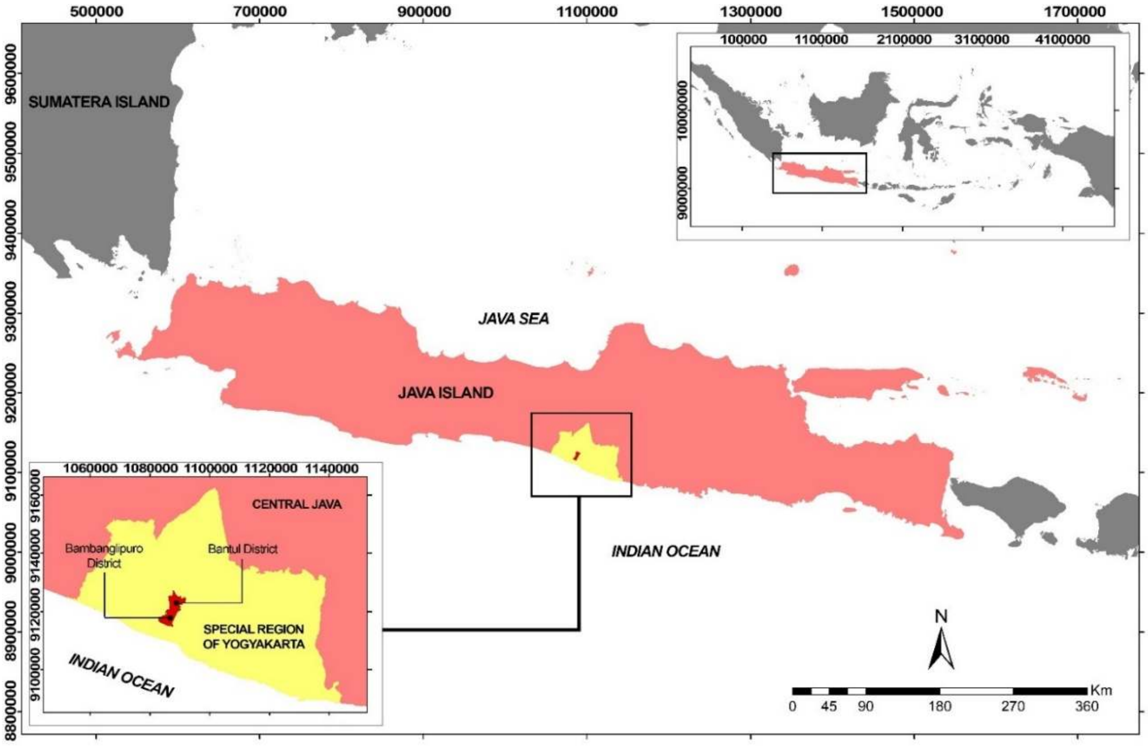

Figure 1. The study area.

The Susceptibility Index (SI) method is one of the emerging methods for assessing specific groundwater vulnerability. It evolved from the DRASTIC method by removing the parameters Soil Media (S), Vadose Zone Impact (I), and Hydraulic Conductivity (C), as well as adding the Land Use (LU) parameter (Stigter et al., 2006). The presence of the land use parameter allows for a spatio-temporal assessment of specific groundwater vulnerability, in addition to the fact that this method is primarily used to estimate specific groundwater vulnerability. Since this method was introduced, various studies have been conducted around the world to estimate specific groundwater vulnerability. Starting from Portugal (Stigter et al., 2006), Malaysia (Shirazi et al., 2013), Tunisia (Anane et al., 2013), and Ecuador (Ribeiro et al., 2016). Following this explanation, the research was subsequently carried out to assess changes in land use conditions and groundwater vulnerability, as well as to investigate the impact of land use changes on groundwater vulnerability.

Material and Methods

Bantul Regency is generally included in the Yogyakarta-Sleman Groundwater Basin system and is divided into three zones: recharge, transition, and discharge. Bantul Regency is located in the discharge zone with a morphology that forms a plain on porous rock, so the groundwater reserves can be considered significant (Snguon et al., 2010; Wijayanti et al., 2018; Brontowiyono et al., 2022; Ratri et al., 2023). The flat morphology makes the groundwater resources easily polluted. In addition, population growth and land use change can add to the threat. Bantul and Bambanglipuro sub-districts were selected for this study (Figure 1) because they experienced faster land use change, population growth, and infrastructure expansion than other sub-districts.

Table 1. Classification and rating of SI method parameters.

Parameters	**Classification**	**Rating**
Depth to Groundwater Table (D)	<1.5 m	100
	1.5-4.6 m	90
	4.6-9.1 m	70
	9.1-15.2 m	50
	15.2-22.9 m	30
	22.9-30.5 m	20
	>30.5 m	10
Groundwater Recharge (R)	>254 m	90
	178-254 m	80
	102-178 m	60
	51-102 m	30
	<51 m	10
Aquifer Media (A)	Karst limestone	100
	Basalt	90
	Sand and gravel	80
	Massive limestone	80
	Massive sandstone	60
	Bedded sandstone, limestone, and shale sequences	60
	Glacial till	50
	Weathered metamorphic/igneous	40
	Metamorphic/igneous	30
	Massive shale	20
Topography (T)	<2 %	100
	2-6 %	90
	6-12 %	50
	12-18 %	30
Land Use (LU)	Agricultural areas (annual corps), paddy fields	90
	Permanent crops (orchards, vineyards)	70
	Heterogeneous agricultural areas	50
	Pastures and agro-forested areas	50
	Artificial areas, industrial waste discharges, landfills	100
	Quarries, shipyards, open-air mines	80
	Urban areas, airports, harbours, areas with industrial or commercial activity, laid-out green spaces	75
	Semi-urban areas	70
	Natural areas, aquatic environments (salt marshes, salinas, inter-tidal zones)	50
	Forests and semi-natural zones	0
	Water bodies	0

Source: Ribeiro et al. (2016)

The comparison of groundwater vulnerability between the years 2009 and 2021 was conducted using the Susceptibility Index (SI) approach within the Geographic Information System (GIS) framework. Input of various spatial information is required to implement this strategy. The raster layers are initially generated using the ArcGIS 10.1 programme in a uniform grid of 100 m × 100 m cells. These layers are then combined to calculate the SI index for each cell, resulting in the generation of the final vulnerability map. In addition, for the study on temporal issues, the earlier data on nitrate contamination have only been accessible for these two locations during the last ten years. A small area in the southwestern part of the Bambanglipuro sub-district was not included in the study because it is located in the Sentolo Formation, while almost the entire study site is located in the Younger Merapi Volcanic Deposits. The Susceptibility Index (SI) is a quantitative vulnerability assessment tool specifically developed to analyse the vertical sensitivity of groundwater to pollution, particularly from agricultural operations. Its development intended to assess the susceptibility of aquifers to contamination on a relatively large to medium scale, specifically ranging from 1:50,000 to 1:200,000 (Ribeiro et al., 2016). The SI method is derived from the DRASTIC model, which includes only four original parameters: water table depth, recharge, aquifer medium, and topography (Ribeiro et al., 2016). Additionally, a new component, land use, has been added. Each parameter has its classification and weight (Table 1).

Direct field measurements were used to determine the depth of the groundwater table for 2021, while secondary data was used to determine other data. Meanwhile, studies by Snguon et al. (2010), Wijayanti et al. (2018), and Brontowiyono et al. (2022) provided information on the groundwater table depth in 2009. Data on groundwater recharge from the River Basin Organization of Serayu-Opak was processed to create regional rainfall, combined with the Yogyakarta sheet's geological map. Aquifer media data was obtained from bore drilling (Santosa and Adji, 2014). Then, slope data is available on the Indonesian Geospatial Information Agency website. Finally, land use data were obtained using the Supervised Classification method on Landsat 5 TM images for 2005 and Landsat 8 OLI for 2021 as the basis for classification.

Each data that has been obtained was then processed into a map, which is then overlaid based on the weight of the SI method into a Groundwater Vulnerability Index. The formula used is as per Equation 1, and the weight of each parameter is listed in Table 2.

$$\text{Susceptibility Index (SI)} = DwDr + RwRr + AwAr + TwTr + LUwLUr \quad \text{………… (1)}$$

where: D = depth to groundwater table. R = net recharge, A = aquifer media, T = topography, LU = land use, w = weight, and r = rating.

Table 2. Parameter weights of SI method.

Parameters	Weights
Depth to Groundwater Table (D)	0.186
Net Recharge (R)	0.212
Aquifer Media (A)	0.259
Topography (T)	0.121
Land Use (LU	0.222

Source: Ribeiro et al. (2016).

The overlay results were categorized after being weighted. The classification has three categories of vulnerability: low, medium, and high. A frequency distribution table was utilized as the statistical approach to determine these three classifications. Equations 2 and 3 illustrate the computation to obtain the classes.

$$\text{Range} = \text{Xmaximum} - \text{Xminimum} \quad \text{…….(2)}$$

$$\text{Class Interval} = \text{Range}/\text{Number of Classes} \quad \text{…….(3)}$$

The collected results are then verified using groundwater quality analysis findings, such as the amount of nitrate (NO_3^-) present at the research location. The nitrate concentration for 2021 was measured directly in the field, as opposed to 2009, when it was determined based on Snguon et al. (2010), Wijayanti et al. (2018), and Brontowiyono et al. (2022) studies. The resulting nitrate content was later classified based on the Indonesian Government (2021) concerning Water Quality Management and Water Contamination Control, i.e., <5 mg/L with a low classification, 5-10 mg/L with a medium classification, and >10 mg/L with a high classification.

Results and Discussion

Landuse change

The parameter of "land use" indicates how the natural and artificial surfaces of the Earth look. Land use conditions will evolve throughout time, one of which is primarily a result of human activity. The SI approach gives this particular parameter the second-largest weight. Table 3 and Figure 2 show the results and the areas for each land use categorization. Table 3 shows that the study area was dominated by paddy fields, i.e., 2120.37 ha in 2009 and 2118.39 ha in 2021. The dominance of paddy fields can be caused by the topographic conditions of the study area, which are in the form of plains and hydrological conditions that supply water for paddy fields in the study area, which is quite a lot. Significant changes can be found in the classification of agroforestry and semi-urban areas.

The agroforestry area decreased by 212.49 ha from 936.06 ha to 723.57 ha, while the semi-urban area increased by 209.81 ha from 828.83 ha to 1038.64 ha. Many changes occurred in Bambanglipuro sub-district, mainly from agroforestry areas to semi-urban areas, indicating an increase in the human population in the area. Another land use classification can be found in the urban area located in Bantul sub-district, which was 490.97 ha in 2009 and became 491.65 ha in 2021. Urban areas are located in Bantul sub-district because of its proximity to the City of Yogyakarta, the centre of human activity in Yogyakarta Special Region Province, and the status of Bantul sub-district as the capital of Bantul Regency also supports why urban areas can be found around here. The remaining classification is the heterogeneous agricultural area, which covers an area of approximately 32 ha and has not changed much. The data indicates a substantial decrease in the extent of agro-forested areas and paddy fields since a significant portion of these areas experienced an alteration to semi-urban land use.

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Table 3. Area of each land use in the study area.

Land Use	**2009**		**2021**		**Changes (ha)**
	Area (ha)	**Percentage (%)**	**Area (ha)**	**Percentage (%)**	
Agro-forested areas	936.06	21.24	723.57	16.46	-212.49
Semi-urban areas	828.83	18.82	1038.64	23.56	209.81
Urban areas	490.97	11.14	491.65	11.16	0.68
Heterogeneous agricultural areas	32.39	0.73	32.41	0.73	0.02
Paddy fields	2120.37	48.10	2118.39	48.07	-1.98

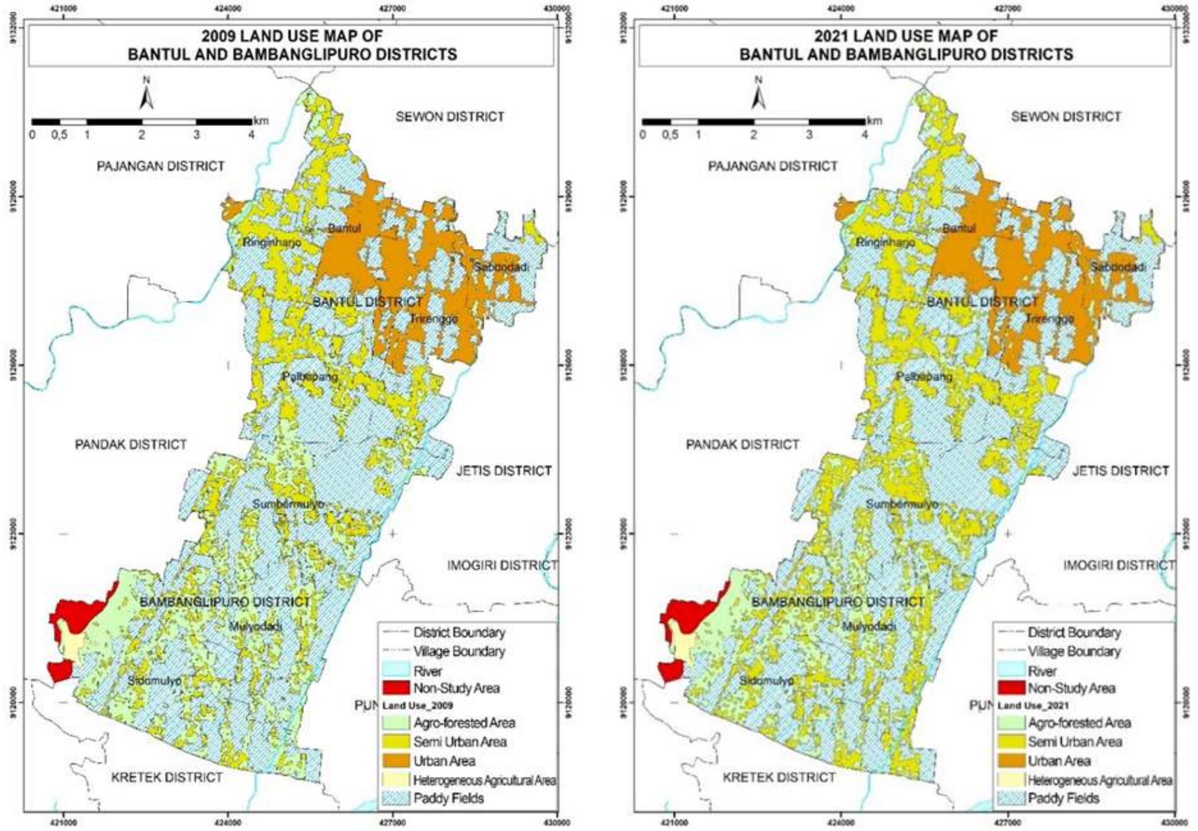

Figure 2. Land use in the research area in 2009 (left) and 2021 (right).

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Depth to groundwater table (D)

The depth to groundwater table parameter in the assessment of groundwater vulnerability is a parameter that describes the distance between the contaminant source above the ground surface and the vertical groundwater table. The shallower the depth of the groundwater table, the easier it is for a groundwater source to be contaminated by contaminants (Patel et al., 2022). The results can be seen in Table 4 and Figure 3. There are four (4) classifications for 2009 and three (3) classifications for 2021. These classifications are <1.5 m, 1.5-4.6 m, 4.6-9.1, and 9.1-

15.2 m. These three (3) initial classifications are the groundwater depth classifications that can be found in 2021. The dominance of the groundwater depth classification is less than 1.5 m from the ground surface, which in Figure 3 is shown in light blue. This finding follows the results of Ratri et al. (2022), which stated that the study area has the characteristics of a groundwater table close to below-ground level.

Table 4. Comparison of depth to groundwater table in the study area.

Depth to Groundwater Table	2009		2021	
	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)
<1.5	3,687.16	84.71	2,618.29	60.13
1.5-4.6	609.47	14.00	1,700.22	39.07
4.6-9.1	52.33	1.20	35.02	0.80
9.1-15.2	3.95	0.09	-	-

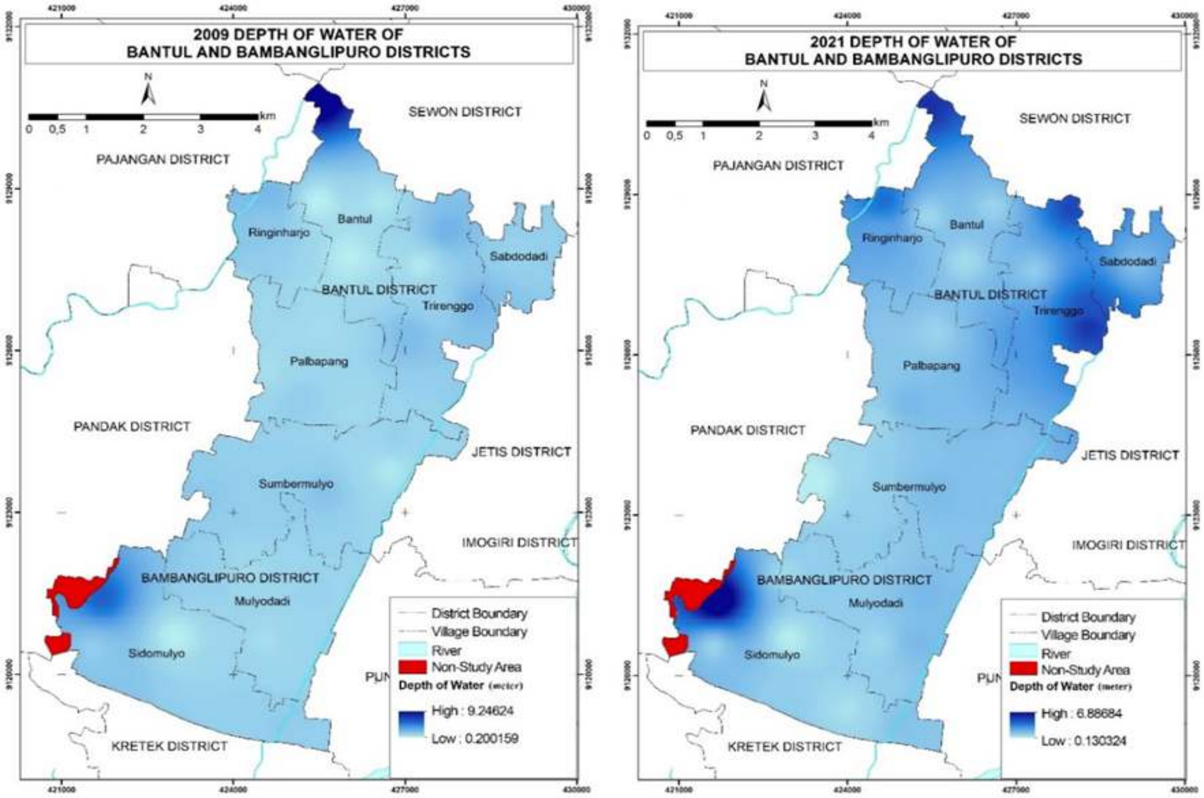

Figure 3. Depth to groundwater table in 2009 (left) and 2021 (right).

Groundwater recharge (R)

Groundwater recharge is a parameter that describes how much water the soil absorbs. Based on the classification of net recharge by the SI method, it is known that the greater the value of net recharge, the easier it is for a groundwater source to experience contamination due to the presence of contaminants such as nitrates. Processing groundwater recharge parameters begins with processing rainfall data into regional rainfall data. The rainfall data used is data from 2004 to 2008 to find the 2009 recharge value and data from 2016 to 2020 to find the 2021 recharge value. The Inverse Distance Weighting (IDW) isohyet method creates regional rainfall distribution. The resulting regional rainfall ranged from 1668.32 mm/year to 1,722.06 mm/year in 2004-2008, while in 2016-2020, it ranged from 1,952.89 mm/year to 2117.19 mm/year. These regional rainfall results were then overlaid with lithology coefficient values based on the Indonesian National Standardization Agency (2002), resulting in the distribution of groundwater recharge, as shown in Figure 4. According to the Indonesian National Standardization Agency (2002) categorization, the entire research region consists of a young volcanic lithological unit with a 30% recharge coefficient. As a result, there are not many differences in the groundwater recharge data values acquired. This fact is actually because the resulting recharge values range over 254 mm/year according to the SI categorization. There is a significant amount of groundwater vulnerability under these circumstances.

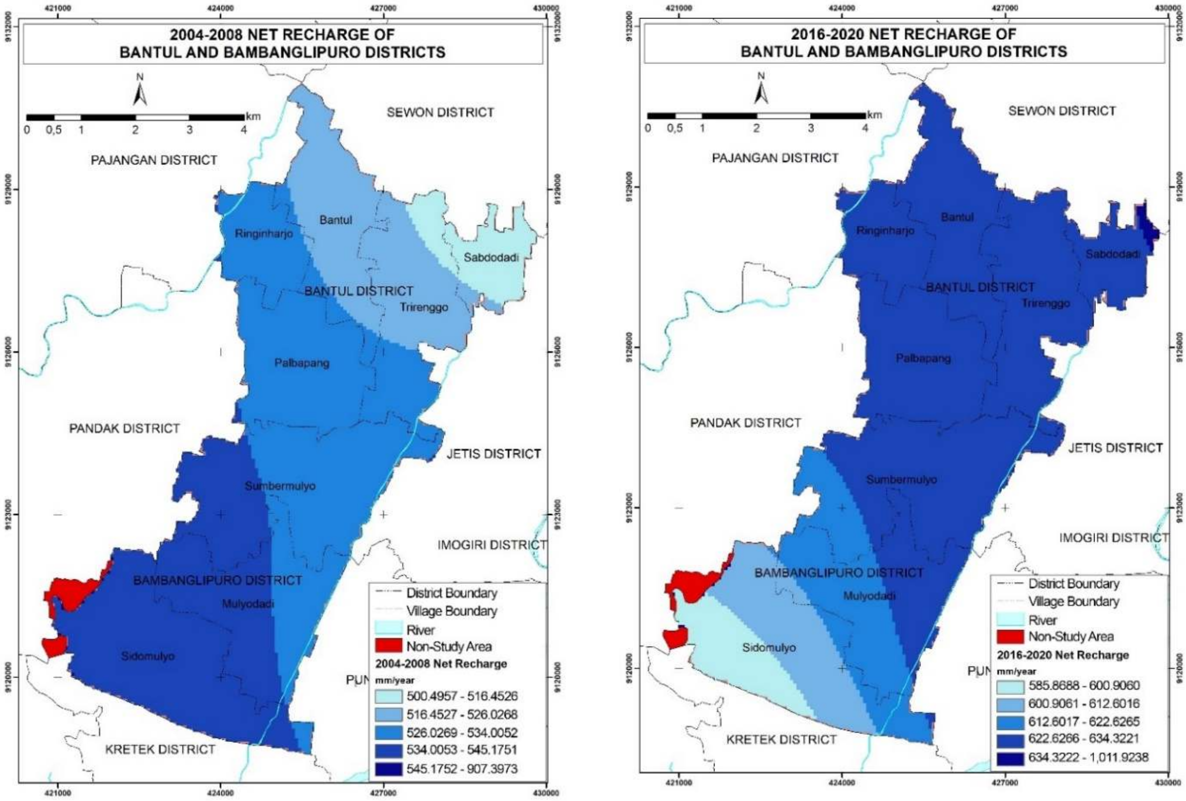

Figure 4. Groundwater recharge in the study area in 2004-2008 (left) and 2016-2020 (right).

Aquifer media (A)

Aquifer media is a parameter that describes the characteristics of aquifers, which vary due to the influence of geological processes and constituent rock materials. Based on the SI method classification, it is known that this parameter has the greatest weight among other parameters. Geoelectric and bore drilling data obtained from the research of Santosa and Adji (2014) were interpreted into aquifer media with Schlumberger configuration using IPI2WIN software to determine the actual resistivity (ρ) value. The result of the interpretation can be seen in Figure 5 (left).

Based on the distribution of aquifer media, it is known that all research locations have aquifer media in the form of sand and gravel. This type of aquifer media is vulnerable to contamination. The permeability level of sand and aquifers is 2.5 m/day to 450 m/day, including a large permeability level (Lu et al., 2024). The greater the permeability value, the greater the ability of the material to pass through water. Jain (2023) added that this property is usually only followed by a little filtering process, so the opportunity for pollutants or contaminants to escape becomes wider.

Topography (T)

Topography is a parameter that describes the topography or slope of the study area. The SI approach assigns the lowest weight to this characteristic. According to Ribeiro et al. (2016), an area's vulnerability will rise to a greater extent the flatter its terrain is. The results obtained can be seen in Figure 5 (right). Most of the study area is classified as less than 2%, as shown in green, which means that the study area has flat topographic conditions. Other variations exist in the northwest and southwest. The northwestern part has small structural hills, while the southwestern part is the foot of hills made of limestone and sandstone of the Sentolo Formation. These predominantly flat topographical conditions lead to a higher risk of contamination.

Specific groundwater vulnerability to contamination

The resulting parameters were then overlaid into a specific groundwater susceptibility to contamination map. The presence of land use parameters in this method determines the level of specific groundwater vulnerability in an area based on the assumption that each land use produces pollutants (Stigter et al., 2006; Barbulescu, 2020). Three (3) classifications are carried out, i.e., low, medium, and high. The classification is obtained from the lowest and highest vulnerability values from 2009 and 2021. The low classification has a range of 65.13-73.58, the medium classification has a range of 73.59-82.03, and the high classification has a range of 82.04-90.48. The results are shown in Table 5 and Figure 6. Table 5 shows that the study area is dominated by a high class of groundwater vulnerability, covering an area of 3,398.86 in 2009 and increasing by 227.11 ha to 3,625.97 in 2021. Meanwhile, the medium vulnerability class in 2009 was 929.4 ha and decreased by 226.93 ha to 702.47 ha. The low vulnerability class occupied only 0.53% or

22.7 ha of the entire study area in 2009 and reduced slightly (0.17 ha) to 22.53 ha. The high vulnerability class covering the study area for the two years studied is due to the land use factor, which is dominated by paddy fields and residential areas in semi-urban and urban areas.

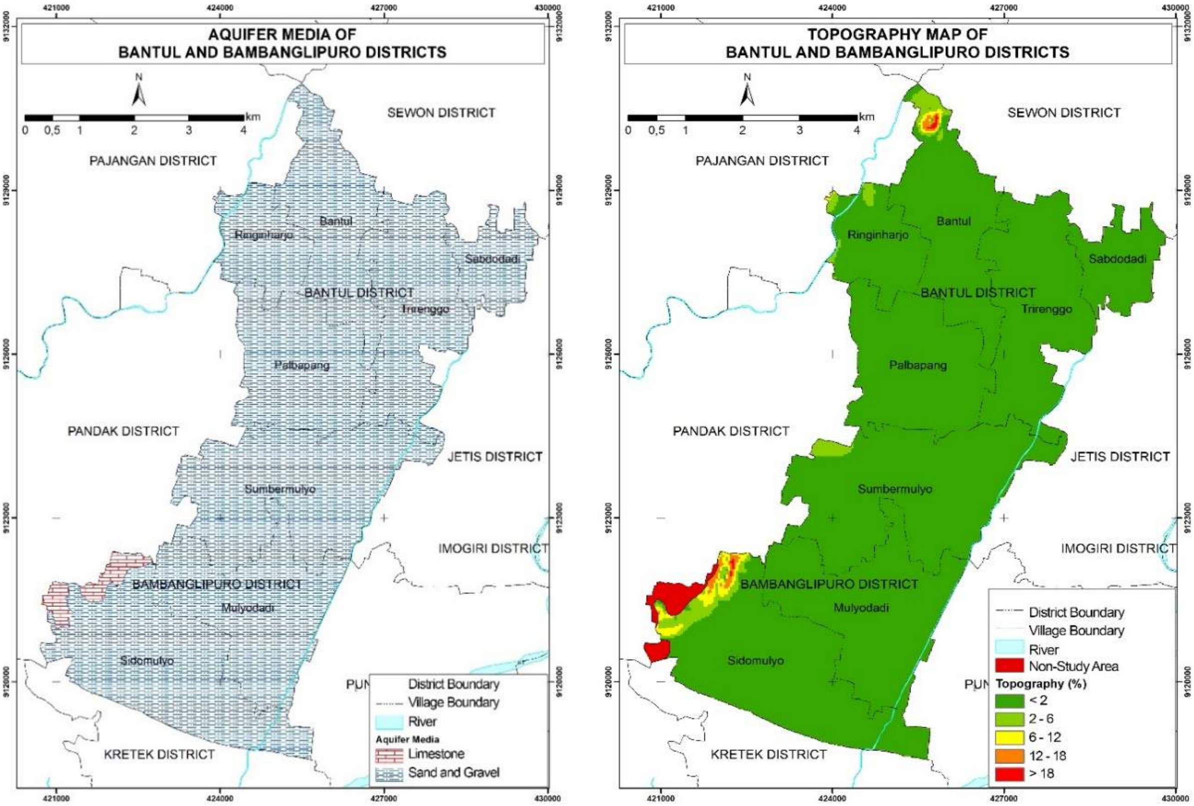

Figure 5. Aquifer media condition (left) and topography condition (right).

Table 5. Comparison of area (ha) of specific groundwater vulnerability.

Class	2009		2021		Changes (ha)
	Area (ha)	Percentage (%)	Area (ha)	Percentage (%)	
Low	22.7	0.53	22.53	0.53	-0.17
Moderate	929.4	21.71	702.47	16.39	-226.93
High	3,398.86	79.38	3,625.97	84.62	227.11

In addition, other parameters are also influential, mainly due to the general characteristics of the study location that can lead to high levels of groundwater vulnerability. Changes in the condition of specific groundwater vulnerability to pollution occur mainly in Bambanglipuro sub-district. The condition of the study area, which is dominated by high groundwater vulnerability classes, theoretically raises concerns about the quality of groundwater resources in the study area. Therefore, there should be waste management rules, such as domestic and agricultural waste, as well as both integrated and individual management.

Validation

To verify the accuracy of the groundwater vulnerability assessment results, tests of groundwater quality were conducted. One of the groundwater quality indicators examined was nitrate (NO_3^-), as the SI approach was developed based on land use characteristics, notably because of agricultural and settlement activities, which might alter groundwater quality conditions. The method uses a validation test matrix, and the classification of nitrate levels is divided into three (3) classes, i.e., low (<5 mg/L), medium (5-10 mg/L), and high (>10 mg/L), as the results are shown in Table 6.

Table 6 shows that the resulting accuracy shows an unacceptable validity classification because it is less than 60% based on the DeVellis classification (2016). The main factor that can be mentioned is that although the study area is dominated by paddy fields, soils in Indonesia generally have a soil horizon layer called the plow tread layer that is between 10-40 cm deep. Patle (2021) mentioned that the presence of this layer can resist the movement of percolation water to facilitate the process of inundation of water on the soil surface and is useful as a water supply for rice plants. The condition causes the content of pollutant sources such as nitrates from fertilizers for rice plants not to enter the soil much so that the value of nitrate content detected becomes small. Paddy fields are mainly found in Bambanglipuro sub-district. On the other hand, Kwon et al. (2022) found that surfaces covered by asphalt, paving, or other materials commonly found in urban areas can cause the entry of contaminants, such as nitrate, from the ground surface to the aquifer to be more hindered. This is why little nitrate enters the soil in urban areas concentrated in the Bantul sub-district. Ribeiro et al. (2016) also added that maps produced by the SI method could cause uncertainty in the results if the characteristics of specific parameters do not have a high level of accuracy.

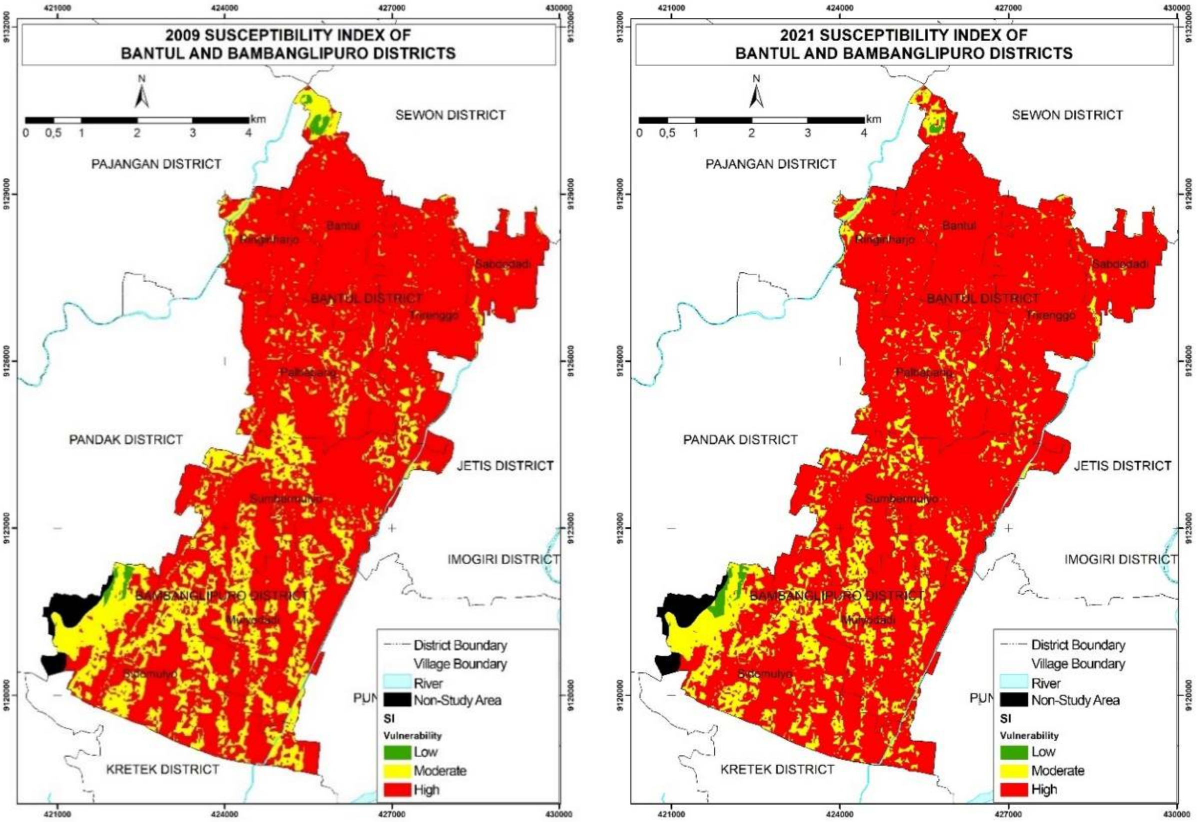

Figure 6. 2009 groundwater vulnerability map (left) and 2021 groundwater vulnerability map (right).

Table 6. Validation test matrix.

		2009 Groundwater Vulnerability			2021 Groundwater Vulnerability		
		High	Moderate	Low	High	Moderate	Low
Nitrate (NO_{3-}) Level	High (>10 mg/L)	9	1	0	3	0	0
	Moderate (5-10 mg/L)	1	1	0	4	1	0
	Low (<5 mg/L)	12	8	0	12	11	1
Total Each Data	32	Accuracy (%)		31.25	Accuracy (%)		15.63

Effect of land use change on specific groundwater vulnerability using SI method

The SI method, which has a land use (LU) parameter, allows for a temporal analysis of how land use change affects groundwater vulnerability in an area. Comparative descriptive analysis is one way to analyze it. Figure 7 explains how the influence is illustrated. Based on Figure 8, it is known that the semi-urban area has increased between 2009 and 2021. A decrease follows this increase in the level of moderate vulnerability and an increase in the level of high vulnerability. The semi-urban area in the SI method is one of the parameters that have a high weight in influencing the level of groundwater vulnerability, which is 70, so the increase in the level of high vulnerability is natural. On the other hand, it is known that the agroforestry area has decreased from 2009 to 2021. This condition was followed by a decrease in the moderate vulnerability level and an increase in the high vulnerability level because agroforestry areas have been transformed into semi-urban areas with a lower weight of 50 in the SI method. However, it was found that it is not only land use change that influences changes in groundwater vulnerability. Other parameters in the SI method can also have an influence, depending on the weight assigned to the method.

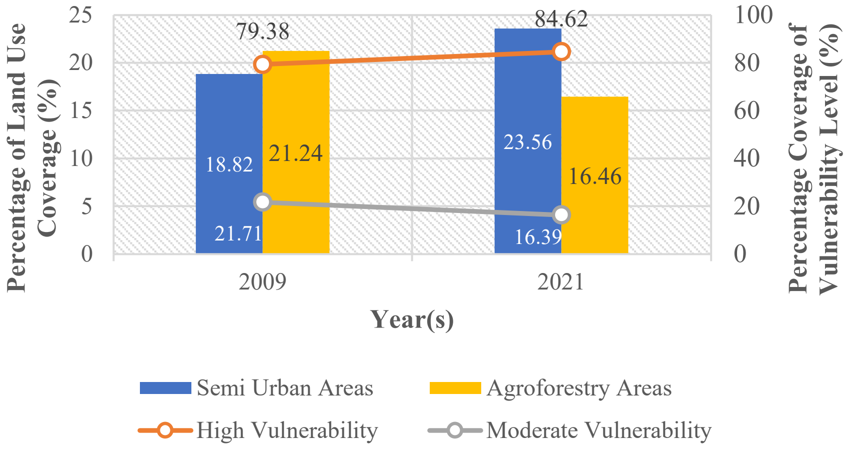

Figure 7. Comparison of percentage change in area coverage between selected land uses and groundwater vulnerability levels.

When compared with other research related to changes in land use that affect the level of groundwater vulnerability, Albuquerque et al. (2013) found that over the past 50 years, urban areas in the Águeda Watershed (between Spain and Portugal) have had an increasing concentration of groundwater vulnerability levels. Another study conducted by Vu et al. (2019) in the Pingtung Basin, Taiwan, also showed that for two decades (1995-2017), there was a decrease in groundwater vulnerability along with a reduction in agricultural areas due to changes in land use. In addition, Ouedraogo et al. (2020) found an increased risk of groundwater pollution as a result of an increase in the human population in areas experiencing urban growth.

Methodologically, the SI method, which incorporates land use parameters (Land Use/LU), is employed to conduct a temporal analysis of the impact of land use changes on groundwater vulnerability in a specific area (Pouye et al., 2022). Lakshminarayanan et al. (2023) argue that comparative descriptive analysis provides a method to examine the correlation between alterations in land use and the susceptibility of groundwater. Even so, research on the relationship between land use change and the level of groundwater vulnerability is still minimally carried out using a statistical approach, so comparative descriptive analysis is still a reliable method of analysis, which we realize is a weakness of this research. The study observed that the SI method effectively correlated nitrate concentrations with locations classified as having varying levels of vulnerability to groundwater contamination. Thioune et al. (2017) additionally discussed how this method might accurately forecast specific vulnerabilities linked to pollution sources and assess the characteristics of pollutants and other elements that have been taken into account in intrinsic vulnerability. Presently, the research area, particularly in Bambanglipuro and Bantul sub-districts, is susceptible to anthropogenic pressure, rendering it prone to environmental and social risks. Thus, utilizing the SI technique is considered adequate for evaluating the susceptibility of groundwater to nitrate contamination resulting from the change from agricultural land to urban areas.

On the other hand, Moges and Dinka (2022) stated that more research is required to enhance the precision of assessing the impact of land use changes on groundwater vulnerability. Specifically, there is a need for further investigation, particularly in the area of statistical tests, to establish the correlation between land use change parameters and the extent to which groundwater is susceptible to pollution, as demonstrated by Smith et al. (2020). Also, according to Abduljaleel et al. (2024), the substantiation of groundwater vulnerability zoning should be enhanced by incorporating a variety of water quality parameters, not just nitrate.

Conclusion

The study site experienced considerable land use changes between 2009 and 2021, with the agroforestry area shrinking by 212.49 ha and the semi-urban area growing by 209.81 ha. The changes indicate an increase in the human population, especially in the Bambanglipuro sub-district, which has undergone many changes. Medium and high levels dominate the groundwater vulnerability in the study area. The research region, which often has features that might generate a high groundwater sensitivity, is to blame for the domination, particularly at the high vulnerability level. Meanwhile, changes in land use indeed have an impact on groundwater vulnerability levels. The level of specific groundwater sensitivity to contamination in Bantul and parts of Bambanglipuro sub-district is influenced by land use characteristics. An evident shift in groundwater vulnerability has occurred in Bambanglipuro sub-district, with the level changing from medium to high. This change can be attributed to the conversion of agroforestry regions into semi-urban areas. Land use parameters are not the only factors that can have an impact. Groundwater level depth characteristics can also exert influence. The extent of the impact may generally be observed by considering the significance of each parameter utilised in the Susceptibility Index (SI) approach.

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References

Abduljaleel, Y., Amiri, M., Amen, E.M., Salem, A., Ali, Z.F., Awd, A., Lóczy, D. and Ghzal, M. 2024. Enhancing groundwater vulnerability assessment for improved environmental management: addressing a critical environmental concern. *Environmental Science and Pollution Research International* 31(13):19185-19205, doi:10.1007/s11356-024-32305-1.

Albuquerque, M.T.D., Sanz, G., Oliveira, S.F., Martínez-Alegría, R. and Antunes, I.M.H.R. 2013. Spatio-temporal groundwater vulnerability assessment-A coupled remote sensing and GIS approach for historical land cover reconstruction. *Water Resources Management* 27(13):4509-4526, doi:10.1007/s11269-013-0422-0.

Anane, M., Abidi, B., Lachaal, F., Limam, A. and Jellali, S. 2013. GIS-based DRASTIC, Pesticide DRASTIC and the Susceptibility Index (SI): comparative study for evaluation of pollution potential in the Nabeul-Hammamet shallow aquifer, Tunisia. *Hydrogeology Journal* 21(3):715, doi:10.1007/s10040-013-0952-9.

Barbulescu, A. 2020. Assessing groundwater vulnerability: DRASTIC and DRASTIC-like methods: A review. *Water* 12(5):1356, doi:10.3390/w12051356.

Brontowiyono, W., Asmara, A.A., Jana, R., Yulianto, A. and Rahmawati, S. 2022. Land-use impact on water quality of the Opak Sub-Watershed, Yogyakarta, Indonesia. *Sustainability* 14(7):4346, doi:10.3390/su14074346.

Carrard, N., Foster, T. and Willetts, J. 2019. Groundwater as a source of drinking water in Southeast Asia and the Pacific: A multi-country review of current reliance and resource concerns. *Water* 11(8):1605, doi:10.3390/w11081605.

DeVellis, R.F. 2016. *Scale Development: Theory and Applications* (4th ed.). Christchurch, New Zealand: Sage Publications.

Harter, T., Davis, H., Mathews, M.C. and Meyer, R.D. 2002. Shallow groundwater quality on dairy farms with irrigated forage crops. *Journal of Contaminant Hydrology* 55(3-4):287-315, doi:10.1016/s0169-7722(01)00189-9.

Indonesian Government. 2021. Implementation of Environmental Protection and Management Act of 2021, 22 Indonesian Government Regulation (*in Indonesian*).

Indonesian National Standardization Agency-SNI. 2002. *Resource Compilation Part 1: Spatial Water Resources* (SNI 19-6728.1-2002). Jakarta: Indonesian National Standardization (*in Indonesian*).

Jain, H. 2023. Groundwater vulnerability and risk mitigation: A comprehensive review of the techniques and applications. *Groundwater for Sustainable Development* 22, doi:10.1016/j.gsd.2023.100968.

Kgaphola, M.J., Ramoelo, A., Odindi, J., Kahinda, J.M.M., Seetal, A.R. and Musvoto, C. 2023. Impact of land use and land cover change on land degradation in rural semi-arid South Africa: case of the Greater Sekhukhune District Municipality. *Environmental Monitoring and Assessment* 195(6), doi:10.1007/s10661-023-11104-0.

Kwon, E., Park, J., Park, W.B., Kang, B.R., Hyeon, B.S. and Woo, N.C. 2022. Nitrate vulnerability of groundwater in Jeju Volcanic Island, Korea. *The Science of the Total Environment* 807, doi:10.1016/j.scitotenv.2021.151399.

Lakshminarayanan, B., Ramasamy, S. and Yadav, B. 2023. Assessing the future groundwater vulnerability of an urban region under variable climatic and land use conditions. *Urban Climate* 52:101691, doi:10.1016/j.uclim.2023.101691.

Lestariningsih, I.D., Widianto, W., Agustina, C., Sudarto, S. and Kurniawan, S. 2018. Relationship between land degradation, biophysical and social factors in Lekso Watershed, East Java, Indonesia. *Journal of Degraded and Mining Lands Management* 5(3):1283-1291, doi:10.15243/jdmlm.2018.053.1283.

Lu, C., Li, L., Xu, J., Zhao, H. and Chen, M. 2024. Research on the critical value of sand permeability particle size and its permeability law after mixing. *Water* 16(3):393, doi:10.3390/w16030393.

Matano, A.S., Kanangire, C.K., Anyona, D.N., Abuom, P.O., Gelder, F.B., Dida, G.O., Owuor, P.O. and Ofulla, A.V.O. 2015. Effects of land use change on land degradation reflected by soil properties along Mara River, Kenya and Tanzania. *Open Journal of Soil Science* 05(01):20-38, doi:10.4236/ojss.2015.51003.

Mhawish, Y.M. and Saba, M. 2016. Impact of population growth on land use changes in Wadi Ziqlab of Jordan between 1952 and 2008. *International Journal of Applied Sociology* 6(1):7-14, doi:10.5923/j.ijas.20160601.02.

Moges, S.S. and Dinka, M.O. 2022. Assessment of groundwater vulnerability mapping methods for sustainable water resource management: An overview. *Journal of Water and Land Development* 52(I-III):186-198, doi:10.24425/jwld.2022.140389.

Muchtar, Z., Hadinata, F. and Putranto, D.D.A. 2023. Decreasing the quality of water resources in the Rawas watershed due to land degradation. *International Journal of Geomate* 25(107), doi:10.21660/2023.107.g12203.

Neshat, A., Pradhan, B. and Dadras, M. 2014. Groundwater vulnerability assessment using an improved DRASTIC method in GIS. *Resources, Conservation, and Recycling* 86:74, doi:10.1016/j.resconrec.2014.02.008.

O'Sullivan, J.N. 2023. Demographic delusions: World population growth is exceeding most projections and jeopardising scenarios for sustainable futures. *World* 4(3):545-568, doi:10.3390/world4030034.

Ouedraogo, I., Girard, A., Vanclooster, M. and Jonard, F. 2020. Modelling the temporal dynamics of groundwater pollution risks on the African scale. *Water* 12(5):1406, doi:10.3390/w12051406.

Patel, P., Mehta, D. and Sharma, N. 2022. A review on the application of the DRASTIC method in the assessment of groundwater vulnerability. *Water Science and Technology: Water Supply* 22(5):5190-5205. doi:10.2166/ws.2022.126.

Patle, G.T. 2021. Estimation of infiltration rate of a paddy growing area in a micro watershed of Sikkim (India). *CIGR Journal* 23(3):13-20.

Pouye, A., Faye, S.C., Diédhiou, M., Gaye, C.B. and Taylor, R.G. 2022. An evaluation of groundwater vulnerability assessment methods in a rapidly urbanizing city: evidence from Dakar, Senegal. *Environmental Earth Sciences* 81(16), doi:10.1007/s12665-022-10531-5.

Ratri, D., Putra, D.P.E. and Wilopo, W. 2021. Groundwater geochemistry and hydrogeochemical processes assessment in Bantul, Yogyakarta, Indonesia. *IOP Conference Series. Earth and Environmental Science* 958(1), doi:10.1088/1755-1315/958/1/012013.

Ratri, D., Putra, D.P.E. and Wilopo, W. 2023. Groundwater vulnerability assessment using total organic carbon and heavy metals in Bantul, Yogyakarta, Indonesia. *Advances in Biological Sciences Research* 26:607-617, doi:10.2991/978-94-6463-086-2_81.

Ribeiro, L., Pindo, J.C. and Dominguez-Granda, L. 2016. Assessment of groundwater vulnerability in the Daule aquifer, Ecuador, using the susceptibility index method. *The Science of the Total Environment* 574, doi:10.1016/j.scitotenv.2016.09.004.

Shirazi, S.M., Imran, H.M., Akib, S., Yusop, Z. and Harun, Z.B. 2013. Groundwater vulnerability assessment in the Melaka State of Malaysia using DRASTIC and GIS techniques. *Environmental Earth Sciences* 70(5):2293-2304, doi:10.1007/s12665-013-2360-9.

Smith, D.N., Ortega-Camacho, D., Acosta-González, G., Leal-Bautista, R.M., Fox, W.E. and Cejudo, E. 2020. A multi-approach assessment of land use effects on groundwater quality in a karstic aquifer. *Heliyon* 6(5):e03970, doi:10.1016/j.heliyon.2020.e03970.

Snguon, L., Putra, D.P.E. and Hendrayana, H. 2015. Groundwater vulnerability of Pandak and Bambanglipuro, Yogyakarta Special Province, Indonesia. *Journal of Applied Geology* 2(2), doi:/10.22146/jag.7254.

Stigter, T.Y., Ribeiro, L. and Dill, A.M.M.C. 2006. Evaluation of an intrinsic and a specific vulnerability assessment method in comparison with groundwater salinisation and nitrate contamination levels in two agricultural regions in the south of Portugal. *Hydrogeology Journal* 14(1-2):79-99, doi:10.1007/s10040-004-0396-3.

Thioune, P.B.D., Ndao, S., Ba, A. and Diaw, E.B. 2017. Assessment of groundwater vulnerability by Susceptibility Index (SI) method in the Niayes area, Senegal. *Journal of Scientific and Engineering Research* 4(11):247-257.

Vollset, S.E., Goren, E., Yuan, C.W., Cao, J., Smith, A.E., Hsiao, T., Bisignano, C., Azhar, G.S., Castro, E. Chalek, J., Dolgert, A.J., Frank, T., Fukutaki, K., Hay, S.I., Lozano, R., Mokdad, A.H., Nandakumar, V......and Murray, C.J.L. 2020. Fertility, mortality, migration, and population scenarios for 195 countries and territories from 2017 to 2100: a forecasting analysis for the global burden of disease study. *The Lancet* 396(10258):1285-1306, doi:10.1016/S0140-6736(20)30677-2.

Vu, T.D., Ni, C.F., Li, W.C. and Truong, M.H. 2019. Modified index-overlay method to assess spatial–temporal variations of groundwater vulnerability and groundwater contamination risk in areas with variable activities of agriculture developments. *Water* 11(12), doi:10.3390/w11122492.

Wijayanti, Y., Yuniasih, B., Verma, N., Krisdiarto, A.W. and Safitri, L. 2018. Groundwater quality mapping of Yogyakarta City, Sleman, Kulonprogo and Bantul regency area of Yogyakarta Province. *IOP Conference Series Earth and Environmental Science* 195:012012, doi:10.1088/1755-1315/195/1/012012.

Winkler, K., Fuchs, R., Rounsevell, M. and Herold, M. 2021. Global land use changes are four times greater than previously estimated. *Nature Communications* 12(1), doi:10.1038/s41467-021-22702-2.