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Hydrogeological Model of an Urban City in a Coastal Area, Case study: Semarang, Indonesia

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Abstract - In Semarang City, groundwater has been exploited as a natural resource since 1841. The groundwater exploited in deep wells is concentrated in confined aquifers. The previous hydrogeological model was developed in one unit of aquifer and refined then by using several hydrostratigraphical units following a regional hydrogeological map without any further analysis. At present, there is a lack of precise hydrogeological model which integrates geological and hydrogeological data, in particular for multiple aquifers in Semarang. Thus, the aim of this paper is to develop a hydrogeological model for the multiple aquifers in Semarang using an integrated data approach. Groundwater samples in the confined aquifers have been analyzed to define the water type and its lateral distribution. Two hydrogeological cross sections were then created based on several borelog data to define a hydrostratigraphical unit (HSU). The HSU result indicates the hydrogeological model of Semarang consists of two aquifers, three aquitards, and one aquiclude. Aquifer 1 is unconfined, while Aquifer 2 is confined. Aquifer 2 is classified into three groups (2a, 2b, and 2c) based on analyses of major ion content and hydrostratigraphical cross sections.

Keywords: hydrogeological model, hydrochemistry, hydrostratigraphical unit, aquifer, Semarang

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Introduction

Semarang is one of big cities in Indonesia, and it is also the capital of Central Java Province located in the northern coast of Java Island. The studied area covers approximately 1,070 km^2 of land including Semarang urban area and Demak suburbs with the total population of up to three million inhabitants. It is located on 419500 to 480250 m in East Longitude and 9212850 to 9258190 m in South Latitude using the Universal Transverse Mercator (UTM) zone 49 South (Figure 1). In Semarang, groundwater has been exploited as a natural resource since the first deep well was drilled at Fort Wilhelm I in 1841 (Dahrin *et al*., 2007). Since then, a number of registered deep wells has increased sharply. In 1900, there were 16 deep wells in total, whereas 260 others were built in 1990s, and 1,194 wells were constructed in the first decade of 2000 with the total groundwater withdrawal of around 45 MCM yr-1 (Directorate of Environmental Geology/DGTL, 2003). Groundwater exploited in deep wells are concentrated in a confined aquifer system.

To develop a hydrogeological model, a hydrostratigraphic unit (HSU) concept was ap-

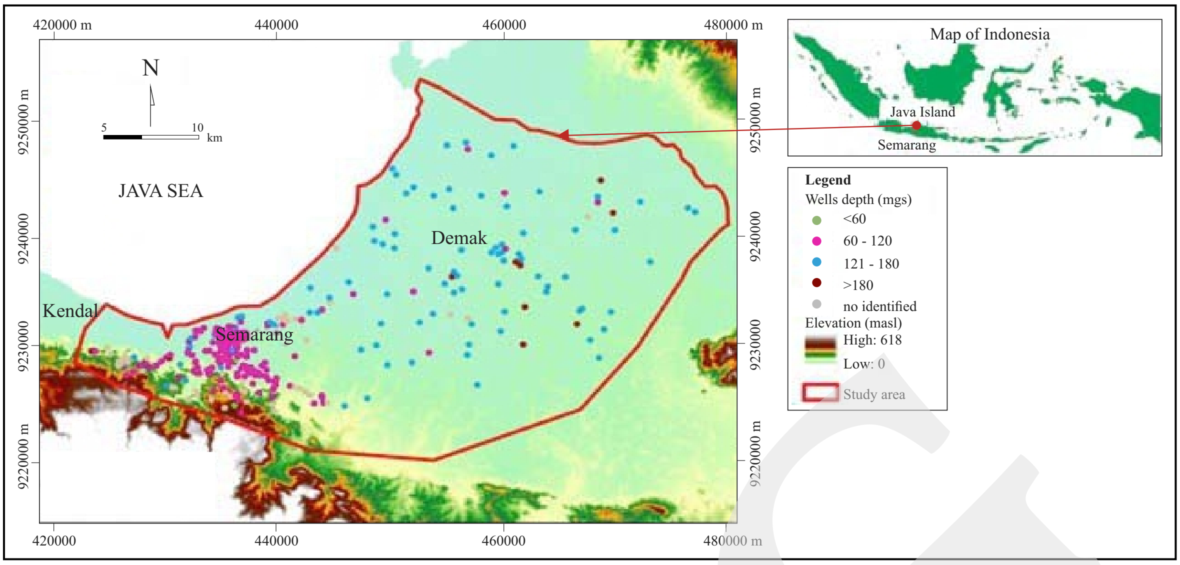

Figure 1. Topographic map of the study area and deep well location. The elevation is derived from Digital Elevation Model/DEM (Jarvis *et al*., 2008).

plied. The term of HSU was originally defined by Maxey (1964) to describe bodies of rock with considerable lateral extent which forms a distinct hydrological system with respect to groundwater flow. A set of geologic, hydrologic, and hydrochemistry data were used to define and to verify the HSU. Spitz (1989) proposed the first hydrogeological model in the Semarang urban area. The hydrogeological model was simplified into one deep confined aquifer system. Haryadi *et al*. (1991) improved the hydrogeological model for the Semarang regional coastal plain. It was constructed by nine HSUs. All units were illustrated as confined aquifers without any aquitard as a confined unit in the model. The lateral distribution was derived from the regional hydrogeological map without any further analysis.

At present, there is a lack of precise hydrogeological model, in particular for a multiple aquifer system in Semarang. Thus, this paper is focused on developing a hydrogeological model of the Semarang multilayer aquifers by using an integration of geological and hydrogeological data.

Geological and Hydrogeological Setting

Similar to other regions in Indonesia, Semarang has two seasons, *i.e.* dry and wet seasons. The wet season (November to April) has monthly rainfall of more than 150 mm mo-1 as the impact of the west monsoon wind that blows from Asia towards Australia bringing abundant moisture from the Java Sea and Indian Ocean. Meanwhile, the east monsoon (May to October) brings much drier air from Australia. In this period, Indonesia experiences the dry season. Thus, the minimum monthly rainfall in July and August is below 50 mm mo-1. Meteorology, Climatology, and Geophysics Agency (BMKG) in Semarang estimated the average monthly rainfall and temperature using 1998 to 2007 data as 174 mm mo-1 and 27.6°C, respectively (BMKG, 2008).

Regionally, the stratigraphy of Semarang is divided into three main groups, those are surficial deposit and sedimentary rocks, volcanic rocks, and intrusive rocks (Figure 2). Based on the regional geological maps of Semarang (Thanden *et al*., 1996), Salatiga (Sukardi and Budhitrisna, 1992), and Kudus (Suwarti and Wikarno, 1992), intrusive andesite (Tma) is the oldest rock (Middle Miocene) in these areas. The sedimentary rocks from old to young are Kerek Formation (Tmk) in the south and Wonocolo Formation (Tmw) in the east; Kalibeng Formation (Tmpk) containing Kapung (Tmkk), Damar (Tmkd), and Banyak (Tmkb) Members; Kaligetas Formation (Qpkg), and Damar Formation (QTd). The vol-

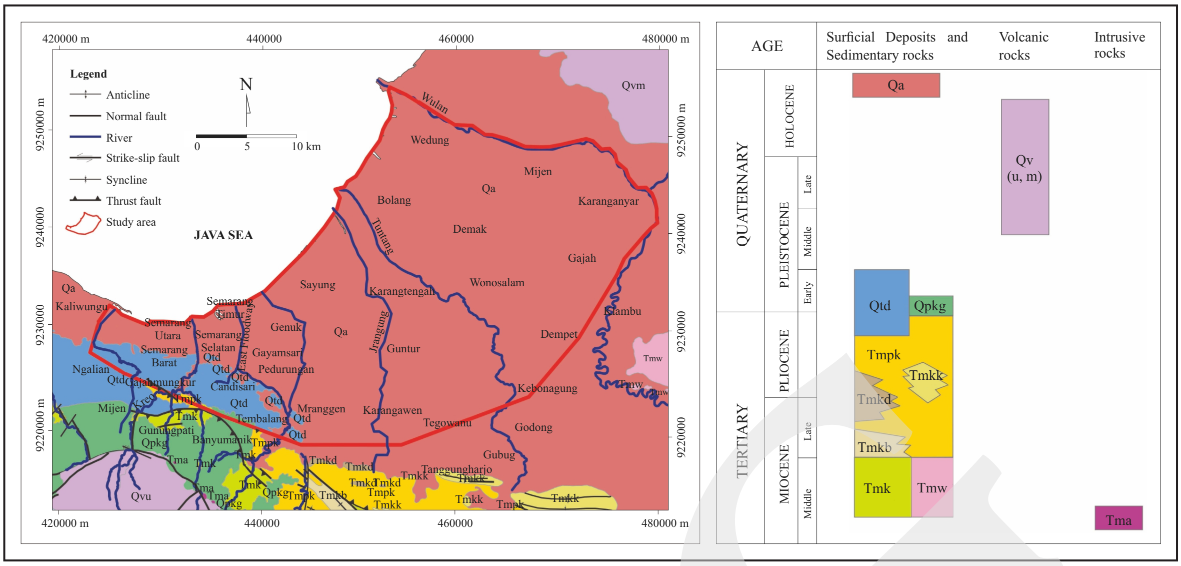

Figure 2. Regional geological map (left) and stratigraphic correlation (right) of Semarang area (Thanden *et al*., 1996; Sukardi and Budhitrisna, 1992; Suwarti and Wikarno,1992). Note: Qa (alluvium); Qv (u,m) volcanic rocks, undifferentiated Ungaran and Muria Mountains; QTd (Damar Formation); Qpkg (Kaligetas Formation); Tmpk (Kalibeng Formation); Tmkd (Damar Members); Tmkk (Kapung Members); Tmkb (Banyak Members); Tmk (Kerek Formation); Tmw (Wonocolo Formation); Tma (Intrusive andesite).

canic rocks (Ov u,m) comprise undifferentiated Ungaran and Muria Mountain products located in the south and northeast, respectively. Those two volcanics consist of breccia, lava, tuff, and laharic breccia. The youngest lithology is alluvium (Qa) as a result of coastal plain, river, and lake processes.

Thanden *et al.* (1996) stated that the Kerek Formation (Middle Miocene) consists of alternating claystone, marl, and limestone. The claystones are partly interlayered with siltstone or sandstone, while locally they contain forams, molluscs, and coral colonies. The limestones are commonly bedded and sandy with the total thickness of more than 400 m. While the Kalibeng Formation (Late Miocene-Pliocene) comprises massive marl in the upper part, locally carbonaceous with tuffaceous sandstone and limestone intercalations.

Damar Formation is composed of tuffaceous sandstone, conglomerate, and volcanic breccia. The latter lithology occurs as lahar deposits in the centre of Semarang area. The Damar Formation which is partly nonmarine, contains molluscs and vertebrate remains. Kaligetas Formation consists of breccia, lava flows, tuffaceous sandstone, and claystone.

Scaheck (1975) stated that the Semarang coastal plain is formed by basin sediments deposited in a marine environment. The bulk of the basin sediments contains alluvium consisting of thick layers of calcareous and shell bearing clay with thin intercalations of sand, and occasionally gravel to pebble or cemented gravel.

Tectonic activities were started at the Early Tertiary by basaltic and andesitic intrusions in the southern part of Semarang, and then continued by uplifting and erosion processes. The erosion formed turbiditic deposits of Kerek Formation in the neritic environment. It was afterward succeeded by the Kalibeng Formation deposited in a bathyal environment. Then, the Damar Formation overlying conformably on top of the Kalibeng Formation, was deposited in transitional to the terrestrial environment. In Plio-Pleistocene, tectonic activities reactivated the result of Early Tertiary deformation, and they dominantly formed faults as shown in the south area (Figure 2). Young Quaternary volcanic deposits rose through weak zones from fractures (Thanden *et al*., 1996).

The groundwater flows from mountainous areas in the south towards the coastal plain in the north, predominantly in an intergranular system consisting of sedimentary deposits, while volcanic rocks form an aquifer system of minor importance. They are fissure, interstice, and fracture aquifer systems (Said and Sukrisno, 1984).

Previous reports describe that there are two aquifer systems in Semarang: an unconfined aquifer and a confined one (Said, 1974; Sihwanto *et al*., 1988; Arifin and Mulyana, 1990; Mulyana and Wahid, 1994; Spitz and Moreno, 1996; Arifin and Wahyudin, 2000). The unconfined aquifer is formed by alluvial deposits consisting of intercalating sand and clayey sand. The groundwater is abstracted by numerous dug wells, mainly for domestic water supplies. The depth of the groundwater table ranges from 0.1 to 21.8 m below ground surface with increasing depth towards hilly areas in the south (Susana and Harnandi, 2007). The fluctuation of water table depends on the seasons: high and low in the rainy and dry seasons, respectively.

Marine sediments in the coastal areas and volcanic ones in hilly areas dominantly form the confined aquifer. Multiple layers separated by clay layers as aquitards set up the confined aquifers. The confined aquifers comprise three groups, those are Quaternary marine, Garang, and Damar. The Quaternary marine and Garang groups are quite similar in the lithologic characteristics. They can only be distinguished by a hydrogeochemical source. Moreover, the Garang aquifer contains fresh water, whereas the Quaternary marine aquifer shows brackish or salty water. The Damar aquifer is dominated by volcanic sedimentary rocks.

Materials and Methods

Firstly, the paper describes geological and hydrogeological settings, and then hydrogeochemical analysis is presented to define the water type and lateral distribution. Lastly, the development of HSU was constructed by the interpretation of two hydrogeological cross sections from several borelogs. The first step in developing a hydrogeological model is to define the geological and hydrogeological settings of the study area to ensure the natural system (Anderson and Woessner, 1992; Spitz and Moreno, 1996; Sefelnasr, 2007; Singhal and Goyal, 2011).

Many sources of hydrogeological and geological data are contributed to the construction of the hydrogeological model. The data were obtained from hydrogeochemical analysis of groundwater samples, while well logs were collected to construct the hydrogeological cross section.

In the hydrogeochemical analysis, major cation and anion contents were analyzed to describe the water types and lateral distribution of the aquifers in the study area. The correctness of the chemical analysis was verified by calculating the ion balance error (IBE) using the following formula (Hötlz and Witthüser, 1999):

$$IBE[\%] = \frac{\Sigma \text{ Cations - } \Sigma \text{ Anions}}{0.5\text{x } [\Sigma \text{ Cations + } \Sigma \text{ Anions}]} \; x100$$

Furthermore, the regional geological (Figure 2) and the hydrogeological maps of Semarang (Said and Sukrisno, 1998) were used to understand the geological and hydrogeological settings in the studied area as well.

Two hydrostratigraphical cross-sections were made to describe the subsurface conditions based on the borelog data. The hydrostratigrapical unit (HSU) concept was applied to define the hydrogeologic conditions in the study area. The term of HSU was first proposed by Maxey (1964) to describe a body of rock with considerable lateral extent composing of a geological framework for a reasonably distinct hydrological system. A systematic analysis using an integration of geology, hydraulic head, and hydrogeochemistry data set was used to define and verify the HSU.

Results and Discussion

Hydrogeochemistry

As mentioned above that the groundwater exploited through deep wells is concentrated in a confined aquifer system, then groundwater samples were taken from fifty-eight deep wells.

The hydrogeochemical characteristics of the confined aquifers were analyzed for major cation (K^+, Ca^{2+}, and Mg^{2+}) and anion (SO_4^{2-}, Cl-, and HCO_{3-}) contents on samples chosen randomly in the study area. Secondary data from unpublished reports (Mulyana and Wahid, 1994; DGTL, 2003; P.T. Gea Sakti, 2006; Susana and Harnandi, 2007) are also collected and used. The correctness of the chemical analysis was verified by calculating the ion-balance error (IBE) using Equation 1. It was found that the IBE of all samples were less than 10% as shown in Table 1, which ensured the reliability of the chemical data.

Furthermore, the major cation and anion contents were plotted in a Piper diagram to determine the water type according to the Furtak and Languth classification (1967), as shown in Figure 3. It clearly depicts that the water type of Garang (Gr) is predominantly (hydrogen-) carbonate alkaline water, while the Quaternary marine (Qm) contains predominantly chloride alkaline water, locally alkaline earth water type. The Damar (Dm) aquifer containing freshwater in volcanic rocks may indicate a deeply and circulate flow path classified as predominant hydrogen-carbonate alkaline earth water with typically higher alkaline. Regarding Appelo and Postma (2007), the cation exchange processes at the interface between salt and fresh water occur when the water composition of Quaternary marine is presented by Ca2+ and HCO3- flowing from intermediate horizon towards lower slopes and plains. Sediments in these areas adsorb Ca2+, while Na+ is released. Thus, the Garang aquifer has a NaHCO3- water type. Meanwhile, groundwater along plain and coastal areas shows dominant Na+ and Cl- ions due to intensive groundwater pumping for a long time that causes seawater to intrude into Qm.

Figure 4 shows water chemistry of confined aquifer groups based on major cation and anion contents. As explained before, the Garang and Quaternary marine aquifers have the same lithologic compositions, which are alluvium deposits, but they have different electrical conductivity (eC) values and facies as shown in a Piper Diagram (Figure 3). The Quaternary marine dominantly spreads out in plain and coastal areas, while the Garang in the centre of Semarang to the northeast, and forms a ridge below surface. While the Damar spreads out in the hilly areas towards an intermediate slope. The Quaternary marine has higher eC value, which is > 807 µS cm-1 than the Garang (Table 1) as an impact of seawater intrusion due to overexploitation (Figure 5). A number of deep wells increased sharply from below 300 wells in 1980s up to more than 1.000 wells with the total abstraction of more than 30 million m3/year (MCM yr-1) in 2010.

Hydrostratigraphical Units (HSU)

It is extremely difficult to correlate stratigraphical details over a significant distance because of lithologic heterogeneity in the study area. The lithologies are clay, clayey sand, tuffaceous sand, sand, conglomerate, and sandy limestone based on the borelog data. They reflected a conceptual diagram of the volca nic sedimentary sequence in Central Java which was developed by Lloyd *et al*. (1985). The volcanic deposit and sedimentary derivatives formed stages related to a volcanic centre: the intermediate and lower slopes and the coastal plains as shown in the hydrogeological cross section. The concept of HSU was applied to generalize the hydrogeological system in the study area (Figure 6), where there are two aquifers, three aquitards, and one aquiclude. Several borelog data in lower slopes and plain areas consist of both Aquifers 1 and 2 (2a and 2b) as well as three aquitards. These units are mainly alluvium (Qa) as shown in borelog from CV Harum Manis to Bulusan (Figure 7, cross section A-B). Aquifer 2c, located in the intermediate slope, consists of the Damar Formation. The aquiclude as the basement comprises the Kalibeng and Kerek Formations as shown by some borelogs in Demak region (Matesih to Wedung, cross section C-D). The description of HSU is discussed based on the hydrostratigraphical cross sections.

From cross section A-B, the unconfined aquifer (Aquifer 1) spreads out from the intermediate slopes to plain areas. In plain areas, it consists of loose deposits such as clayey sand and sand (alluvium deposit), while in the lower and

Table 1. The Major Ion Contents of Groundwater Samples (Mulyana and Wahid, 1994; DGTL, 2003; P.T. Gea Sakti, 2006; Susana and Harnandi, 2007)

No.	Location	eC	Major Ion Contents [meq L^{-1}]							IBE [%]	Aquifer Type
		[µS cm^{-1}]	K^+	Ca^{2+}	Mg^{2+}	Na^+	SO_4^{2-}	Cl^-	HCO_{3-}		
1	Obs. Pelabuhan	3.010	0.36	9.87	5.91	25.2	0.36	35.0	3.02	7.53	Qm
2	Obs. STM Perkapalan	1.447	0.36	1.47	3.35	13.0	0.40	9.49	8.52	-1.06	Qm
3	Obs. LIK Kaligawe	4.650	0.63	1.95	16.2	29.6	0.95	42.4	4.83	0.34	Qm
4	Obs. Unisula 2	23.900	0.43	36.5	149	313	0.84	444	37.1	3.55	Qm
5	Obs. Kec. Pedurungan	914	0.37	1.85	2.96	6.52	0.29	4.10	7.84	-4.38	Qm
6	Desa Gemolak	1.006	0.13	0.83	1.34	8.70	0.26	3.23	6.70	7.61	Qm
7	Obs. Standart Battery	363	0.17	2.69	1.21	1.57	0.13	1.23	4.24	0.57	Dm
8	Obs. Citra Land	226	0.29	0.71	0.49	1.35	0.66	0.73	1.29	6.19	Gr
9	Obs. PT. Kimia Farma	457	0.19	2.43	1.84	1.22	0.24	0.47	5.17	-3.39	Dm
10	Obs. Sumberejo	1.024	0.08	1.06	0.19	10.4	0.62	3.99	6.58	5.01	Qm
11	Aquaria	672	0.15	1.25	0.74	5.74	1.10	0.55	5.91	4.26	Gr
12	Obs. Katon Sari	3.580	1.11	18.9	6.82	20.0	1.35	27.9	14.7	6.43	Qm
13	Obs. Batu	1.762	0.24	1.09	2.77	13.0	0.76	7.05	8.52	4.90	Qm
14	Hotel Rahayu	1.902	0.23	7.08	1.30	27.0	0.46	28.3	3.96	8.49	Qm
15	Es Prawito Jaya Baru	370	0.17	2.43	1.10	1.13	0.20	0.59	4.00	0.90	Dm
16	Gudang PT Djarum	789	0.14	3.13	1.52	4.22	0.78	4.10	4.55	-4.56	Gr
17	SU Mangunharjo	626	0.24	0.54	0.35	5.00	0.35	3.59	2.49	-4.81	Qm
18	PT Sandratex	1.220	0.41	3.49	2.65	6.09	0.99	7.28	4.15	1.75	Qm
19	Bukit Perak	452	0.18	2.73	1.30	1.61	0.14	1.26	4.21	3.39	Dm
20	CP Prima	673	0.09	2.32	0.41	3.48	1.35	1.62	3.11	3.72	Gr
21	PT Sarana Mina	807	0.08	0.78	0.54	6.26	1.79	1.56	4.52	-2.65	Gr
22	Desa Bulusari	850	0.06	0.70	0.32	6.52	2.05	2.57	2.37	8.46	Qm
23	RRI Kuripan	911	0.26	1.85	0.74	6.43	1.66	1.31	5.94	4.09	Qm
24	Kartika sirup Gubug	584	0.22	1.45	0.57	4.35	0.25	1.38	5.11	-2.32	Qm
25	Obs PRPP	1.623	0.42	1.44	2.93	11.3	0.60	11.5	4.89	-5.68	Qm
26	Aorta. Kaligawe	636	0.09	1.02	0.12	5.57	1.18	1.16	4.52	-0.89	Gr
27	Bulusan Karangtengah	1.183	0.26	0.43	0.11	10.6	0.95	5.95	4.40	0.86	Qm
28	Desa Karangsari	631	0.04	0.24	0.50	5.57	1.32	1.56	2.92	9.02	Qm
29	Desa Trengguli	3.890	0.50	15.5	6.81	19.1	1.59	35.3	6.31	-3.05	Qm
30	Desa Rejosari	2.300	0.17	2.16	1.07	21.7	0.80	22.9	2.12	-2.55	Qm
31	PT. Ny.Meneer-1	704	0.17	0.50	0.49	5.22	1.93	1.01	3.64	-3.01	Gr
32	Obs. Indofood	349	0.15	2.12	1.47	1.17	0.45	0.32	3.91	5.27	Dm
33	Obs. Sampokong	671	0.64	0.61	0.04	4.30	0.46	1.12	3.85	2.90	Gr
34	PT. Panca Tunggal-1	2.370	1.25	3.25	2.20	18.6	0.97	21.4	4.24	-5.22	Qm
35	Hotel Oewa Asia	1.023	0.26	1.28	1.26	7.83	1.26	6.46	3.32	-3.92	Qm
36	PT. INAN	1.372	0.13	0.44	0.66	6.52	1.36	3.84	2.81	-3.47	Qm
37	Obs. SD Kuningan	759	0.26	0.19	2.39	6.43	1.49	1.05	6.21	5.62	Gr
38	PT. Sango Keramik	408	0.15	2.06	0.99	1.30	0.23	0.39	4.29	-8.57	Dm
39	Dolog Mangkang	557	0.23	2.25	1.35	2.17	0.80	1.61	3.80	-3.30	Dm
40	Hotel Santika	1.341	0.26	2.69	2.42	6.96	0.31	6.31	5.83	-1.11	Qm
41	PT Wahyu Utomo	373	0.15	2.31	1.12	2.17	1.47	0.35	4.40	-7.67	Dm
42	PT. Gentong Gotri	1.020	0.39	1.81	2.85	5.83	0.32	4.89	4.94	6.85	Qm
43	Tambakharjo. Tugu	2.790	0.47	0.53	4.94	13.9	0.46	18.7	1.92	-6.03	Qm
44	Tambak Udang. Mangkang	790	0.31	0.13	0.74	7.13	2.57	3.14	2.78	-2.31	Qm
45	PT. Damaitex	1.240	0.36	7.13	0.99	2.39	0.89	4.94	4.52	4.93	Qm
46	Desa Donorejo	1.650	0.06	0.96	0.64	12.0	3.39	5.00	6.07	-5.67	Qm
47	Guntur	1.350	0.24	0.88	0.44	10.8	3.46	2.81	6.27	-1.63	Qm
48	PDAM Manyaran	900	0.30	2.65	1.82	1.61	0.14	0.36	5.78	1.59	Dm
49	RS Kariadi	680	0.19	3.38	1.71	2.17	0.34	1.22	5.29	8.50	Dm
50	Hotel Metro Int	1.200	0.27	2.13	1.10	7.30	1.66	6.07	4.15	-9.40	Qm
51	Jamus Mranggen	800	0.16	0.88	0.44	5.65	0.75	0.77	5.27	4.97	Qm
52	PT Amor Abadi	690	0.20	0.41	0.26	6.09	1.39	1.02	4.27	4.06	Gr
53	Pabrik Kembang Gula Sano	685	0.20	1.40	0.99	5.87	1.11	0.59	7.61	-9.64	Gr
54	Hotel Siranda	740	0.19	4.50	1.94	2.70	0.37	1.97	6.20	8.86	Dm
55	Sendangguwo	694	0.19	3.40	1.73	2.22	0.34	1.15	5.34	9.66	Dm
56	Rowosari	1.259	0.20	0.90	1.73	6.96	0.44	0.70	7.75	9.57	Qm
57	Tandang	694	0.20	3.45	1.71	2.39	0.35	1.21	5.51	9.23	Dm
58	Ngalian	982	0.13	4.33	3.10	0.96	0.32	1.58	6.16	5.63	Dm

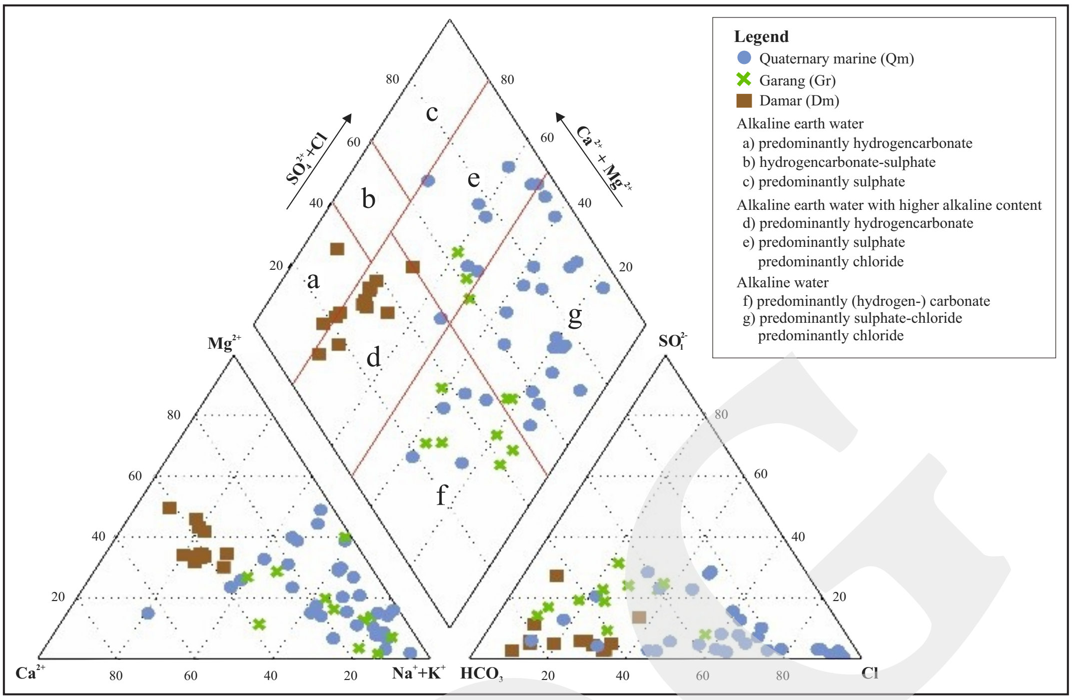

Figure 3. The hydrogeochemistry classification of groundwater samples in a confined aquifer using a Piper plot of the Furtak and Langguth (1967) classification.

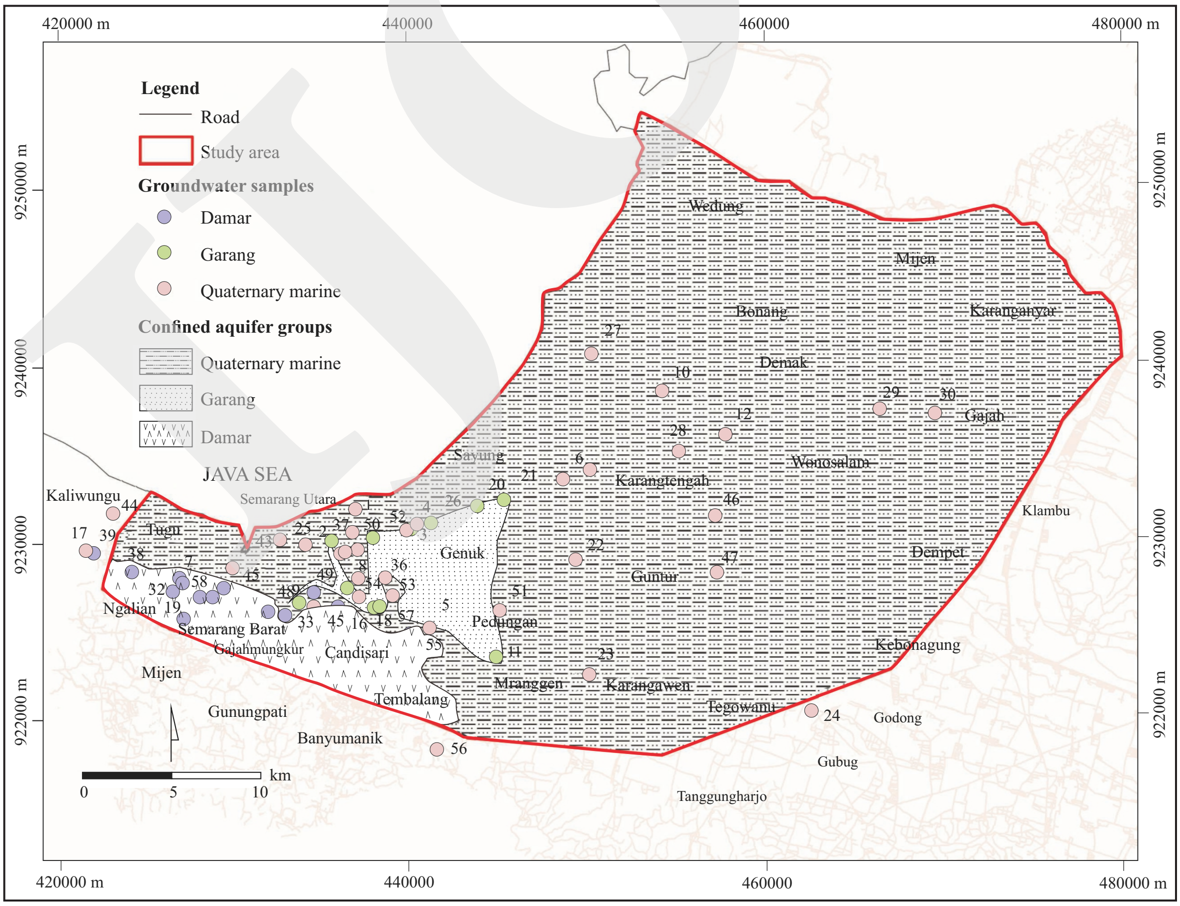

Figure 4. Map showing water chemistry of confined aquifer groups.

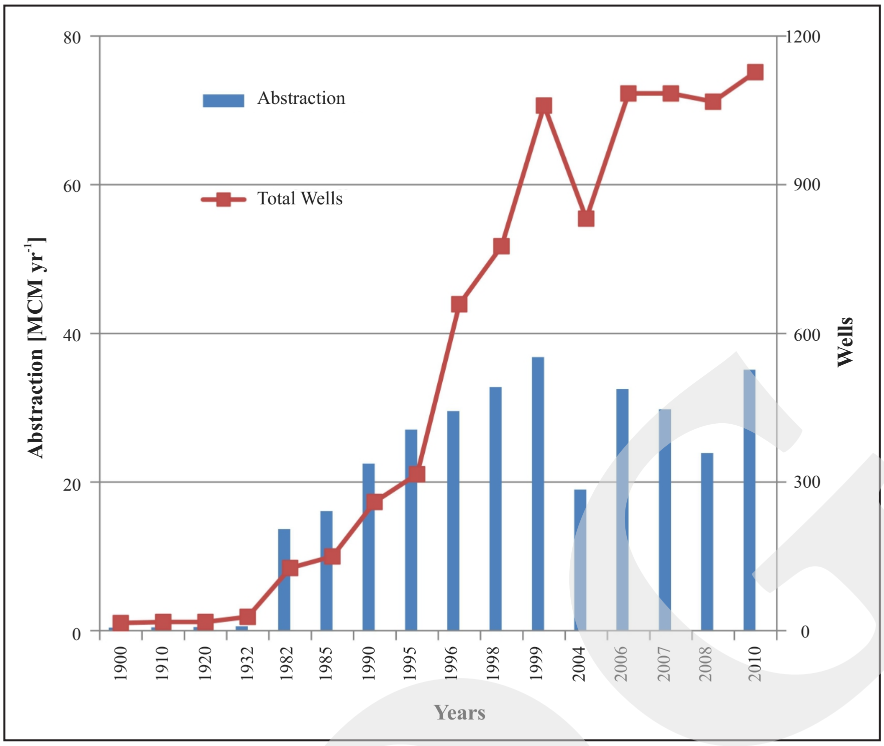

Figure 5. Number of registered deep wells and total abstraction in Semarang-Demak groundwater basin (DGTL, 2003; DESDM Prov. Jateng, 2012).

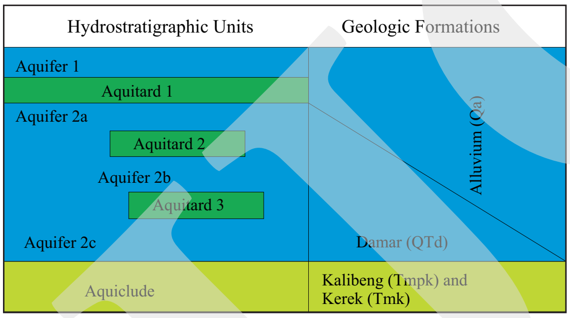

Figure 6. Hydrostratigraphy units of the study area.

middle slopes it is composed of clayey sand, conglomerate, and sand (sedimentary and volcanic sediments). Groundwater head of the unconfined aquifer is controlled by morphological forms. The groundwater level is deeper in the southern part in accordance with topographic expression which is higher in the south. From the cross section C-D, the topography is relatively flat (plain areas) and the groundwater head of unconfined aquifer is close to the surface.

The clay layer in both cross sections (A-B and C-D) separating the unconfined and confined aquifers, forms an aquitard. The confined aquifers (Aquifers 2) consist of three groups which are the Garang (2a), Quaternary marine (2b), and Damar (2c) aquifers. The Quaternary marine and Garang aquifers are surficial deposits (Qa), while the Damar aquifer comprises sedimentary rocks (QTd). There are three aquitards in the cross sections. Aquitard 1 is found in all areas varying from 5 to 30 m thick in the centre towards the north, and becomes thinner to the south. Conversely, Aquitards 2 and 3 spread unevenly in the study area. They are inserted in Aquifer 2 varying in thickness from 5 - 20 m.

As an impact of intensive groundwater abstraction in the central Semarang area, groundwater head of the confined aquifer in cross section A-B becomes about 20 m depth in the lowland area. In case of cross section C-D, the groundwater head is close to the surface in the east. Groundwater flows from the hilly area in the south towards the plain area in the north. Sandy limestone in the bottom of confined aquifer is an impermeable zone/aquiclude and acts as a basement in the hydrogeological system (Figure 7).

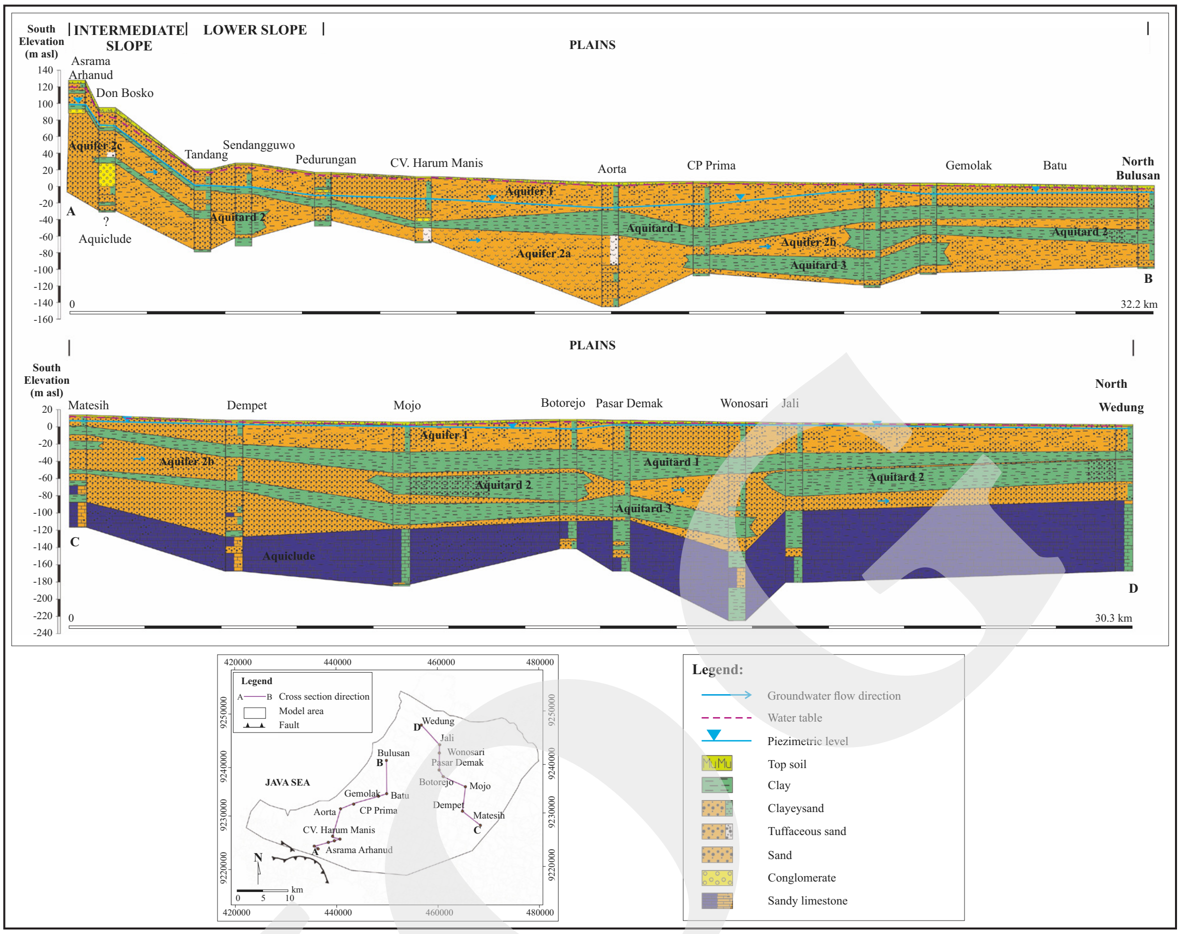

Figure 7. Aquifer system in the study area.

Conclusion

The present study integrates geological and hydrogeological data to construct a hydrogeological model of the aquifer system in Semarang. The hydrostratigraphical units of Semarang consist of two aquifers (Aquifer 1 and Aquifer 2), three aquitards, and one aquiclude. Based on the hydrogeochemistry analysis of ion content, Aquifer 2 is divided into three groups, *i.e.* the Garang (Aquifer 2a), Quaternary marine (Aquifer 2b), and Damar (Aquifer 2c). Aquifers 2a and 2b have the same lithologic compositions, those are alluvium deposits, but they have different electrical conductivity (eC) values and groundwater facies. Aquifer 2b has a higher eC value (> 807 µS cm-1) than the Garang as an impact of seawater intrusion due to over exploitation. Aquifer 2b predominantly contains chloride alkaline water, locally alkaline earth water type, while the groundwater facies of Aquifer 2a predominantly contains (hydrogen-) carbonate alkaline water. Aquifer 2c contains freshwater in volcanic deposits classified as hydrogen-carbonate alkaline earth water with typically higher alkaline.

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