7.5 Model Calibration

7.5.1 Calibration of 3-D Model

(1) Preparation of pumpage data

Groundwater pumpage is one of the most important parameters for the simulation. The historical pumpage data of Case-2, which were estimated from the database prepared by the Study Team as mentioned in Chapter 5.3, were used for the model calibration. Each production well can be located on the 1 km x 1 km grid system from its UTM coordinates. Then, the pumpage of each model grid was computed horizontally by well location. The pumpage data cover not only the Study Area but also the whole seven (7) provinces.

Vertical distribution of the pumpage was carefully examined because it is very important for the 3-D model. The tapped aquifer(s) of each well was identified from its screen depth(s) or well depth by comparing with the bottom depth of each aquifer unit at the grid. If the well does not have the data of screen depth(s) and well depth, the tapped aquifer was estimated from the other wells located in the same grid. No wells extract groundwater from UC and BC layers. In case the well tapped two (2) or more aquifers, the pumpage was divided by the number of tapped aquifers and then distributed into each aquifer unit at the location.

A yearly pumpage data file and a quarterly data file covering the period from 1983 to 1992 were prepared for the model calibration. The yearly data were used for the piezometric level calibration and the quarterly data were used for the calibrations of piezometric level and land subsidence. For preparing the quarterly pumpage data, the quarterly groundwater pumpage coefficients (QGPC) by type of user were used. The exact date of issuance of water permits for each private well was also considered.

The QGPC values were obtained from the wells having monthly pumpage data measured by flow meter. The average values of QGPC by user type are given in Table 7.5.1.

Table 7.5.1 AVERAGE VALUES OF QUARTERLY GROUNDWATER PUMPAGE COEFFICIENTS (QGPC)

Type of User	Quarter 1 (Jan-Mar)	Quarter 2 (Apr-Jun)	Quarter 3 (Jul-Sep)	Quarter 4 (Oct-Dec)
PRIVATE WELLS				
Domestic	1.053	0.965	1.049	0.933
Institutional	1.088	0.972	0.964	0.976
Commercial	1.032	1.052	0.960	0.956
Industrial	0.989	1.027	0.993	0.991
PUBLIC WELLS	0.999	1.024	0.993	0.984

(Annual average pumpage = 1.000)

The QGPC values are generally higher in the first quarter and the second quarter, indicating that the pumpage in the dry season is larger than that in the rainy season.

Figures 7.5.1 shows the historical pumpage in the Study Area by aquifer unit from 1983 to 1992. The pumpage from NL Aquifer is the largest throughout the period, that is 553,009 m3/day in 1983 and 640,850 m3/day in 1992. However, the percentage of NL Aquifer to the total pumpage decreased from 49.51% in 1983 to 43.27% in 1992. This is mainly due to the reduction of the MWA pumpage. The pumpage from NB Aquifer is second largest, having 289,930 m3/day (25.96%) in 1983 and 396,054 m3/day (26.74%) in 1992. This pumpage also decreased from 1985 to 1986 due to the reduction of the number of MWA wells. It is noted that the rate of pumpage from deeper aquifers have significantly increased from 1983 to 1992. For instance, the pumpage from SK Aquifer increased from 11,559 m3/day (1.03%) to 55,257 m3/day (3.73%) from 1983 to 1992. This indicates that the groundwater exploitation from the deeper aquifers has grown over the decade.

Figure 7.5.2 and Figure 7.5.3 show the distribution of groundwater pumpage from PD Aquifer in 1983 and 1992, respectively. Heavily pumped grids can be seen from both figures along the Chao Phraya River in Samut Prakan. Numbers of pumped grids have increased in the eastern parts of Samut Prakan, Bangkok, and Pathum Thani. The distribution of pumpage from NL Aquifer in 1983 (Figure 7.5.4) indicates that the pumpage was concentrated in the central part of Bangkok in 1983. But by 1992, the heavily pumped grids spread to wide areas in Samut Prakan, eastern Bangkok, Pathum Thani, and Samut Sakhon (Figure 7.5.5). However, the pumpage in central Bangkok has decreased due to the phase-out of the MWA wells. The groundwater of NB Aquifer was mainly used in the central part of Bangkok, Nonthaburi, and Pathum Thani in 1983 (Figure 7.5.6). After a decade, heavily pumped area spread to Pathum Thani, eastern Bangkok, Samut Prakan, and Samut Sakhon (Figure 7.5.7).

(2) Steady-state heads calibration

The steady-state calibration was carried out prior to the historical calibration. The purposes of the steady-state calibration are to understand model behavior, to check boundary conditions, to estimate approximate values of assumed hydrogeological parameters, and to generate initial piezometric heads at the beginning of 1983 for each aquifer unit. The pumpage data in 1983 were used for the steady-state calibration.

A duration of 30 years was taken for the steady-state simulation using the constant pumpage rate with a time step of three (3) years. The reason for using the 30-year period is that intensive groundwater development in the Study Area could have started from the 1950s. The initial piezometric heads for the steady-state calibration were given as the ground elevation for UC and BC layers and 0 m in elevation for the other layers.

During the calibration, the constant head boundaries were extended to the upstream areas of BK to NB layers where each layer occurred just below the ground surface. The cells in this area were previously identified as the recharge cells, but due to lack of data and variation of the vertical hydraulic conductivity, the recharge rate was only assumed. The initial piezometric levels at these cells were likewise assumed to be the same levels as the ground surface. The values of vertical hydraulic conductivity, which is also one of the assumed parameters in the Study Area, were modified. On the other hand, the hydraulic conductivity and specific capacity remained at their originally estimated values.

As a result, it was found out that the computed heads of BC to TB layers were almost stable within the first three (3) steps (= 9 years) starting from the initial piezometric heads. Meanwhile, the heads of PN layer continue to decline even though the declining rate is small. This is due to the small vertical hydraulic conductivity of PN layer that allows small amount of upward leakage. The computed piezometric heads reasonably matched the observed piezometric heads. The computed heads were then used as the initial heads for the historical calibration.

(3) Historical heads calibration

The annual historical pumpage data from 1983 to 1992 were input to the model. During the historical calibration, computed piezometric heads were carefully compared with the observed heads. Then, the values of vertical hydraulic conductivity were modified by the trial-and-error method. The values of other parameters such as hydraulic conductivity and specific storage were not modified because if several parameters were modified at the same time, the effect of each parameter change cannot be identified.

After modifying the parameters, the historical simulation was re-run together with the steady-state simulation because the parameter change affected the initial piezometric heads for the historical simulation. Therefore, simulation of 20 time steps, which consists of 10 time steps of steady-state simulation (1 time step = 3 years) and 10 time steps of historical simulation (1 time step = 1 year), was carried out.

The calibration of the 3-D model is a complicated task because even if only one (1) parameter value of a cell is modified, both the piezometric heads of the horizontal and vertical surrounding cells will also be affected. The pumpage distribution of each aquifer unit near the cell and the possible range of variation of the parameter must also be considered. The process is like a complex puzzle so that a logical calibration procedure is necessary. About 30 DMR monitoring stations were selected to carry out a realistic simulation by considering the monitoring period and location. Then, reasonable parameter values were identified from the upper to the lower aquifer units with the top layer being maintained as the constant head boundary. Several historical simulations were made before the observed and the computed heads at most of the points were in good agreement with each other.

Later, it was found out that modifying only the vertical hydraulic conductivity resulted into the matching of the computed heads with the observed heads. This means that the originally input parameters of hydraulic conductivity and specific storage of each aquifer unit were reasonably estimated. There were some monitoring stations where the computed heads did not match the observed heads. Several factors could have contributed to this such as, screen position of the monitoring well is not exactly located at the aquifer unit, some problems in the well structure, influence of nearby pumpage, difference between actual and estimated pumpage, etc. In these cases, even if the hydraulic conductivity and/or specific storage were modified, the computed heads did not match the observed heads. It was noted that the accuracy of pumpage data greatly affected the simulation results, especially in the piezometric level changes. Several cases were made to estimate groundwater pumpage in the Study Area. Case-2 estimation, which was used for the model calibration, is considered the best estimate for the Study Area based on the result of the simulation.

Finally, the 50 time steps historical calibration was carried out by inputting the quarterly pumpage data. The simulation consisted of 10 time steps of steady-state simulation (1 time step = 3 years) and 40 time steps of historical simulation (1 time step = 91.25 days). The pumpage of the first quarter in 1983 was input to the first 10 time steps. The quarterly pumpage data from 1983 to 1992 were later used from the 11th step to the 50th step.

Figure 7.5.8 shows the comparisons between the simulated piezometric heads by the 50 time steps historical calibration and the observed piezometric heads at the DMR monitoring stations. The computed heads were reasonably simulated at the stations. The recoveries of piezometric levels at ST005 and ST055 were also revived by the model. Figures 7.5.9 to 7.5.11 show the comparisons between the simulated and observed heads of PD, NL, and NB Aquifers at the end of 1992.

Figure 7.5.12 shows the simulated piezometric heads in the modeled area from BC layer to SK layer in 1992. The piezometric head of BC layer ranges from 0 to -10 masl. The depression of piezometric head in BK layer is located in southern part of the Study Area, ranging from -15 to -20 masl. Two (2) large depressions can be seen in NL and NB layers; one is located from Samut Prakan to Pathum Thani and the other is located in Samut Sakhon. In SK layer, the center of depression is located in Pathum Thani.

(4) Land subsidence calibration

The quarterly computed piezometric heads from 1983 to 1992 were used for the land subsidence model. It is important for land subsidence simulation to input quarterly piezometric heads data because in case of cyclic loading and unloading, the volume compressibility changes during the consolidation process. From the results of the consolidation tests, the volume compressibility at the time of unloading (m_v') is only about 1/5 to 1/20 of that at the time of loading (m_v). Therefore, the logarithmic average value of m_v and the typical value of the m_v / m_v' ratio of each clay were input to the model. The thickness of clay layer in each aquifer unit was given by each model grid from the isopach map and the clay content map of the aquifer unit.

During the calibration, the computed compression of each clay layer and the total computed land subsidence were checked. The changes in computed piezometric heads were also carefully examined to identify the parameters because any change greatly affects the computed compression. After several calibration trials, the values of m_v and m_v / m_v' were identified as shown in Table 7.5.2.

Table 7.5.2 IDENTIFIED VALUES OF m_v AND m_v / m_v'

Clay Layer	m_v	m_v / m_v'
BC	6.75E-02	20.0
BK	7.70E-03	10.0
PD	2.12E-03	10.0
NL	1.25E-03	10.0
NB	6.72E-04	10.0
SK	4.83E-04	5.0
PT	4.00E-04	5.0
TB	3.00E-04	5.0
PN	2.35E-04	5.0

It was found out that the identified m_v and m_v / m_v' satisfied the calibration without modifying the thickness of clay layers and without considering regional variation of m_v and

m_v / m_v' values. Figure 7.5.13 shows the simulated land subsidence from 1983 to 1992. The actual land subsidence values for the period were not available because the RTSD did not conduct leveling survey from 1982 to 1984. However, the model can compute reasonable distribution of land subsidence which can be compared to the observed land subsidence distribution.

(5) Water balance

Water balance in the Study Area was examined based on the result of the historical heads calibration. The MODFLOW can compute storage change, recharge from constant head, horizontal and vertical exchange, and well discharge in the specified area for each aquifer unit. Figure 7.5.14 shows the water balance in 1992.

Because the model assumes constant head in UC layer, the recharge from UC layer to BC layer is computed as 1,133,152 m^3/day. Considering the area, average recharge in the Study Area is computed as 64.6 mm/year, which is 4.3% of mean annual rainfall (= 1501.3 mm) at Bangkok Metropolis.

The storage change in BC layer is -473 m^3/day even though no wells are pumping from the layer. The negative sign of storage change indicates that the piezometric level has declined since the previous year. The decline of piezometric level was caused by the downward leakage.

The inflow to BK layer is 1,133,626 m^3/day from BC layer, 4,728 m^3/day from outside of the Study Area, and 2 m^3/day from PD layer. However, the storage change is -4,147 m^3/day due to pumpage (33,713 m^3/day), lower exchange (1,107,571 m^3/day), and horizontal outflow (1,217 m^3/day). The total inflow to PD layer is 1,141,467 m^3/day, consisting of recharge from upper layer (1,107,571 m^3/day, 97.0% of the total amount), horizontal inflow (30,845 m^3/day, 2.7%), and recharge from lower layer (3,015 m^3/day, 0.3%).

The groundwater pumpage from NL layer is the largest, occupying 43.3% of total pumpage. This results larger downward leakage in upper layers and larger upward leakage in lower layers. However, the storage change in NB layer (-32,239 m^3/day) is more serious than that in NL layer (-21,211 m^3/day). It is noted that the positive sign of storage change indicates the piezometric levels in some parts of the layer have been recovered since the previous year.

In deeper layers such as PT, TB and PN layers, the amounts of storage decreased are larger than pumpage. This indicates that the decline of piezometric levels are caused by not only pumpage but also upward leakage toward the main aquifers.

Table 7.5.3 summarizes the water balance in the Study Area in 1992. The table shows that the pumped groundwater is originated from storage change in layers, recharge from constant head (= ground surface), and inflow from the outside area. The percentages of those contributions are; storage change 9.2%, recharge from constant head 76.5%, and horizontal inflow 14.3%.

Table 7.5.3 SUMMARY OF WATER BALANCE IN THE STUDY AREA IN 1992

	IN (m^3/day)	OUT (m^3/day)	IN - OUT (m^3/day)
Storage	135,955	34	135,921
Constant head	1,133,152	0	1,133,152
Horiz. exchange	216,362	4,373	211,989
Exchange (upper)	4,568,596	210,303	4,367,294
Exchange (lower)	201,303	4,568,596	-4,367,294
Pumpage	0	1,481,062	-1,481,062
Sum of the layers	6,255,368	6,255,368	0

(6) Volume of groundwater

Volume of groundwater in the Study Area was estimated from volume of layer, clay content and effective porosity. Table 7.5.4 shows the result of estimation. For this estimation, the layers up to -600 m in elevation were taken into account.

Total volume of each aquifer unit can be computed from each isopach map. Total volume of layers was computed as 3,852,720 MCM. Then, volume of sandy layers and clayey layers in the aquifer unit was computed using the clay content map. The clay content of BC layer was assumed to be 100%. The total volume of sandy layers and clayey layers was estimated as 1,955,368 MCM and 1,897,352 MCM, respectively.

If the layer is saturated with groundwater, the volume of groundwater can be estimated by volume of the layer and its effective porosity. Typical values of effective porosity by geologic facies are given by Linsley et al. (1958). Based on the typical values, the effective porosity of sandy layer and clayey layer was assumed to be 0.20 and 0.03, respectively.

As a result, the total volume of groundwater in the Study Area is estimated as 447,994 MCM. The estimated volume of groundwater in PD, NL, and NB layers is 53,026 MCM, 56,339 MCM, and 59,544 MCM, respectively. The estimated groundwater volume is quite larger than the present pumpage (= 540.6 MCM/year in 1992). However, it is impossible to use all the volume from technical and socio-economical points of view.

7.5.2 Calibration of Vertical 2-D Land Subsidence Model

(1) Preparation of pumpage data

The historical pumpage data of Case-2 were used for the calibration. For the horizontal assignment of pumpage to the model, the relationship between the location of the model grid and the UTM 1 km x 1 km grid system was checked. Then a data file was prepared to correlate each model grid to the 1 km x 1 km grid locations. Based on the data file, historical pumpage data for the model were arranged by aquifer unit from the original pumpage data files using the UTM grid system.

Since the vertical model has several cells in an aquifer unit arranged vertically, one (1) assumption is to distribute the pumpage of the aquifer unit to each cell. If wells do not have screen depth(s) data, the pumped cells cannot be properly identified. Likewise, if a well has a long screen or several screens, equal amount of pumpage cannot be assigned to the corresponding cells. The piezometric heads at the cells having small hydraulic conductivity, such as clay cells, will drop significantly causing unrealistic large amount of compression during the subsidence simulation.

It is necessary, therefore, that the pumpage be distributed to each cell by considering each cell's hydraulic conductivity. Another assumption is that the pumpage from a cell is proportional to the hydraulic conductivity of the cell. For example, if the aquifer unit consists of two (2) cells having 100 m/day and 50m/day, the total pumpage of 300 m^3/day is proportioned into 200 m^3/day and 100 m^3/day, which will then be input to the cells. During the model calibration, the pumpage data were recalculated after modifying the hydraulic conductivity.

Figure 7.5.15 shows the distribution of pumpage in 1992. The pumpage from NL Aquifer is significant in the model domain. Pumpage from PD Aquifer is mainly distributed in the southern part. No pumped cells are found below NB Aquifer.

(2) Historical heads calibration

The historical calibration of 50 time steps was carried out using the quarterly pumpage data from 1983 to 1992. The first 10 steps (1 time step = 3 years) are steady-state calculation using the first quarterly pumpage data in 1983. The historical calibration is from the 11th step to the 50th step where the quarterly pumpage data from 1983 to 1992 were inputted.

During the calibration, the horizontal hydraulic conductivity and the ratio of the vertical to the horizontal hydraulic conductivity were modified. Specific storage values at (sand + clay) cells, sand cells, and (sand + gravel) cells were given from the typical value of storage coefficient considering the thickness of the cells. At clay cells, the values of specific storage were estimated from their volume compressibility values by aquifer unit. The specific storage values were not modified from the beginning of calibration.

After several trials, the computed heads were in good agreement with the observed heads without modifying the specific storage. It was understood that the hydraulic conductivity at clay cells affects the vertical distribution of piezometric heads.

Figure 7.5.16 shows the simulated piezometric heads in 1992. The heads below -50 masl are distributed in PD, NL, and NB Aquifers. No pumpage is distributed in the Bangkok Soft Clay (BSC) and BK Aquifer. However, the piezometric levels declined due to the downward leakage. The simulated piezometric head in BSC layer was in good agreement with the actual distribution of pore water pressure measured at Site-A (Column No. = 29). The simulated piezometric heads in PT and TB Aquifers near Site-A are about -20 masl which matched the observed piezometric heads. The lowering of piezometric heads is due to the upward leakage because only (sand + clay) cells, without clay cells, are distributed in the aquifers. Therefore, the groundwater can easily move upward.

It is noted that the higher piezometric heads are still remaining in the clay cells in the main aquifers due to the small hydraulic conductivity. However, they will gradually decline in the future even if the pumpage is maintained at constant amount. This will cause continuous compression of the clay.

(3) Land subsidence calibration

The computed quarterly piezometric heads from the calibrated model were used for the subsidence calibration. Volume compressibility values at (sand + clay) cells were assumed to be 1/2 of clay cells in the aquifer unit. For BC clay, logarithmic average values of m_v analyzed by an interval of 5m depth were input to the model. The ratios of m_v / m_v' were input based on the typical values from the consolidation tests.

As a result, the computed land subsidence was reasonably simulated without modifying the initial input parameters. Figure 7.5.17 shows the simulated compression from 1983 to 1992. Higher compression of more than 0.6 cm/m can be found in BSC and BK layers. The compression in the upper portion of BSC layer is small because the top of the layer is assigned as the constant head boundary. The compression values are controlled not only by the volume compressibility but also by the changes in piezometric head. Therefore, the simulated compression in BK layer is larger than that in BSC layer. The compression in PD and NL layers ranges from 0.1 cm/m to 0.4 cm/m. The maximum compression in NB and SK layers does not exceed 0.2 cm/m. The compression of more than 0.1 cm/m cannot be seen from PT to PN layers.

Figure 7.5.18 shows the results of land subsidence simulation. The simulated maximum land subsidence from 1983 to 1992 is 52.1 cm at near Minburi, Bangkok (Column No. = 27). At Site-A, the simulated land subsidence is 44.9 cm for the said period. The values of total subsidence mainly depend on the compression of BSC and BK layers. The simulated land subsidence at Site-A over time is shown in the lower graph of Figure 7.5.18. The compression of BSC and BK layers occupies 48% of the total subsidence, that is almost the same ratio as the actual value.

7.5.3 Calibration of Vertical 2-D Solute Transport Model

(1) Preparation of pumpage data

The historical pumpage data of Case-2 were used for the calibration. The method of data preparation is the same as mentioned in Section 7.5.2. For the model calibration, yearly pumpage data were prepared from 1983 to 1992. The cell by cell pumpage was recalculated after modifying hydraulic conductivity during the model calibration.

Figure 7.5.19 shows the distribution of groundwater pumpage in 1992. The wells become deeper going toward north. BK and PD layers are the main aquifers in the southern portion of the modeled area. In the central part, the pumped cells are mainly located in NL and NB Aquifers. In Pathum Thani, NB and SK layers are the main aquifers.

(2) Historical heads calibration

The piezometric heads calibration is still very important for the solute transport model, because the model computes changes in concentration based on the groundwater flow. The heads calibration was carried out using the MODFLOW program.

The historical calibration of 20 time steps was carried out using the yearly pumpage data from 1983 to 1992. The first 10 steps (1 time step = 3 years) are steady-state calculation using the pumpage data in 1983. The historical calibration is from the 11th step to the 20th step where the yearly pumpage data from 1983 to 1992 were inputted. During the calibration, the values of hydraulic conductivity and the ratio of the vertical to the horizontal hydraulic conductivity were modified. The specific storage values were given by the same method mentioned in Section 7.5.2.

After several trials, the computed heads were in good agreement with the observed heads without modifying specific storage. It was again understood that the hydraulic conductivity at clay cells affected the vertical distribution of piezometric heads.

Figure 7.5.20 shows the simulated piezometric heads in 1992. The depression of piezometric head is located at NB and SK Aquifers in Pathum Thani, showing below -50 masl. The piezometric head of NL Aquifer below -30 masl is distributed in Pathum Thani and Bangkok.

(3) Solute transport calibration

The process of sea water intrusion follows the Ghyben-Herzberg principle. At first, the distribution of chloride ion concentration in the steady-state conditions without pumpage was simulated by the MOCDENSE program, which can simulate two-dimensional density-dependent flow. In this simulation, the southern margin of the model grid (Column No. = 43) was assumed to be the Gulf of Thailand. From the top to the bottom of the grid, the Cl^- concentration and density of sea water, which are 35,000 mg/L and 1.025 g/cm^3, respectively, were uniformly assigned. The top layer of the grids located in the marsh near the shore line (Column No. 40 to 42) was assumed to have 30,000 mg/L in Cl^- concentration. The concentration of 100 mg/L in Cl^- concentration was given to the rest of the model cells. The hydraulic conductivity values (L/T) identified from the historical heads calibration were converted into the values of intrinsic permeability (L2). The initial piezometric heads were also converted into the initial fluid pressures considering the density of the saline water. The top layer and the southern column of the model are the constant boundary for the fluid pressure and the Cl^- concentration.

Figure 7.5.21 shows the simulated Cl^- concentration by the steady-state simulation. The tongue of salt water entering from the right can be simulated as similar to the Ghyben-Herzberg relation. The transition zone between fresh water and salt water is simulated wider because longitudinal dispersivity was assumed to be 30.48 m. The result shows that the isochlor line of 10,000 mg/L enters 14 km from the shore line in NL and NB Aquifers. The line of 20,000 mg/L is located 9 km from the sea.

The MT3D program was used to simulate historical Cl^- concentration. The density flow cannot be simulated by MT3D. However, since the observed groundwater flow system is highly disturbed by the pumpage, it can be assumed when using MT3D that the movement of saline water is mainly dependent on the groundwater flow caused by the pumpage. The simulated Cl^- concentration by MOCDENSE shown in Figure 7.5.21 was used as the initial concentration for the simulation. Figure 7.5.22 shows the simulated Cl^- concentration in 1992 after the 20 time steps simulation. The saline water in NB and SK Aquifers further moves toward north. The saline water in BK, PD, and NL Aquifers do not move inland because the saline groundwater is extracted by the wells which tapped at the aquifers. As a result, the actual occurrence of saline water in the inland area such as Nonthaburi and

Pathum Thani cannot be explained by the model situation, which assumes that the origin of saline water is sea water.

Therefore, the following two (2) cases were prepared to simulate the occurrence of saline water in the inland area:

Case-1: Source of saline water is the Chao Phraya River Water
Case-2: Source of saline water is the Bangkok Soft Clay

Case-1 is based on the fact that the Chao Phraya River is a tidal river. The basis of Case-2 is that the salt content of Bangkok Soft Clay is high. According to the results of core analyses, the shallow soils up to a depth around 50 m have high chloride content. The results of microfossil analyses conforms with Case-2 because the depositional environment of the Bangkok Soft Clay is estimated as the marginal sea environment. It was confirmed at the JICA monitoring stations that no fossil water occurs in the deeper portions.

For Case-1 simulation, constant Cl^- concentration values ranging from 2,000 mg/L to 10,000 mg/L were given to the top cells where the Chao Phraya River is located. The top cells at the Gulf of Thailand and the marsh near the shore line have the same Cl^- concentration values of the MOCDENSE simulation model. The initial Cl^- concentration from Layers No. 2 to 41 is given as 100 mg/L.

Figure 7.5.23 shows the simulated Cl^- concentration in 1992 by Case-1. The saline water mainly moves downward from top cells where the Chao Phraya River is located. The movement is controlled by the layer facies and groundwater flow, however, the occurrence of saline water is limited near the river course. The result of Case-1 simulation cannot match the actual wide distribution of saline water in the inland area.

For Case-2 simulation, constant Cl^- concentration values ranging from 2,000 mg/L to 10,000 mg/L were given to the Bangkok Soft Clay layer. The top cells at the Gulf of Thailand and the marsh near the shore line have the same Cl^- concentration values of the MOCDENSE simulation model. The initial Cl^- concentration from BK layer to TB layer is given as 100 mg/L.

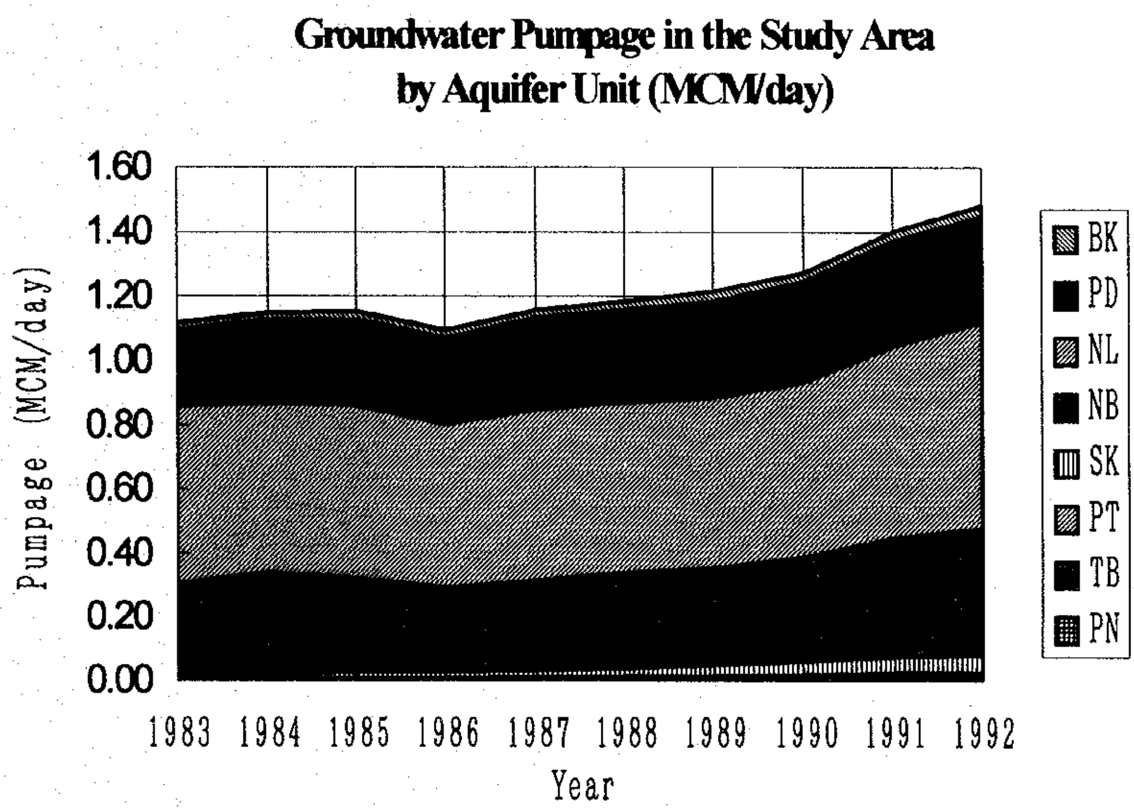
The simulated Cl^- concentration in 1992 is shown in Figure 7.5.24. The simulated distribution pattern of saline water in the inland area is similar to the observed saline water distribution. The affected area by saline water decreases with increasing depth. The saline water mainly moves downward following the groundwater flow direction, but controlled by the hydrogeological structures and the screen locations of pumping wells.

It is concluded from the simulation results that there are two (2) sources of saline water in the Study Area. One (1) is the sea water from the Gulf of Thailand, and the other is from the Bangkok Soft Clay. The sea water intrusion occurred in the Study Area, but the affected area is limited within about 20 km from the shore line. The mechanism of saline water occurrence in the inland area can be explained by the simulation model, assuming that the saline water originates from the Bangkok Soft Clay. The results of the simulation were in good agreement with not only the actual distribution of saline water but also with the difference in chemical composition of saline water between the inland area and the coastal area.

Table 7.5.4 VOLUME OF LAYER AND GROUNDWATER IN THE STUDY AREA

Aquifer unit	Volume of layer						Volume of groundwater			
	Total (MCM)	(%)	Sand (MCM)	(%)	Clay (MCM)	(%)	Sand* (MCM)	Clay** (MCM)	Total (MCM)	(%)
BC	88476	2.30	0	0.00	88476	4.66	0	2654	2654	0.59
BK	234133	6.08	137337	7.02	96796	5.10	27467	2904	30371	6.78
PD	395625	10.27	242104	12.38	153521	8.09	48421	4606	53026	11.84
NL	406888	10.56	259604	13.28	147285	7.76	51921	4419	56339	12.58
NB	563645	14.63	250791	12.83	312854	16.49	50158	9386	59544	13.29
SK	334411	8.68	185770	9.50	148641	7.83	37154	4459	41613	9.29
PT	330373	8.58	175696	8.99	154676	8.15	35139	4640	39780	8.88
TB	477482	12.39	193221	9.88	284261	14.98	38644	8528	47172	10.53
PN	1021687	26.52	510845	26.13	510842	26.92	102169	15325	117494	26.23
Total	3852720	100.00	1955368	100.00	1897352	100.00	391074	56921	447994	100.00

* Effective porosity of sandy layers is assumed to be 0.20.
** Effective porosity of clayey layers is assumed to be 0.03.



GROUNDWATER PUMPAGE IN THE STUDY AREA BY AQUIFER UNIT

Year	Pumpage (m^3/day)								
	BK	PD	NL	NB	SK	PT	TB	PN	Total
1983	24092	236114	553009	289930	11559	169	811	1344	1117028
1984	25490	257075	530359	318831	13916	478	1203	3684	1151037
1985	26830	265076	541452	293482	17750	475	1742	5784	1152591
1986	27734	268639	511464	260767	20266	677	1749	6037	1097332
1987	28023	281856	533159	281416	23599	1297	1841	6676	1157867
1988	28535	286765	533790	298745	26860	1409	1853	7798	1185756
1989	30138	298823	532979	303360	33610	1863	1920	10125	1212818
1990	30394	309841	546690	324886	41642	3484	3256	12445	1272639
1991	32520	325379	598820	372068	50574	4610	4799	13538	1402309
1992	33714	328218	640850	396054	55257	6719	6924	13327	1481062

Figure 7.5.1	HISTORICAL GROUNDWATER PUMPAGE IN THE STUDY AREA BY AQUIFER UNIT
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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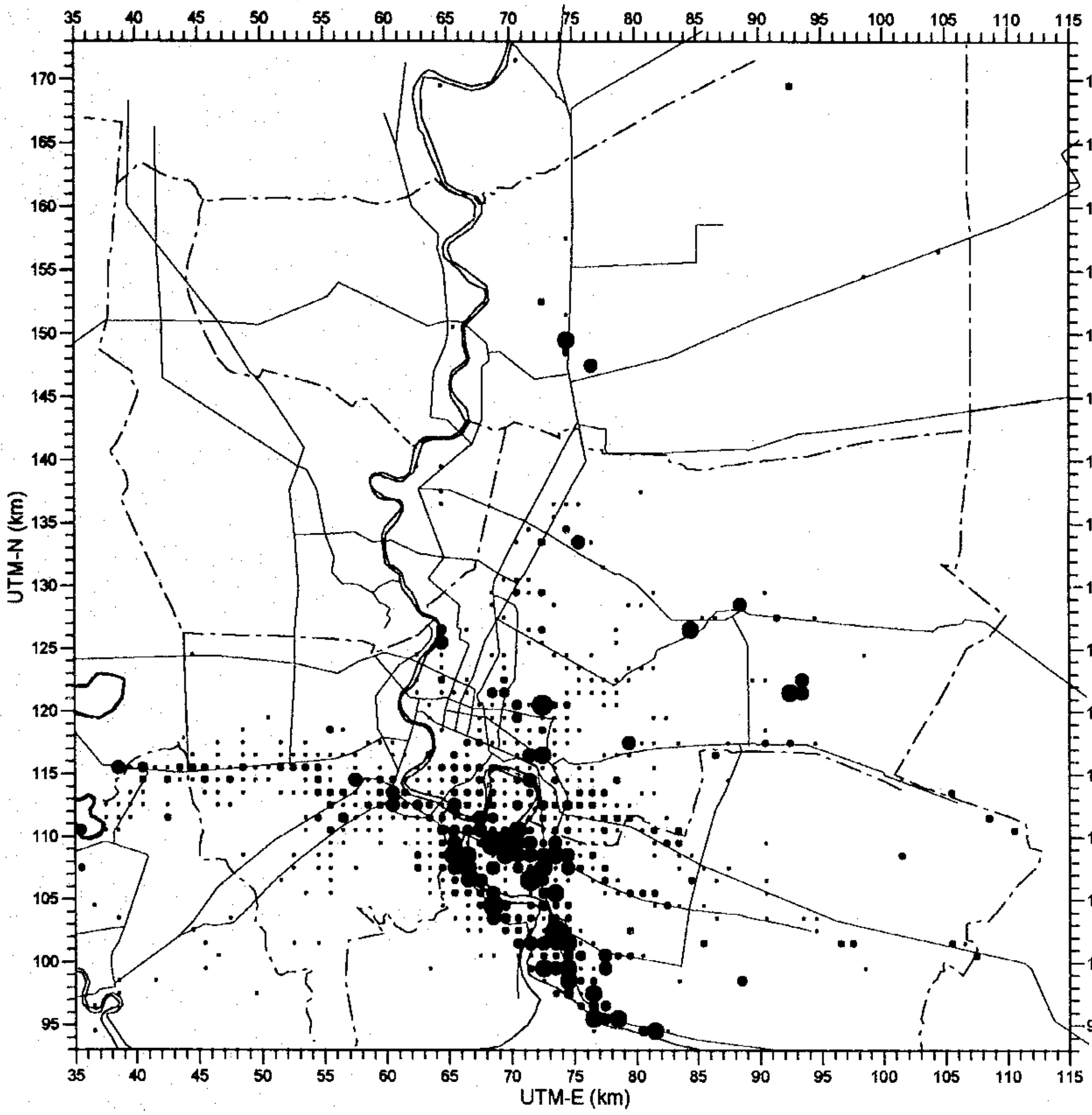

PUMPAGE DISTRIBUTION FROM PD AQUIFER IN 1983

LEGEND

Groundwater Pumpage (m^3 /day)
per 1km x 1km grid

- 1 to 99
- 100 to 499
- 500 to 999
- 1,000 to 1,999
- 2,000 to 4,999
- 5,000 to 9,999
- More than 10,000

Total Pumpage from PD Aquifer in 1983 = 236,114 m^3/day
= 86.18161 MCM/year

Figure 7.6.2	**DISTRIBUTION OF GROUNDWATER PUMPAGE FROM PD AQUIFER IN 1983**
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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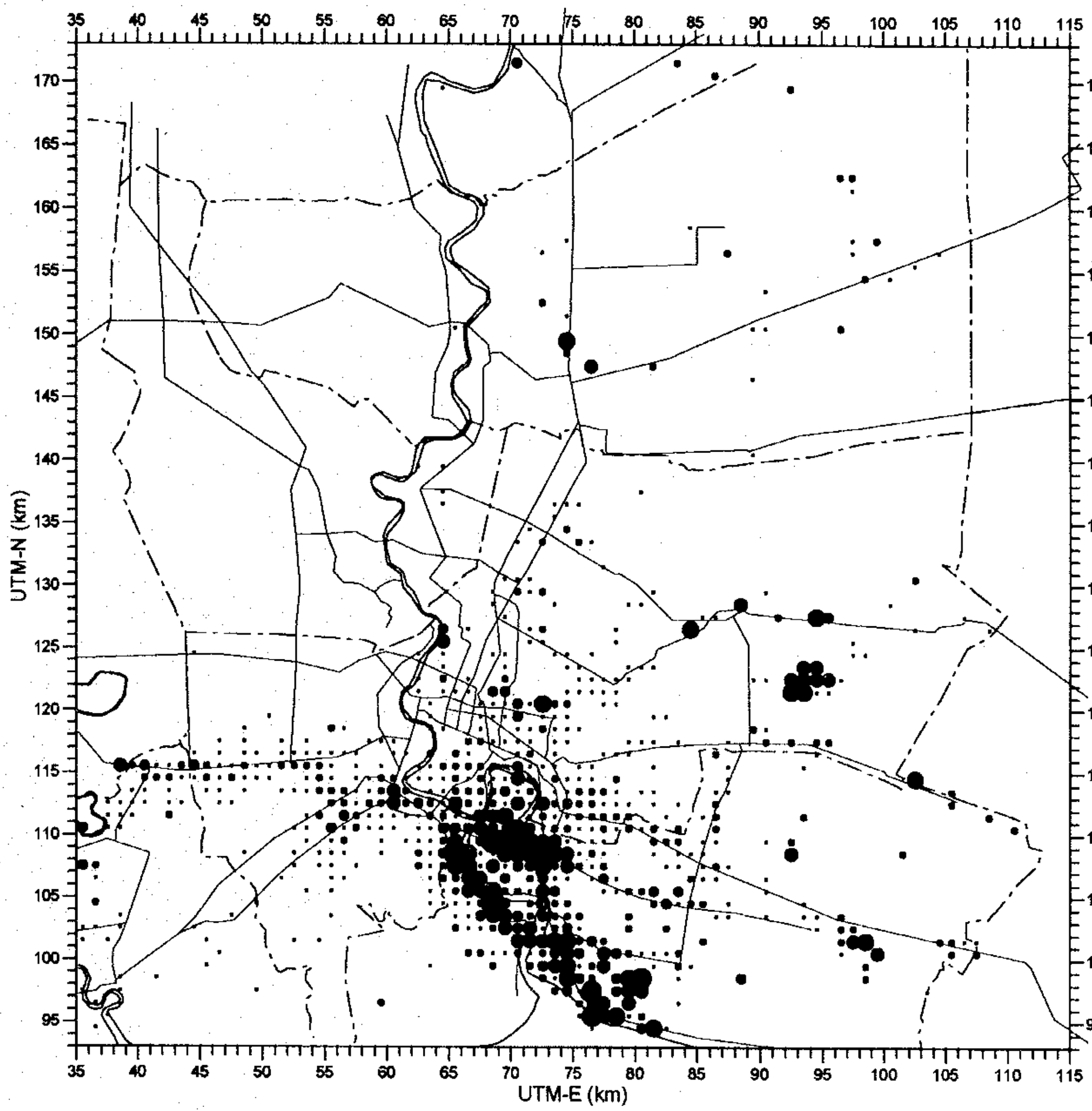

PUMPAGE DISTRIBUTION FROM PD AQUIFER IN 1992

LEGEND

Groundwater Pumpage (m³ /day) per 1km x 1km grid

- 1 to 99
- 100 to 499
- 500 to 999
- 1,000 to 1,999
- 2,000 to 4,999
- 5,000 to 9,999
- More than 10,000

Total Pumpage from PD Aquifer in 1992 = 328,218 m^3/day
= 119.7995 MCM/year

Figure 7.5.3	DISTRIBUTION OF GROUNDWATER PUMPAGE FROM PD AQUIFER IN 1992
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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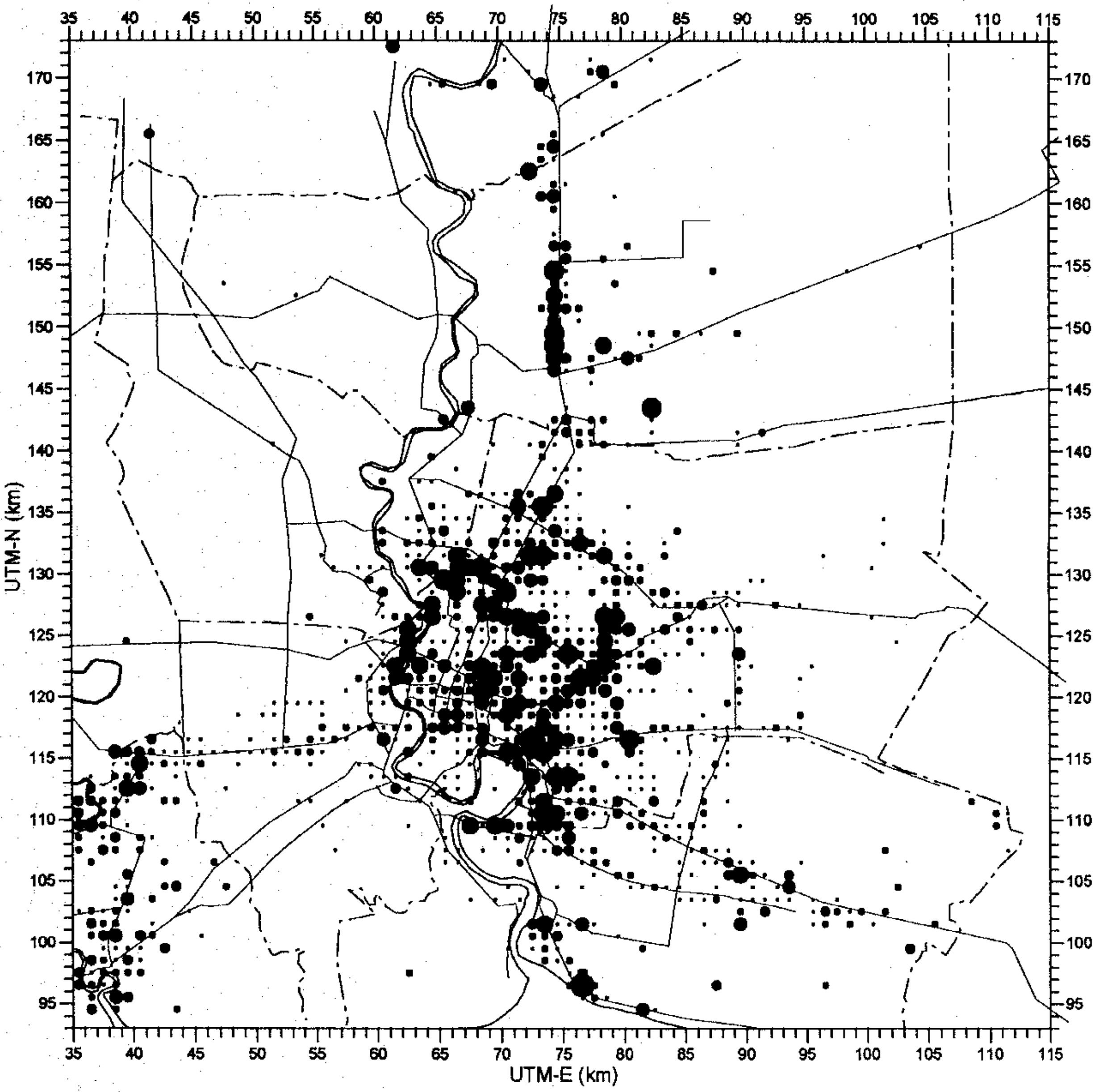

PUMPAGE DISTRIBUTION FROM NL AQUIFER IN 1983

LEGEND

Groundwater Pumpage (m³ /day) per 1km x 1km grid

- 1 to 99
- 100 to 499
- 500 to 999
- 1,000 to 1,999
- 2,000 to 4,999
- 5,000 to 9,999
- More than 10,000

Total Pumpage from NL Aquifer in 1983 = 553,009 m^3/day
= 201.8482 MCM/year

Figure 7.5.4	DISTRIBUTION OF GROUNDWATER PUMPAGE FROM NL AQUIFER IN 1983
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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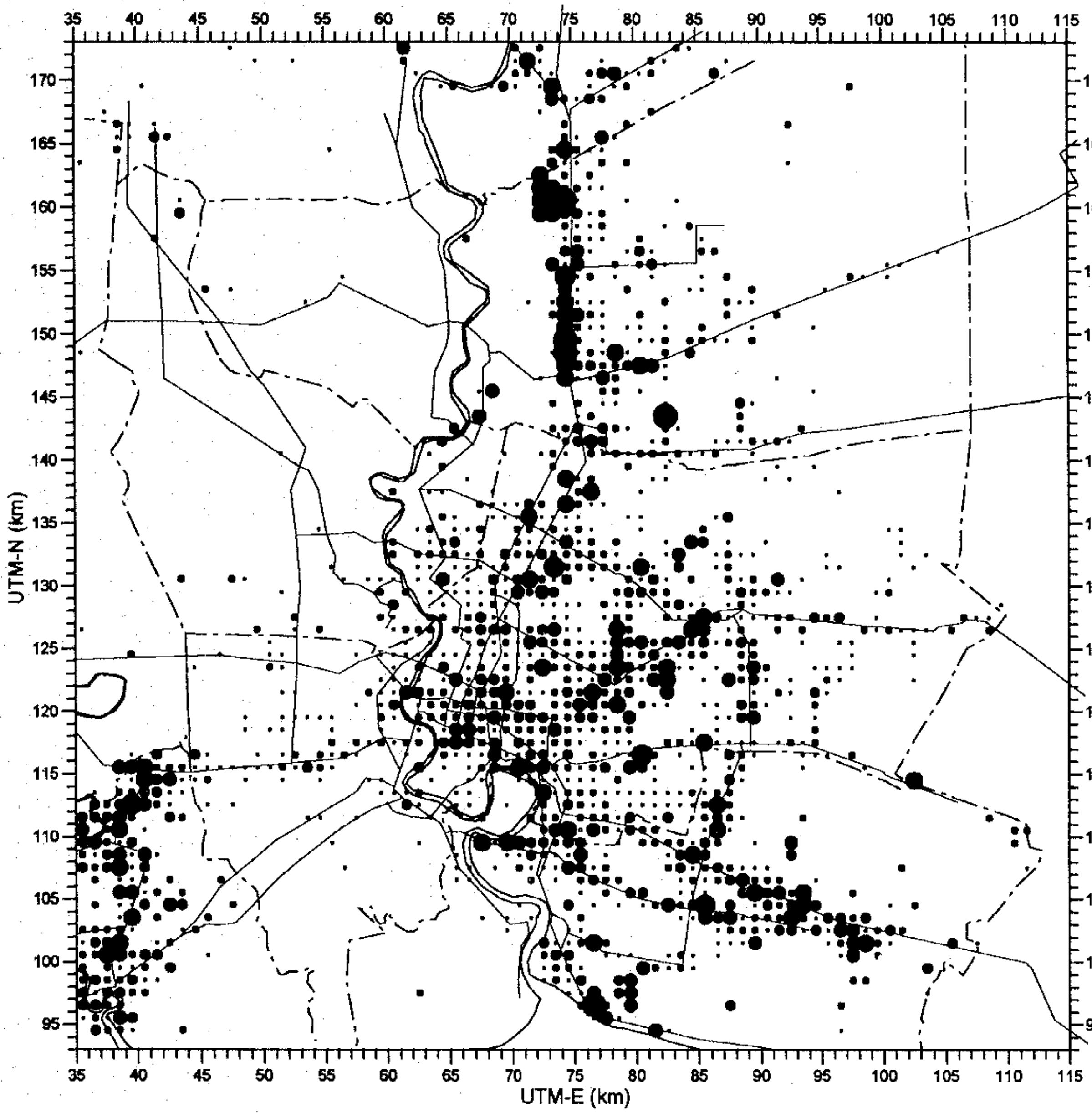

PUMPAGE DISTRIBUTION FROM NL AQUIFER IN 1992

LEGEND

Groundwater Pumpage (m^3 /day)
per 1km x 1km grid

- 1 to 99
- 100 to 499
- 500 to 999
- 1,000 to 1,999
- 2,000 to 4,999
- 5,000 to 9,999
- More than 10,000

Total Pumpage from NL Aquifer in 1992 = 640,850 m^3/day
= 233.9102 MCM/year

Figure 7.5.6	DISTRIBUTION OF GROUNDWATER PUMPAGE FROM NL AQUIFER IN 1992
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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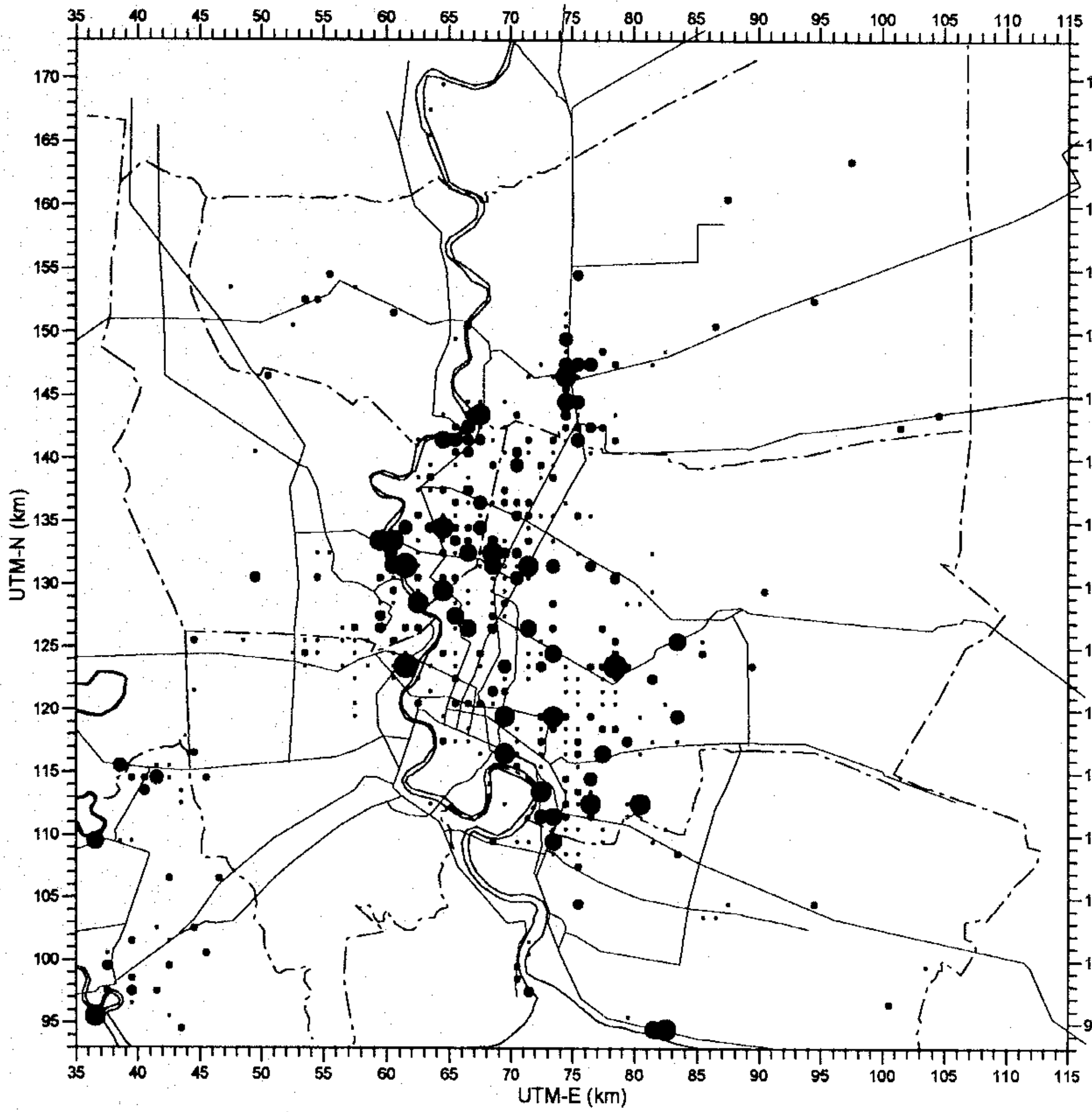

PUMPAGE DISTRIBUTION FROM NB AQUIFER IN 1983

LEGEND

Groundwater Pumpage (m^3 /day)
per 1km x 1km grid

- 1 to 99
- 100 to 499
- 500 to 999
- 1,000 to 1,999
- 2,000 to 4,999
- 5,000 to 9,999
- More than 10,000

Total Pumpage from NB Aquifer in 1983 = 289,930 m^3/day
= 105.8244 MCM/year

Figure 7.5.6	DISTRIBUTION OF GROUNDWATER PUMPAGE FROM NB AQUIFER IN 1983
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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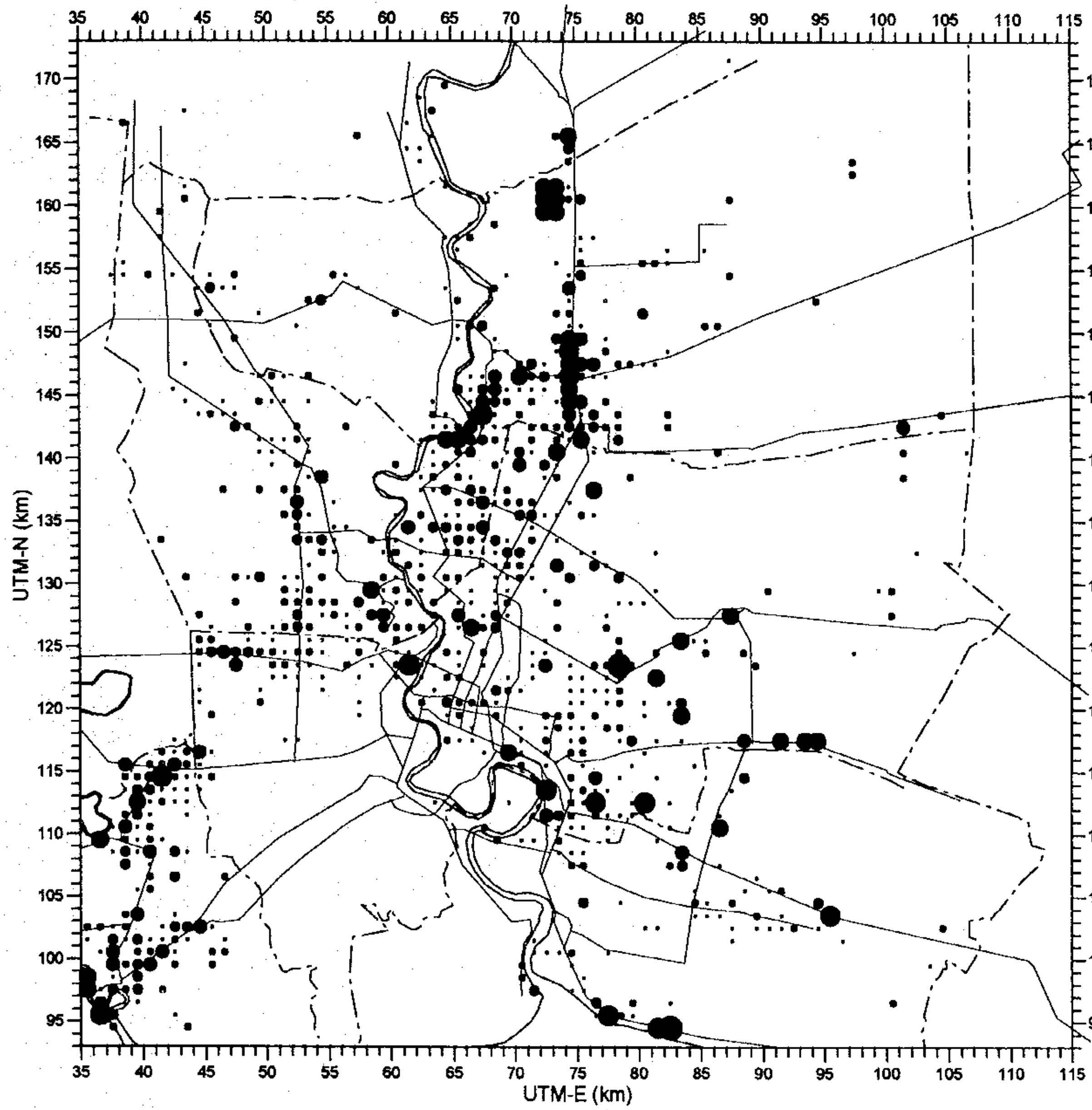

PUMPAGE DISTRIBUTION FROM NB AQUIFER IN 1992

LEGEND

Groundwater Pumpage (m^3 /day)
per 1km x 1km grid

- 1 to 99
- 100 to 499
- 500 to 999
- 1,000 to 1,999
- 2,000 to 4,999
- 5,000 to 9,999
- More than 10,000

Total Pumpage from NB Aquifer in 1992 = 396,054 m^3/day
= 144.5597 MCM/year

Figure 7.5.7	DISTRIBUTION OF GROUNDWATER PUMPAGE FROM NB AQUIFER IN 1992
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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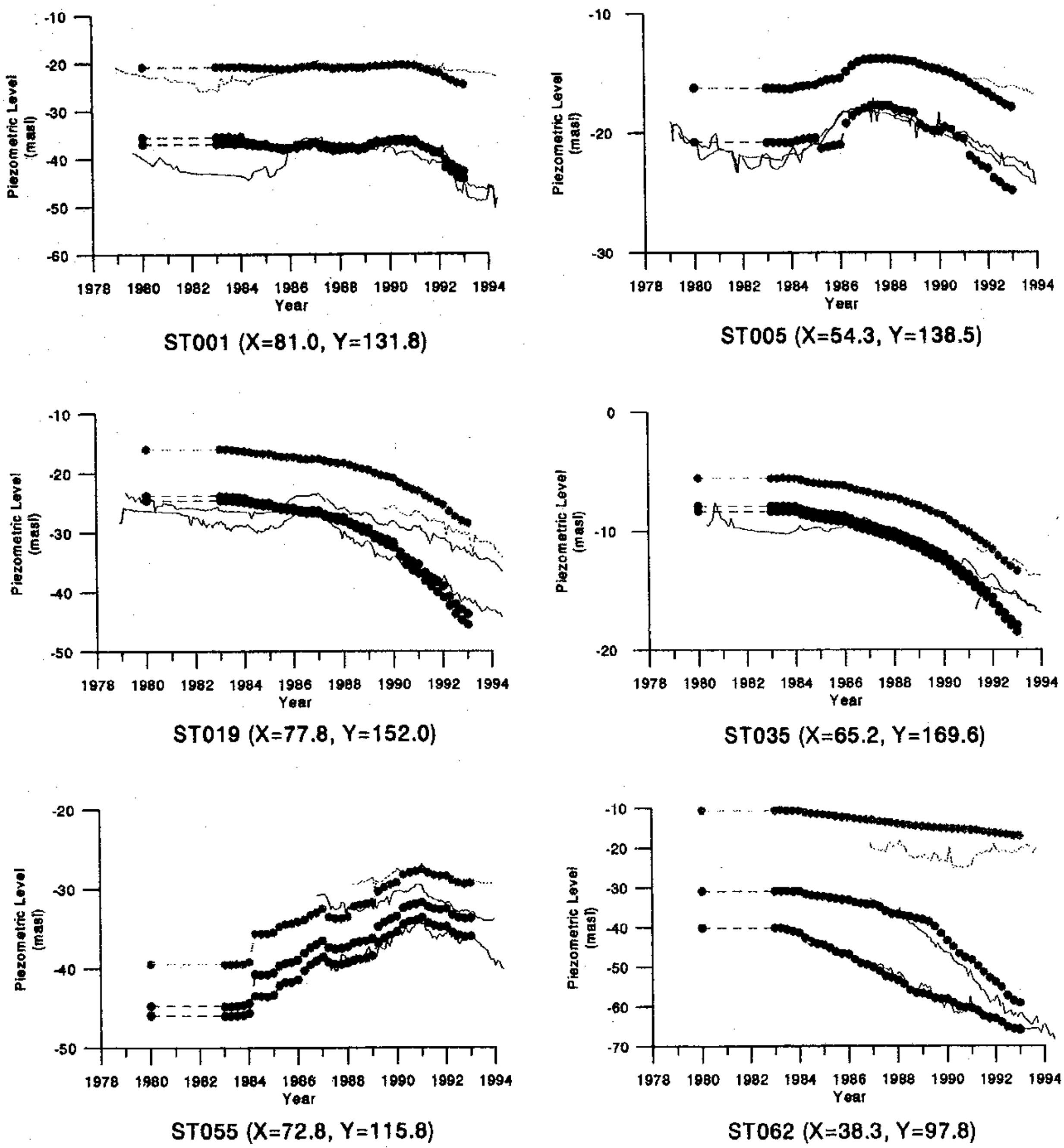

LEGEND

- Simulated PD
- Simulated NL
- Simulated NB
- Actual PD
- Actual NL
- Actual NB

Figure 7.5.8	COMPARISON OF SIMULATED HEADS BY 3-D MODEL WITH ACTUAL HEADS
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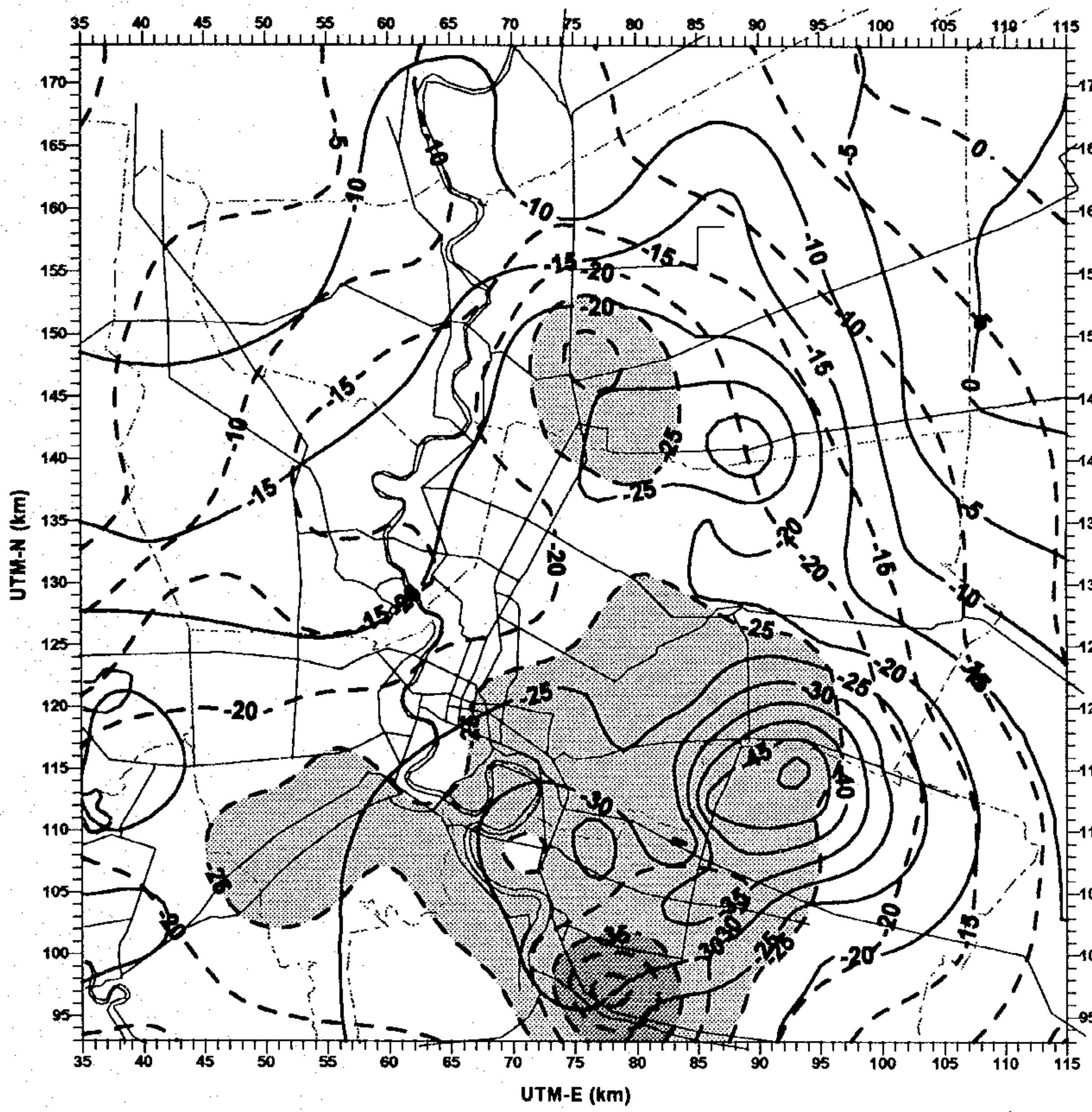

SIMULATED AND ACTUAL PIEZOMETRIC LEVELS OF PD AQUIFER AT THE END OF 1992

——— Actual Piezometric Level (masl)

– – – – Simulated Piezometric Level (masl)

Figure 7.5.9	SIMULATED AND ACTUAL PIEZOMETRIC LEVELS OF PD AQUIFER AT THE END OF 1992
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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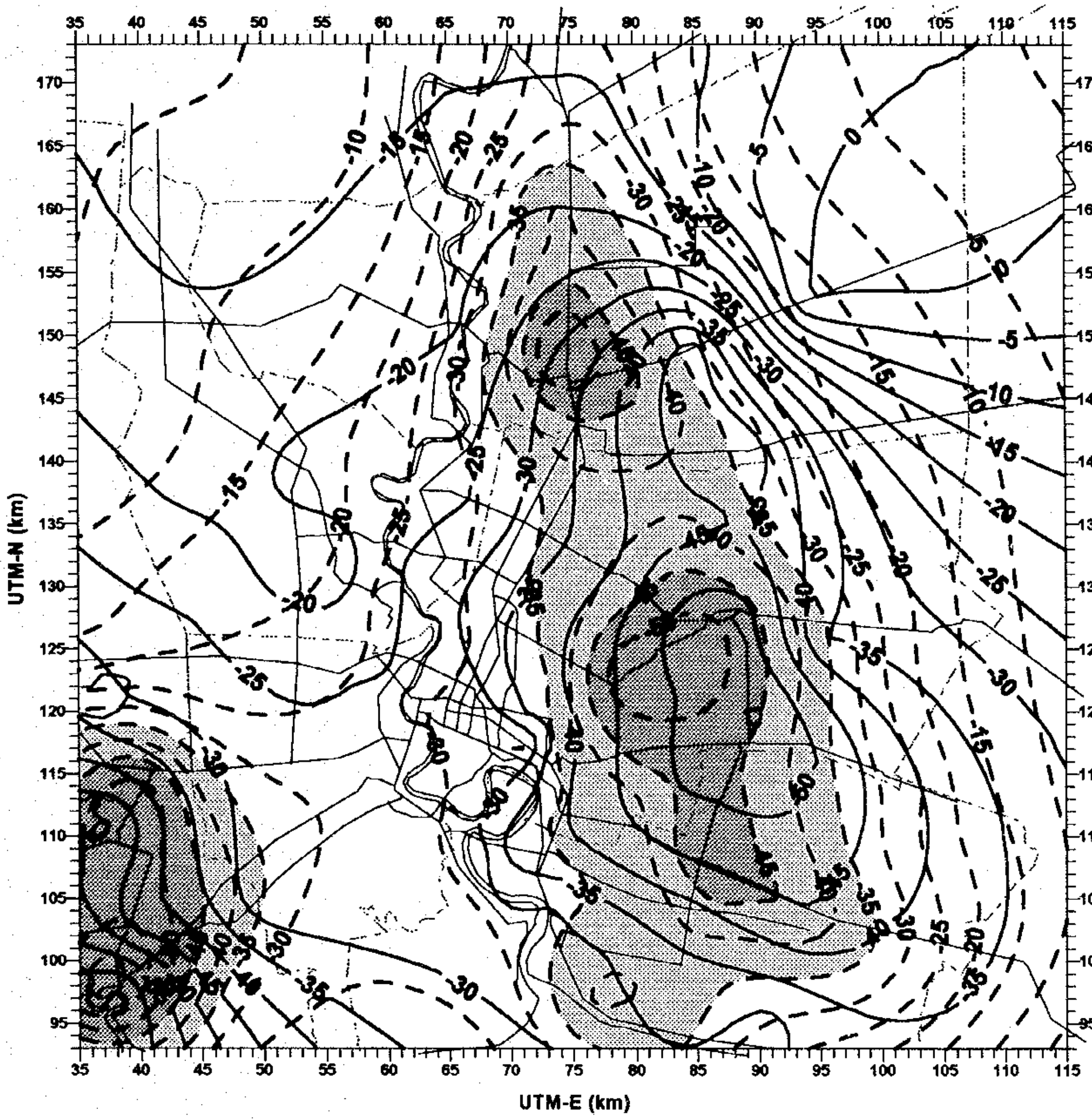

SIMULATED AND ACTUAL PIEZOMETRIC LEVELS OF NL AQUIFER AT THE END OF 1992

——— Actual Piezometric Level (masl)

– – – – Simulated Piezometric Level (masl)

Figure 7.5.10	SIMULATED AND ACTUAL PIEZOMETRIC LEVELS OF NL AQUIFER AT THE END OF 1992
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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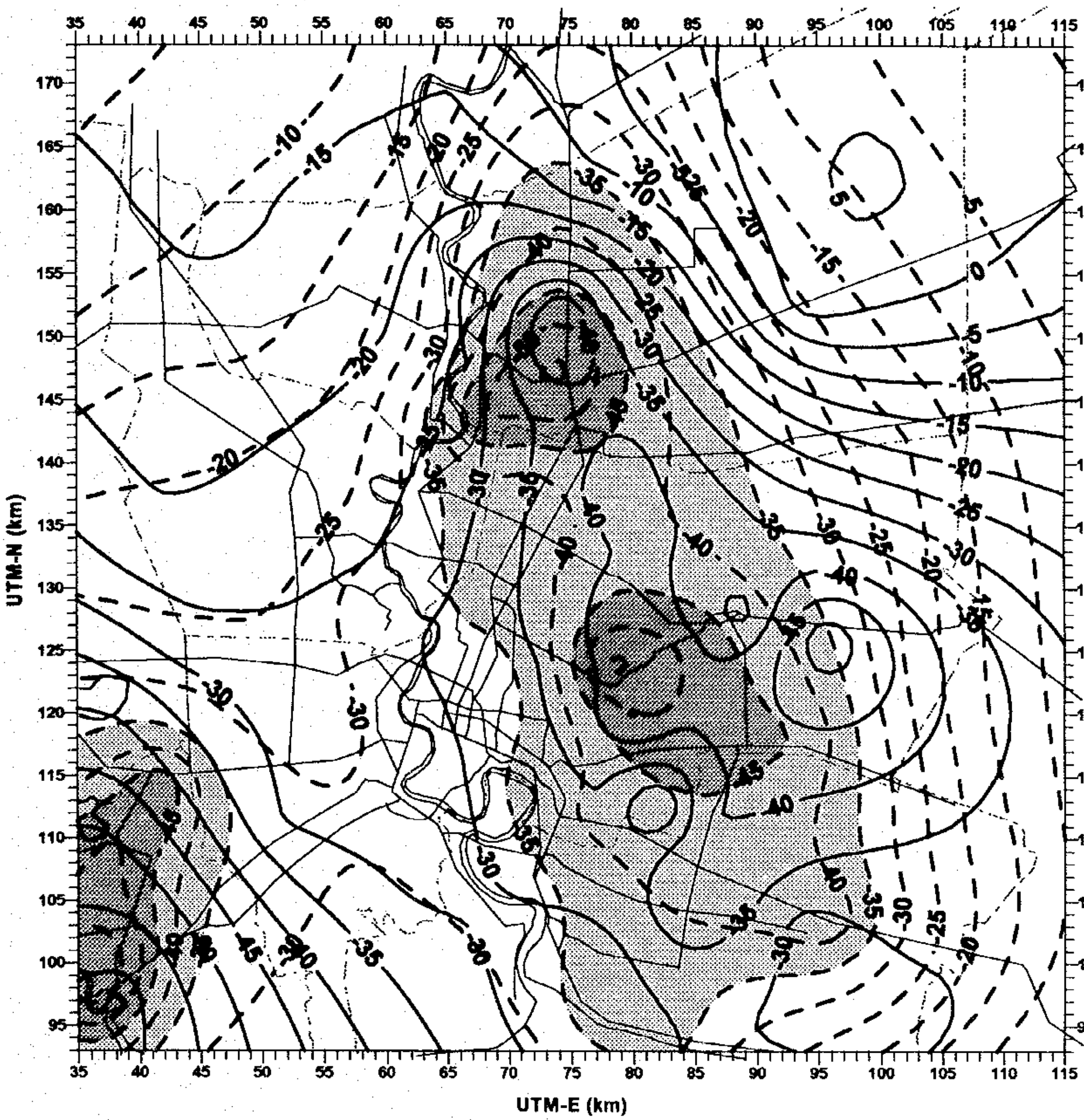

SIMULATED AND ACTUAL PIEZOMETRIC LEVELS OF NB AQUIFER AT THE END OF 1992

——— Actual Piezometric Level (masl)

– – – – Simulated Piezometric Level (masl)

Figure 7.5.11	SIMULATED AND ACTUAL PIEZOMETRIC LEVELS OF NB AQUIFER AT THE END OF 1992
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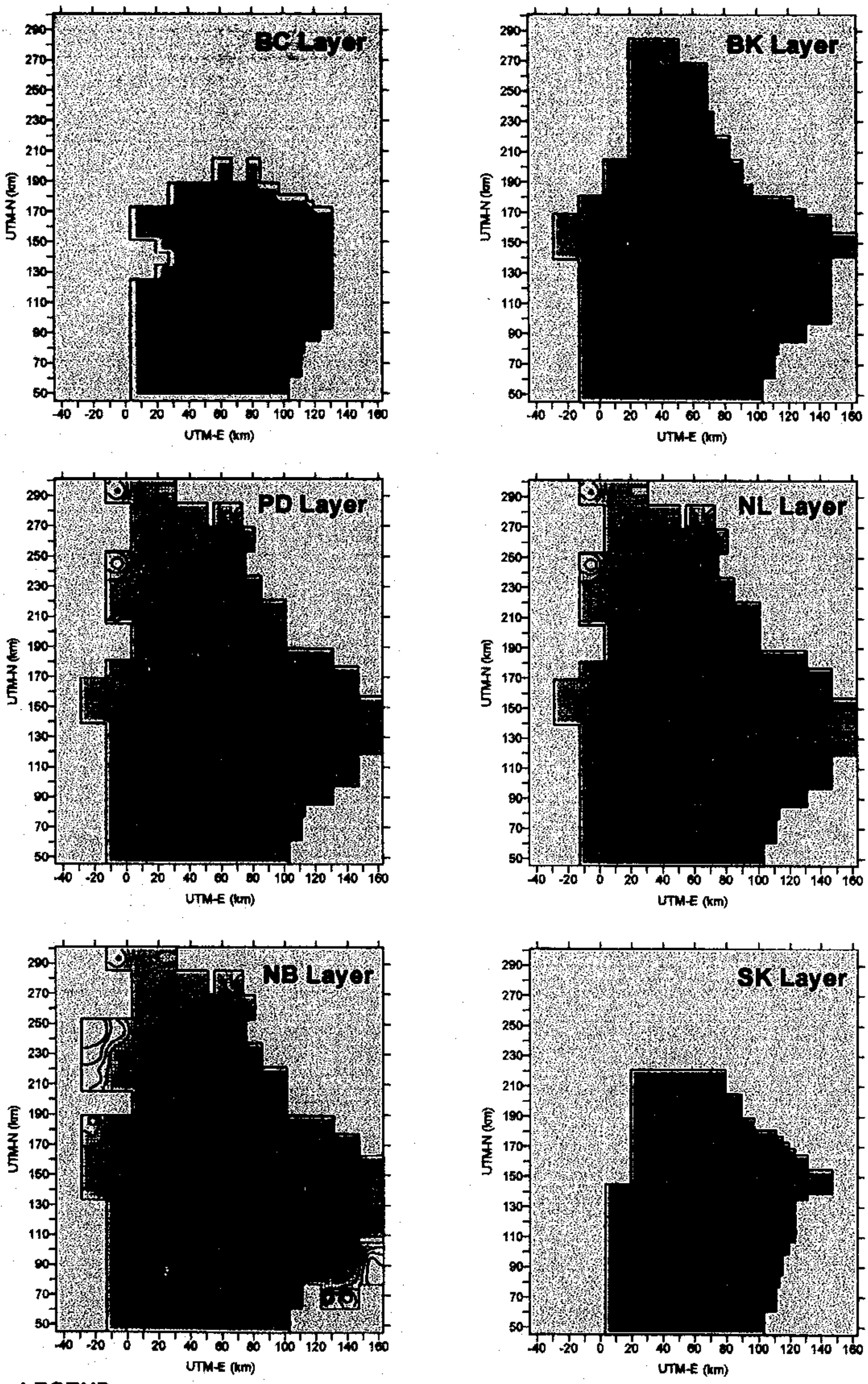

LEGEND

- Simulated piezometric heads (masl)
- Layer boundary
- Study area

Figure 7.5.12	SIMULATED PIEZOMETRIC HEADS IN 1992 BY 3-D MODEL
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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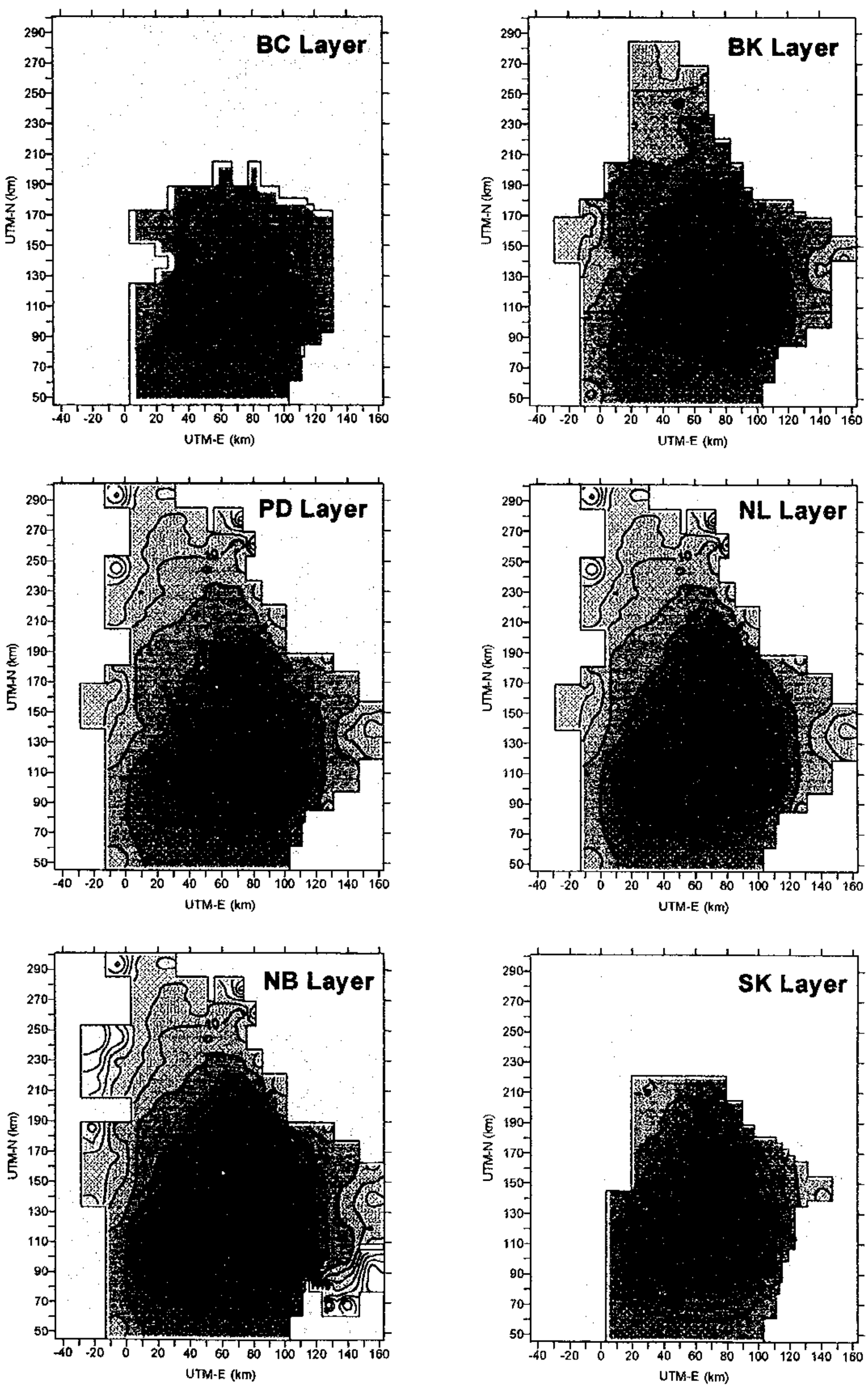

LEGEND

- Simulated piezometric heads (masl)
- Layer boundary
- Study area

Figure 7.5.12	SIMULATED PIEZOMETRIC HEADS IN 1992 BY 3-D MODEL
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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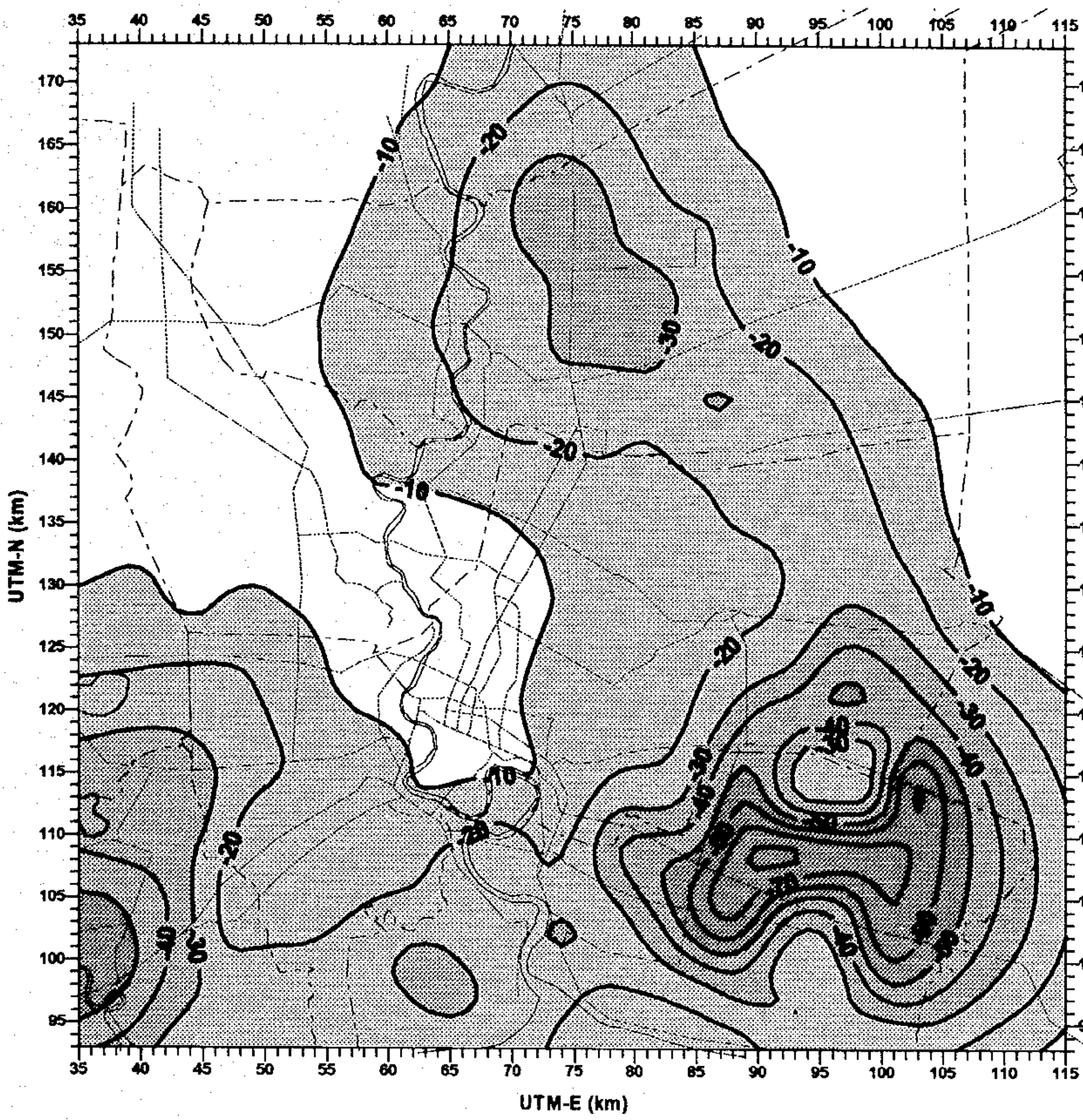

SIMULATED LAND SUBSIDENCE FROM 1983 TO 1992

——— Equal Line of Simulated Land Subsidence (cm/10 years)

Figure 7.5.13	SIMULATED LAND SUBSIDENCE FROM 1983 TO 1992
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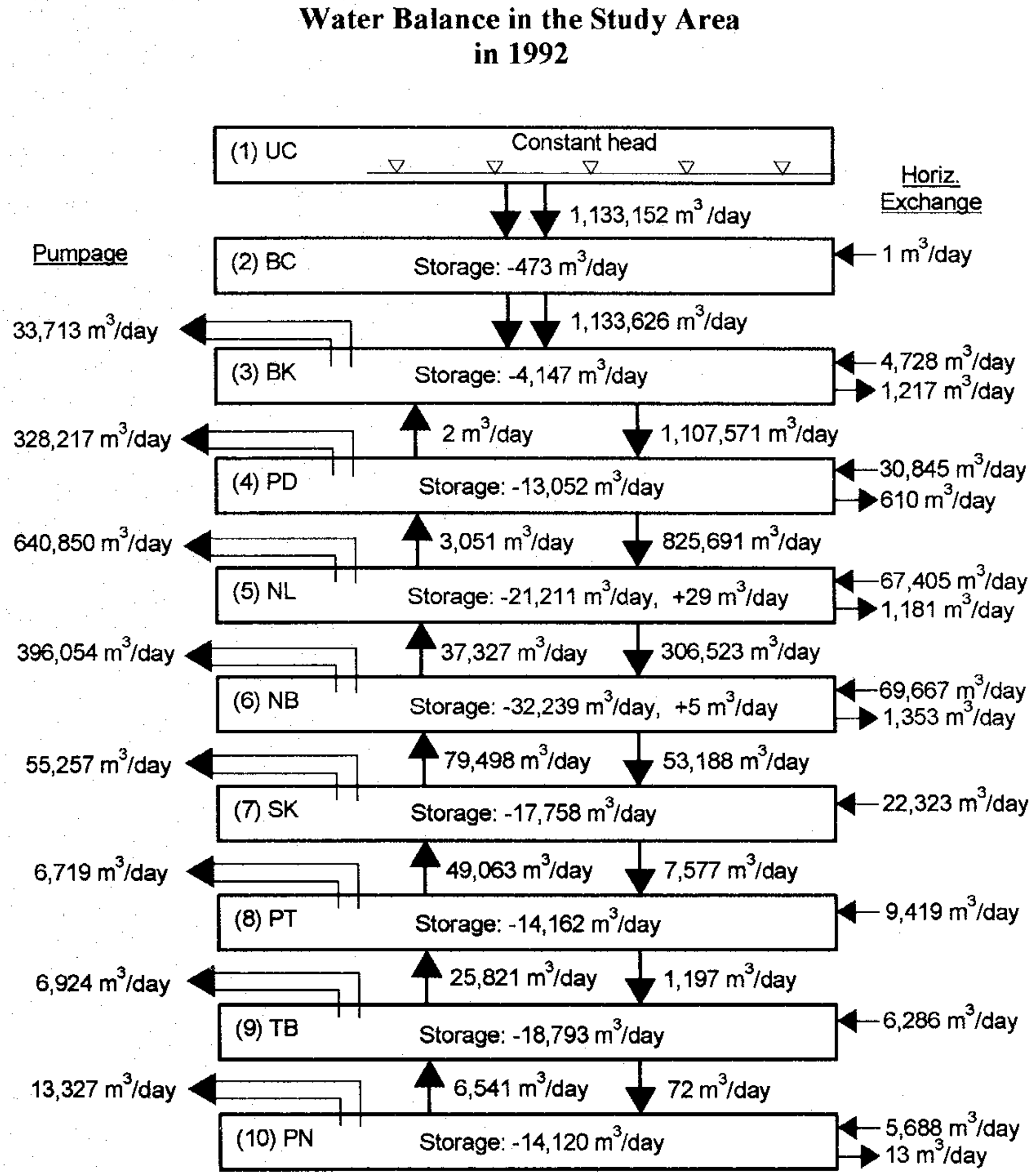

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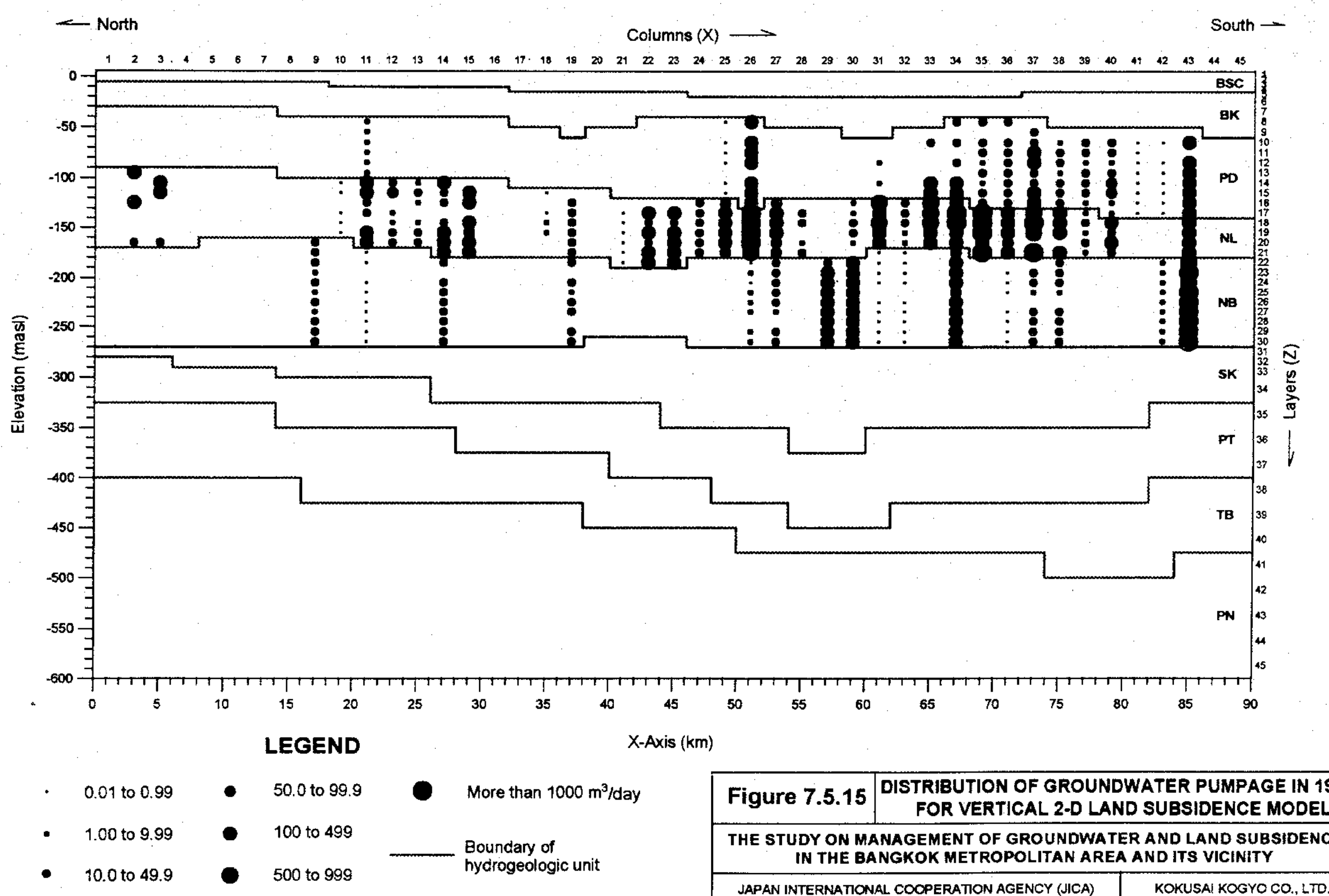

Figure 7.5.15	DISTRIBUTION OF GROUNDWATER PUMPAGE IN 1992 FOR VERTICAL 2-D LAND SUBSIDENCE MODEL
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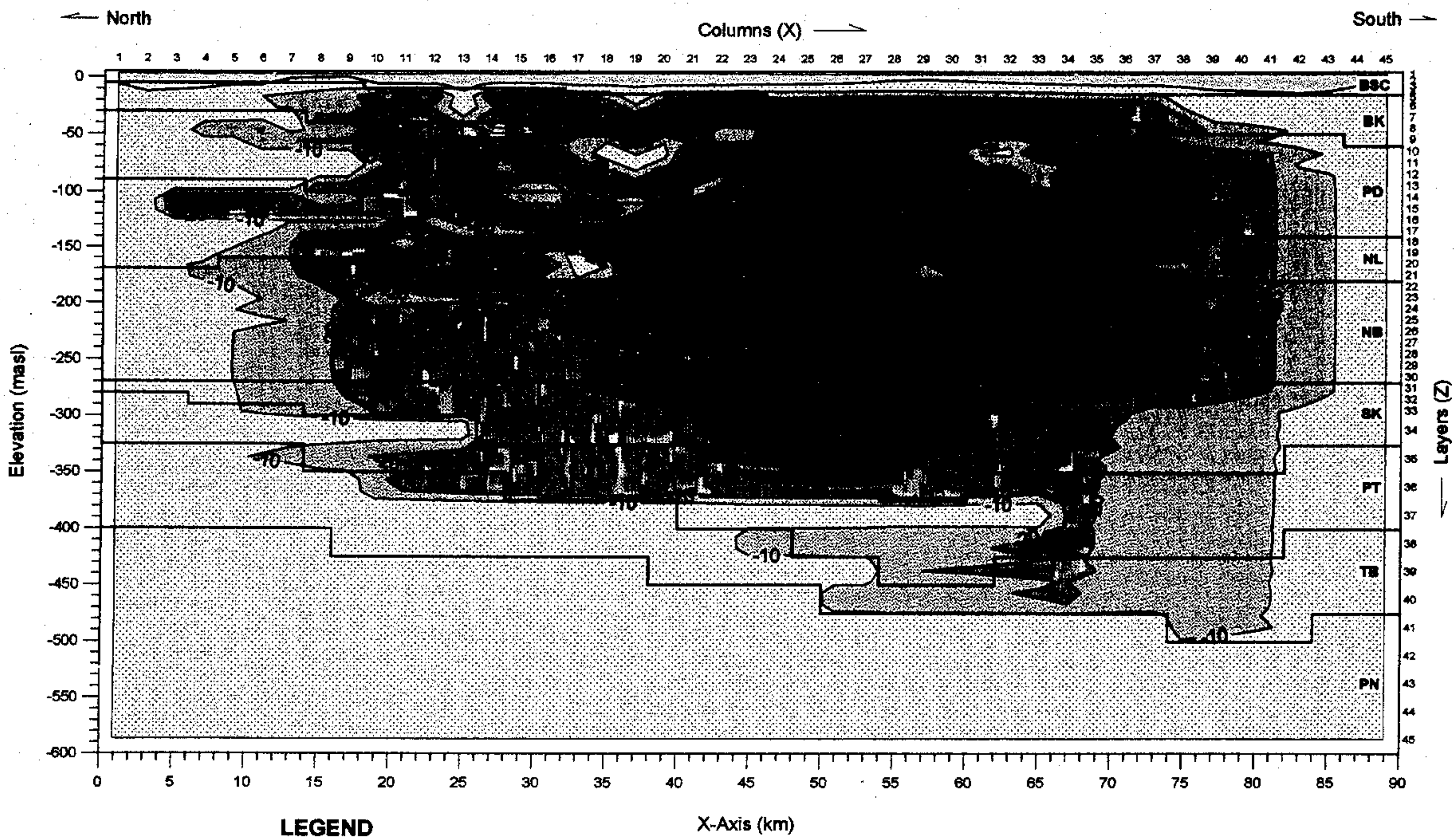

LEGEND

- Boundary of hydrogeologic unit
- Equal Line of Simulated Piezometric Head (masl)

Figure 7.5.16	SIMULATED PIEZOMETRIC HEADS IN 1992 BY VERTICAL 2-D LAND SUBSIDENCE MODEL
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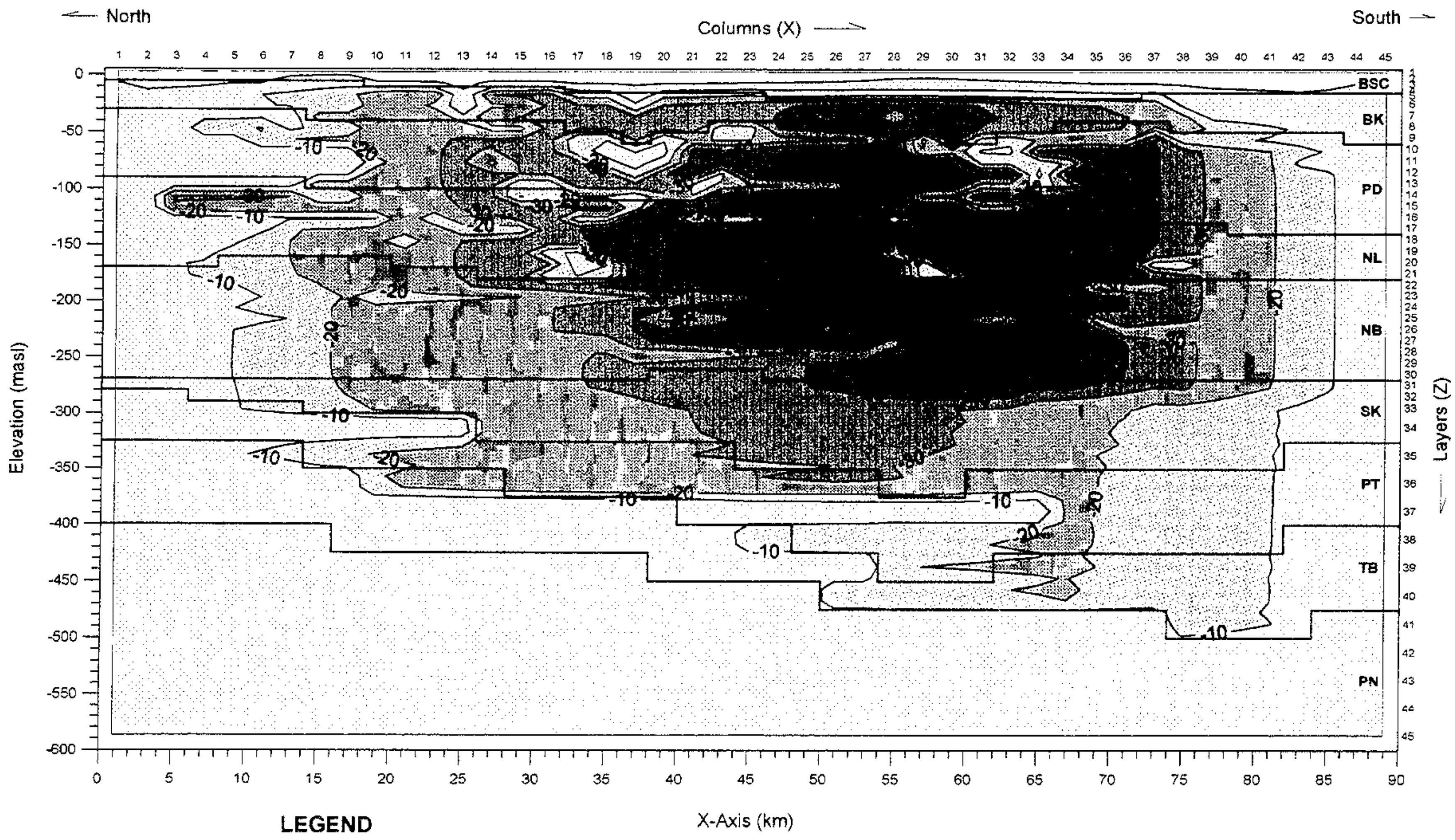

LEGEND

Boundary of hydrogeologic unit

Equal Line of Simulated Piezometric Head (masl)

Figure 7.5.16	SIMULATED PIEZOMETRIC HEADS IN 1992 BY VERTICAL 2-D LAND SUBSIDENCE MODEL
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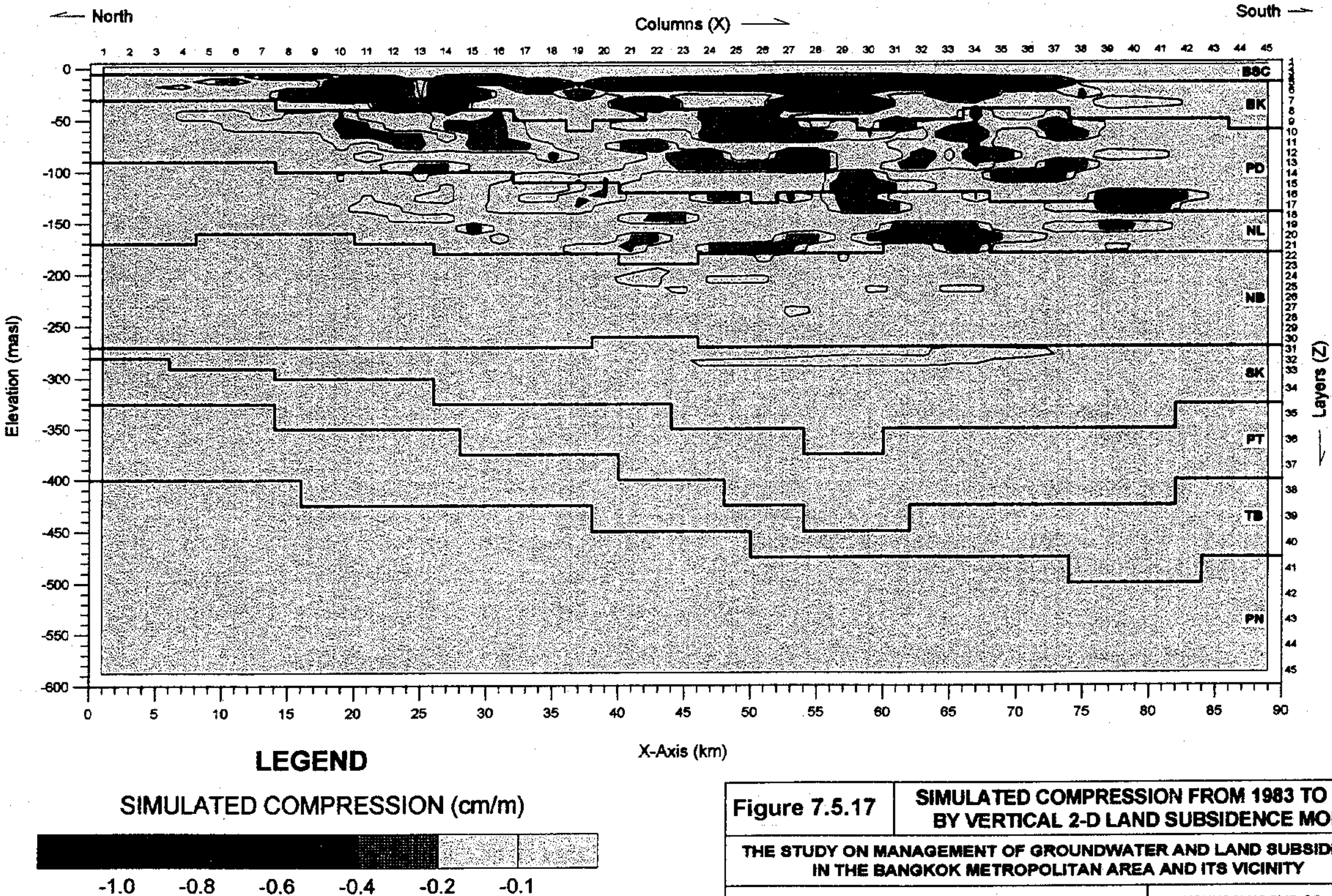

Figure 7.5.17	SIMULATED COMPRESSION FROM 1983 TO 1992 BY VERTICAL 2-D LAND SUBSIDENCE MODEL
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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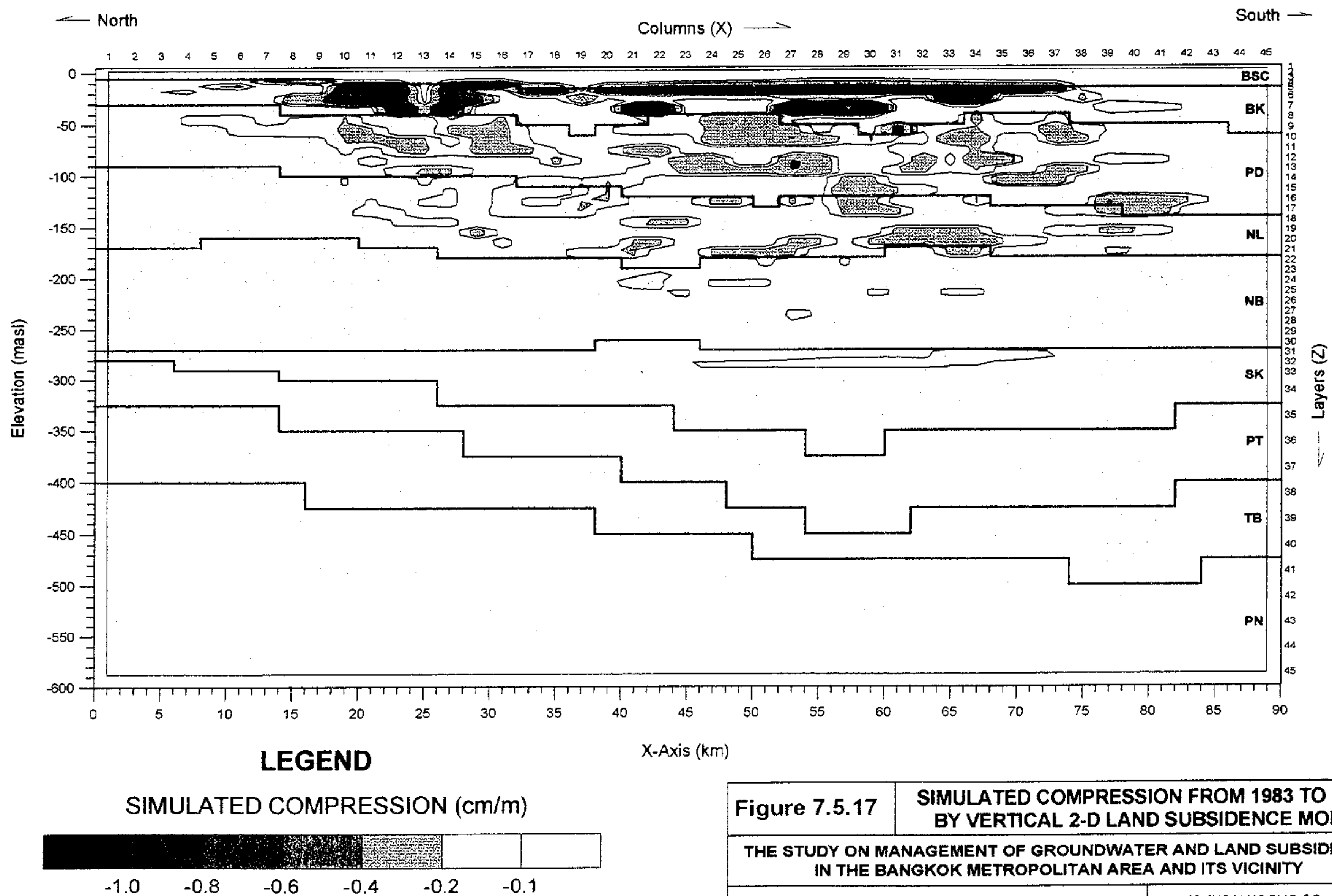

Figure 7.5.17	SIMULATED COMPRESSION FROM 1983 TO 1992 BY VERTICAL 2-D LAND SUBSIDENCE MODEL
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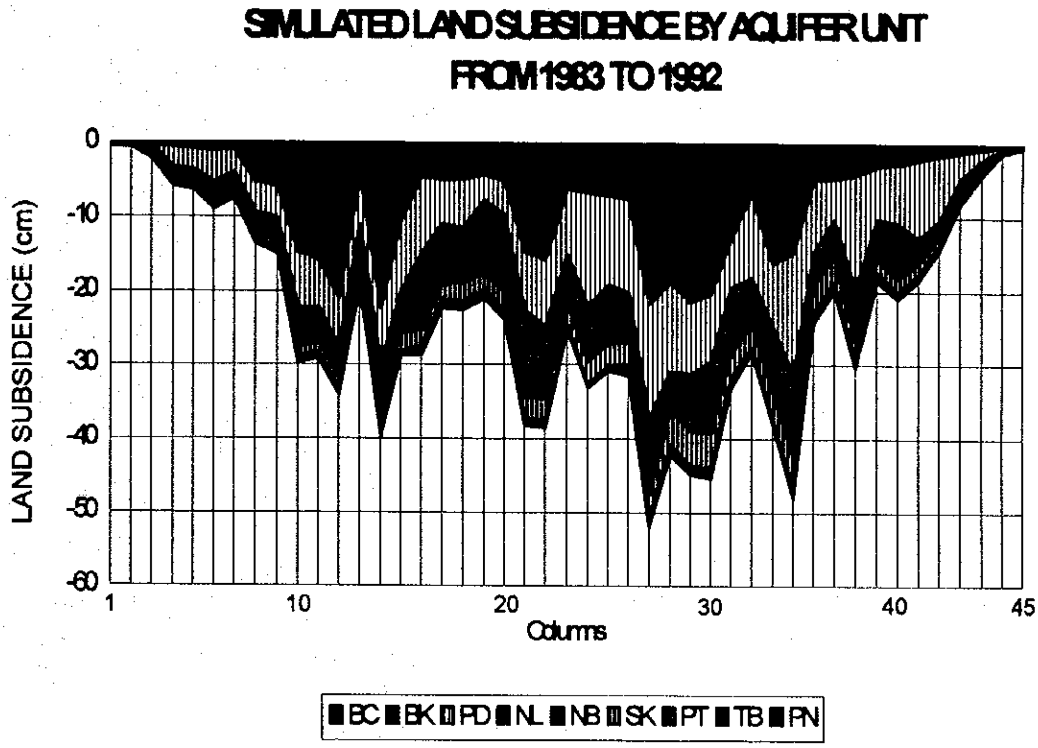

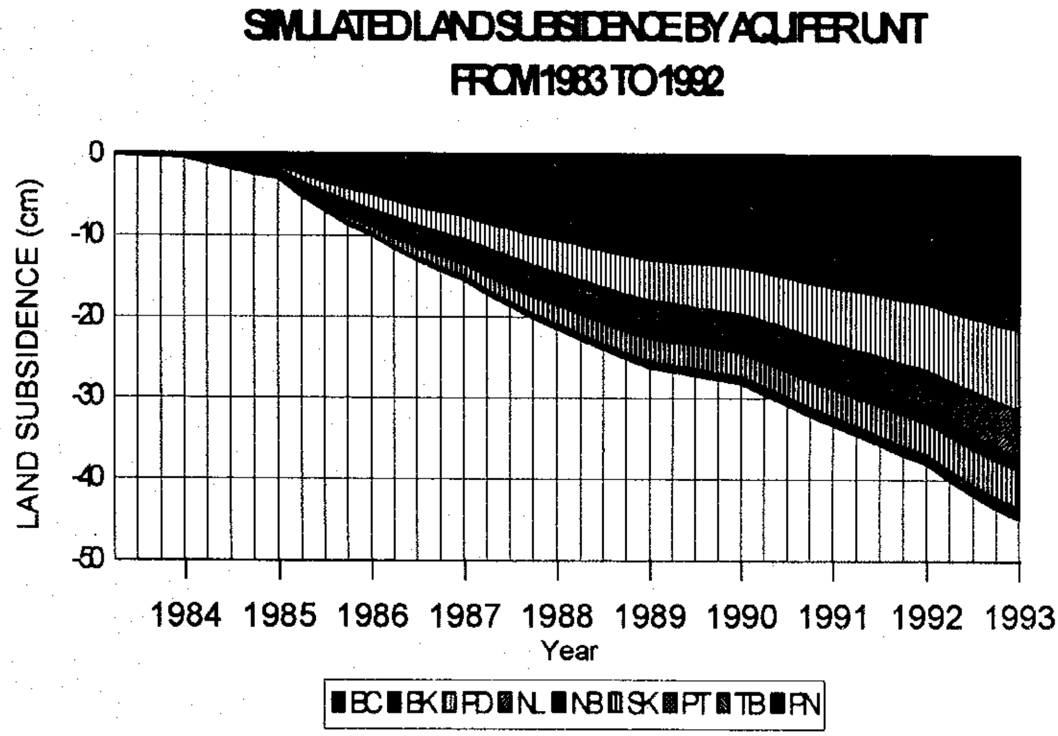

Figure 7.5.18	RESULTS OF LAND SUBSIDENCE SIMULATION BY VERTICAL 2-D MODEL
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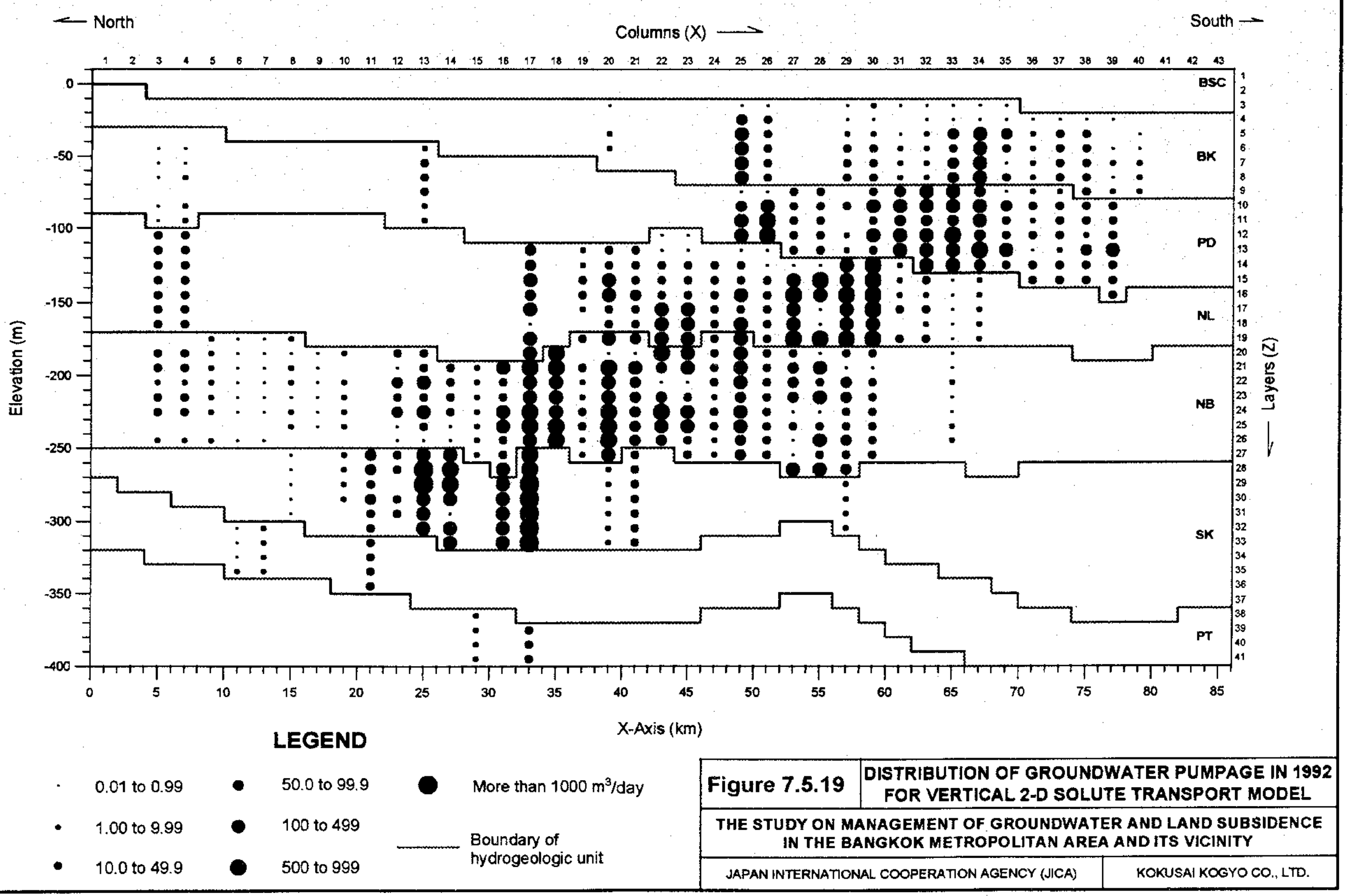

Figure 7.5.19 DISTRIBUTION OF GROUNDWATER PUMPAGE IN 1992 FOR VERTICAL 2-D SOLUTE TRANSPORT MODEL

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

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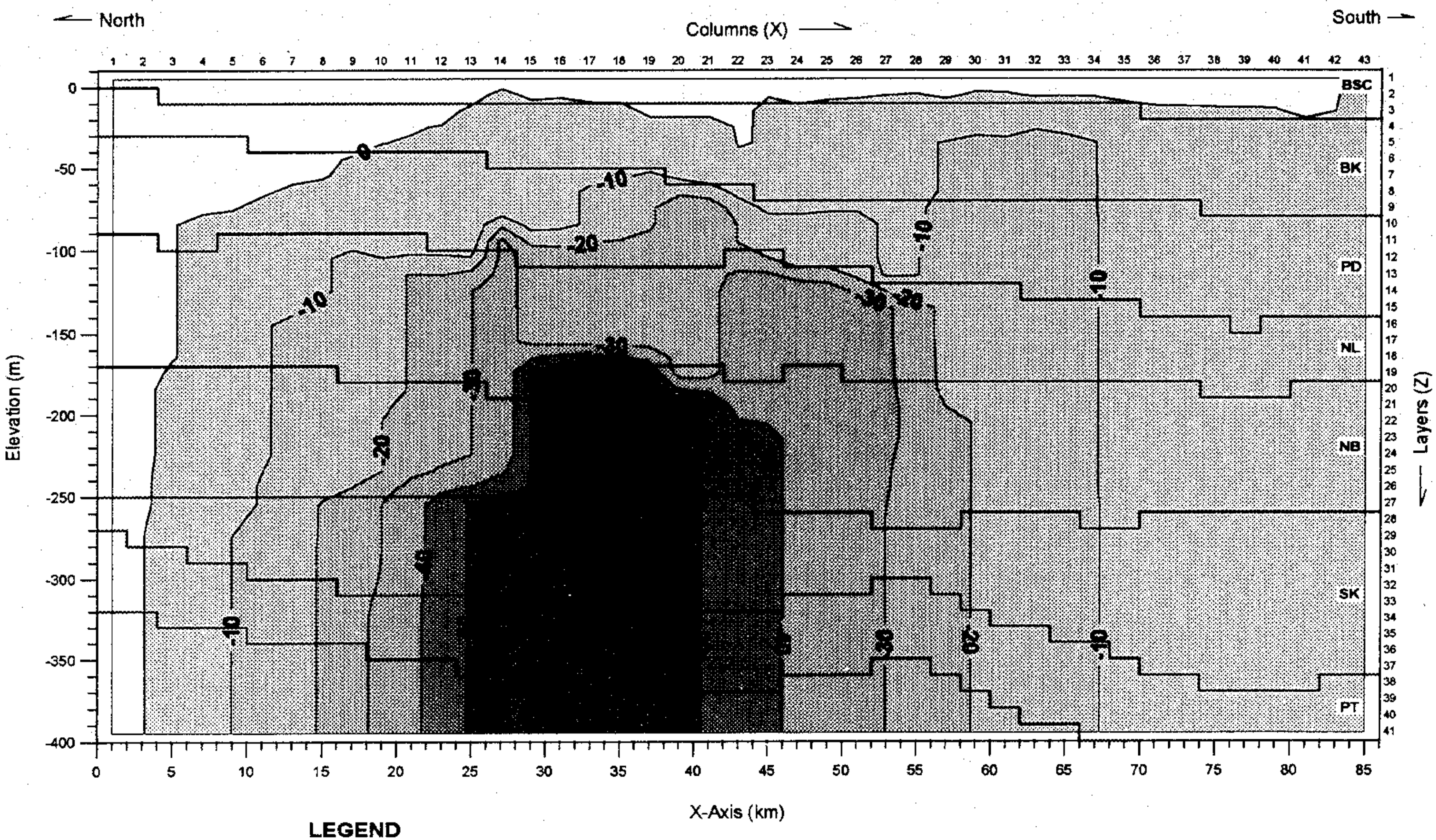

LEGEND

Boundary of hydrogeologic unit

Equal Line of
Simulated Piezometric Head (masl)

Figure 7.5.20	SIMULATED PIEZOMETRIC HEADS IN 1992 BY VERTICAL 2-D SOLUTE TRANSPORT MODEL
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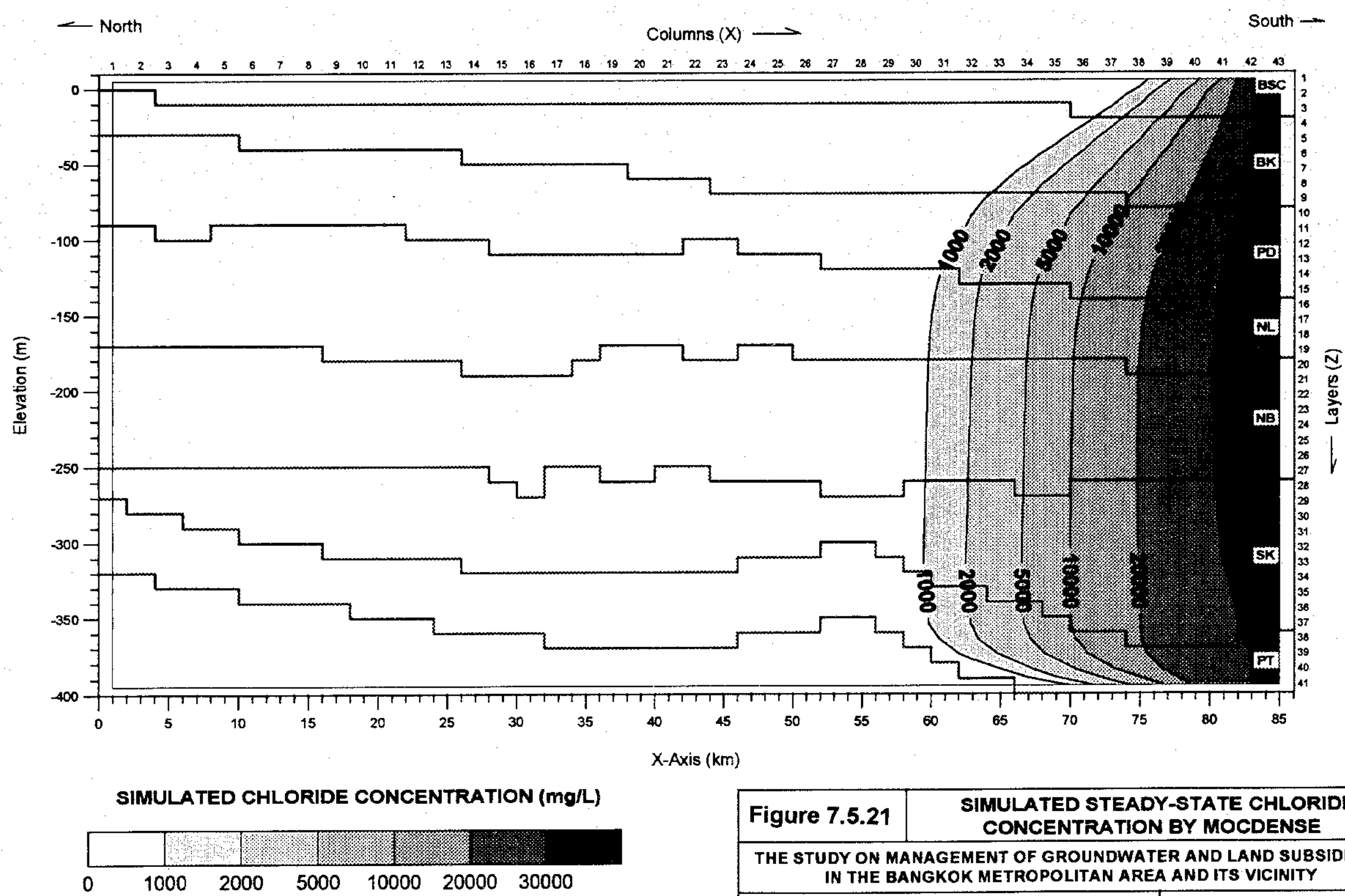

Figure 7.5.21	SIMULATED STEADY-STATE CHLORIDE CONCENTRATION BY MOCDENSE
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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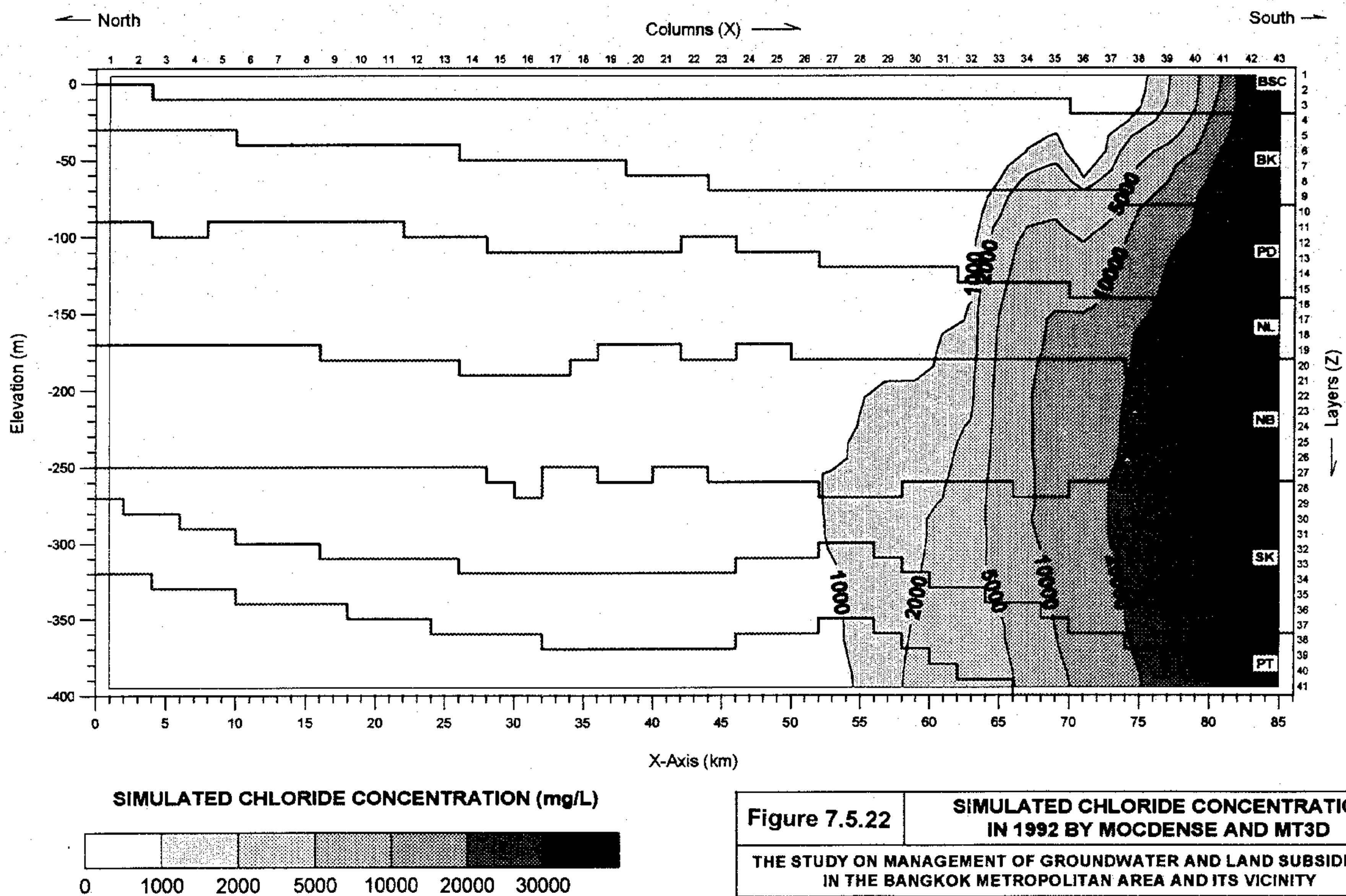

Figure 7.5.22	SIMULATED CHLORIDE CONCENTRATION IN 1992 BY MOCDENSE AND MT3D
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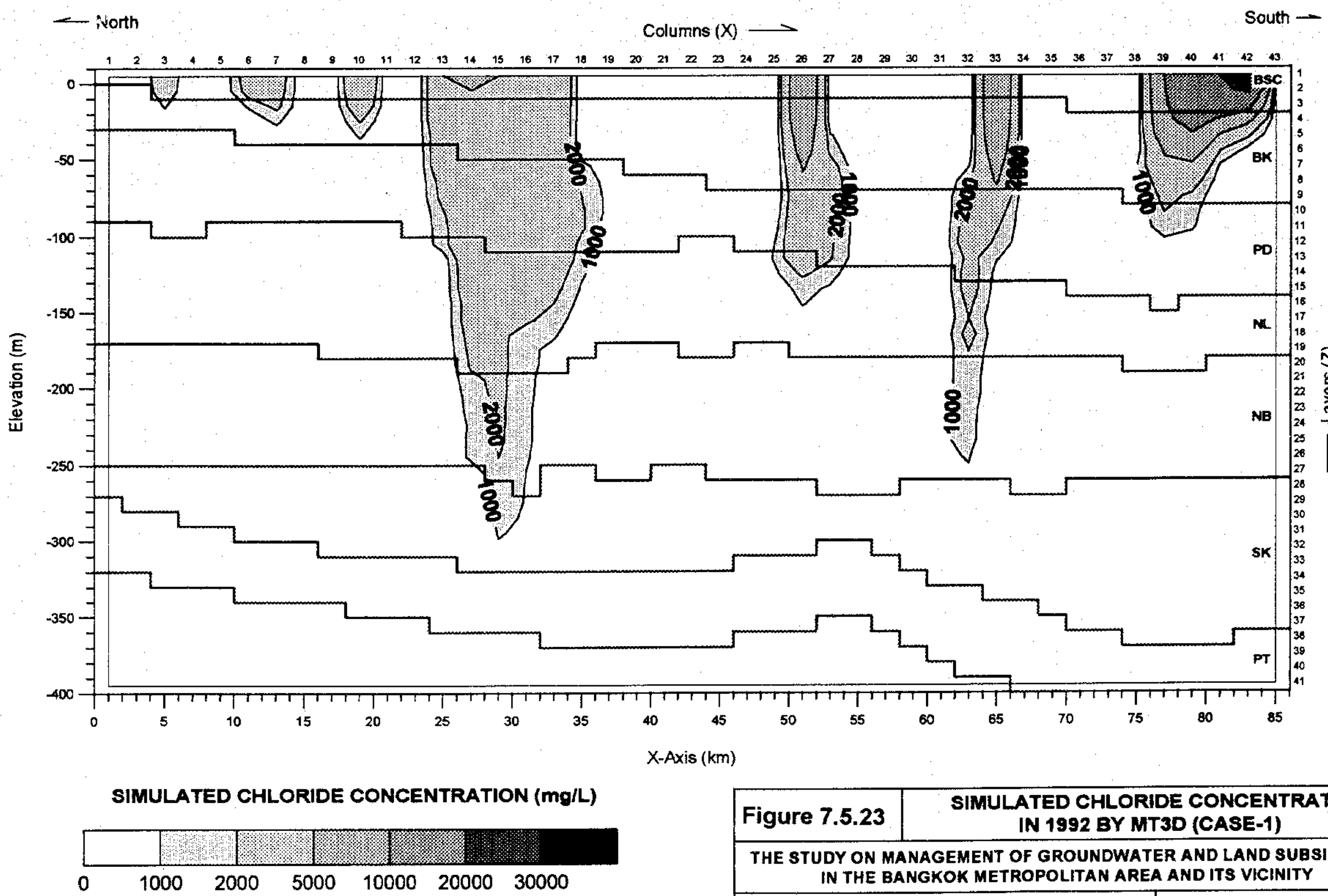

Figure 7.5.23	SIMULATED CHLORIDE CONCENTRATION IN 1992 BY MT3D (CASE-1)
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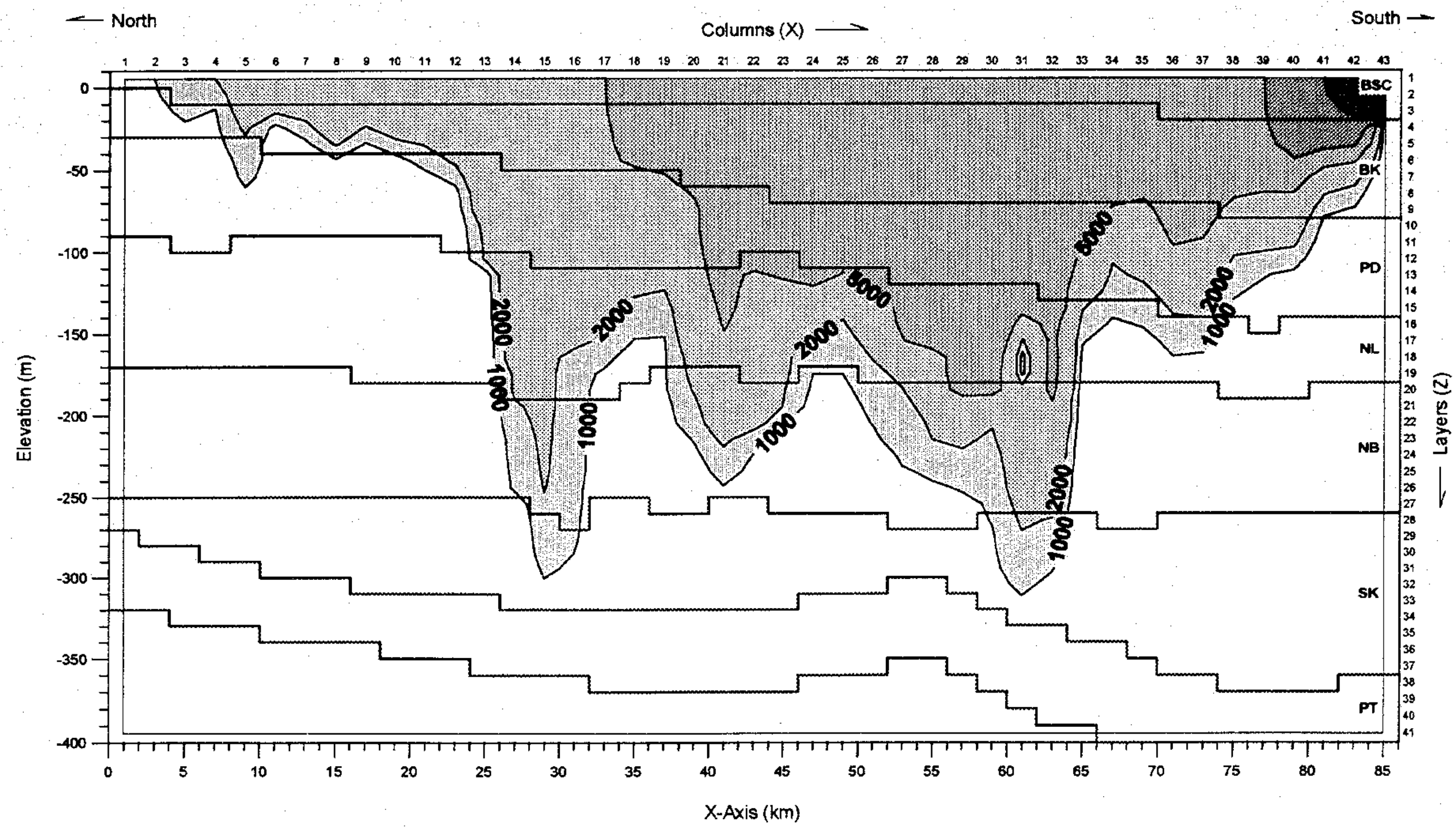

SIMULATED CHLORIDE CONCENTRATION (mg/L)

0 1000 2000 5000 10000 20000 30000

Figure 7.5.24	SIMULATED CHLORIDE CONCENTRATION IN 1992 BY MT3D (CASE-2)

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

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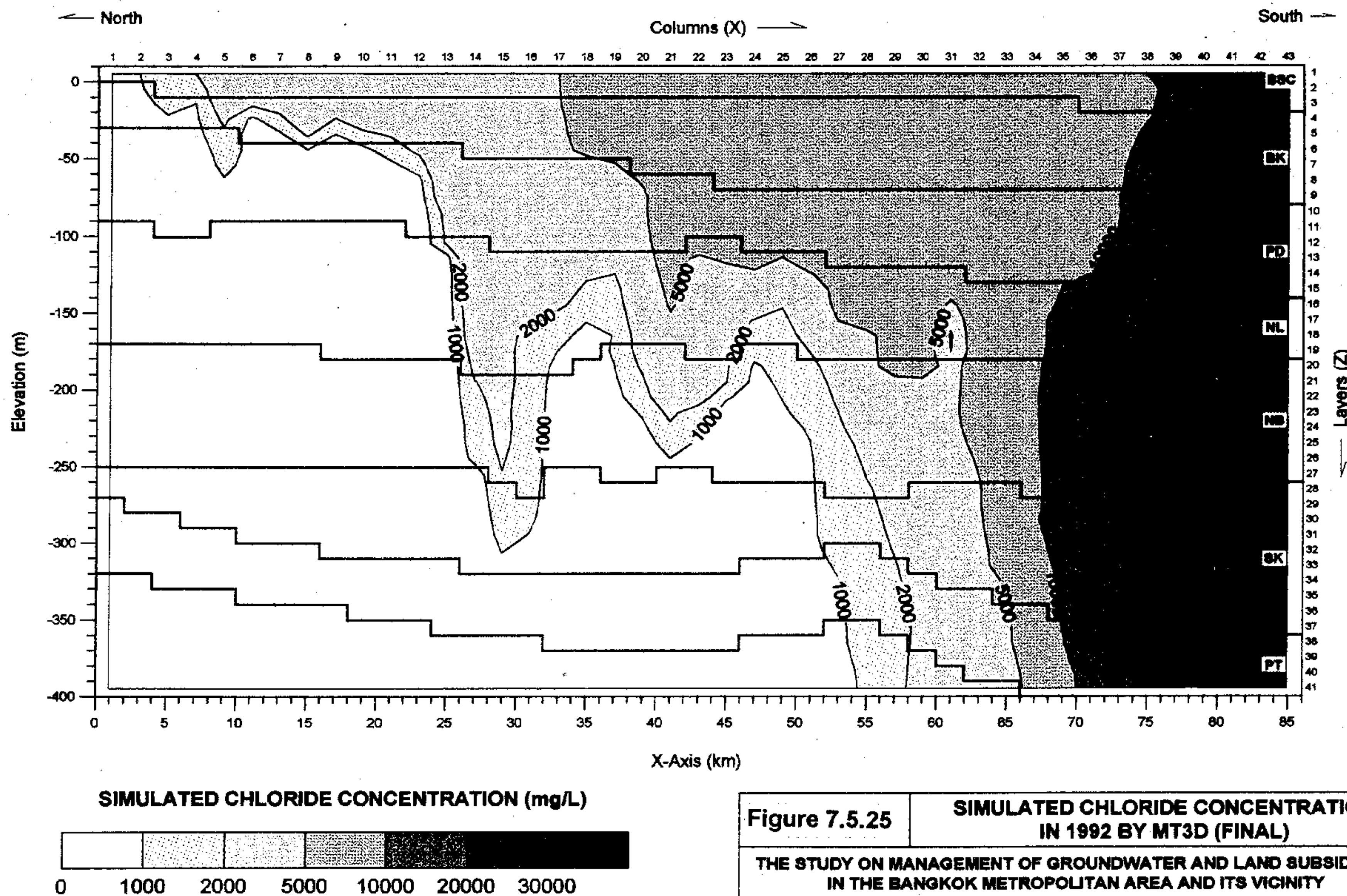

Figure 7.5.25	SIMULATED CHLORIDE CONCENTRATION IN 1992 BY MT3D (FINAL)
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JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

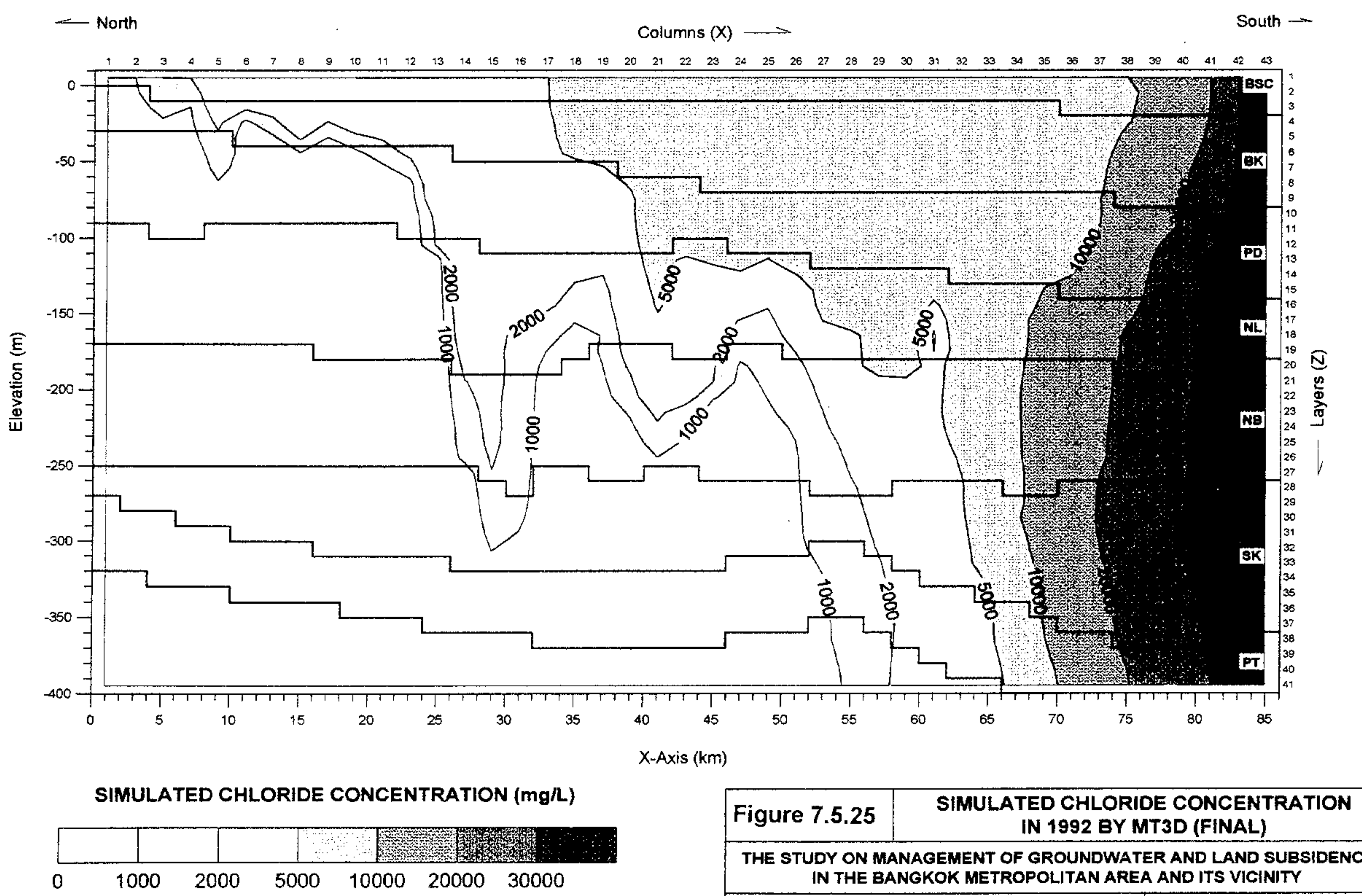

Figure 7.5.25	SIMULATED CHLORIDE CONCENTRATION IN 1992 BY MT3D (FINAL)
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