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STUDY OF GROUNDWATER VULNERABILITY TO POLLUTION IN THE TAMBAKBAYAN WATERSHED IN 2006 AND 2017

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ABSTRACT

Tambakbayan is one of the watersheds in Yogyakarta, Indonesia that is experiencing changes in land use. The research aims to analyze the distribution of intrinsic and specific groundwater vulnerability in the watershed that was influenced by land-use changes from 2006 to 2017. The data used are the RBI maps (containing topographic and land-use information, 2006 and 2017), SRTM imagery, rainfall recorded at the Kambil, Prumpung, Bronggang, Santan, Gemawang, and Karang Ploso stations (2006-2017), soil map, and aquifer map. Land-use change was analyzed by comparing the RBI maps of 2006 and 2017; while the groundwater vulnerability was assessed with the Susceptibility Index a development of the DRASTIC method. The intrinsic groundwater vulnerability was generated based on physical conditions, including depth to the water table, aquifer media, groundwater recharge, and topography, while the specific groundwater vulnerability was a function of these attributes added with one anthropogenic parameter: land use. Then, all of these parameters were analyzed with a map overlay. The results showed two levels of intrinsic vulnerability: low (2.18% of the watershed area) and medium (97.8%); and three classes of specific vulnerability: low (0.02%), medium (5.06%), and high (94.92%) in 2006. From 2006 through 2017, the areal percentage of the medium vulnerability increased, while that of the high vulnerability decreased due to the conversion of agricultural land to a reservoir in 2009.

Keywords: Intrinsic Vulnerability; Specific Vulnerability, Susceptibility Index

INTRODUCTION

Groundwater is one of the water sources that the population in the Tambakbayan Watershed withdraws and uses daily. With the ongoing development activities that pose positive and negative impacts, groundwater is subject to either sustainable use or pollution. The latter is attributable to activities that generate pollutants. Uncontrolled contamination levels can cause problems, especially groundwater quality (Abdillah and Adji, 2018). Depending on its physical conditions, the environment can filter the entry of potential pollutant sources into a subsurface system. This attribute is responsible for groundwater vulnerability to pollution; a term used to define environmental conditions that either prevent or allow groundwater contamination by naturally occurring pollutants (intrinsic vulnerability)—often associated with hydrogeological factors and prevailing processes—and harmful elements generated by human activities in particular land use (specific vulnerability)

(Haq et al., 2013). If the space above the groundwater is allocated for different waste-generating activities, it will lead to spatially diverse vulnerability levels that can affect pollution severity (Hadi, 2004).

Regional developments grow in parallel with human needs for shelter and food that persistently increase as population size multiplies every year. Tambakbayan, a sub-watershed of Opak, lies in multiple administrative units in the Special Region of Yogyakarta (SRY): Sleman Regency, Yogyakarta City, and Bantul Regency. In 2006, these areas were inhabited by 879,825, 443,112, and 1,008,295 people (BPS Statistics Indonesia for SRY, 2007), which increased to 995,264, 422,732, and 1,193,512 people, respectively, in 2017 (BPS Statistics Indonesia for SRY, 2018). This condition has induced developments and changes in rural-urban physical features in many parts of the watershed area. When carried out without paying attention to the environment, development can result in unchecked land-use change threatening the sustainability of natural resources and the environment itself. One of the essential natural resources in human lives is groundwater, which is increasingly exposed to population growth, land-use change, and their detrimental impacts on its quality and quantity.

There are many methods for assessing groundwater vulnerability with different assumptions and procedures for porous or fractured media. Data availability is a determinant in choosing suitable methods. Intrinsic groundwater vulnerability can be assessed with parametric methods, which select several representative parameters to determine the degree of vulnerability (Ribeiro et al., 2017). Examples of these methods are DRASTIC, AVI (Aquifer Vulnerability Index), and GOD. Meanwhile, specific vulnerability considers land use and human activities and works better than intrinsic vulnerability assessment alone (Stigter et al., 2006, Ribeiro et al., 2017), warranting the need for an in-depth study of this method. Ribeiro et al. (2017) explain that SI (Susceptibility Index) effectively identifies specific vulnerabilities. Compared to EPIK that factors in lithology, SI is rather oriented to pollutants, particularly nitrates. SI takes into account several parameters: depth to water table (D), groundwater recharge (R), lithology (A), topography (T), and land use (LU). It is a development of the DRASTIC method (Aller et al., 1987 in Fernandes, 2002).

Groundwater vulnerability parameters in the Tambakbayan Watershed vary in conditions and, thus, have different effects on the spatial distribution of groundwater vulnerability. Land use is a parameter experiencing the most dynamic shifts; a change in its state can lead to a different degree of vulnerability. Therefore, this research was designed to analyze the spatial distributions of the intrinsic and specific groundwater vulnerability using the SI method in the Tambakbayan Watershed in 2006 and 2017.

RESEARCH METHOD

Tambakbayan is a watershed in the Special Region of Yogyakarta, Indonesia, that is experiencing fairly intensive physical regional developments in the three administrative units within its physical boundaries because of substantial population growth from 2006 until 2017 (BPS Statistics Indonesia for SRY, 2007, 2018). Increased demand on land triggers the conversion of non-built-up to built-up land, in which waste-generating human activities partly control groundwater vulnerability. Land-use change dynamics in the watershed are fascinating to study.

The tools used in this research were ArcMap 10.3.1 and Microsoft Office programs. The research materials included (1) SRTM imagery for slope analysis, (2) Digital Indonesia Topographic (RBI) Map Scaled 1: 25,000 in 2006 (an interpretation of the 1993/1994 aerial photographs scaled 1: 50,000; data production in 2000 and the seamless year 2006) and 2017 (property of the Land and Spatial Planning Services for Sleman Regency in 2017; digital interpretations of SPOT image captured in 2017, High-Resolution Satellite Images (HSRI) in 2013–2015, and the Indonesia Topographic Maps scaled 1: 25,000 in 2006) for land-use change analysis, (3) rainfall data recorded at Kambil, Prumpung, Bronggang, Santan, Gemawang, and Karang Ploso Stations in 2006–2017 (property of the Main Station of Serayu River Basin), (4) soil maps, and (5) aquifer maps.

The data processing stages were as follows. First, depth to water tables and aquifer media were secondary data collected from previous studies: Sadiq (2013) and Purnama et al. (2016), respectively. The depth to water table was grouped into three classes: <1.5 m, 1.5–4.6 m, and 4.6–9.1 m. Second, groundwater recharge was assessed by multiplying regional rainfall data by the lithology coefficients or scores. The missing maximum rainfall data were filled with the Inverse Square Distance method, followed by consistency tests and correction. Afterward, the rainfall data were processed with the Inverse Distance Weighting (IDW) on ArcMap 10.3.1 according to prevailing landforms to produce regional precipitation. Third, slope gradients were calculated with the 'geoprocessing tool for terrain' feature on ArcMap 10.3.1; the z factor was set at 1 and without warning notification from the ArcMap system. Per the SI method, the slopes were grouped into four classes with different scores: 0–5%, 5–10%, 10–30%, and >30%.

Intrinsic and specific groundwater vulnerability maps were produced with the Susceptibility Index (SI), as introduced by Ribeiro et al. (2017), Stigner et al. (2006), and Riyanto & Widyastuti (2016). The intrinsic vulnerability map consists of four SI parameters: depth to the water table, groundwater recharge, aquifer media, and slope gradient, while the specific vulnerability map combines these four parameters with land use. These maps were produced by overlaying all parameters and multiplying the SI parameter score by its weight value. The formulas used to calculate the intrinsic and specific groundwater vulnerability were as follows.

Susceptibility Index (SI) for intrinsic vulnerability = DwDr + RwRr + AwAr + TwTr (1)

Susceptibility Index (SI) for specific vulnerability = DwDr + RwRr + AwAr + TwTr + LUwLUr (2)

where:

w = weight value
r = rate/score
D = Depth to Water Table
R = Groundwater Recharge
A = Aquifer Media/Lithology
T =Topography/Slope Gradient
LU = Land Use

Finally, the total weights were added up and made as a reference for groundwater vulnerability classification (Table 1), resulting in three classes: low, medium, and high, which were determined using the formulas below:

Data Range=Xmaximum – Xminimum (3)

Class Interval=Data Range/Number of Classes (4)

Table 1. Intrinsic and Specific Groundwater Vulnerability Classification

	Susceptibility Index (SI)		
Interval	32–49	49–67	67–84
Class	Low	Medium	High

FINDINGS AND DISCUSSION

Conditions of the Parameters of Groundwater Vulnerability to Pollution

a. Depth to Water Table

Analyses of the data gathered from previous research (Sadiq, 2016) showed that the depths to the water table in Tambakbayan varied from <1.5 to 9.1 m. However, in most parts of the watershed, it ranged from 1.5 to 4.6 m, indicating shallow and unconfined groundwater (Sejati, 2020). The deepest water table was found in parts of Ngaglik and Depok Districts. Based on the data range, this parameter was divided into several classes, and each was assigned a score: 100 for <1.5 m, 90 for 1.5–4.6 m, and 70 for 4.6–9.1 m. Shallower water tables (higher scores) indicate groundwater that is more vulnerable and quicker to change when pollutants are introduced into the system (Putranto, 2019). When situated at a narrow depth, the water table allows contaminants to reach groundwater at a fast rate.

b. Groundwater Recharge

Groundwater recharge is a function of rainfall and coefficient of lithology made into one scoring. Lithological control means that the more porous the constituent rocks, the greater the rainfall share that penetrates the subsurface system. Tambakbayan Watershed receives 90–120 mm of rainfall per day, with more rain falling in the east than in the west. The recharge coefficient was determined based on the lithological unit; the watershed is part of the Old Volcanic, Mixed Sediment, and Young Sediment (Geological Map of Yogyakarta). Because the constituent materials varied from old volcanic to young sediment, the recharge coefficient was 20%.

Classification showed that the watershed recharge varied from 18 to 129 mm. The higher the groundwater recharge, the higher its score. According to Wijaya and Purnama (2017), this parameter is highly related to groundwater infiltration and the entire subsurface system. High recharge means a substantial amount of water is absorbed into the ground and that the groundwater system has considerable potential. However, high water recharge can also mean even more significant damage to the groundwater because it may introduce more contaminants to the system, creating a greater risk of pollution. It also signifies a place for rainwater to absorb into groundwater (Murtono et al., 2013).

The largest water recharge was 129 mm or 26.50 km2 (Tabel 2). At this level, most parts of the watershed are vulnerable to pollution, though at varying degrees. The northernmost part appeared to have medium groundwater recharge.

Table 2. Groundwater Recharge Classification and Scoring

Recharges (mm)	Areas (km2)	Percentages (%)	Scores
18	2.137	4.31	10
78	0.767	1.55	30
82	2.584	5.21	30
105	17.574	35.46	60
129	26.502	53.47	60

Source: Data analysis (2021)

c. Slope Gradient

There are five classes of slopes distributed throughout the watershed: <2%, 2–6%, 6–12%, 12–18%, and >18%. Smaller slope gradients allow water to infiltrate easier than steeper slopes because the former immediately converts water into flow or runoff (Widiastuti & Widyastuti, 2012), while the latter tends to prevent runoffs from seeping into the soil and carries away all contaminants instead. The majority of the watershed lies in terrains with a 2–6% slope gradient, while slopes of more than 18% are only found in the river valleys (Table 3). The lower slopes indicate a high chance of contaminants reaching groundwater or, in other words, high vulnerability to pollution. Steep slopes will transform more rainwater into runoff rather than infiltration (Alfiyan, 2011). Smaller slope gradients will retain water for a certain amount of time, allowing infiltration to occur during this period and contaminants to enter a subsurface system.

Table 3. Slope Gradient Classification and Scoring

Slope Gradients	Areas (km2)	Percentages (%)	Scores
<2	5.19	10.95	100
2–6	27.87	58.75	90
6–12	13.01	27.43	50
12–18	1.15	2.43	30
>18	0.20	0.43	10

Source: Data analysis (2021)

d. Aquifer Media

Aquifer media refers to a type of aquifer material found in the research location. The Tambakbayan Watershed has three types of aquifer media (Purnama et al., 2016), namely (1) loose lahar deposits, sand, gravels, and boulders in the north, (2) andesitic sand and gravel in the middle, and (3) clay at the lower course of the river. Loose lahar deposits are included in the aquifer unit Merapi I; therefore, the aquifer media is a metamorphic rock. Andesitic sand is part of Merapi II, while sand and clay are parts of Merapi III; hence, both aquifer media are categorized into sand and gravels.

As presented in Table 4, the sand-and-gravel aquifer had the highest score, 80, while metamorphic rock had a lower score, 40. Boulders were included in the weathered igneous aquifer media, considering that the lahar comes from igneous volcanic materials. Besides, according to the Geological Map of Yogyakarta, boulders are classified as Old Volcanic Deposits composed of breccia, agglomerate, andesite, and basalt. The scores assigned to each class of aquifer media are based on the condition of the material. For instance, the sand-and-gravel has high permeability, meaning that the groundwater has a very low filter of impurities, while the weathered igneous aquifer media consists primarily of rocks that have a relatively low ability to absorb groundwater (Cahyadi et al., 2011). The high or fast permeability of porous media significantly affects the degree of vulnerability to pollution. The sand-and-gravel aquifer covered a larger area of the watershed than the weathered igneous rock. As a result, in most parts of Tambakbayan, the groundwater is substantially vulnerable to pollution.

Table 4. Slope Gradient Classification and Scoring

Materials	Areas (km^2)	Percentages (%)	Aquifer Media	Scores
Loose lahar deposits, sand, gravels, and boulders	0.786	1.65	Metamorphic/weathered igneous rocks	40
Andesitic sand and gravel	34.216	72.13	Sand and gravels	80
Sand and clay	12.429	26.20	Sand and gravels	80

Source: Data analysis (2021)

e. Land Use

The land use data were interpreted from two different map sources with different classifications—this is one of the data limitations in the research area. The 2006 Indonesia Topographic Map (Geospatial Information Agency) categorizes land cover/use into shrubs, lakes, grasslands, plantations, settlements, rice fields, and dry agricultural lands. The 2017 land-use data organized by the Land and Spatial Planning Services of Sleman Regency consists of lakes/reservoirs, rivers, multiple-species plantations, freshwater fish ponds, grasslands, settlements, non-residential built-up lands, other open lands, irrigated rice fields, and dry agricultural fields. Settlements encompass yards, rural residential buildings, and urban residential buildings, while non-residential built-up lands include industrial, commercial, and office buildings, other non-residential buildings, runways, stadiums, and sports facilities, airport terminals, and golf courses.

Based on Tables 5 and 6, the land use with the score zero (0) covered a larger area in 2017 than in 2006 because of the Tambakboyo reservoir construction in Depok, Sleman Regency, in 2009. The reservoir has an area of 7.8 hectares and is used for conservation and tourism purposes (Ministry for Public Works and Settlements, 2009). Meanwhile, the land use with a score of 50 covered a similar area to the one scored 70–75, indicating an increase in built-up land in the 2017 land use classification. Rice fields and dry agricultural fields, scored 90, in 2017 shrank significantly compared to its distribution in 2006.

Table 5. Slope Gradient Classification and Scoring

Land Uses	Areas (km^2)	Total Areas per Score (km^2)	Percentages (%)	Scores
Shrubs	0.037	0.048	0.101	0
Lakes	0.011			0
Grasslands	0.176	2.665	5.565	50
Plantations	1.947			50
Settlements	17.377	17.377	37.122	75
Rice Fields	22.871	27.393	57.212	90
Dry Agricultural Fields	4.522			90

Source: Data analysis (2021)

The areal differences from the 2006 and 2017 land uses for each score showed that land-use change affected specific groundwater vulnerability. Rice fields and dry agricultural fields were scored the highest (90), assuming the waste product of fertilizer dissolution by water from these land uses was substantial and could directly seep into the soil (Nurkholis et al., 2018).

Table 6. Land Use Area of the Tambakbayan Watershed in 2017

Land Uses		Areas (km^2)	Total Areas per Score (km^2)	Percentages (%)	Scores
Lakes/Reservoirs		0.125	0.126	0.27	0
Rivers		0.001			0
Multiple-species Plantations		1.636	2.662	5.61	50
Freshwater Fish Ponds		0.227			50
Grasslands		0.799			50
Settlements	Yards	0.004	10.335	21.79	70
	Rural residential buildings	10.331			70
	Urban residential buildings	12.524	14.714	31.02	75
Non-residential Built-up Lands	Industrial, commercial, and office buildings	1.105			75
	Other non-residential buildings	0.397			75
	Runways	0.081			75
	Stadiums and sports facilities	0.101			75
	Airport terminals	0.325			75
	Golf courses	0.166			75
Other Open Lands		0.015			75
Irrigated Rice Fields		18.502	19.594	41.31	90
Dry Agricultural Fields	With horticultural crops	0.365			90
	With secondary crops (palawija)	0.727			90

Source: Data analysis (2021)

Groundwater Vulnerability to Pollution

Many scholars have compared Susceptibility Index (SI) with other groundwater vulnerability assessment methods and found advantages and disadvantages in its application. SI is adapted and developed from the DRASTIC method, which is used primarily to determine the spread of pollutants from agricultural activities. SI removes two parameters: soil properties and the effect of the vadose zone because they are considered to have less direct effects on contaminations associated with agricultural activities (Stigter et al., 2006). In many cases, the DRASTIC method requirements are not met due to limitations in the data, particularly bore logs (Hasan et al., 2019). For this reason, SI provides an alternative as it adds land use into the parameter observed, an advantage of this method.

In several studies, SI proves more representative of the actual vulnerability conditions, especially after validated with the nitrate parameter. Research in Kathmandu, Nepal, confirms that it is highly correlated with the risk of pollution and the observed NO3-N values, meaning that, in this area, SI is more suitable for determining groundwater vulnerability and risk of pollution than DRASTIC and GOD (Shrestha et al., 2017). According to Stigter et al. (2006), the SI method tends to overestimate the actual vulnerability but is deemed better for planning purposes than other methods with underestimated results.

a. Intrinsic Vulnerability

Based on the Susceptibility Index, the intrinsic vulnerability in the Tambakbayan Watershed differentiates into two: low and medium. Higher vulnerabilities indicate that the hydrogeological system has a greater capacity to transfer contaminants from the surface into groundwater (Shrestha et al., 2017). Figure 1 shows the distribution of intrinsic vulnerability in the watershed observed.

The intrinsic vulnerability scores ranged from 32 to 84, thus, classified as low and medium vulnerability. The majority of the watershed area, 4,639 km2 or 97.8%, had a medium vulnerability, and only a small part of it, 1,034 km2 or 2.18%, had a low vulnerability to pollution. The latter was distributed in Pakem District (northern end and the upper course of the river) and Depok District (the middle part of the watershed). The factor influencing low vulnerability in a localized area is aquifer media, which was given the highest weight value in the Si-based vulnerability assessment. Aquifer media describes the type of materials composing an aquifer; the easier the material drains pollutants, the higher the vulnerability. Areas with low vulnerability were composed of a mixture of sand, gravels, and boulders (score 40), whereas high vulnerability was caused by a mixture of sand and gravels in the aquifer media (score 80).

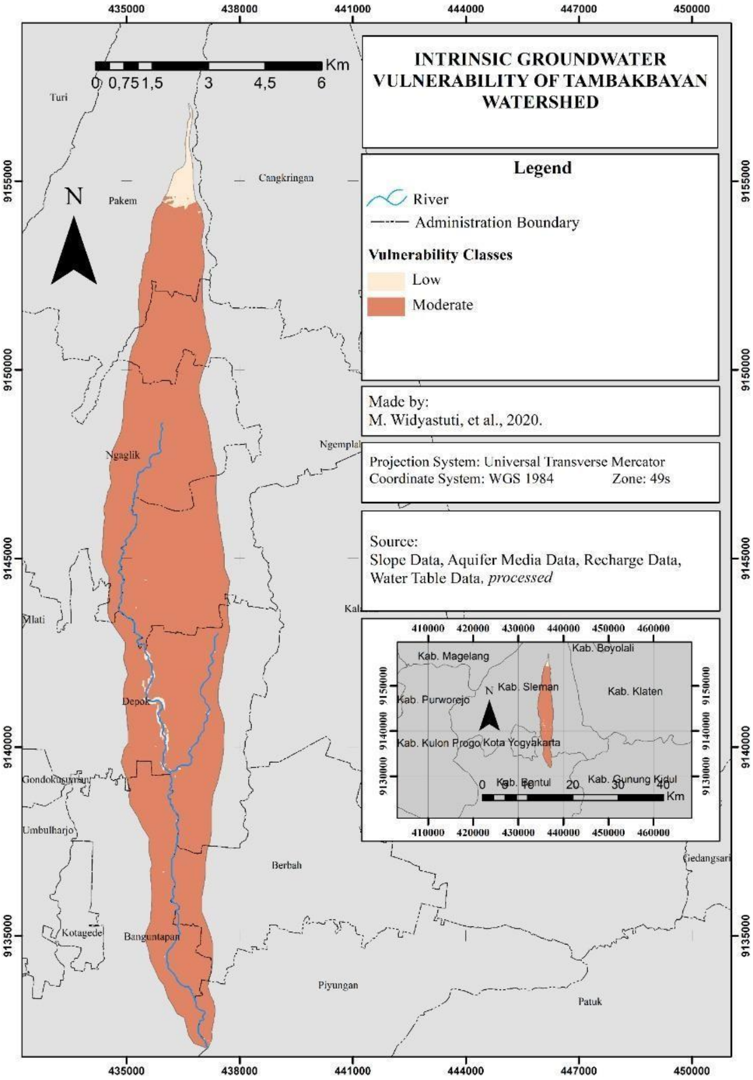

Figure 1. Map of Intrinsic Groundwater Vulnerability of the Tambakbayan Watershed, Yogyakarta

b. Specific Vulnerability

The specific vulnerability was assessed with the SI method that added land use conditions into its analyzed parameters. Land use is considered to influence pollutant input from anthropogenic activities to groundwater. Huan et al. (2012, in Hei et al., 2020) state that an increase in nitrate concentrations is directly related to human activities in urban and agricultural areas. As seen in the maps presented in Figures 1 and 2, there are differences in vulnerability levels between the specific and intrinsic vulnerability classification. The watershed had three specific vulnerability levels: low, medium, and high, but only two intrinsic vulnerability classes: low and medium. A study in Tata City, Morocco, shows that the implementation of DRASTIC coupled with the land use index produces higher vulnerability than the use of DRASTIC alone, indicating that hazards coming from human activities contribute more to the risk of pollution than the inherent hazards of natural conditions like depth to groundwater, aquifer media, soil, and topography (Hei et al., 2020). This finding is in line with the results of this research, where specific vulnerability shows a higher degree of vulnerability than its intrinsic counterpart.

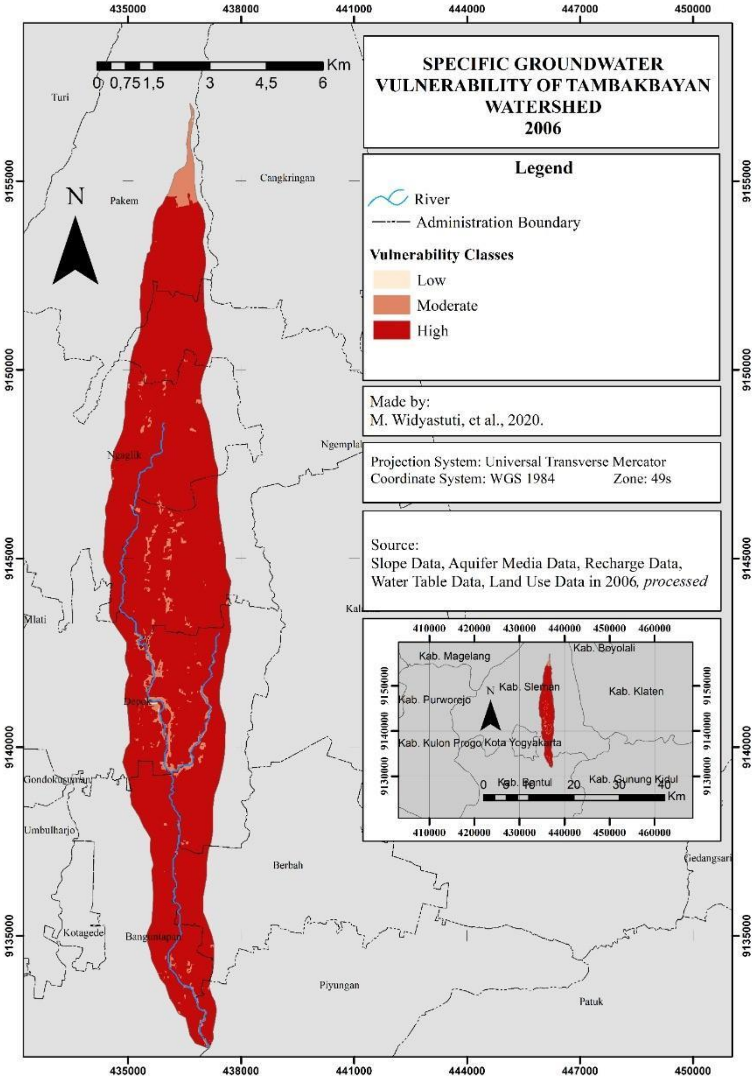

Figure 2. Map of Specific Groundwater Vulnerability of the Tambakbayan Watershed in 2006

Population growth and human activities are believed to have caused the land-use change between 2006 and 2017. Figures 2 and 3 present the maps of the specific groundwater vulnerability classification of the Tambakbayan Watershed. Areal changes in the vulnerability classes between the two periods were not significant. The proportion of areas with high specific vulnerability decreased from 97.131% in 2006 to 96.974% in 2017. Over 16 years, areas with medium vulnerability increased from 2.862% to 3.02%, while those with low vulnerability decreased from 0.007% to 0.006%. Table 7 shows the areas of each intrinsic vulnerability class (in km2 and percentage) in 2006 and 2017

Table 7. Slope Gradient Classification and Scoring

No	Classes	2006		2017	
		Areas (km^2)	Percentages (%)	Areas (km^2)	Percentages (%)
1	Low	0.0103	0.021	0.0041	0.009

2	Medium	2.403	5.062	2.668	5.623
3	High	45.069	94.915	44.770	94.367

Source: Data analysis (2021)

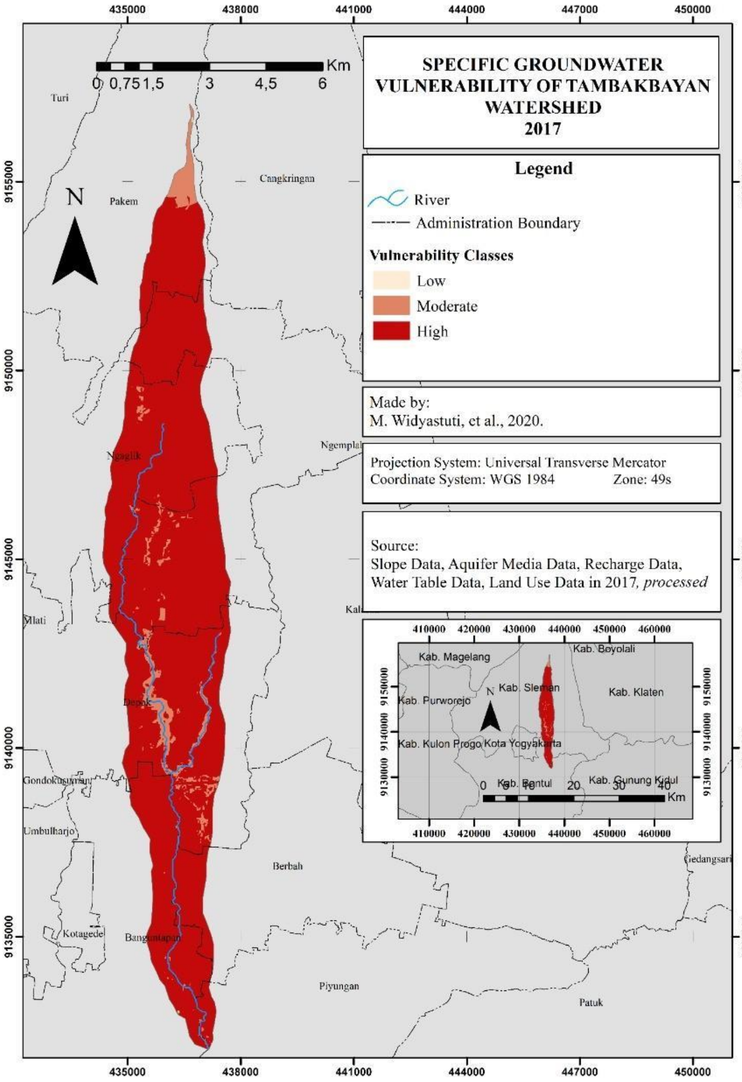

Figure 3. Map of Specific Groundwater Vulnerability of the Tambakbayan Watershed in 2017

Agricultural lands had the highest score (90) and the most substantial effects on the specific vulnerability. The lower score, 75, was assigned to settlements and non-residential buildings. In 2006 and 2017, the watershed area was mainly used for these three purposes; therefore, the high specific vulnerability was dominant in both years. Also, the medium vulnerability had the second-largest areal percentage and was distributed in the northern and middle parts of the watershed. In the north, intrinsic vulnerability (low) played a more significant role in determining the specific vulnerability. In the middle part, the areal percentage of the high specific vulnerability decreased, while that of the medium vulnerability increased. These changes occurred due to the conversion of agricultural land to a reservoir that had a lower vulnerability score. The low specific vulnerability covered a very small portion of the watershed and had decreased by 0.001% in 2017.

The mapping results showed that high specific groundwater vulnerability to pollution was dominant in the Tambakbayan Watershed for both years. Apart from the hydrogeological conditions, land use is also a factor influencing this degree of vulnerability. In the watershed observed, agricultural and residential lands were potential sources of contaminants. Waste management in farming and domestic activities provides an alternative way to protect groundwater from contamination.

Compared with other studies, the research confirms that aquifer media, depth to the water table, and the land use above it are key determinants of groundwater vulnerability. Applying the SI method to Campina de Faro and Campina de Luz, Stigter et al. (2006) categorize the vulnerability scores (0–90) into seven classes. Like the Tambakbayan Watershed, the groundwater of the Campina de Faro area is highly vulnerable to pollution, mainly because the aquifer is composed of limestones and has shallow water tables; hence, this parameter is scored 70–80. However, the intensive horticultural crop cultivation makes groundwater highly vulnerable (score 80-90), classifying the underlying sandy aquifer as very high to high. Campina de Faro also has medium to low vulnerability (score 50-60) and low vulnerability (score 40-50), especially in areas with deep water tables, low recharges, and steep slopes. Compared to these vulnerability classes, only a small portion of the Campina de Luz area has a very high vulnerability, which is attributable to aquifer material and a very shallow water table. High and medium to high vulnerability classes are found in karstified limestone aquifers with varying land uses. Medium to low and low vulnerability classes are found in steeply sloping areas with deep water tables.

Another study by Marjuanto et al. (2019) in Semarang City divides vulnerability scores into three classes, with administrative boundaries as the analysis unit. High vulnerability (score 72–89) is found around the coast, which has a sandy aquifer and very shallow water tables (1.5–<1.5 meters). While aquifer media is the most influencing factor of intrinsic vulnerability, settlement is a strong determinant of a specific vulnerability. The specific vulnerability appears to be higher in the northern part of the city (coastal areas), where most of its land is covered with marshes and dense settlements. The coastal areas have a very gentle slope used for residential buildings and a sandy aquifer, the combination of which leads to the highest vulnerability score. The low vulnerability class (score 36–53) in the south is influenced by aquifer media that is composed of igneous rocks and a slope of >18%. Overall, most of the city has medium vulnerability (5,788.79

hectares), while the rest has low and high vulnerabilities (963.75 and 4,649.78 hectares). These results show the possibility of high vulnerability occurring in a large area due to the contributions of land use and aquifer media (sand) in the coastal region. Deepwater tables of up to 30 m are the cause of low groundwater vulnerability in the city. In contrast, the Tambakbayan Watershed has shallow groundwater with the deepest water table of merely 9.1 m; hence, the high groundwater vulnerability.

Based on these studies, aquifer media is the most influential parameter because it has the highest weight value. Land use also has a significant role in increasing vulnerability because this parameter has the second-highest weight value, which is especially true for waste-generating activities in agricultural fields and settlements. In this research, aquifer media and land use are the two parameters behind the high groundwater vulnerability. Most of the Tambakbayan Watershed area is used as residential and agricultural land, contributing to high groundwater vulnerability to pollution.

CONCLUSIONS

The Tambakbayan Watershed has two classes of intrinsic groundwater vulnerability to pollution: low and medium (score 32–84). The majority of the area has medium vulnerability (4,639 km2 or 97.8%), and only a small portion has low vulnerability (1,034 km2 or 2.18%). Tambakbayan also has three specific vulnerability classes: low, medium, and high. There was no significant change in the specific vulnerabilities in 2006 and 2017. During this period, the medium class experienced a decrease in areal percentage, while the high class showed the contrary (an increase) because of the conversion of agricultural land to a reservoir with a lower vulnerability score. The areal percentage of the high class decreased from 97.131% in 2006 to 96.974% in 2017, while that of the medium class increased from 2.862% in 2006 to 3.02% in 2017. Areas with low vulnerability experienced a decrease in percentage from 0.007% to 0.006% for the observation years.

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