Risk Assessment of Groundwater Abstraction Vulnerability Using Spatial Analysis: Case Study at Salatiga Groundwater Basin, Indonesia

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Abstract - Salatiga Groundwater Basin (SGB) is located in Java Island, Indonesia. Administratively, it covers Semarang Regency, Salatiga City, and Boyolali Regency. Industry and community use groundwater to fulfil their daily need. Increasing number of deep wells that extract groundwater will cause some environmental problems, such as lowering groundwater level and subsidence at SGB. Thus, there is a need to assess the adverse impacts of groundwater abstraction. Risk assessment of groundwater vulnerability due to abstraction is the goal of this study. The research method was taking account of weighting of geological parameters, such as response characteristics of the aquifers, characteristics of aquifer storage, aquifer thickness, piezometric depth, and distance from the shoreline to conduct the groundwater vulnerability mapping. It was then overlaid on a map of regional spatial plan to develop the map of vulnerability risk due to abstraction. The groundwater vulnerability due to abstraction is categorized in the medium level. After being overlaid by the land use map, the risk of groundwater vulnerability due to abstraction is classified into three kinds, which are low, medium, and high. Regions with a low class can be neglected. Areas with moderate risk require an exhaustive review of technical requirements of the use of borewell. Areas with high-risk need a comprehensive consideration to use artesian wells by monitoring wells with drill licenses, tightening the permit to add new production wells, and conducting periodic review of groundwater monitoring.

Keywords: risk assessment, groundwater, vulnerability, abstraction, aquifer, Salatiga Groundwater Basin

Introduction

The term of groundwater vulnerability was introduced by a French hydrogeologist, Margat, in 1968, and the first vulnerability map was constructed in France by Albined in 1970. Since the early 1980s, more complex methods of groundwater vulnerability assessment have been developed, and a considerable number of vulnerability maps of various scales and objectives have been produced throughout the world (Witkowski *et al*., 2007). The risk assessment of groundwater vulnerability due to abstraction is developed by aggregating some major vulnerability parameters to one vulnerability index, involving various steps of selection, transforming some parameters into raster data, rating, and weighting. In this research, groundwater vulnerability is mainly formulated as an intrinsic property of the aquifer system that relies on the sensitivity of the system to human and/or natural impact.

Salatiga groundwater basin/SGB is located in Java Island, Indonesia. It covers Semarang Regency, Salatiga City, and Boyolali Regency (Figure 1) with a total number of industry, both small and big,was around 2.981 in 2011 and increased up to 3.030 in 2013. In this basin, there were 249.081 inhabitants in 2011, and became 253.297 people in 2013 (Badan Pusat Statistik Kabupaten Boyolali, 2004; Badan Pusat Statistik Kabupaten Semarang, 2004; Badan Pusat Statistik Kota Salatiga, 2014).

Both industry and community use groundwater to fulfil their daily need. They withdraw groundwater through deep wells in confined aquifers. The number of deep wells that extract groundwater will cause some environmental problems, such as lowering groundwater level, subsidence, and seawater intrusion if the groundwater extraction is over its potency. Thus, there is a need to assess the adverse impacts of groundwater extraction at SGB.

Based on the regional geological map of Magelang-Semarang and Salatiga (Sukardi and Budhitrisna, 1992; Thanden *et al*., 1996) SGB, from old to young, consists of some formationsas shown in Figure 2. Payung Formation (Qp) consists of lahar, claystone, breccia, and tuff. They locally spread in the south-west of SGB. Payung Formation is of Pleistocene age.

Merbabu Volcanic Rock Formation (Qme) contains volcanic breccia, lava, tuff, and laharic breccia. They entirely spread at the SGB area. Merbabu volcanic rocks are of Holocene age. Sumbing Lava Formation (Qls) consists of lava flow, and the dome consists ofaugite-hornblende andesite. They spread at the south-west of SGB, *i.e.* belowMount Merbabu. This formation is of the Holocene age. Basalt (Qba) is composed of volcanic rocks which are grey, dense, scoriaceous, and porphyritic. The alluvium (Qa) is formed by river and lake deposits which consist of pebble, cobble, sand, and silt with the thickness ranging of 1 - 3 m.

Based on the results of the study of groundwater potency by Dinas Pertambangan dan Energi Provinsi Jawa Tengah (2005) as shown in Figure 3, SGB has moderately and low groundwater potency in both unconfined and confined aquifers, respectively. The aquifers consist of young volcanic products of Mount Merbabu, and groundwater flows through fissures and interstices. The medium potency has groundwater discharge from
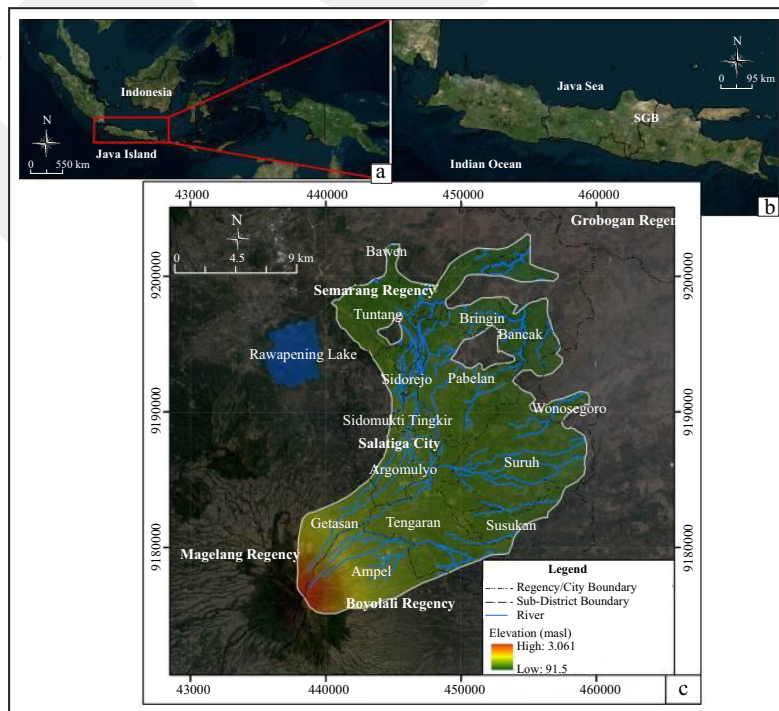

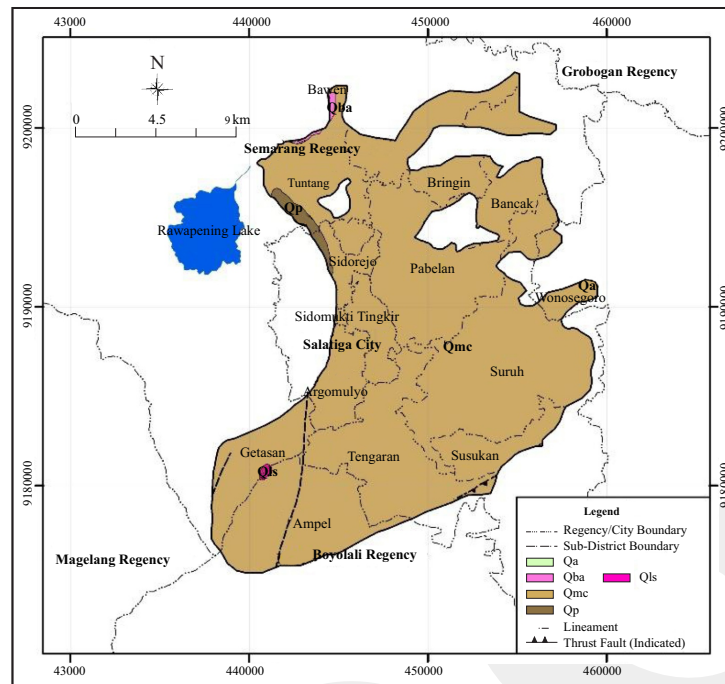Figure 1. Locality map of studied area of SGB.

Figure 2. Regional geological map of Salatiga Groundwater Basin.
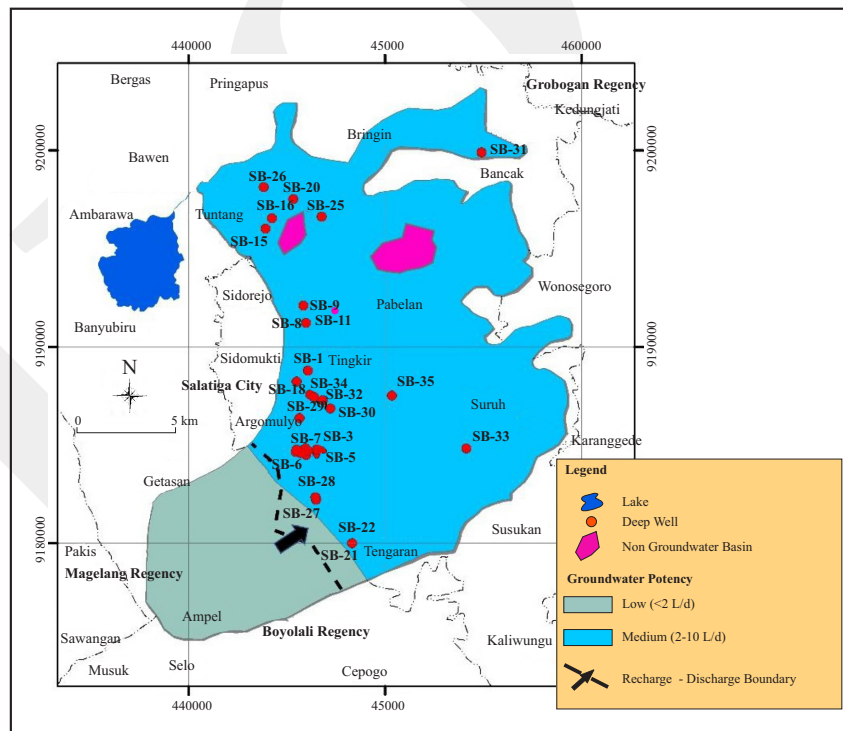

Figure 3. Locality map of deep wells at the SGB.

2 to 10 l/sec, located in the centre to the north of SGB. While the low potency is distributed in the south of SGB. These areas have groundwater discharge of up to 2 l/sec.

Materials and Method

There were thirty-five deep wells located at SGB (Figure 3). Table 1 provides the total

depth of wells, the aquifer thickness, and the piezometric levels measuredon May 2015.

Four wells did not identify piezometric level due to the maintenance of the piezometer on the wells. To assess the groundwater vulnerability, aprevious study applied spatial analysis to construct some thematic maps using Geographic Information System/GIS (Ghayoumian*et al.*, 2006; Baker *et al.*, 2007; Jha*et al.*, 2007; Al-Quadah and Abu-Jaber, 2009; Chowdary *et al.* 2009; Chenini*et al.*, 2010). The groundwater vulnerability to abstraction in the groundwater basin involves the class and score of relevant overlying parameters (Putra and Indrawan, 2014) in raster GIS format (Table 2).

The highest score represents the highest vulnerability of the parameters due to abstraction.All parameters were transformed into raster images,then calculated by using araster calculator in the spatial analysis tool in ArcGIS. The sum of the total score parameters was 5 to 25. Thus, the intrinsic groundwater

vulnerability due to abstraction can be classified (Table 3).

Figure 4 shows the cross-section of the subsurface setting based on the borehole and georesistivity measurement.

There were two cross-sections, *i.e.* the cross-section in A - A' from the south to the north and B - B' depicted from the west to the east. The lithology consists of topsoil, clay, and tuff, in some parts it comprises andesite, breccia, sandstone, and claystone.

To assess the risk of groundwater vulnerability due to abstraction, the result of an intrinsic groundwater vulnerability map was overlaid on the land use map (Figure 5). The land use map in the studied area is classed based on its risk to groundwater abstraction (Table 4).

The highest score of land use represents the highest groundwater used. The result of the risk of groundwater abstraction was classified in Table 5 (Putra and Indrawan, 2014).

Table 1. Deep Wells in the SGB

Well Code	Elevation (masl)	Total depth (m)	Piezometric Level (masl)	Aquifer thickness (m)
SB-1	620	135	28	20
SB-2	733	90	20	10
SB-3	719	90	20	10
SB-4	734	90	20	10
SB-5	728	90	20	10
SB-6	746	90	20	10
SB-7	735	90	20	10
SB-8	540	100	12	20
SB-9	551	100	12	20
SB-10	551	100	12	20
SB-11	551	100	12	20
SB-12	740	90	23	10
SB-13	745	90	23	10
SB-14	644	90	25	20
SB-15	412	81	34	10
SB-16	458	81	34	20
SB-17	509	15	10	5
SB-18	652	90	25	20
SB-19	651	100	25	10
SB-20	386	75	18	20
SB-21	717	90	13	20
SB-22	717	120	18	20
SB-23	722	70	12	10
SB-24	720	115	10	10
SB-25	400	100	15	20
SB-26	433	100	17	20
SB-27	765	100	10	10
SB-28	762	100	10	10
SB-29	692	96	12	5
SB-30	689	120	42	7
SB-31	143	56	ni	5
SB-32	676	80	39	20
SB-33	534	70	ni	5
SB-34	651	110	ni	14
SB-35	667	90	ni	13

Note: ni (not identified)

Table 2. Parameters of Groundwater Vulnerability due to Abstraction

Parameter	Symbol	Unit	Class	Score
Characteristic of respond aquifer	T/S	m^2/day	<10	1
			10 - 100	2
			100 - 1.000	3
			1.000 - 100.000	4
			>100.000	5
Characteristic of aquifer storage	S/R	yr/mm	<0.0001	1
			0.0001 - 0.001	2
			0.001 - 0.01	3
			0.01 - 0.1	4
			>0.1	5
Aquifer thickness	s	m	>100	1
			50 - 100	2
			20 - 50	3
			10 - 20	4
			<10	5
Piezometric depth	H	m	>50	1
			20 - 50	2
			10 - 20	3
			5 - 10	4
			0 - 5	5
Coastline distance	L	km	>100	1
			10 - 100	2
			1 - 10	3
			0.1 - 1	4
			<0.1	5

Note: T: Transmissivity; S: Storativity; R: *Recharge*; H: piezometric depth; L: Coastline distance

Table 3.Class of GroundwaterVulnerabilityDue to Abstraction

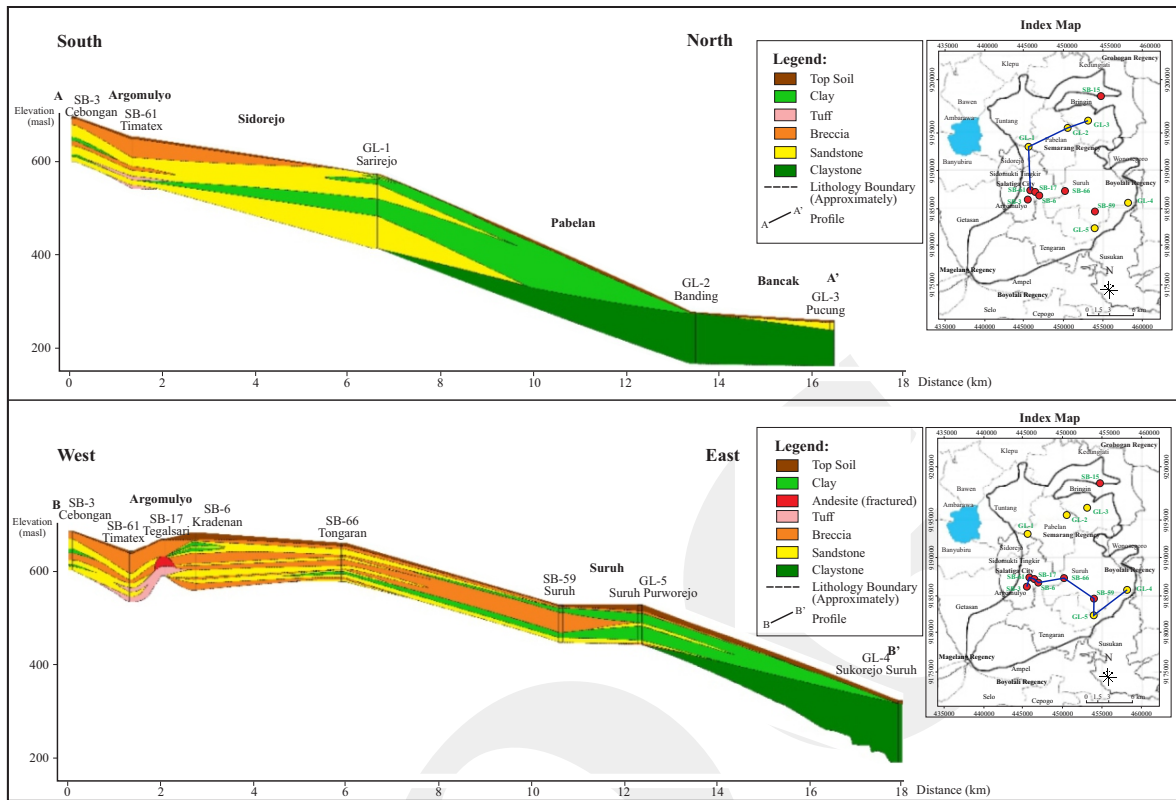| Class of vulnerability	Total score
Extremely high	20 - 25
High	15 - 20
Moderate	10 - 15
Low	5 - 10

Figure 4. Geological cross-section based on borehole and geoelectricity measurement.

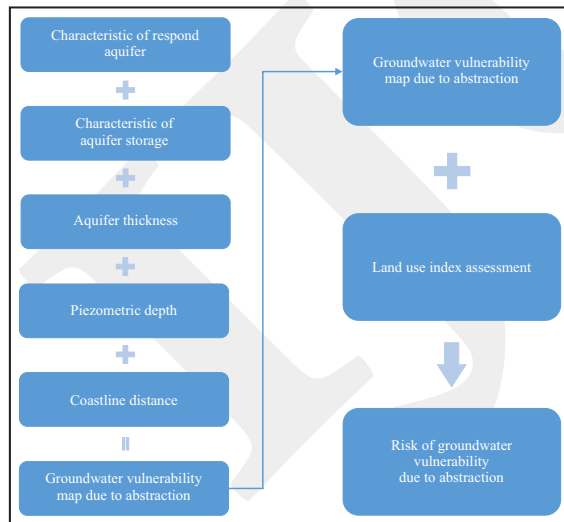Figure 5. Spatial analysis processes to define the risk of groundwater vulnerability to abstraction.

Table 4. Land Use Index

Land use	Score
Protected forest areas, catchment areas, Merbabu national park	1
Production forest areas, limited production forest areas	2
Wet land, dry land	3
Settlement, industrial zone	4

RESULTS AND DISCUSSION

Groundwater Vulnerability to Abstraction

The parameter of respond aquifer represents two groups related to the transmissivity and its storativity values (Figure 6). The thickness of the confined aquifer is 2 - 32.3 m with the hydraulic conductivity of 6.2 - 100.1 m²/day. The value of

Table 5. Classification of the Risk of Groundwater Vulnerability Due to Abstraction

Relative groundwater exploitation yield (RGOV)	Negative impact of groundwater abstraction Risk group = RGOV + AQS			
Extremely High/EH (4)	M (5)	H (6)	H (7)	EH (8)
High/H (3)	M (4)	M (5)	H (6)	H (7)
Moderate/M (2)	L (3)	M (4)	M (5)	H (6)
Low/L (1)	L (2)	L (3)	M (4)	M (5)
	Low/L (1)	Moderate/M (2)	High/H (3)	Extremely High/EH (4)
	Aquifer Susceptibility Class (AQS)			

storativity (27%) is derived from the value of specific yield of unconfined aquifer composition (medium sandstone) due to vertical compression of associated aquitard which is not considered in this study. Thus, the scores of this parameter are on 2 and 3 with the class values of 10 - 100 m²/day and 100.1 - 1.000 m²/day. Based on the meteoric water balance calculation, the recharge of SGB is 1.777 mm/yr, and the storativity is up to 27%. Thus, the characteristic of aquifer storage is around 1.5 x 10 - 4mm/yr (Figure 7). This value is on the score of 2 of the class which is 0.0001 - 0.001.

Figure 8 shows that the thickness of the confined aquifers is 2 - 32.3 m. Thus, this parameter is

divided into three groups. The score of this parameter is from 3 to 5 based on its class values.

Several deep well data describe that the piezometric levels at SGB are 10.1 - 41.1 m depth. Thus, this parameter can be classed into two groups based on the piezometric depth level (Figure 9). The scores of this parameter are 2 and 3 based on their classes to the piezometric level.

Meanwhile, the SGB is located on 30 - 50 km away from the Java Sea representing the parameter of coastline distance as shown in Figure 10. Thus, the score of this parameter is 2 with the class value is 10 - 100 km away from the coastline (Figure 10).
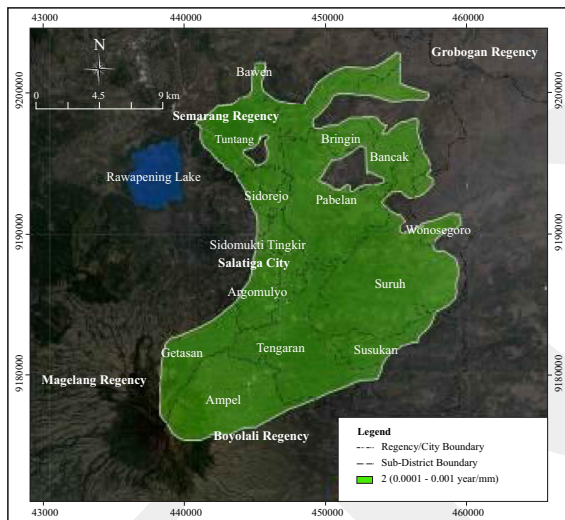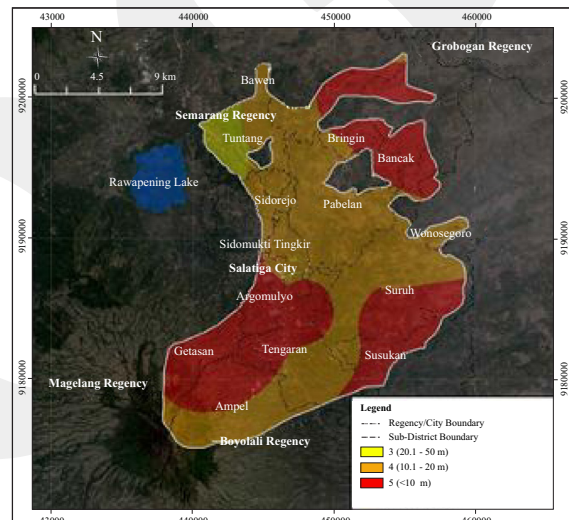

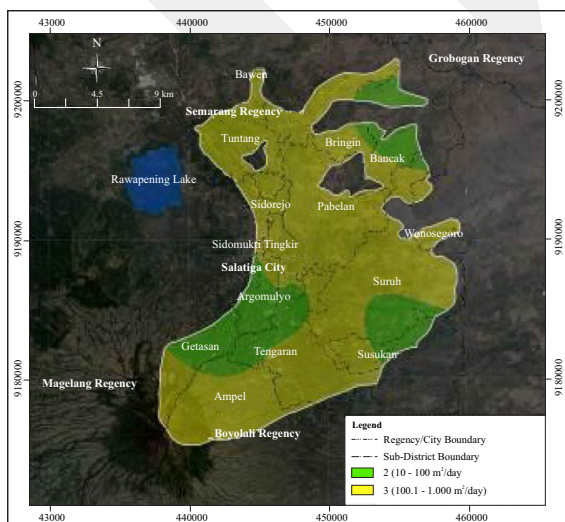Figure 6. Respond aquifer.

Figure 8. Aquifer thickness.

Figure 7. Aquifer storage.
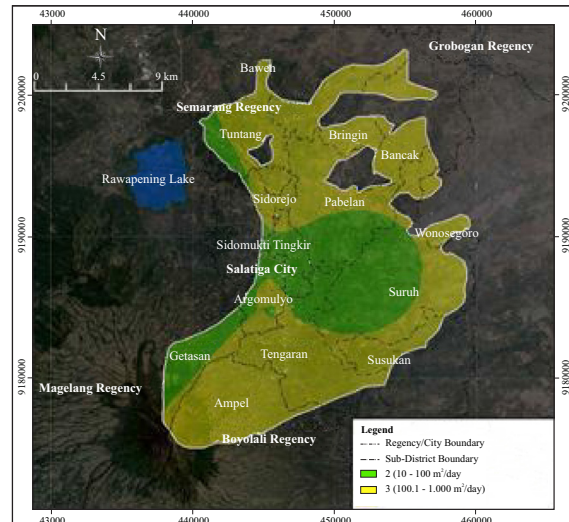
Figure 9. Piezometric depths.

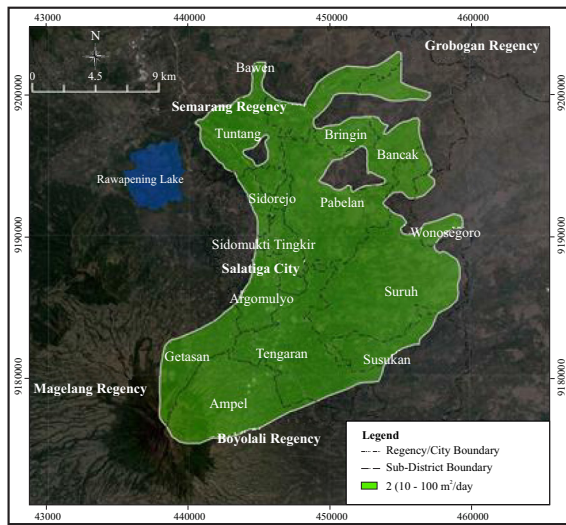Figure 10. Coastline distance.

The results of overlying five parameters of intrinsic groundwater show the total scores of 12 - 15. Thus, the vulnerability due to abstraction depicted at SGB is moderately vulnerable in all regions (Figure 11). This moderate vulnerability class reflects that the impact of groundwater abstraction at SGB would appear when the groundwater exploitation exceeds its potency.

Risk of Groundwater Vulnerability to Abstraction

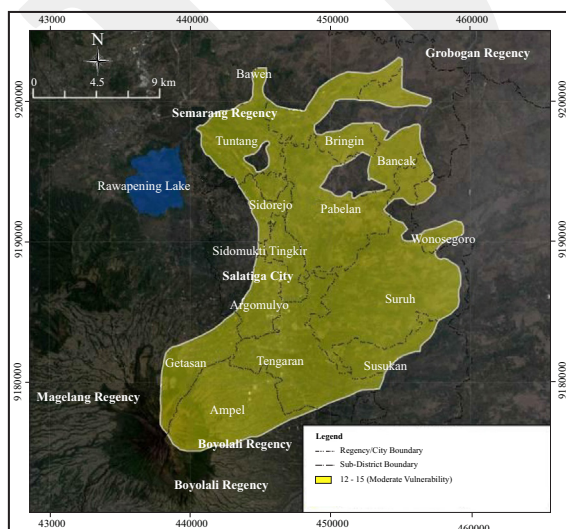The groundwater vulnerability map due to abstraction as shown in Figure 11 represents

the intrinsic parameter of groundwater vulnerability. Thus, it is necessary to overlay the land use map (BAPPEDA Kabupaten Boyolali, 2010; BAPPEDA Kota Salatiga, 2010) to conduct a risk mapping showing an adverse effect of groundwater abstraction at SGB.

The land use of SGB (Figure 12) area is classified into four groups based on Table 4. Protected forest, catchment area, and Merbabu National Park representing the lowest level, have score 1 of groundwater used. While the highest level, score 4 of groundwater used, occurs in settlement and industrial zones. Production forest, wetlands, and drylands represent the moderate level, scores 2 and 3 of groundwater used.

For the assessment risk of groundwater vulnerability due to abstraction, the map of groundwater vulnerability is converted as relative groundwater exploitation yield (RGOV) as shown in Table 5.

The vulnerability map is in moderate class having a score of 2. While the scores of land use map represent aquifer susceptibility class (AQS). Finally, the total score of the risk of groundwater vulnerability due to abstraction is represented by summing up RGOV and AQS scores, respectively.

Figure 13 depicts the risk of groundwater vulnerability to abstraction which is divided into three zones which are low (score 3), moderate (score 4 - 5), and high (score 6).
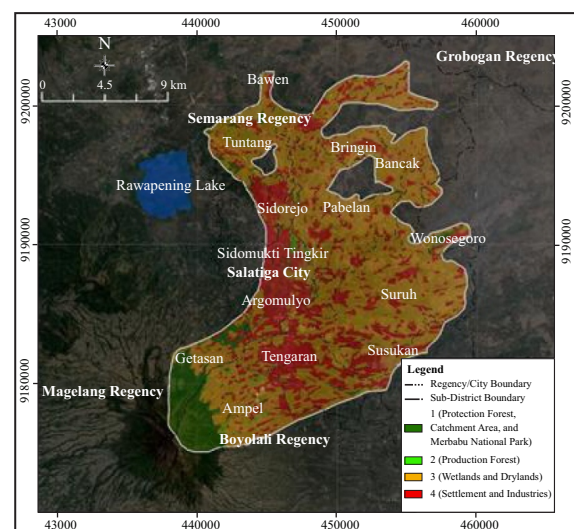

Figure 11. Map of groundwater vulnerability to abstraction at SGB.

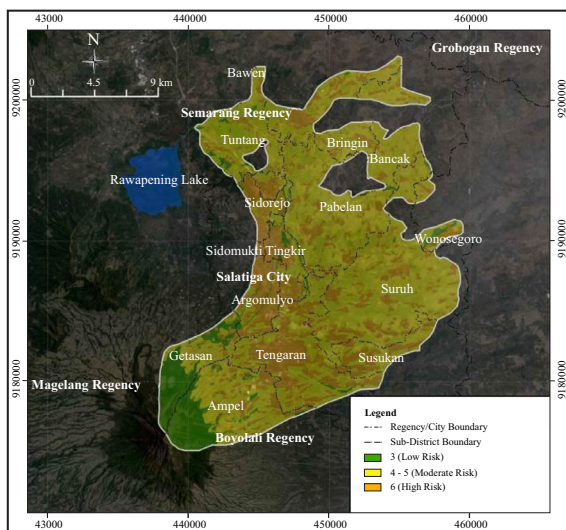Figure 12. Land use map of SGB area.

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Figure 13. Map of groundwater vulnerability risk to abstraction at SGB.

The moderate-risk zones are dominantly situated at the SGB area, while the high-risk zones are located in the settlement and industrial zones in Salatiga City, in the centre of SGB. Another zone that is the low-risk zone is situated in the southwest of SGB, especially in the protected forest, catchment area, and Merbabu National Park. The highest risk zones represent the immediate impact to become a part due to extensive use of groundwater through deep wells.

In the high-risk zone, it is mandatory to have a continuous evaluation and data record related to groundwater abstraction through deep wells. Moreover, there should be a strict control on new permits as well as on the existing deep wells. Regular monitoring of groundwater quality and measuring of groundwater level are essential to manage the groundwater use. The local government is also recommended to develop monitoring wells in the industrial zones and at industrial companies which have three to five wells in one production area (GW- MATE, 2005).

Groundwater use in the moderate risk areas is still feasible for abstraction through deep wells, but in the implementation, monitoring should be done regularly related to the groundwater discharge as well as groundwater level. The limit of discharge of deep wells must be in the range of 2 - 10 L/sec with the deep well distance of

100 - 1.000 m following the groundwater potency study (Dinas Pertambangan dan Energi Provinsi Jawa Tengah, 2005).

In the low-risk areas, the negative impact of groundwater used can be neglected, because these regions are recharge zones of groundwater as shown in Figure 3. These areas are mainly protected areas to preserve groundwater storage and its sustainability. Therefore, no deep wells are available in these areas. Springs are primarily fulfiling the water need in this region.

Groundwater is a crucial and valuable resource for human activities which represents the most fundamental source of fresh potable water (Howard, 2007). The presence and demand for groundwater that has a fundamental impact on society and environment are consequently of critical concern (Putranto *et al*., 2016). The pressures are on population concentration, industrial zone, water efficiency, and environmental necessity (Arnell, 1999). The risk assessment of groundwater vulnerability due to abstraction is a valuable approach for sustainable urban groundwater management to fulfil fundamental needs for the inhabitants (Pardo, 2009).

Conclusions

A spatial analysis is the most fascinating and astonishing aspect of Geographic Information System. Using a spatial analysis, information from many geological and hydrogeological parameters can be combined, and new sets of results can be derived by applying a sophisticated set of spatial calculation. Moreover, new modified data sets can be useful to obtain new results related to the evaluation of current environmental setting.

In this research, intrinsic groundwater vulnerability at SGB has the moderate class which means that the impacts of groundwater used has a minor or less impact on the aquifer properties.

The evaluation of an intrinsic vulnerability map which is overlaid by a land use map conducts the risk of groundwater vulnerability map due to abstraction that can be classified

into three risk classes which are low, moderate, and high. The low and moderate risk areas need to be conserved and monitored related to the groundwater abstraction through deep wells to preserve groundwater storage and its water level. While the high-risk zone requires technical assessment of groundwater abstraction through deep wells as well as regular monitoring of groundwater level and groundwater quality. A strict regulation related to the new permit of groundwater abstraction through deep wells needs to be implemented. Moreover, an evaluation of discharge to the existing deep wells is the way to achieve groundwater sustainability and to mitigate degradation groundwater, both in quality and quantity.

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