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Spatial Analysis to Evaluate Groundwater Vulnerability to Contamination of Unconfined Aquifer in Semarang Lowland Area Using DRASTIC Method

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Abstract. The increasing population up to 1.67% per year in the urban coastal city such as Semarang affects enormous stress on the natural resources – groundwater, in particular. To assess groundwater vulnerability to contamination the DRASTIC method was applied. DRASTIC was one method in compiling a zone of groundwater vulnerability to contamination. This method required seven parameters, namely D (water table depth), R (recharge zone), A (media aquifer), S (soil media), T (topography), I (vadose zone), and C (hydraulic conductivity). Processing of each parameter to calculate the Drastic Index (DI) was developed by using spatial analysis in ArcGIS. The results conduct there is three-level of groundwater vulnerability to contamination namely low, medium, and high. The low vulnerability has the number of DI of 61 to 100, while the DI of moderate is around 101-140. The high level is represented by 141-180 of DI. The low level is distributed in some areas in the south of Semarang, while the medium is dominated in the Ngaliyan area, Gajahmungkur, Semarang Selatan, also found in Tugu, Semarang Barat, Candisari, and some areas in the Semarang Tengah. Indeed, the high level is found in the plains areas in the northern, in the western, and eastern part of Semarang.

1. Introduction

The outcome of climate change on water resources, and consequently on water availability, is one of the most challenging aspects of long-term sustainable water management. National and international studies most often deal with climate change effect to surface water resources; while climate change effects on groundwater resources have not been completely dropped. It is although many regions are significantly dependant on groundwater resources for irrigation, industrial use including mining, and urban supply (Baron et al. 2010). Moreover, the increasing population also annexes environmental problems to the fulfilment of the need for freshwater. Nowadays, the urban cities are facing some environmental problems i.e. land subsidence, lowering groundwater level, degradation of groundwater quality, seawater intrusion, flooding etc.

The increasing population around 1.66% per year [1] in the urban coastal city such as Semarang affects enormous stress on the natural resources – groundwater, in particular. Groundwater represents the most valuable drinking water resource. Water quality analysis is one of the most fundamental aspects of groundwater studies [2] assess of groundwater quality of unconfined aquifer via some graphical interpretation as well as interpolation of water quality data on maps. The assessment conducts the actual condition of physical groundwater properties such as pH, EC, Salinity, and DO values to achieve sustainable development of groundwater management in Semarang coastal plains and lowlands. The physical parameters of the samples that in the north and the east of the coastal plains and lowlands of Semarang show a higher value than in the centre and the south. The pH values of the water in coastal plains and lowlands of Semarang were mostly neutral around 6.5-8.2. EC and Salinity values have a range 1,500-6,370 μS/cm and 750-3,600 mg/L respectively. The highest and lowest of DO values were 1.5 and 0.06 mg/L respectively.

Moreover, [3] develop groundwater conservation based on three parameters that are groundwater quality, water table depth, and land subsidence rate. There are four conservation zones, which are secure, vulnerable, critical, and damaged. The increasing threat to groundwater quality degradation, it is necessary to continue studies related to the groundwater vulnerability zones to contamination. This research aims at evaluating, monitoring, and assessing groundwater vulnerability using the DRASTIC method in Semarang lowland.

2. Data and Methods

2.1. Study area

The study area was located in Semarang lowland area in Central Java Province which has 115 km^2 width. The land use of the study area is mainly occupied by residence, ponds, trade, and transportation facilities such as airport, train, and bus station. Based on the hydrogeological field campaign in May 2019, there were 30 dug wells which were measured the groundwater depth, obtained the groundwater samples, and in situ of physical measurements such as, TDS/Total Dissolved Solids, pH, and Electrical Conductivity (EC) of the unconfined aquifer. The distribution of samples was chosen randomly to present the groundwater level and its direction as well as the quality of groundwater (Figure 1).

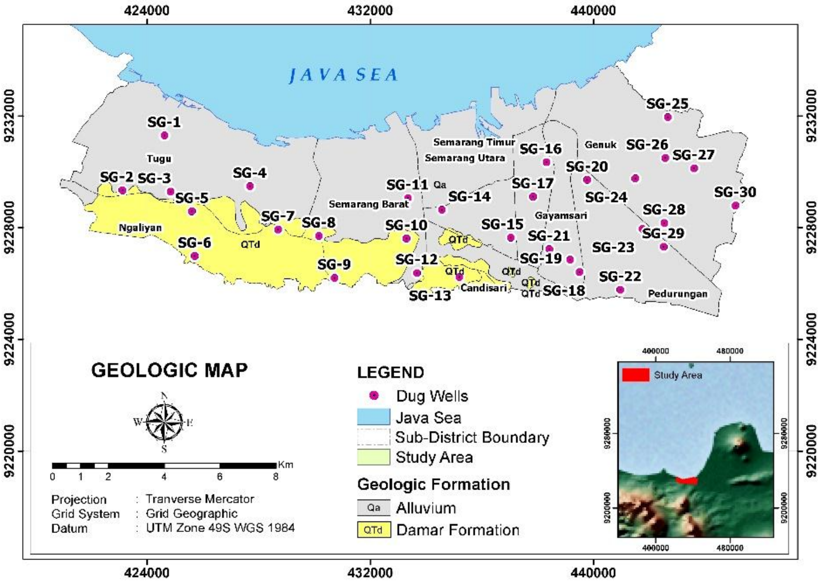

Figure 1. The study area and its geologic setting

Based on the regional geology of Magelang-Semarang sheet [4], the geologic setting of the study area is composed by Damar Formation (QTd) and Alluvium (Qa). Damar Formation consists of tuffaceous sandstone, conglomerate, and volcanic breccia. It is mainly distributed in the south of Semarang lowland areas. Alluvium as the youngest sediments is deposited in the centre, in the north, in the east and the west of study area. It consists of thick layers of calcareous and shell bearing clay with thin intercalations of sand and occasionally gravel to pebble or cemented gravel.

Meanwhile, the hydrogeological setting of the study area is focused on the unconfined aquifer. The groundwater flows predominantly in an intergranular system from hilly areas in the south to lowland areas in the north. The fluctuation of water table appears depending on the season, i.e. high in the wet season and low in the dry seasons. Groundwater is abstracted by numerous dug wells, mainly for domestic water supply.

2.2 DRASTIC Methods

Groundwater vulnerability is a creative system to help planners to protect aquifers as economic resources [5]. The concept of groundwater vulnerability integrates the hydraulic confidentially of the saturated zone to the entrance of pollutants, with the attenuation capacity of the strata overlying the saturated zone as a result of physicochemical retention or reaction of pollutants [6]. Assessments of the vulnerability of groundwater to contamination range in scope and complexity from simple, qualitative, and relatively inexpensive approaches to rigorous, quantitative, and costly assessments have been adopted by several researchers [7]-[11].

Many techniques that exist to estimate groundwater vulnerability, among the simplest and widely used techniques are DRASTIC index that measures intrinsic vulnerability developed by US EPA [12]. The intrinsic vulnerability is closely dependent on the hydrological, geological and hydrogeological characteristics of the study area. The name DRASTIC is taken from the initial letters of the seven parameters used to evaluate the intrinsic vulnerability of aquifer systems. The following symbols are used in the computation of DRASTIC vulnerability index.

D : Depth to the water table, weight 5
R : Recharge, weight 4
A : Aquifer media, weight 3
S : Soil media, weight 2
T : Topography (slope), weight 1
I : Impact to vadose zone, weight 5
C: Hydraulic Conductivity, weight 3

Determination of the DRASTIC index number is done by multiplying each parameter classes by its weight and adding together. Each parameter is rated on a scale from 1 to 10, a rating of 10 indicating a high pollution potential of the parameter. The DRASTIC Index is then computed by applying a linear combination of all factors according to the following equation:

$$\textbf{DRASTIC Index} = \mathbf{D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w} \qquad \text{(Eq. 1)}$$

Where D, R, A, S, T, I, and C were the seven parameters and the subscripts **r** and **w** were corresponding to classes and weights, respectively.

The depth to water table was divided into seven classes, i.e. 0-1.5, 1.3-3, 3-9, 9-15, 15-22, 22-30, and above 30 m depth below the surface. Groundwater recharge zone depicted the amount of water entering the aquifer and then becomes saturated with water. The value can be calculated by the empirical equation which is including the evapotranspiration value, runoff and precipitation. Class of recharge was divided into two, i.e. 103-178 mm/yr and 179-254 mm/yr. The aquifer media was divided into two which were igneous weathered and sand and gravel. While the soil media was grouped into non-shrinking and loam. Topography indicated the slope of the area. Higher slopes can reduce the potential for pollution of the area. The slope was divided into five classes, i.e. 0-2%, 2-6%, 6-12%, 12-18%, and above 18%. The vadose zone referred to as the zone of unsaturated water above the groundwater level. The research area was divided into two groups, namely the sand-gravel zone and the sand and gravel zone with sufficient clay and silt. Based on [12] that the higher the value of hydraulic conductivity the greater the potential for contaminated water. Different types of rocks with different compaction levels will produce different conductivity values. In the study area, these parameters were divided into two, namely less than 0.86 m/day and 0.86-2.59 m/day.

3. Results and Discussion

3.1 Hydrogeological field campaign

The hydrogeologic data as shown in Table 1 indicate that the groundwater depth has a range from 0.1 to 34 m depth below ground surface (mgs). The shallowest is found in Mangkang Wetan, Tugu Subdistrict (SG-1), while in Kembangarum, Semarang Barat subdistrict, has the deepest groundwater depth (SG-13). Based on the physical measurements of groundwater samples, the high value of TDS shows identical to the high value of EC. The highest EC is profound in Triwulyo (SG-25), Genuk Subdistrict, which is 8,200 μS/cm. The taste is salty and unsuitable for groundwater drinking. The geologic unit of the aquifer in this sample is Alluvium. Moreover, the lowest of EC value is located in Beringin, (SG-6), Ngalian Subdistrict, which the value is 348 μS/cm. The aquifer in Ngalian Subdistrict consists of Damar Formation. Meanwhile, the pH of all samples indicates the standard value which has a range from 6.64 to 8.07.

Table 1. Hydrogeological mapping data and its physical measurements of groundwater samples

No	Location	Sampel Code	Coordinate		Well Depth (m)	Water table (masl)	Groundwater Depth (mgs)	Elevation (masl)	Geologic unit	Physical Measurement		
			X	Y						TDS (mg/L)	pH	EC (µS/cm)
1	Ngebro, Mangkang Wetan, Tugu	SG-1	424618	9231297	15	10.9	0.1	11	Alluvium	978	7.25	1,462
2	Mangun Harjo, Tugu	SG-2	423118	9229335	9	7.1	2.94	10	Alluvium	700	6.93	1,046
3	Randu Garut, Tugu	SG-3	424838	9229281	6	11.6	0.4	12	Alluvium	2,000	7.24	3,000
4	Tapak, Tugu	SG-4	427684	9229475	3	14.8	0.2	15	Alluvium	1,340	7.04	2,010
5	Karang Sari, Ngaliyan	SG-5	425607	9228579	15	30.6	3.4	34	Damar	420	6.72	627
6	Beringin, Gondoriyo	SG-6	425685	9226859	35	47.8	30	77.8	Damar	223	6.70	348
7	Arum manis, Ngaliyan	SG-7	428692	9227928	10	18.9	1.15	20	Alluvium	520	6.64	777
8	Krapyak, Semarang Barat	SG-8	430156	9227699	20	11.4	4.6	16	Alluvium	520	7.21	779
9	Kembang Arum, Semarang Barat	SG-9	430713	9226199	10	36.2	1.8	38	Damar	428	6.70	640
10	Salaman Mloyo, Semarang Barat	SG-10	433292	9227606	16	14.9	3.12	18	Alluvium	564	7.04	842
11	Gang Pringgodani II, RT 3, RW 12	SG-11	433349	9229056	7	1.7	5.3	7	Alluvium	560	7.55	838
12	Simongan, Semarang Barat	SG-12	433668	9226375	12.83	19.3	2.71	22	Alluvium	444	7.18	660
13	Kembangarum	SG-13	430871	9226243	35	16.9	34	50.9	Damar	387	6.63	605
14	Sadeweo , Semarang Tengah	SG-14	434568	9228631	6	12.5	0.47	13	Alluvium	284	7.56	423
15	Karang kidul, Semarang Tengah	SG-15	437039	9227641	8	7.0	0.98	8	Alluvium	460	7.00	690
16	Cimanuk raya, Semarang Timur	SG-16	438310	9230343	4	14.6	0.4	15	Alluvium	1,040	7.50	1,555
17	Musi Raya Bugangan, Semarang Timur	SG-17	437834	9229105	4.2	12.5	0.5	13	Alluvium	900	7.35	1,347
18	Beruang raya 9 RT 06/02	SG-18	439501	9226410	12	3.5	1.5	5	Alluvium	648	7.27	970
19	Gayamsari	SG-19	439164	9226849	4.45	4.5	0.5	5	Alluvium	608	7.20	909
20	Karanganyar	SG-20	439770	9229704	3.4	15.8	0.2	16	Alluvium	524	7.32	785
21	Bintoro, Gayamsari	SG-21	438412	9227224	12	8.1	0.92	9	Alluvium	776	7.16	1,162
22	Palebon, Pedurungan	SG-22	440963	9225772	5.4	8.7	0.32	9	Alluvium	716	7.17	1,073
23	Tlogosari Wetan, Pedurungan	SG-23	441752	9227959	4.8	6.5	0.5	7	Alluvium	572	7.09	856
24	Widuri Raya, Genuk	SG-24	441498	9229755	4.4	14.5	0.55	15	Alluvium	1,548	7.94	2,320
25	Trimulyo, Genuk	SG-25	442661	9231953	5.3	3.5	1.5	5	Alluvium	5,468	7.35	8,200
26	Banjardowo, Genuk	SG-26	442569	9230491	5	15.5	0.5	16	Alluvium	628	7.64	942
27	Banjardowo, Genuk	SG-27	443602	9230121	4.8	12.2	1.77	14	Alluvium	1,788	7.16	2,680
28	Banget Ayu Wetan	SG-28	442535	9228163	5.7	11.9	0.12	12	Alluvium	680	7.16	1,016
29	Tlogo Mulyo, Pedurungan	SG-29	442509	9227313	6.3	2.5	1.51	4	Alluvium	720	7.25	1,080
30	Kudu, Genuk	SG-30	445092	9228787	8.5	13.9	1.06	15	Alluvium	668	7.23	998

3.2. Groundwater vulnerability using DRASTIC method

The seven parameters of groundwater vulnerability to the contamination that have been analyzed are then overlaid to produce a map called the DRASTIC map.

3.2.1. Depth to groundwater. Based on the hydrogeological field camping, there are seven classes on the depth of water table as shown in Figure 2a. The lowest depth is 0.1 m below surface and indicates the highest groundwater vulnerability. Based on Figure 2a the highest vulnerability is located in the north, the east, and some part in the west. It has a range 0-1.5 m depth with the class value is 10. While the deepest of water table is 34 m depth and located in the southern part of the study area (Semarang Barat subdistrict) with the range above 30 m depth and the class value is 1.

3.2.2. Groundwater recharge. Groundwater recharge can affect the flow path of contaminants vertically and spread horizontally to the unconfined aquifer. Recharge rate is affected by precipitation, runoff, and evapotranspiration. Based on the water balance analysis related to the three parameters above, groundwater recharge in the study area can be grouped into two, i.e. 103-178 mm/yr and 179-254 mm/yr which are classified into class 6 and 8 respectively as depicted in Figure 2b. The highest class indicates the fastest of contaminants to reach the saturated zone.

3.2.3. Aquifer media. The aquifer media map (Figure 2c) was constructed using 25 georesistivity measurements in the study area. Generally, the aquifer can be grouped into 2, i.e. igneous weathered and sand and gravel. Sand and gravel indicate easier of contaminant flowing into the aquifer than igneous weathered thus, the class value is 8. Igneous weathered has the class of 4.

3.2.4. Soil media. Soil media properties influence the amount of infiltration from the ground surface. The study area can be divided into two, i.e. loam and non-shrinking as shown in Figure 2d. Loam spread in the north, the centre, the east and the west with the class value is 5. While soil media with non-shrinking is located in the south. The class value is 1 and indicates less permeable of contaminant transport into the aquifer.

3.2.5. Topography. Topography/Slope also determines infiltration at the ground surface. The slope can be derived from Digital Elevation Model data. The gentle slope (0-2%) indicates less runoff and more retention of water resulting in more infiltration, and thus higher potential of contamination which is located in the north, in the centre, in the east and some areas in the west. The gentle slope has the highest vulnerable with the value of 10. In the study area, the slope can be grouped into 5 classes as shown in Figure 2e.

3.2.6. Impact to vadose zone. The impact of the vadose zone on groundwater contamination relies on permeability and attenuation characteristics of the sediments. The vadose zone can be grouped into two classes: sand and gravel with sufficient silt and clay, and sand and gravel. The latest has a lower class, 4, while sand and gravel with sufficient silt and clay have class 4 as depicted in Figure 2f.

3.2.7. Hydraulic conductivity. Hydraulic conductivity of an aquifer indicates the ability of aquifer media (soil and rock) to transmit water through pore spaces or fractures and plays a fundamental role in pollutant migration velocity and dispersion. The value of hydraulic conductivity can be group into two, as shown in Figure 2g.

3.2.8. Groundwater vulnerability assessment using DRASTIC Method. The DRASTIC Index (DI) is calculated by considering seven parameters with their classes and weights using Eq. (1). The range of total DI is 61-180. The DRASTIC index is classified into 3 classes: low, medium, and high as shown in Figure 3. The low vulnerability has 61-100 DI. It spreads locally in the south of West Semarang Subdistrict and South Semarang Subdistrict. Low level means only vulnerable to conservative pollutants in the long-term when continuously and widely discharge or leached. The medium level has the DI 101-140 and dominated in the Ngaliyan area, Gajahmungkur, Semarang Selatan, also found in Tugu, Semarang Barat, Candisari, and some areas in the Semarang Tengah. Medium level indicates vulnerable to some pollutants but only when continuously discharge or leached. Meanwhile, the high level has a DI range from 141 to 180 and spreads in the plains areas such as in the northern and eastern part of the research area. These areas include Tugu, Semarang Barat, Semarang Utara, Semarang Tengah, Semarang Timur, Gayamsari, Genuk, Pedurungan, some areas in Ngaliyan, and Semarang Selatan. High level means vulnerably to many pollutants, excepts those strongly absorbed or readily transformed in many pollutant scenarios. In general, areas with flat to gently slope have a higher vulnerability to pollution compared to high topography, so this study is expected to be a consideration for groundwater management in the local government (Semarang City).

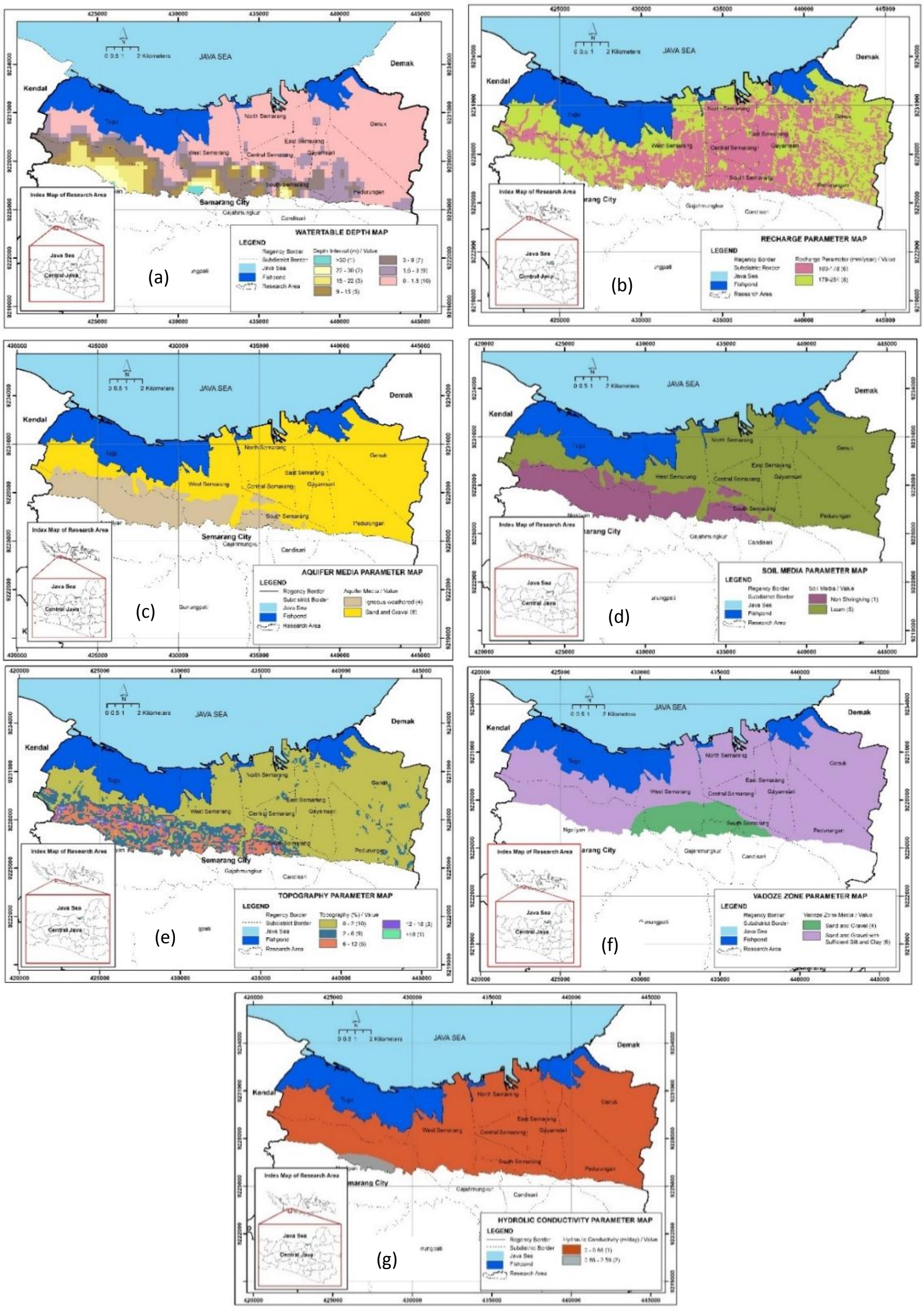

Figure 2. DRASTIC parameters. (a) **D**epth to water table; (b) **R**echarge rate; (c) **A**quifer media; (d) **S**oil media; (e) **T**opography; (f) **I**mpact to vadose zone; (g) Hydraulic **C**onductivity.

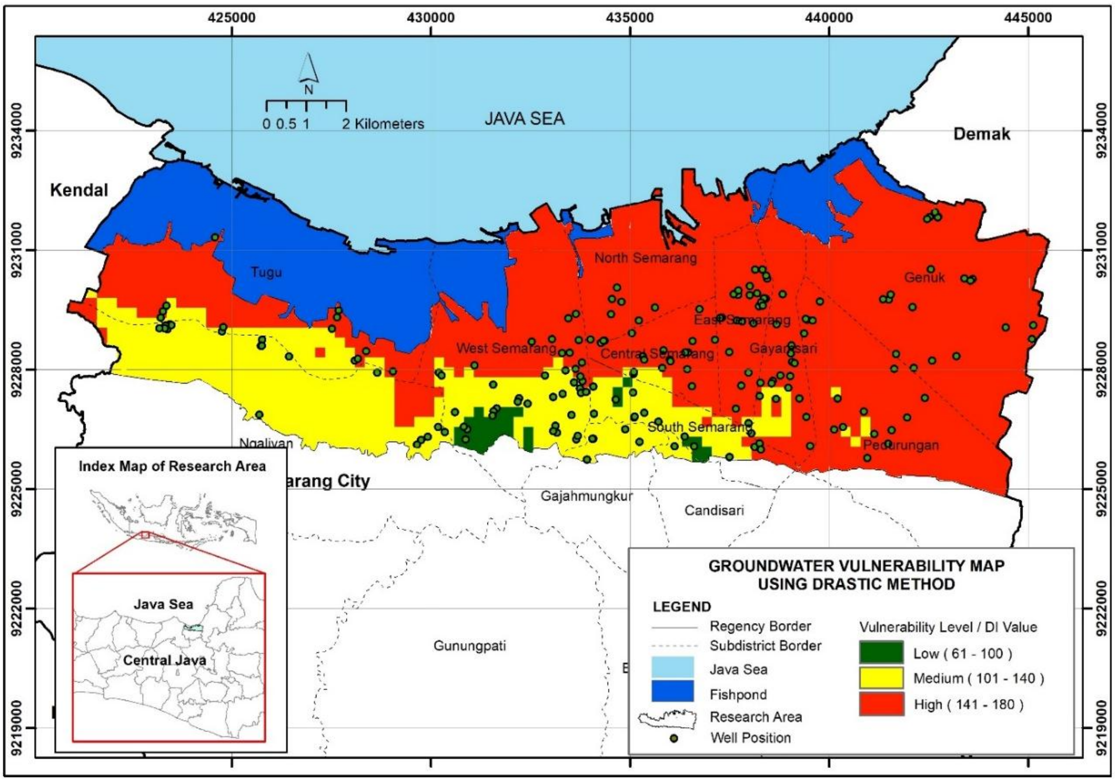

Figure 3. Groundwater vulnerability map using DRASTIC method.

4. Conclusions

The increasing threat to groundwater quality degradation, it is necessary to continue studies related to the groundwater vulnerability zones to contamination as well as measuring performance management of groundwater used. Groundwater vulnerability assessment has become an integrated hydrogeological measure for sustainable management of groundwater resources. The results of groundwater vulnerability zones and measuring performance management of groundwater used will be applied to mitigate hazard of groundwater problems Semarang lowland areas have three levels of groundwater vulnerability, namely low, medium, and high. Efficient management strategies for the protection of groundwater quality should be established by carrying out vulnerability and integrated risk assessments.

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