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# Identification of aquifer system in the whole Red River Delta, Vietnam

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**ABSTRACT: The Red River Delta is one of two biggest deltas in Vietnam. People living in the delta depend entirely on groundwater for their domestic water. However, the aquifer system in the whole Red River Delta remains poorly understood due to the lack of available data. Recently, we were nominated to construct a hydrogeological database. Using these valuable data contained in this database, this paper comprehensively analyzed the best number of 778 boreholes including well logs and their hydrogeological parameters obtained from pumping tests for the first time in order to identify the entire aquifer system and characterize hydrogeological conditions in the whole delta for potential groundwater resources. Great efforts have been made to establish and analyze hydrogeological maps, cross sections, and contour maps of main aquifers' thickness and transmissivity. As for the results, we found that groundwater mainly exists in Quaternary unconsolidated sediments as porous water forming the topmost Holocene unconfined aquifer (HUA) and the shallow Pleistocene confined aquifer (PCA) sandwiching the Holocene-Pleistocene aquitard (HPA), while cleft and karst water exist in consolidated Neogene formations and Mesozoic rocks constituting the Neogene water bearing layer (NWL) and Mesozoic fractured zones (MFZ), respectively. PCA is almost entirely distributed over the delta. It serves as the highest groundwater potential and the most important aquifer for water supply. HUA is also widely distributed about 88% over the delta and has a high groundwater potential. NWL and MFZ, placed below PCA but exposed on the surface outside the delta, are minor sources for local domestic water supply only. These findings are indispensable for further groundwater analyses needed to ensure the sustainable groundwater development for the high-security water requirements in the delta, but have never been completed sufficiently before due to the unavailability of large-scale basic data sets.**

**Key words:** hydrogeological database, pumping test, aquifer system, groundwater resources, the Red River Delta

## 1. INTRODUCTION

Sustainable management of groundwater resources is one of the essential objectives for the future of developing countries like Vietnam, especially when the rising demand for clean drinking water by these fast growing communities is considered (Mende et al., 2007). The Red River Delta including Vietnamese capital, Hanoi, is particularly addressing this because: (1) Demand for clean water for the rapid expansion of industry, population, and services has been becoming rather urgent; (2) Water supply greatly depends on groundwater resources due to the uneven distribution and heavy suspended deposits of surface water resources. The amount of groundwater abstraction has been rapidly and continuously increasing; (3) Undue groundwater exploitation without the wise management and adequate understanding of the aquifer system characteristics have caused some serious problems, such as: drying up of shallow wells, decline of groundwater level, land subsidence, and groundwater pollution in this area (Tong, 2000; Bui, 2005).

Understanding and quantifying groundwater resources is a very complex and difficult task, considerably more problematic and uncertain than surface water hydrology. 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 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, e.g., Europe, Australia, Japan, and North America, where a wide range of information and sound technical and financial resources are available (Mende et al., 2007). However, the case of limitations of the necessary input data and the broad lack of basic information, e.g., systematic geological or hydrogeological maps as well as detailed information about well logs with geotechnical and hydrogeological parameters, is typical for developing countries and causes insufficient under-

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standing about characteristics of the aquifer system. It also 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, obtaining basic data adequately and understanding 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 fundamentals before going to assess groundwater resources in the Broken Hill Region, Australia. Many other works demonstrating the necessities of portraying the aquifer system from the viewpoint of groundwater resources had been investigated in the Lower Mississippi Valley, USA (Boswell, 1996); 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 Red River Delta.

In Vietnam, there have been a large number of water resource studies on the two biggest deltas, the Red River Delta (Doan and Boyd, 2003; Agusa, et al., 2005; Ngo et al., 2007; Berg et al., 2001, 2007; Funabiki et al., 2007; Larsen et al., 2008) and the MeKong River Delta (Nguyen, 2008; Kohnhorst, 2005; Shinkai et al., 2007; Kazama et al., 2007; Ta et al., 2002; Mekong River Commission, 2005), due to their important roles in the development of Vietnam. Most of them were concerned about the origin, evolution, and development of the deltas, surface water and groundwater pollution, especially arsenic pollution, and they were limited to small local cites within the delta. There are few other original groundwater investigations for the Hanoi area existing in the literature. Among these, Gupta and Truong (1999) and Duong et al. (2003) considered groundwater quality, pollution and monitoring system design; Nguyen and Helm (1996) and Trinh and Fredlund (2000) investigated land subsidence due to excessive groundwater exploitation in some urban portions of the Hanoi area. However, no one has accomplished a comprehensive analysis of the entire Red River Delta aquifer system, while comprehensive understanding of the aquifer system and hydrogeological conditions is a key factor and prerequisite for those studies. The aquifer system in the Red River Delta was only briefly indicated in our earlier studies but just qualitatively, dispersedly and locally based on few borehole data, and they are just published as local reports (Tong, 2000; Bui, 2005; Bui et al., 2007; Tong and Bui, 2004). Although we had roughly identified the aquifer system in the delta as an intermediary task for specific purposes such as groundwater pollution modeling (Bui et al., 2007), artificial recharge to groundwater (Tong and Bui, 2004), and groundwater balance modeling (Nguyen et al., 2007), those works just analyzed for limited areas within Hanoi and based on very few numbers of boreholes. So far, there has been no comprehensive work focusing on aquifer system identification and characterization for the whole delta as a primary goal due to the unavailability of basic data.

Initiating 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 as the first case where our investigation could put all the basic data together, especially borehole data, from various sources throughout the delta. In this paper, these internally-available data sets including well logs and their hydrogeological properties, such as: materials, aquifer thicknesses and depths, hydraulic conductivities, transmissivities, water yield coefficients, specific capacities, water levels, discharges, and so on were comprehensively analyzed for the entire delta.

To take advantage of our unique data sets as much as possible, the main objectives of this paper are to identify and characterize the aquifer system of the whole Red River Delta. This work has focused on acquiring, compiling, and analyzing hydrogeological data from the highest number of existing boreholes, thereby establishing hydrogeological maps to gain visual demonstrations of the surface distribution of aquifers and drawing lateral and longitude hydrogeological cross-sections demonstrating the vertical framework of the aquifer system. Furthermore, we hydrostratigraphically interpolated strata data of well logs to create contour maps of aquifer thickness and depth from the ground surface. Especially we analyzed pumping test data to evaluate the groundwater potential of identified aquifers by establishing histogram of aquifer parameters and contour maps of transmissivities. Once these findings are internationally documented, they could provide indispensable fundamentals and basic references for further hydrogeological studies in the delta.

## 2. STUDY AREA AND DATA USED

### 2.1. Study Area

A delta is a landform that is formed from the deposition of the sediment carried by a river over a long period of time and created at the mouth of a river. Thus, in this paper, the Red River Delta is defined as the area consisting of the surface covered with sediments within the border shown in

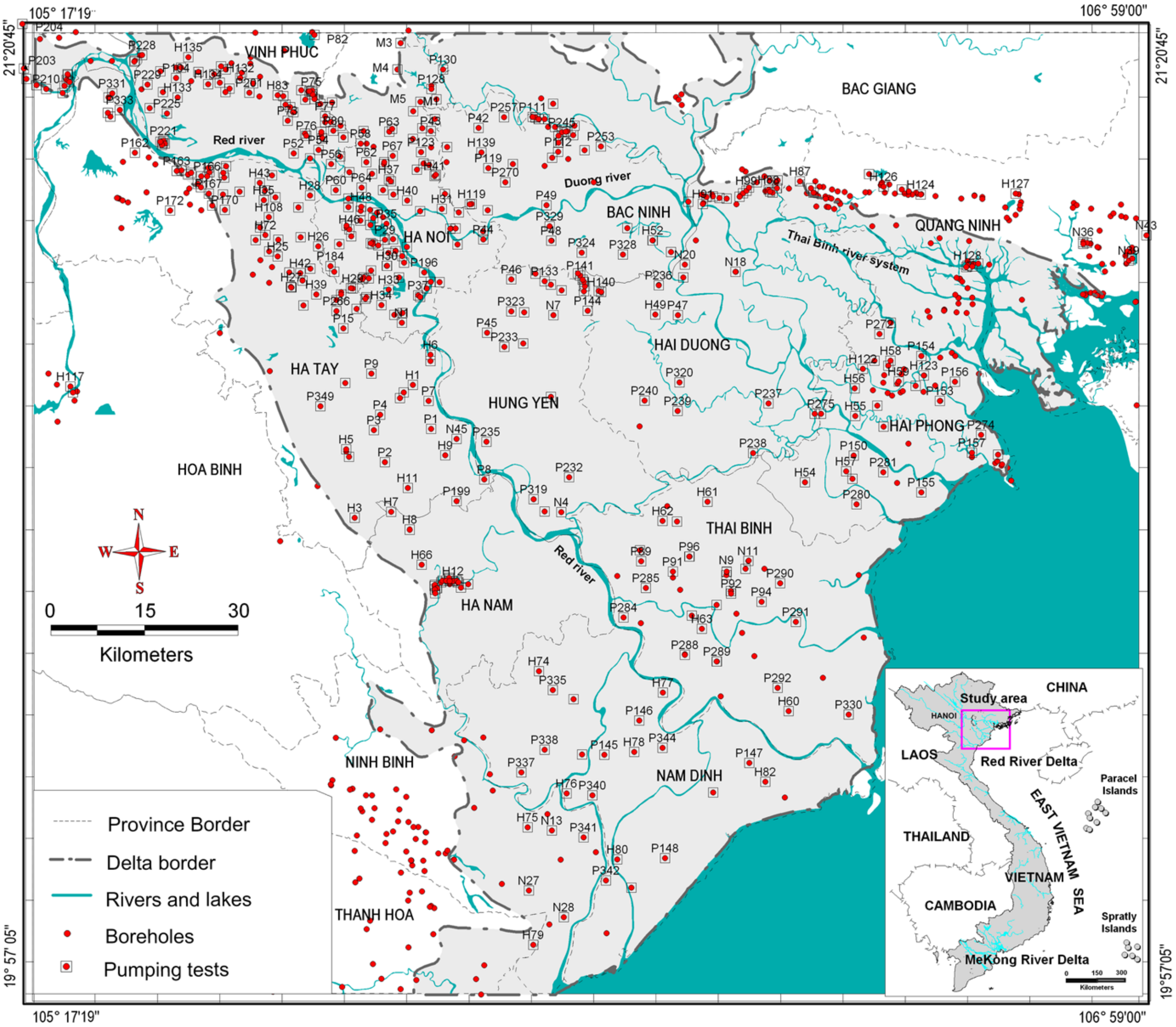

**Fig. 1.** Location of study area and borehole distribution.

Figure 1.

The Red River Delta has a surface area of about 13,000 km$^2$ in the northern part of Vietnam, covering 4.5% of the total Vietnam area. It is the most developed area of Vietnam comprised 13 provinces and cities as shown in Figure 1. The population was about 19 million in 2007, occupying 22% of the Vietnam's population. Many important centers of economics in Vietnam, such as Hanoi and Haiphong are located there. The major type of topography here is flood plains with elevation mainly below 12 m.

The delta belongs to the tropical monsoonal area with two distinctive seasons. The rainy season is from May to October and the dry season lasts from November till April. The annual rainfall is about 1,600 mm of which rainfall in the rainy season occupies about 75%. The annual average humidity is about 80%, and the average temperature is around 24 °C. Evaporation is quite high with an annual average of 900 mm (Tong, 2007).

The river network in the delta is quite dense with a density of about 0.7 km/km$^2$. The river slope is around 0.03 m/km. Average discharge of the Red River at the Hanoi station is 385 m$^3$/s in the dry season and 14,800 m$^3$/s in the rainy season. The water of the Red River is at a high level of suspended load throughout the year. The tidal range along the coast is approximately 4 m. Surface water, especially in lakes, in some cities over the delta has been seriously polluted due to insufficiency of infrastructure and unwise management of dumping waste (Tong, 2007).

Groundwater thus has become a main source of water supply in the delta. The amount of groundwater abstraction has been rapidly and continuously increasing. In Hanoi, for example, almost 100% of domestic water is from groundwater (Tong, 2000; Bui, 2005). Some bio-chemical indexes like ammonia, microbe, heavy metal, arsenic concentration and so on have increased over the years (Agusa et al., 2005; Berg et al., 2001, 2007; Bui et al., 2007; UNICEF Vietnam, 2001).

## 2.2. Establishment of National Hydrogeological Database

The reliability and validity of groundwater analyses strongly depend on the availability of a large volume of high-quality data (Gogu et al., 2001). Data availability is also essential to develop 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: Vietnamese geological survey departments, local to national environmental agencies, public and private research institutions, consultant firms, and many others. There are large differences in data format, quality, and storage media. 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 a 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 (1 USD = 15,000 VND) 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 the delta. All basic data, both tables and maps, are managed and handled by a central computer program called HYDROGEOBANK. Details about this project and the database were described in the final report of the project (Tong, 2004).

The Red River Delta has the densest hydrogeological data in Vietnam with a large number of data owners. Therefore, implementation of the database project in the delta 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, chemical, and borehole-structural information were collected, integrated, and computerized from various sources. General information includes: the owner, completion time, geographical coordinates, administrative address, and ground surface elevation. Hydrogeological information consists of pumping rates, specific capacity, water level, hydraulic conductivity, transmissivity, and storage coefficient. Stratigraphical information contains: material, geological age, and depth of each formation. Borehole-structural information includes: drilling depth, types and dimensions of filter pipe and casing. Chemical information consists of the content of TDS (total dissolved solids), pH, hardness, cations, anions, etc. The other information such as distribution of well fields and the map of the groundwater monitoring network was also gathered. These valuable data sets maintain a vital role for further groundwater studies in the delta, but now are not open to public, just internally accessible by project-involved agencies and staff like us. This paper was the first analysis utilizing our established database. Hopefully, these data sets will be available in the next stage, because without these data sets it is very hard to implement necessary groundwater analyses ensuring the sustainable groundwater development in the delta.

## 2.3. 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 the 778 boreholes as shown in Figure 1 and hydrogeological survey data including geological map and their descriptions. The boreholes were completed from 1966 to 2003 and mainly concentrated at developed cities, such as: Hanoi, Haiphong, Hatay as shown in Figure 1. The average density of boreholes over the delta is around 0.05 borehole/km$^2$. One hundred boreholes reach their depth at Neogene-aged formations and 7 boreholes were drilled in Mesozoic-aged formations. The remaining 671 boreholes were drilled within Quaternary-aged formations. Amongst the data from 778 boreholes, there were 637 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 413 conducted for Pleistocene confined aquifer (PCA), but only 147 for the topmost Holocene unconfined aquifer (HUA), 70 for Neogene water bearing layer (NWL) and 7 for Mesozoic fractured zones (MFZ) of Mesozoic bedrocks. No pumping test has been conducted for Holocene-Pleistocene aquitard (HPA). The pumping tests were conducted to estimate aquifer parameters (e.g., hydraulic conductivity, specific storage or storativity, transmissivity, specific yield, leakage coefficient, and so on). After the test, only the aquifer parameters estimated and information about hydrogeology, stratigraphy, chemistry, and borehole-structure of the pumping tests were documented and maintained. Hence, the data and information during the pumping such as pumping rates, records of drawdown and recovery of groundwater levels, distances from pumping well to observation wells, and so on were not integrated into our hydrogeolocal database.

There are two kinds of pumping tests, single-borehole test and cross-borehole test. In comparison with single-borehole test, cross-borehole test has the advantages of sampling a larger volume of the porous medium, yielding more reliable estimates of specific storage, providing indications of aquifer boundaries, and dealing with anisotropic media. Field data of the specific yield of unconfined aquifer and the storage coefficient of confined aquifer were only obtained from cross-borehole tests. Only 2 pumping tests out of 147 for HUA and 19 out of 413 for PCA were cross-borehole tests. Therefore, specific yield and storage coefficient were measured only for HUA and PCA, not for HPA, NWL, and MFZ. The specific yield and storage coefficient are important parameters to estimate potential pumping storage of a specific aquifer which plays a vital role for practical groundwater pumping.

## 3. IDENTIFICATION OF HYDROGEOLOGICAL FRAMEWORK

In any hydrogeological investigation, aquifers and aquitards are needed to be properly understood. Distribution of aquifers and aquitards in a region is determined by the stratigraphic, lithological characteristics and structure of the geological strata. Hydrostratigraphy involves the combination or separation of units with similar hydraulic conductivities into aquifers or aquitards. Hydrogeological mapping is an effective way to visually depict the hydrogeological characteristics beneath the land surface. Several techniques are used in hydrogeological mapping in which hydrogeological map and cross-section are the techniques commonly used for visually depicting a hydrogeological system.

In this paper, first we gathered field data as stated in the former section, and then integrated them to gain visual demonstrations of the surface distribution of aquifers, resulting in drawing the surface hydrogeological map shown in Figure 2. Figure 2 reveals that HUA is the topmost aquifer and distributes widely with a total area of about 11,450 km$^2$ occupying about 88% of the delta area. There is a confining

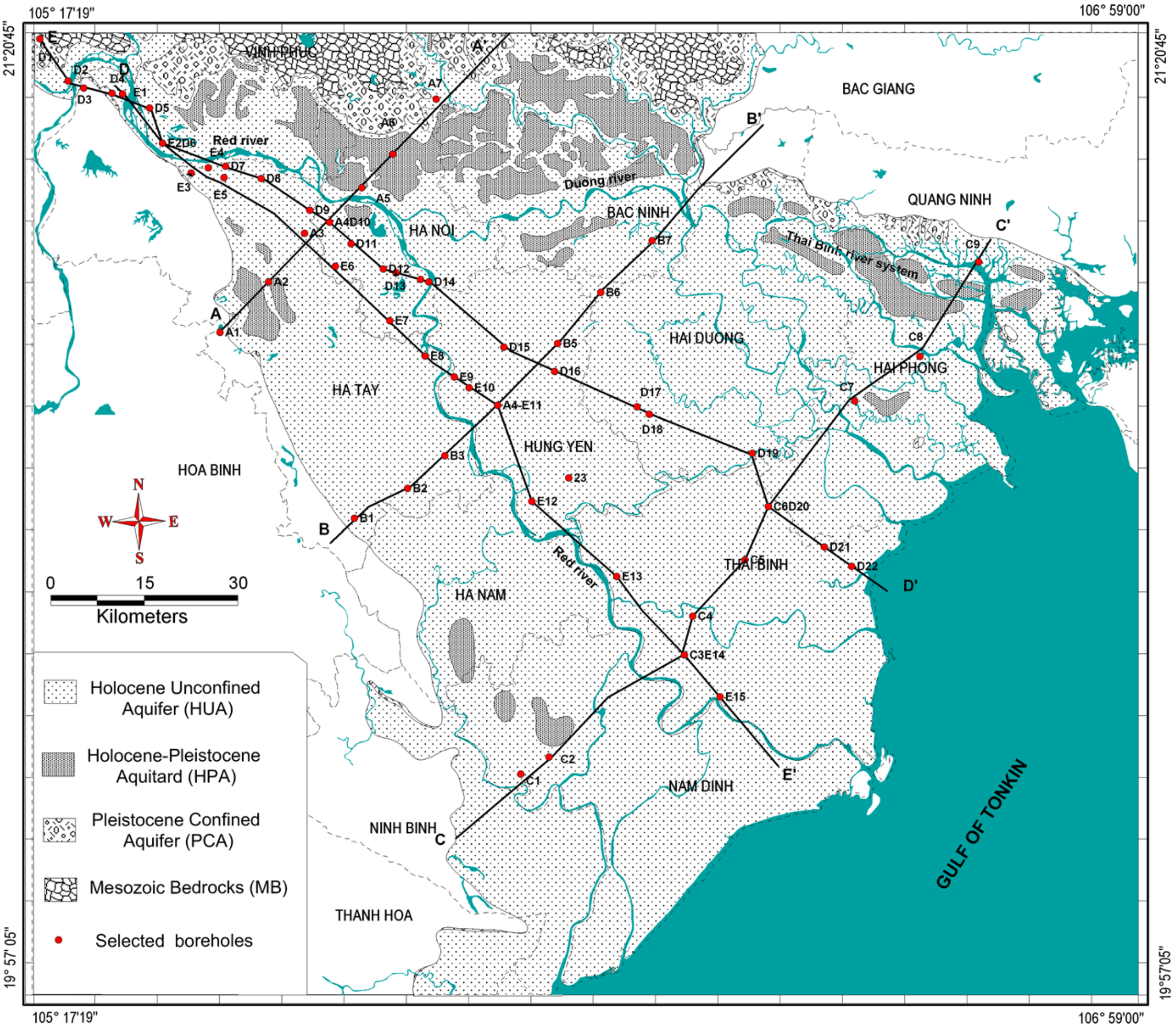

**Fig. 2.** Surface hydrogeological map of the Red River Delta.

layer, aged from Holocene to Pleistocene, named HPA, sandwiched between HUA and PCA. HPA is mostly located under HUA but exposed out on the surface around the northern border of the delta with total area of about 5% of the delta. PCA, placed under HUA and HPA, is distributed almost entirely the delta. Furthermore, there are only several small areas of PCA dispersedly present on the surface in the north. In the northern part of the delta, majority of PCA is just covered with HPA owing to the absence of HUA. In some other places where HPA has been thinned out, PCA directly is covered with HUA and they share a unique hydraulic head. Figure 2 also indicates that Mesozoic bedrocks exposed on the surface of the ground create mountainous areas outside the border of the delta. Due to geological cracks and weather erosion, some fractured parts of Mesozoic bedrocks create MFZ which are capable of storing, receiving, and transmitting water. Since MFZ are distributed sparsely in small zones within Mesozoic bedrocks, it is difficult to show them in Figure 2.

Furthermore, we hydrostratigraphically interpolated strata data from a number of well logs to draw lateral and longitude hydrogeological cross-sections demonstrating the vertical framework of the aquifer system. Figures 3 and 4 show five typical hydrogeological cross-sections A-A’, B-B’,

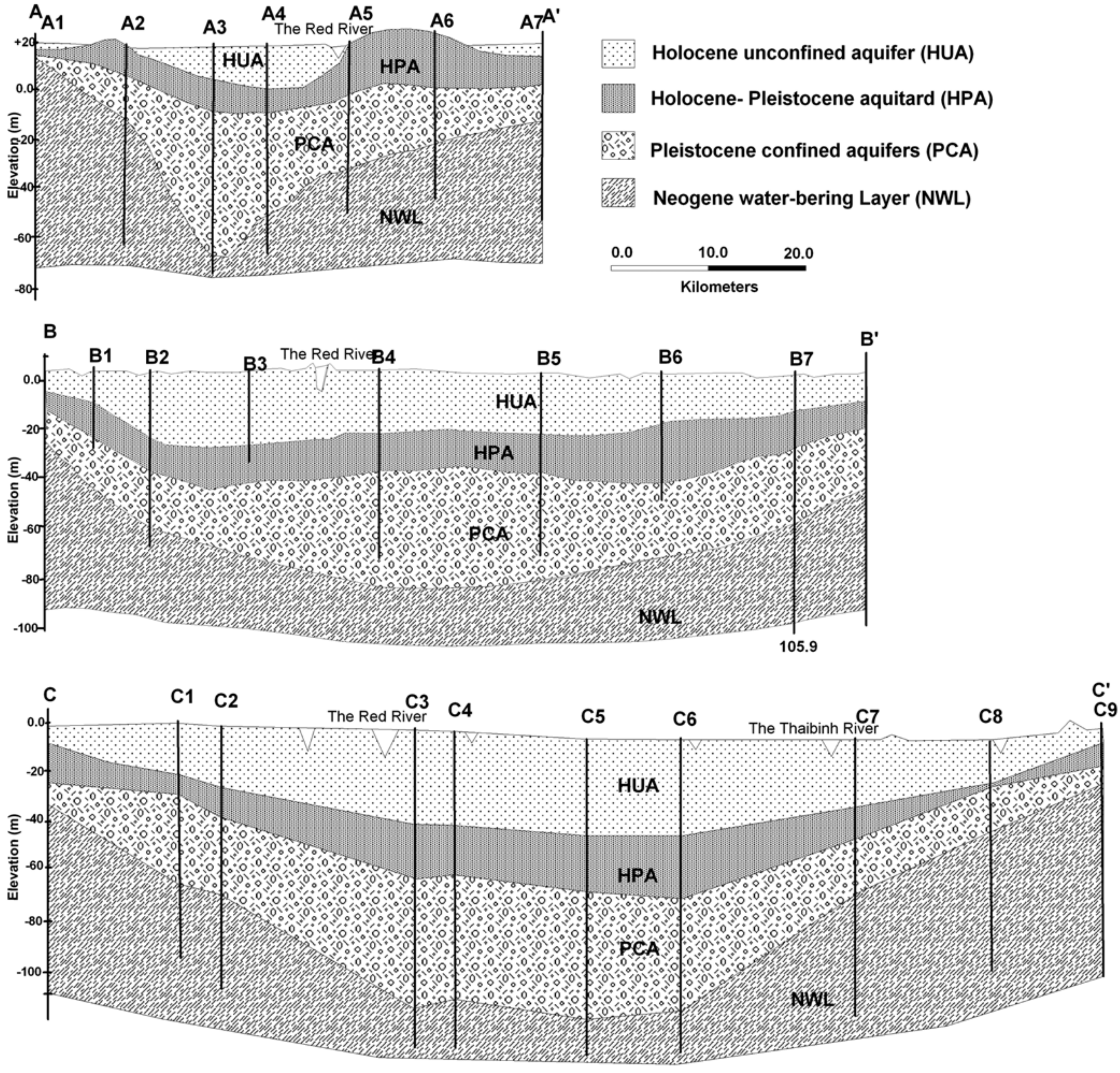

**Fig. 3.** Hydrogeological cross-sections along A-A’, B-B’, C-C’ lines as shown in Figure 2.

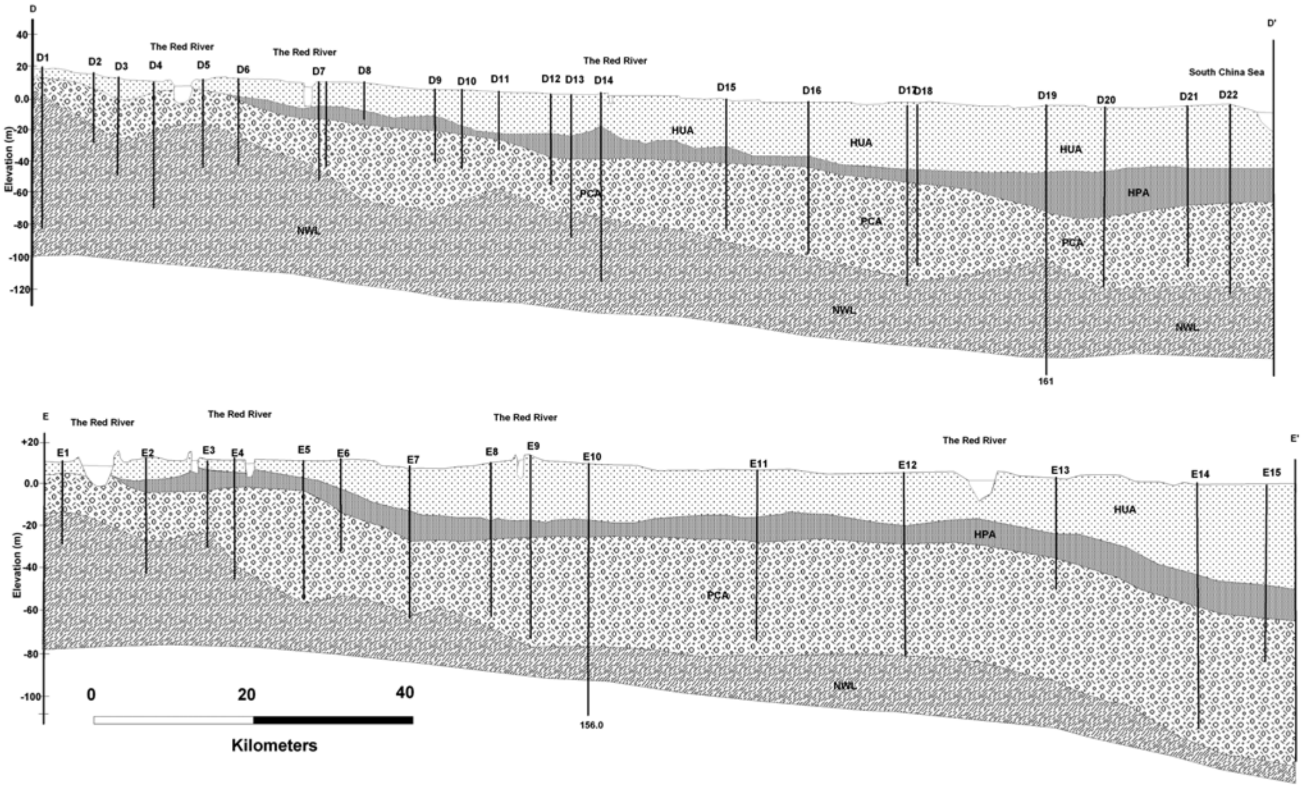

**Fig. 4.** Hydrogeological cross-sections along D-D', E-E' lines as shown in Figure 2. Legend of Figure 4 is the same as in Figure 3.

C-C', D-D', E-E' as shown in Figure 2 which were selected considering the density of boreholes. These figures demonstrate a straightforward framework of the aquifer system and hydrogeological conditions in the delta. A-A', B-B', and C-C' illustrate the aquifer structure along the coastline from Hanoi to the sea. On the other hand, D-D' and E-E' shows the aquifer structure along the Thaibinh River and the Red River, respectively. These cross-sections were made by interpolating 7, 7, 9, 22, 15 borehole columnar section data, respectively as shown in Figures 3 and 4.

By establishing Figures 3 and 4, we found that the Red River Delta is composed of Quaternary-aged unconsolidated sediments with a maximum thickness of 100 meters, lying directly over the bedrocks aging from the Neogene period of the Cenozoic era to the Triassic period of the Mesozoic era. Groundwater of the Quaternary-aged sediments mostly exists as porous water forming the topmost HUA and the shallow PCA sandwiching HPA, while cleft and karst water exist in consolidated Neogene formations and Mesozoic bedrocks constituting NWL and MFZ. Both HUA and PCA are thicker in the center than the edge of the delta and increasing downward to the sea. The Red River is an important natural recharge source for groundwater storage in the delta because it runs across HUA and across PCA in some places due to stream-bed erosion. In general, the main recharge sources of these aquifers are from river water, rainfall and irrigation water.

Moreover, we analyzed the geological formations and material ages based on the collected well logs and their descriptions. We found that the delta has a complex geological setting. Quaternary-aged sediments have diversity of strata and lithological materials. Deposits usually have their origins of 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). In more details, HUA could be separated into three parts: uppermost, upper, and lower parts. However, they have a unique hydraulic system so they are grouped in one HUA. HPA are mainly composed of slightly permeable or impermeable formations. The thickness and hydraulic properties of conning layer are key factors in determining the vulnerability of an aquifer system. Analysis showed that HPA has an average thickness of about 10m and low permeability, less than 0.1 m/day. PCA could also be divided into two sub-aquifers (upper and lower PCA). They share a unique groundwater level, thus, they are grouped into one PCA. NWL and MFZ are mainly formed by geological cracks, weather erosion, and unconsolidated sediments. Details about materials of each formation were summarized in Table 3 which we will discuss after.

According to preliminary analyses in our earlier reports (Tong, 2007, Bui, 2005), HUA groundwater levels are usually situated within 4 meters under the ground surface. The flow direction generally moves from northwest to southeast corresponding to the delta's topography. They greatly vary from around 0.5 m above the mean sea level in coastal areas to about 7.0 m in the upper parts of the delta. Their annual cycle was strongly governed by those of rainfall and river water level with average amplitude of about 2 m. On the other hand, PCA groundwater levels showed rapid decline trends over the area with a speed of about 0.2 m/year due to excessive groundwater exploitation. Large cones of depression have formed in many urban areas such as Hanoi, Haiphong, and Namdinh. PCA groundwater levels fluctuate in a large range of –20 to 10 m with average amplitude of annual cycle of about 1.7 m. The groundwater levels of other minor water bearing units (NWL and MFZ) are still poorly observed.

## 4. AQUIFER SYSTEM CHARACTERIZATION

### 4.1. The Holocene Unconfined Aquifer (HUA)

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

A contour 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. These methods produce visually appealing maps from irregularly spaced data (Bakkali and Amrani, 2008). Kriging is distinguished from other interpolation methods by taking into consideration the variance of estimated parameters. There are a number of kriging types (e.g., simple Kriging, ordinary Kriging, universal Kriging, and many others), and in this paper the ordinary Kriging was utilized, since it has been used widely as a reliable estimation method and most commonly adopted for environmental studies (Poon et al., 2000; Nas and Ali, 2010). It uses a local mean, which re-estimates each value at each grid node from the data within the search neighborhood. The typical assumptions for the practical application of ordinary kriging are: i) intrinsic stationarity or wide sense stationarity of the field (i.e., any two locations that are a similar distance and direction from each other should have a similar difference squared); ii) enough observations to estimate the variogram (Ragavan, 2009). Thus, ordinary

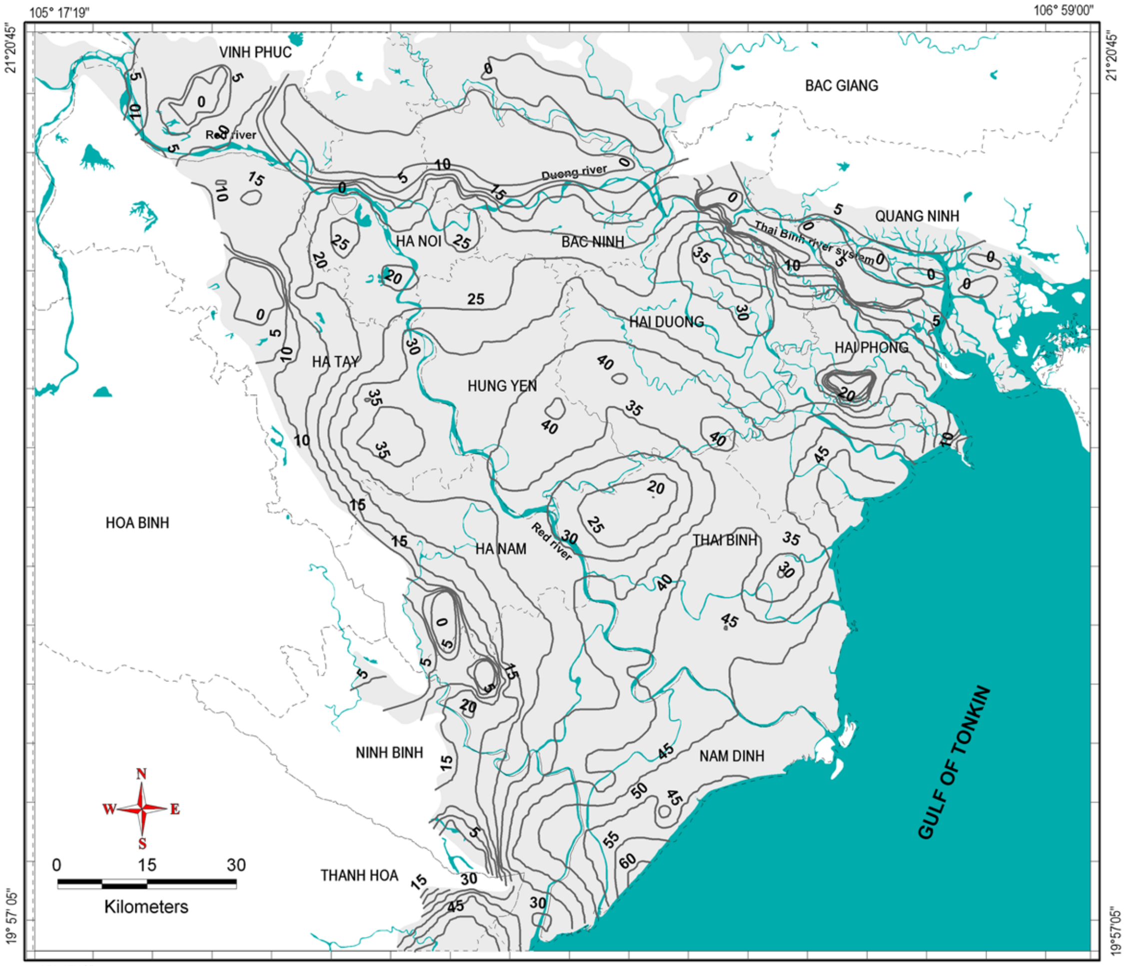

Fig. 5. Contour map of HUA's thickness.

kriging is a powerful and popular method of spatial interpretation with various type of data distribution. Kriging applies weighting functions according to a mathematical model of the variogram. In this study, a simple linear variogram was used as the fitting model since it usually generates an acceptable grid (Nas and Ali, 2010). Even though Kriging is a robust technique and the best linear unbiased estimator in the sense of the least variance, it still has some limitations. For example, it tends to produce smooth images of reality. Hence, extremes are underestimated and short scale variability is poorly reproduced. It also requires the specification of a spatial covariance model, which could be difficult to infer from sparse data, and consumes much more computing time than conventional gridding techniques (Armstrong, 1998). The output surface of Kriging interpolation is often affected by two directional components: global trends (i.e., an overriding process that affects all measurements) and anisotropy (a characteristic of a random process that shows higher autocorrelation in one direction than another). A more detailed description of the Kriging is given by Stein (1999).

Even though we used those robust methods, creating sensible contour maps was a difficult task because boreholes are very small features on the scale of the heterogeneities of an aquifer. Values of hydrodynamic parameters obtained from pumping tests vary widely over a short distance depending on exactly where the wells are drilled. In this paper, therefore, we not only utilized those methods but also interpreted and compared to the observational data by hand to draw the realistic contour maps. The results estimated by Kriging interpolation only served as initial basis which is used for reference when drawing the contour maps by hand. Figure 5 shows the contour map of HUA thickness which clarifies the vertical extent of HUA. This contour map was drawn using strata data from 721 well logs out of 778 boreholes due to missing strata data. From this figure, it is depicted that HUA thickness varies up to more than 60 m. On the whole, there is an increasing tendency from the northwest to the southeast of the delta, whereas there exists a thin area with the thickness of less than 30 m in the middle of the delta. The thickness is zero in the north and some other places around the border of the delta because no HUA exists there as shown in Figure 2.

Figure 6 shows the histogram of hydrogeological parameters, i.e., specific capacity ($q$), total dissolved solid (TDS), and transmissivity ($T$), obtained from 147 pumping tests. The number of $q$, TDS, $T$ values are 114, 111, and 101 as shown in Figure 6a, b, and c, respectively due to missing data. They are good indicators for the level of potential groundwater resources. The value of $q$ is an important hydraulic parameter indicating the transmitting properties of an aquifer and is used to assess the water-bearing and yielding potential of aquifers. Many papers have extensively discussed the use of $q$ to estimate $T$ (Darko, 2005). Figure 6a exhibits that number of $q$ values more than 1 L/s/m is 61 out of 114 boreholes which revealed that more than half of boreholes had high potential of groundwater according to the Vietnam guidelines for the aquifer test (Tran, 2000). Since the focus of this paper is on the identification of aquifer system in the whole Delta, detailed assessment of groundwater quality remains as subsequent works. Only TDS is briefly analyzed here, as TDS content of a water is the most common measure of its overall mineralization and is the best measure of the salinity of a groundwater (Paul, 2007). From Figure 6b, 96 TDS values are less than 1 g/L indicating that groundwater of HUA is fresh by the Vietnam drinking water standards. However, the other 15 TDS values represent brackish water with the area from cross-section B-B' (Fig. 2) to the sea. Figure 6c shows that the transmissivities of HUA vary up to 2,200 $m^2$/day and about 60% of transmissivity values are more than 200 $m^2$/day indicating high potential of groundwater.

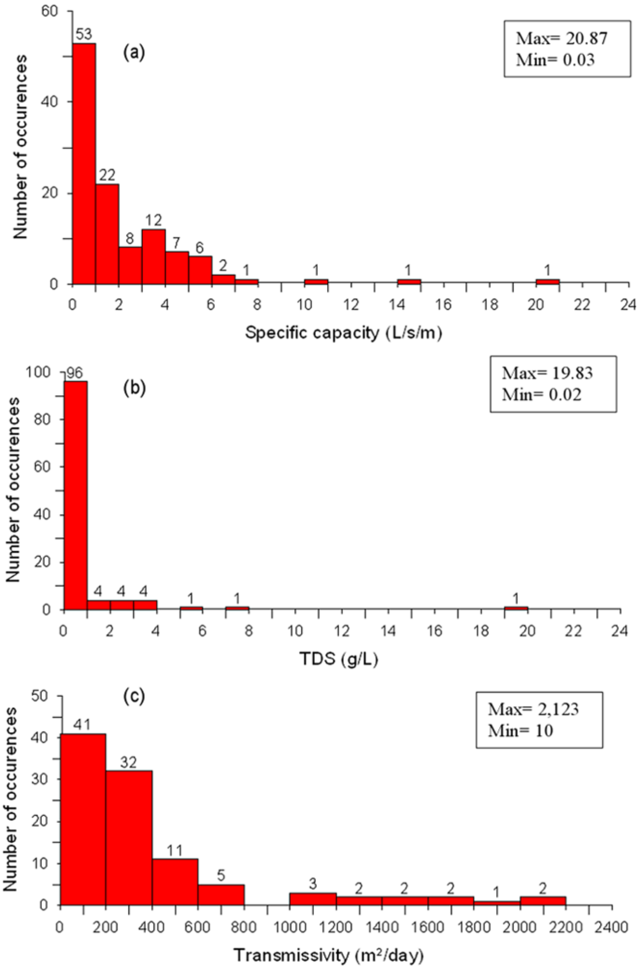

**Fig. 6.** Histogram of specific capacity (a), TDS (b), and transmissivity (c) from HUA boreholes.

Using 101 transmissivity data, we attempted to find out the general tendency of the spatial $T$ distribution through using the same way of making the Figure 5. The results of

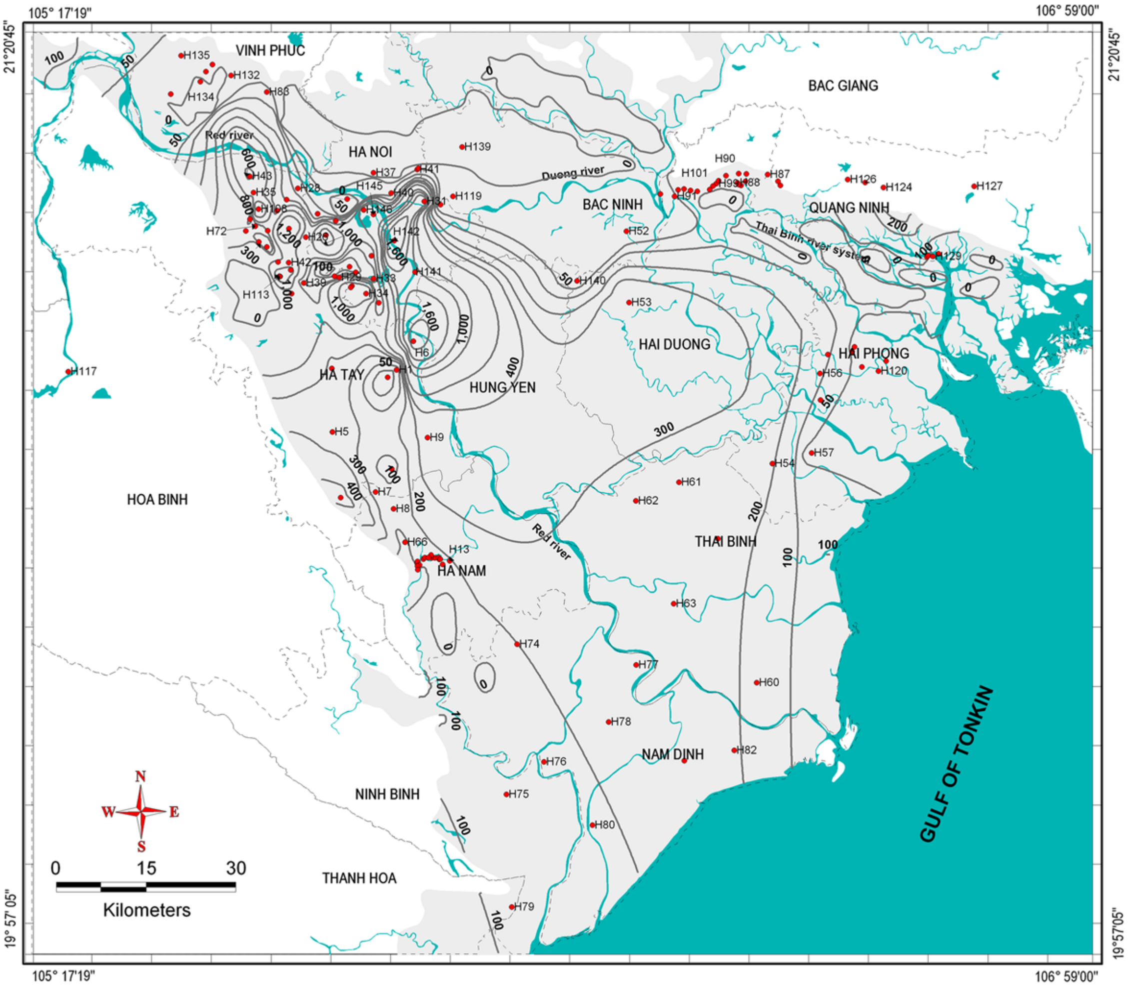

**Fig. 7.** Rough contour map of transmissivity of HUA.

contour map of transmissivity are showed in Figure 7. As shown in of Figure 7, the transmissivity roughly increases from the delta boundary to the center around Hanoi, Hatay, Hungyen provinces. There are two areas of more than 1,600 $m^2$/day along the Red River near the borehole H142 and H6 presenting high potential groundwater resources. Furthermore, specific yields, $S_y$ are useful parameters for quantitative estimation of potential groundwater storage of the aquifer. The $S_y$ values, obtained from 2 cross borehole tests (H142 and H72) around the border between Hanoi and Hatay province shown in Figure 7, were 0.09 and 0.1. Groundwater storage capacity of HUA was roughly estimated about 10 billion $m^3$ considering the average height of groundwater level (around 10 m), the surface area (11,450 $km^2$), and $S_y$ values (0.095).

Judging from the obtained results, HUA has relatively high potential of groundwater resources and is sufficient for medium scale domestic water supply.

### 4.2. The Pleistocene Confined Aquifer (PCA)

Applying the same procedures explained in the former section, the contour maps of PCA depth from the ground surface (Fig. 8) and PCA thickness (Fig. 9) were created based on the strata data of 721 well logs. Figure 8 reflects great changes in PCA depth from region to region with an increasing tendency from the northwest to the southeast along the Red River. The depth is only less than 10 m in the north at Vinhphuc province, but around 30 to 40 m in Hanoi, and up to 60 to 70 m in Namdinh, Thaibinh provinces. Figure 9 indicates that the thickness of the PCA also fluctuates over a large range, up to 80 m and has an increasing tendency from the northwest to the southeast of the delta. Three areas of more than 60 m in thickness are located around Namdinh province, the center of the delta, and Hanoi province. Distribution tendencies of PCA depth and thickness are relatively similar.

There exit the greatest number of 413 pumping tests drilled in this aquifer in which 19 of them are cross-borehole tests. Table 1 shows $q$, TDS, $T$, and storage coefficient ($S$) obtained from those cross-borehole tests. $S$ value is a useful parameter to estimate the potential pumping storage of the confined aquifer. As seen in Table 1, the $S$ values

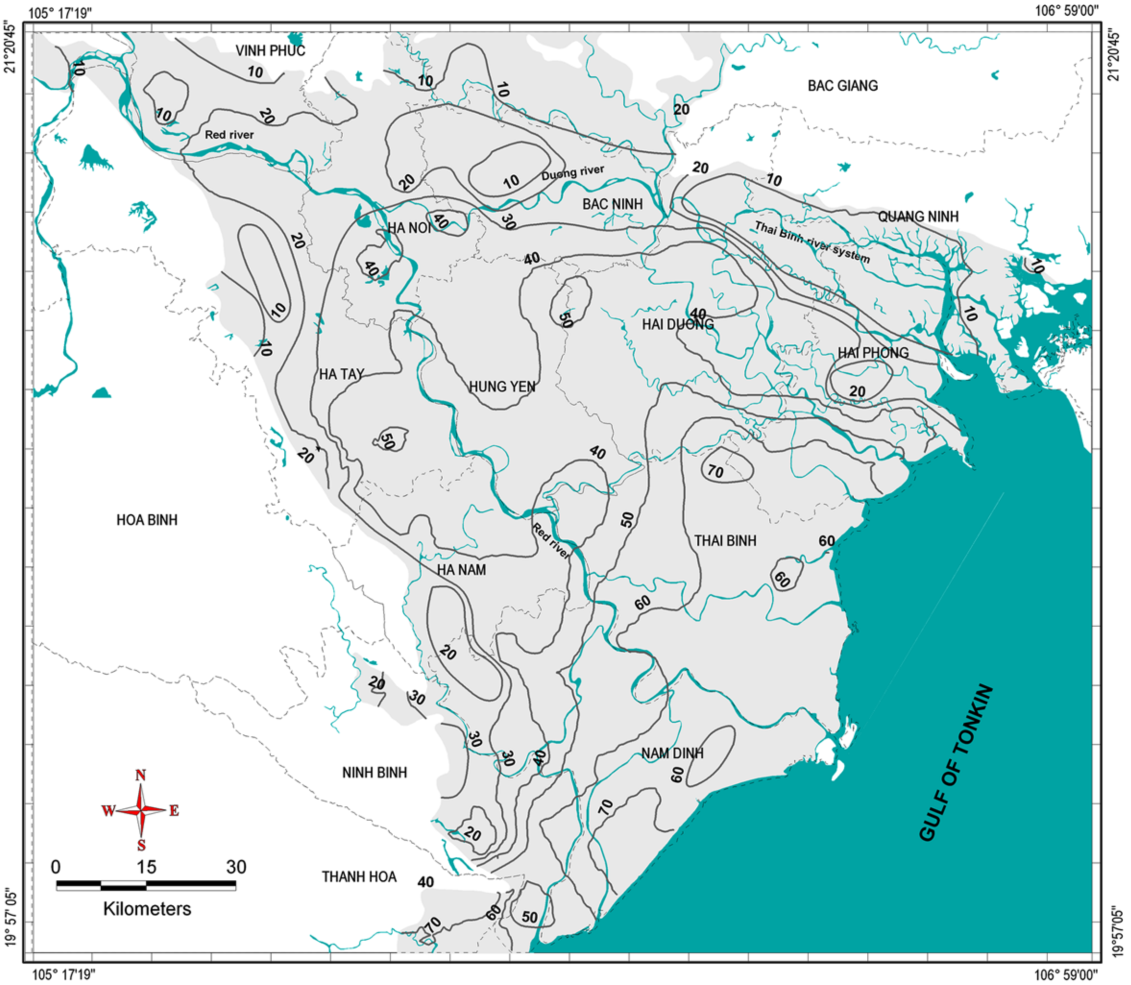

**Fig. 8.** Contour map of the depth from the ground surface down to the top of PCA.

vary in a wide range with the average of 0.024. Using *S* values (0.024), average thickness (around 45 m), and the surface area of PCA (around 13,000 km$^2$), groundwater storage capacity of PCA was roughly estimated about 13 billion m$^3$. Moreover, *q* values from all cross-borehole tests are more than 1 L/s/m which indicate high potential of groundwater resources.

Considering total 413 pumping tests including 398 single borehole tests, numbers of *q*, TDS, and *T* values are 356, 340, and 348 as shown in Figure 10a, b, and c, respectively. From Figure 10a, there are 284 boreholes of high potential groundwater ($q > 1$ L/s/m) occupying 80% of total boreholes. Figure 10b reveals that 290 TDS values are less than 1 g/L indicating freshwater. Total area of freshwater is about 7,500 km$^2$ occupying about 57% of the delta area. Generally, spatial distribution of TDS of groundwater in PCA is quite similar to that in HUA. Figure 10c indicates that *T* values reach up to 6,720 m$^2$/day in which about 70% of *T* values of more than 350 m$^2$/day presenting very high potential of groundwater.

Contour map of PCA transmissivity was presented in Figure 11 to clarify the general tendency of the spatial *T* distribution using 348 transmissivity data. This figure shows that *T* values vary greatly from location to location with the increasing tendency from the border to the center of the delta. The highest *T* value zone of more than 3,000 m$^2$/day is placed around the southern Vinhphuc province near the Red River. Comparing to HUA (Fig. 7), the distribution of *T* values of PCA is rather complicated with several peaks expressing a very high potential of groundwater resources. These peaks are located not only in Hanoi but also in other areas along the Red River and Duong River.

Based on aforementioned analyses, we could conclude that the PCA has a very high potential of groundwater resources. Accompanied with its great thickness, PCA is sufficient for large scale domestic water supply.

### 4.3. Minor Water Bearing Units

As described in Chapter 3, two other minor water bearing units in pre-Quaternary formations are NWL and MFZ. Analyzing the strata data, we found that the depth from the

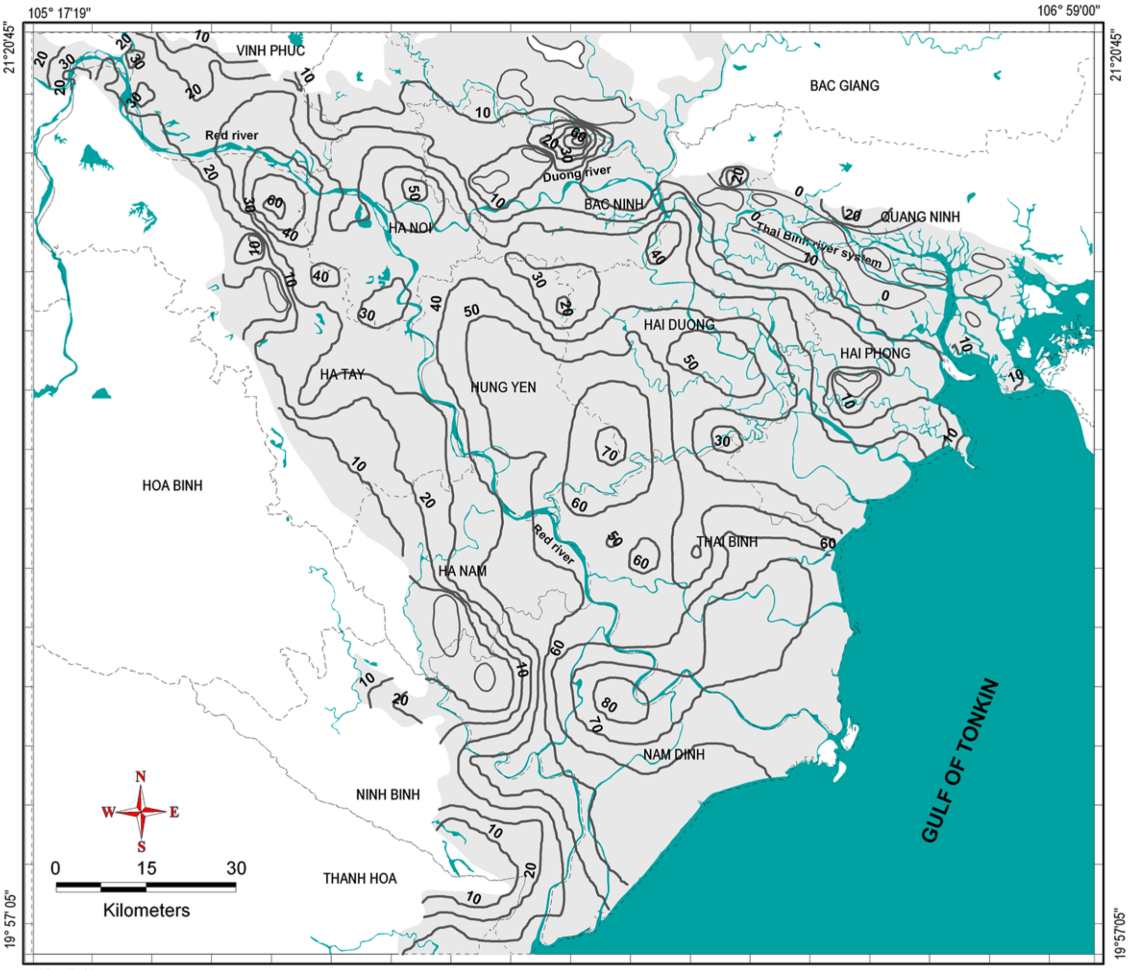

**Fig. 9.** Contour map of PCA's thickness.

**Table 1.** Cross borehole test results of Pleistocene confined aquifer (PCA)

| Boreholes | $q$(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 |
| P19 | 5.48 | 0.225 | 800 | 0.029 |

ground surface to the top of NWL varies up to 100 m and the thickness could reach up to 1,000 m at the center of the delta. Hydrogeological parameters gained from 70 single-borehole tests include 42 $q$ values, 37 TDS values, and 37 $T$ values as presented in Figure 12a, b, and c, respectively. In Figure 12a, 19 values (45%) are more than 1 L/s/m indicating relatively high groundwater potential. Figure 12b shows that 26 TDS values are less than 1 g/L indicating that groundwater of NWL is fresh. Referring to locations of these boreholes in Figure 1, freshwater of NWL is covered from the northwest of the delta to Hanoi, Hungyen provinces. Figure 12c depicted that about 60% of transmissivity values are more than 200 m$^2$/day that is quite similar to HUA (Fig. 6c), but practical pumping capacity of NWL could be less than that of HUA because NWL is placed in much deeper parts and composed of less permeable deposits than HUA.

Table 2 shows MFZ hydrogeological parameters of only 7 single-borehole pumping tests drilled in northern Hanoi from which we attempted to explore the basic characteristics of MFZ of Mesozoic bedrocks. In the Table 2, $q$ values

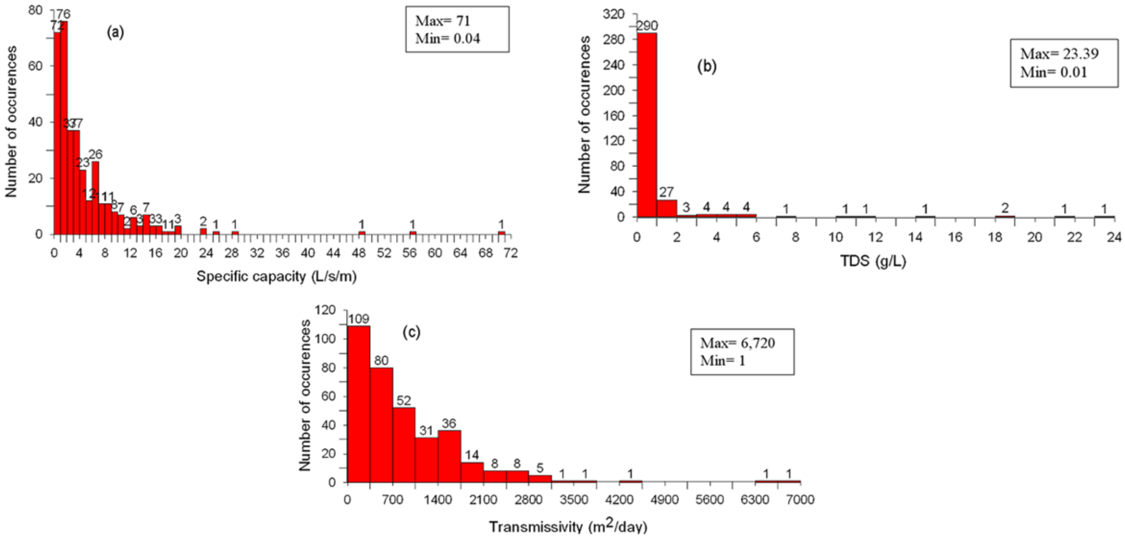

**Fig. 10.** Histogram of specific capacity (a), TDS (b), and transmissivity (c) from PCA boreholes.

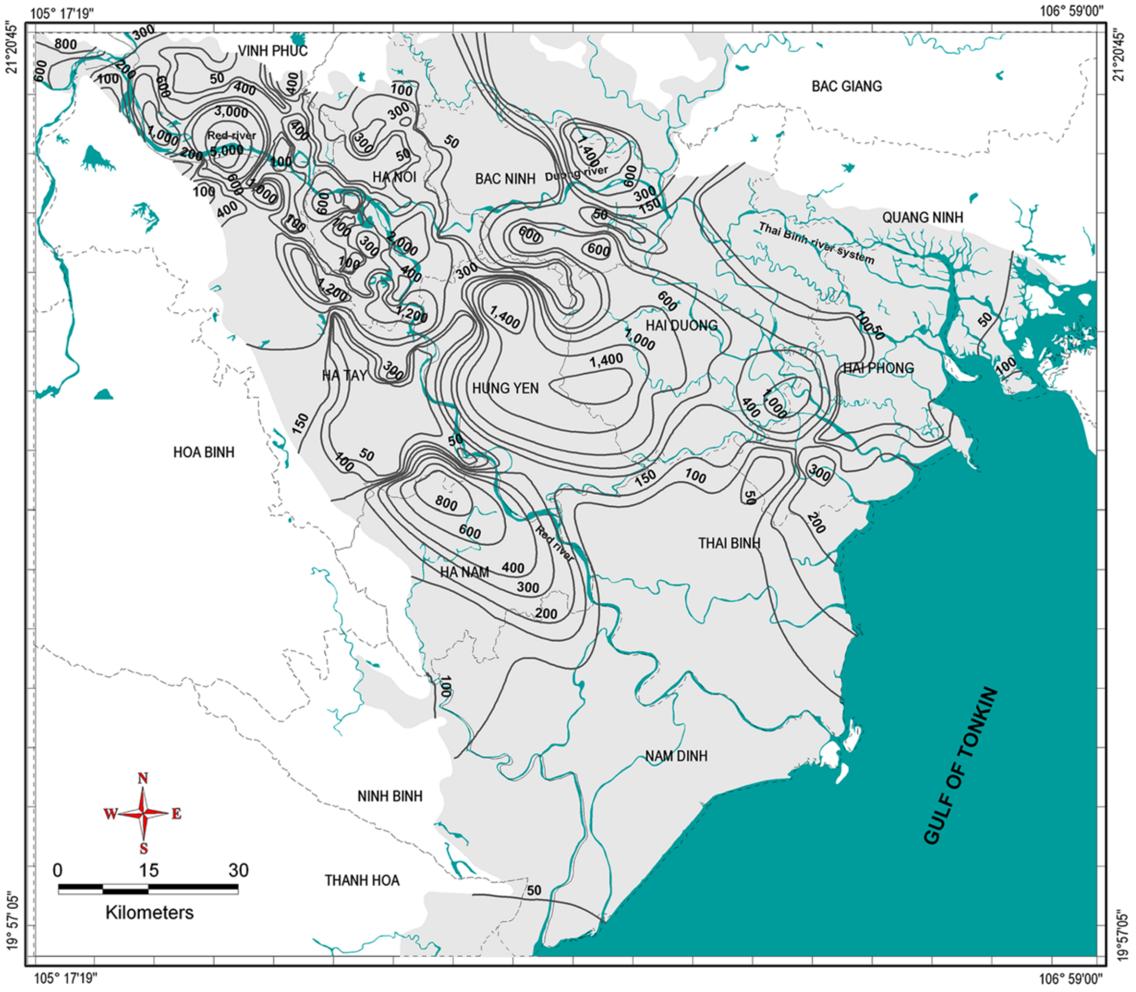

**Fig. 11.** Contour map of transmissivity of PCA.

are mainly less than 1 L/s/m being the sign of poor to medium potential of groundwater resources. Only some small parts like the location of M5 can store considerable amounts of groundwater with high $q$ value. The groundwater here is fresh proven by small TDS values of less than 1 g/L. $T$ values were generally small reflecting the limitation

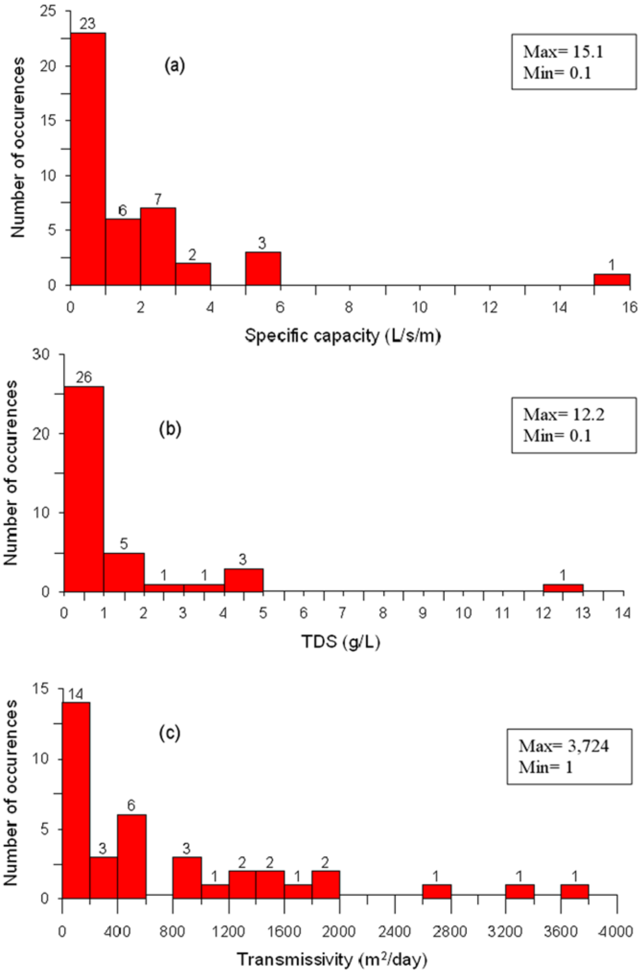

**Fig. 12.** Histogram of specific capacity (a), TDS (b), and transmissivity (c) from NWL boreholes.

of groundwater resources.

Actually, MFZ of Mesozoic bedrocks provides limited but very important water sources for local residents. Hydrogeological surveys have revealed that local communities in the northern Hanoi, dominated by Mesozoic bedrocks, have commonly employed hand-dug shallow wells to gain groundwater for individual uses, but the wells start drying up in the dry season.

**Table 2.** Pumping test results of Mesozoic fractured zones (MFZ)

| Boreholes | $q$ (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 | – |
| M6 | 0.12 | – | – |
| M7 | 0.23 | – | – |

## 5. CONCLUSION

In this paper, taking advantages of our recent project on constructing a National Hydrogeological Database, the best number of 778 boreholes including well logs and their hydrogeological parameters were comprehensively analyzed to provide the first look about the aquifer system and hydrogeological conditions in the entire Red River Delta from the viewpoint of potential groundwater resources. Hydrogeological data were interpolated and the aquifer system of the delta was identified by creating the hydrogeological map and hydrogeological cross sections. Also, we focused on analyzing hydrogeological parameters of these water bearing formations in more detail, especially HUA and PCA, by making contour maps of thicknesses, depths, and transmissivities. Table 3 tabulates the overall characteristics of the aquifer system of the Red River Delta. As for the results, the delta is composed of Quaternary-aged unconsolidated sediments which consist of HUA, PCA and HPA, directly overlaying on the older formations which

**Table 3.** Characteristics of aquifer system in the Red River Delta

| Aquifer system | Geological ages | Hydrogeological conditions | Depth to the layer's top (m) | Thickness (m) | $q$ (L/s/m) | TDS (g/L) | $T$ (m$^2$/day) | $S_y/S$ | Materials | Groundwater potential | Groundwater storage capacity (billion m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| HUA | Holocene | Unconfined aquifer | 0 | 0–60 | 0.3–20.87 | 0.02–19.83 | 10–2,123 | 0.09–0.1 | Clay slurry, sandy dust, and gray sand | High potential | 10 |
| HPA | Holocene-Pleistocene | Aquitard | 0–60 | 0–40 | No data | No data | No data | No data | Silty clay,<br>clay sand, clay | No potential | No data |
| PCA | Pleistocene | Confined aquifer | 0–70 | 0–80 | 0.04–71 | 0.01–23.39 | 1–6,720 | 0.00004–0.145 | Mediumcoarse sands, gravel, cobble | Highest potential | 13 |
| NWL | Neogene | Discontinuous aquifer | 0–100 | 0–1,000 | 0.1–15.1 | 0.1–12.2 | 1–3,724 | No data | Cemented gravel,<br>cemented clay,<br>arkosic sand-stone,<br>argillite,<br>and clay carbon | Medium potential | No data |
| MFZ | Mesozoic | Fractured zones | No data | No data | 0.12–6.15 | 0.15–0.293 | 64–305 | No data | Sandstone and porphyry | Low potential | No data |

form the NWL and MFZ. HUA is widely distributed at a rate of about 88% over the delta. HUA has relatively high potential of groundwater resources and is sufficient for medium scale domestic water supply. PCA, on the other hand, is distributed almost entirely the delta. It has the highest groundwater potential and serves as the most important aquifer for water supply. NWL and MFZ, in contrast, have limited groundwater potentials. The groundwater in all water bearing formations (HUA, PCA, NWL, and MFZ) is commonly fresh from the northwest border to the center of the delta.

Our findings are indispensable for further hydrogeological studies to ensure the sustainable groundwater development in the delta.

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