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Aquifer system for potential groundwater resources in Hanoi, Vietnam

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Abstract:

Predictions in Ungauged Basins (PUB) mainly focus on surface water, but there are much higher prediction uncertainties inherent in groundwater. Hanoi depends entirely on groundwater for its domestic water supply. However, the characteristics of the entire Hanoi aquifer system remain poorly understood due to the lack of available data. Recently, we were nominated to construct a hydrogeological database. Using the valuable data contained in this database, this paper comprehensively analyzed the best number of 240 boreholes including well logs and their hydrogeological parameters obtained from pumping tests for the first time in order to identify the entire Hanoi aquifer system and characterize the hydrogeological conditions for potential groundwater resources. Great efforts have been made to establish and analyze the hydrogeological maps, cross sections and the isopach maps of main aquifers' thickness and transmissibility. As for the results, we found that groundwater mainly exists in the topmost Holocene unconfined aquifer and the shallow Pleistocene confined aquifer (PCA), while cleft and karst water exists in the Neogene water bearing layer and the Mesozoic fractured zones. These aquifers are adequately, quantitatively characterized and evaluated from the viewpoint of potential groundwater resources. We found the PCA serving as the highest groundwater potential and the most important aquifer for the water supply. The findings are indispensable for further groundwater analyses contributing to ensuring the sustainable groundwater development not only in Hanoi but also in poorly gauged or ungauged neighboring basins. Copyright © 2012 John Wiley & Sons, Ltd.

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INTRODUCTION

The sustainable management of groundwater resources is one of the essential and challenging objectives for the future of developing countries like Vietnam. In this area, many poorly gauged and ungauged basins exist, and their hydrological predictions are becoming more and more important to overcome the water crisis in the 21st century (Sivapalan *et al*., 2006; Mende *et al*., 2007). The Vietnamese capital, Hanoi, the centre of economy, culture and politics for Vietnam is also addressing this because: (1) The demand for clean water is becoming rather urgentm (2) The water supply greatly depends on the groundwater resources (up to almost 100%). The amount of groundwater abstraction has been rapidly and continuously increasing, (3) The undue exploitation of the groundwater without wise management and an adequate understanding of the aquifer system characteristics have caused some serious problems such as: the drying up of shallow wells, groundwater pollution, land subsidence and the decline of groundwater level in this area (Tong, 2000; Bui, 2005).

Improving the understanding and prediction of ungauged basins are key goals of the new International Association of Hydrological Sciences Decade for Predictions in Ungauged Basins (PUB) (Sivapalan *et al*., 2006) which started in 2001. The PUB mainly focus on surface water, but there are much higher prediction uncertainties inherent in groundwater. The key step in groundwater modeling and forecasting is aquifer system characterization which is used to estimate model parameters and to establish a conceptual model and its boundary conditions. The aquifer system must be properly understood in order to make better process-based PUB.

Understanding and quantifying groundwater resources is a very complex and difficult task. Groundwater investigations thus require a comprehensive understanding of the host geological formations (aquifers) and the hydrological processes which control the storage and movement of water within the subsurface. Although the geophysical methods and remote sensing techniques can assist with hydrogeological interpretations, the most useful and reliable information is observed field data obtained from boreholes (Lewis *et al*., 2008).

Since the 1990s, several methodologies for groundwater management and assessment have been developed, which are increasingly being applied within GIS and database environments. The vast majority of these projects have been carried out in developed countries where a wide range of information and sound technical and financial resources are available (Mende *et al*., 2007). However, the limited amount of necessary input data and the broad lack of basic

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information, e.g. systematic geological or hydrogeological maps as well as detailed information about well logs with geotechnical and hydrogeological parameters, are typical for developing countries and cause insufficient understanding about characteristics of the aquifer system. It hardly allows for the application of sophisticated groundwater management tools in these areas, and the results of those approaches tend to cause great uncertainty.

Therefore, adequately obtaining basic data and understanding the characteristics of the aquifer system are fundamental for the validity of other hydrogeological studies. Researchers in the world have done a great deal of studies aimed at identifying the aquifer system. Zhang *et al*. (2007) conducted a comprehensive analysis of basic hydrogeological data to clarify the aquifer system in the Southern Yangtse Delta, China, in which hydrostratigraphic units of two aquifers and three aquitards with their hydrogeological properties were quantitatively characterized. Recently, Lewis *et al*. (2008) revealed the hydrogeological system of five distinctive hydrogeological systems as fundamental before going to assess groundwater resources in the Broken Hill Region, Australia. Many other works demonstrating the necessities of portraying the aquifer system as groundwater resources had been investigated in the Lower Mississippi Valley, USA (Boswell, 1996); Kali-Ganga sub-basin, India (Umar *et al*., 2001); Central Kalimantan, Indonesia (Ludang *et al*., 2007); southeast coastal plain aquifers, North Carolina, USA (McCoy *et al*., 2007); the Bengal basin in India and Bangladesh (Mukherjee *et al*., 2009); an altered wetland in Jordan (Litaor *et al*., 2008); and, many others. The subjects of aquifer system identification and characterization have been done for many other areas by many researchers over the world but have not been done yet for the entire city of Hanoi.

In Vietnam, there have been a large number of water resource-related studies on the Red River Delta (Berg *et al*., 2001, 2007; Doan and Boyd, 2003; Agusa *et al*., 2005; Funabiki *et al*., 2007; Ngo *et al*., 2007; Larsen *et al*., 2008) and the MeKong River Delta (Ta *et al*., 2002; Nuber and Stolpe, 2004; Kohnhorst, 2005; Mekong River Commission, 2005; Kazama *et al*., 2007; Shinkai *et al*., 2007). However, most of them were concerned about the origin, evolution and development of the Deltas, as well as water pollution, especially arsenic pollution, and these studies were limited to small local cities within the Deltas. Few original investigations of the groundwater in the Hanoi area exist in literature as well. Among these, Gupta and Truong (1999) and Duong *et al*. (2003) considered the groundwater quality, pollution and monitoring system design; Nguyen and Helm (1996) and Trinh and Fredlund (2000) investigated the land subsidence due to excessive groundwater exploitation in some urban portions of the Hanoi area. Although we had roughly identified the aquifer system in Hanoi as an intermediary task for specific purposes such as groundwater pollution modeling (Bui *et al*., 2007) and artificial recharge to groundwater (Tong and Bui, 2004), those works just analyzed limited areas within Hanoi and were based on very few numbers of boreholes. So far, there has been no comprehensive work focusing on aquifer system identification and characterization for the entire Hanoi area as a primary goal due to the unavailability of basic data, while comprehensive understanding of the aquifer system and hydrogeological conditions is a key factor and prerequisite for those studies.

Starting from these practical difficulties, we recently have implemented a National Hydrogeological Database Project under the support and nomination of the Department of Geology and Minerals of Vietnam where during the first case, our investigation could carry out empirical works to get all of the observational data and the basic data together, especially borehole data, from various sources throughout all of Hanoi. To take advantage of our unique, internally available data sets as much as possible, the main objectives of this paper are to identify the entire Hanoi aquifer system and characterize its hydrogeological properties adequately and quantitatively from the viewpoint of potential groundwater resources. To achieve the aims aforementioned, this work has focused on acquiring, compiling and analyzing hydrogeological data from many field sites within the city and from the highest number of existing boreholes, thereby establishing hydrogeological maps, cross sections and the expected ranges of groundwater parameters for the different aquifers. Once these findings are internationally documented, they could provide indispensable, fundamental information and serve as a basic reference for further hydrological studies, not only in Hanoi but also in poorly gauged or ungauged neighboring basins.

STUDY AREA AND DATA USED

Study area

From August 1, 2008 in the Hatay province, parts of Vinhphuc and Hoabinh provinces were merged into the metropolitan area of Hanoi. New Hanoi's total area increased three times to 3344 km^2 and was divided into 29 subdivisions. The new population is around 6.2 million (Tong, 2008). However, this study was carried out for old Hanoi before it was merged. Therefore, the study area in this paper is only old Hanoi city which we call just Hanoi.

Hanoi city stretches from near the centre to the northeast of the Red River Delta plain. The area is around 920 km^2, with nine urban districts and five rural districts (Soc son, Dong Anh, Gia Lam, Thanh Tri, Tu Liem) as shown in Figure 1 with about 3.1 million habitants. This accounts for the highest population density in Vietnam.

Hanoi's topography has a gradually shifting tendency towards sea level from the North to the South of Hanoi with an average slope of 4%. Most of Hanoi (90%) lies on a plain with an elevation between 5 and 20 m above sea level, except for some mountainous areas with an elevation from 20 to 374 m in the north of the city. The major topographical type here is flood plain (Tong, 2008).

Hanoi belongs to the tropical monsoonal area with two distinctive seasons in the year, the rainy season from May to October and the dry season from November to April of the following year. The rainy season accounts for about 70–80% of the annual rainfall, which is about 1550 mm. The average humidity is about 80%, and the average

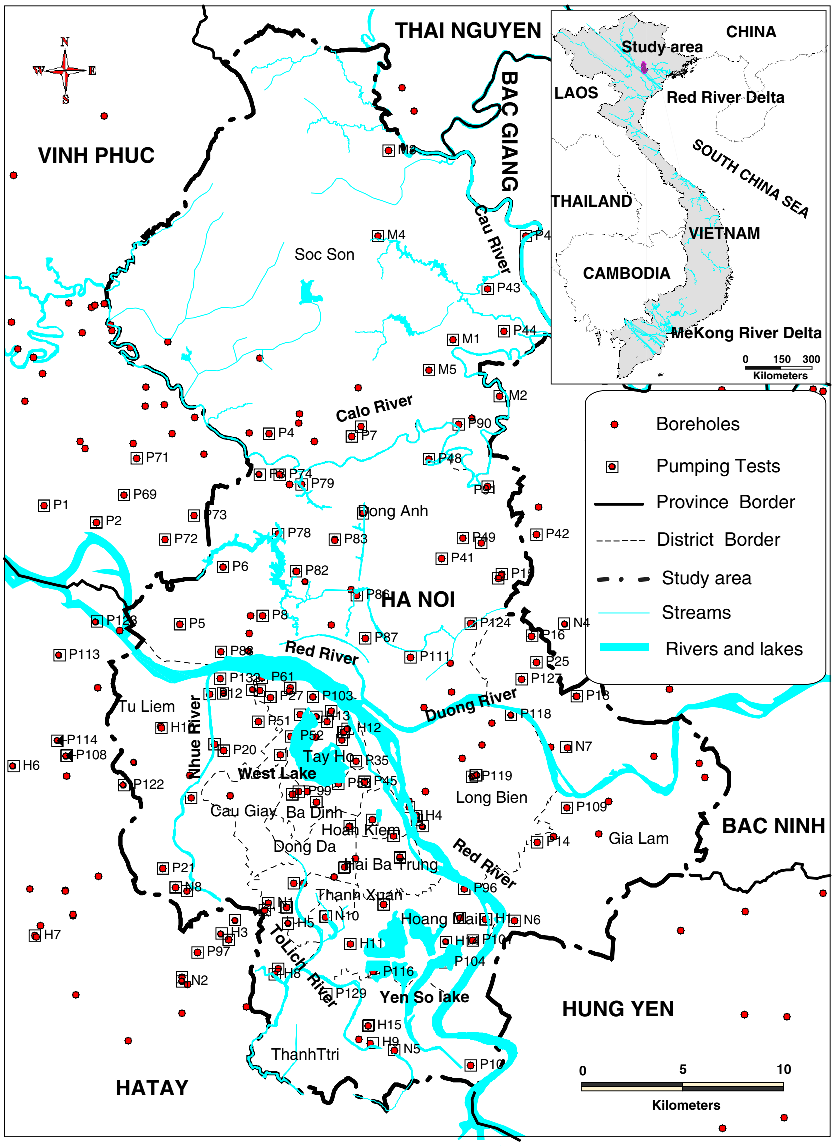

Figure 1. Location of study area and borehole distribution

temperature is around 24.3 °C. Evaporation is quite high, with an annual average of 933 mm (Tong, 2008).

The river network is quite dense in Hanoi with its density of about 0.7 km/km^2, and this includes the main rivers, such as: the Red, Duong, Cau, Calo, Nhue and To Lich rivers as shown in Figure 1. In addition, there are also 111 lakes with a total surface area of up to 2180 hectares. The biggest lake is the West Lake with an area of 526 hectares (Tong, 2008).

The Red River catchment area, the biggest one in the north of Vietnam, stretches over Hanoi city. The average discharge of the Red River at Hanoi station is 385 m^3/s in the dry season and 14,800 m^3/s in the flood season. The water of the Red River has a high level of suspended deposits at any one time. Due to the insufficiency of infrastructure and unwise management of dumping waste, the surface water, especially in lakes, in Hanoi has been seriously polluted (Tong, 2008).

Groundwater thus becomes a main source of the water supply in Hanoi. The amount of groundwater abstraction has been rapidly and continuously increasing. The average pumping rate now is around 496,000 m^3/day and predicted to be up to 1,000,000 m^3/day by 2020. The excessive exploitation of the groundwater without wise management and an adequate understanding of the aquifer system have caused some serious problems, such as: groundwater pollution, groundwater level decline and land subsidence in Hanoi (Tong, 2000; Bui, 2005; Vu and Bui, 2005) as mentioned in the introduction. Depression cones of the groundwater table in the confined aquifer have occurred seriously in the south of the Red River, which is continuously expanding with seasonal fluctuation (Tong and Bui, 2004). Some bio-chemical items like ammonia, microbe, heavy metal, arsenic concentration and so on have increased over the years (Berg *et al*., 2001, 2007; UNICEF Vietnam, 2001; Agusa *et al*., 2005; Bui *et al*., 2007).

Establishment of National Hydrogeological Database Project

The reliability and validity of the groundwater analysis strongly depend on the availability of a large volume of high-quality data (Gogu *et al*., 2001). Data availability is also essential for developing complicated, integrated approaches for groundwater management and monitoring (Rossetto *et al*., 2007). In Vietnam, however, hydrogeological data are sparse, seldom systematically organized and accessible to a very limited number of users. These primary data sets come from various sources, such as: the Vietnamese geological survey departments, local or national environmental agencies, public and private research institutions, consultant firms and many others. There are large differences in the data format, quality and storage media. Hanoi could be regarded as a poorly gauged region. This problem is an obstacle to the application of integrated groundwater management on a large basin scale.

A time-consuming and costly project named the 'National Hydrogeological Database Project' was therefore initiated under the Ministerial Decision which was part of the Prime Minister's own decisions (Prime Minister of Vietnam, 2001). The project lasted from 2002 to 2004 and cost 7.4 billion VND (1USD = 15,000VND) in which Dr. Tong, one of the authors, was nominated as project leader to construct the GIS-based hydrogeological database. Various empirical works had been implemented for the first time to get observational and basic data over Hanoi. All basic data, both tables and maps, are managed in GIS-based environment and handled by a central computer program called HYDROGEOBANK. This approach for synthesizing existing information and data is easier to use than conventional approaches because GIS provides the capability for dynamic query and analysis, display of information and a more understandable representation. The common advantages of a GIS-based database approach include the reduction in data redundancy, the proper maintenance of data integrity and quality, it is self-documenting or self-describing, helps to avoid inconsistencies and has security restrictions. Details about this project and the database were described in the final report of the project (Tong, 2004).

Hanoi has the densest hydrogeological data with a large number of data owners in Vietnam. Therefore, the implementation of the database project in Hanoi was much more difficult and valuable than any of the others. The basic data about boreholes, dig wells and springs with their hydraulic properties, such as: general, hydrogeological, stratigraphical, borehole structure, chemical and other surveyed information were collected, integrated and computerized from various sources. General information includes: the borehole owner, name of the borehole drilling investigation, time of borehole completion, geographical coordinates, administrative address and ground surface elevation of boreholes. Hydrogeological information consists of pumping rates, specific capacity, water level, hydraulic conductivity, transmissibility and storage coefficient. The stratigraphical information contains: material, geological age and depth information of each formation. The borehole structural information includes: the drilling depth, types and dimensions of filter pipe and casing. The chemical information about the content of total dissolved solids (TDS), pH, hardness, cations, anions, etc. as well as local geological and hydrogeological survey data at investigated sites, such as, the distribution of well fields and the map of the groundwater monitoring network, were also gathered. These valuable data sets maintain a vital role for further groundwater studies in Hanoi, but now are not open to the public, just internally accessible by agencies involved in the project and staff members. This paper was the first analysis utilizing the established database from our project. Hopefully, these data sets will be available online in the next stage, because without these data sets, it is very hard to implement the necessary groundwater analyses to ensure the sustainable utilization of groundwater resources for the high-security urban water requirements in Hanoi.

Data used

To take advantage of the data from our National Hydrogeological Database Project as much as possible, we made the best use of all of the 240 boreholes and hydrogeological survey data, including the geological map and their descriptions. One hundred sixty-four boreholes throughout Hanoi and 76 boreholes in the surrounding areas with an average density of around 0.2 boreholes/km^2 as shown in Figure 1 formed the basis for our study. All data (well logs data and values of aquifer parameters) used in this paper has never been analyzed or published elsewhere. Thirty boreholes reach their depth at Neogene-aged formations, and five boreholes were drilled to a depth of Mesozoic-aged formations. The remaining 205 boreholes were drilled within Quaternary-aged formations. Amongst the data from 240 boreholes, there were 169 pumping tests. The number of pumping tests was different from aquifer to aquifer in proportion to the degree of the aquifer's importance for the water supply. There have been 139 conducted for the Pleistocene confined aquifer (PCA), but only 14 for the topmost Holocene unconfined aquifer (HUA), 11 for the Neogene water-bearing layer (NWL), and 5 for the Mesozoic fractured zones (MFZ). No pumping test has been conducted for the Holocene–Pleistocene aquitard (HPA).

The field data of the specific yield of the unconfined aquifer and the storage coefficient of the confined aquifer were only obtained from cross-borehole tests. Only 1 pumping test out of 14 for the HUA and 18 pumping tests out of 139 for the PCA were cross-borehole tests. The rest were single-borehole tests. Therefore, the specific yield and storage coefficient were measured only for the HUA and the PCA, not for the HPA, NWL and MFZ. The specific yield and storage coefficient are important parameters to estimate the potential pumping storage of a specific aquifer which plays a vital role for practical groundwater pumping. The boreholes were completed from 1966 to 2003. This paper focused on analyzing hydrogeological properties, such as: the surface boundaries of aquifers, materials, the aquifer thicknesses and depths, transmissibilities, storage coefficients, specific yields, specific capacities.

IDENTIFICATION OF HYDROGEOLOGICAL FRAMEWORK

In any hydrogeological investigation, the identification of aquifers and aquitards, are needed to be properly understood. Hydrogeological mapping is an effective way to visually depict the hydrogeological characteristics beneath the surface of the land. Several techniques are used in hydrogeological mapping, in which the hydrogeological map and cross-section are the most commonly used techniques for visually depicting a hydrogeological system.

In this paper, we first gathered the field data as stated in the former section and then integrated the data to gain visual demonstrations of the surface distribution of aquifers, resulting in drawing the surface hydrogeological map shown in Figure 2. Geological faults taken from the geological map were also included in Figure 2 to present the places with a certain degree of fractures, water storage and movement in consolidated deposits and bedrocks. Figure 2 shows the display of an aquifer system on the surface where the HUA is the topmost aquifer and is distributed widely from the Red and Duong Rivers, to the south of the city, with a total area of about 530 km^2, occupying about 55% of the study area. There is a confining layer, aged from Holocene to Pleistocene, named HPA, sandwiched between the HUA and PCA. The HPA is mostly located under the HUA in the south but is exposed on the surface, around the centre of Hanoi in the Dong Anh District and the Calo River. The total area is about 25% of Hanoi. The PCA is located underneath the HUA and HPA. Furthermore, there are only several small dispersed areas of PCA present on the surface in the north. Mesozoic bedrocks exposed on the surface of the ground create mountainous areas with a size of about 120 km^2 in the Soc Son District in the north, as shown in Figure 2. MFZ, the fractured parts of Mesozoic bedrock, is distributed sparsely in small zones of Mesozoic bedrock which is difficult to see in Figure 2.

Furthermore, we hydrostratigraphically interpolated strata depth data from a number of well logs. Figure 3

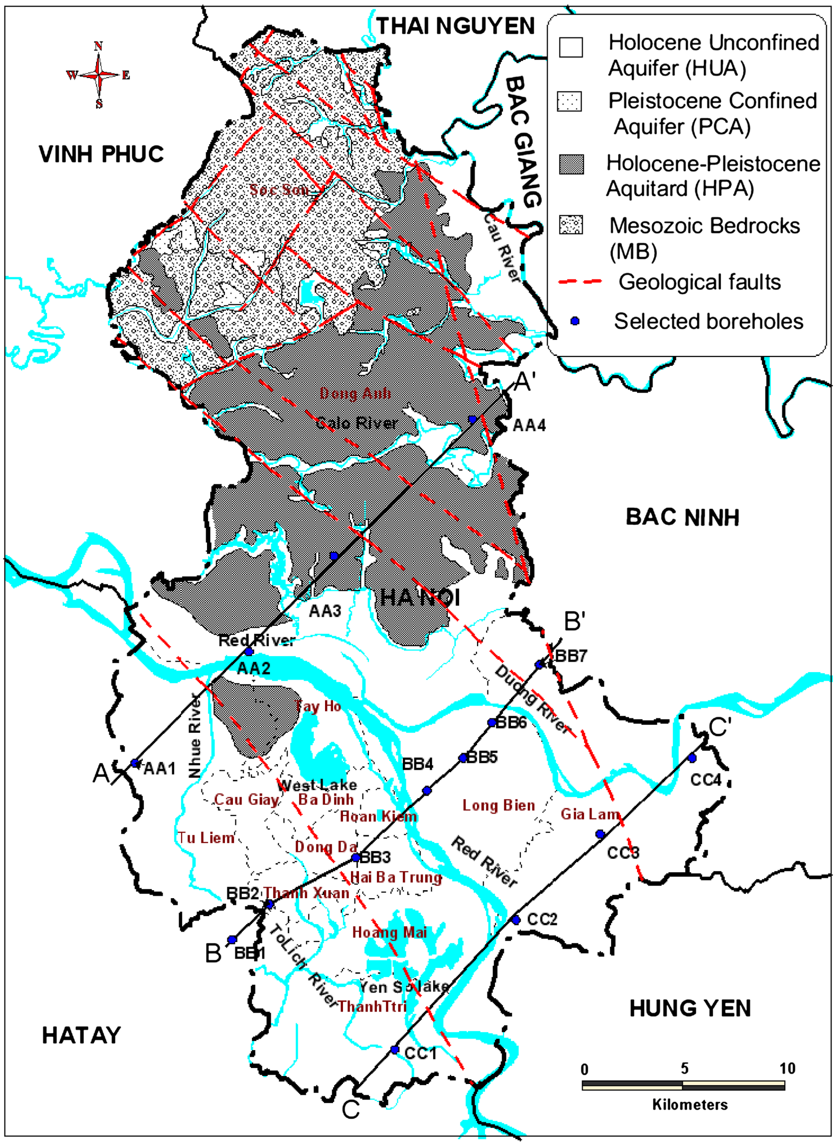

Figure 2. Hydrogeological map of Ha Noi city

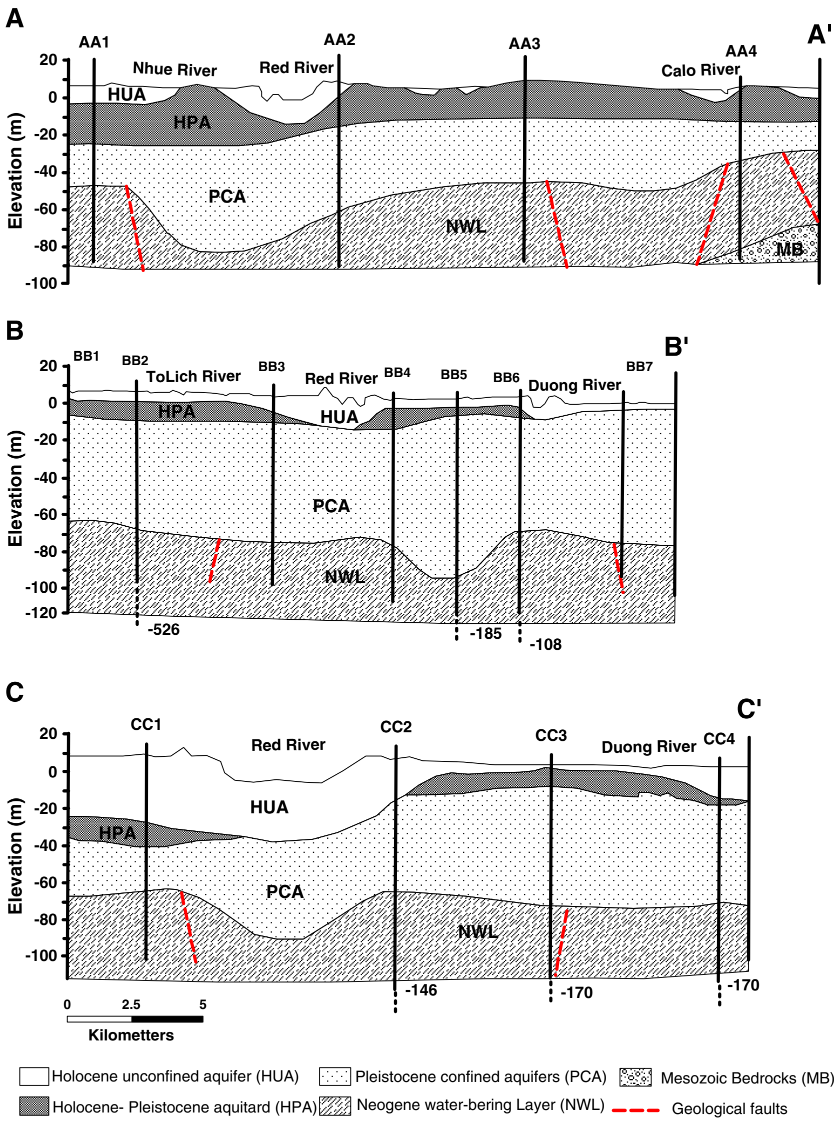

Figure 3. Hydrological cross sections along A-A', B-B', C-C' lines as shown in Figure 2

shows the hydrogeological cross sections demonstrating the hydrostratigraphy of the aquifer system of Hanoi. The cross section lines A-A', B-B', C-C', shown in Figure 2, were selected in the south of the city considering the density of boreholes and the absence of main aquifers in the north. These hydrological cross sections A-A', B-B', C-C' were made by interpolating 4, 7, 4 borehole columnar section data, respectively, as shown in Figure 3. This figure demonstrates a straightforward framework of the aquifer system and hydrogeological conditions in Hanoi.

Figure 3 and other geological information from borehole drilling reports indicated that Hanoi is composed of Quaternary-aged unconsolidated sediments with a maximum thickness of 100 m, lying directly over the bedrocks, aging from the Neogene period of the Cenozoic era to the Triassic period of the Mesozoic era. The groundwater of the Quaternary-aged sediments mostly exists as porous water forming the topmost HUA and the shallow PCA, sandwiching the HPA, while cleft and karst water exist in consolidated Neogene formations and Mesozoic rocks constituting NWL and MFZ. The Red River is an important natural recharge source for groundwater storage in Hanoi because it runs across HUA and in some places across PCA due to stream-bed erosion. In general, the main recharge sources of these aquifers are from river water, rainfall and irrigation water.

Geological formations and material ages from the collected well logs and geological description show that Hanoi has a complex geological setting. Quaternary-aged sediments have a diversity of strata and lithological materials. Deposits usually have their origin in rivers, floods, lakes, marshes, seas or modern alluvium. River-origin deposits commonly form aquifers (HUA and PCA) but sea-origin deposits build up aquitards or aquicludes (HPA).

HUA are mainly composed of silty clay and various kinds of sands mixed with gravel. In more detail, based on lithological components, HUA could be separated into three parts: uppermost, upper and lower parts. The uppermost part is slight and less permeable. Two other parts have a much higher permeability than that of the uppermost part. However, they have a unique hydraulic system so they are grouped in one HUA. HPA are mainly composed of silty clay mixing with black-gray plants or clay sand. Twelve slug tests showed that this confining layer has a small amount of permeability, less than 0.1 m/day (Nguyen *et al*., 2007). The thickness of this layer varies greatly, up to 40 m as shown in Figure 3. The main materials are highly permeable deposits like sands, gravels and cobbles. The PCA could also be divided into two sub-aquifers (upper and lower PCA), the coarseness of which continues to increase downward. Two sub-aquifers share a unique groundwater level, so they are grouped into one PCA.

The NWL and the MFZ are mainly formed by geological cracks, weather erosion and unconsolidated sediments. The information from well logs indicated that the materials of NWL include: cemented gravel, cemented clay, arkosic sandstone, argillite and clay carbon. The MFZ mainly consists of sandstone and porphyry.

AQUIFER SYSTEM CHARACTERIZATION

The Holocene unconfined aquifer (HUA)

This study revealed that two major aquifers (HUA and PCA) and two minor water-bearing units (NWL and MFZ) are dominant within the study area.

An isopach map is typically used to create a continuous picture from discrete sampling sites. Kriging, a geostatistical gridding method, and GIS have been effectively used in various fields of study. Those methods produce visually appealing maps from irregularly spaced data (Bakkali and Amrani, 2008). Even though we used those methods, creating sensible isopach maps was a difficult task because boreholes and exploration wells are very small features on the scale of the heterogeneities of an aquifer. The values of the hydrodynamic parameters obtained from pumping tests vary widely over short distances depending on exactly where the wells are drilled. In this paper, therefore, we not only utilized those methods for Hanoi but also interpreted and compared them to the observational data to draw the realistic isopachs. Figure 4 shows the isopach map of HUA thickness which clarifies the vertical extent of HUA. This isopach map was drawn using strata data from 160 well logs out of 240 boreholes because of missing strata data in the other boreholes. The figure shows that the aquifer thickness varies up to more than 35 m with an average of about 15 m. There is a roughly increasing tendency from

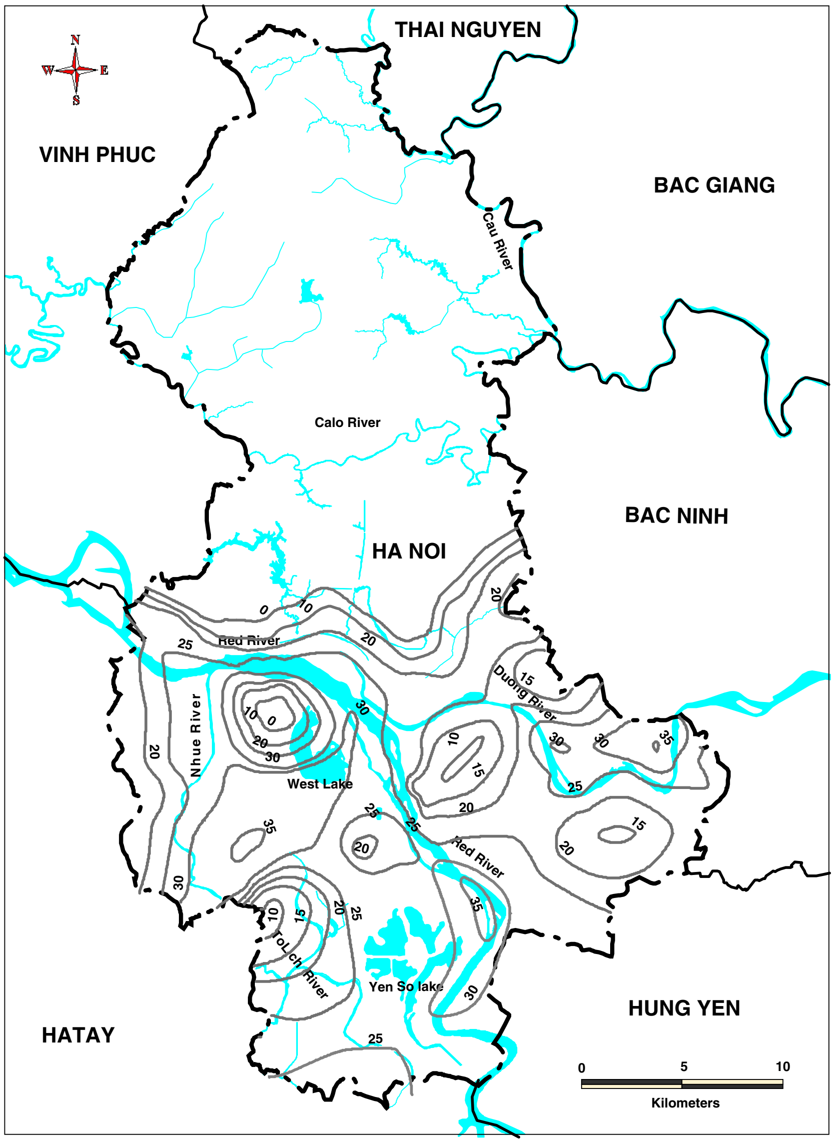

Figure 4. Isopach map of HUA's Thickness

the north to the south of Hanoi in which there are three areas of more than 30 m thickness. The first one is located in the east of the Yen So Lake along the Red River. The second one is in the southwest of the West Lake and the last one is in the east of the city along the Duong River. As shown in Figure 4, the thickness is zero in the north of the city because there is no HUA in this area as shown in Figure 2.

Hydrogeological parameters that were gained from 14 pumping tests, one being the multi-well test and the 13 others being the single-well tests, are summarized in Table I. The four main parameters presented in the table are: specific capacity (q), TDS, transmissibility (T) and specific yield (Sy). They are good indicators for the level of potential groundwater resources. According to Table I, we can see that the q values are mainly less than 5 L/s/m except for borehole H12, which is located between the Red River and the West Lake as shown in Figure 1. The reason for this exceptional case could be explained by the direct relationship between the surface water of the Red River and the groundwater of HUA. There are 11 boreholes of high potential groundwater ($q > 1$ L/s/m), one borehole of medium potential groundwater ($1 > q > 0.2$ L/s/m) and two boreholes of less potential groundwater ($q < 0.2$ L/s/m) according to the classifications quoted in the Vietnam guidelines for the aquifer test (Tran, 2000). The TDS values of all wells are less than 0.5 g/L indicating that groundwater of HUA is fresh by the Vietnam drinking water standards. Sy is a useful parameter for the quantitative estimation of the potential groundwater storage of the aquifer. The groundwater storage capacity of HUA was roughly estimated at about 572 million m^3, considering the average distance from the water level down to the bottom, the surface area and Sy value of the HUA.

The transmissibilities of HUA vary from 20 to 1788 m^2/day as shown in Table I. With only 12 total transmissibility data collected from pumping tests, we attempted to find out the general tendency of the spatial T distribution of the HUA through mapping its rough isopach map using the Kriging method as shown in Figure 5. The map shows that the transmissibility roughly increases from the city boundary in the south to the centre of the city. There are two areas of great transmissibility presenting high potential groundwater resources. The highest transmissibility of more than 1500 m^2/day is placed around borehole H4 near the Red River. That is why the only multi-well pumping test was set up there. The other area with a transmissibility of about 1000 m^2/day is situated in the north of the West Lake.

Table I. Pumping test results of Holocene unconfined aquifer (HUA)

Well Number	q(L/s/m)	TDS(g/L)	T (m^2/day)	Sy
H1	1.90	0.314	95	-
H2	3.00	-	184	-
H3	1.51	-	32	-
H4	2.70	0.218	1788	0.09
H5	0.42	0.290	160	-
H6	4.66	0.415	363	-
H7	3.08	0.235	530	
H8	1.30	0.352	370	-
H9	0.18	-	-	-
H10	1.31	-	149	-
H11	0.76	-	20	-
H12	20.87	0.222	790	-
H13	4.50	0.280	1389	-
H14	1.49	0.420	-	-

The results above indicate that the HUA contains a relatively high potential of groundwater resources and is sufficient for a small to medium scale domestic water supply.

The Pleistocene confined aquifer (PCA)

Applying the same procedures explained in the former section, the isopach maps (Figure 6 and Figure 7) were created from strata data of 160 well logs. Figure 6 shows the isopach map of the depth from the ground surface down to the top of the PCA, which provides useful information for practical pumping. Figure 7 is an isopach map of the PCA thickness which is a good indicator for groundwater potential. Figure 6 reflects great changes in the PCA depth from region to region with an increasing tendency from the north to the south. The depth is only less than 10 m in the north of the Soc Son District, but around 20 m in Dong Anh District, and up to 40 m in the south of the Red River. Figure 7 indicates that the thickness of the PCA also fluctuates over a large range, up to 50 m with the average of about 35 m, and has an increasing tendency from the north to the south except for three areas of more than 40 m in thickness. The locations of the three areas have quite a similar tendency towards the HUA thickness distribution as shown in Figure 4.

In Hanoi, the greatest percentage of the 139 pumping tests was drilled in this aquifer, but 121 of them are single-borehole tests. Eighteen boreholes are cross-borehole tests as shown in Table II. Table II only showed the results of cross-borehole tests including: q, TDS, T and storage coefficient (S). The single-borehole tests are not included in the table, but the analysis for PCA in this paper is based on all the data of both kinds of 139 pumping tests. The S value is a useful parameter to estimate the potential pumping storage of the confined aquifer for practical groundwater pumping. In Table II, the S values obtained from cross-borehole tests vary from 0.00004 to 0.066 with an average of 0.0233. Using S values, the average thickness and the surface area of the PCA, the groundwater storage capacity of the PCA was roughly estimated at about 627 million m^3. The q values from all boreholes are higher than 1 L/s/m which indicate the high potential for groundwater resources, according to the Vietnam guidelines for the aquifer test (Tran, 2000). The TDS value is less than 1 g/L representing fresh water by Vietnamese drinking water standards. The q and TDS values obtained not only from Table II but also from all of the 139 pumping tests show the same results.

Table II shows that the T values ranging from 700 to 2900 m^2/day indicate a very high potential of groundwater resources. T values from the 139 total pumping tests also have the same conclusion. The isopach map of transmis-

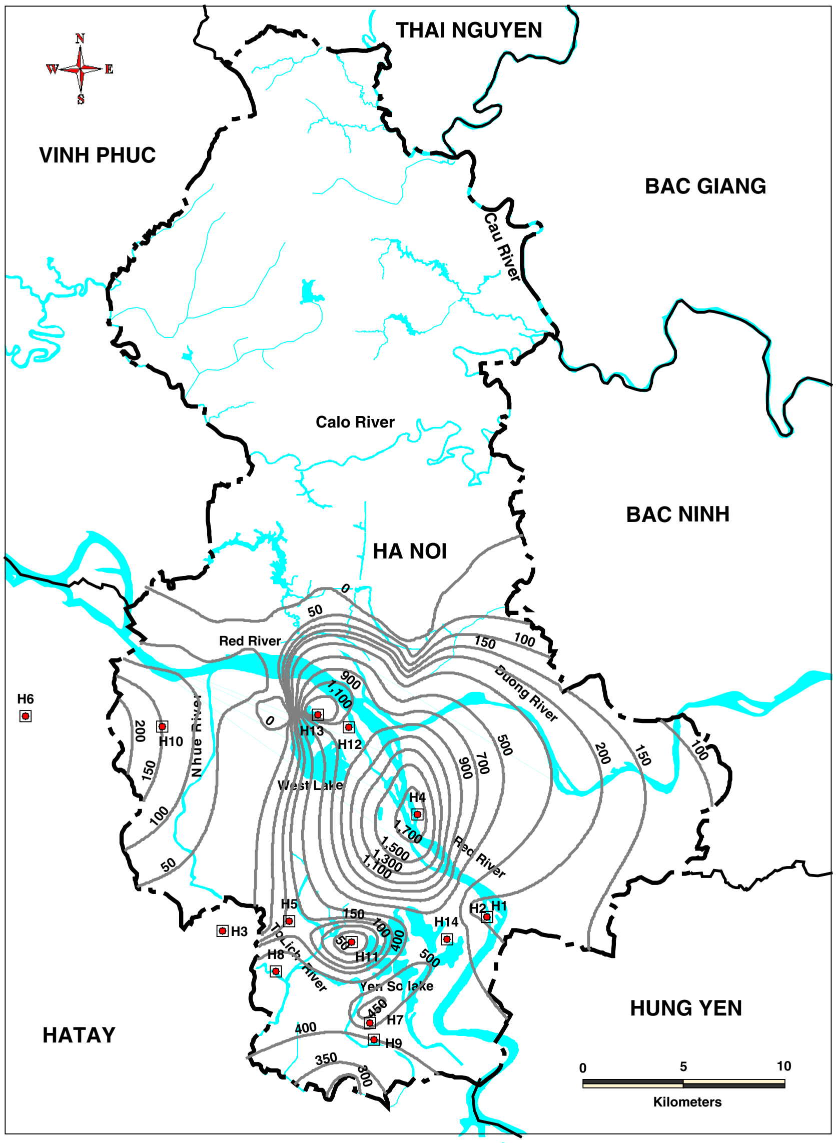

Figure 5. Rough isopach map of transmissibility of HUA

sibility was mapped from the results of these pumping tests to elucidate the spatial T distribution as shown in Figure 8. It shows that the T value varies greatly from region to region with the increasing tendency from the north to the south and from the city border to the city centre. There are three zones of great transmissibility presenting a very high potential of groundwater resources. These zones are situated along the Red River in the southern Hanoi. The highest T value zone with more than about 2700 m^2/day is placed around the centre of the southern Hanoi. The second and the third ones are located in the northeast and the south of the highest T value zone along the Red River with more than 2100 m^2/day and 1500 m^2/day, respectively.

Based on the aforementioned analysis, we could conclude that the PCA has a very high potential of groundwater resources. Accompanied with its great thickness, PCA is sufficient for medium to large scale domestic water supply. The findings also reflect a corresponding distribution of hydrogeological characteristics between PCA and HUA. With better pumping test data in PCA, hydrogeological findings for PCA have a higher accuracy than those for HUA.

Minor water-bearing units

As we described in Chapter 3, two other minor water-bearing units are the NWL and the MFZ. The depth from the ground surface to the top of NWL is around 20 m at the north but increases up to 100 m or more in the south. Hydrogeological parameters gained from 11 single-borehole tests are presented in Table III including: q, TDS and T. In Table III, boreholes N5 and N6 along the Red River and borehole N7 along the Duong River in the southeastern part of the city have q values of more than 1 L/s/m reflecting a high groundwater potential, while the others have less than 1 L/s/m indicating low groundwater potential according to the Vietnam guidelines for pumping tests (Tran, 2000). The TDS values of boreholes N8 and N10, located in the Tu Liem district and Thanh Xuan district in the south-western part of Hanoi, are more than 1 g/L indicating brackish

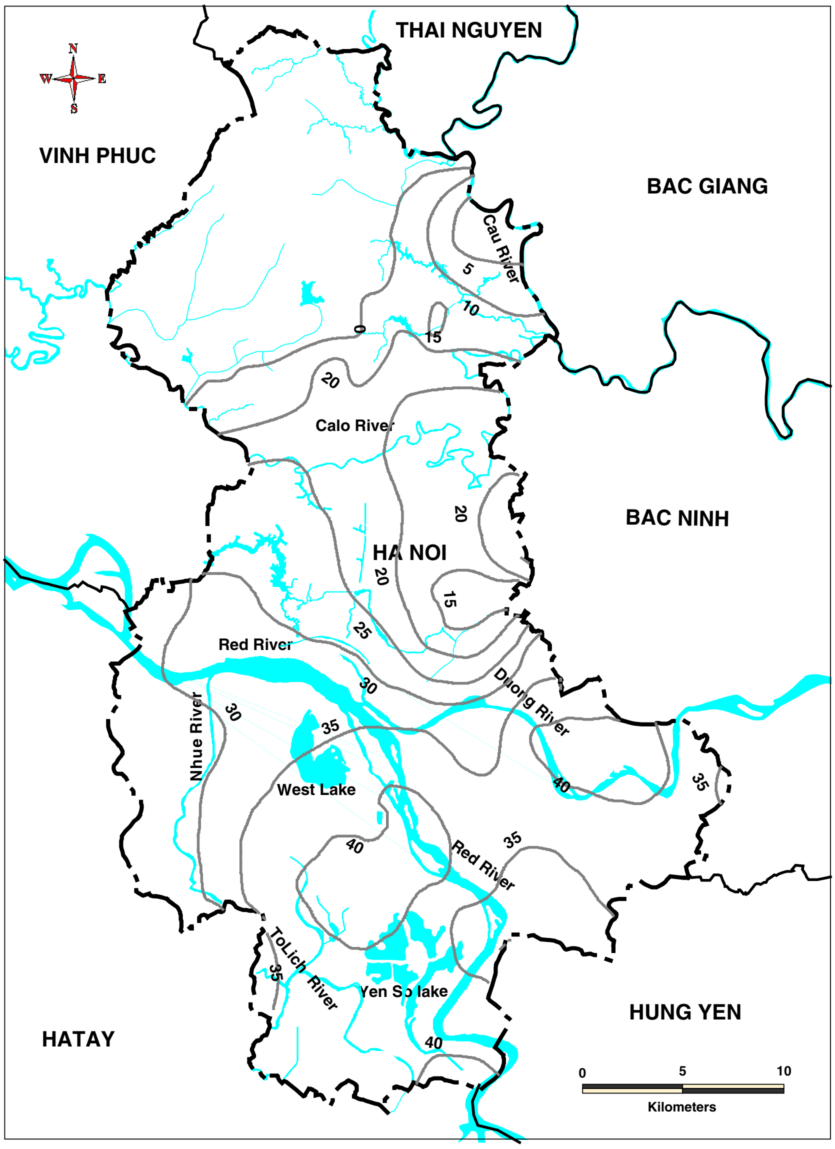

Figure 6. Isopach map of the depth from the ground surface down to the top of PCA

water not suitable as potable water. Four *T* values show that the good potential groundwater areas correspond to the locations of boreholes N6 and N7.

Table IV shows hydrogeological parameters of MFZ gained from five single-borehole tests including: *q*, TDS and *T*. In Table IV, the *q* values are mainly less than 1 L/s/m except for M5, which is a sign of poor to medium potential of groundwater resources. The groundwater here is proven to be fresh by small TDS values of less than 1 g/L. *T* values in the range of 64 to 305 m^2/day also reflect the limitation of groundwater resources. Only some small weathered parts can store considerable amounts of groundwater like the location of M5 with high *q* values.

The *T* values of NWL and MFZ are much smaller than those of the porous aquifers, HUA and PCA. The available data of both NWL and MFZ are insufficient for estimating their groundwater storage capacities. The information from surveyed notes stated that local communities in the north, dominated by Mesozoic bedrocks, have frequently employed hand-dug shallow wells to gain groundwater for individual use, but the wells start drying up in the dry season. Therefore, the groundwater in MFZ and NWL is only sufficient for domestic use on a very limited scale.

CONCLUSION AND DISCUSSION

In this paper, taking advantage of our recent project on constructing a National Hydrogeological Database, the best number of 240 boreholes including well logs and their hydrogeological parameters were comprehensively analyzed for the first time in order to identify the aquifer system and characterize the hydrogeological conditions in all of Hanoi city from the viewpoint of potential groundwater resources. The hydrogeological data were interpolated, and the aquifer system of Hanoi city was identified by creating the hydrogeological map and hydrogeological cross sections. Also, we focused on analyzing the hydrogeological parameters of HUA and

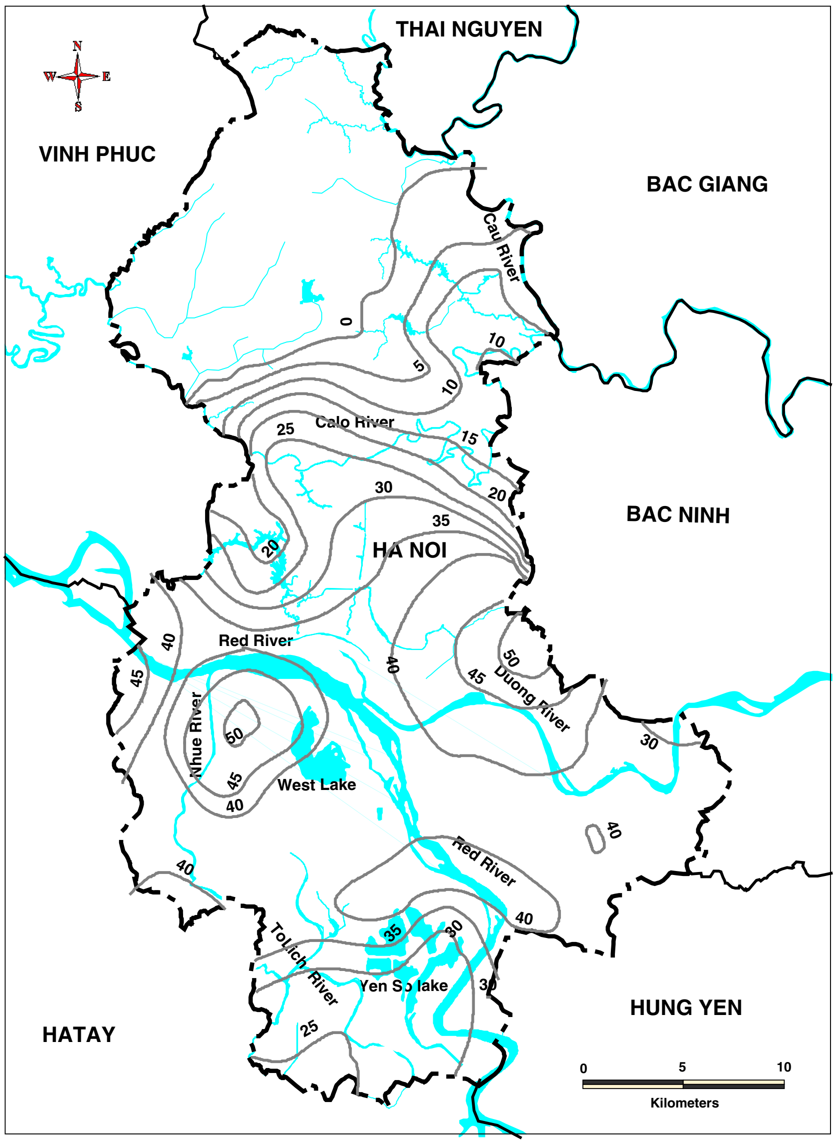

Figure 7. Isopach map of PCA's Thickness

Table II. Cross-borehole test results of Pleistocene confined aquifer (PCA)

Well Number	q(L/s/m)	TDS(g/L)	T (m^2/day)	S
P1	9.87	0.185	2574	0.06600
P2	13.60	-	2179	0.07000
P3	8.49	0.200	1295	0.04600
P4	5.03	0.221	991	0.02400
P5	9.00	0.124	2838	0.01400
P6	6.04	0.138	2756	0.00100
P7	3.31	0.240	700	0.00200
P8	7.65	0.247	2900	0.14500
P9	4.47	0.185	1500	0.00270
P10	7.73	0.272	800	0.02700
P11	14.46	0.440	1230	0.00030
P12	10.22	0.348	2319	0.00004
P13	3.99	0.345	1565	0.00034
P14	5.60	-	1556	0.01700
P15	1.27	0.145	727	0.00300
P16	-	-	1228	0.00013
P17	-	-	1074	0.00033
P18	-	-	849	0.00022

PCA in more detail by making isopach maps of thicknesses, depths and transmissibilities. As for the results, Hanoi is composed of Quaternary-aged unconsolidated sediments which consist of HUA, PCA and HPA, directly overlaying the hard formations which aged from the Neogene period to the Triassic period and form the NWL and MFZ.

In more detail, the HUA is distributed at a rate of about 55% in the south of the city area. HUA has a relatively high potential of groundwater resources and is sufficient for the small to medium scale domestic water supply. On the other hand, PCA is widely distributed at a rate of about 80% in the south of the city and has the highest groundwater potential serving the most important aquifer for water supply. In contrast, both the NWL and MFZ have very limited groundwater potential as proven by small q and T values. The confining layer HPA is mostly located under HUA. The groundwater in all water-bearing formations (HUA, PCA, NWL and MFZ) is fresh except for some brackish water parts of NWL in the south-western part of Hanoi.

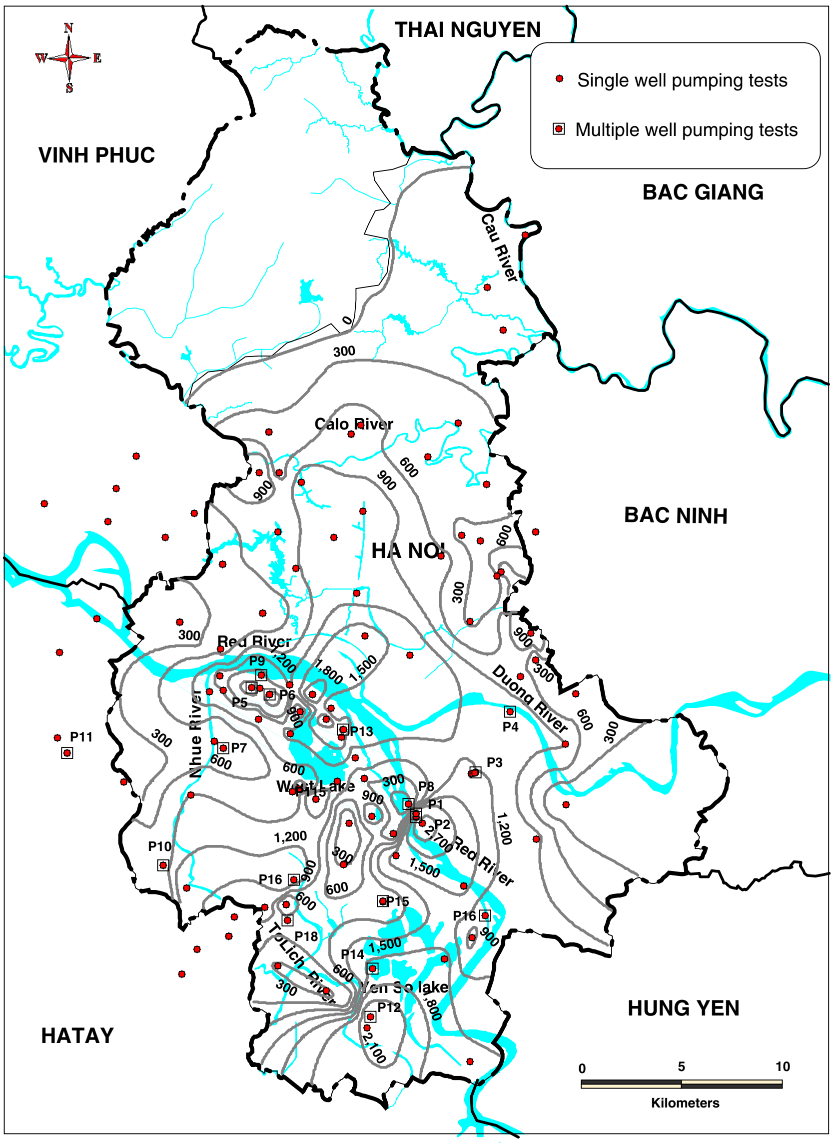

Figure 8. Isopach map of transmissibility of PCA

Table III. Pumping test results of Neogene water-bearing layer (NWL)

Well Number	q(L/s/m)	TDS(g/L)	T(m^2/day)
N1	0.01	-	-
N2	0.05	-	-
N3	0.87	-	-
N4	0.66	-	-
N5	1.42	-	-
N6	3.46	0.270	840
N7	3.75	0.240	440
N8	0.01	2.230	-
N9	0.10	-	-
N10	0.03	1.115	50
N11	0.73	-	55

Table IV. Pumping test results of Mesozoic fractured zones (MFZ)

Well Number	q(L/s/m)	TDS(g/L)	T(m^2/day)
M1	0.58	0.249	305
M2	0.14	0.274	64
M3	0.31	0.293	153
M4	0.34	0.233	82
M5	6.15	0.150	-

Table V tabulates the overall characteristics of the Hanoi aquifer system. In Vietnam, the two biggest cities, Ho Chi Minh and Hanoi, are located in two of the largest deltas, the Mekong River Delta and the Red River Delta, respectively. In comparison with the Red River Delta in Hanoi, the Mekong alluvial in Ho Chi Minh city has a rather complicated aquifer system with four interconnected aquifers (Holocene, Pleistocene, Lower Pleistocene, Neocene aquifers) (Nguyen, 2008). The hydrogeological characteristics of the topmost unconfined Holocene aquifers are quite similar in both thickness and materials. The materials of the deeper PCA of Mekong alluvial in Ho Chi Minh city is also similar to those of Hanoi's PCA but the aquifer thickness is much bigger, up to 110 m. The Pleistocene-aged sediments in Ho Chi Minh city form two

Table V. Characteristics of aquifer system in Hanoi

Aquifer system	Geological Ages	Hydrogeological conditions	Depth to the layer's top (m)	Thickness (m)	q(L/s/m)	T(m^2/day)	Sy/S	Materials	Groundwater potential	Groundwater Storage capacity, million m^3
HUA	Holocene	Unconfined aquifer	0	0–35	0.18–20.87	20–1788	0.09	Silty clay, clayer sand, sands mixed with gravels	High potential	572
HPA	Holocene–Pleistocene	Aquitard	0–35	0–40	No data	No data	No data	Silty clay, clay sand	No potentials	No data
PCA	Pleistocene	Confined aquifer	0–40	0–50	1.27–14.46	10–2900	0.00004 –0.066	Medium–coarse sands, gravel, cobble	Highest potential	627
NWL	Neogene	Discontinuous aquifer	20–100	No data	0.01–3.75	50–840	No data	Cemented gravel, cemented clay, arkosic sandstone, argillite, and clay carbon	Medium potential	No data
MFZ	Mesozoic	Fractured zones	No data	No data	0.14–6.15	64–305	No data	Sandstone and porphyry	Low potential	No data

Table VI. Comparison of aquifer systems in Hochiminh and Shanghai to Hanoi

Regions	Deltas	Number of aquifers	HUA		PCA		NWL		MFZ	Qualitative groundwater potential
			Thickness (m)	Materials	Total Thickness (m)	Materials	Thickness	Materials		
Hochiminh (Vietnam)	Mekong River	4	Similar (0–35)	Similar	Thicker (0–110)	Similar	No data	Similar	No data	More
Shanghai (China)	Yangtze River	6	Similar (0–35)	Similar	Thicker (0 –85)	Similar	No data	No data	No data	Less

distinctive aquifers, Pleistocene and Lower Pleistocene aquifers, whereas there is just one PCA in Hanoi. There are Neocene aquifers with limited groundwater potential in both regions.

In addition, the aquifer framework of Hanoi is much more straightforward than the Shanghai Region of the Yangtze River Delta, a main river delta in China. The Shanghai Region has a multi-system of up to six aquifers and six aquitards (Xu *et al.*, 2009). However, thickness and materials of the topmost unconfined Holocene aquifers in both regions are quite similar. For example, the aquifer thickness also variably extends down to 35 m, and the aquifer is also mainly composed of silty clay, sandy silt, clayey silt and fine-grained sands in Shanghai region. Although the deeper Pleistocene aquifers in both regions are confined aquifers and mainly composed of highly permeable sediments like sands, gravel and cobble, there are differences in the ranges of their thicknesses: Shanghai Region (0–85 m) and Hanoi (0–50 m). In contrast, with reference to the Hanoi aquifer system, the 'aquifer system' of the Yellow River lower reaches plain, China, is just present within the extent of 10–20 km along the river, which are defined as the influence zone of recharge of the Yellow River water on the groundwater. This region is mainly composed of less permeable sediments like silty clay, clay and fine sand. The groundwater potential is very limited (Eryong *et al.*, 2009). Thus, it could be said that the aquifer system in Hanoi is distinctive and that the groundwater reserves in Hanoi might be less than of Ho Chi Minh of the Mekong Delta and the Shanghai Region of the Yangtze Delta, yet much more than Yellow River lower reaches plain. The brief comparison of aquifer systems in Hochiminh and Shanghai to Hanoi was roughly summarized in Table VI.

The findings are indispensable for further groundwater analyses contributed to ensure the sustainable groundwater development not only in Hanoi, but also in poorly gauged or ungauged neighboring basins.

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