

# ASSESSMENT OF AQUIFER SUSCEPTIBILITY DUE TO EXCESSIVE GROUNDWATER ABSTRACTION; A CASE STUDY OF YOGYAKARTA-SLEMAN GROUNDWATER BASIN

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## Abstract

Yogyakarta-Sleman groundwater basin is one of productive groundwater basins in Indonesia. The groundwater basin is built by unconfined sand-aquifer system. Since the early 1980's many schools, universities and hotels have been developed in this area to support education and tourism activities, and since the beginning of 2000's the number of buildings has increased significantly. The development has resulted in a rapid rate of land use and population changes with the consequence of increasing groundwater pumping. Measurement results show that the rate of groundwater table degradation exceeds 0.5 m/year at some districts underlain by the groundwater basin. Because of this condition, it is necessary to assess the susceptibility of the aquifer to negative impacts due to the excessive groundwater pumping. The assessment was conducted by overlying factors such as aquifer response characteristics, aquifer storage characteristics, thickness of the aquifer, depth to groundwater table and distance from the sea. The assessment results show that the excessive groundwater abstraction to the aquifer has caused moderate to high susceptibility. It means that the groundwater pumping activities on this groundwater basin should be managed and controlled.

**Keywords:** Aquifer susceptibility, Groundwater exploitation, Negative impacts of overexploitation, Yogyakarta-Sleman groundwater basin

## Introduction

Yogyakarta-Sleman basin is located in the central-part of Java Island, and known as one of productive groundwater basins in Indonesia (Figure 1). In the last two decades, urbanization has transformed the area underlain by the groundwater basin. In 1930s, the population of this area was approximately only 60.000 [3], while nowadays it reaches almost 2,500,000. Since 1980s, the settlement pattern has shifted to many directions, defined by main road networks and service centres. New business, education, and tourism centres have grown with new settlements, made changes in the structure of the space organization, and increased pressure on water resources [11]. About less than 5% of the population in the Yogyakarta-Sleman groundwater basin is served by sewers system and less than 30% of urban population has access to clean water which is supplied by the local public water-work. Most of the population and activities depend on groundwater. As a result, the groundwater pumping increases, and impact of the groundwater exploitation is the groundwater table degradation which exceeds 0.3 m/year at some districts [10]). The groundwater abstraction on the groundwater basin is predicted to be up to 150 million m<sup>3</sup>/year in 2015 and 300 million m<sup>3</sup>/year in 2025 following the increase in number of population and economic development (tourism, commercial, industries, etc) [10]. Due to the increase in groundwater abstraction, the groundwater level in the study area is expected to continue to decline toward an

“unacceptable” situation indicated by severe negative environmental impacts, such as reduction of river flows and missing of spring flows.

The concept of aquifer susceptibility from the negative impacts of excessive groundwater abstraction were introduced by Foster [6] and also proposed by Adams & MacDonald [1]. The concept of susceptibility from negative impact of groundwater over exploitation is developed in the same manner, and be as useful as that of vulnerability to pollution. The term of susceptibility is used to avoid confusion with the term vulnerability which is generally related to the susceptibility of aquifer from contamination [1]. If the potential impacts of excessive exploitation can be identified before they occur, or at least before they become significant, management measures can be taken to avoid or mitigate undesirable effects [1].

This paper presents an assessment of aquifer susceptibility due to groundwater overexploitation in Yogyakarta-Sleman. The method is essentially a modified method initially proposed by Foster [6] with some modifications. The assessment will be useful to define the management strategies on this groundwater basin [1], mainly by provides a tool to planners responsible for regional development to enable them to assess the long term inter-relationship between development (spatial land use planning) and their effects to the regional groundwater resources.

## **Literature Review**

### **Hydrogeology of the Study Area**

The groundwater basin is located at the south of Merapi volcano slope, bordered by two main rivers in the east and west (Opak river and Progo river, respectively), and ended in the south by Indian Ocean [5,8]. Morphologically, the groundwater basin is also bordered by Kulonprogo and Baturagung hills (Figure 1). Geologically, the groundwater basin is bordered by two main faults, i.e., a fault along Opak river at east side and a fault along Progo river at west side. In addition, normal faults in the groundwater basin formed Bantul and Yogyakarta grabens [5,8]. The groundwater basin consists of Yogyakarta Formation underlain by Sleman Formation. Both rock formations are volcanic materials of Merapi Volcano and very potential aquifer layers [8].

The aquifer in the groundwater basin can be classified into two main aquifers: upper and lower aquifers [8] (see Figure 2). Both aquifers are composed of an inter-bedded middle to coarse sands, gravels, silts, clays and lenses of breccia. In the upper aquifer, sand and gravels are to be more prevalent in the top 10 to 25 m [8]. The lower aquifer consists of generally coarser deposits than the upper aquifer [7]. The thickness of the aquifer ranges from 20 to 120 m, but is very variable. The thickness of the aquifer is larger in the central part of the basin and decreases to the direction of the basin boundaries [11]. The average hydraulic conductivity of the aquifer system is about 8.64 m/d [7], while the average effective porosity of the aquifer is about 20 % [2]. The hydraulic characteristics of the aquifers are listed in Table 1. The regional groundwater flow in the study area is from north to south, where the groundwater gradient varies from 1/50 in the north and 1/250 in the south [8].

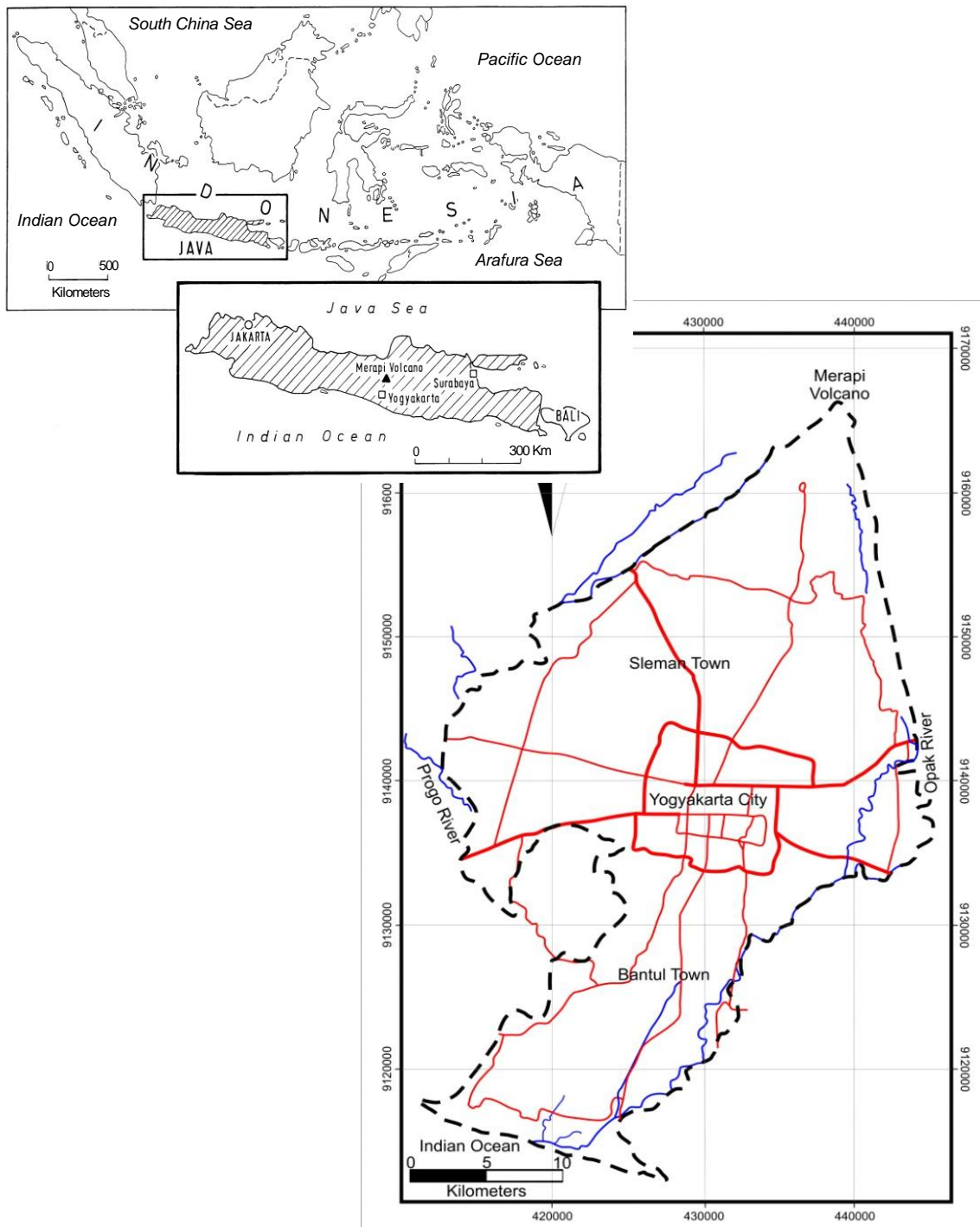


Figure 1. Location of Yogyakarta – Sleman groundwater basin (bordered by dash line)

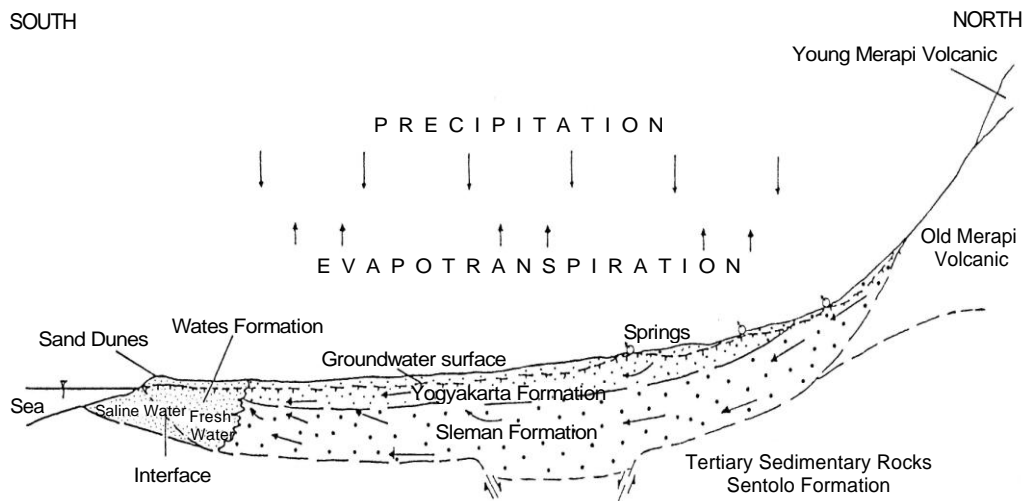


Figure 2. South-North cross section of hydrogeological concept of aquifer in the Yogyakarta-Sleman groundwater basin [8]

**Table 1. Hydraulic Characteristics of Aquifer in the Yogyakarta-Sleman Groundwater Basin**

No.	Aquifer Characteristics	Unit	Range of value
1	Transmissivity	m <sup>2</sup> /day	10 – 3000
2	Hydraulic Conductivity	m/day	3 – 700
3	Specific Capacity	l/s/m	0.1 – 35
4	Specific Yield (upper aquifer layer)	-	0.1 – 0.3
5	Storativity (lower aquifer layer)	-	0.06 – 0.1

The specific yield and storativity indicate that the upper and lower aquifer layers can be classified as unconfined aquifer type (Storativity  $\approx 0.1$ ). Both aquifers are therefore likely hydraulically connected and groundwater exploitation on the lower aquifer will likely affect the upper aquifer. This may lead to susceptibility due to pumping activities to the aquifers.

### Negative Impacts of Groundwater Overexploitation

The groundwater over-exploitation is a concept that is still poorly defined. The term over-exploitation tends to depend on a concept of “undesirable results” or “negative side-effects” [1]. There are a number of well known consequences of groundwater exploitation that may not be desirable, which are [9]:

*Declining Groundwater Level and Decreasing Discharges of Spring, River Baseflow, and Wetland Area*

It is common for over-exploitation to be defined as the condition which exists when total groundwater abstraction exceeds the recharge, giving rise to significant groundwater-level decline [1]. However, most aquifers show a water level decline as part of a natural cycle, even when they are not exploited, at least in some areas for part of the time. The water level decline may be seasonal, during a normal dry season, or it may be a longer term in response to a prolonged drought. During these periods, river and spring flows and discharge to wetlands are provided by release of water from aquifer storage causing water levels in the

aquifer to decline. Subsequent periods of recharge permit water levels to rise again as water is brought back into aquifer storage. In case of overexploitation, water levels will not rise again because no water is brought back into the aquifer storage [9].

### *Land Subsidence*

A sedimentary formation is initially formed as a soft sand, silt or mud. As the sediment builds up and subsequent layers are deposited, the increasing weight of the overburden compresses the lower beds, but the system keeps in equilibrium because the intergranular stress in the skeleton of the formation balances the weight of the overburden. Pressure of the water within the pores between the individual sediment particles also helps to support some of this weight. Groundwater pumping or dewatering of any sedimentary strata causes a decrease in the pore water pressure and, subsequently, an increase in the effective stress of the overlying strata of the aquifer. When the increase in effective stress is greater than a critical value, known as the preconsolidation stress, the sediment compaction becomes irrecoverable or *inelastic* [9]. In the multilayered aquifer system, cumulative compaction of the aquitard layers can result in significant subsidence of the ground surface [1].

### *Deterioration in Groundwater Quality*

The abstraction of significant amounts of groundwater can lead deterioration of water quality by such means as induction of contaminant flow as a result of a new hydraulic head distribution, saline intrusion, and geochemical evolution of groundwater [1]. Saline intrusion is an important consideration for aquifers adjacent to the coast or other saline bodies. The mobility of such saline waters depends upon the hydraulic gradients, which are locally disturbed by groundwater abstraction, the permeability of the aquifer, and the presence or absence of hydraulic barriers. A consideration of the time period involved in displacement of a saline front is important to an assessment of over-exploitation. A displacement time of a few years would be a matter of concern, indicating a high probability of 'overexploitation', but hundreds or thousands of years could well be acceptable in the context of long-term management strategies [9]. There is example of specific assessment method for sea water intrusion on the coastal aquifer such as GALDIT Method [4].

The probability of serious adverse side-effects of excessive groundwater abstraction varies quite widely with hydrogeological environment (Table 2) [9]. Although this table can provide a preliminary estimate of susceptibility, detailed hydrogeological investigations are required to make a full diagnosis of the situation and to model probable future scenarios under various management options. Moreover, the time scale is an important consideration in the assessment of susceptibility of an aquifer to groundwater level decline. The more susceptible of an aquifer is, the sooner the impact is likely to become apparent.

Foster [6] and Adams & MacDonald [1] suggested several factors to be considered in detailed hydrogeology investigation to estimate susceptibility to the negative impacts of groundwater over-exploitation: (1) Aquifer response characteristics, (2) Aquifer storage characteristics, (3) Available drawdown to productive aquifer horizon, (4) Depth to water table, (5) Proximity of saline water interface and (6) vertical compression of associated aquitard (Table 3). In Table 3, Foster [6] has also already classified the class of susceptibility for each of the factors.

**Table 2. Susceptibility of Different Hydrogeological Settings to Adverse Side-Effects during Excessive Abstraction [9]**

Hydrogeological Setting		Type of Side-Effect		
		Saline intrusion or up-coning	Land subsidence	Induced pollution
<i>Major alluvial and coastal</i>	coastal	++	++	++
<i>Plain Sediments</i>	inland	+	+	++
<i>Intermontane valley-fill</i>	With lacustrine deposits	++	++	+
	Without lacustrine deposits	+	+	++
	With permeable lavas/breccias	+	-	++
	Without permeable lavas/breccias	+	-	+
<i>Glacial deposits</i>		+	+	++
<i>Loessic plateau deposits</i>		+	+	-
<i>Consolidated sedimentary aquifers</i>		++	+*	+
<i>Recent coastal calcareous formations</i>		++	-	++
<i>Extensive volcanic terrains</i>		++	-	+
<i>Weathered basement complex</i>		-	-	++

++ major effect    + occurrences known    - non applicable or rare

\* can occur where associated with overlying aquitards

**Table 3. Factors Affecting the Susceptibility of Aquifers to Adverse Side-Effects from Excessive Abstraction [6]**

Hydrogeology Factor	Symbol	Unit	Susceptibility to adverse side-effects			
			High $\Rightarrow$	Moderate $\Rightarrow$	Low	
Aquifer response characteristic	T/S	m <sup>2</sup> /day	100,000	1,000	100	10
Aquifer storage characteristics	S/R	year/mm	0.1	0.01	0.001	0.0001
Thickness of aquifer (Available drawdown to productive aquifer horizon)	s	m	10	20	50	100
Depth to water table	h	m	2	10	50	200
Distance from the coast line (Proximity of saline water interface)	L	km	0,1	1	10	100
Vertical compression of associated aquitard	$\alpha$	m <sup>2</sup> /N	10 <sup>-6</sup>	10 <sup>-7</sup>	10 <sup>-8</sup>	10 <sup>-9</sup>

T transmissivity m<sup>2</sup>/day, S storativity (dimensionless), R average recharge rate (mm/year)

The approach suggested by Foster [6] is to have a single measure of susceptibility which is related to groundwater level decline, saline/sea water intrusion and subsidence. The approach may not be pragmatic but it can show a general susceptibility map of potential impacts of groundwater over-exploitation.

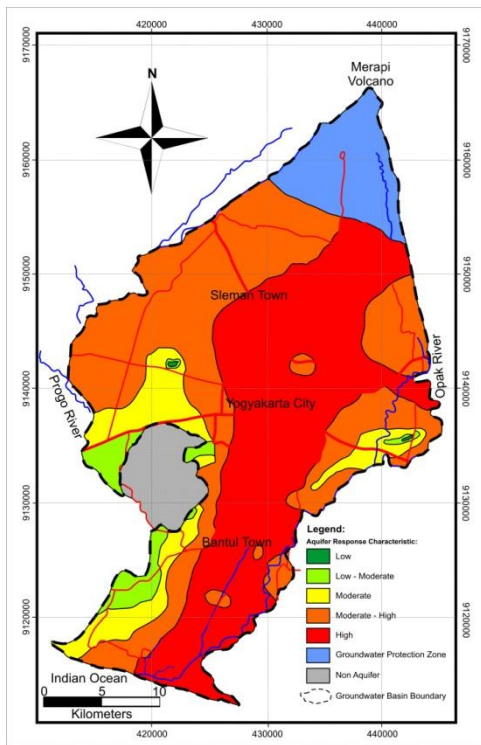
## Methodology of Research

To assess the aquifer susceptibility to negative impacts of groundwater exploitation in the study area, five factors were considered: (1) aquifer response characteristics, (2) aquifer storage characteristics, (3) thickness of aquifer to represent the available drawdown to productive aquifer horizon, (4) depth to water table, and (5) distance from coastline to represent the proximity of saline water interface (Table 4). As the aquifer in the study area is an unconfined aquifer system, vertical compression of associated aquitard is not considered on this study, because is only reasonable for confined aquifer in which aquifer layers commonly separated by aquitard.

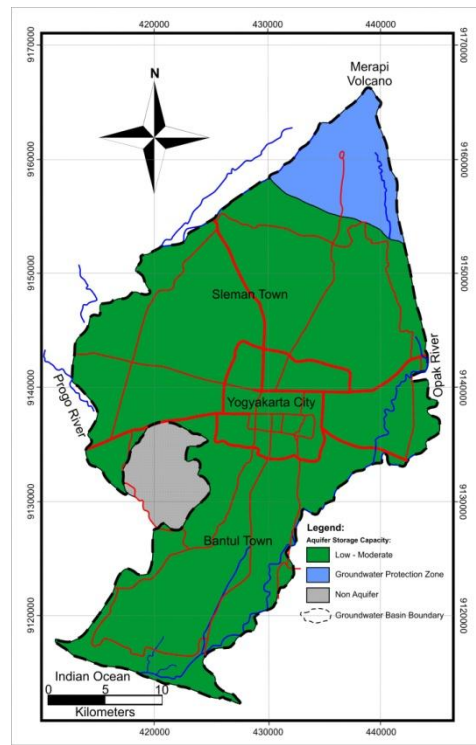
In order to assess the aquifer susceptibility to negative impacts of groundwater over-exploitation, a multi-point score method was employed. Each factor was given a score ranging from 1 to 5. The lowest score represented the lowest susceptibility and the highest score represented the highest susceptibility. The scoring range was determined based on the range of values suggested by Foster [6] (see Table 3) with modification only for the depth to water table factor according to the local condition of the aquifer characteristics (see Table 4). This modification is necessary because the groundwater depths in the study area are commonly deeper than 2 m from the ground surface. Finally, to get the final map of aquifer susceptibility, all of the factors were overlain using a Geographic Information System (GIS) software, where the final classification of aquifer susceptibility were determined from the sum of the score. The assumption used in the overlay method was that all factors had equal weight. It could be argued that a greater weight should be given to any factor, however for regional susceptibility assessment; it will be more objective to give equal weight for each factor. The final classification of aquifer susceptibility is presented in Table 5.

Factor	Symbol	Unit	Class	Score
Aquifer response characteristic	T/S	m <sup>2</sup> /day	< 10	1
			10 - 100	2
			100 - 1000	3
			1000 - 100.000	4
			>100.000	5
Aquifer storage characteristics	S/R	year/mm	< 0.0001	1
			0.0001 - 0.001	2
			0.001 - 0.01	3
			0.01 - 0.1	4
			>0.1	5
Aquifer Thickness (available drawdown)	s	m	>100	1
			50 - 100	2
			20 - 50	3
			10 - 20	4
			< 10	5
Depth to water table*	h	m	0 - 5	5
			5 - 10	4
			10 - 20	3
			20 - 50	2
			>50	1
Proximity of saline water interface	L	Km	< 0.1	5
			0.1 - 1.0	4
			1.0 - 10	3
			10 - 100	2
			>100	1

\*class is modified based on the study area condition

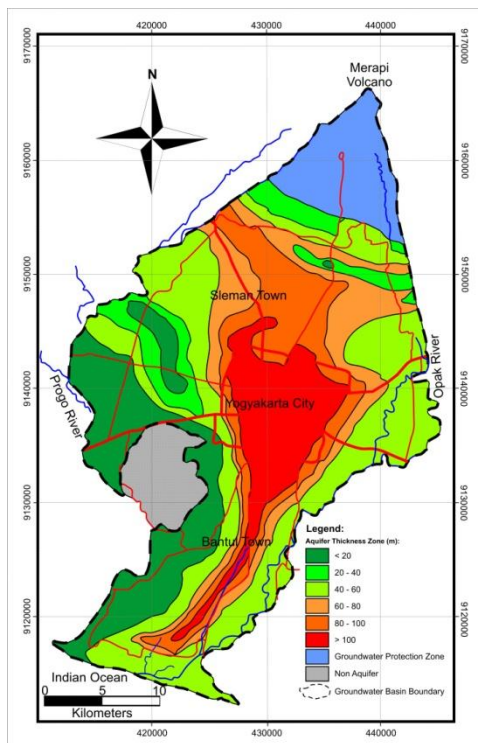


(a)

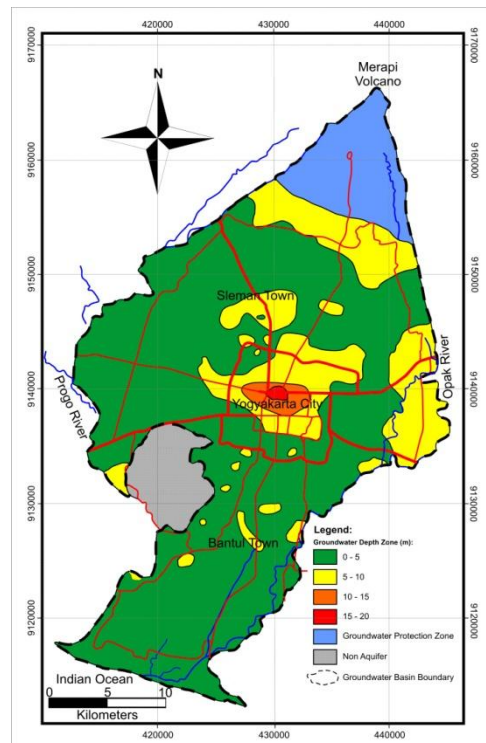


(b)

Figure 3. (a) Aquifer storage characteristics (T/S) and (b) aquifer response characteristics (S/R) of the aquifer in the study area



(a)



(b)

Figure 4. (a) Thickness of aquifer and (b) depth to water table in the study area



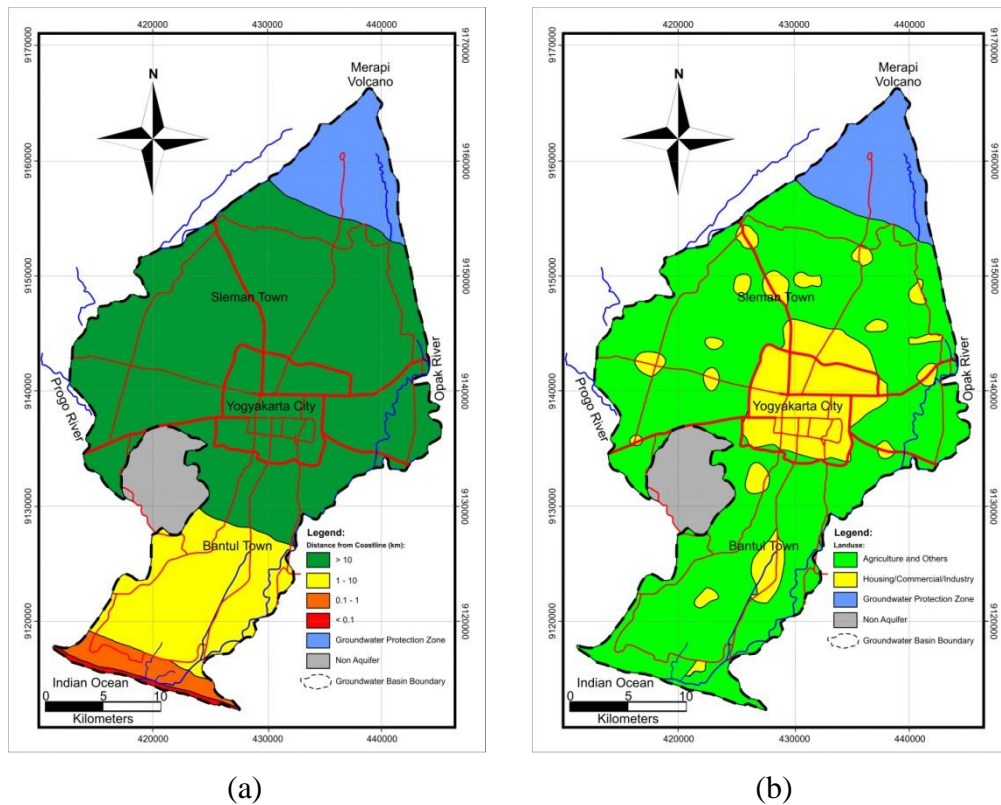


Figure 5. (a) Distance zone from coastline and (b) simple classification of the land use in the study area

**Table 5. Final Classification of Aquifer Susceptibility to Overexploitation**

Susceptibility Class to Groundwater Over-exploitation	Final Score
Extreme Susceptibility	20 – 25
High Susceptibility	15 – 20
Moderate Susceptibility	10 – 15
Low Susceptibility	5 - 10

The susceptibility map resulted from above method will only show the intrinsic factors of aquifer susceptibility. Therefore, it is necessary to combine the susceptibility map and the land use to obtain a hazard map showing negative effects of groundwater over-exploitation in the study area. The land use map (Figure 5b) was classified into two groups; (1) Housing, commercial and industrial areas and (2) Agriculture and open space areas. The first group was associated with a high usage of groundwater, while the second group was associated with a low usage of groundwater because water was supplied by the rivers along the basin through the irrigation system [10].

For the evaluation of hazard of negative effects induced by groundwater over-exploitation, a matrix subject rating method was used to define the class of hazard, as shown in Table 6. The class of hazard was determined based on two factors: (1) *relative groundwater exploitation yield (RGOV)*, which was based on the land use groups and (2) *aquifer susceptibility class (AQS)*. Each factor was then given a score and the final score of hazard was obtained by summing the total scores of both factors, as shown in Table 6.

**Table 6. Matrix of Object Specific Rating used to Assign Hazard Map of Negative Effects of Groundwater Over-Exploitation**

		Relative groundwater exploitation-yield (RGOV)	Class of Negative Effects Hazard Due to Groundwater Over-Exploitation			
			Hazard Class = RGOV + AQS			
Land Use	Housing, Commercials, Industries	High (2)	Low (3)	Medium (4)	High (5)	Extreme (6)
	Agriculture, open spaces, etc	Low (1)	Low (2)	Low (3)	Medium (4)	High (5)
Note:			Low (1)	Moderate (2)	High (3)	Extreme (4)
<b>RGOV</b>						
Low (Score 1), High(Score 2)						
<b>AQS</b>						
Low (Score 1), Moderate (Score 2)						
High (Score 3), Extreme (Score 4)						
		<b>Aquifer Susceptibility Class (AQS)</b>				

## Results and Discussion

Result of overlying the five hydrogeological factors shows that two zones of aquifer susceptibility to negative impacts of groundwater exploitation in the study area, which are; (1) High susceptibility (score 15-18) and (2) Moderate susceptibility (score 10 to 15). The high susceptibility zones are dominant than the moderate susceptibility zones through the basin (Figure 6a). The more susceptible an aquifer is, the sooner the impact is likely to become apparent [9]. When response of an aquifer to exploitation is rapid, the opportunity to mitigate negative effects is commensurately limited. Conversely, in a less responsive aquifer, a slow progressive side-effect provides opportunities to fully evaluate the problem and identify options to manage or mitigate the worst effects. The assessment shows that almost all parts of the study area will show a rapid impact due to high exploitation of groundwater.

Result of matrix evaluation of RGOV and AQS factors shows that high hazard due to groundwater over-exploitation will occur rapidly and majorly in the center of Yogyakarta-Sleman groundwater basin (Yogyakarta City) and (see Figure 6b). Most of the study area is categorized as a moderately hazard area, indicating that the side effects of groundwater exploitation is minor on this recent condition. Moreover, it can be also concluded that there are still large areas in the study area which is classified as a low hazard of negative effects, especially in the east-part of the study area.

Actually, impacts of groundwater exploitation have occurred in the middle and the southern parts of the groundwater basin. In the middle part of Yogyakarta city, nowadays, the depth of groundwater level is 15-20 m from the surface, which was uncommon in the last 10 years. In the southern part, salty groundwater is detected near the coastal area, presumably due to salt water intrusion. These areas are located in the high susceptible area.

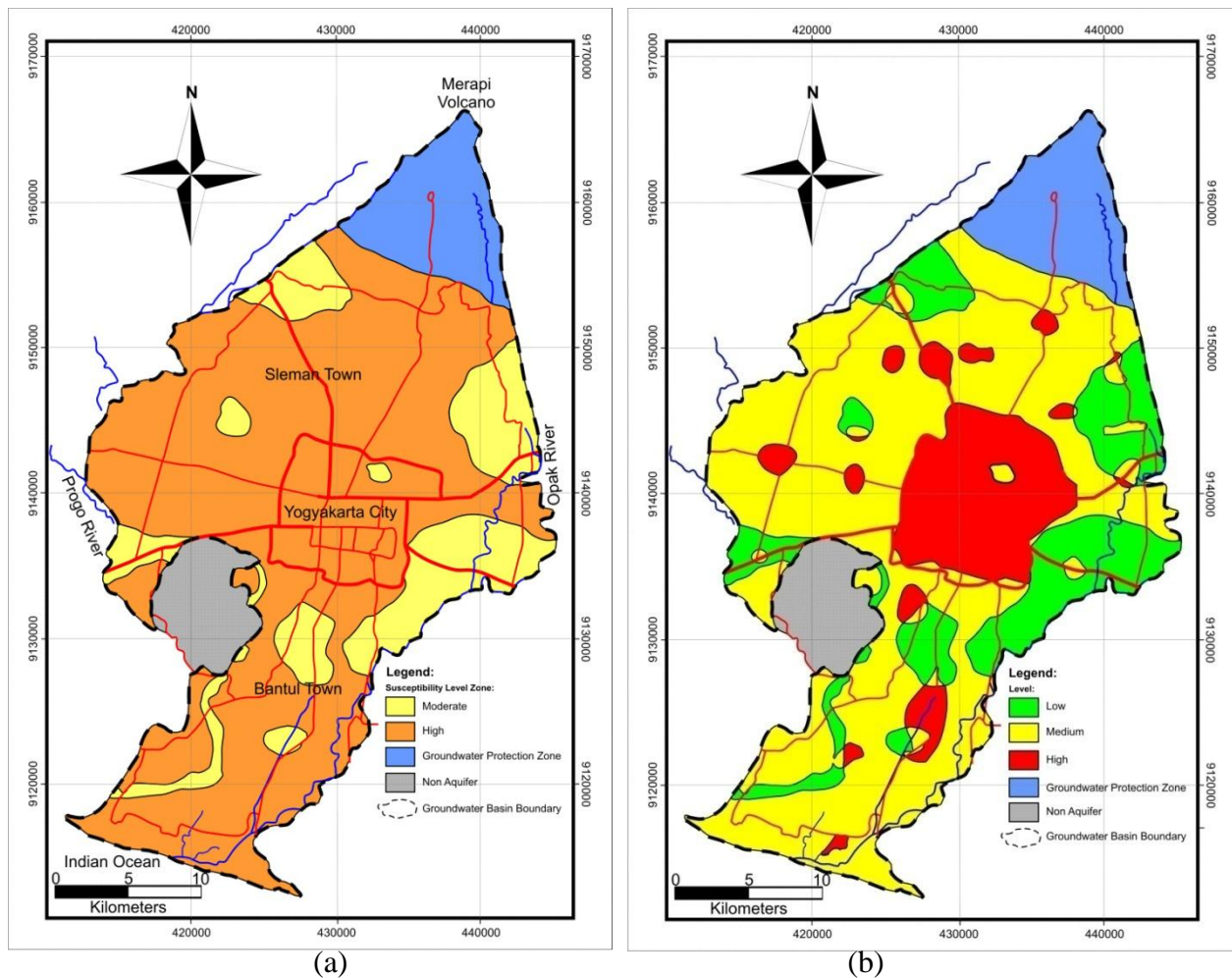


Figure 6. (a) Aquifer susceptibility and (b) hazard map to negative impacts due to groundwater exploitation in the research area

Based on the results of this research, groundwater in the Yogyakarta-Sleman groundwater basin, especially in the high hazard of groundwater exploitation, should be immediately managed. The possible mitigation to minimize the impact of groundwater exploitation in the study area is by controlling groundwater abstraction and distributing the area of groundwater exploitation. A strict control of groundwater pumping should be taken in the high hazard area to avoid worst impacts of groundwater exploitation. In hazard area, it would be necessary to apply pumping discharge regulation/limitation, disincentives and incentives of groundwater abstraction cost to reduce groundwater usage, and promoting conjunctive usage of groundwater and surface water resources. In moderate and low hazard areas, the land zoning of groundwater conservation and protection should be started, including development of a blue-print plan of permissible location of groundwater well and level of pumping discharge.

## Conclusions

An approach to the determination of aquifer susceptibility due to over-exploitation is presented. A map of aquifer susceptibility to negative impacts due to groundwater exploitation and a hazard map of negative impacts due to groundwater exploitation in Yogyakarta-Sleman groundwater basin were developed. The map of aquifer susceptibility shows that the Yogyakarta-Sleman groundwater basin can be divided into two zones: high susceptible and moderate susceptible areas. Matrix evaluation of RGOV and AQS allows to

develop a hazard map due to groundwater exploitation. The matrix evaluation indicates there are three zones of hazard in the study area; low, medium and high hazard areas associated with the side effects of groundwater over-exploitation occurring in the study area, such as declining of groundwater level in the Yogyakarta City and salt water intrusion in the coastal area.

The modification of aquifer susceptibility assessment reported on this paper, has some limitations, such as the equal weight assumption and simple matrix assessment. However, the assessment results were proven to be correlated with the occurring negative impacts of groundwater exploitation in the study area. The modified concept of assessment is, therefore, considered to be appropriate to be used on regional basis and the developed maps may help stakeholders/planners on groundwater resources in the study area to mitigate the negative impacts of groundwater over-exploitation.

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