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EVOLUTION OF GROUNDWATER CHEMISTRY ON SHALLOW AQUIFER OF YOGYAKARTA CITY URBAN AREA

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Abstract

Since 1980s, accelerated by urbanization, Yogyakarta City was shifting to many directions defined by main road networks and service centres. Urbanization has transformed rural dwellings to become urban settlements and generated urban agglomeration area. Until now, new business centres, education centres and tourism centres are growing hand in hand with new settlements (formal or informal) without proper provision of water supply and sanitation system. This condition increase the possibility of groundwater contamination from urban wastewater and a change of major chemistry of groundwater as shallow unconfined aquifer is lying under Yogyakarta City. To prove the evolution of groundwater chemistry, old data taken on 1980s were comparing with the recent groundwater chemistry data. The evaluation shows that nitrate content of groundwater in 1980s was a minor anion, but nowadays become a major anion, especially in the shallow groundwater in the centre of Yogyakarta City. This evidence shows that there is an evolution of groundwater chemistry in shallow groundwater below Yogyakarta City due to contamination from un-proper on-site sanitation system.

Keywords: *urbanization, Yogyakarta city, rural dwellings, settlements, agglomeration, contamination, groundwater.*

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1 Introduction

Yogyakarta City is located on the central-part of Java Island. It is a capital city of Yogyakarta Special Province and one of the most important cultural centres in Indonesia (Figure 1). Based on the regional context, Yogyakarta City and its agglomeration area are sited on aquifers which are part of the Merapi Aquifer System (Figure 2). MacDonald & Partners (1984) and Hendrayana (1993) differentiated the Merapi Aquifer System into two major Formations; Yogyakarta Formation as the upper aquifer and Sleman Formation as the lower aquifer. The results of the lithostratigraphy correlation from borehole data within the study area shows that there are actually five quarternary layers or successions, which build the multilayer aquifers of the Merapi Aquifer System beneath Yogyakarta City. Each layer consists of a heterogeneous composite of gravel, sand, clayey sand, and clay facies, and they are separated by laterally uncontinuous sandy silt to clay layers. The laterally uncontinuous semi-permeable to impermeable layers make incomplete separation between the aquifers and cause hydraulic windows. As a consequence, the aquifers of this multilayer system are connected directly to each other in some places (Putra, 2007). Thus, it is possible that any contamination on the upper aquifer can induced to the deeper aquifer layers.

Historically, in 1930s, Yogyakarta was just a small town in the interior of Java with the population of approximately 60.000 populations

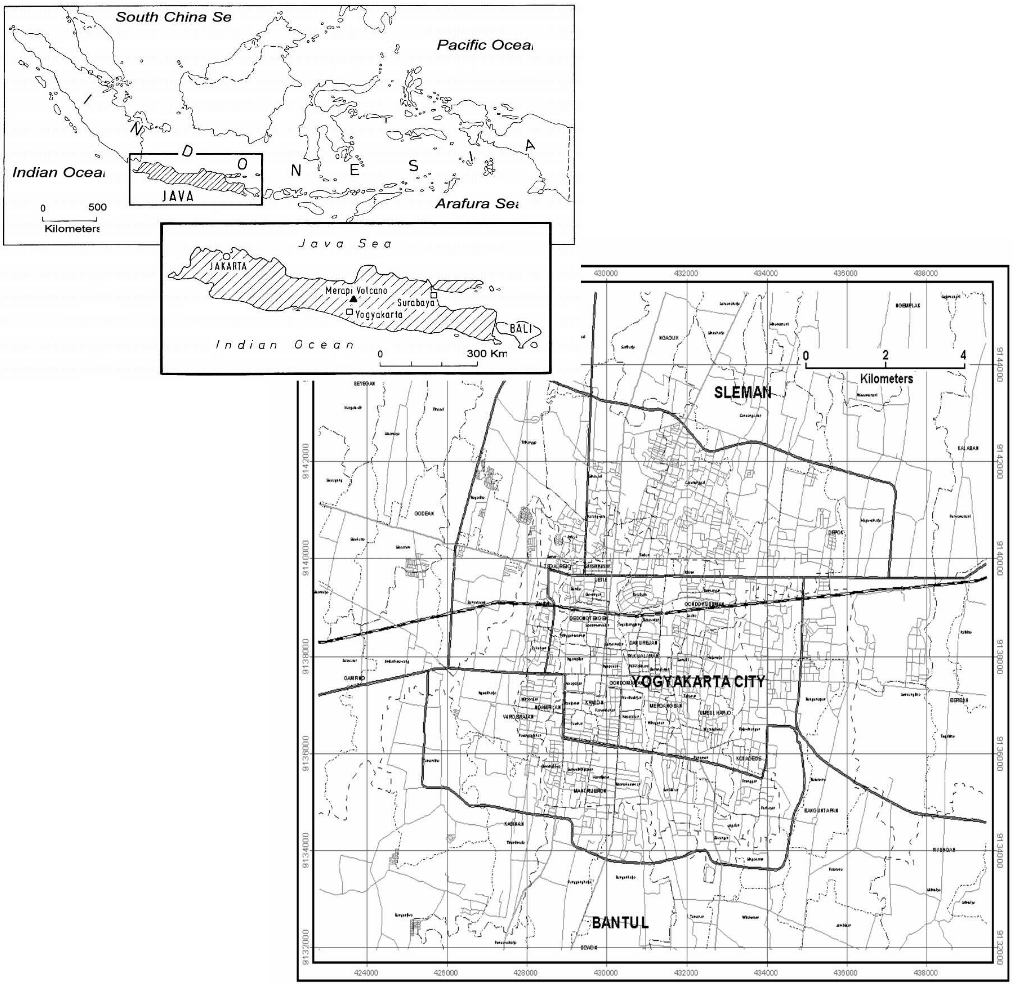

Figure 1: Yogyakarta City and its urban agglomeration area

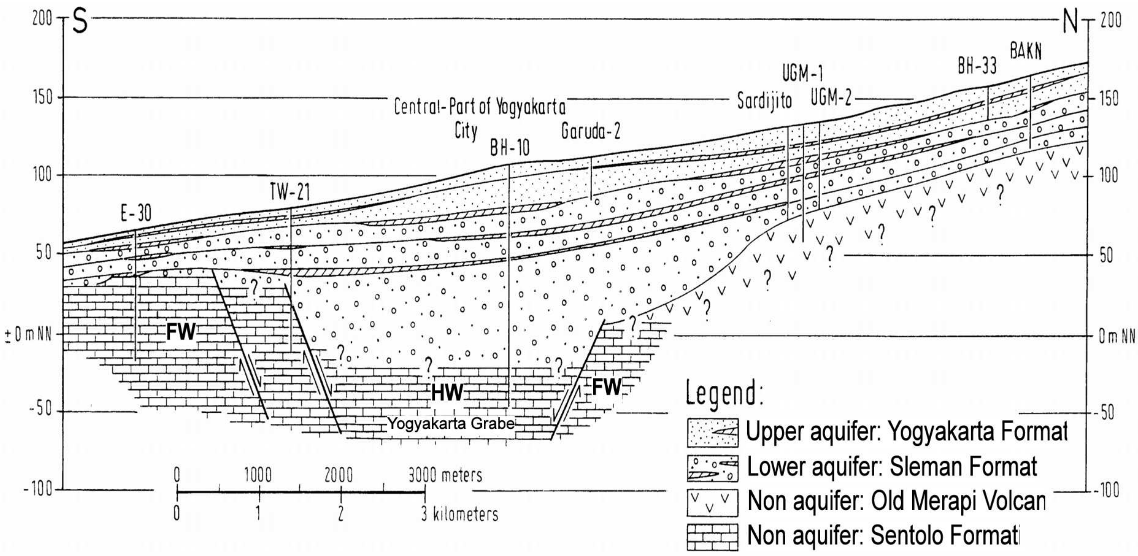

Figure 2: Concept of aquifer system underlying Yogyakarta City area (Putra, 2007)

(Baiquni, 2004). Since 1980s accelerated by urbanization, Yogyakarta City settlement pattern was shifting to many direction defined by main road networks and service centres. Urbanization has transformed rural dwellings to become urban settlements and generated urban agglomeration area. Until now, new business centres, education centres and tourism centres are growing hand in hand with new settlements (formal or informal) without proper provision of water supply and sanitation system. Actually, in the first half of the twentieth century, sanitation system in Yogyakarta City was served by a main sewerage system built by Dutch engineers. This old system was supplemental by a new one in 1998. However, the sewage system with the old and new sewage system can serve only 9 % of the city population (Sukarma and Pollard, 2002). As a result, more than 90 % of the population (total population ca. one million peoples) are using on-site sanitation systems. The other characteristics of urbanization in Yogyakarta City is the wide use of shallow infiltration wells, as alternative way to dispose domestically non human body waste or even small workshops wastewater directly into the ground. The practice of infiltration wells is good in terms of maintaining recharge; however, it turns to become a potential source of groundwater contamination. Nevertheless, this practice of shallow infiltration wells occurs due to lack of an integrated sewerage system. On its relation with the lack of sewerage system and the wide usage of on-site sanitation systems i.e. septic tank systems, latrines, together with the direct disposal of waste water to the ground, it is reasonable to assume that water taken from domestic dug wells are potentially contaminated and thus can harm the human health. It is known that water quality surveys of domestic wells in unsewered areas have revealed a widespread chemical (i.e. nitrate) and microbial (i.e. faecal coli) contamination of shallow groundwater (Sinton, 1982, Morris et al., 1994, GWMAP, 2000). Based on above facts, the objective of this study is to recognize the evolution of groundwater chemistry in upper shallow aquifer of Yogyakarta City and its agglomeration area and to correlate the changes with the urbanization aspect.

2 Literature review

2.1 Urbanization and groundwater

One of the most important issues of the growing city is the interaction between urban development and groundwater, especially on cities located above shallow unconfined aquifer. The interaction between urban development and groundwater may be explained in the relation with the pattern and stage of city evolution on affecting the quantity and quality of groundwater. Two important studies of the impact of urbanization on groundwater have been well reported by Foster *et al.* (1993) and Morris *et al.* (1994). From both studies, two main issues can be concluded, which are; 1) urbanization changes groundwater recharge or cycle, with modification to the existing recharge and the introduction of the new sources, 2) the introduction of new sources of recharge in urbanization cause extensive but essentially diffuse groundwater contamination. Another issues related to the changes in the quantity and quality of groundwater in urbanized areas are the uncontrolled aquifer exploitations, fluctuation of groundwater levels and problems with the underground structure (Chilton, 1999, Vásquez-Suňé *et al.*, 2005).

It is often thought that urbanization reduces infiltration to groundwater due to the impermeabilisation of the catchment by paved areas, buildings and roads. However, the reserve is often true and recharge beneath cities is usually substantially greater than the pre-urban values (Foster *et al.*, 1993). The increase of groundwater recharge is closely related with the occurence of three main sources of recharge which exist in urbanized area: rainwater, wastewater and main leakage from water supply system. Lerner *et al.* (1990) mentioned that in humid areas, leakage recharge (waste water and water supply system) may balance the loss of precipitation recharge caused by the impermeable areas and the overall effect of urbanization will be small. However, in arid and semi arid areas, leakage recharge will always significanttly larger than precipitation recharge. In fact, Lerner (2002) mentioned that in cities, where no sewers are present to take waste water away, the most important recharge route would be the infiltration of waste water from large numbers of septic tanks, latrines, and soakaways.

The sources and pathways for groundwater recharge in urbanized area are more numerous and complex than in rural environments. Nevertheless, the increase of groundwater recharge in this area is known to be closely related to three main sources: rainwater, wastewater and main leakage from water supply networks. In cities where waste water is not exported (cities without sewers for waste water transport), as much as 90 % of abstracted and/or imported water may return as groundwater recharge (Lerner *et al.*, 1990). In these cities, the most important recharge source would be the infiltration of waste water from large numbers of septic tanks, latrines, and soakaways (Lerner, 2002).

According to Lerner *et al.* (1990), the effect of urban recharge sources will be always significantly larger than precipitation recharge in semi arid and arid regions. But in humid areas, urban recharge may only balance the loss of precipitation recharge caused by the impermeable areas, and the overall effect of urbanization will be small. On the other hand, cities which use the local groundwater for their water supply, the effects of urbanization on recharge are in general smaller than in cities that import water. Therefore, it can be also concluded that almost all urbanization processes can potentially increase the rate of infiltration to groundwater. In contrast to the effect of urbanization on the quantity of recharge, the net effect of urbanization on the quality of recharge is generally adverse, especially if waste water is an important component (Table 1). From Table 1, it can be seen that the quality of recharge water from waste water (e.g. on site sanitations, leakage sewers, etc) is commonly poor. This table also shows that the causes of groundwater quality deterioration in urbanized area are complex, involving a combination of contaminants. From all possible contaminant in the groundwater under urban area, nitrate is the main important contaminants that are derived from on-site sanitation (Foster and Hirata, 1988). Therefore, nitrate is commonly used as a marker species for groundwater contamination from urban on-site sanitation.

2.2 Background value of Yogyakarta's groundwater chemistry

According to MacDonald and Partners (1984), the inorganic chemical quality of the groundwater in the study area was very good for irrigation, drinking and most industrial purposes (see Table 2). Physical-chemical characteristics of water ranged between less than 100 µS/cm for Specific Electric Conductivity (EC) or 70 mg/L for Total Dissolved Solid (TDS) in spring water and 600 µS/cm for EC or 500 mg/L for TDS in near geological boundaries of south, east and west. In fact, nitrate concentration, which is commonly used as marker species for agricultural practice and urban on-site sanitation, was less than 2.8 mg/L. The degradation of inorganic chemical quality of shallow groundwater due to human activities in the study area was recognized in the late 80s and early 90s as reported by Sudharmaji (1991) and Hendrayana (1993). Both studies stated that groundwater quality degradation was indicated to occur in the central-part of Yogyakarta City. However, the groundwater quality at that time was generally good, and only in few local areas, the nitrate concentration was greater than 10 mg/L.

3 Methodology

In order to prove the evolution of groundwater chemistry in the shallow groundwater system under Yogyakarta City and Its Agglomeration Area, old data of groundwater chemistry taken in 1980s was compared with the recent data. On this comparison, major cations (Na^+, K^+, Ca^{2+} and Mg^{2+}) and major anions (Cl^-, SO_4^{2-}, HCO_3^-) including NO_3^- (as common marker species for groundwater contamination from urban on-site sanitation) of groundwater is compared. To show the difference between nitrate content of shallow groundwater of Yogyakarta City in 1980s and recent condition, a

Table 1: Impact on groundwater quality from various sources of urban recharge (Morris *et al.*, 2003)

Recharge/source of contaminant loading	Importance	Water quality	Contaminants/contamination indicators
Leaking water mains	Major	Excellent	Generally no obvious indicator
On site sanitation systems	Major	Poor	N, B, Cl, FC, DOC
On site disposal / leakage of industrial waste water	Minor to Major	Poor	HC, diverse industrial chemicals, N, B, Cl, FC, DOC
Leaking sewers	Minor	Poor	N, B, Cl, FC, SO_4, diverse industrial chemicals
Pluvial drainage from surface by soakaway drainage	Minor to Major	Good to poor	N, Cl, FC, HC, DOC, diverse industrial chemicals
Seepage from canals and rivers	Minor to Major	Moderate to poor	N,B, Cl, FC, SO_4, DOC, diverse industrial chemicals
B Boron Cl Chloride and salinity general DOC Dissolved organic carbon FC Faecal Coliforms		HC Hydrocarbons (Fuels, Oils and Grease) N Nitrogen compounds (nitrate and ammonium) SO_4 Sulphate	

Table 2: Summary of hydrochemical analyses of groundwater from Merapi Aquifer (MacDonald and Partners 1984)

Source	Parameter	Unit	Wet Season		Dry Season	
			range	mean	range	mean
Deep and Shallow Wells	EC	µS/cm	256-691	394	214-627	334
	pH		6.9-8.1	7.4	6.8-7.6	7.1
	TDS	mg/L	191-504	291	161-458	247
	Hardness	mg/L	144-317	221	131-252	131
	Ca^{2+}	mg/L	18-55	34	25-48	32
	Mg^{2+}	mg/L	24-44	33	15-35	25
	K^{+}	mg/L	1.5-86	4.6	0.9-6.2	2.3
	Na^{+}	mg/L	4-19	12	4-22	8
	Fe (total)	mg/L	0.05-1.06	0.27	0.02-1.32	0.22
	Cl^{-}	mg/L	13-27	22	8-26	14
	SO_4^{2-}	mg/L	1.3-39	9	4.7-14	12
	HCO_3^{-}	mg/L	98-386	173	87-370	157
	NO_3^{-}	mg/L	0.12-2.8	1.27	0.09-0.75	0.33
Springs	EC	µS/cm	99-475	203	106-514	226
	pH		6.8-8.3	74	6.8-8.6	7.2
	TDS	mg/L	73-352	150	79-381	168
	Hardness	mg/L	65-179	117	60-297	118
	Ca^{2+}	mg/L	13-31	22	10-33	21
	Mg^{2+}	mg/L	6-26	15	6-22	12
	K^{+}	mg/L	1.1-5.5	2.4	0.6-4.2	1.3
	Na^{+}	mg/L	2-19	6	2-16	5
	Fe (total)	mg/L	0.01-0.9	0.06	0-0.12	0.06
	Cl^{-}	mg/L	5-37	13	5-43	11
	SO_4^{2-}	mg/L	0.6-14	6	2-46	15
	HCO_3^{-}	mg/L	79-189	116	81-174	118
	NO_3^{-}	mg/L	<0.9	0.3	0-0.6	0.15

distribution map of nitrate content in shallow groundwater is developed. More over, to evaluate the impact of population density (urban – rural area) to nitrate content in shallow groundwater, a XY-graph is developed between nitrate concentration in groundwater and number of population.

4 Results and Discussion

For this research, 10 groundwater samples were taken for the routine water analysis and about 152 samples were taken for nitrate content analysis. Routine water analysis involves measuring the concentration of the standard test of constituents of major ions such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^-, SO_4^{2-}, Cl^- and NO_3^- as well as pH, total dissolved solid and electric conductivity. Result of the analysis shows that almost all major components meet the National Drinking Water Standard, except one sample which contains nitrate concentration greater than 50 mg/L (Table 3). The comparison between the recent average concentrations of principle groundwater quality and their background values based on the data from MacDonald and Partners (1984) does reveal dramatic changes in water quality, especially for the anions group. Based on its anions content, the hydrochemistry of the shallow groundwater in Yogyakarta City and its agglomeration area can be differentiated into 3 water types: 1) HCO_3–SO_4 to HCO_3– Cl–SO_4 water, 2) HCO_3–NO_3 water and 3) NO_3–HCO_3–SO_4 water. By its relation to the urbanization process and assuming the homogeneity of the shallow groundwater system beneath the study area, type 1 (MI-01, MI-02, MI-03, MI-04, MI-07, MI-08, MI-09, MI-10) is the dominant type of groundwater found beneath sub urban/rural areas (less developed area). Whilst due to limited data, type 2 (MI-06) may the type of groundwater found in the boundary between sub urban and urban area (moderate developed area). Type 3 (MI-05) may represent the type of groundwater found in the central-part of urban area (old developed area). A composite map of the shallow groundwater type and the major land use in the study area is shown in Figure 3.

Despite the reservation of the limited data, a comparison between the recent groundwater chemistry (Table 3) and the background groundwater chemistry in the study area (Table 2) shows clearly that the concentration of sulphate and nitrate have increased over time. These changes in groundwater composition of the study area should have occurred during the last 20 years or more, presumably parallel to the evolution of the urban development/land use change in the study area. Besides due to sub urban/urban contamination sources, the salinization process of the shallow groundwater in the study area may also occur due to natural condition. Sample MI-03 that was taken on the south geological boundaries of the study area is a good example of this anomaly. It contains the highest concentration of Ca^{2+}, Mg^{2+}, HCO_3^-, Cl^- and SO_4^{2-} of all groundwater samples (see Table 1) although it was sampled from the shallow groundwater beneath sub urban-rural area. This condition occurs presumably due to water mixing processes between the upper aquifer (predominantly HCO_3 water) and the lower aquifer (predominantly Cl–SO_4 water) together with the influence of dissolving Ca-Mg-Carbonate of the Tertiary Rocks Formation (non-aquifer). This process reveals higher concentration of EC and TDS in groundwater near the geological boundaries as also already mentioned by MacDonald and Partners (1984).

For the nitrate contaminant in groundwater, a total 152 secondary data of nitrate content were used. The data were taken on 2005. According to Sudharmaji (1990), the nitrate background value on shallow groundwater of Yogyakarta City in 1985 was found to be 0.03 – 12.92 g/L (mean value 2.82 mg/L), while older data showed that nitrate content on groundwater of Merapi aquifer was between 0.00 – 2.8 mg/L (MacDonald & Partners, 1984). The recent data shows that the nitrate content on shallow groundwater of Yogyakarta City and its surrounding area are between 0.28 – 151.70 mg/L (see Figure 4).

Figure 4 shows the nitrate content in shallow groundwater under Yogyakarta City on year 1985 and 2005. From this figure, it can be concluded that for about 20 years, the nitrate

Table 3: Physical-chemical characteristics and major ions of shallow groundwater in the study area. Unit: mg/L, except for EC (μS/cm) and pH

Sample	EC	TDS	pH	K	Ca	Mg	Na	SO_4	NO_3	Cl	HCO_3
MI-01	282	200	6.6	9	20.0	8.2	15	8	10.9	5	72
MI-02	305	200	6.8	9	22.2	12.6	13	26	3.7	10	102
MI-03	1080	700	7.2	1	124	29.0	52	96	25.1	100	258
MI-04	654	400	7.1	14	49.7	21.3	63	76	12.9	35	215
MI-05	753	500	6.8	13	57.7	13.5	93	76	147	52	132
MI-06	370	200	6.4	11	24.8	14.0	25	25	44.6	17	97
MI-07	423	300	6.9	10	29.2	15.5	29	68	4.7	25	88
MI-08	265	100	6.6	7	16.6	9.1	13	30	12.6	14	52
MI-09	298	200	7.1	9	18.4	10.6	17	44	1.6	12	68
MI-10	254	200	6.7	7	19.6	11.1	11	35	24.1	6	67
Average	468	300	6.8	9	38.2	14.5	33	51	28.7	28	115

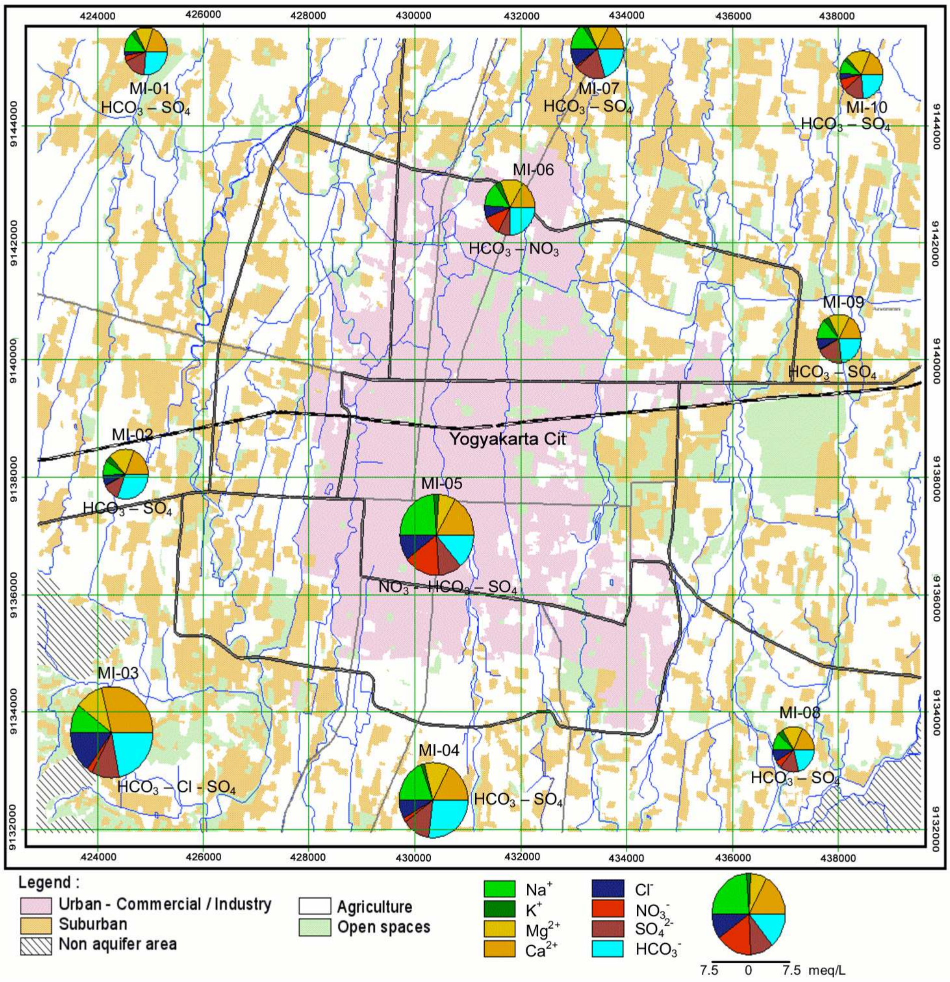

Figure 3: Composite map of shallow groundwater type and major land use in the study area

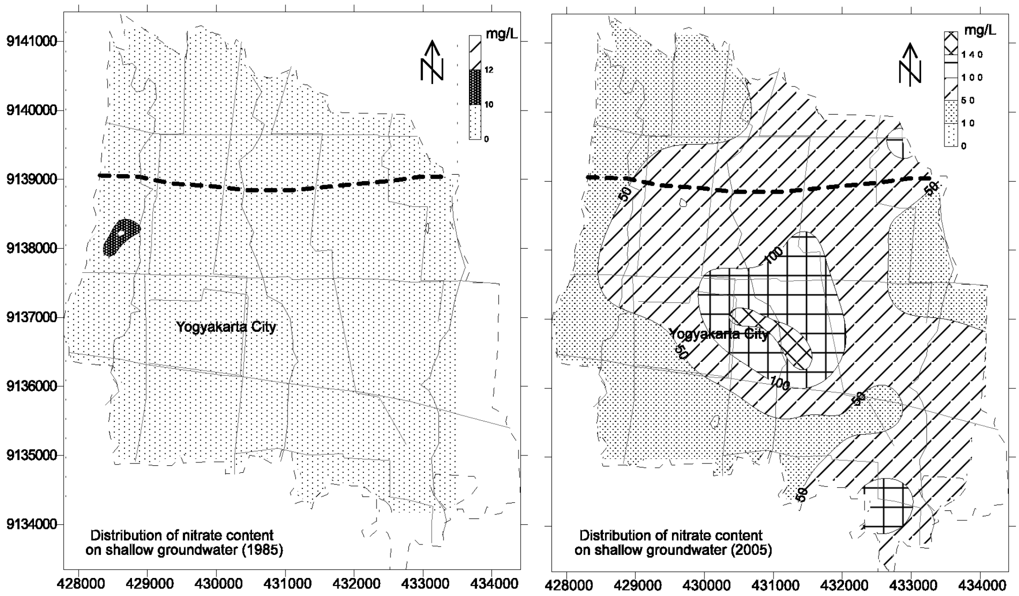

Figure 4: NO_3 concentration of shallow groundwater in central part of Yogyakarta City area

content was increasing dramatically in shallow groundwater of Yogyakarta City. Moreover, by comparing the population density and nitrate content in shallow groundwater in the research area according to the cross-section from North to South across central-part of Yogyakarta City. It is reasonable to conclude that the denser the population the higher the nitrate concentration in shallow groundwater (see Figure 5). This fact reveals due to high possibility of existing sources of contamination and loading of nitrate from improper on-site sanitation system on the urban area.

5 Conclusions

Based on this research, it can be concluded that the shallow groundwater chemistry of upper aquifer Yogyakarta City is change with time due to the impact of urban wastewater from improper on-site sanitation. As a result, the groundwater beneath highly urbanized area contains extremely high nitrate compare to groundwater in sub-urban/rural area, which contains lower nitrate. If about 20 years ago, bicarbonate and sulphate ions are the dominant anion of shallow groundwater chemistry, nowadays, nitrate ion becomes a major anion in groundwater of upper aquifer especially below the central part of Yogyakarta City.

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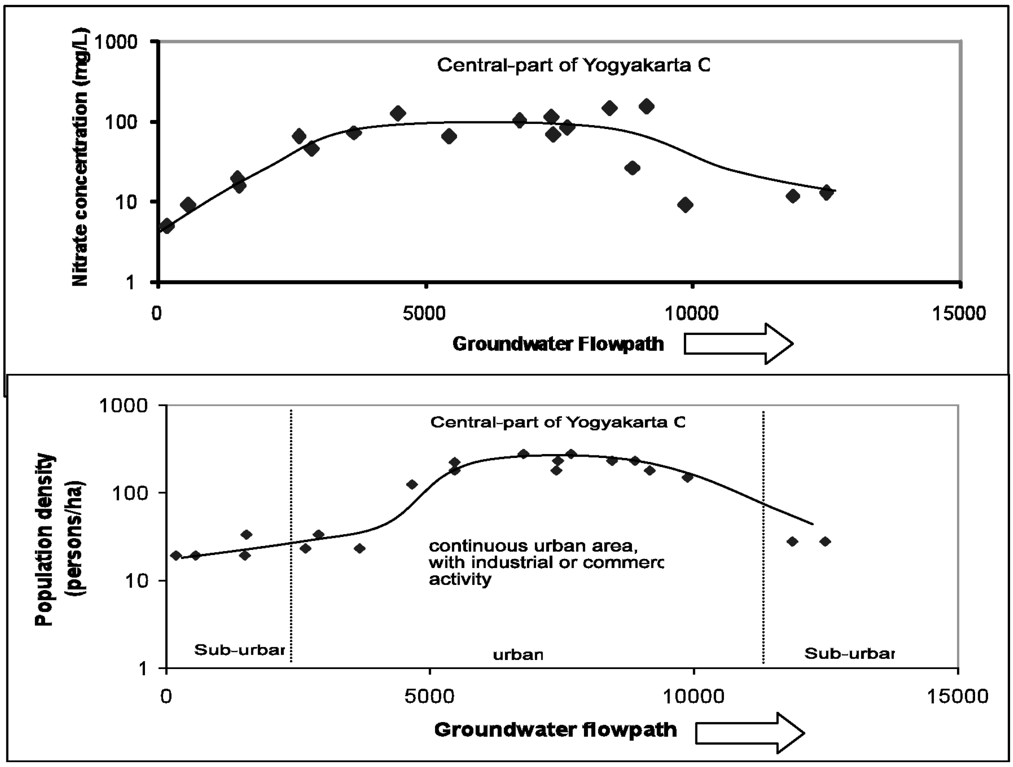

Figure 5: Relations between changes of population density and nitrate groundwater content in the research area from north to south across central-part of Yogyakarta City

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