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ASSESSMENT OF CONTAMINATION VULNERABILITY OF GROUNDWATER USING SUSCEPTIBILITY INDEX METHOD: SEMARANG CITY AS CASE STUDY

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Abstract

Groundwater is an essential part of natural resources that has unique characteristics compared to other resources due to its renewability and dynamic nature. Semarang City, which is located in Central Java Province Indonesia, is currently facing some environmental problems such as degrading groundwater quality, lowering groundwater level, and flooding. A study is needed to assess the quantity and quality in detail to maintain the existence of groundwater in the long run. One of the efforts to evaluate the potential and quality of groundwater is through studying the groundwater vulnerability to contamination. The objective of this research is to assess the Vulnerability Index of the unconfined aquifer to contamination in the alluvial plain of Semarang City using the Susceptibility Index method. The result conducts three levels of vulnerability: low, moderate, and high. The high level dominantly spreads in the northern, the centre, and the east of the study area. The specific vulnerability map conduct industries and settlements highly contribute to the increasing level of vulnerability. The specific vulnerability map can be represented as a useful tool for the local government to protect and assess groundwater resources.

Keywords: Groundwater, Semarang, Susceptibility Index, Vulnerability.

1. Introduction

Groundwater is an essential part of natural resources that has unique characteristics compared to other resources due to its renewability and dynamic nature [1]. Since Groundwater is one of the components in water circulation on earth or hydrological cycle, groundwater thus can be replenished. Nevertheless, groundwater resources are not to be exploited without limits [2]. Due to being plentiful, reachable, and in good quality, groundwater has become one of the clean water sources with the highest interest for humans [3]. Due to the heightened interest, groundwater needs to be appropriately managed in its utilisation [4]. Groundwater is also susceptible to contamination due to the hydrogeological condition that can affect the entry of diluted contaminants into groundwater [5]. The increasing land usage also influences the change of its function due to the pressure of increasing population [6].

Semarang City currently faces many environmental problems such as degrading groundwater quality, saline water intrusion, and floods. All due to the overexploitation of groundwater [7]. It is predicted that by the year 2030, Semarang City will face a water crisis due to the 90% consumption of groundwater as clean water by the industrial sector in 2010 [8]. Groundwater exploitation in Semarang was done for the first time in 1842 through the drilled well in Wilhelm I Fort [9]. Based on the records since 1900, there was 16 groundwater extracting wells with a total discharge of 1,170 m^3/day. The other 260 wells were constructed in the 1990s and 1,194 wells developed in the first decade of 2000 [10].

In managing the sustainability of groundwater resources, a specific study is needed to observe the quantity and the quality of groundwater, and one of the efforts the maintain the potential and quality of groundwater is by studying the groundwater vulnerability to contaminant [11]. Groundwater vulnerability to the contaminant is the level of vulnerability of groundwater to contaminants based on the hydrogeology condition [12]. The study of groundwater vulnerability to contamination is critical because of groundwater protection both in quantity and quality [13]. Several studies related to groundwater vulnerability in several countries have been conducted, such as in United States [14], Sweden [15], France [16], Italy [17], and Portugal [18-20]. They all applied parametric system assessment using point count system models (PCSM) such as DRASTIC and SINTACS.

The Susceptibility Index (SI) method is one of the methods to evaluate groundwater vulnerability using PCSM, which is developed from DRASTIC method [11, 18, 19, 21]. SI can be applied to determine the location of the vulnerable areas according to land use, especially to evaluate pollution of the unconfined aquifer according to nitrate contamination (agriculture) [22, 23, 11]. The nitrate concentration can be employed to validate the SI map [19].

Several previous researchers have also attempted using the SI method in regions with sparse farmlands since the SI method also provides assessment towards other sources of contamination aside from farming [20, 21, 24, 25]. Several other sources of contamination from agriculture also come from human-made and natural environments. The validation result of the groundwater quality test with the SI method is not further apart on each groundwater vulnerability assessment despite resulting in a lower rating from the groundwater quality test result [11].

The objective of this research is to assess and analyse the distribution of groundwater vulnerability to contaminant using the SI method in the alluvial plain of Semarang City and its validation using nitrate concentration. The hydrogeological field campaign and geochemical analysis will conduct primary data in measuring the water table and analyse the nitrate concentration.

2. Materials and Methods

2.1. Study area

The city of Semarang is growing fast in the industrial and commercial sectors as the primary hub connecting Jakarta in West Java and Surabaya city in East Java, and cities in the southern interior of Java, i.e., Surakarta and Yogyakarta. Semarang City has two morphologies which are coastal, and lowlands situated in the north and mountains in the south.

The study area is on the alluvial plain of Semarang City with a coordinate of 110° 17’00.7” longitude to 110° 30’24.6” and 6° 55’53.3” latitude to 7° 0’44.7”. It has an area of 115.75 km^2 (Fig. 1). Semarang city is the capital city of Central Java Province, which is located on the northern coast of Java (Indonesia). The research area covers 12 sub-districts in the alluvial plain of Semarang City. In 2016, Semarang had a population of 1,729,428 with a growth rate of 1.66%, compared to 2014, with a population of 1,572,188 [26].

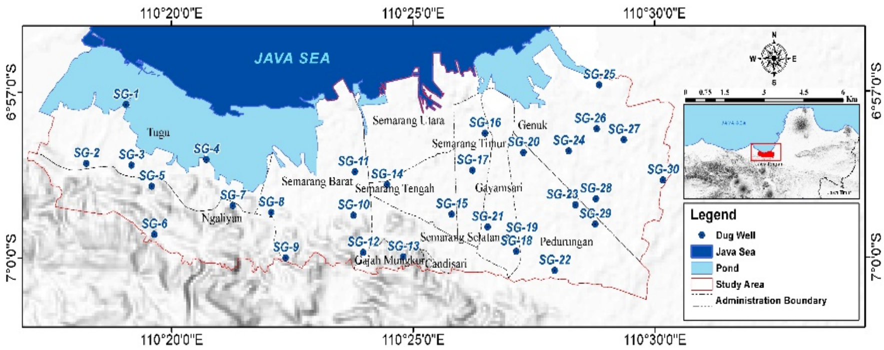

Fig. 1. Study area map.

The geologic setting of the study area consists of basin sediment contain alluvium (Qa) in the center to the north, and Damar Formation (QTd) contains volcanic breccia in the south. Alluvium forms a coastal plain, river, and lake deposit [27]. Coastal plain generally contains clay, sand, and has 50 m thick or more. Sand deposit commonly forms a delta deposit as an aquifer with a thickness of greater than 80 m. River and lake deposits are consisting of pebble, cobble, sand, and silt range in thickness of 1-3 m. While Damar Formation is mainly non-marine deposit consist of tuffaceous sandstone, breccia, conglomerate.

According to the regional hydrogeological map of Semarang [28], in the lowland of Semarang city, the aquifer is mainly flowing in the intergranular system. It has multi-layer aquifers with the productive to the extensive high aquifer. Groundwater level varies, generally near the land surface with well yield from 5-10 L/sec. The primary lithology in this aquifer system is alluvial deposits.

2.2. Methods

2.2.1. Susceptibility index

Groundwater vulnerability assessment can be divided into two, i.e., intrinsic vulnerability and specific vulnerability. The intrinsic vulnerability was the specific susceptibility of the aquifer systems in their various parts and the variety of geologic and hydrogeologic settings. It was to absorb and diffuse the fluid and contaminant, which affected groundwater quality in the function of space and time. The intrinsic vulnerability depended on the three main factors [17] which were:

i. The infiltration process and the time travel of water through the unsaturated zone to reach the underlying saturated zone

ii. The groundwater flow dynamics in the saturated zone

iii. The contaminant impact based on the residual concentration of the contaminant as it reaches the saturated zone

The combination of the intrinsic vulnerability and land use conducted the specific vulnerability. Each parameter had a different assessment system, especially for the rating and weight. These were influenced by the parameter influence level towards groundwater contamination [11, 25]. Nitrate (NO_3^-) was a primary form of nitrogen compound in groundwater and the primary nutrients for the growth of plants and algae. Nitrate was easily diluted in water and stable in nature [29]. Nitrate was a contaminant that can easily pollute groundwater from the surface. Therefore, the nitrate parameter in farmlands can be considered as the indicator of how nitrate contamination can easily pollute the groundwater, thus can be used as the determining concept of vulnerability level [30].

Nitrate, as a contaminating parameter, also comes from domestic waste (households). Bacteria chemically altered ammonia (NH_3) resulting from these wastes into nitrate through nitrification reaction. Nitrification was an oxidation process of ammonia into nitrate and an essential process in the cycle of nitrogen [29]. A high nitrate level can be toxic and poses a threat to human health. According to [31], a high nitrate concentration in the urban area was caused by a large number of household wastes that are the consequence of the urban population density. The presence of nitrate in groundwater was also produced by human activities such as using artificial fertilizers. Changing groundwater flow direction can also trigger nitrate distribution. Moreover, converting the recharge zone into the discharge zone due to uncontrolled groundwater extraction affected the decreasing of groundwater level and raising hydrostatic pressure. Thus, allowing pollutants were to migrate along with groundwater into the aquifer [32].

The Susceptibility Index (*SI*) was conducted by overlaying the parameters mapping of depth to the water table, groundwater recharge, aquifer media, topography, and land use. The *SI* was then calculated based on multiplying their rating (r) and weight (w) of each parameter by using spatial analysis in the ArcGIS Pro software, as shown in Table 1 following Eq. (1) below [11]:

$$SI = (Dw \times Dr) + (Rw \times Rr) + (Aw \times Ar) + (Tw \times Tr) + (LUw \times LUr) \quad (1)$$

The five parameters employed in the SI methods according to [11] are Depth of water (*D*), Recharge (*R*), Aquifer media (*A*), Topography (*T*), and Land use (*LU*).

2.2.2. Depth of water

The field campaign conducted 30 dug wells to measure the depth of water in the study area, as shown in Fig. 1 and Table 2. It was measured in April 2019. The water table was then subtracted from the topography surface to obtain the map of the depth of the water table.

Table 1. Weight and rating of groundwater vulnerability parameters [11].

Parameters	Classification	Weight	Rating
Depth to Water Table		**0.186**	
	<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		**0.212**	
	<51 mm/year		10
	51-102 mm/year		30
	102-178 mm/year		60
	178-254 mm/year		80
	>254 mm/year		90
Aquifer Media		**0.259**	
	Massive shale		20
	Metamorphic/igneous rock		30
	Weathered metamorphic/igneous		40
	Glacial deposition		50
	Sandstone, limestone, and shale layers		60
	Massive sandstone		60
	Massive limestone		80
	Sands and gravels		80
	Basalt		90
	Karst limestone		100
Topography		**0.121**	
	<2 %		100
	2 - 6 %		90
	6 - 12 %		50
	12 - 18 %		30
	>18 %		10
Land Use		**0.222**	
	Seasonal plants, rice fields		90
	Permanent plants		70
	Heterogenous farmlands		50
	Pasture fields and agroforestry area		50
	Waste-producing industries & disposal area		100
	Mining area, shipyard, mines		80
	Urban area, airport, trains stations, industrial and commercial area, green spaces		75
	Semi-urban area		70
	Waterfront ecosystem (swamps, lagoons, tidal zones)		50
	Forest and semi-natural zones		0
	Waterbody		0

Table 2. Hydrogeology field campaign.

No.	Code	X	Y	Elevation (masl)	Groundwater depth (m)	Aquifer media	NO_3^- (mg/L)
1	SG-1	424618	9231297	11	0.1	Sand	3.1
2	SG-2	423118	9229335	10	2.94	Sand	103.1
3	SG-3	424838	9229281	12	0.4	Sand	1.0
4	SG-4	427684	9229475	15	0.2	Sand	0.0
5	SG-5	425607	9228579	34	3.4	Breccia	34.7
6	SG-6	425704	9226979	77	15.5	Breccia	18.9
7	SG-7	428692	9227928	20	1.15	Sand	4.0
8	SG-8	430156	9227699	16	4.6	Sand	8.9
9	SG-9	430713	9226199	38	1.8	Breccia	0.0
10	SG-10	433292	9227606	18	3.12	Sand	10.5
11	SG-11	433349	9229056	7	5.3	Sand	0.0
12	SG-12	433668	9226375	22	2.71	Sand	32.1
13	SG-13	435190	9226233	33	9.6	Breccia	11.3
14	SG-14	434568	9228631	13	0.47	Sand	0.0
15	SG-15	437039	9227641	8	0.98	Sand	30.3
16	SG-16	438310	9230343	15	0.4	Sand	0.0
17	SG-17	437834	9229105	13	0.5	Sand	0.0
18	SG-18	439501	9226410	5	1.5	Sand	0.5
19	SG-19	439164	9226849	5	0.5	Sand	0.0
20	SG-20	439770	9229704	16	0.2	Sand	0.0
21	SG-21	438412	9227224	9	0.92	Sand	2.6
22	SG-22	440963	9225772	9	0.32	Sand	0.0
23	SG-23	441752	9227959	7	0.5	Sand	2.9
24	SG-24	441498	9229755	15	0.55	Sand	0.7
25	SG-25	442661	9231953	5	1.5	Sand	2.8
26	SG-26	442569	9230491	16	0.5	Sand	1.1
27	SG-27	443602	9230121	14	1.77	Sand	9.3
28	SG-28	442535	9228163	12	0.12	Sand	0.2
29	SG-29	442509	9227313	4	1.51	Sand	0.1
30	SG-30	445092	9228787	15	1.06	Sand	12.8

2.2.3. Recharge

Groundwater recharge was a hydrologic process where water infiltrates downward from precipitation into the saturated zone**.** Groundwater recharge depended on several factors, such as precipitation, runoff, and evapotranspiration. The average precipitation and temperature in the study area are 2,204 mm/yr and 27.5°C [26]. In [33] converted mass precipitation to mass runoff by using a surface runoff Curve Number (*CN*). It was based on soils, plant covers, and number of impervious areas, interception, and surface storage, as follows in Eqs. (2) and (3).

$$Ro = \frac{(P-0.2S)^2}{(P+0.8S)} \tag{2}$$

$$S = \frac{25400}{CN} - 254 \tag{3}$$

where *Ro* was a surface runoff, precipitation (*P*), and Soil and cover condition (*S*) of the watershed through the *CN*. *CN* are 35, 49, 65, and 92 that represent other agricultural lands, open space, cultivated agricultural land, and residential, respectively. Evapotranspiration (E_t) was calculated using Turc equation [34], as follows in Eq. 4. Turc equation depended on precipitation and temperature.

$$E_t = \frac{P}{\sqrt{0.9 + \left[\frac{P^2}{(300+25*T+0.05*T^3)^2}\right)\right]}} \tag{4}$$

where *P* was precipitation (mm/yr), and *T* represents temperature (°C).

2.2.4. Aquifer media, topography, and land use

The aquifer media was constructed based on the geological map of Magelang and Semarang sheet (scale 1:100.000) [27] and borehole logs data [35].

The topographic surface was derived from the Indonesian Geospatial Agency by using the Digital Elevation Model National (DEMNAS). The spatial resolution of DEMNAS is 0.27-arcsecond with a vertical datum of the Earth Gravitational Model (EGM) 2008. The surface topography has a range from near the sea level up to 80 m above sea level (masl)

The land use of the alluvial plain in Semarang City was dominated by settlements, industrial, paddy fields [26]. These land uses were the most contributed to the contamination related to their wastes and agricultural activities using fertilizer.

The example of the calculation Susceptibility Index (*SI*) is addressed below. SG-20 has a depth to the water table of 0.2 m (rating 100) with groundwater recharge 107-178 mm/yr (rating 60). Aquifer media consists of sand (rating 80) with topography is flat (<2%, rating 100), and land use is an urban area (rating 75).

$$SI = (0.816 \times 100) + (0.212 \times 60) + (0.259 \times 80) + (0.121 \times 100) + (0.222 \times 75) = 80.79$$

3. Results and Discussion

The groundwater level is an essential factor in studying groundwater vulnerability to contamination since the depth of the water table can be used to determine the required time for contaminants to pollute the aquifer [12, 14]. Figure 2 shows the map of depth to groundwater as a result of measuring the distance between the surface and the water table in the field campaign. Following the Susceptibility Index method (Table 1), the depth of water is divided into 3 (three) classes, as seen in Fig. 2.

The lowest depth (<1.5 m) is located in the east. The city center to the north and west have a groundwater level range of 1.5-4.6 m. In contrast, the south is the deepest more than 4.6 m depth. It means that groundwater in the unconfined aquifer follows the topographic that is higher to the south dan flows from the south to the north [16, 35]. Moreover, the shallow depth of water indicates contaminants easily reach the saturated zone in the aquifer system. Thus, the highest rating (100) is addressing to the shallowest depth of water which consists of alluvium, while the lowest rating (70) is assigned to the volcanic product.

Fig. 2. Depth of water table map.

Based on the water balance analysis using equation 2 to 3, Fig. 3 shows the groundwater recharge in the study area can be grouped into two, i.e., 103-178 mm/yr and 179-254 mm/yr. Factors that affect groundwater recharge are precipitation, runoff, and evapotranspiration. Residential has the lowest recharge due to the impervious area has over 65% with the curve number (*CN*) around 92 indicate the highest runoff [33]. High recharge contributes to a high possibility to contaminate groundwater [5, 11, 19, 20]. Thus, the north, the west, and the east of the study area have the possibility of vulnerable to contaminants.

The delineated classification of aquifer media produced an area distribution with specific aquifer media classification. There is an area with weathered igneous rock (volcanic breccia) across the study area in the south, and areas with sand aquifer media are dominated in the north, the center, and the east of the study area as depicted in Fig. 4. The highest rating of 80 is addressed to sand which indicates more vulnerable to contaminants to reach the saturated zone. While the rating of 40 indicates less permeability to reach the saturated zone and low possible vulnerability to contaminants [20, 21, 24, 25].

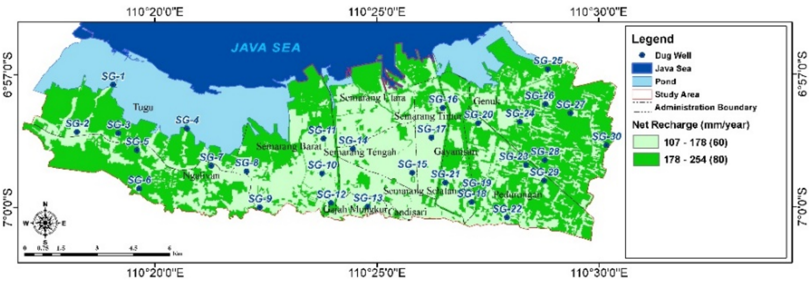

Fig. 3. Groundwater recharge classification.

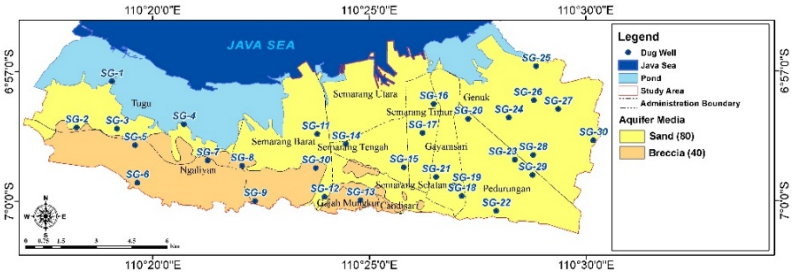

Fig. 4. Aquifer media classification.

The arranged classification of topography produced an area distribution with specific topography classification. There are five classes of topography classification, i.e., 0-2%, 2-6%, 6-12% 12–18%, and more than 18%, as shown in Fig. 5.

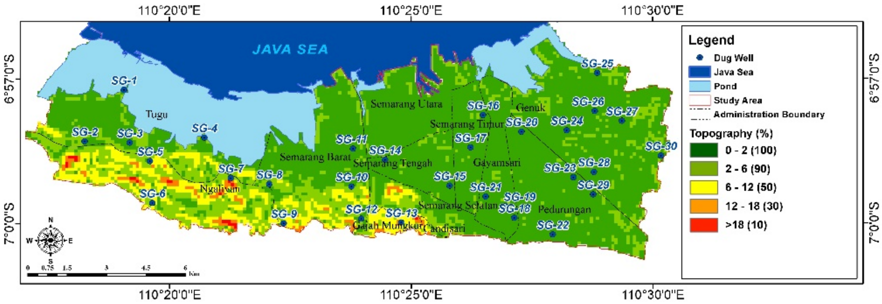

Fig. 5. Topography classification.

The area with a low slope (0-2%) is addressed with the highest rating (100) that indicates a high possibility of groundwater vulnerability of contamination due to retaining water longer and extremely potential for contaminants [5, 11, 12].

Land Usage of Semarang City can be categorized into 13 (thirteen) types with distribution as depicted in Fig. 6. In 2017 [26], Semarang City has industrial, rice fields, and residential areas that posed as a potential source of numerous nitrate pollutants according to [11]. The highest threat of nitrate pollutants, with a rating of 100, is produced by industrial activity of waste disposal and farming activities of fertilizer in the paddy field (rating 90) that is diluted in water. The highest threat of nitrate pollutants from residences is the waste from domestic activities. The lowest threat of nitrate pollutants is from natural usage of lands such as water bodies, forests, and ponds [11, 19, 20, 24].

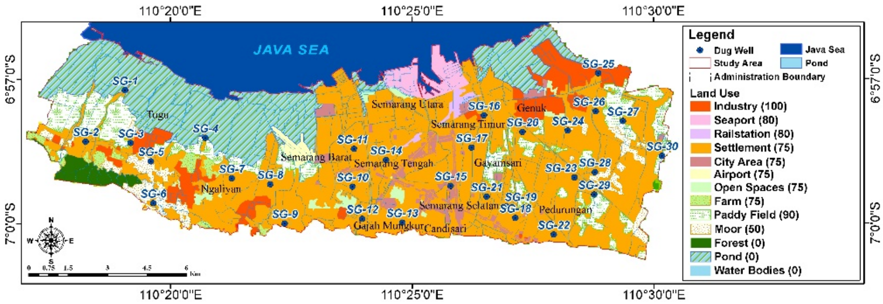

Fig. 6. Land use classifications.

3.1. Groundwater vulnerability maps

Intrinsic groundwater vulnerability of alluvial plain of Semarang City that is considering the geogenic factor is divided into three classes: high, moderate, and low as depicted in Fig. 7. The parameters that affect the vulnerability level are depth of water table, groundwater recharge, aquifer media, and topography. The aquifer media consists of sand is addressed as the most parameter of groundwater vulnerability to contamination. It spreads in the north, the east, the center, and locally in the west. The high groundwater recharge (178-254 mm/yr) is further accelerating vulnerability to contamination in line with other researchers [11, 13, 17, 19]. Indeed, the depth of water (up to 4.6 m) impacts the high level of vulnerability, especially in the north and the east. This condition is also supported by the low topography (<2%) in those areas.

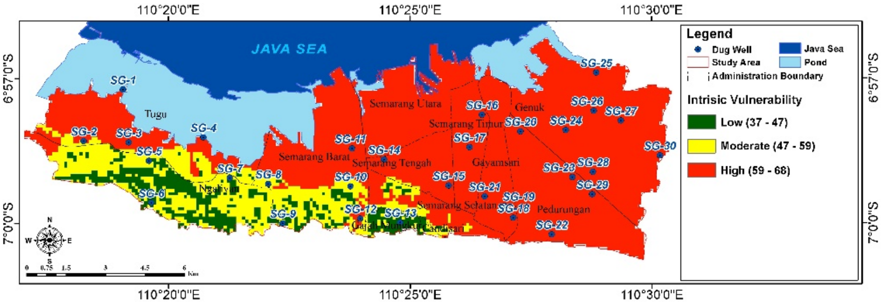

Fig. 7. Intrinsic vulnerability.

While the moderate vulnerability has a volcanic product as the aquifer media, medium groundwater recharge (107-178 mm/yr), depth to water table from 1.5 m to 4.6 m depth, and 2-12% slope of topography. The moderate level of vulnerability spreads from the center to the west.

The low level of vulnerability conducts a low rating in all parameters. Aquifer media consists of volcanic product, groundwater recharge (102-178 mm/yr), depth to water table more than 4.6 m, and topography has a slope from 12% to more than 18%. The areas spread in the south of the study area.

The *SI* method results in a specific vulnerability map are obtained by overlaying the intrinsic vulnerability map and land use parameter. The result of a specific vulnerability map, as shown in Fig. 8 has three levels: low, moderate, and high. In the intrinsic vulnerability map with a high level, the industrial areas contribute to the highest groundwater vulnerability in the specific vulnerability map. The industrial has the highest rating because of the contribution of waste and disposal areas in their location. Indeed, the settlement also contributes to high vulnerability with their domestic wastes.

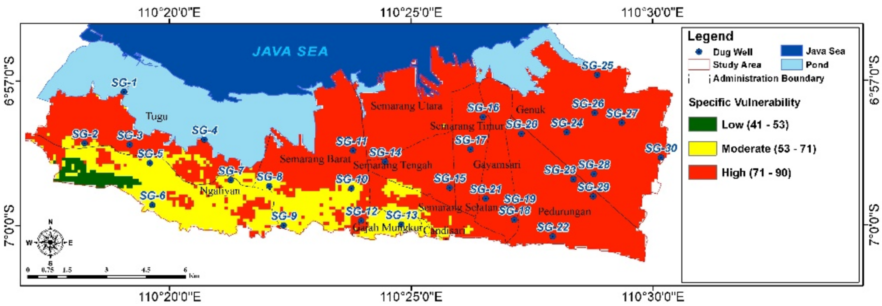

Fig. 8. Specific vulnerability.

Meanwhile, there is a change in vulnerability level in the south of the study area. Domestic wastes from the settlement increase the vulnerability to the medium level. In comparison, low level spreads locally in the southwest of the study area.

High vulnerability areas should be regulated strictly concerning waste disposal, especially waste infrastructure such as communal waste. Industrial and residential zone placement should be directed to areas with low groundwater vulnerability. Farmlands management should emphasize more on permanent irrigation channels and fertilizer dosage management. Areas with moderate groundwater vulnerability should be closely monitored in the same way as the high vulnerability to prevent the increased risk of groundwater vulnerability.

According to [12, 27, 36], the high level of vulnerability indicates that the aquifer vulnerable to many pollutants, except those strongly adsorbed or readily transformed in many pollution scenarios. The vertical time to the aquifer is 5-25 years.

The moderate level means that aquifers vulnerable to some pollutants, but only when continuously discharge or leached. It has 25-50 years of vertical time to the aquifer.

The low level represents that aquifer only vulnerable to conservative pollutants in the long term when continuously and widely discharge or leached. It needs 50-100 years to reach the aquifer.

3.2. Nitrate distribution

Nitrate level distribution in Semarang City is obtained from groundwater quality measurement of 30 samples. Classification of nitrate level is referring to [37]. Nitrate classification in alluvial flatlands of Semarang City into three classes: low (0 – 5 mg/L), moderate (5 – 10 mg/L), and high (> 10 mg/L). Based on these classifications, the water samples can be classified as 20 samples in a low class, 2 in moderate, and 8 in high, as seen in Fig. 9.

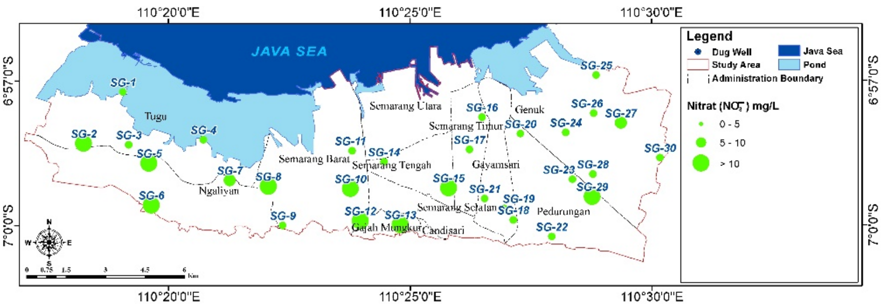

Fig. 9. Nitrate distribution.

3.3. Nitrate validation

Validation of intrinsic and specific groundwater vulnerability is applied to verify the accuracy of the method used to measure groundwater vulnerability to contamination. Groundwater vulnerability validation is achieved by comparing the resulted groundwater vulnerability assessment to the water quality test. The parameter used in the water quality test is nitrate concentration. Nitrate indicates the presence of contamination by farming activities and household wastes, similar to the results of some researchers [29, 33, 38]. Nitrate concentration is divided into 3 classes which are high with a concentration >10 mg/L, medium (5-10 mg/L), and low (< 5 mg/L).

The accuracy of the intrinsic groundwater vulnerability assessment is 20%, as shown in Fig. 10. The *SI* method accuracy is at 20% that is below the minimum threshold of 63% and 71% [24]. The validation of specific vulnerability with the nitrate concentration produced similar variations with the intrinsic groundwater vulnerability (Table 3 and Fig. 11). The high level of intrinsic vulnerability is only available in 5 dug wells which has nitrate concentration above 10 mg/L. Similar to the high level of intrinsic vulnerability, the high level of specific vulnerability also spreads in 5 dug wells in the study area (Table 3). Low concentration of nitrate is dominated in all high level of vulnerability (intrinsic and specific). The validation result is yet to conclusively determine the unsuitability of deploying the SI method to the area of the study. The validation rating is under the minimum threshold because the *SI* method is a development from the DRASTIC method which is applied by [18, 19]. The SI method is a quantitative method [39] that has been modified according to the experience of the researcher and the regional characteristics of the research area by adding parameters and changing the weight of the parameters [11]. Judging from the weight change and additional parameters, there is a specific factor that is unsuitable to the study area.

Table 3. Nitrate validation in dug wells

Vulnerability Level		**Nitrate Classification**		
		High (> 10 mg/L)	**Moderate (5-10 mg/L)**	**Low (0-5 mg/L)**
Intrinsic	High	SG-2, SG-12, SG-15, SG-29, SG-30	SG-27	SG-1, SG-3, SG-4, SG-11, SG-14, SG-16, SG-17, SG-18, SG-19, SG-20, SG-21, SG-22, SG-23, SG-24, SG-25, SG-26, SG-28
	Moderate	SG-5, SG-6, SG-8, SG-10	-	-
	Low	SG-13	SG-7	SG-9
Specific	High	SG-2, SG-12, SG-15, SG-29, SG-30	SG-27	SG-1, SG-3, SG-4, SG-11, SG-14, SG-16, SG-17, SG-18, SG-19, SG-20, SG-21, SG-22, SG-23, SG-24, SG-25, SG-26, SG-28
	Moderate	SG-5, SG-6, SG-8, SG-10, SG-13	SG-7	SG-9
	Low	-	-	-

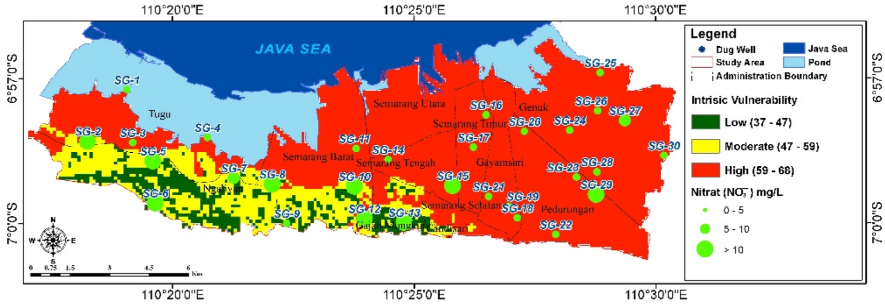

Fig. 10. Intrinsic vulnerability and nitrate.

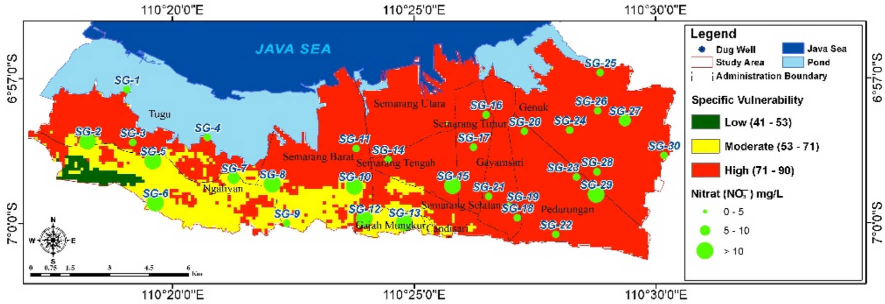

Fig. 11. Specific vulnerability and nitrate.

The parameter that produced an unsuitable rating is groundwater recharge with a rating of more than 254 mm/year. It is likely due to the tropical climate of the area with a precipitation of more than 2,000 mm/year. The difference in climate determined the difference in precipitation and groundwater recharge in a certain location. It results in the groundwater vulnerability assessment using the *SI* method that falls below the accuracy threshold. It is also supported by [21] that the *SI* method applied in the same climate as Portugal should produce an acceptable accuracy rating. Aside from the groundwater recharge parameter, the nitrate parameter in the groundwater quality test is also unsuitable. Nitrate parameter classification, according to [11] is unsuitable with the classifications in Indonesia.

4. Conclusions

The application of the Susceptibility Index method for the assessment of groundwater vulnerability conducts several benefits in groundwater management in Semarang City. Most of Semarang City in the northern, the center, the eastern, locally in the western are highly vulnerable to contamination. Lowering groundwater depth, high recharge, flat topography, and land use area with impervious over 65% contribute to the high level of vulnerability.

Moreover, the porous of the aquifer that consists of alluvium (sand) indicated that the aquifer is a high risk of contamination by nitrate. Poor agricultural methods and sanitation facilities in the settlement areas affect the low quality of groundwater in the alluvial plan of Semarang City. Therefore, the implementation of a monitoring well network is a must to protect groundwater for daily needs. Moreover, developing a groundwater conservation zone is highly recommended to prevent groundwater sources and the sustainability of groundwater in the future.

Although the accuracy of NO_3^- concentration measurement to validate the SI map (specific vulnerability map) is low (around 20%), this map can be represented as a useful tool for the local government to protect and assess groundwater resources for implementing sustainability of groundwater management.

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Nomenclatures

Ar	Rating of Aquifer Media
Aw	Weight of Aquifer Media
CN	Curve Number
Dr	Rating of Depth to the water table
Dw	Weight of Depth to the water table
E_t	Evapotranspiration
LUr	Rating of Land Use
LUw	Weight of Land Use
P	Precipitation
Rw	Weight of Groundwater Recharge
Rr	Rating of Groundwater Recharge
S	Soil and Cover condition
SI	Susceptibility Index
T	Temperature
Tr	Rating of Topography
Tw	Weight of Topography

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