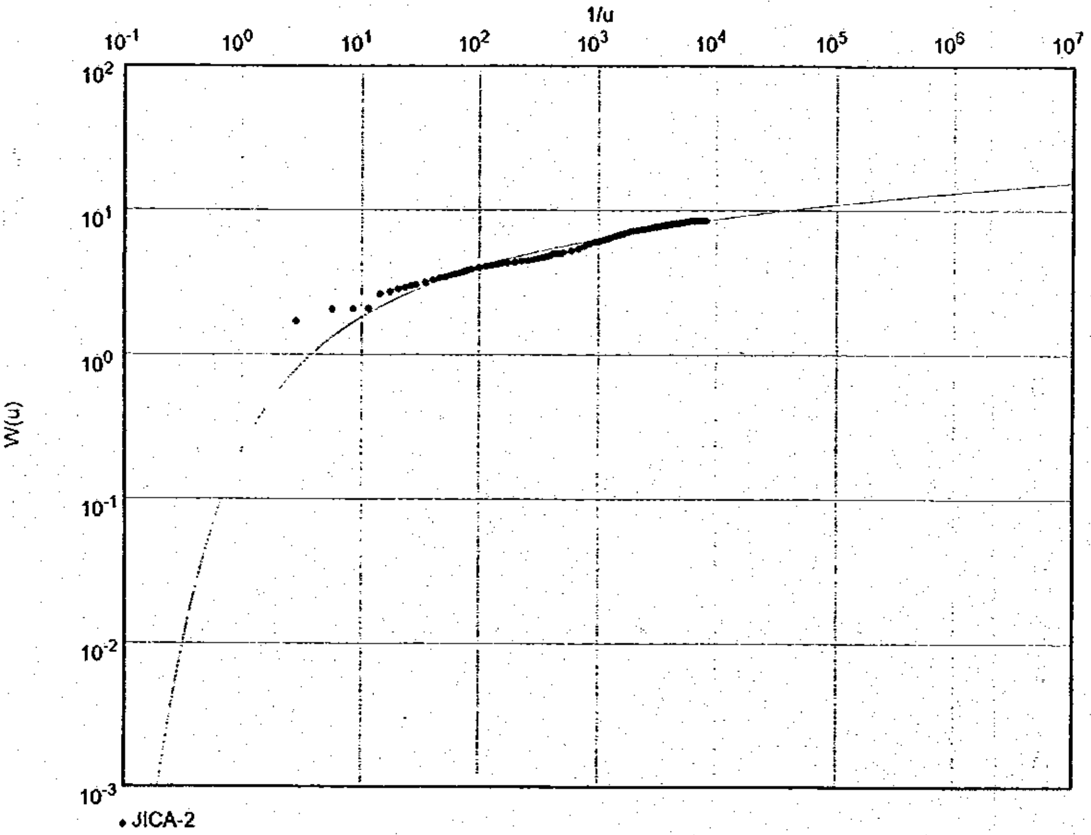
JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis Theis analysis method Confined aquifer	Page 1 **Figure 3.29** Project: JICA GROUNDWATER STUDY Evaluated by:	 Date: 10.06.1999

Pumping Test No.	Test conducted on: 04/06/1999
JICA-2 (Hoa Thuong)	
Discharge 1440.00 m³/d	



Transmissivity [m²/d]: 1.73×10^2

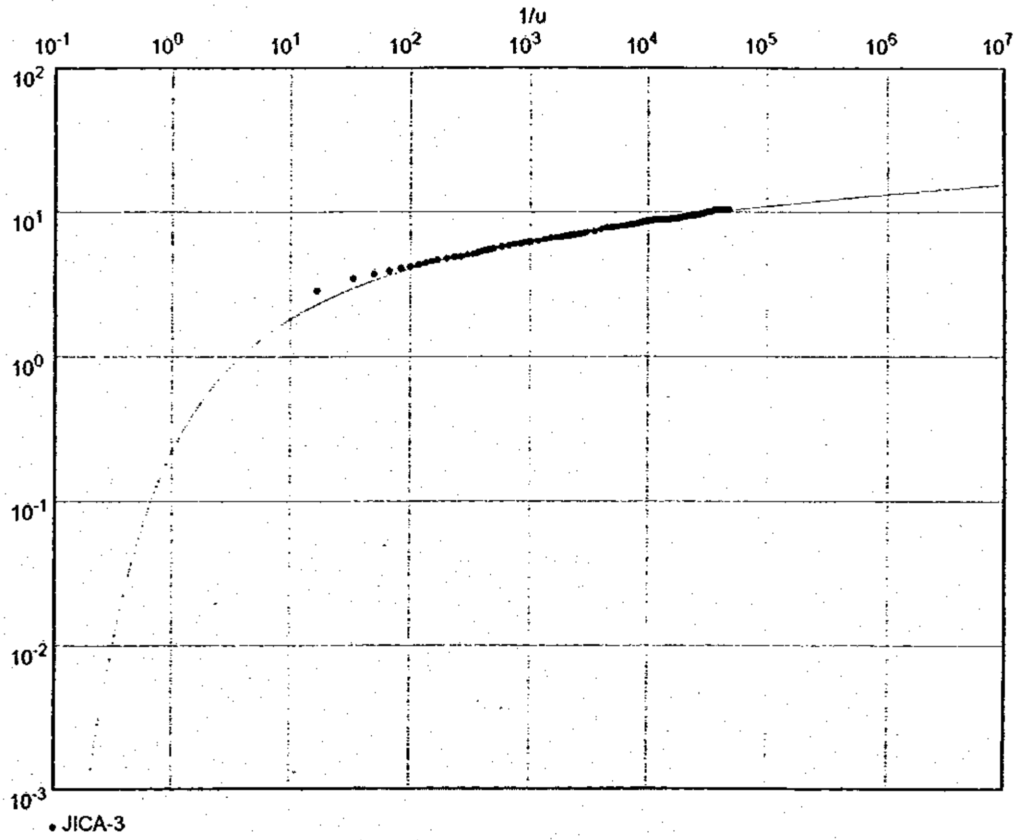
Hydraulic conductivity [m/d]: 7.24×10^0

Aquifer thickness [m]: 24.000

Storativity: 3.01×10^1

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis Theis analysis method Confined aquifer	Page 1 **Figure 3.30** Project: JICA GROUNDWATER STUDY Evaluated by: Date: 09.06.1999

Pumping Test No.	Test conducted on: 16/04/1999
JICA-3	
Discharge 138.24 m³/d	



Transmissivity [m²/d]: 2.40×10^{1}

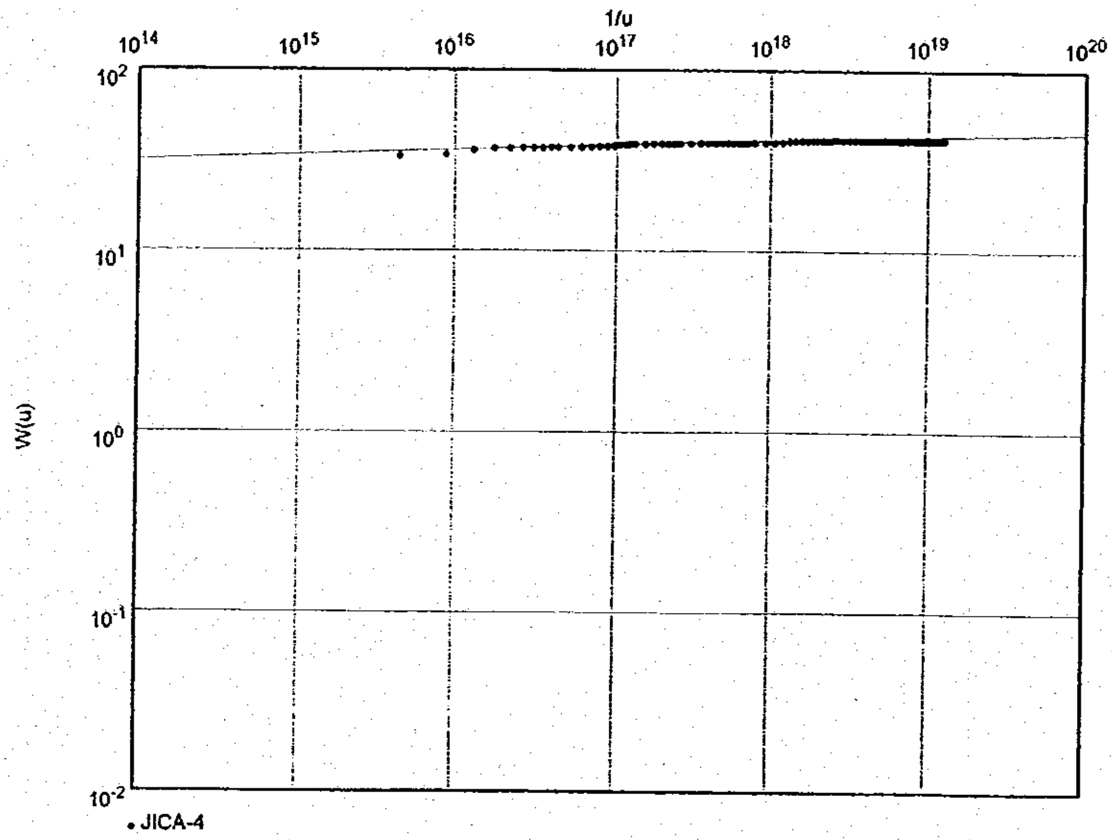
Hydraulic conductivity [m/d]: 2.00×10^{0}

Aquifer thickness [m]: 12.000

Storativity: 7.09×10^{-1}

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis Theis analysis method Confined aquifer	Page 1 **Figure 3.31**	
		Project: JICA GROUNDWATER STUDY	
		Evaluated by:	Date: 10.06.1999

Pumping Test No.	Test conducted on: 28/05/1999
JICA-4 (Thinh Duc)	
Discharge 188.35 m³/d	



Transmissivity [m²/d]: 3.32×10^{1}

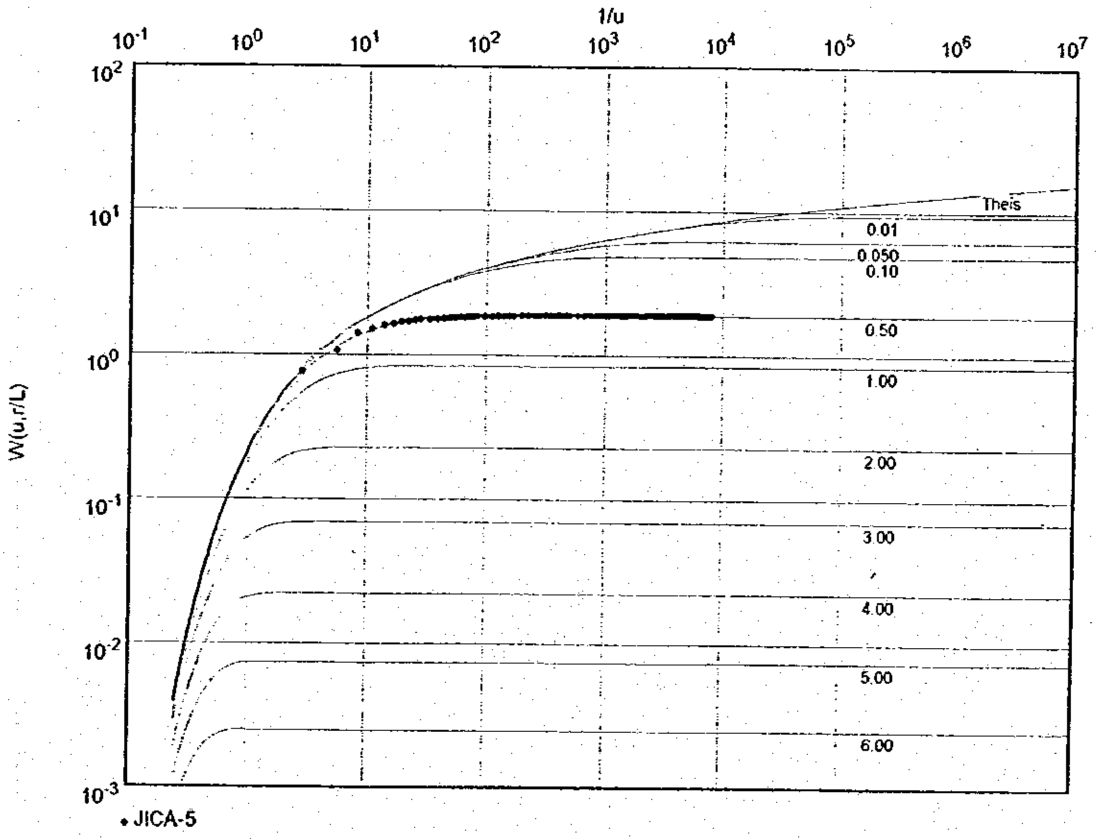
Hydraulic conductivity [m/d]: 1.38×10^{0}

Aquifer thickness [m]: 24.000

Storativity: 3.71×10^{-15}

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis HANTUSH's method Leaky aquifer, no aquitard storage	Page 1 **Figure 3.32**	
		Project: JICA GROUNDWATER STUDY	
		Evaluated by:	Date: 09.06.1999

Pumping Test No.	Test conducted on: 07/03/1999
JICA-5	
Discharge 345.60 m³/d	



Transmissivity [m²/d]: 1.21×10^{0}

Hydraulic conductivity [m/d]: 2.76×10^{-2}

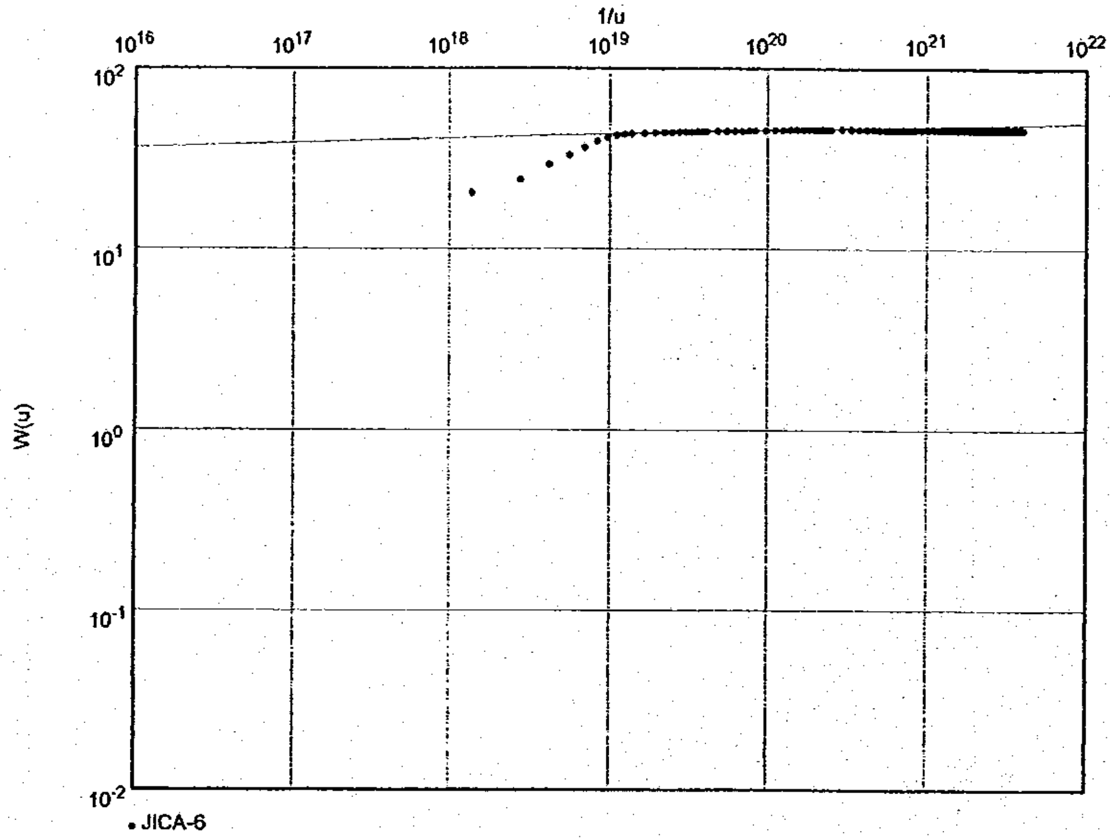
Aquifer thickness [m]: 44.000

Storativity: 2.15×10^{-1}

Hydraulic resistance (c) [d]: 1.84×10^{0}

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis Theis analysis method Confined aquifer	Page 1 **Figure 3.33** Project: JICA GROUNDWATER STUDY Evaluated by: Date: 10.06.1999

Pumping Test No.	Test conducted on: 18/03/1999
JICA-6 (Yen Thang)	
Discharge 230.40 m³/d	



Transmissivity [m²/d]: 1.53×10^{1}

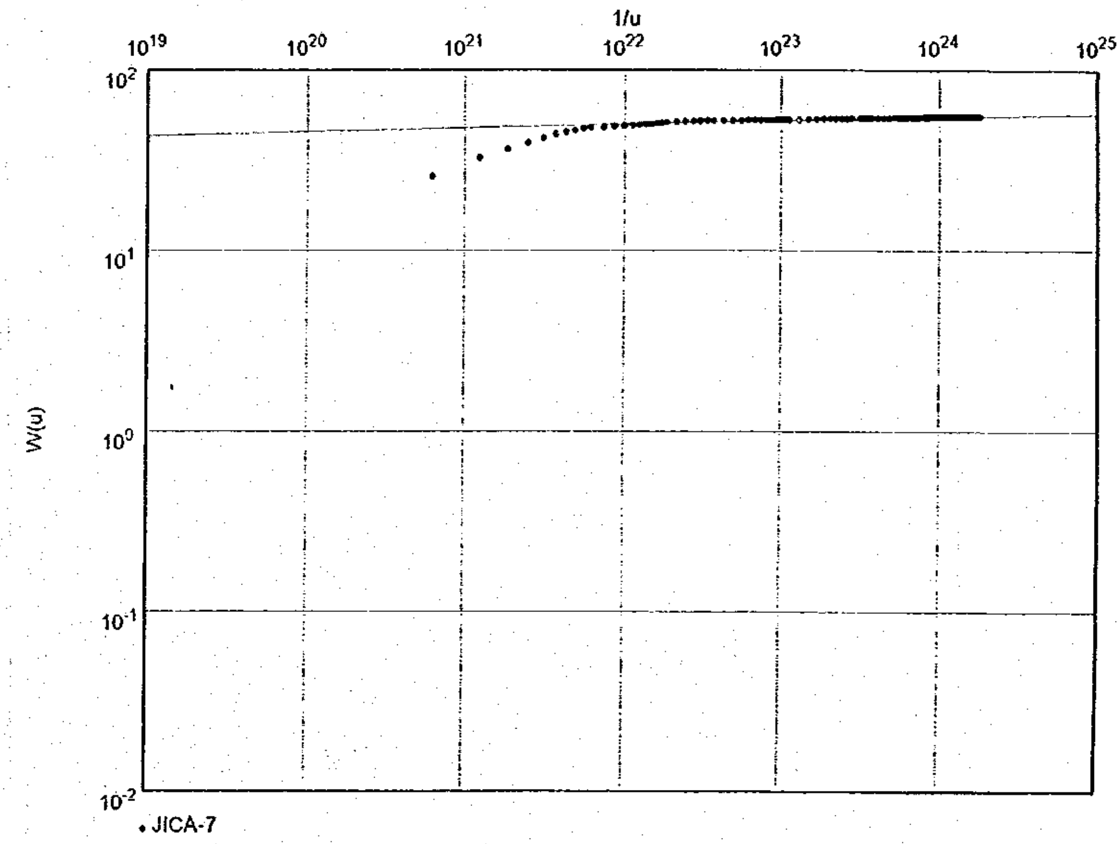
Hydraulic conductivity [m/d]: 5.11×10^{-1}

Aquifer thickness [m]: 30.000

Storativity: 5.42×10^{-18}

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis Theis analysis method Confined aquifer	Page 1 **Figure 3.34** Project: JICA GROUNDWATER STUDY Evaluated by: Date: 08.06.1999

Pumping Test No.	Test conducted on: 24-05-1999
JICA-7 (Dong Phong)	
Discharge 1728.00 m³/d	



Transmissivity [m²/d]: 8.62×10^2

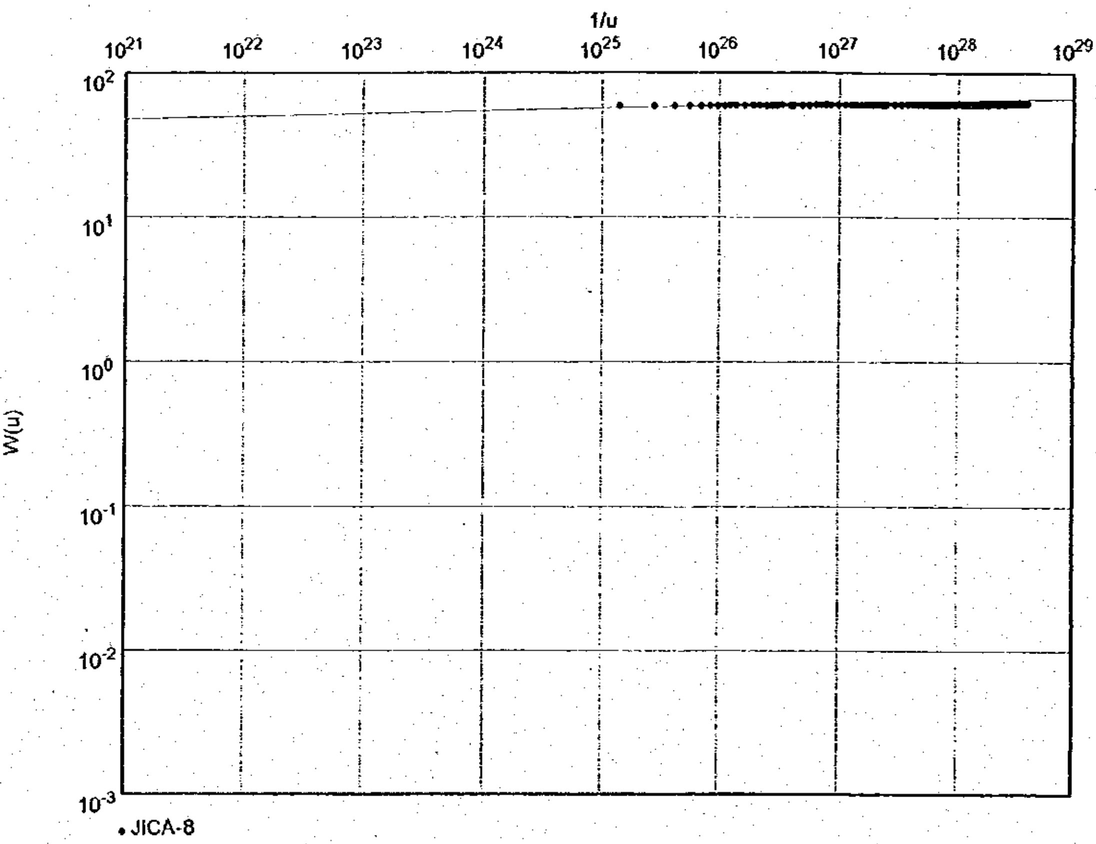
Hydraulic conductivity [m/d]: 2.69×10^1

Aquifer thickness [m]: 32.000

Storativity: 6.82×10^{-19}

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis Theis analysis method Confined aquifer	Page 1 **Figure 3.35**	
		Project: JICA GROUNDWATER STUDY	
		Evaluated by:	Date: 08.06.1999

Pumping Test No.	Test conducted on: 06/02/1999
JICA-8 (Van Thang)	
Discharge 613.16 m³/d	



Transmissivity [m²/d]: 4.70×10^{1}

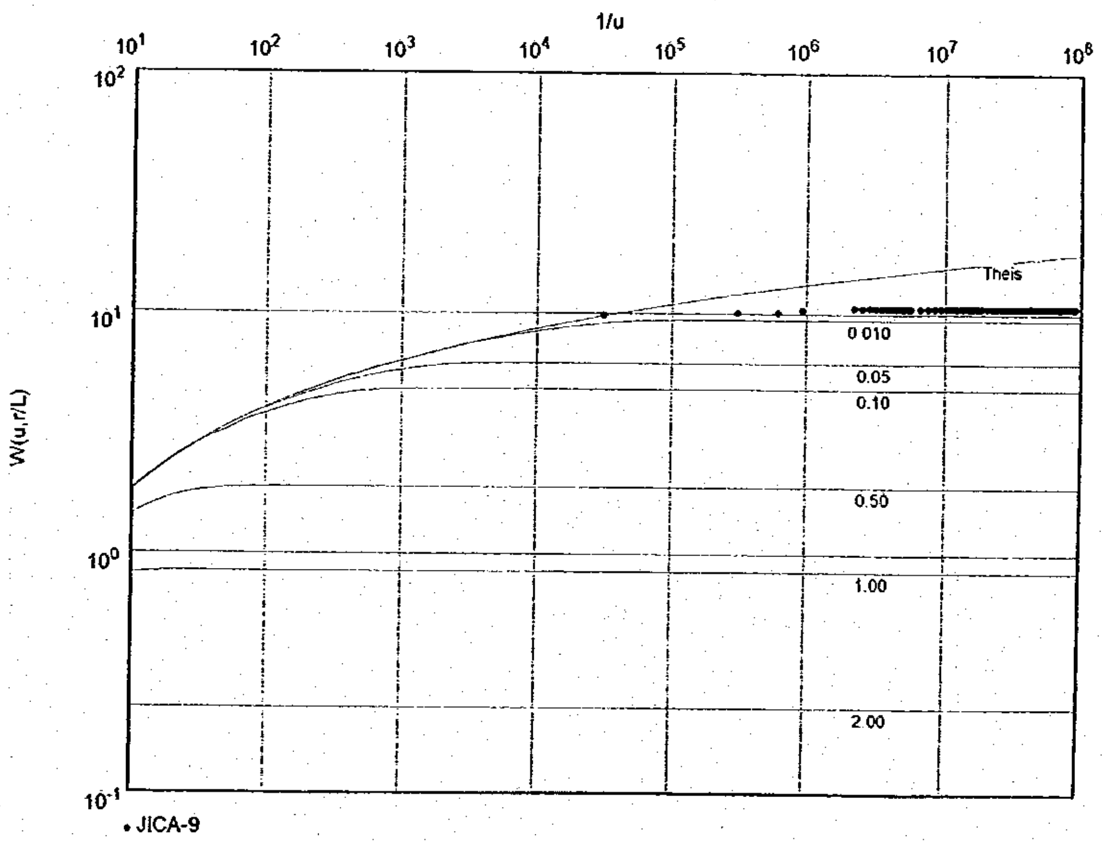
Hydraulic conductivity [m/d]: 2.35×10^{0}

Aquifer thickness [m]: 20.000

Storativity: 1.66×10^{-24}

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis HANTUSH's method Leaky aquifer, no aquitard storage	Page 1 **Figure 3.36** Project: JICA GROUNDWATER STUDY Evaluated by: / Date: 08.06.1999

Pumping Test No.	Test conducted on: 12/02/1999
JICA-9 (Thieu Hung)	
Discharge 1411.20 m³/d	



Transmissivity [m²/d]: 1.18×10^2

Hydraulic conductivity [m/d]: 7.42×10^0

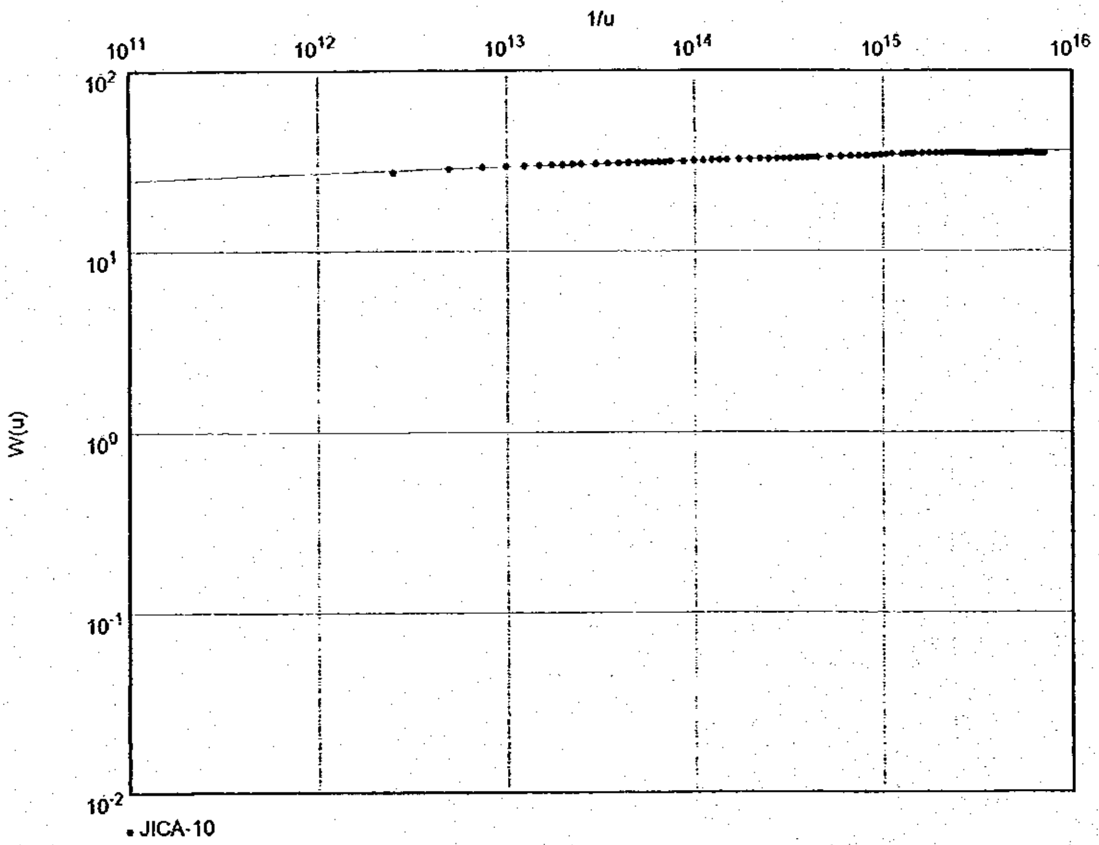
Aquifer thickness [m]: 16.000

Storativity: 1.87×10^{-3}

Hydraulic resistance (c) [d]: 4.73×10^{-1}

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis Theis analysis method Confined aquifer	Page 1 **Figure 3.37**	
		Project: JICA GROUNDWATER STUDY	
		Evaluated by:	Date: 08.06.1999

Pumping Test No.	Test conducted on: 11-04-1999
JICA-10 (Dinh Tuong)	
Discharge 1720.00 m³/d	



Transmissivity [m²/d]: 6.74×10^2

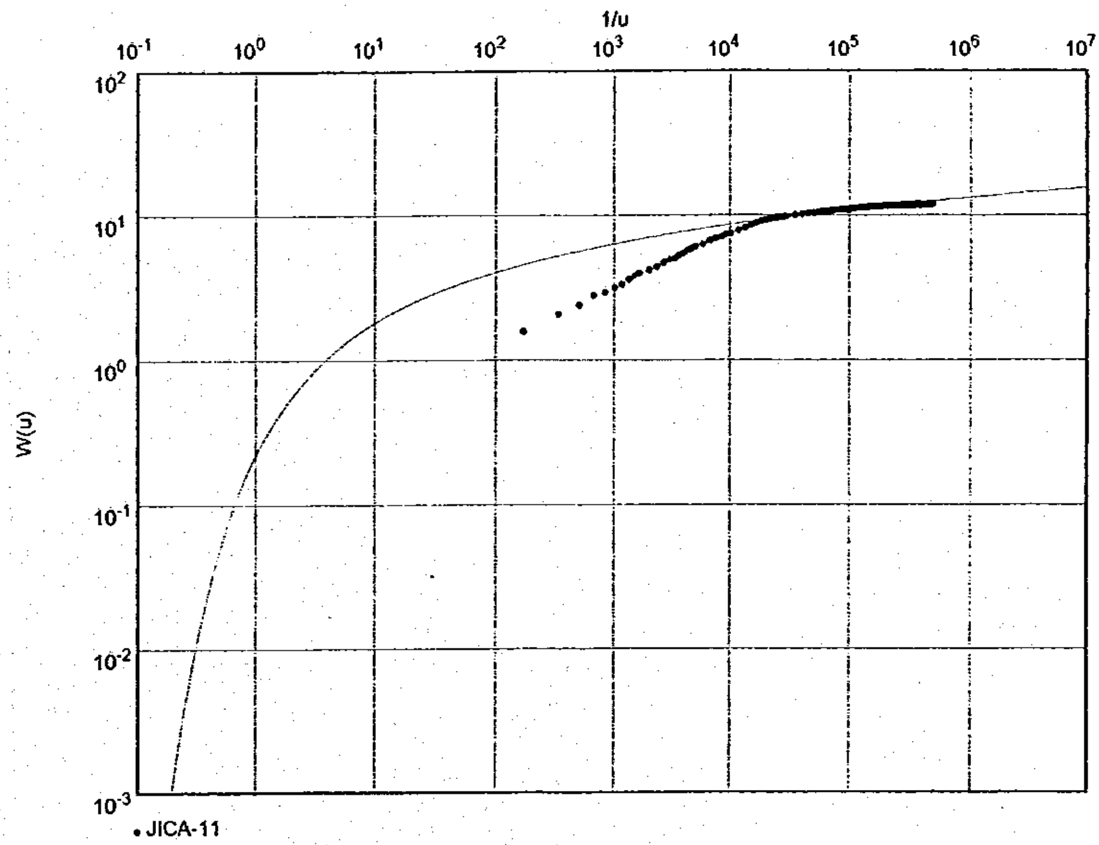
Hydraulic conductivity [m/d]: 2.10×10^1

Aquifer thickness [m]: 32.000

Storativity: 1.34×10^{-10}

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis Theis analysis method Confined aquifer	Page 1 **Figure 3.38** Project: JICA GROUNDWATER STUDY Evaluated by: / Date: 07.06.1999

Pumping Test No.	Test conducted on: 27-04-1999
JICA-11 (Vinh Thanh)	
Discharge 1512.00 m³/d	



Transmissivity [m²/d]: 8.69×10^{1}

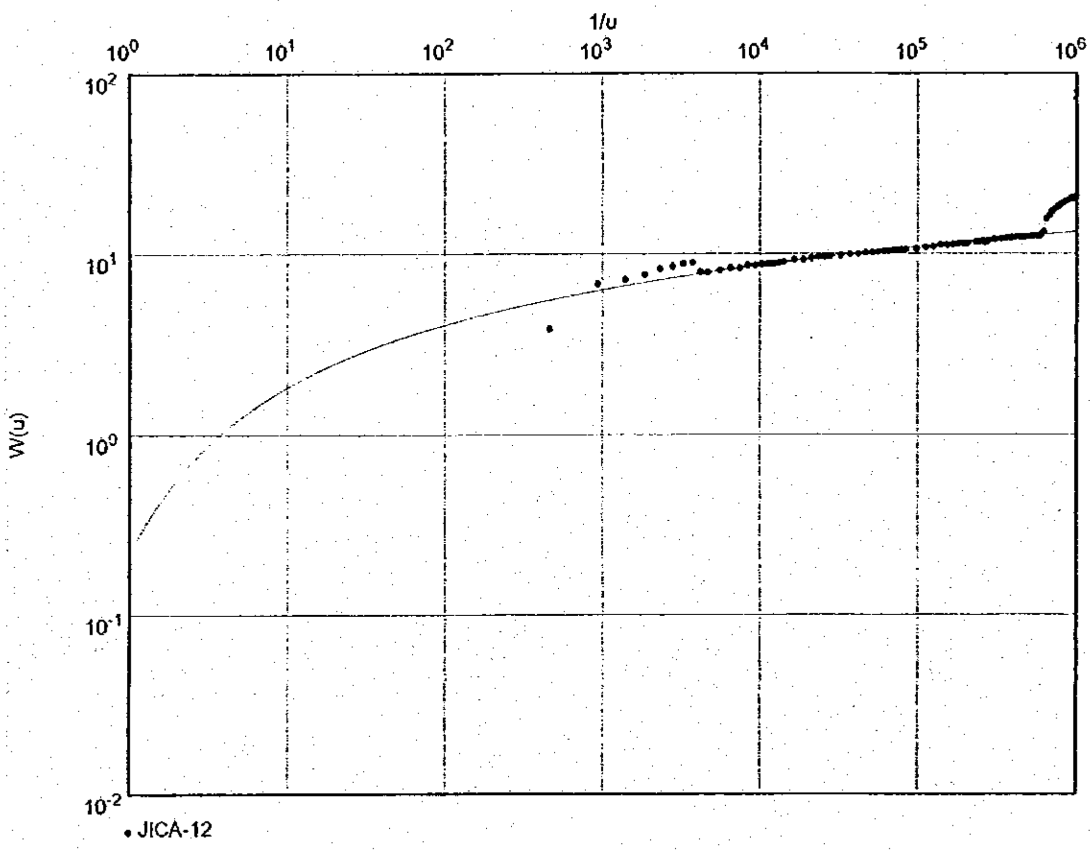
Hydraulic conductivity [m/d]: 2.71×10^{0}

Aquifer thickness [m]: 32.000

Storativity: 2.52×10^{-1}

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis Theis analysis method Confined aquifer	Page 1 **Figure 3.39**	
		Project: JICA GROUNDWATER STUDY	
		Evaluated by:	Date: 09.06.1999

Pumping Test No.	Test conducted on: 06/03/1999
JICA-12 (Duc Yen)	
Discharge 432.00 m³/d	



Transmissivity [m²/d]: 5.13×10^{1}

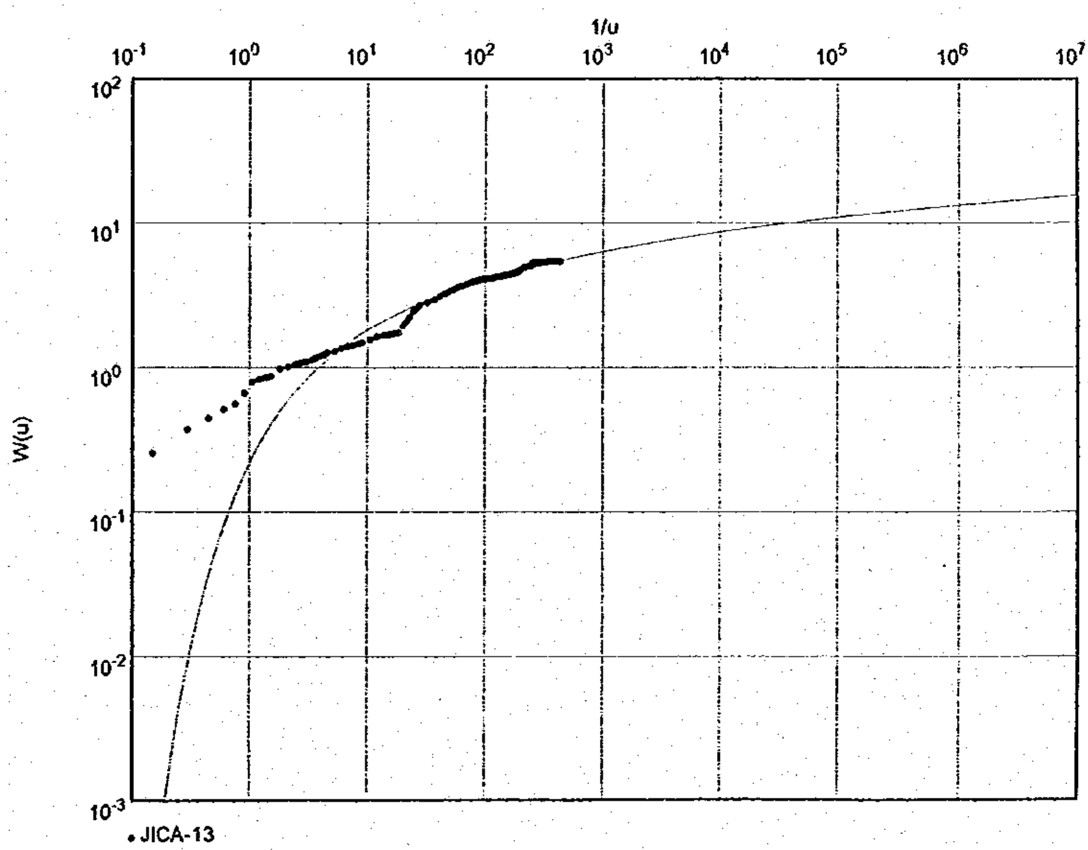
Hydraulic conductivity [m/d]: 2.13×10^{0}

Aquifer thickness [m]: 24.000

Storativity: 5.41×10^{-2}

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis Theis analysis method Confined aquifer	Page 1 **Figure 3.40** Project: JICA GROUNDWATER STUDY Evaluated by: Date: 10.06.1999

Pumping Test No.	Test conducted on: 09/04/1999
JICA-13 (Trung Le)	
Discharge 25.92 m³/d	



Transmissivity [m²/d]: 4.91×10^{-1}

Hydraulic conductivity [m/d]: 2.04×10^{-2}

Aquifer thickness [m]: 24.000

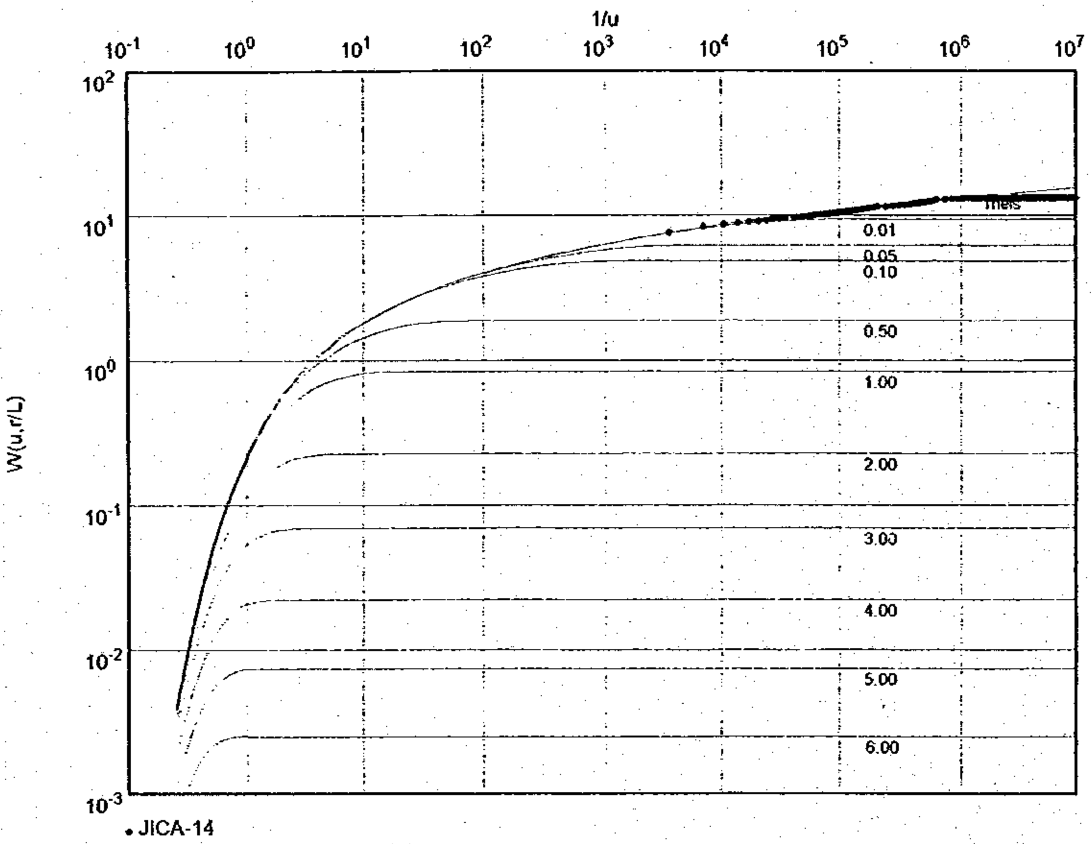
Storativity: 1.59×10^{0}

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis HANTUSH's method Leaky aquifer, no aquitard storage	Page 1 **Figure 3.41** Project: JICA GROUNDWATER STUDY Evaluated by: Date: 09.06.1999

Pumping Test No. Test conducted on: 30/03/1999

JICA-14 (Thieu Do)

Discharge 1900.80 m³/d



Transmissivity [m²/d]: 1.41×10^{2}

Hydraulic conductivity [m/d]: 7.06×10^{0}

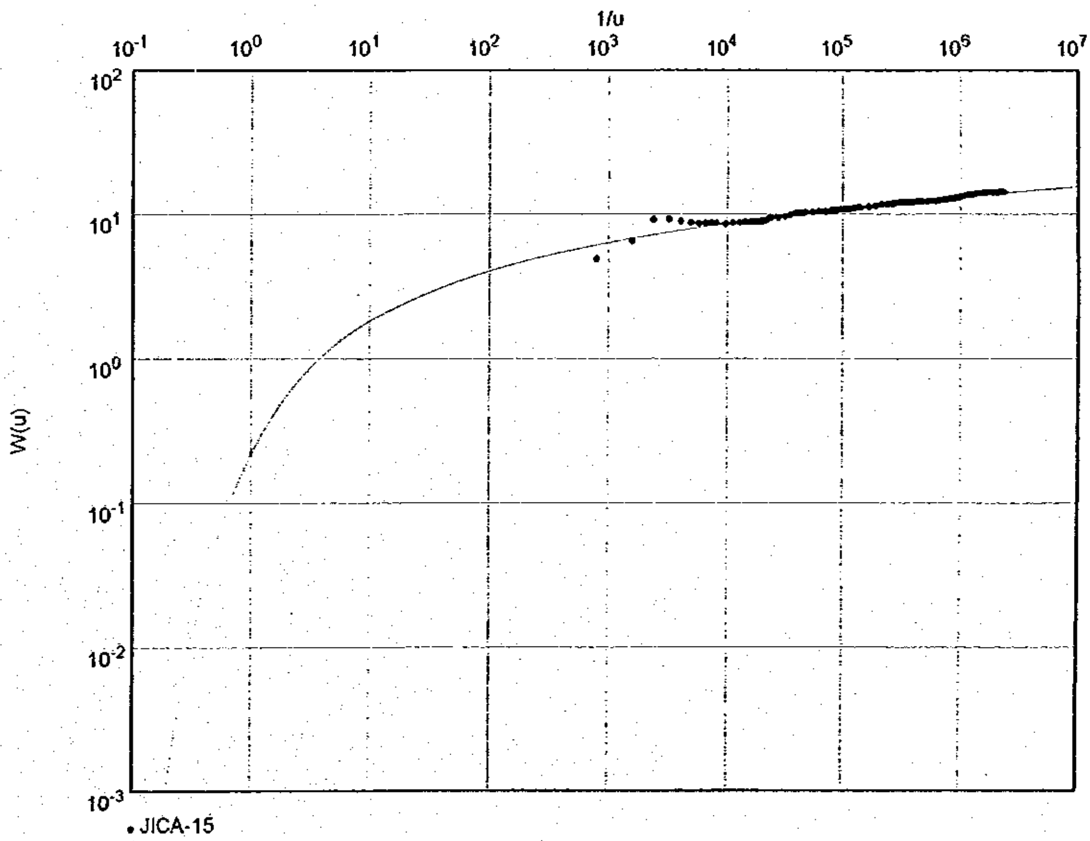
Aquifer thickness [m]: 20.000

Storativity: 1.98×10^{-2}

Hydraulic resistance (c) [d]: 3.98×10^{-1}

JICA STUDY TEAM ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	Pumping test analysis Theis analysis method Confined aquifer	Page 1 **Figure 3.42** Project: JICA GROUNDWATER STUDY Evaluated by: / Date: 09.06.1999

Pumping Test No.	Test conducted on: 02/04/1999
JICA-15 (Trung Le)	
Discharge 259.20 m³/d	



Transmissivity [m²/d]: 4.35×10^1

Hydraulic conductivity [m/d]: 2.17×10^0

Aquifer thickness [m]: 20.000

Storativity: 2.67×10^{-2}

CHAPTER 4

GROUNDWATER MODELING OF HANOI AREA

CHAPTER 4 GROUNDWATER MODELING OF HANOI AREA

4.1 Purpose

For making a groundwater development plan at the target communes in Hanoi Area, it is thought that groundwater modeling studies greatly contribute to find an optimal plan for sustainable use of groundwater resource. It was very common in the past that a groundwater development plan was implemented without carrying out proper hydrogeological and groundwater modeling studies in the cities like Hanoi. The well sites were simply selected by the results of geophysical exploration such as resistivity survey, and well yields were determined only by the results of pumping tests. Such groundwater development projects have caused various kinds of groundwater problems, such as severe decline of groundwater levels, land subsidence, and saline water intrusion.

The groundwater modeling techniques are widely employed in many groundwater basins in the world to confirm present groundwater flow situation as well as to evaluate groundwater resources. The accuracy of the model is depending on the quality and quantity of available data, however, the present groundwater flow is imitated by the model and the groundwater balance is also understood by the modeling study. The results of groundwater simulation help to realize groundwater potential quantitatively and to establish groundwater development and/or groundwater management strategies.

In Hanoi Area, the groundwater resource has been extensively exploited in a past decade for supplying water for domestic use and industrial use. It is known that the groundwater levels have been declined not only in the well sites but also in the wide area of Hanoi City. Subsequently, it has been reported that shallow wells were dried up and a significant amount of land subsidence has occurred in many parts of the city.

The two (2) target communes of the Study, namely Dong Ngac and Xuan Dinh, are located closed to the urbanized area of Hanoi City. There are several production wells in the communes for both public and private use. Particularly, the well fields of the Hanoi Water Supply System are located near the communes, and it is planned to construct new well fields in and around the communes. Figure 4.1 shows locations of the major groundwater well fields and their pumping rate in Hanoi Area. According to the data collected by JICA (1997), a total groundwater pumpage in the major 8 well fields is 365,800 m^3/day in 1995. The Ngoc Ha well field, which is located about 2 km south of Xuan Dinh Commune, has 11 production wells and the total pumpage is 50,300 m^3/day in 1995. The Mai Dich well field, which is located about 3 km southwest of Xuan Dinh Commune, has 18 production wells with a total pumpage of 64,200 m^3/day in 1995.

Therefore, the Study Team decided to carry out a groundwater modeling study to evaluate present groundwater flow conditions in Hanoi, and to find an optimal and sustainable groundwater development plan for the target communes.

4.2 Concept

A groundwater model represents an approximation of a field groundwater situation. Because the occurrence of groundwater is generally invisible and the velocity of groundwater flow is much smaller than that of surface water, studies of groundwater under both natural and artificial conditions have employed modeling techniques.

Groundwater models can be divided into physical models and mathematical models. Mathematical models, which have been widely used with development of computer technology, can simulate groundwater flow indirectly by means of a governing equation considered to represent the physical processes that occur in the system, together with equations that describe heads or flows along the boundaries of the model. Mathematical models can be solved analytically or numerically.

For mathematical models, the groundwater system and surrounding systems should be divided into several subsystems. For instance, the groundwater in a groundwater basin is divided into shallow unconfined groundwater and deep confined groundwater. The aquifer system is also subdivided into several aquifer units such as aquifer, aquiclude, aquifuge, and aquitard. Further, the characteristics of each aquifer unit are expressed by several parameters. For instance, the ability of aquifer to transmit water is described by transmissivity, which can be obtained by the thickness of aquifer multiplied by its hydraulic conductivity. Therefore, a mathematical groundwater model includes a set of boundary and initial conditions as well as a site-specific nodal grid and site-specific parameter values and hydrologic stresses.

The groundwater modeling is aimed at predicting the behavior of groundwater flow against a proposed action. However, the predictive model requires detailed model calibration. Because if the model cannot imitate actual groundwater flow satisfactorily, prediction results from the model may have less reliability. Thus, groundwater modeling and calibration works require integrated knowledge not only on geology and hydrogeology but also socio-economic factors such as existing and historical groundwater use.

4.3 Simulation Program

Groundwater flow in a groundwater basin is by nature three-dimensional. The MODFLOW, which was used in the Study and is widely used for groundwater flow simulation throughout the world, uses the following partial-differential equation to describe the three-dimensional movement of groundwater of constant density through porous earth material (McDonald and Harbaugh, 1988):

$$\frac{\partial}{\partial x}\left(Kxx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Kyy\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kzz\frac{\partial h}{\partial z}\right)-W=Ss\frac{\partial h}{\partial t} \qquad (4.1)$$

where

Kxx, *Kyy*, and *Kzz* are values of hydraulic conductivity along the *x*, *y*, and *z* coordinate axis, which are assumed to be parallel to the major axes of hydraulic conductivity (LT^{-1});

h is the potentiometric head (L);

W is a volumetric flux per unit volume and represents sources and/or sinks of water (T^{-1});

Ss is the specific storage of the porous material (L^{-1}); and

t is time (T).

In general, *Ss*, *Kxx*, *Kyy*, and *Kzz* may be functions of space (*Ss*5*Ss* (*x*,*y*,*z*), *Kxx*5*Kxx* (*x*,*y*,*z*), etc.) and *W* may be a function of space and time (*W*5*W* (*x*,*y*,*z*,*t*)); equation (4.1) describes groundwater flow under nonequilibrium conditions in a heterogeneous and anisotropic medium, provided the principal axes of hydraulic conductivity are aligned with the coordinate directions.

4.4 Required Parameters and Boundary Conditions

The MODFLOW program requires the following hydrogeologic parameters:

- Top and bottom elevations of each layer

- Type of each layer
- Effective porosity
- Specific storage or storativity (storage coefficient)
- Horizontal hydraulic conductivity or transmissivity
- Vertical hydraulic conductivity or vertical leakance
- Initial groundwater levels or piezometric heads
- Recharge rate
- Pumping rate by grid and layer

It is also needed to specify following simulation parameters and data for the groundwater flow simulation:

- Simulation Type (Steady-state or transient)
- Stress period and time step
- Control parameter for numerical solution

The following boundary conditions should be specified considering the actual hydrogeological settings:

- Constant-head boundary
- No-flow boundary
- River boundary, drain boundary, general-head boundary, etc (if necessary)

4.5 Hydrogeological Settings

4.5.1 Aquifer Unit Classification

Based on the available existing data, the Hanoi aquifer system consists of two (2) aquifers and two (2) aquitards. The First Aquifer consists of Holocene sediments. The aquifer is under unconfined to semi-confined conditions. The Second Aquifer consists of the sediments of middle to upper Pleistocene. The aquifer is under confined conditions, and considered as a main aquifer of Hanoi Area.

The main confined aquifer is underlain by Neogene sediments, which forms hydrogeologically impermeable basement for the Hanoi groundwater basin. There is an alluvial clayey formation above the First Aquifer. The detailed information is not available about this clayey formation, however, this layer could be a aquitard overlying the First

Aquifer.

As a result, it is reasonable to understand that the Hanoi groundwater basin consists of four (4) layers, viz. First Aquitard, First Aquifer, Second Aquitard, and Second Aquifer.

4.5.2 Location of Existing Wells

Figure 4.2 shows the distribution of existing wells in Hanoi area based on the data collected by the Study Team. There are several spots where many existing wells are concentrated; most of these are the well fields of the Hanoi Water Supply System.

Figure 4.3 shows the location of observation wells and surface water observation points. There are two (2) kind of observation wells in Hanoi Area. One is pure observation wells monitoring static groundwater level or piezometric heads, whereas the other is observed production wells, that is basically groundwater production wells with monitoring dynamic groundwater level or piezometric heads. The surface water monitoring points measure the water levels of river water.

4.5.3 Changes in Surface Water Level

Figure 4.4 shows the monthly changes in surface water level. The water levels of the Red River show clear seasonal fluctuation. At T-2 observation point near Long Bien bridge, the highest monthly water levels were recorded in July in years 1990 and 1991. In 1990, the highest water level of 10.42 masl (m above sea level) was measured in June and the lowest water level was 2.74 masl in January. The patterns of water level changes at T-1 and T-2 are very similar to that of T-2.

On the other hand, surface water levels of small rivers in Hanoi Area do not show clear seasonal changes. This indicates that the river water levels inside the city area were not affected by the Red River, in other words, rivers in the city may be controlled artificially.

4.5.4 Changes in Groundwater Level

Groundwater levels of the Upper Semi-confined Aquifer have been monitored at seven (7) monitoring wells as shown in Figure 4.5. Seasonal changes of groundwater levels can be seen at C21, C17, and C10 observation wells. These wells are located relatively close to the Red River. The groundwater levels are high in July and August, that shows a similar fluctuation patterns of the Red River water level. However, the difference between high water level and low water level of groundwater is 3.34 m at C17 well in 1990. The groundwater level at C10 well tends to decline over time.

The groundwater levels of the wells located in the central to southern part of Hanoi City do not show seasonal fluctuations. Groundwater levels over time are almost flat at C7, C12, C16, and C25 wells. However, particularly at C16 well, decline of groundwater level was observed, and the groundwater level declined at 26.16 masl in December 1991.

4.5.5 Changes in Piezometric Head

Figure 4.6 shows the changes in piezometric head of the Lower Confined Aquifer. The seasonal changes in piezometric head can be observed at A10, A17, and A14 wells. The piezometric heads are high in July and August and low in January to March. The seasonal changes in piezometric head tend to decrease with distance from the Red River. At A10 well located near Xuan Dinh Commune, decline of piezometric head over time was recognized.

In the southwestern part of Hanoi City, piezometric head was almost stable but slightly declining as shown at A8 and A25 wells. For example, piezometric head at A25 well in December 1989 was 25.51 masl, while the head in December 1991 became 26.08 masl.

4.5.6 Distribution of Groundwater Table

Figure 4.7 shows the distribution of groundwater table measured at observation wells of First Aquifer in May 1991. A depression of groundwater table can be seen at the central part of Hanoi City. The lowest groundwater table was 26.46 masl. The groundwater table near the Red River is almost same as the Red River water level.

4.5.7 Distribution of Piezometric Surface

Figure 4.8 shows the distribution of piezometric surface of Lower Confined Aquifer measured at pure observation wells in May 1991. The piezometric surface was assumed to be static, without influence of nearby production wells. The deepest piezometric surface is below 210 masl in the southern part of Hanoi City. The size of depression cone is larger than that of the First Aquifer. The piezometric surface in most city area except along the Red River is below 0 masl. From the map, it is understood that piezometric surface of Xuan Dinh Commune is lower than Dong Ngac Commune.

4.5.8 Distribution of Transmissivity

From the results of existing pumping test data, the transmissivity map of Second Aquifer was prepared as shown in Figure 4.9. In Hanoi area, the transmissivity values are generally high, ranging from 600 to 1,500 m^2/day. The areas having higher transmissivity are located in the western part and southern part of the city. From the map, transmissivity at Dong Ngac Commune is estimated from 800 to 1,000 m^2/day, whereas transmissivity of Xuan Dinh is estimated from 800 to 1,200 m^2/day.

4.5.9 Distribution of Hydraulic Conductivity

Values of hydraulic conductivity can be obtained from transmissivity values and the thickness of aquifer. If the well structure is known, the hydraulic conductivity of aquifer portion can be computed by (transmissivity)/(screen length). Figure 4.10 shows the distribution of hydraulic conductivity of Second Aquifer. The hydraulic conductivity in Hanoi area ranges from 17 to 50 m/day. The areas having more than 40 m/day are located in the western and southern parts of the city. According to the map, hydraulic conductivity of Dong Ngac and Xuan Dinh Communes is estimated from 17 to 25 m/day.

4.5.10 Groundwater Pumpage

The groundwater pumpage data, that was collected by the Study Team, are mostly pumped from Lower Confined Aquifer. Therefore, the pumpage values were compiled by model cell and given to Layer-4.

The pumpage data were available from 1990 to 1996. Figure 4.11 shows the distribution of the average well discharge in 1991. The groundwater pumpage in 1991 was used for the steady-state model calibration mentioned in the next chapter. Figure 4.12 shows the input groundwater pumpage in 1996.

4.6 Model Framework

4.6.1 Model Structure

Considering the hydrogeological settings of Hanoi area, the structure of 3-D simulation model was determined. Figure 4.13 shows the schematic structure of the 3-D model having 4 layers structures. Figure 4.14 shows the model grid for the simulation. It is decided that the model has four (4) layers, and each model grid has 500 m3500 m in size. The modeled domain has 20 km in E-W direction and 20 km in N-S direction. Therefore, the total number of cell is (40 rows)3(40 columns)3(4 layers)56,400 cells.

The aquifer type of each model layer is assigned as follows:

Layer-1: (First aquitard):	Confined/Unconfined
Layer-2: (Upper Semi-confined Aquifer):	Confined/Unconfined
Layer-3: (Second Aquitard):	Confined
Layer-4: (Lower Confined Aquifer):	Confined

4.6.2 Boundary Conditions

Based on the hydrogeological settings of Hanoi Area, constant-head boundaries are assigned at the Red River, Duong River, and West Lake as shown in Figure 4.15. The constant-head boundaries are set only in Layer-1. Water levels at the constant-head boundaries are given from the data of the surface water observation points. The perimeters of the modeled domain are treated as no-flow boundaries.

4.6.3 Input Parameters

The necessary parameters for the MODFLOW program, that was mentioned earlier, were prepared based on the hydrogeological settings. Followings are the initially input data to the model. Table 4.1 summarizes the input parameters to the model.

(1) Top and bottom elevations of each layer

Top and bottom elevations of each layer were prepared from the existing lithologic data. The top elevation of Layer-1 is the elevation of ground surface, so that the nodal values of ground elevation were interpolated from the USGS digital elevation data.

Layer-1: Top: 8.1 to 30.2 masl
Bottom: 21.5 to 217.3 masl
Layer-2: Top: 21.5 to 217.3 masl
Bottom: 27.8 to 233.9 masl
Layer-3: Top: 27.8 to 233.9 masl
Bottom: 221.7 to 249.4 masl
Layer-4: Top: 221.7 to 249.4 masl
Bottom: 250.5 to 2110.6 masl

(2) Effective porosity

0.25 is given to all layers uniformly.

(3) Specific storage or storativity (storage coefficient)

Specific storage of 0.0001 (m^{-1}) is given to all layers uniformly.

(4) Horizontal hydraulic conductivity or transmissivity

At first, nodal values of transmissivity and thickness of Layer-2 and Layer-4 were obtained by Kriging method. The hydraulic conductivity value of each cell for Layer-2 and Layer-4 was then computed by (transmissivity) / (layer thickness). The hydraulic conductivity of Layer-1 and Layer-3 was uniformly given.

Layer-1: 0.1 m/day
Layer-2: 10.0 to 35.4 m/day
Layer-3: 0.01 m/day
Layer-4: 20.1 to 70.9 m/day

(5) Vertical hydraulic conductivity or vertical leakance

Initially, the vertical hydraulic conductivity of each layer was assumed to be 1/10 of the horizontal hydraulic conductivity, because it was taken into account that the layers consist of Quaternary sediments so that the vertical hydraulic conductivity is smaller than the horizontal hydraulic conductivity.

Layer-1: 0.01 m/day
Layer-2: 1.0 to 3.54 m/day
Layer-3: 0.001 m/day
Layer-4: 2.01 to 7.09 m/day

(6) Initial groundwater levels and piezometric heads

The initial groundwater levels of Layer-1 were given from the water levels measured at the surface water monitoring points. The groundwater levels of Layer-2 were given from the groundwater table measured at the observation wells of Upper Semi-confined Aquifer. The initial piezometric heads of Layer-3 and Layer-4 were given from the piezometric heads measured at the pure observation wells of Lower Confined Aquifer. The data of water levels and piezometric heads were measured in May 1991. The nodal values of each layer were interpolated by Kriging method.

Layer-1: 3.36 to 4.47 masl
Layer-2: 26.33 to 7.95 masl
Layer-3: 210.63 to 5.19 masl
Layer-4: 210.63 to 5.19 masl

(7) Recharge rate

Although a detailed study of water balance in Hanoi area has not been carried out yet, a temporal recharge rate is estimated as 1.1 mm/day (5401.5 mm/year). The recharge rate was uniformly given to the active top cells of the model.

(8) Pumping rate by grid and layer

The groundwater pumpage data, that was collected by the Study Team, are mostly pumped from Lower Confined Aquifer. Therefore, the pumpage values were compiled by model cell and given to Layer-4.

The pumpage data were available from 1990 to 1996. The groundwater pumpage in 1991 was used for the steady-state model calibration mentioned in the next chapter.

(9) Future Pumping rate by grid and layer

To predict the influence of the future groundwater development in the target communes of the Study, future simulations were carried out using the calibrated model. It is assumed that one well in Dong Ngac Commune (I59, J513) and one well in Xuan Dinh Commune (I59, J514) will be constructed, and they will extract groundwater from the Second Aquifer (Layer-4).

For the future groundwater pumpage, the Hanoi Water Supply System has a plan to expand the existing well fields as shown in Figure 4.16. According to NHEGD-DGM (1998), Cao Dinh well field is proposed along the right side bank of the Red River. In the new well field, 26 production wells will be constructed, and a total of 97,964 m^3/day will be pumped. Yen Phu well field is also planned to be expanded along the Red River. A total of 13 production wells will be constructed additionally. The additional pumpage of Yen Phu well field will be 60,777 m^3/day. For the future simulation, it is assumed that the groundwater pumpage is the pumpage of 1996 with the planned pumpage of Cao Dinh well field and additional Yen Phu well field. Therefore, the future simulation was carried out assuming that the total groundwater pumpage in Hanoi Area is 612,431 m^3/day. This pumping situation is named "Case-0".

The following two (2) cases of future pumping plan in the target communes were prepared based on the daily maximum groundwater demand designed by the Study:

Case-1: Dong Ngac Q51,260 m^3/day, Xuan Dinh Q52,850 m^3/day
Case-2: Dong Ngac Q51,890 m^3/day, Xuan Dinh Q54,275 m^3/day

The pumpage of Case-1 is the designed daily maximum groundwater demand. The pumpage of Case-2 is 1.5 times of Case-1 pumpage.

The future simulation was carried out by transient simulation. The simulation duration is 10 years, having 10 time steps. The prepared pumping plans were input to the model. The recharge was uniformly given to the top active cells of the model at a rate of 1.1 mm/day throughout the simulation period. The initial groundwater levels and piezometric heads were brought into each layer from the final simulated heads of the transient simulation from 1990 to 1996. The water levels at constant-head boundaries were the same as that of the transient simulation.

In the future simulation, firstly future piezometric heads were computed without the pumpage of the target communes using Case-0 pumpage. Then, the pumpage of Case-1 and Case-2 was added to the pumpage of Case-0. The simulated piezometric drawdown of Case-1 and Case-2 after 10 years of operation was obtained by comparing the simulated piezometric heads of Case-1 and Case-2 with the simulated heads of Case-0.

Figure 4.17 shows the input groundwater pumpage for Case-1.

Table 4.1 Input Parameters to The 3-D Simulation Model

Model Layer	Aquifer Unit	Aquifer Type	Top and Bottom Elevation (masl)	Effective Porosity	Specific Storage (m^{-1})	Hydraulic Conductivity Horizontal (m/day)	Hydraulic Conductivity Vertical (m/day)	Initial Heads (masl)	Recharge Rate (mm/day)	Pumping Rate (1991) (m^3/day)
Layer-1	First Aquitard	Confined/Unconfined	Top: 8.1 to 30.2 Btm: −1.5 to −17.3	0.25	1.00E−04	0.1	0.01 (0.03)*	3.36 to 4.47	1.1	0
Layer-2	First Aquifer	Confined/Unconfined	Top: −1.5 to −17.3 Btm: −7.8 to −33.9	0.25	1.00E−04	10.0 to 35.4	1.0 to 3.54	−6.33 to 7.95	0	0
Layer-3	Second Aquitard	Confined	Top: −7.8 to −33.9 Btm: −21.7 to −49.4	0.25	1.00E−04	0.01	0.001 (0.04)*	−10.63 to 5.19	0	0
Layer-4	Second Aquifer	Confined	Btm: −21.7 to −49.4 Btm: −50.5 to −110.6	0.25	1.00E−04	20.1 to 70.9	2.01 to 7.09	−10.63 to 5.19	0	383,034

*: Modified value by the model calibration

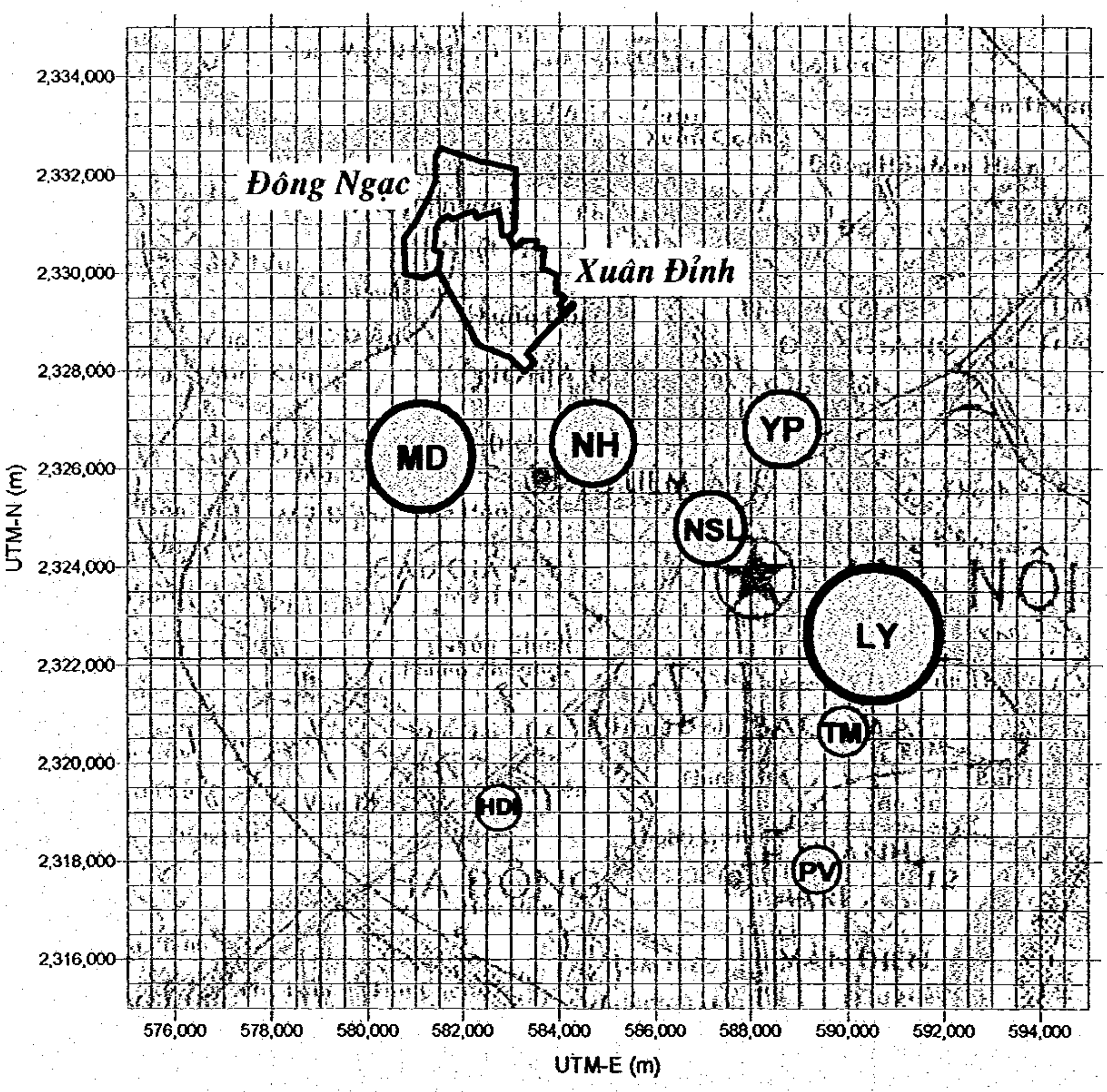
Table 4.2 Groundwater Pumpage in Hanoi Area from 1990 to 1996

(Unit: m^3/day)

Year	1990	1991	1992	1993	1994	1995	1996
HNWS Major Well Field							
PHAP VAN	46,248	37,968	39,120	32,544	28,752	34,548	21,360
MAI DICH	42,240	55,728	61,176	65,112	59,400	56,904	55,800
NGOC HA	39,576	57,672	40,752	44,640	39,000	45,720	44,328
LUONG YEN	–	–	25,968	79,056	77,016	74,160	57,744
TUONG MAI	–	–	30,744	26,736	26,496	27,648	23,184
HA DINH	–	–	30,696	27,504	30,720	31,032	29,232
NGO SY LIEN	49,200	53,160	45,240	44,592	42,168	33,672	30,504
YEN PHU	49,032	46,584	45,960	47,928	37,728	39,096	29,328
HNWS Major Total	226,296	251,112	319,656	368,112	341,280	342,780	291,480
Other Total	133,986	131,922	135,930	142,500	149,070	155,640	162,210
Grand Total	360,282	383,034	455,586	510,612	490,350	498,420	453,690

[Data source]
Hanoi Dept. of Sci. & Enviro. Tech. and Hanoi Univ. of Mining and Geology (1998)
Dept. of Geology and Minerals of Vietnam (1998)
Nguyen Van Hoang (1993)

Major Groundwater Well Fields in Hà Nội Area



	Name of Well Fields	Number of Wells	Pumping Rate (m^3/day)	Feasible Discharge (m^3/day)
1	Yen Phu	13	44,500	110,000
2	Ngo Si Lien	19	43,200	30,000
3	Ngoc Ha	11	50,300	30,000
4	Phap Van	9	27,700	30,000
5	Mai Dich	18	64,200	45,000
6	Ha Dinh	9	27,200	25,000
7	Luong Yen	15	79,500	80,000
8	Tuong Mai	10	29,200	30,000
	TOTAL	104	365,800	380,000

[after JICA (1997)]*

*Note:
1) Data as of 1995.
2) Number of Wells includes standby wells.
3) "Feasible Discharge" was based on FINNIDA M/P (1993) and approved by the Government of VN.

Figure 4.1 Major Groundwater Well Fields and Pumping Rates in Hà Nội Area

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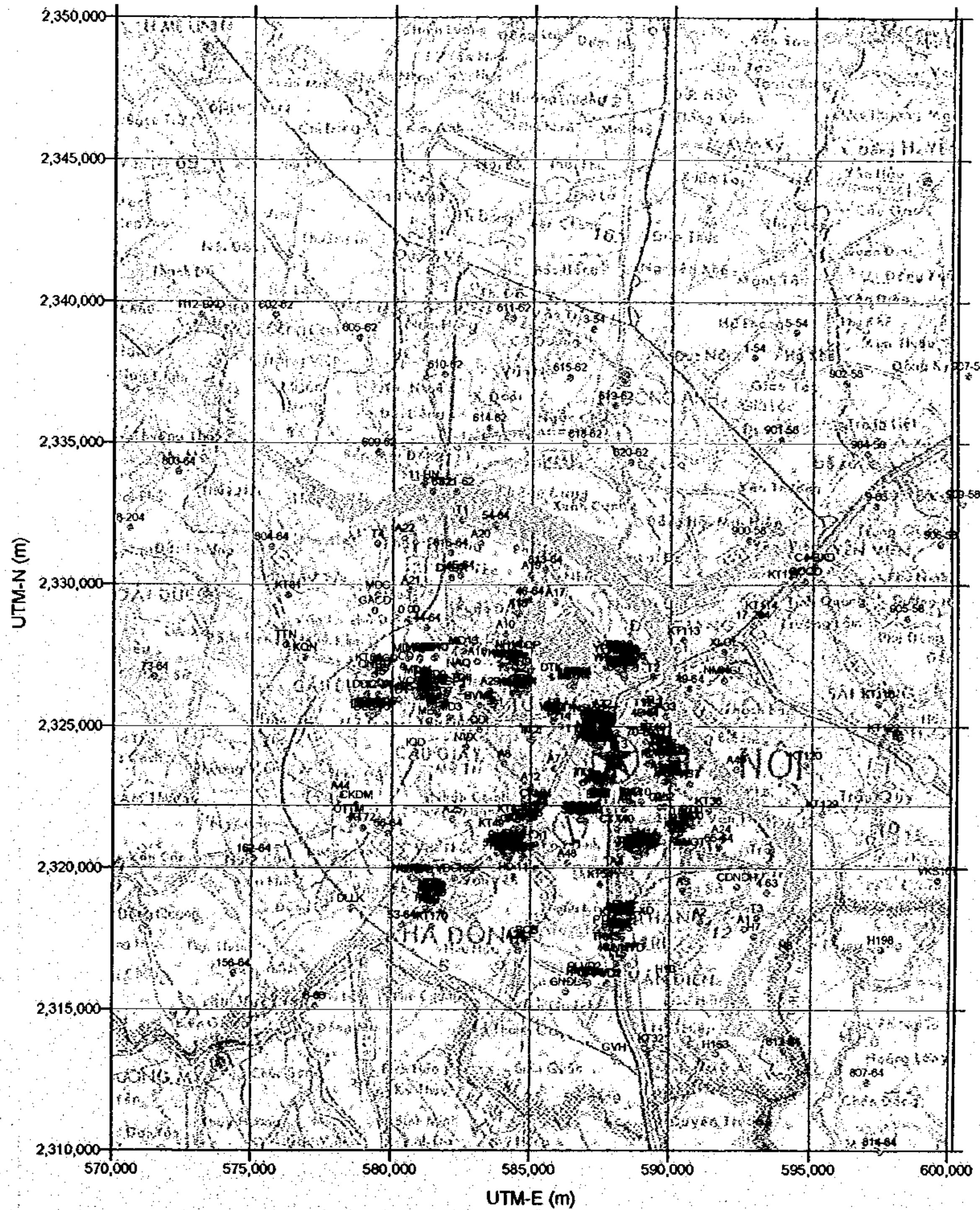

Existing Well with No.

Figure 4.2	**Location of Existing Wells in Hà Nội Area**

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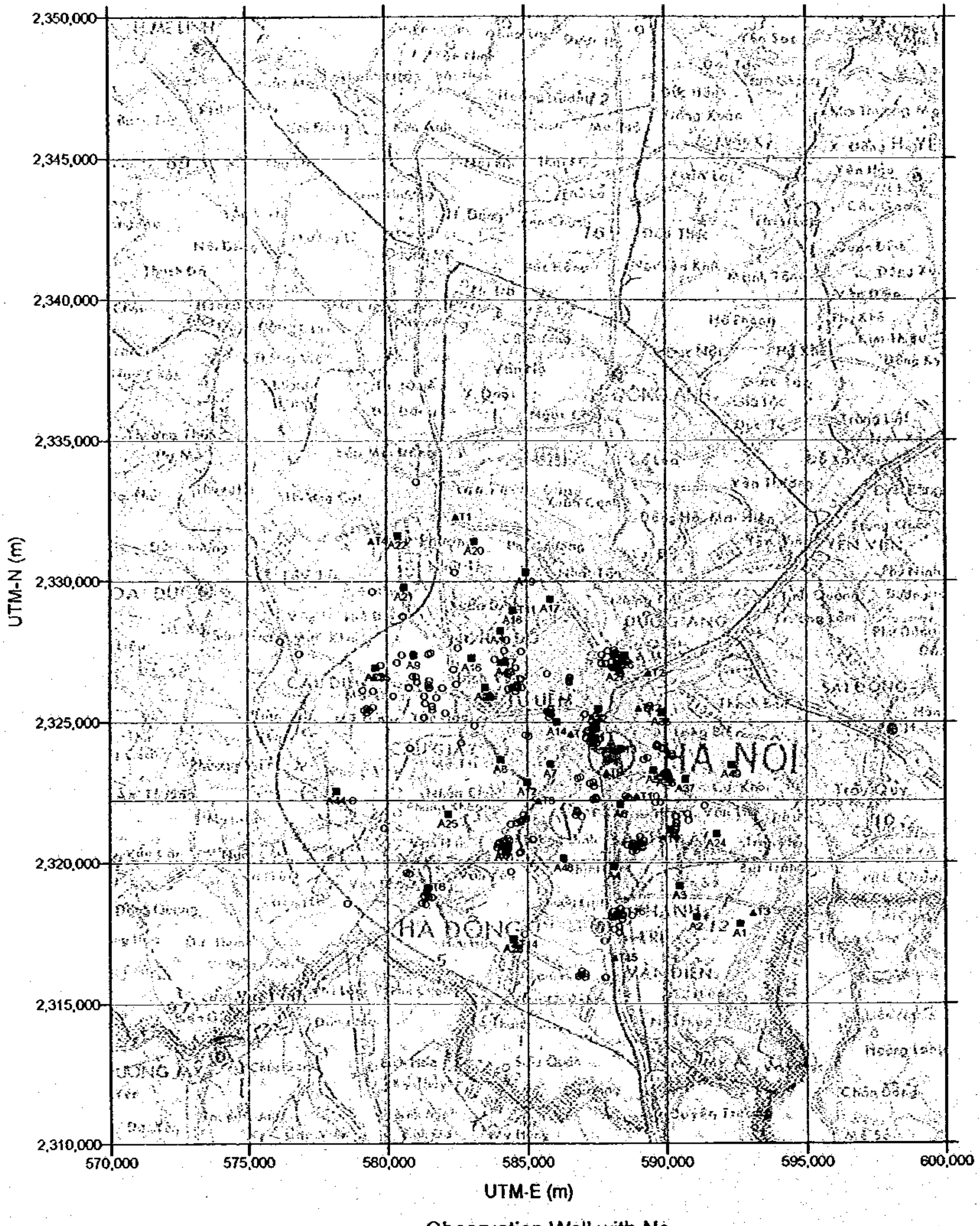

■ A10 Observation Well with No.

○ Observed Production Well

▲T2 Surface Water Observation Point with No.

Figure 4.3	**Location of Observation Wells in Hà Nội Area**
THE STUDY ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	
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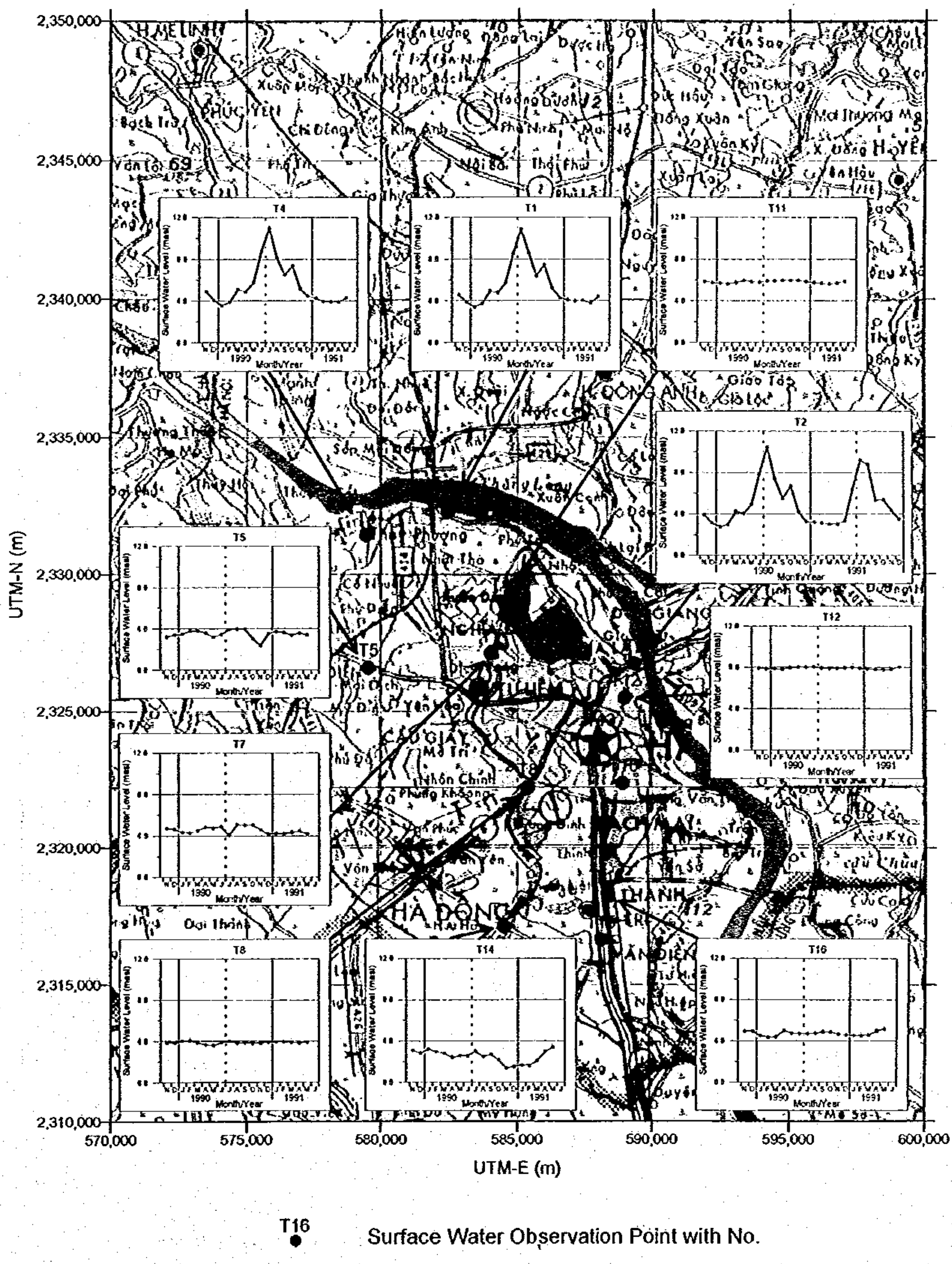

Figure 4.4	**Monthly Changes in Surface Water Levels of Hà Nội Area**

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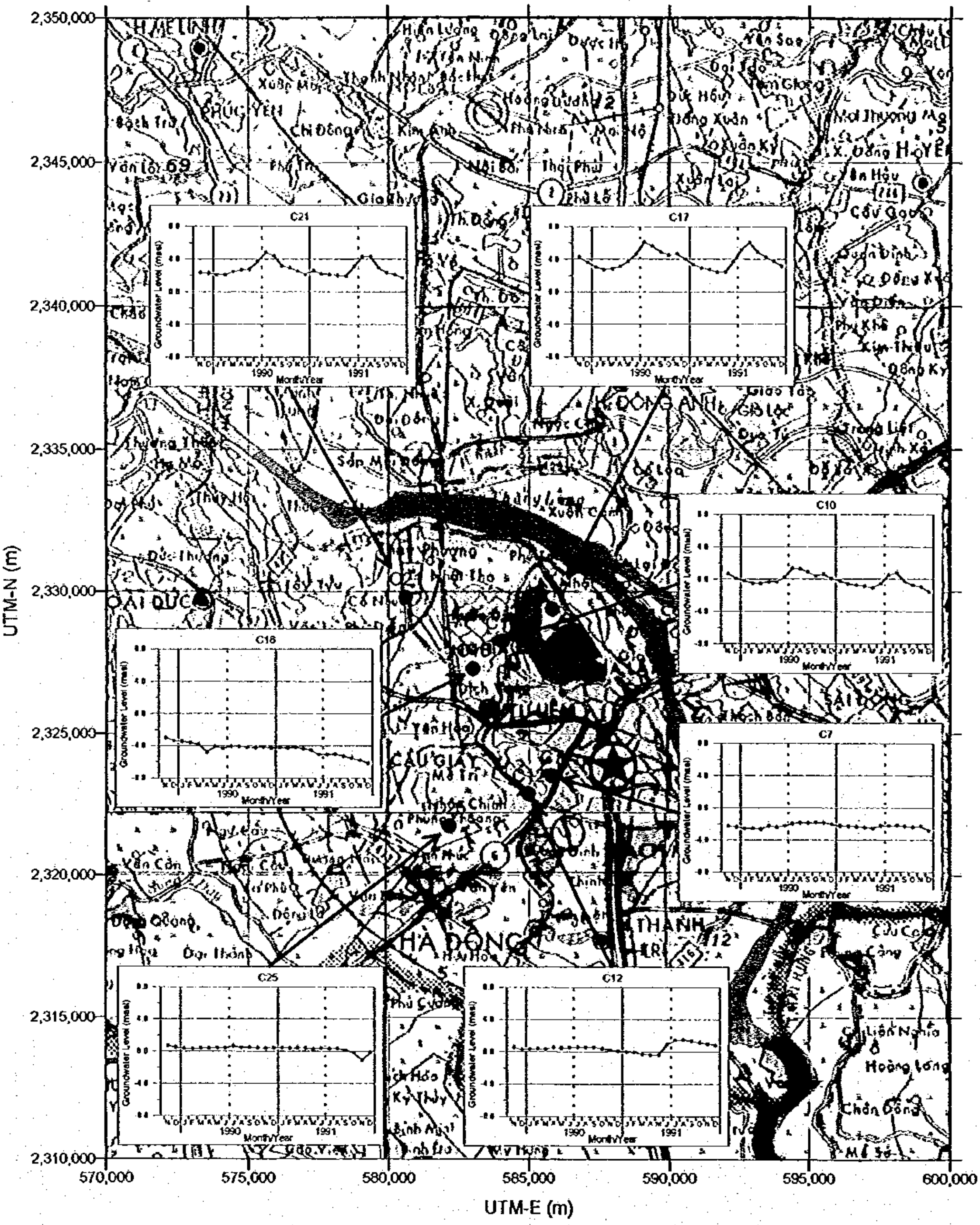

C10 ● Observation Well of Unconfined Aquifer with No.

Figure 4.5	Monthly Changes in Groundwater Levels of Hà Nội Area
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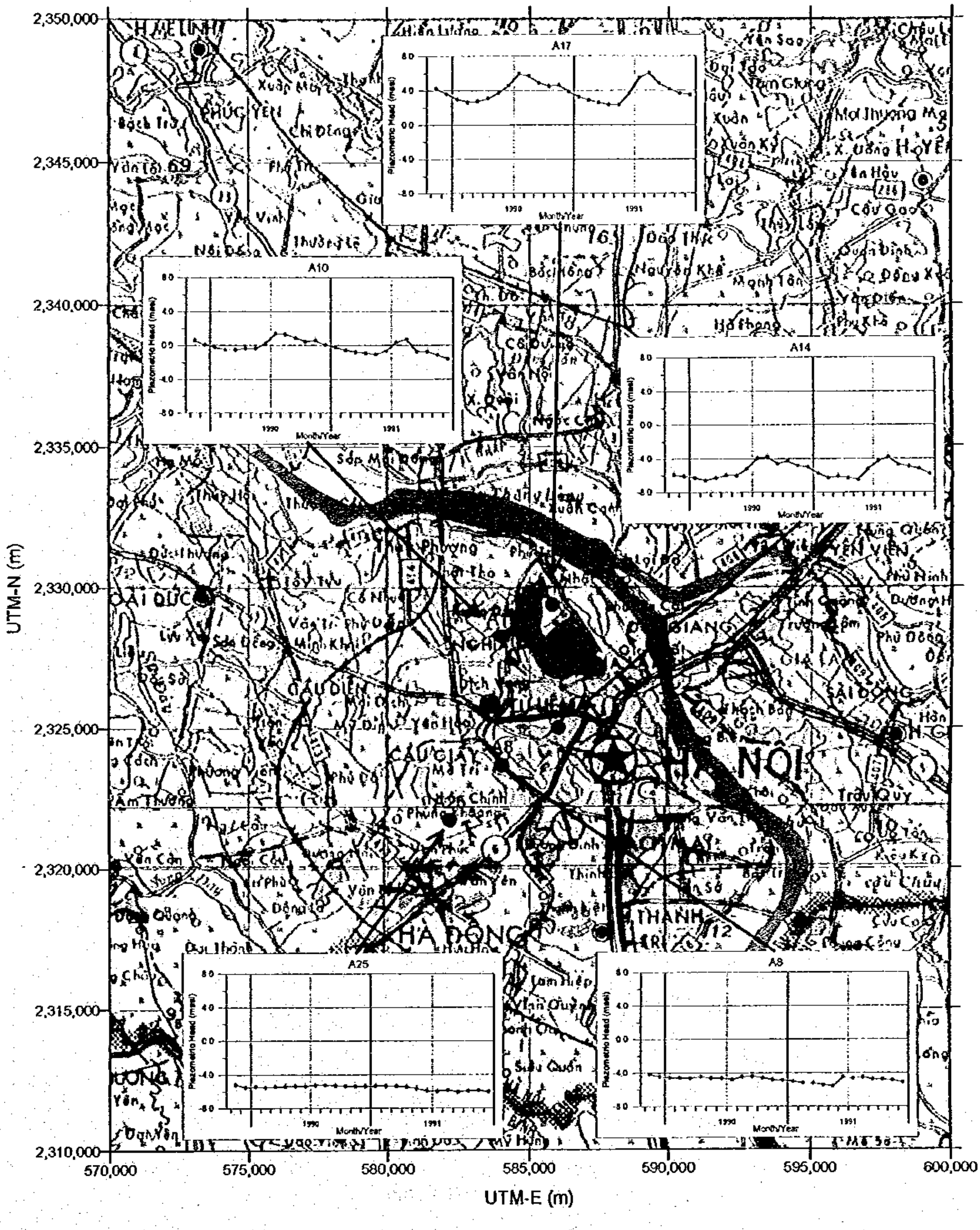

A17 ● Observation Well of Confined Aquifer with No.

Figure 4.6	**Monthly Changes in Piezometric Heads of Hà Nội Area**

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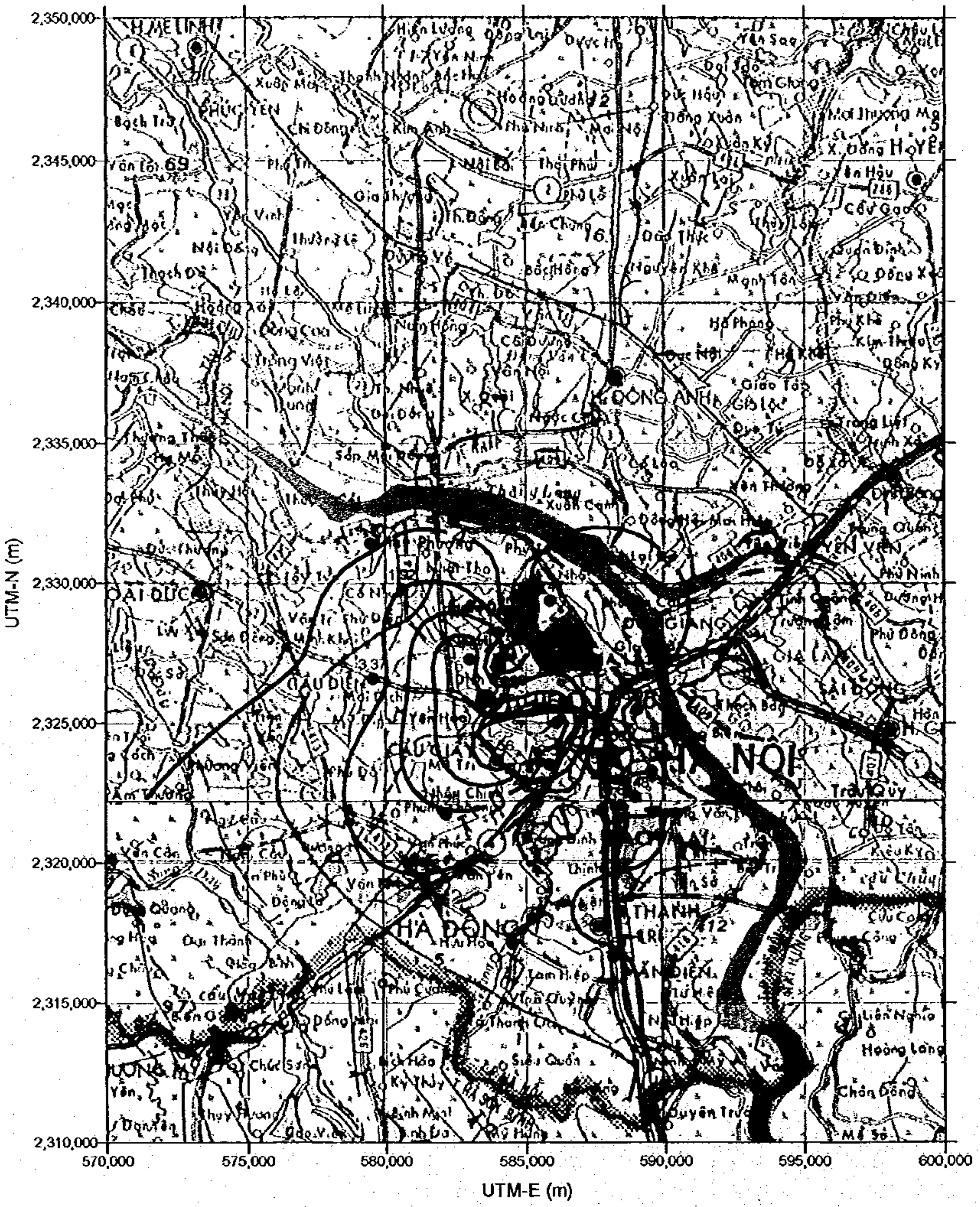

-2 Equal Line of Groundwater Table (masl)

-6.46 ● Observation Well with Groundwater Level (masl)

(Only pure observation wells were used to draw groundwater table.)

Figure 4.7	**Distribution of Groundwater Table in Hà Nội Area (May 1991)**
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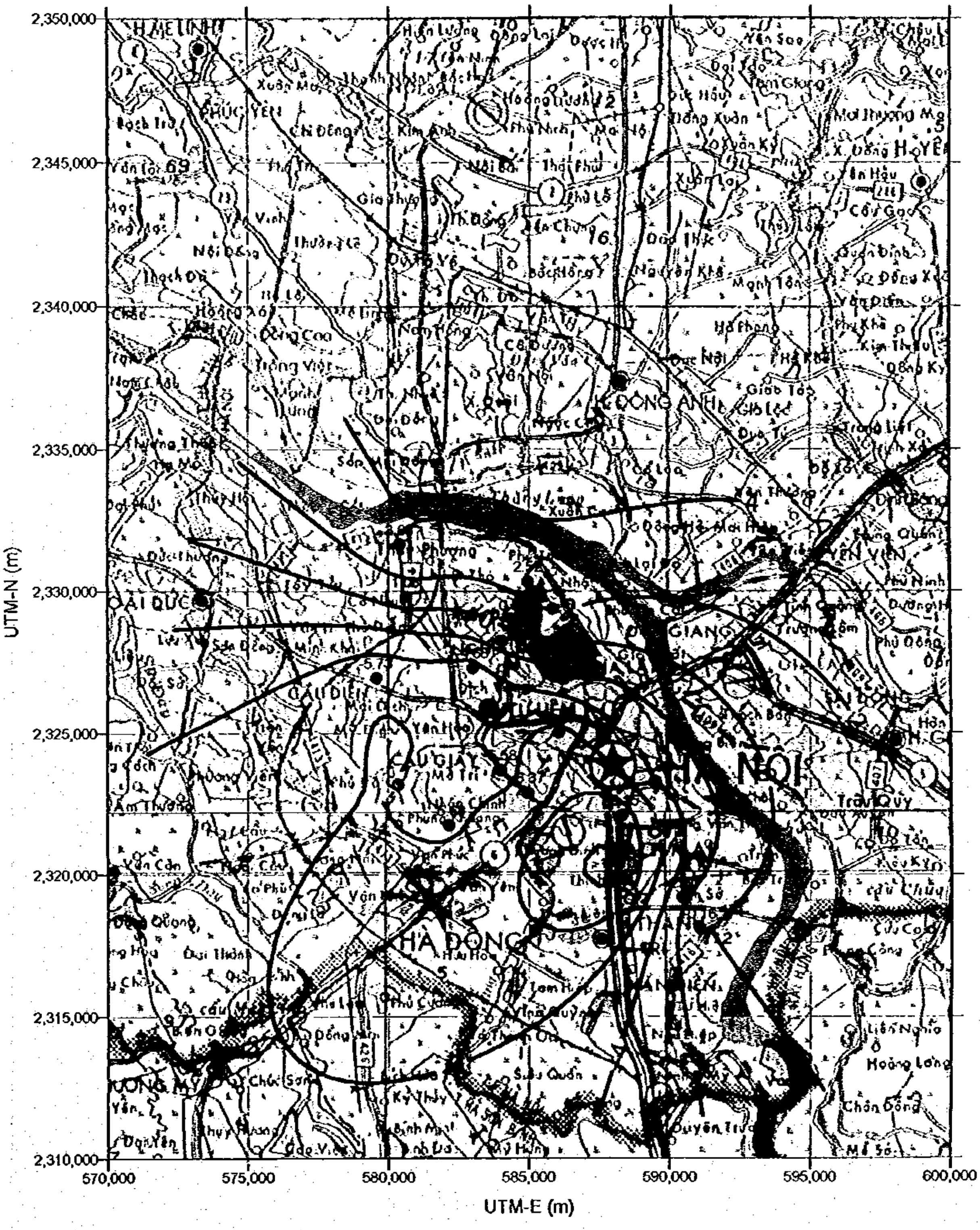

-3 Equal Line of Piezometric Head (masl)

-10.70 Observation Well with Piezometric Head (m)

(Only pure observation wells were used to draw piezometric surface.)

Figure 4.8	Distribution of Piezometric Surface in Hà Nội Area (May 1991)
THE STUDY ON GROUNDWATER DEVELOPMENT IN THE RURAL PROVINCES OF NORTHERN PART IN THE SOCIALIST REPUBLIC OF VIETNAM	
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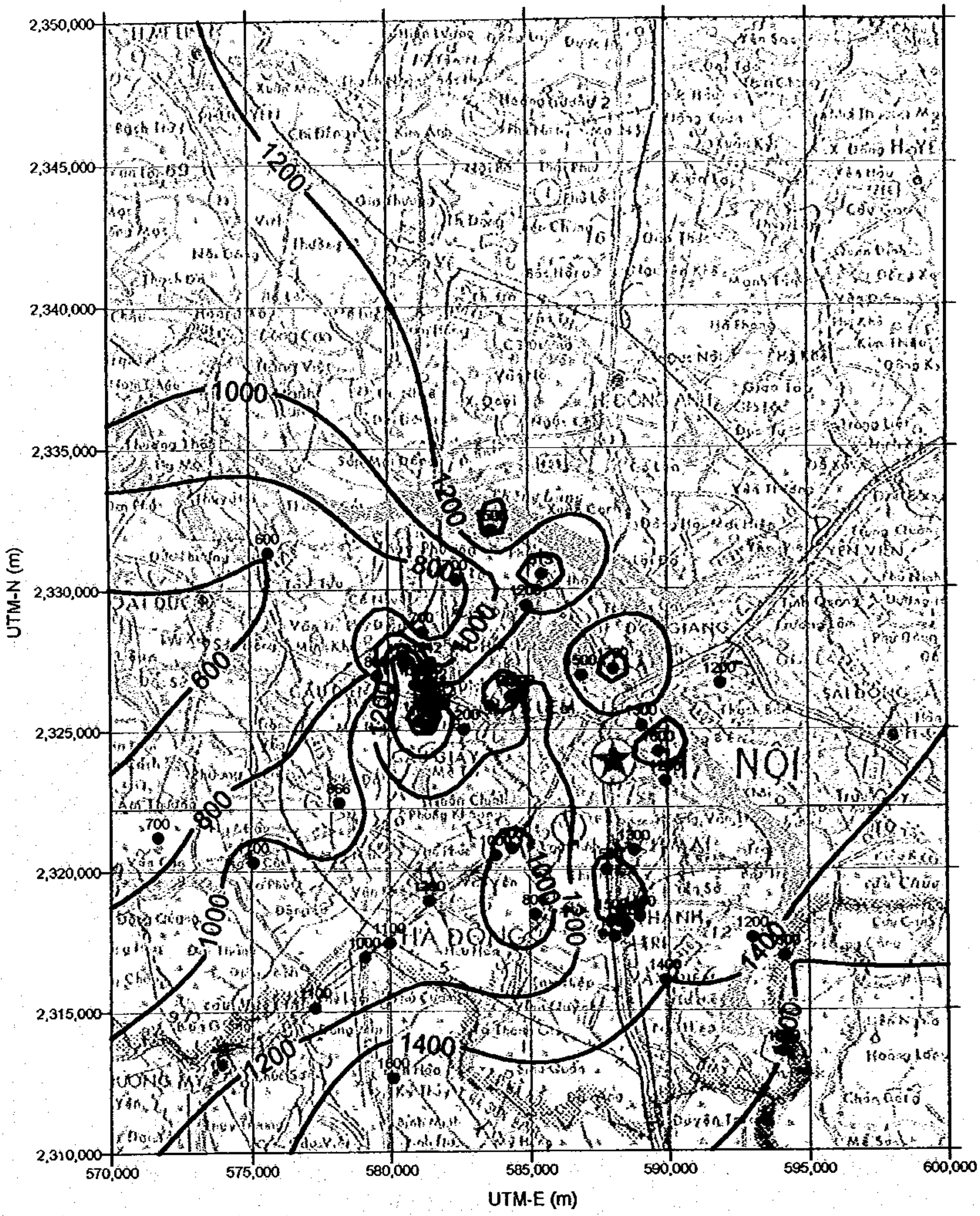

1000 Equal Line of Transmissivity, T (m^2/day)

1200 ● Well location with T value (m^2/day)

(Transmissivity values were determined by pumping tests.)

Figure 4.9	Distribution of Transmissivity in Hà Nội Area
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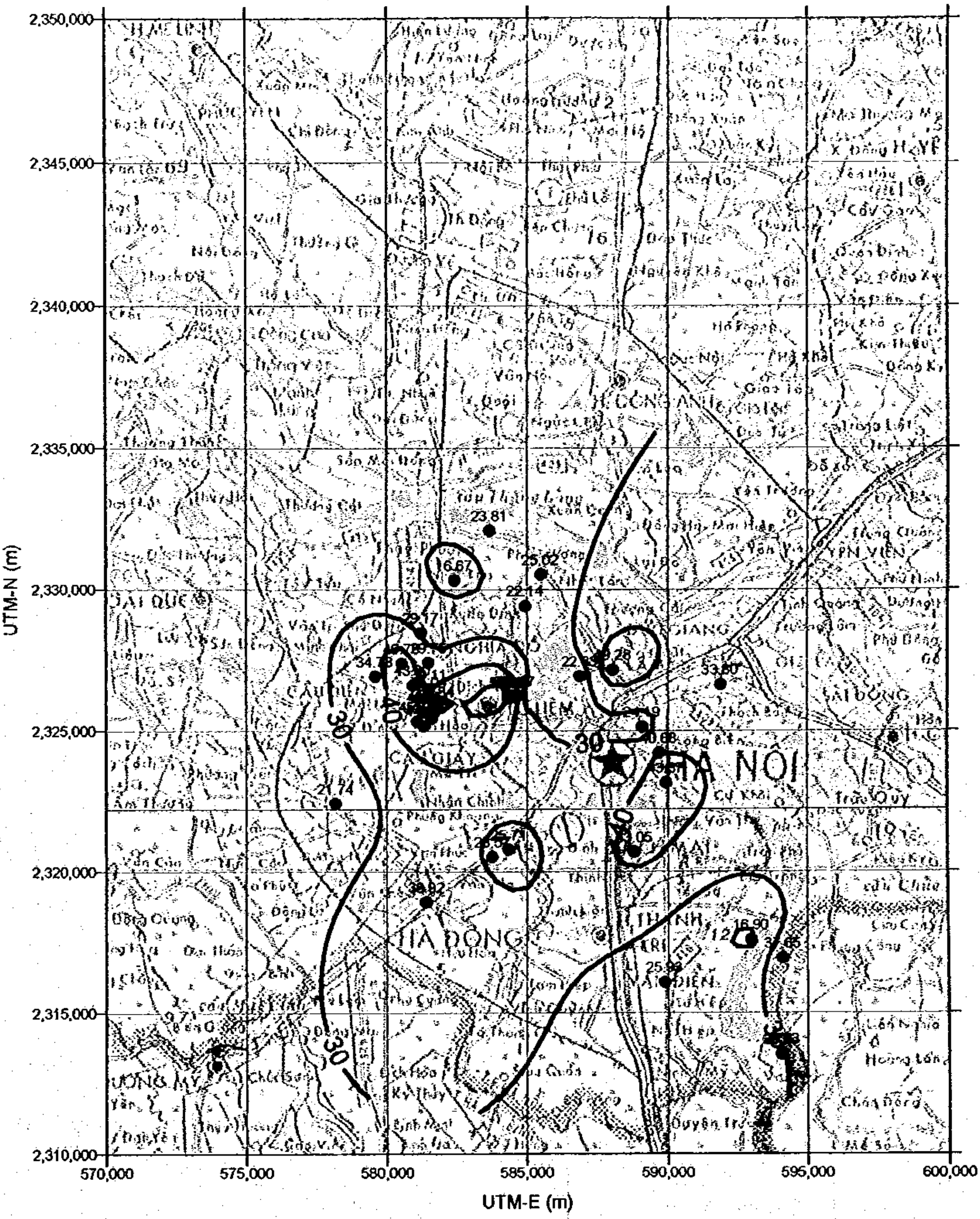

50 Equal Line of Hydraulic Conductivity, *k* (m /day)

25.12 Well location with *k* value (m/day)

(Hydraulic Conductivity values were determined by pumping tests.)

Figure 4.10	**Distribution of Hydraulic Conductivity in Hà Nội Area**
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