CHAPTER 7 GROUNDWATER MODELING

7.1 Modeling Approach

The techniques of groundwater modeling were employed for a basin-wide groundwater management in order to come up with appropriate strategies for prevention of land subsidence. The Study Team used three (3) kinds of groundwater simulation models as shown in Table 7.1.1.

Table 7.1.1 Groundwater models used for the Study

Model Name	Program Name	Purpose
3-D Groundwater Flow and Land Subsidence Model	MODFLOW SUBPRO-1	Analyze 3-D groundwater flow and land subsidence distribution
Vertical 2-D Groundwater Flow and Land Subsidence Model	MODFLOW SUBPRO-2	Analyze detailed 2-D groundwater flow and land subsidence
Vertical 2-D Solute Transport Model	MOCDENSE MT3D	Analyze movement of saline water

The flow of groundwater modeling is shown in Figure 7.1.1. After defining the purpose, each model was established based on accurate hydrogeological investigations and analyses. Appropriate boundary conditions and geohydrologic parameters were assigned to each model. Initial calibration for each model was carried out by steady-state simulation to understand the model behavior. The assigned boundary conditions and the input parameters were checked and/or modified by comparing computed piezometric heads with the observed piezometric heads.

After preparing the historical pumpage data from 1983 to 1992, each model was carefully calibrated by transient simulation. In the process, some earlier assumed parameters and boundary conditions were finally fixed. The historical calibration was carried out using the input pumpage data. The calibration continued until the computed piezometric heads agreed satisfactorily with the observed data.

The land subsidence models and solute transport model were subsequently calibrated based on the final historical computed piezometric heads. These calibrations were repeated until the computed subsidence or concentration were in good agreement with the observed data.

These calibrated models can be used to predict future groundwater flow, piezometric heads, land subsidence, and chloride concentration based on future groundwater pumpage plans. Several future pumpage scenarios were generated from 1993 to 2017.

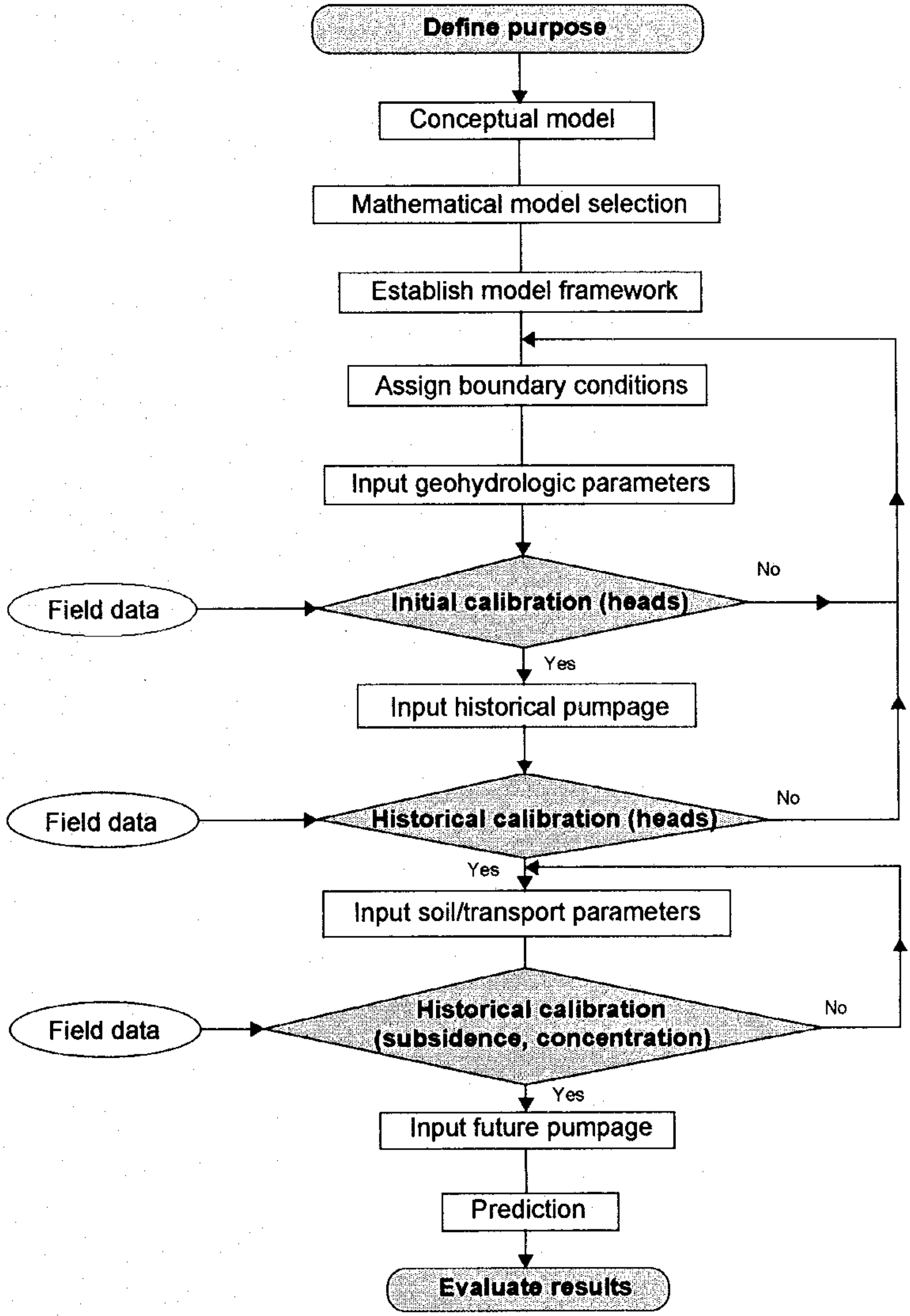

Figure 7.1.1	FLOW OF GROUNDWATER MODELING
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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7.2 Model Grid

(1) Grid for 3-D Groundwater Flow and Land Subsidence Model

The Study Area covered a portion of the Lower Central Plain. The detailed hydrogeological study was concentrated in the Study Area. However, it was necessary to consider the hydrogeological conditions of the Lower Central Plain in order to simulate basin-wide regional groundwater flow. The advantages of taking a model domain up to the basin boundaries were to reflect the structures of the groundwater basin in the model and to increase reliability of simulation at marginal coverage of the Study Area. For instance, it was difficult to assign proper boundary conditions at the margin if only the Study Area was taken as a model domain, because the aquifers continued outside the limits of the Study Area. Furthermore, the groundwater flow in areas outside the Study Area affected the groundwater flow within the Study Area, especially near the northern and western boundaries. Therefore, the model grid was determined as shown in Figure 7.2.1.

The grid size in the Study Area was fixed at 2 km × 2 km. The grid in the outside area varied from 2 km × 4 km to 16 km × 16 km as size increased with increasing distance from the Study Area. A total number of modeled grids in one (1) layer is 2,860 (55 rows × 52 columns). The number of grids in the Study Area is 1,600.

The model was divided into ten (10) layers based on the hydrogeological classification and the memory size of the personal computer. The total number of 3-D cells is 28,600 (55 rows × 52 columns × 10 layers). The structure of the 3-D model is given in Figure 7.2.2. The top layer is an unconfined aquifer (UC), which was not confirmed from the field investigations. However, this layer was needed for the model to express almost constant levels of surface water existing on the Bangkok Clay, otherwise a constant head boundary must be assigned to Bangkok Soft Clay. If not, the heads in the clay could not be simulated. The Bangkok Soft Clay (BC) was taken as an independent layer because the clay contributed to the land subsidence significantly in the Study Area. The aquifer units of Bangkok Aquifer (BK) to Pak Nam Aquifer (PN) were based on the hydrogeological classification studied in the previous stage. The units included not only sand and gravel facies but also silt and clay facies. The Stiff Clay of Bangkok Clay (Moh *et al.*, 1969) was significantly older than the Soft Clay (AIT, 1980) and its physical properties were quite different from the Soft Clay so that the Stiff Clay was treated as a member of Bangkok Aquifer in the model.

(2) Grid for Vertical 2-D Groundwater Flow and Land Subsidence Model

The vertical 2-D groundwater flow and land subsidence model was constructed based on the hydrogeological profile of N-5 prepared by the Study Team. The N-5 profile line is located from the DMR station No. 31 in the north to station No. 8 in the south (Figure 7.2.3). The profile was selected for the modeling because the line passes the severe land subsidence section of the Study Area and the hydrogeological information at Site-A station can be utilized.

The grid width and length were fixed at 2 km as shown in Figure 7.2.4. The total length of the model is 90 km and the number of columns is 45. Then the vertical grid system was prepared as shown in Figure 7.2.5. The thickness of the cells in shallow portion from 5 m to

-20 m elevations was given as 5 m so as to simulate piezometric heads and soil consolidation in detail. A thickness of 10 m was given to the cells from -20 m to -300 m elevations. The grids located from -300 m to -600 m had 25 m thickness. Therefore, the model has 2025 cells (45 columns×45 layers).

The boundaries of hydrogeological units and screens of the production wells located in the modeled area are also shown in Figure 7.2.5. The screen's data were retrieved from the database system. Majority of the production wells in the modeled area extracted groundwater from Nakhon Luang Aquifer.

(3) Grid for Vertical 2-D Solute Transport Model

The vertical 2-D solute transport model was constructed based on the hydrogeological profile of N-3 prepared by the Study Team. The N-3 profile line is located from the DMR station No. 35 in the north to station No. 10 in the south (Figure 7.2.3). The profile was selected for the modeling because the line passes the area where saline water was found. According to the results of groundwater quality analysis as mentioned in Chapter 4, two (2) types of saline water were found along the profile. Therefore, the model location was selected to simulate the movement of those types of saline water .

The grid width and length were fixed at 2 km as shown in Figure 7.2.6. The total length of the model is 86 km and the number of columns is 43. Then the vertical grid system was prepared as shown in Figure 7.2.7. A thickness of 10 was uniformly given to the cells from -10 m to -400 m elevations, because the MOCDENSE program does not allow changes in thickness. There is also a limitation about numbers of columns and layers in the MOCDENSE so that the elevation of only up to -400 m was considered for modeling purposes.

The boundaries of hydrogeological units and screens of the production wells located in the modeled area are also shown in Figure 7.2.7. The screen's data were retrieved from the database system. It is noted that most production wells in Samut Prakan have screens set at Phra Pradaeng Aquifer and Bangkok Aquifer. Screen depths become deeper toward the north. The production wells in Pathum Thani extract groundwater from Nonthaburi Aquifer and Sam Khok Aquifer.

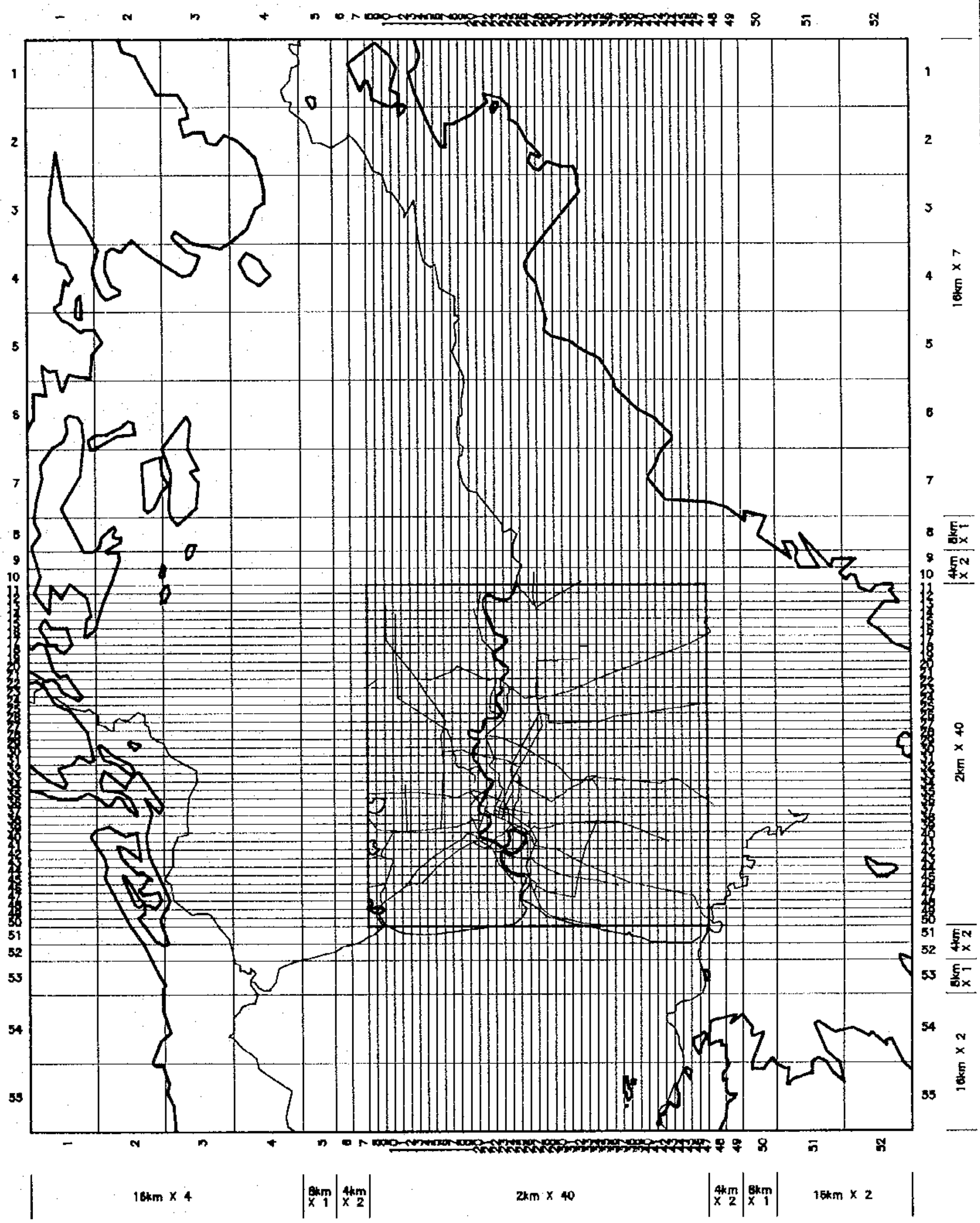

Figure 7.2.1	GRID FOR 3-D MODFLOW MODEL
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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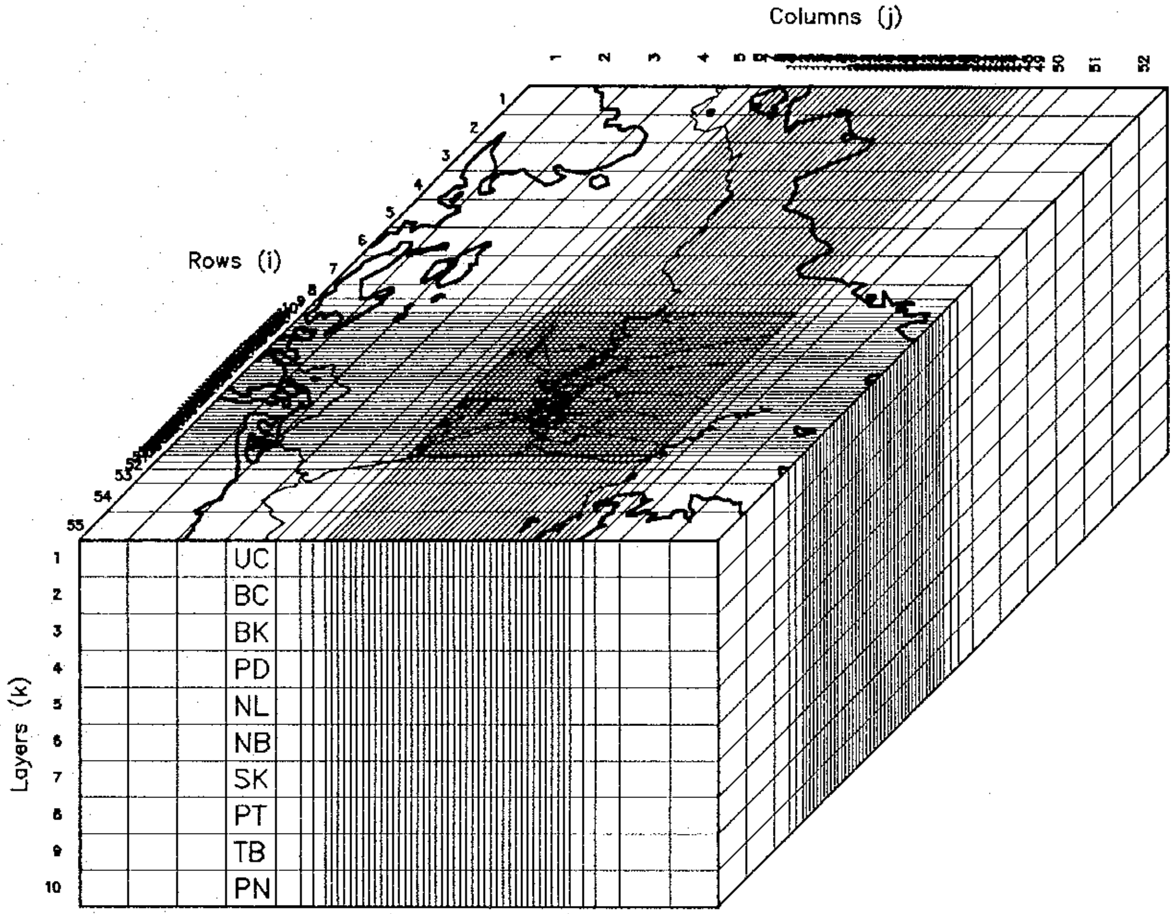

AQUIFER UNITS

UC: Unconfined (constant head)
BC: Bangkok Soft Clay
BK: Bangkok Aquifer
PD: Phra Pradaeng Aquifer
NL: Nakhon Luang Aquifer
NB: Nonthaburi Aquifer
SK: Sam Khok Aquifer
PT: Phayathai Aquifer
TB: Thonburi Aquifer
PN: Pak Nam Aquifer

Figure 7.2.2	STRUCTURE OF 3-D MODEL
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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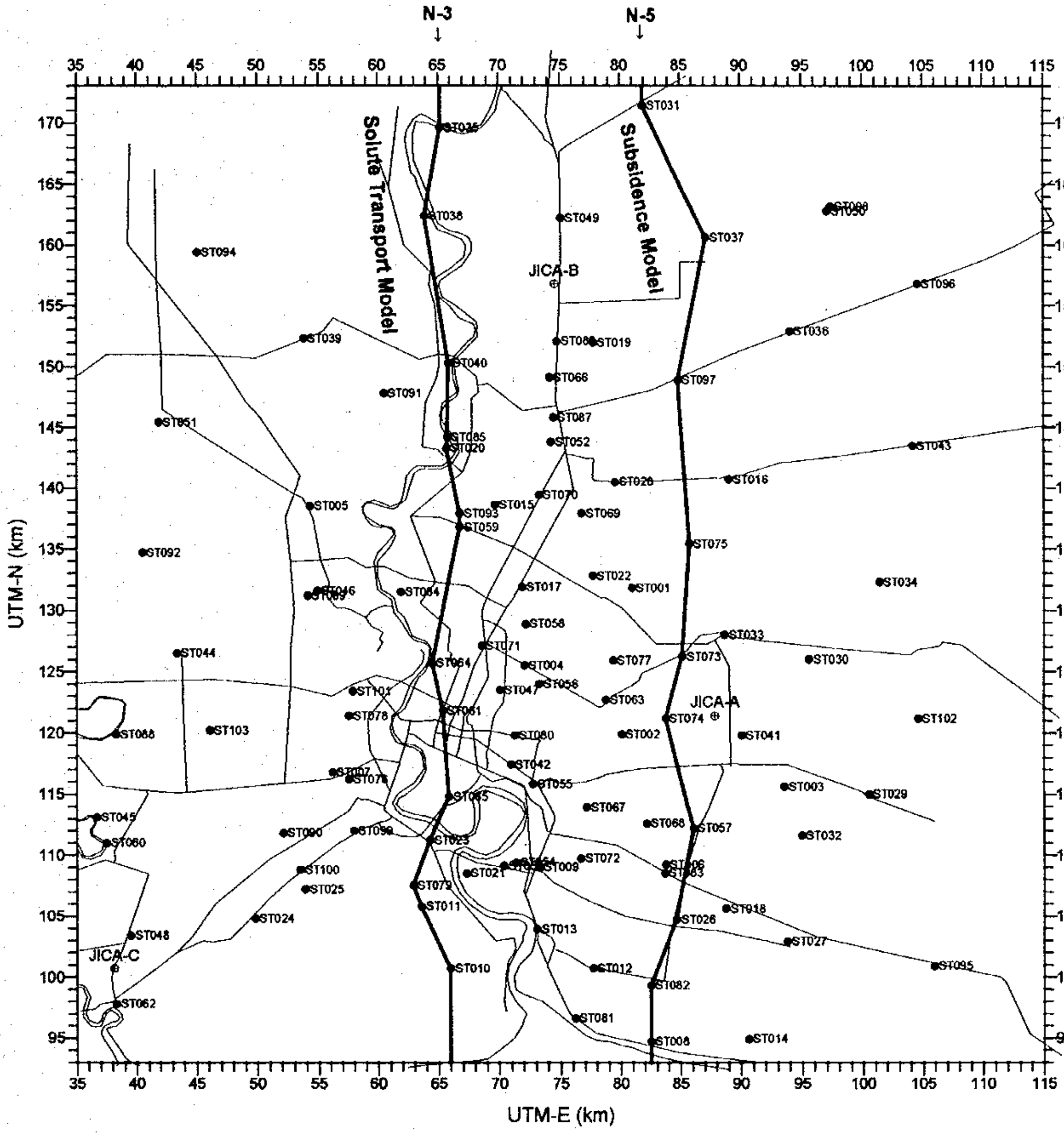

LEGEND

▬▬	Location of Vertical Model
N-3	Hydrogeologic Profile No.
⊕	Location of JICA Monitoring Station
•	Location of DMR Monitoring Station with Station No.

Figure 7.2.3	LOCATION OF VERTICAL 2-D MODELS
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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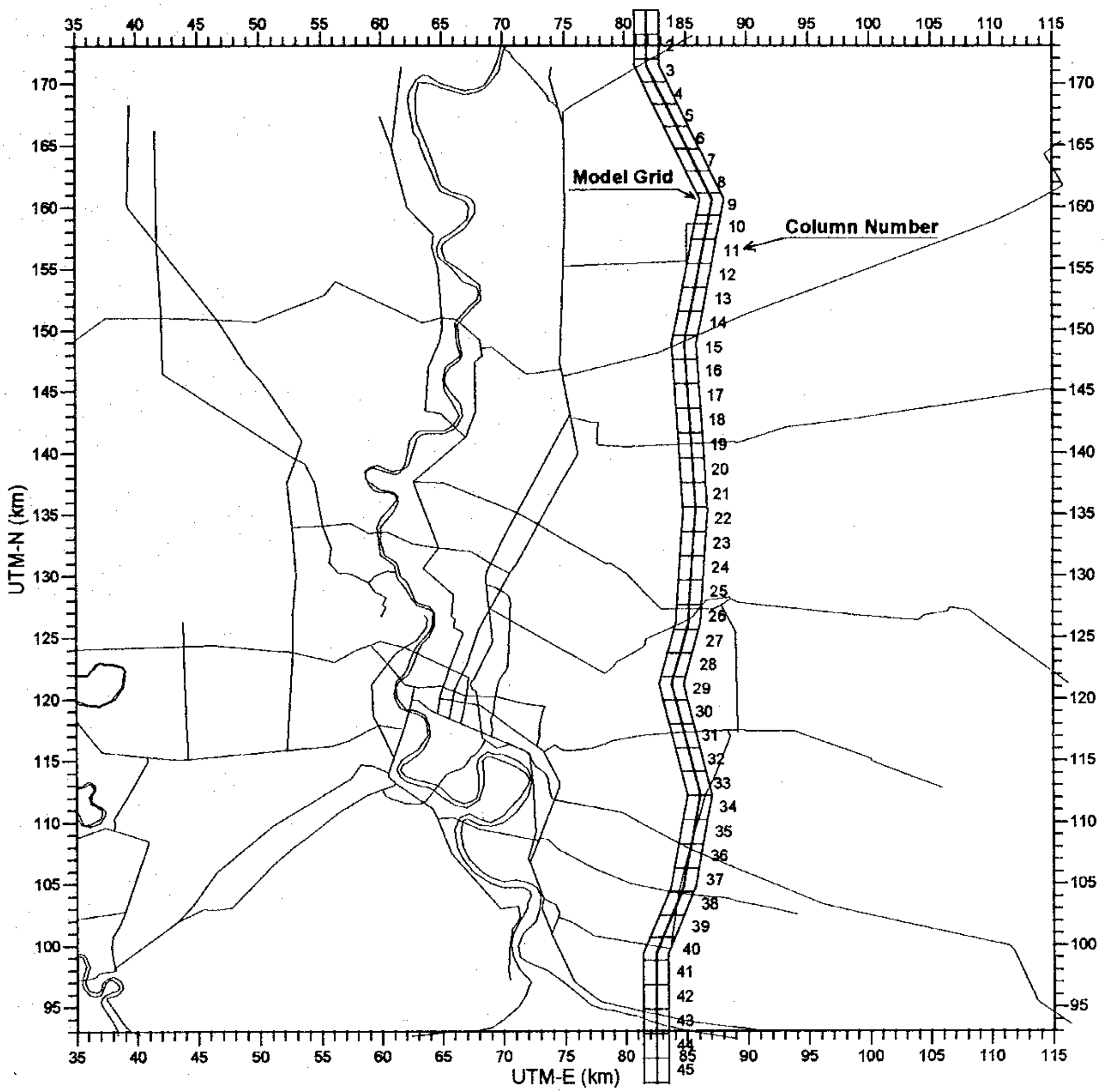

Figure 7.2.4	LOCATION OF VERTICAL 2-D LAND SUBSIDENCE MODEL
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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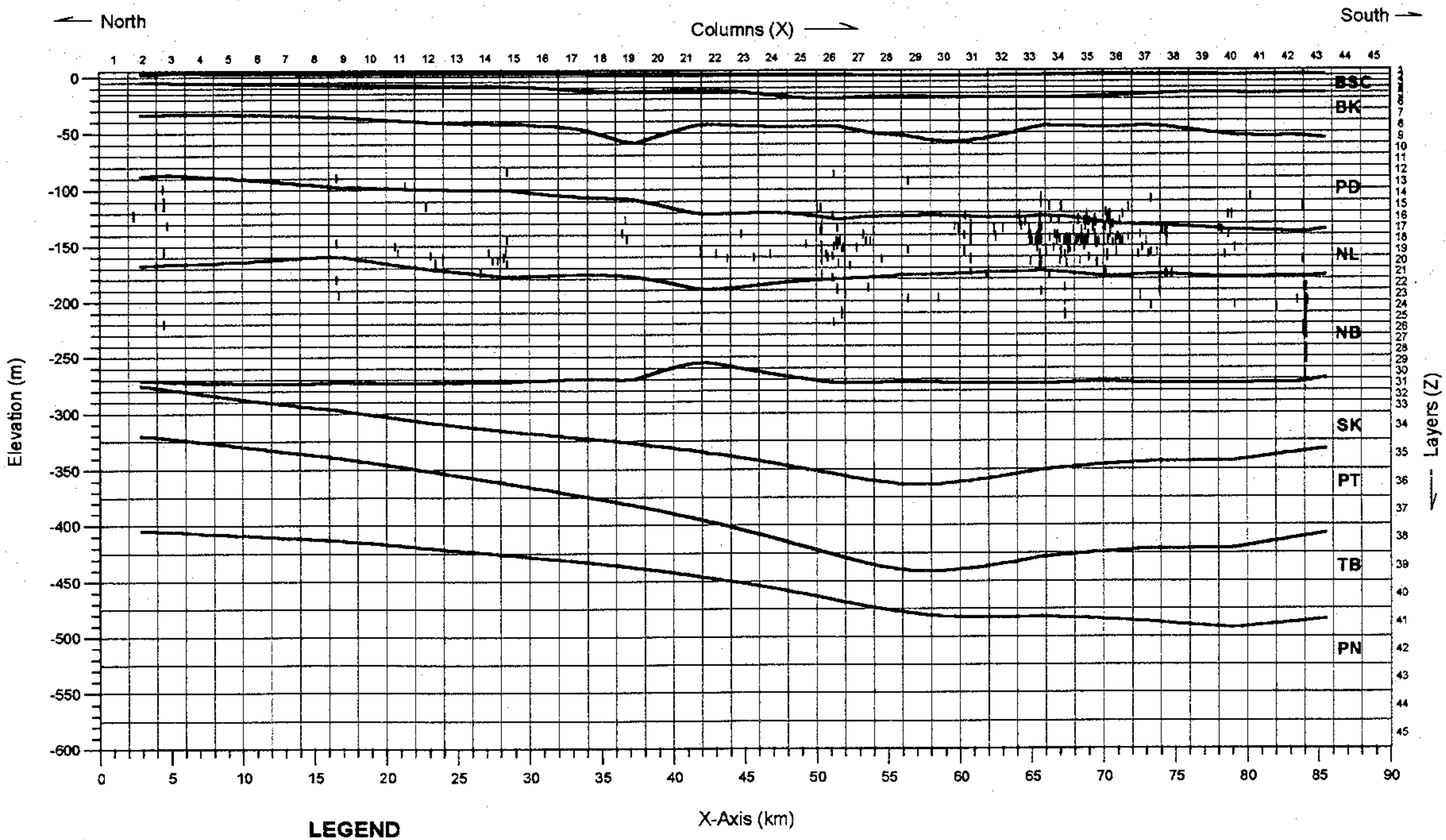

LEGEND

— Boundary of hydrogeologic unit

| Screen of production well

Figure 7.2.5	**VERTICAL 2-D LAND SUBSIDENCE MODEL GRID**
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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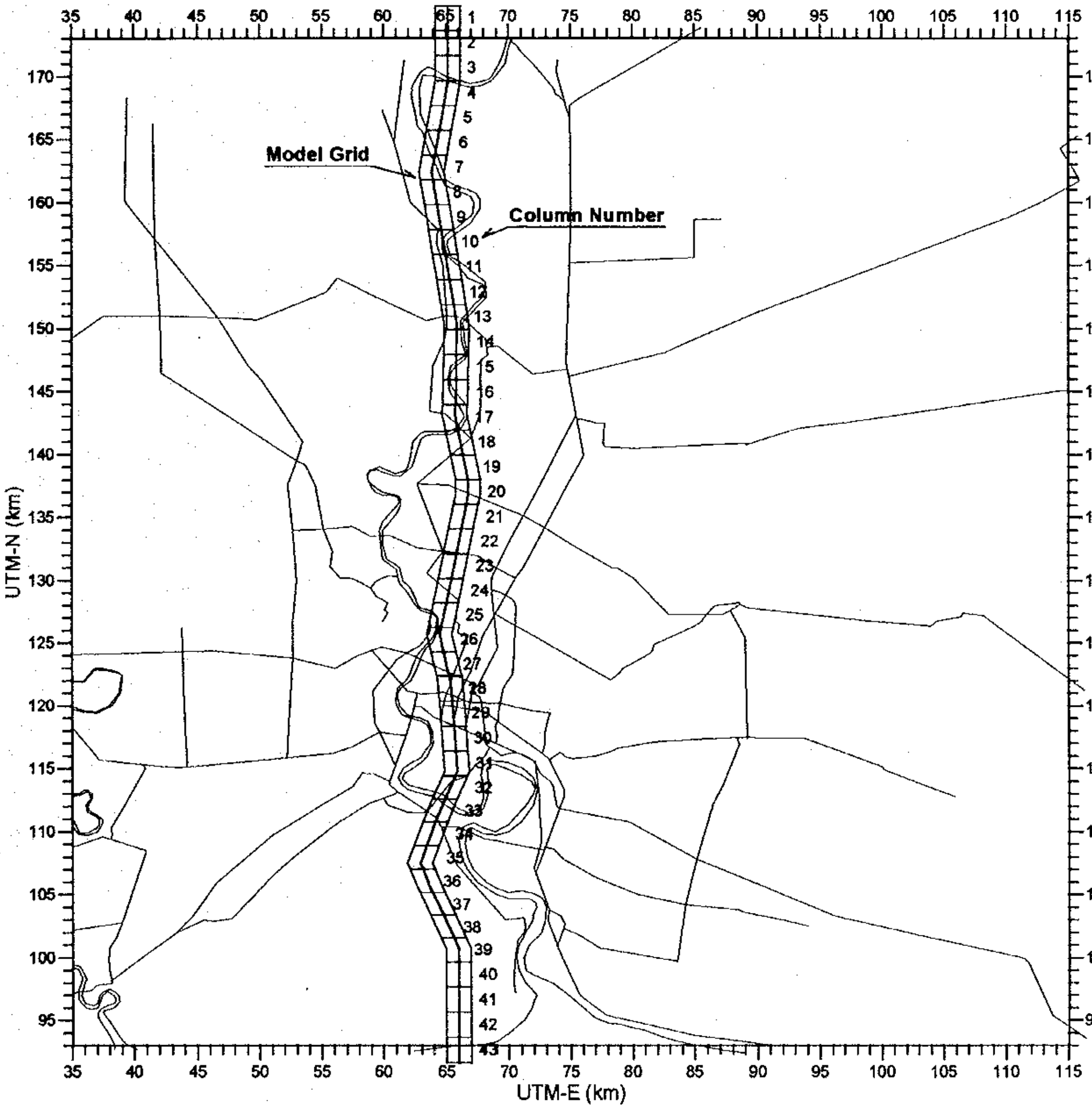

Figure 7.2.6	LOCATION OF VERTICAL 2-D SOLUTE TRANSPORT MODEL
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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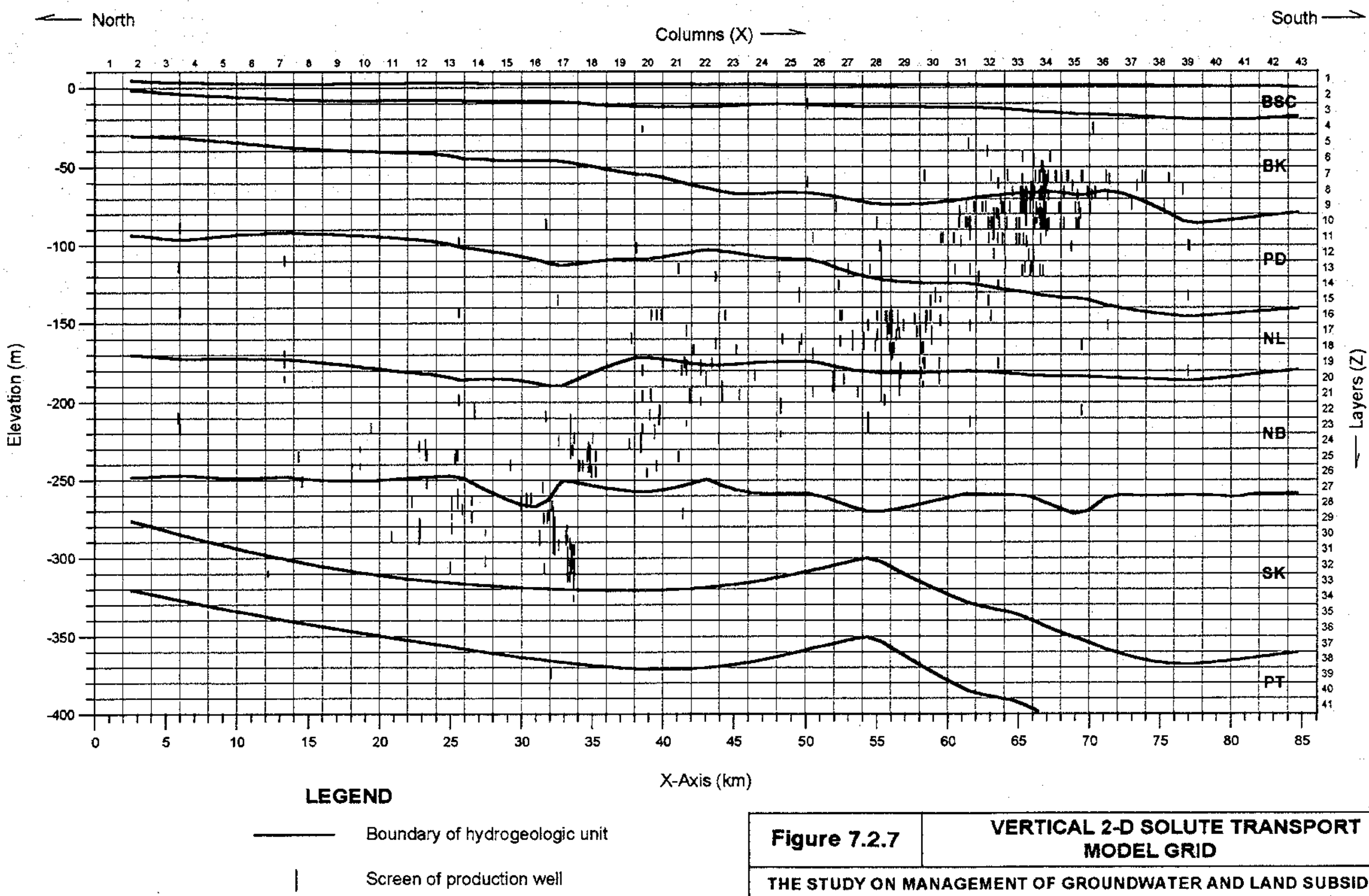

Figure 7.2.7 VERTICAL 2-D SOLUTE TRANSPORT MODEL GRID

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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7.3 Boundary Conditions

(1) Boundary Conditions for 3-D Model

Appropriate boundary conditions were specified for numerical calculation based on the hydrogeological information. At first, the extent of each aquifer unit was defined based on the geological studies done in the previous stage. Figure 7.3.1 shows a schematic profile of the Bangkok Aquifer system and the concept of the 3-D model applied to the aquifer system.

According to the geological information, Bangkok area is underlain by Bangkok Clay (BC), but the extent of the clay is limited by Ayutthaya on the north, by Nakhon Nayok on the northeast, and by Nakhon Pathum on the west (AIT, 1980). The schematic geological diagram of the Lower Central Plain made by the Study Team indicates that the area from Ayutthaya to Chai Nat is underlain by the sediments of Ayutthaya Delta and Chai Nat Delta which can be correlated to the Bangkok Aquifer (BK). The eastern and western marginal areas of the Lower Central Plain are underlain by fan deposits and middle terrace deposits, which can be correlated to Phra Pradaeng (PD) Aquifer and Nakhon Luang (NL) Aquifer The higher terrace deposits in those areas can be correlated to Nonthaburi (NB) Aquifer. On the other hand, the sediments of Sam Khok (SK) Aquifer to Pak Nam (PN) Aquifer do not have outcrops. The schematic profile of Figure 7.3.1 (a) was made based on the above information considering the depths of the bedrock.

The geological settings of the Bangkok Aquifer system were conceptually modeled as shown in Figure 7.3.1 (b). An unconfined layer (UC) at the top was created on the BC layer to make the top of BC layer constant head. Some recharge were given to the cells of BK, PD, and NB layers where those layers were outcropping. The layers from SK to PN are bounded by the bedrock.

The areal boundaries of the aquifer units are shown in Figures 7.3.2 and 7.3.3. The NB layer is most widely distributed in the modeled area up to the bedrock outcrops. The extent of PN layer is limited by the bedrock structure.

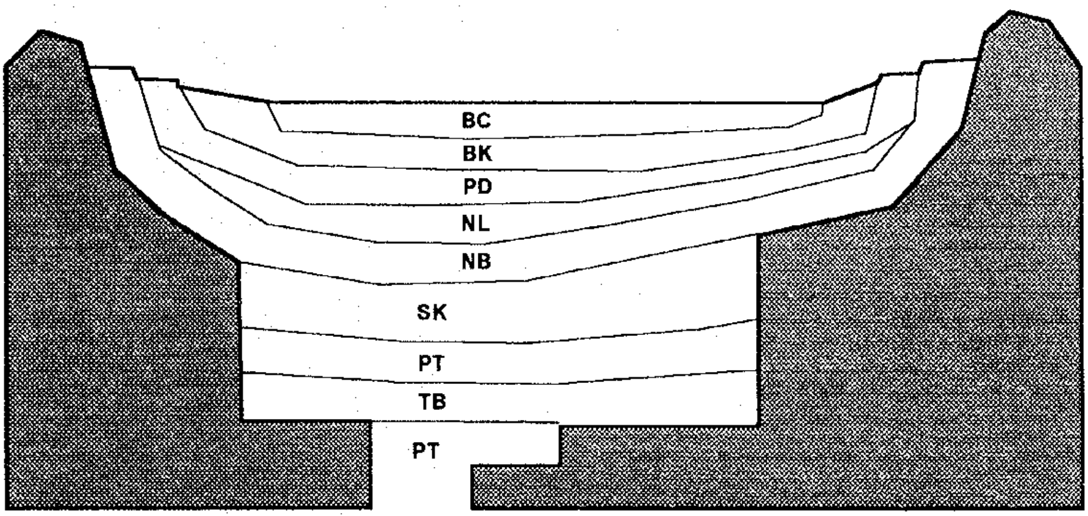
The cells located outside the boundary in each layer were treated as inactive cells in the model. Constant head boundary condition was assigned to the entire active cells of UC layer. Also the constant head boundaries were given to the active cells located in the southernmost row (row No. 55) within the Gulf of Thailand for each layer. The constant flow boundary was assigned to the active cells at northernmost row in NB layer because the layer continued toward the north. The rest of the boundaries in each layer were treated as no-flow boundaries.

(2) Boundary Conditions for Vertical 2-D Land Subsidence Model

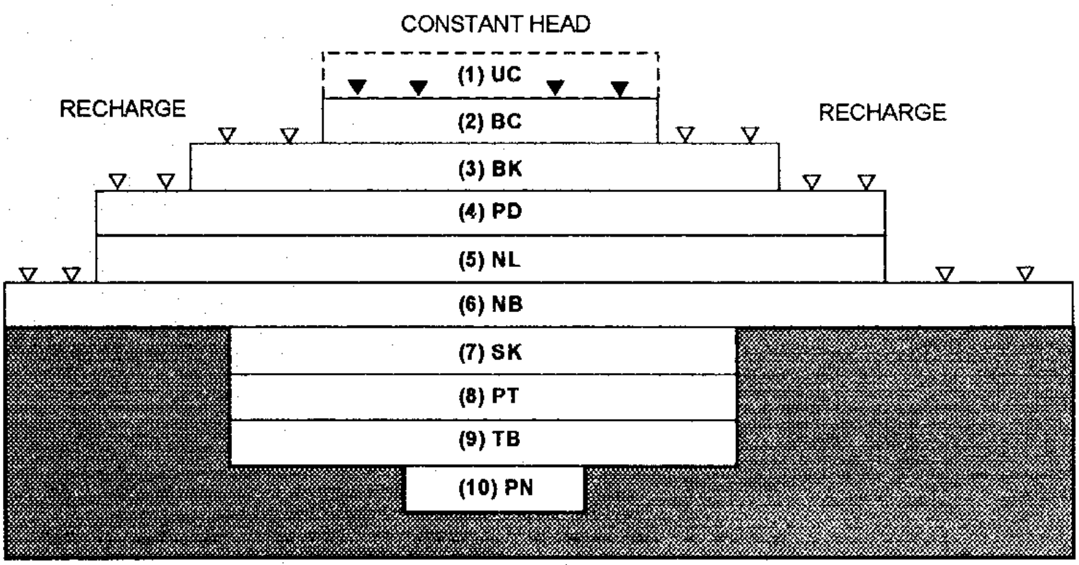
The entire cells of the model are active. The constant head boundary was assigned to the top layer, expressing that the heads on top of the Bangkok Soft Clay are constant. The boundaries at the northern side and southern side of the model (column Nos. 1 and 45) were also treated as constant head boundaries from top layer to bottom layer, because the actual layers continued to the outside. The no-flow boundary was assigned to the bottom of the model.

(3) Boundary Conditions for Vertical 2-D Solute Transport Model

The entire cells of the model are active. The modeled grid is surrounded by no-flow boundaries to preclude the flow of water across the boundaries. The constant pressure boundary was given to the top layer. The left side and right side of the model (column Nos. 1 and 43) were also specified as constant pressure boundaries.



(a) Schematic Profile of Bangkok Aquifer System



(b) 3-D Groundwater Model Applied to Bangkok Aquifer System

Figure 7.3.1	CONCEPT OF 3-D MODEL APPLIED TO BANGKOK AQUIFER SYSTEM
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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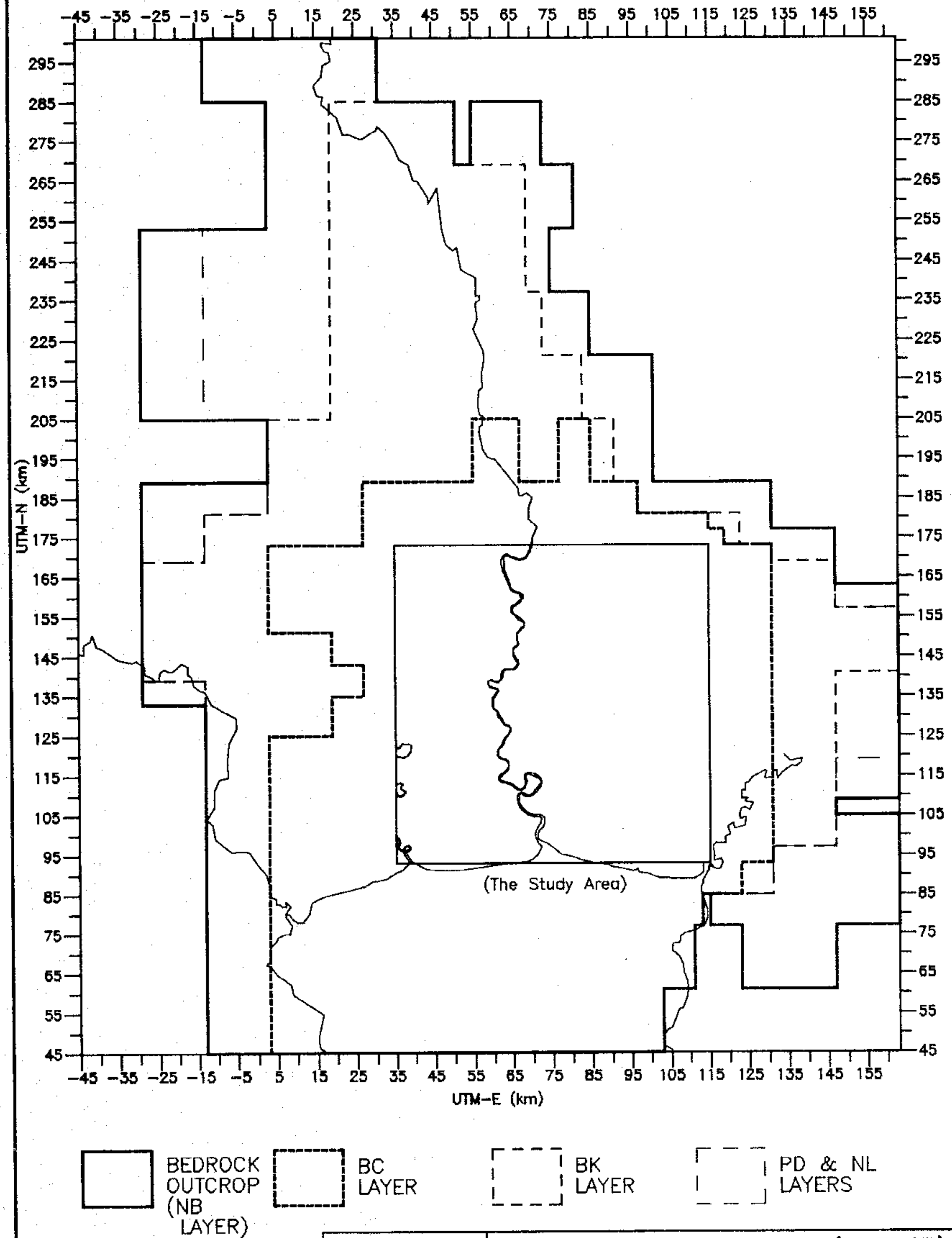

Figure 7.3.2	BOUNDARIES OF AQUIFER UNITS (BC TO NB) FOR MODFLOW 3-D MODEL
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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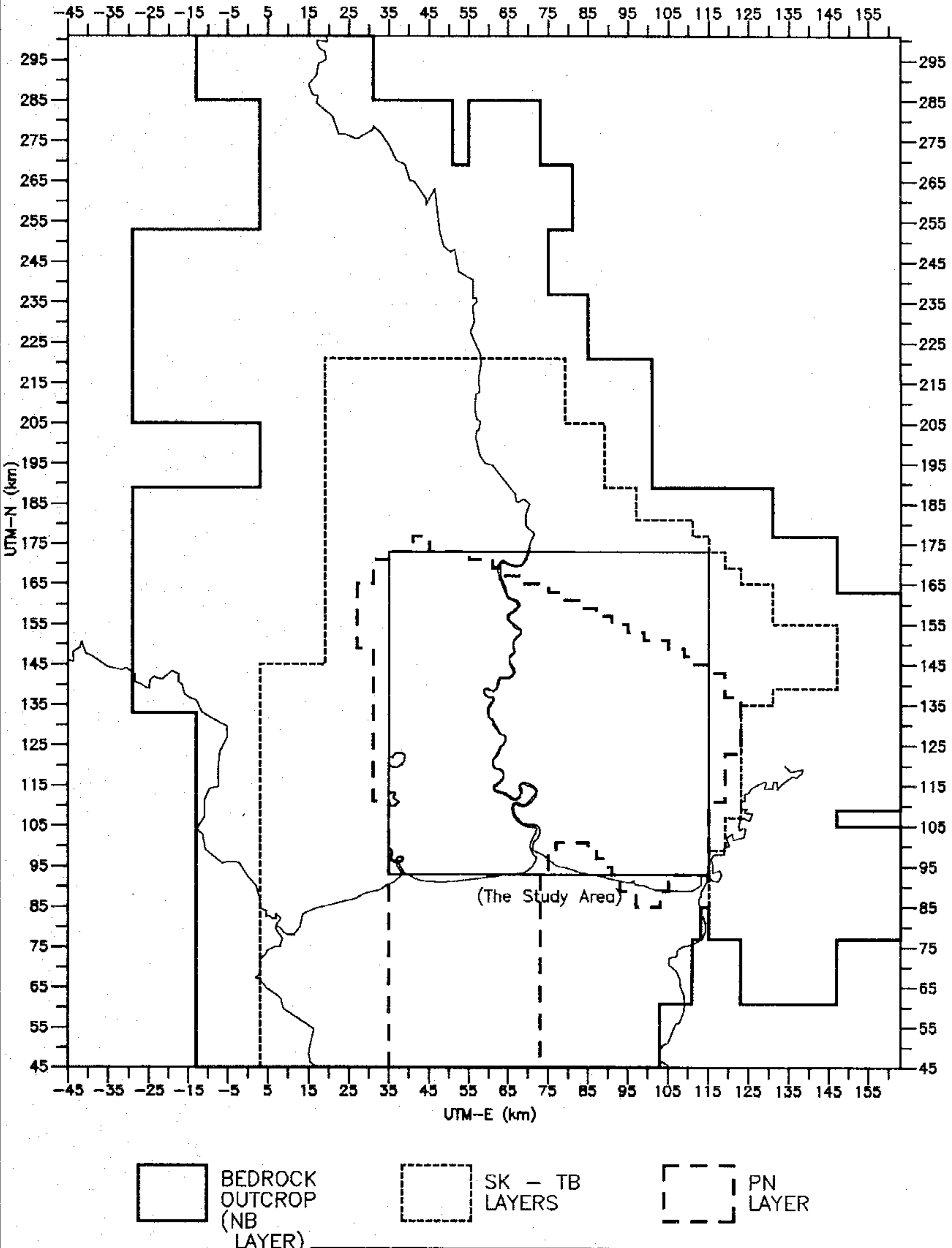

Figure 7.3.3 BOUNDARIES OF AQUIFER UNITS (NB TO PN) FOR MODFLOW 3-D MODEL

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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7.4 Hydrogeologic Parameters

(1) Hydrogeologic Parameters for 3-D Model

1) Required parameters

The MODFLOW program requires the following hydrogeologic parameters:

- Top and bottom elevations of each layer
- Type of each layer
- Porosity
- Specific storage
- Hydraulic conductivity
- Vertical hydraulic conductivity or vertical leakance
- Initial piezometric heads
- Recharge rate

The land subsidence model (SUBPRO-1) requires the following parameters:

- Volume compressibility during loading
- Volume compressibility during unloading

These parameters were prepared from the hydrogeological studies and the well database system.

2) Top and bottom elevations

Top and bottom elevations of each layer were based from a ground elevation map and the bottom depth map of each aquifer unit. The data of ground elevation in the Study Area were obtained from the latest elevation of the DMR and RTSD benchmarks. The elevations of the outer area were taken from the 1:50,000 scale toposheets and the 1:250,000 scale geological maps. Figure 7.4.1 shows the ground elevation in the modeled area.

The top and bottom elevations of each layer except UC and PN layers were determined based from the above. The top elevation of UC layer was derived from:

$$Top\ elevation\ of\ UC = Ground\ elevation + 1m \qquad (7.4.1)$$

The bottom elevation of UC layer is the same as ground elevation. The bottom elevation of PN Aquifer was given as -600 m uniformly.

Figure 7.4.2 shows the isopach of Bangkok Soft Clay (BC) prepared from borehole data and lithologic logs of the DMR monitoring wells. The bottom depth maps of BK, PD, NL, and NB Aquifers were prepared based on the aquifer classification (see Chapter 3). The bottom depth maps of SK, PT, and TB Aquifers were also prepared from the hydrogeological profiles made by the DMR (1987) and the hydrogeological profiles (Chapter 3). These maps are included in the Supporting Report. The aquifer classification was extended to the outside of the Study Area by using the lithologic logs stored in the database. From the foregoing, the top and bottom elevations for each aquifer in the modeled area were obtained..

MODFLOW calculates the thickness of each cell during the computation.

3) Type of each layer

An aquifer type was specified for each layer. The confined aquifer type was assigned to the layers except UC layer.

4) Porosity

For the simulation of steady state flow, porosity is not required by MODFLOW. However, porosity is required by MODPATH program, which is the subprogram of MODFLOW for the calculation of the flow velocities. Therefore, this parameter is required by MODFLOW input program, PREMOD. The porosity value of 0.05 was uniformly given to the model.

5) Specific storage

The Block-Centered Flow (BCF) Package of MODFLOW program requires dimensionless storage coefficient values in each layer of the model. PREMOD converts the specific storage value of the cell material into dimensionless storage coefficient by multiplying the layer thickness of the cell.

The values of storage coefficient obtained from pumping tests usually had a wide range of variation. However, Walton (1970) suggested that the range of storage coefficient values in confined aquifers should vary between 1.0×10^{-5} and 1.0×10^{-3} for all soils and between 5.0×10^{-5} and 1.0×10^{-2} in productive aquifers. Therefore, the initial storage coefficient of each layer except UC and BC was assumed to be 1.0×10^{-3}. This value was then converted into specific storage by dividing it by the thickness of the cell.

The specific storage values of BC were computed by following the equation from the volume compressibility values obtained from consolidation tests:

$$Ss = m_v \cdot \gamma_w / 10 \qquad (7.4.2)$$

where, Ss is specific storage (1/m), m_v is volume compressibility (cm^2/kgf), and γ_w is unit weight of water (g/cm^3). Details of estimating the volume compressibility values are discussed in Section 10. The specific storage values of UC were based on the values of BC.

6) Hydraulic conductivity

Transmissivity is the most important parameter for the model. PREMOD computes transmissivity from horizontal hydraulic conductivity (or permeability) by multiplying the layer thickness. An anisotropy factor (*Tyy/Txx*) was specified in the model.

Generally, transmissivity values were obtained from pumping tests. The Study Team collected previous pumping tests' data and carried out pumping tests at the newly constructed monitoring wells. However, the number of pumping tests and obtained aquifer parameters were insufficient to evaluate regional aquifer characteristics. Therefore, the transmissivity values by aquifer were obtained from the hydrogeological information and specific capacity data of the production wells stored in the database. The method of estimating transmissivity is as follows:

a) Classify production wells by aquifer using screen depths. Compute specific capacity value.
b) Estimate apparent transmissivity from specific capacity using well data.
c) Estimate permeability from apparent transmissivity and screen length.
d) Compute clay content of each aquifer unit.
e) Compute transmissivity of aquifer facies from estimated permeability.
f) Compute hydraulic conductivity for MODFLOW input by dividing transmissivity of aquifer facies by thickness of layer.

The production wells having screen length and production test data were used to compute specific capacity. The aquifer name of each well was identified by the bottom depth maps. Figure 7.4.3 shows the distribution of specific capacity values by aquifer with a logarithmic average and a range of the standard deviations. The distribution maps of specific capacity for BK Aquifer to PN Aquifer with locations of the production wells are presented in the Supporting Report.

Transmissivity values of the production wells were estimated by following three (3) methods:

- Unsteady-state estimation
- Steady-state estimation
- Estimation method by Logan (1964)

If the well has the data of discharge, drawdown, pumping time, and well radius, the specific capacity is given by the approximate nonequilibrium equation without well loss in confined. aquifers presented by Cooper and Jacob (1946), that is:

$$Sc = \frac{Q}{s} = \frac{4\pi T}{2.30 \log(2.25Tt / r^2S)} \qquad (7.4.3)$$

where, Sc is specific capacity (m^2/d), Q is well discharge (m^3/d), T is transmissivity (m^2/d), t is pumping duration (day), r is well radius (m), and S is storage coefficient (dimensionless). If S can be assumed as mentioned before, T can be obtained by solving Equation (7.4.3) numerically.

The steady-state estimation was used for wells not having pumping time. The equilibrium equation for confined aquifers developed by Thiem (1906) is written as:

$$T = \frac{Q \ln (r_2 / r_1)}{2\pi (s_1 - s_2)} \qquad (7.4.4)$$

where, s_1 (m) and s_2 (m) are drawdowns of piezometric level at distances r_2 (m) and r_1 (m), respectively. Klimentov (1967) gave an empirical equation for computing the radius of influence as below:

$$r_2 = 2s \sqrt{T} \qquad (7.4.5)$$

where, s (m) is drawdown in a well having well radius r (m). Changing from natural to common log base and substituting Equation (7.4.5) in Equation (7.4.4), Sc can be written as:

$$Sc = \frac{Q}{s} = \frac{5.46T}{\log(4Ts^2 / r^2)} \qquad (7.4.6)$$

Then, T can be obtained by solving Equation (7.4.6) by some numerical methods.

If the well has only the value of specific capacity, transmissivity can be estimated based on the following equation presented by Logan (1964):

$$T = 1.22\, Sc \qquad (7.4.7)$$

The estimated transmissivity can be called as "apparent transmissivity", because the estimated transmissivity describes the ability of the perforated portion of the aquifer to transmit water. After obtaining the apparent transmissivity of the well by the said methods, the permeability k value was computed based on the definition of transmissivity given by:

$$k = T / b \qquad (7.4.8)$$

where, b is the screen length. Figure 7.4.4 shows the distribution of estimated permeability by aquifer. The distribution maps of estimated permeability by aquifer are presented in the Supporting Report.

The clay content maps of BK Aquifer to NL Aquifer were prepared based on the lithologic logs of the DMR monitoring wells and some production wells. The clay content was computed by:

Clay content = Total thickness of clay beds / (aquifer thickness) × 100 (%)

In case the layer is sandy clay, a value of 0.7 was multiplied to the thickness. Similarly, a value of 0.3 was used to multiply the thickness when the layer is clayey sand. The clay content maps of NB to TB Aquifers were prepared based on the lithologic logs of production wells, because the DMR monitoring wells do not penetrate NB Aquifer. Figures 7.4.5 to 7.4.11 show the aquifer thickness (isopach) of BK Aquifer to TB Aquifer. The distribution maps of clay content for BK Aquifer to TB Aquifer are found in the Supporting Report.

The thickness of aquifer facies such as sand and gravel in each aquifer unit was then computed as follows:

Thickness of aquifer facies = (100 - clay content (%)) × (isopach) / 100

The transmissivity of the whole aquifer facies was later computed for each cell by:

Transmissivity of aquifer facies = (thickness of aquifer facies) × (permeability)

The transmissivity of clay beds can be neglected due to the small values of permeability, meaning that the estimated transmissivity of aquifer facies can represent the transmissivity of the aquifer unit. Figures 7.4.12 to 7.4.19 show the final estimated transmissivity of BK Aquifer to PN Aquifer. For PN Aquifer, although the bottom depth is not confirmed from the field data, the elevation up to -600 m was taken into account.

For MODFLOW input, the estimated transmissivity values were converted to hydraulic conductivity values by dividing the transmissivity by the layer thickness.

The hydraulic conductivity of BC layer was estimated from the permeability obtained from the consolidation tests as follows:

$$k = c_v \cdot m_v \cdot \gamma_w / (1\text{x}10^5) \qquad (7.4.9)$$

where, k is permeability of clay (m/d), c_v is coefficient of consolidation (cm^2/d), m_v is volume compressibility (cm^2/kgf), and γ_w is unit weight of water (g/cm^3). Figure 7.4.20 shows the distribution of clay permeability by aquifer unit. The obtained hydraulic values for BC layer were also given to UC layer.

7) Vertical hydraulic conductivity or vertical leakance

The MODFLOW needs an input data set of vertical hydraulic conductivity or vertical leakance to calculate the vertical groundwater flow terms. If the data set type is selected as "vertical hydraulic conductivity", PREMOD calculates the vertical leakance with the equation:

$$\frac{1}{L} = \frac{d_1/2}{k_{fv,1}} + \frac{d_2/2}{k_{fv,2}} \qquad (7.4.10)$$

where, L is vertical leakance (1/day), $k_{fv,1}$ and $k_{fv,2}$ are vertical hydraulic conductivity of the upper aquifer and the lower aquifer (m/d), d_1 and d_2 are thicknesses of the upper aquifer and the lower aquifer (m). Actually, the leakance value is one of the unknown parameters from the field investigations, so the tentative values were estimated from the method mentioned below, then the appropriate values were identified from the model calibration.

As mentioned earlier, each layer of the model consists of sandy facies and clayey facies except BC and UC layers. These facies beds occur alternately in the layer. So the average vertical hydraulic conductivity of the layer was computed based on the thickness and the permeability of each facies by the equation:

$$\log (k'_{av}) = [b_s \cdot \log (k'_s) + b_c \cdot \log (k'_c)] / b \qquad (7.4.11)$$

where, k'_{av} is average vertical hydraulic conductivity of the layer (m/d), k'_s and k'_c are vertical hydraulic conductivities of sandy facies and clayey facies (m/d), b_s and b_c are thicknesses of sandy facies and clayey facies (m), and b is the total thickness of the layer. The values of k'_s and k'_c were estimated from Figures 7.4.4 and 7.4.20 considering the effect of sedimentary structure, which may reduce vertical permeability values as compared with the horizontal permeability values.

8) Initial piezometric heads

The initial piezometric heads of UC and BC layers for the initial steady-state calibration were given as the ground elevation shown in Figure 7.4.1. The initial heads of the other layers were assigned to be 0 m elevation. For the historical calibration of the period from 1983 to 1992, the computed heads by the steady-state calibration were input as the initial heads.

9) Recharge rate

The recharge cells were identified based on the boundaries of the layers. A tentative recharge rate was given to the cells as 5% of annual precipitation.

10) Volume compressibility

The SUBPRO-1 needs a data set of volume compressibility at loading (m_v) and volume compressibility at unloading (m_v') for each layer. The values of compressibility were obtained from the consolidation tests done by the Study Team. Figure 7.4.21 shows the distribution of volume compressibility by aquifer unit. It is noted that the volume compressibility value of each sample was taken at the hydrostatic pressure, because the value changes over the loading steps. It is also noted that the identification of the preconsolidation pressure is difficult from deeper samples. Figure 7.4.22 shows the relation between sample depth and volume compressibility at the CI stations. The graph also indicates that the values sharply increase with decreasing depth.

Figure 7.4.23 shows that the changes in volume compressibility with ground water pressure at Site-A. The graph indicates that the values of volume compressibility at shallower depths generally decrease with decreasing groundwater pressure. The changes of the values below 300 m in depth were very small even though the groundwater level dropped 70 m. Hence, appropriate volume compressibility values were given to the shallow layers.

The m_v' value is smaller than m_v. The ratio of m_v' / m_v differs by aquifer unit and groundwater pressure. Based on the consolidation tests, appropriate m_v' values were input to the model.

(2) Hydrogeologic Parameters for Vertical 2-D Land Subsidence Model

The hydrogeological unit and facies label were assigned to each grid. Then, the required hydrogeological parameters were given to each cell. The values of hydraulic conductivity and specific storage were estimated based on the methods mentioned in the previous section.

The model can simulate soil compression in detail especially for the Bangkok Soft Clay. The e- log P curves of shallow clayey soils at a depth interval of 5 m were used in order to simulate behavior at different depth. Similarly, the log m_v - log P_{av} curves of the clayey soils were made. Based on these data, appropriate volume compressibility values were given to the cells assigned to the Bangkok Soft Clay. The e- log P curves and the log m_v - log P_{av} curves are presented in the Supporting Report.

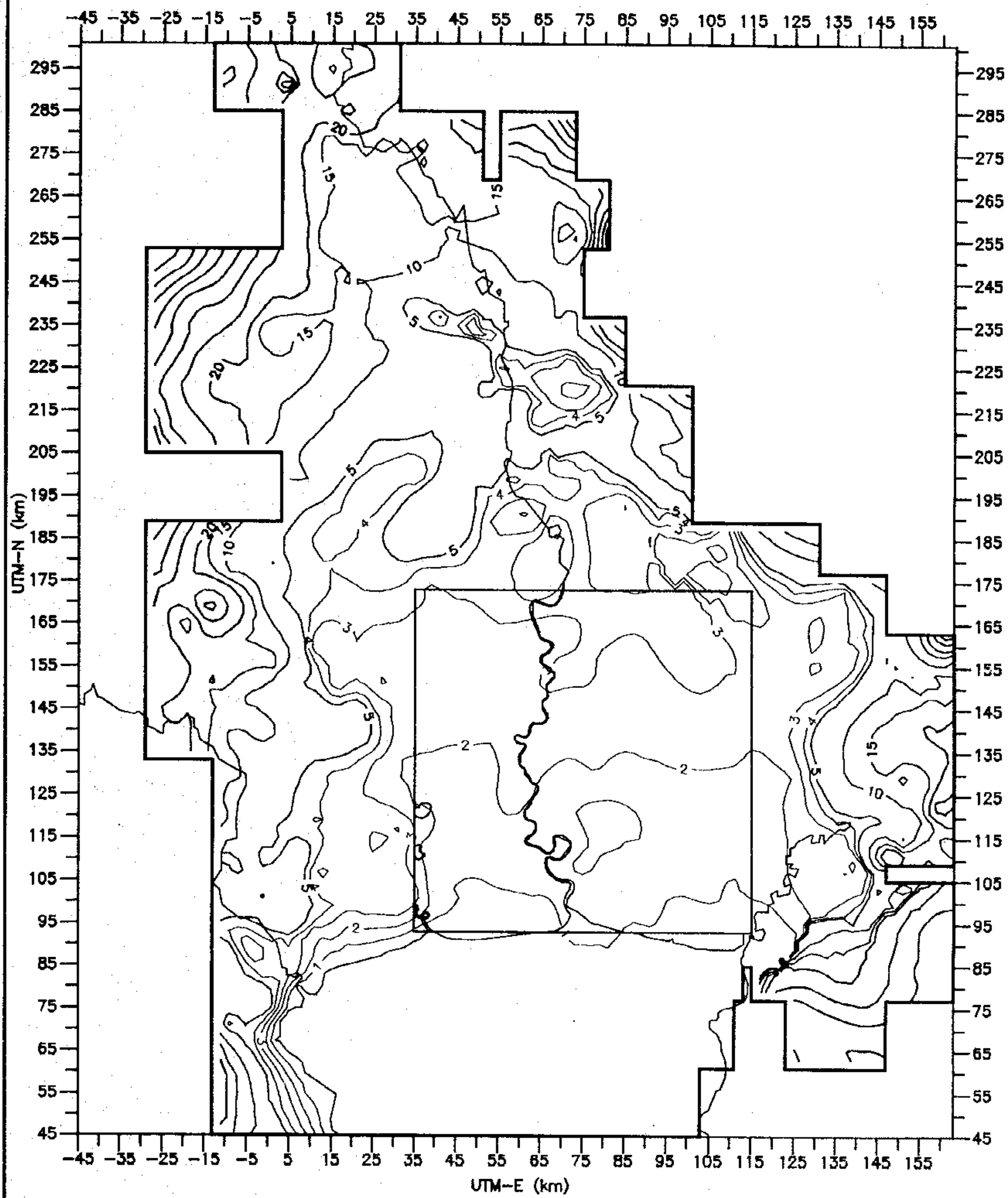
(3) Hydrogeologic Parameters for Vertical 2-D Solute Transport Model

The hydrogeologic unit and facies label were assigned to each grid. Then the required hydrogeologic parameters were given to each cell. The values of hydraulic conductivity and specific storage were estimated based on the methods mentioned in the previous section.

For MOCDENSE input, the intrinsic permeability (physical permeability) must be specified instead of hydraulic conductivity, because the hydraulic conductivity values in the fresh water zone and saltwater zone are different. The relation between hydraulic conductivity and intrinsic permeability is:

$$k = k_p \frac{\gamma_w g}{\mu} \qquad (7.4.12)$$

where, k is hydraulic conductivity (LT^{-1}), k_p is intrinsic permeability (L^2), γ_w is unit weight of water (ML^{-3}), g is gravity acceleration (LT^{-2}), and μ is dynamic viscosity of water ($ML^{-1}T^{-1}$). The initial piezometric heads were also converted into piezometric pressure. The initial concentration of sea water and initial density of sea water were assumed to be 35,000 mg/L and 1.025 g/cm^3, respectively.



(Unit: m above sea level)

Figure 7.4.1	ELEVATION OF GROUND SURFACE

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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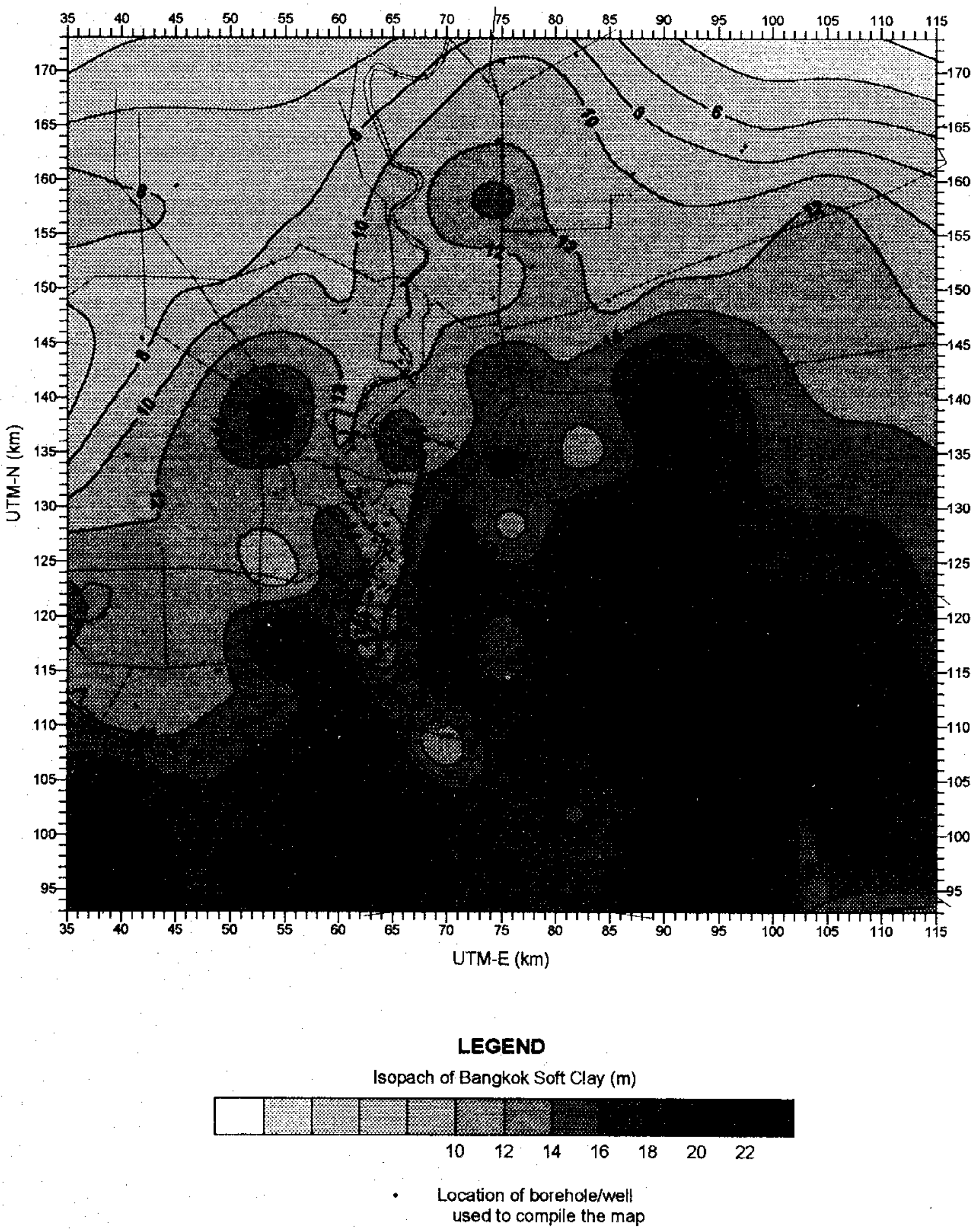


Figure 7.4.2	ISOPACH MAP OF BANGKOK SOFT CLAY
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

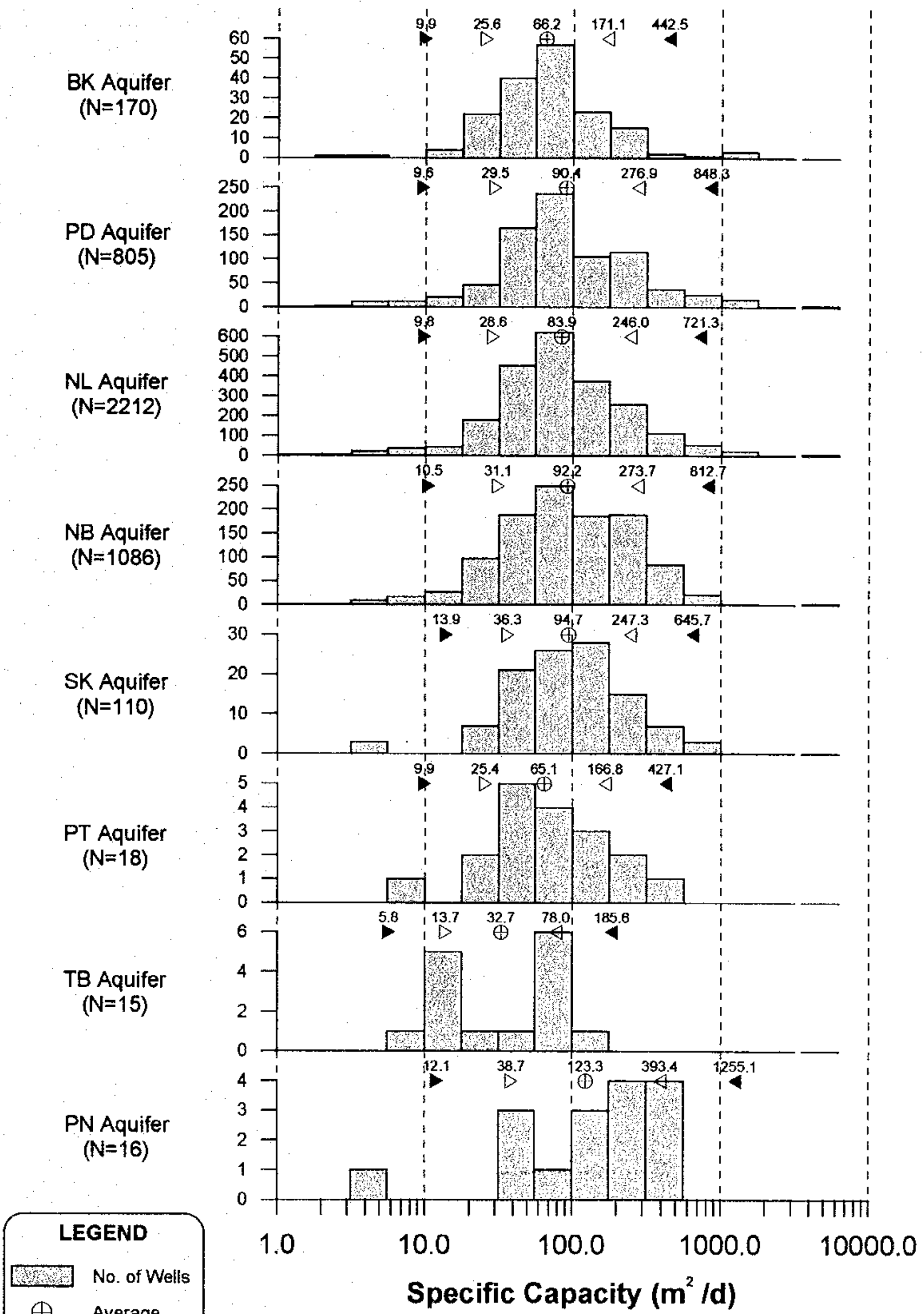
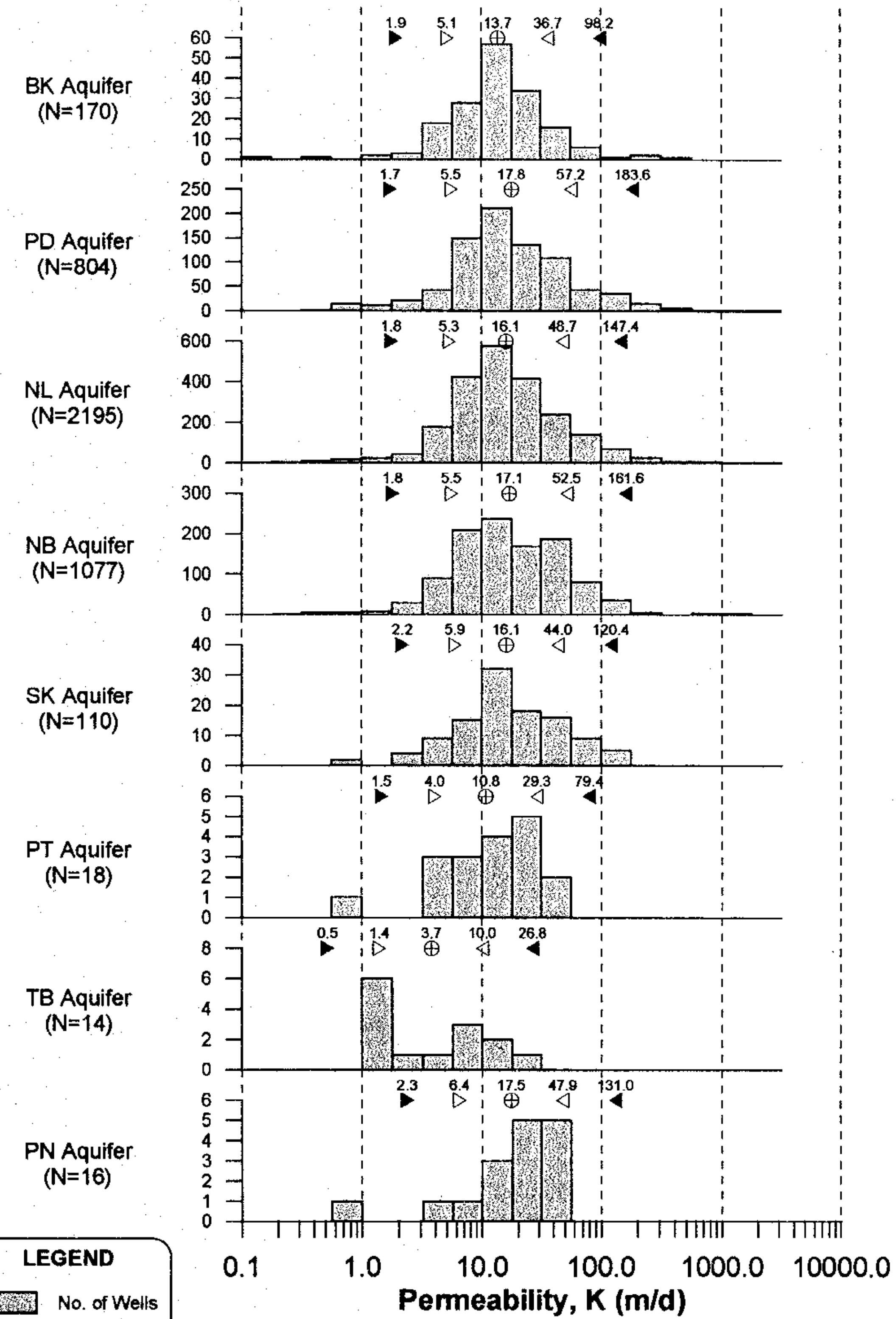


Figure 7.4.3	DISTRIBUTION OF SPECIFIC CAPACITY VALUES OBTAINED FROM PRODUCTION WELLS DATA
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



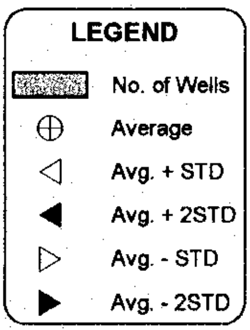


Figure 7.4.4	DISTRIBUTION OF PERMEABILITY VALUES ESTIMATED FROM PRODUCTION WELLS DATA
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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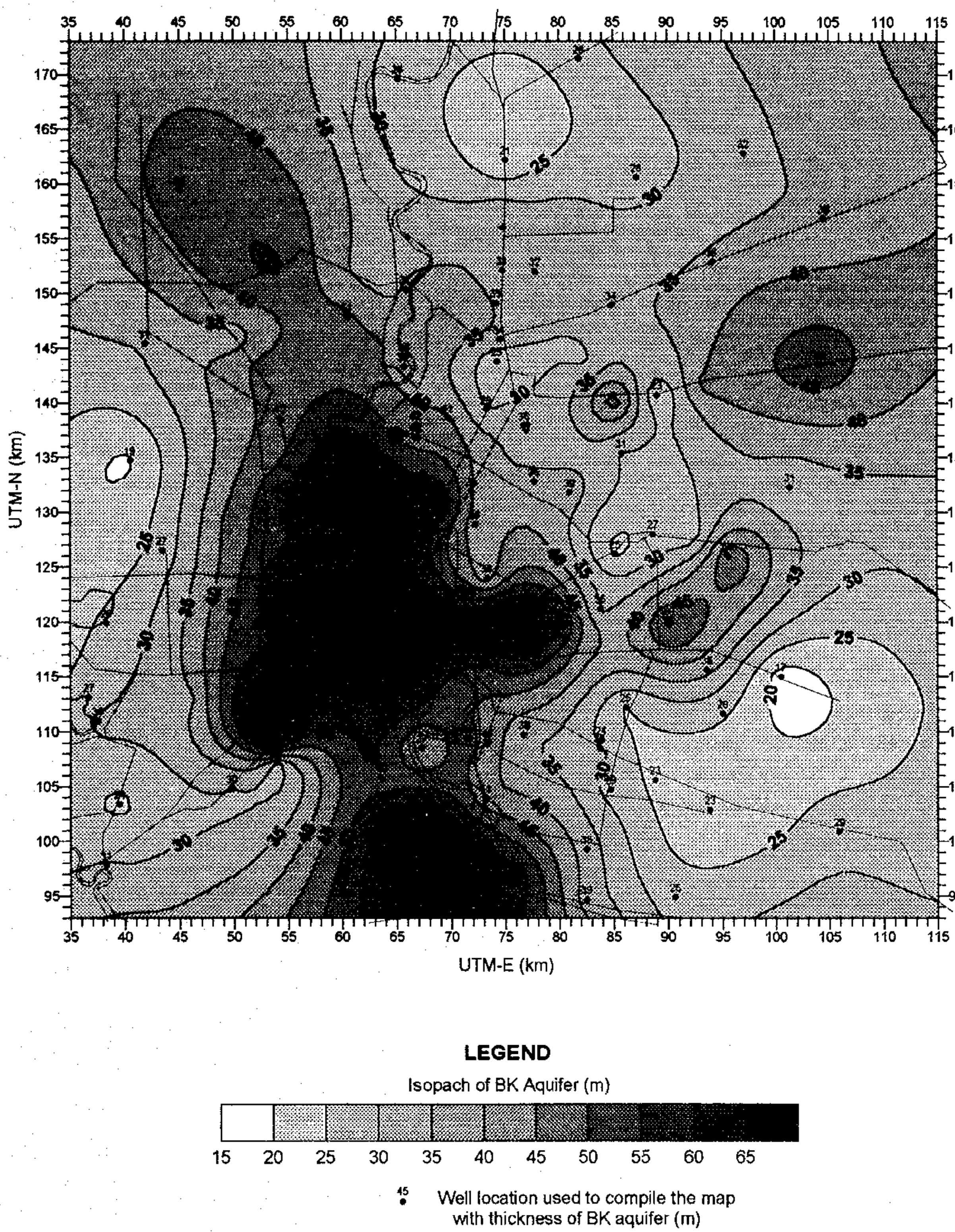

Figure 7.4.5	ISOPACH MAP OF BK AQUIFER

THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

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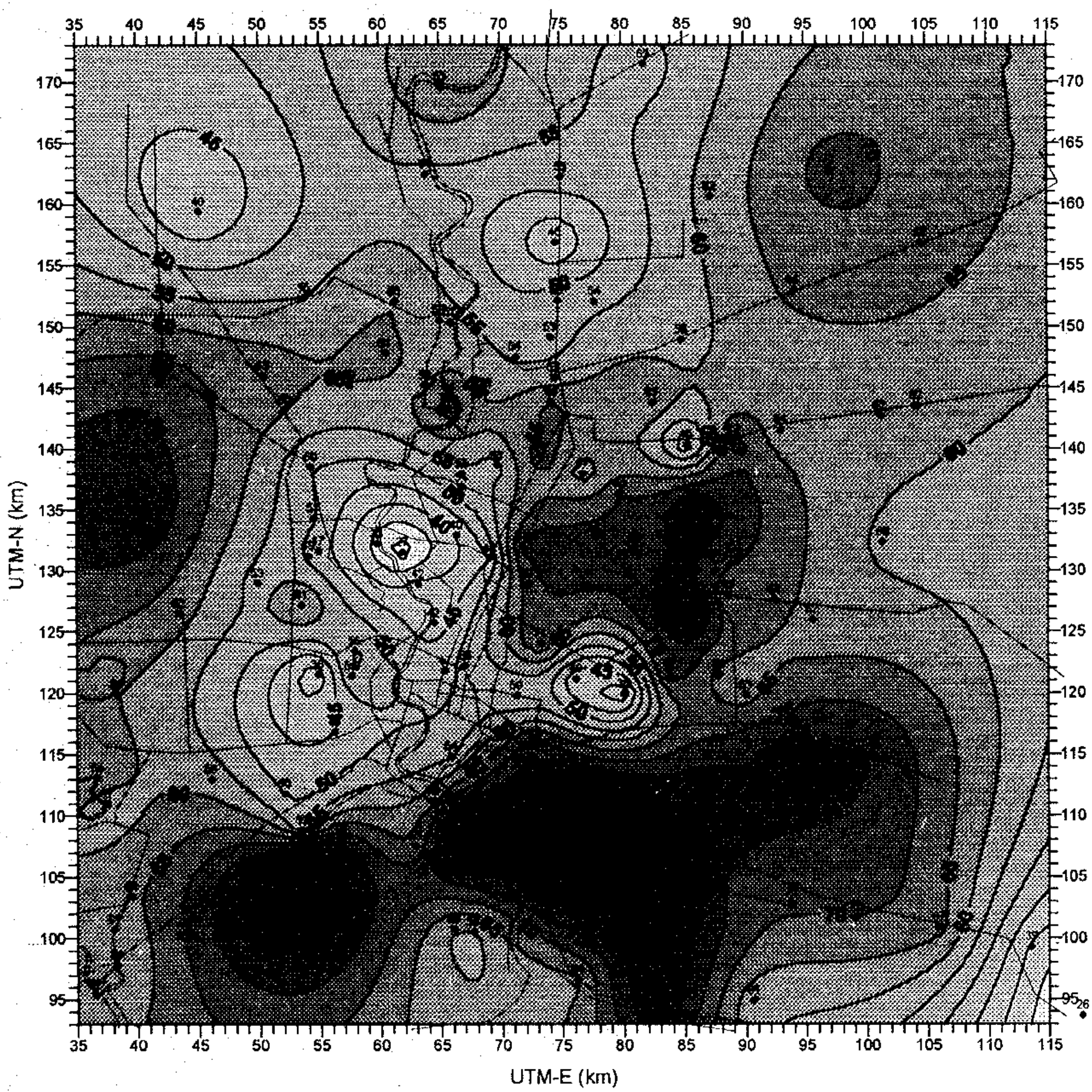

LEGEND

Isopach of PD Aquifer (m)

25 30 35 40 45 50 55 60 65 70 75 80 85 90 95

65 Well location used to compile the map with thickness of PD aquifer (m)

Figure 7.4.6	**ISOPACH MAP OF PD AQUIFER**
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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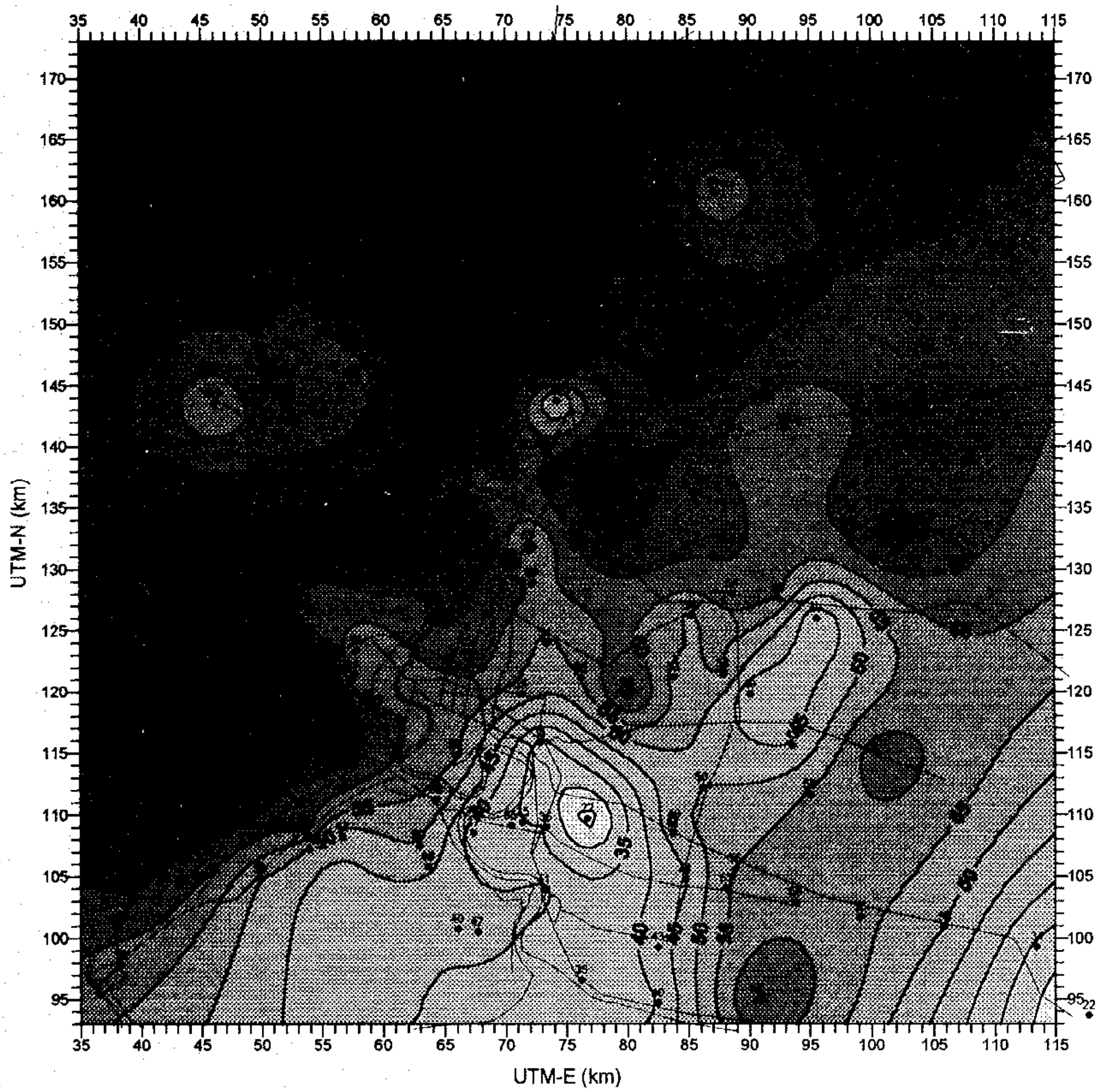

LEGEND

Isopach of NL Aquifer (m)

20 25 30 35 40 45 50 55 60 65 70 75 80 85

55 • Well location used to compile the map with thickness of NL aquifer (m)

Figure 7.4.7	ISOPACH MAP OF NL AQUIFER
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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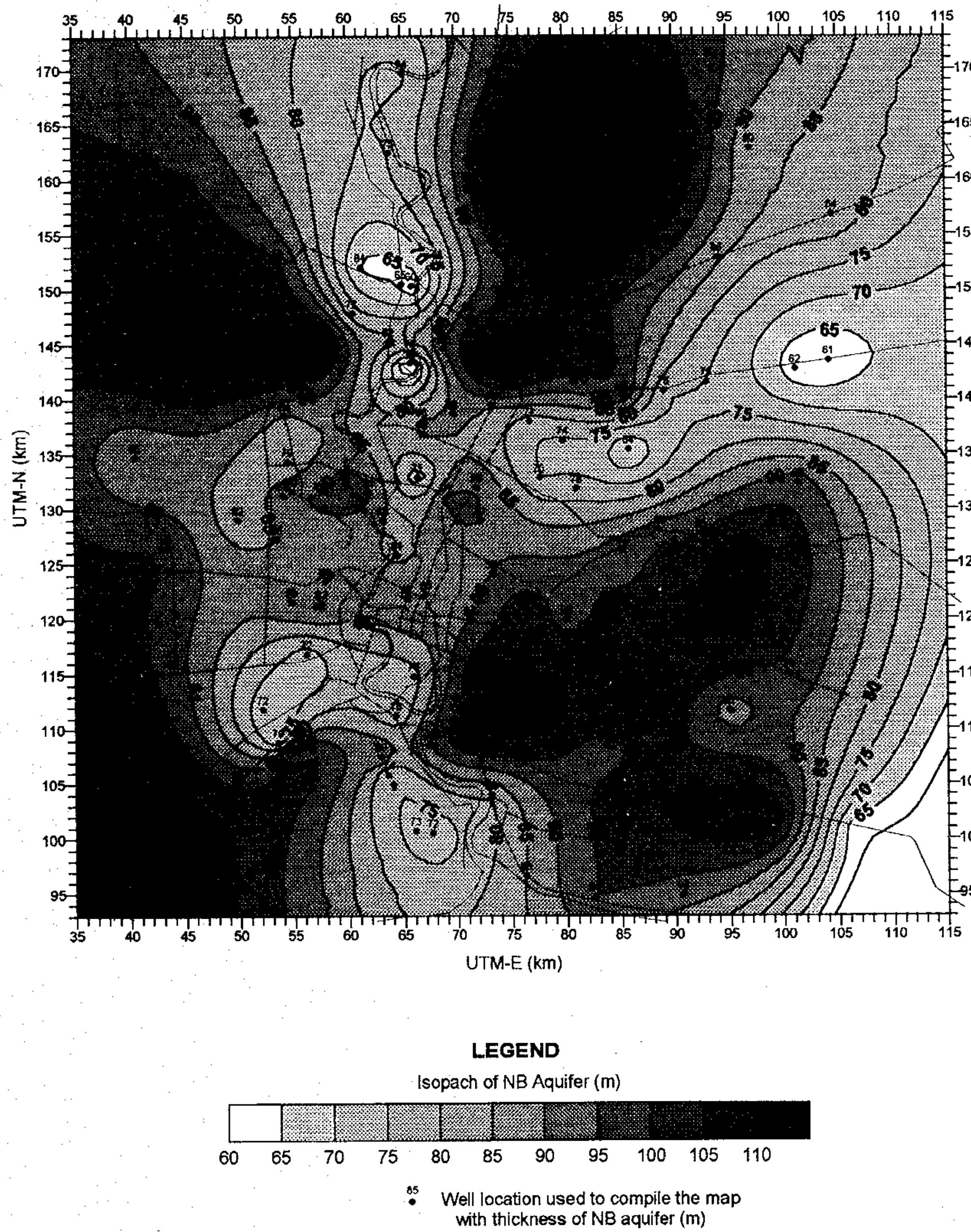

Figure 7.4.8	ISOPACH MAP OF NB AQUIFER
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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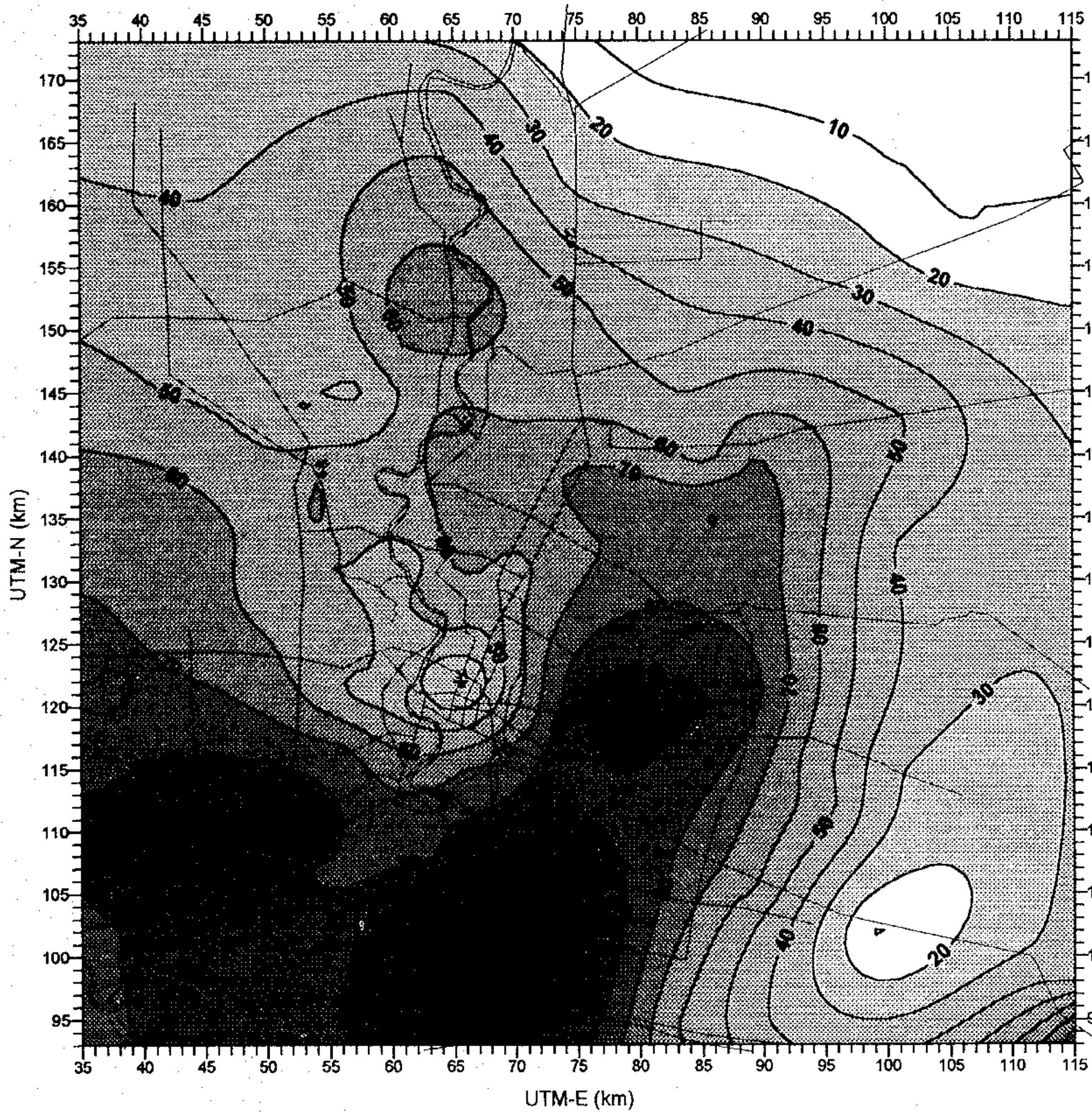

LEGEND

Isopach of SK Aquifer (m)

10 20 30 40 50 60 70 80 90 100 110

Well location used to compile the map with thickness of SK aquifer (m)

Figure 7.4.9	**ISOPACH MAP OF SK AQUIFER**
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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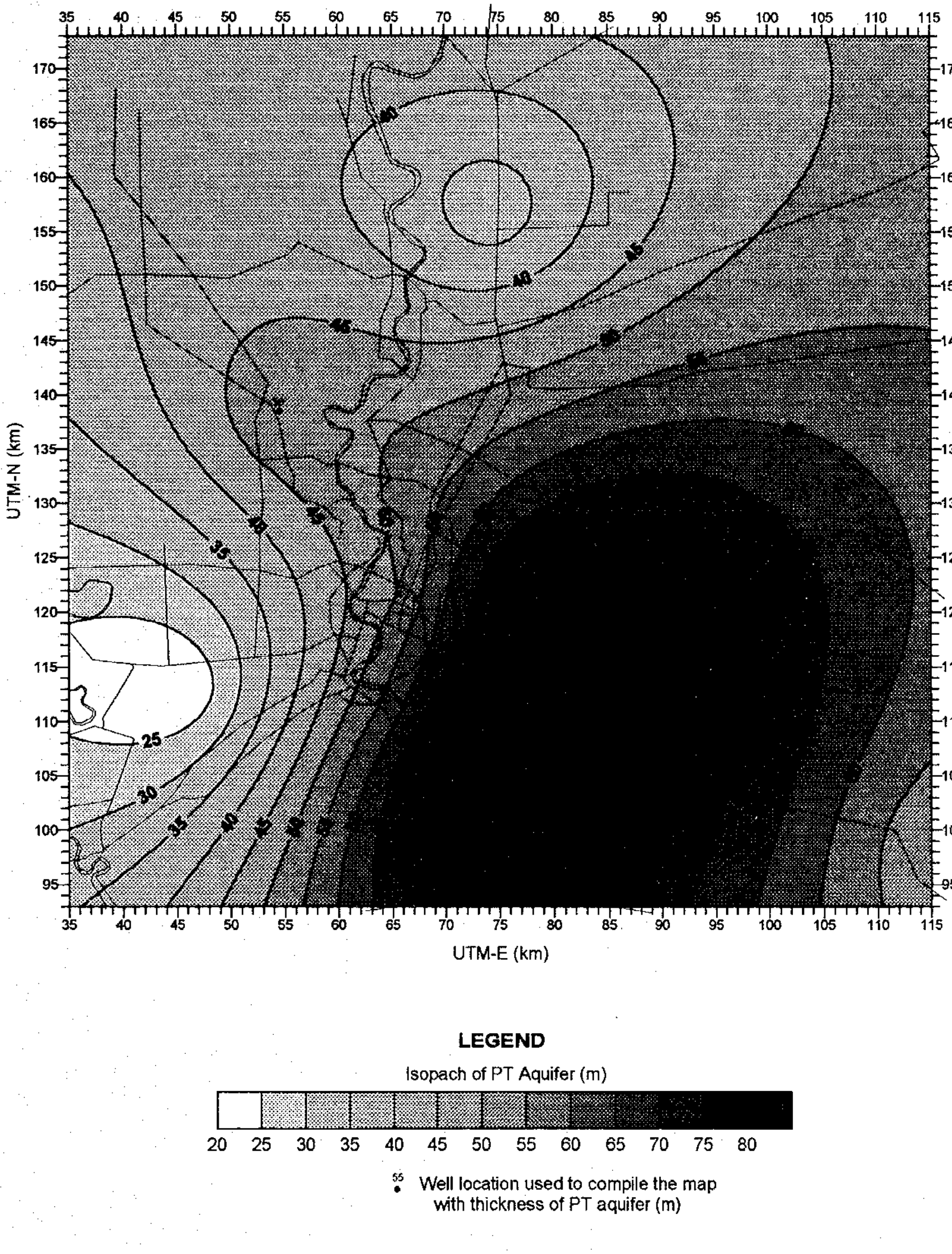

Figure 7.4.10	ISOPACH MAP OF PT AQUIFER
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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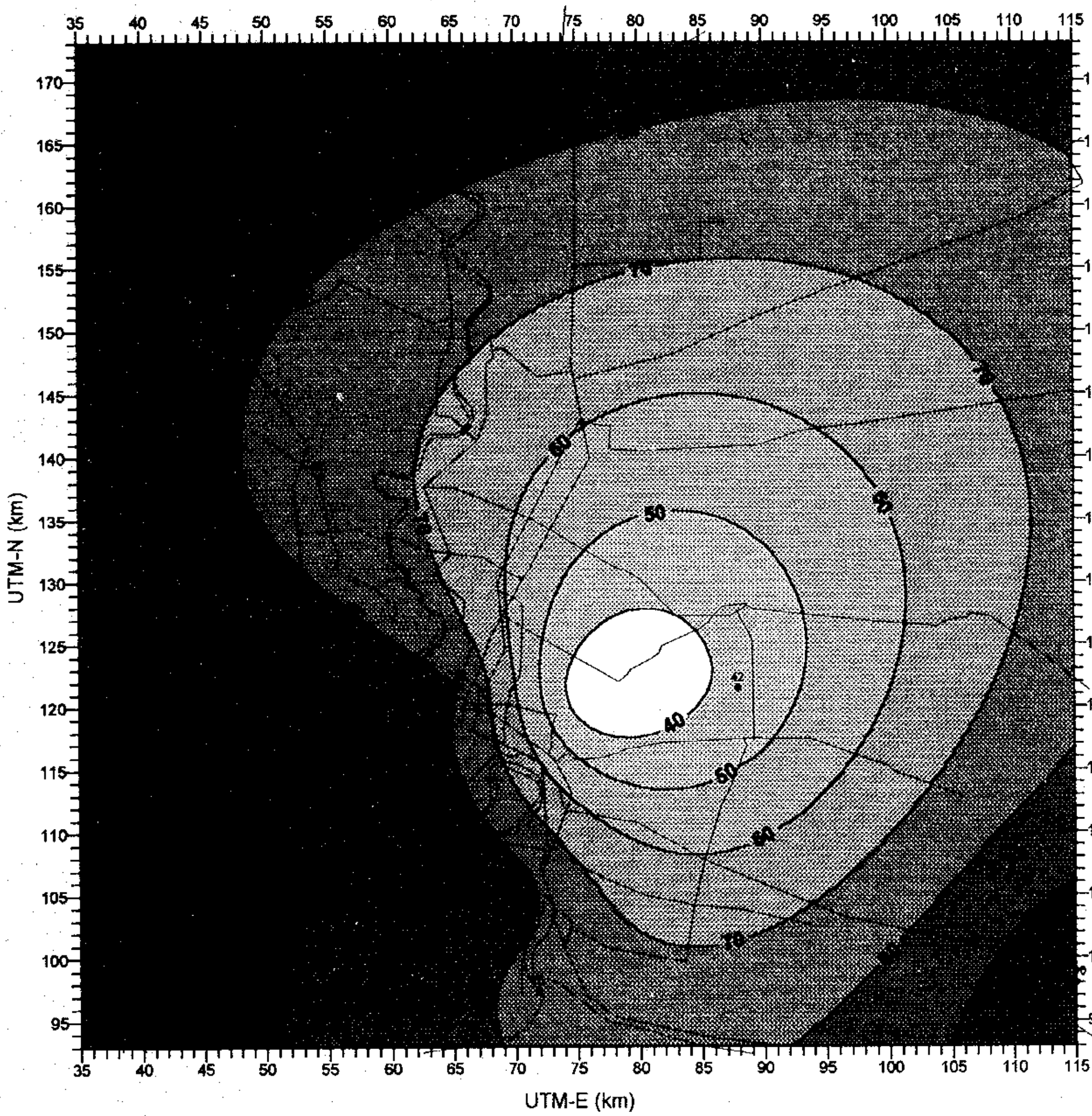

LEGEND

Isopach of TB Aquifer (m)

30 40 50 60 70 80 90 100

65 Well location used to compile the map with thickness of TB aquifer (m)

Figure 7.4.11	ISOPACH MAP OF TB AQUIFER
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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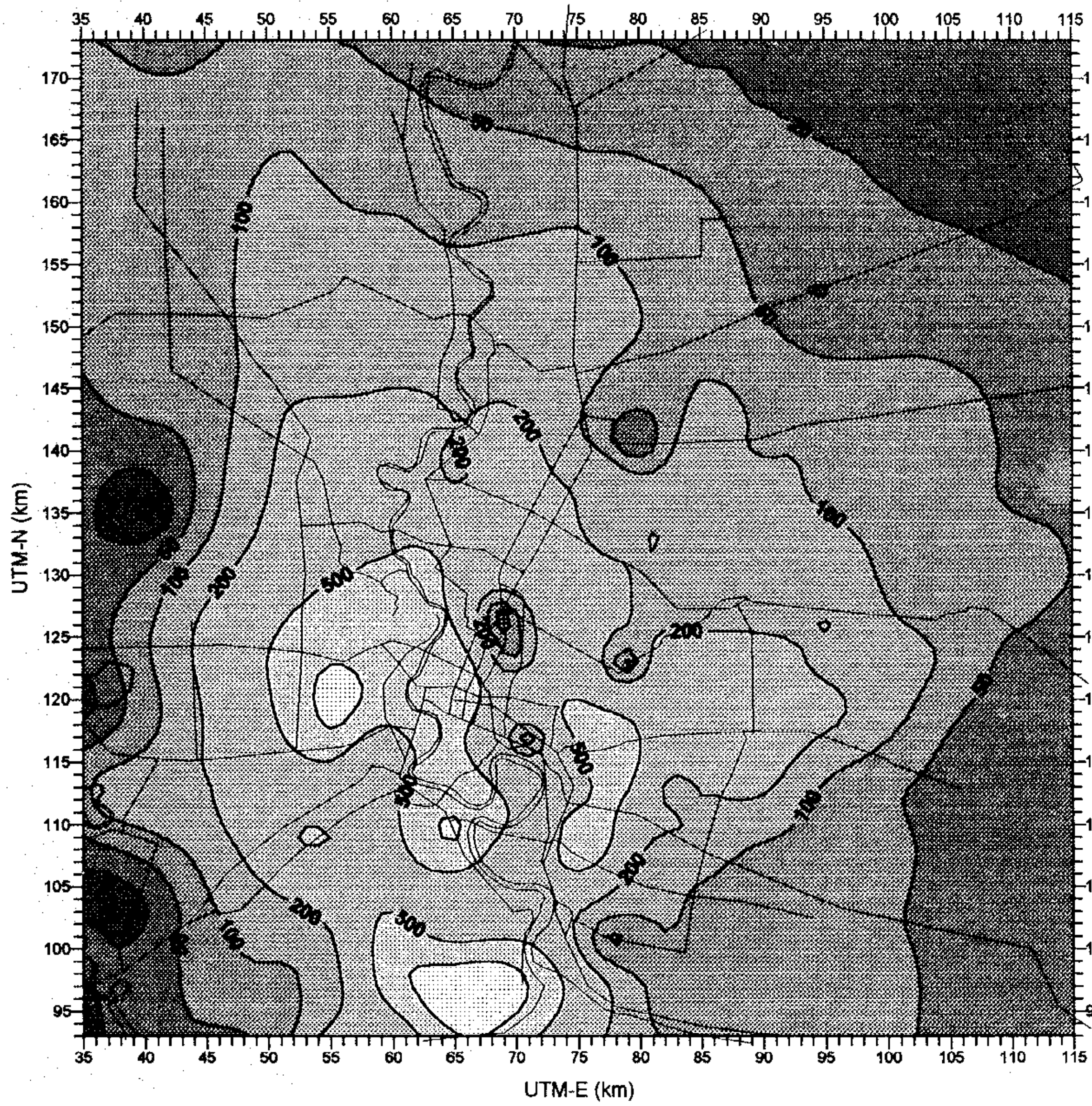

LEGEND

Estimated Transmissivity of BK Aquifer (m^2/d)

20 50 100 200 500 1000 2000

(Estimated transmissivity) = (estimated permeability) x (isopach) x [100 - (clay content)] / 100

Figure 7.4.12	ESTIMATED TRANSMISSIVITY OF BK AQUIFER
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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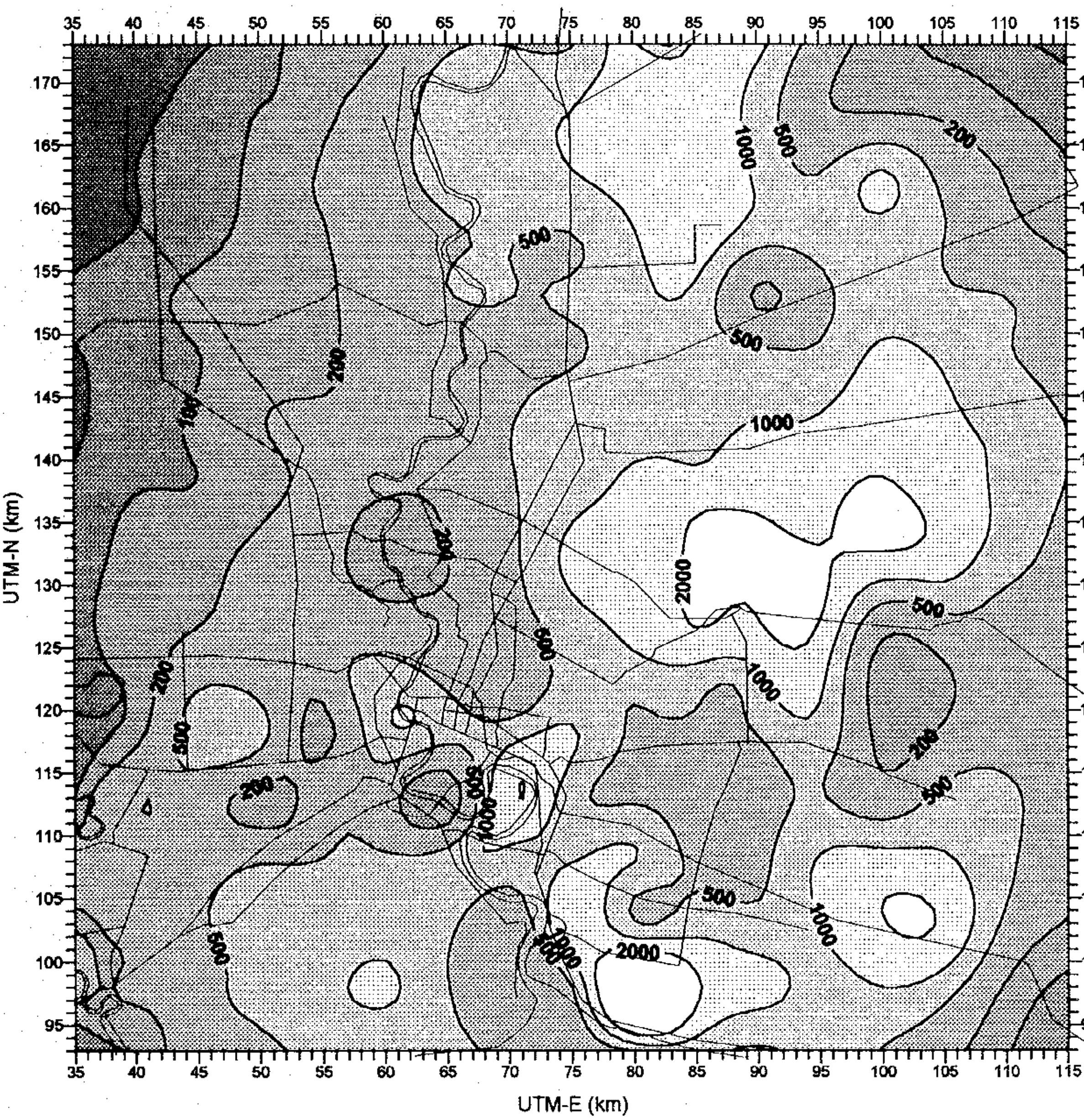

LEGEND

Estimated Transmissivity of PD Aquifer (m^2/d)

	20	50	100	200	500	1000	2000

(Estimated transmissivity) = (estimated permeability) x (isopach) x [100 - (clay content)] / 100

Figure 7.4.13	**ESTIMATED TRANSMISSIVITY OF PD AQUIFER**
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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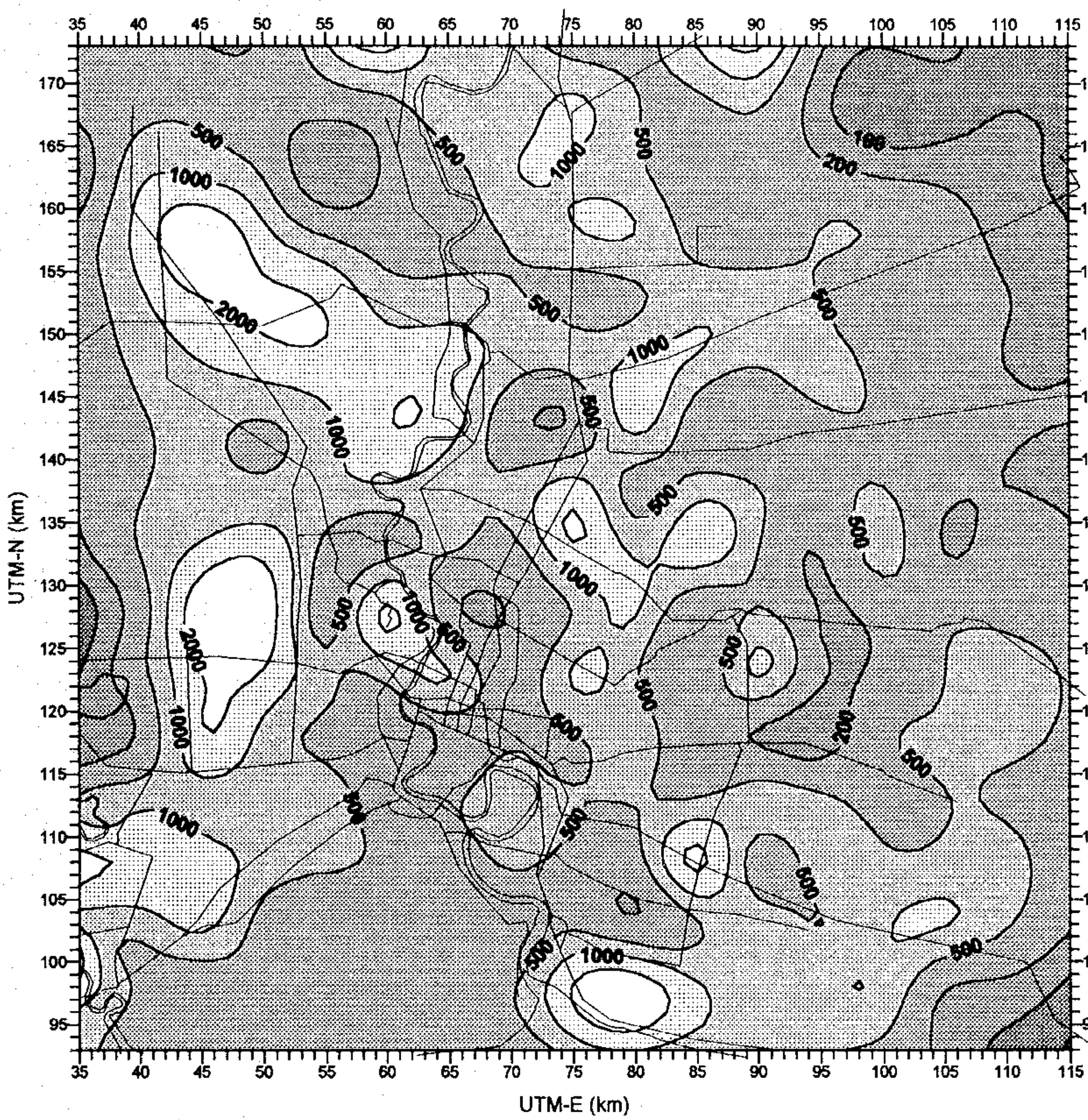

LEGEND

Estimated Transmissivity of NL Aquifer (m^2 /d)

	20	50	100	200	500	1000	2000

(Estimated transmissivity) = (estimated permeability) x (isopach) x [100 - (clay content)] / 100

Figure 7.4.14	**ESTIMATED TRANSMISSIVITY OF NL AQUIFER**
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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