CHAPTER 7 GROUNDWATER MODELING

CHAPTER 7 GROUNDWATER MODELING

7.1 Modeling Approach

Three (3) kinds of groundwater simulation models were designed to formulate strategies for the groundwater basin management and measures for land subsidence.

Table 7.1 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

7.2 Modeled Area and Grid

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

The modeled area covered the Lower Central Plain in order to simulate basin-wide regional groundwater flow. The grid size of the Study Area was 2km x 2km. The grid outside the Study Area varied from 2km x 4km to 16km x 16km in size 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 x 52 columns). The number of grids in the Study Area is 1,600 (Figure 7.1.1).

The model was divided into ten (10) layers based on the hydrogeological classification. In addtion to the 8 major aquifers, an unconfined aquifer (UC) and Bangkok Soft Clay (BC) were put in the model as the top most and the second layer, respectively (Figure 7.1.2).

(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 went across the land subsidence zone of eastern Bangkok from north to south and was suitable for analysis of groundwater movement and land subsidence (Figure 7.2). The modeled area has a length of 90km and a depth of 600m. The total number of the grid is 2,025 (Figure 7.3.1).

(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 went across the area of saline water from the right bank of the Chao Phraya River to the coastal area. It was suitable for the analysis of groundwater salinity (Figure 7.2). The modeled area has a length of 86 km and a depth of 400 m. The total number of grid is 1,763 (Figure 7.3.2)

7.3 Boundary Conditions

(1) Boundary Conditions for 3-D Model

The boundary conditions were determined based on the hydrogeological profiles and the extent of aquifers.

The constant head was assigned to the boundary cells if the aquifers continue outside the modeled area. In other boundaries, the no-flow (or closed) condition was assigned. The constant head (mean sea level) was also assigned to the southmost cells located at the Gulf of Thailand (Figure 7.4).

(2) Boundary Conditions for Vertical 2-D Models

The upper most cells were assigned constant head as well as both sides of the model. The bottom of the model was specified as the no-flow boundary.

7.4 Hydrogeologic Parameters

The groundwater models required hydrogeologic parameters, i.e., depth and thickness of layer,
specific capacity, porosity, hydraulic conductivity, leakance, initial piezometric head, pumping rate and recharge rate. These parameters were obtained from the geological data, pumping tests, groundwater levels and estimate of pumpage, etc. 35,000 mg/l was input to the Solute Transport Model as initial condition at the source.

7.5 Model Calibration

Three (3) groundwater models were calibrated in order to obtain good agreement with computed value and observed value. The steady-state calibration was carried out for 10 years at a constant rate of pumping in order to stabilize model response and obtain initial conditions of the non-steady state simulation. The historical pumpage data from 1983 to 1992 were later input into the models, and the non-steady state calibration was performed to obtain good historical match of computed and observed values of piezometric head, land subsidence and chloride concentration. In the calibration process, assumed parameters, such as the leakance, were modified. The historical pumpage was also modified on the assumption that pumping continued after expiration of the water permit, particularly in central Bangkok. This assumption resulted into good agreement with the computed and observed groundwater levels (Figure 7.5).

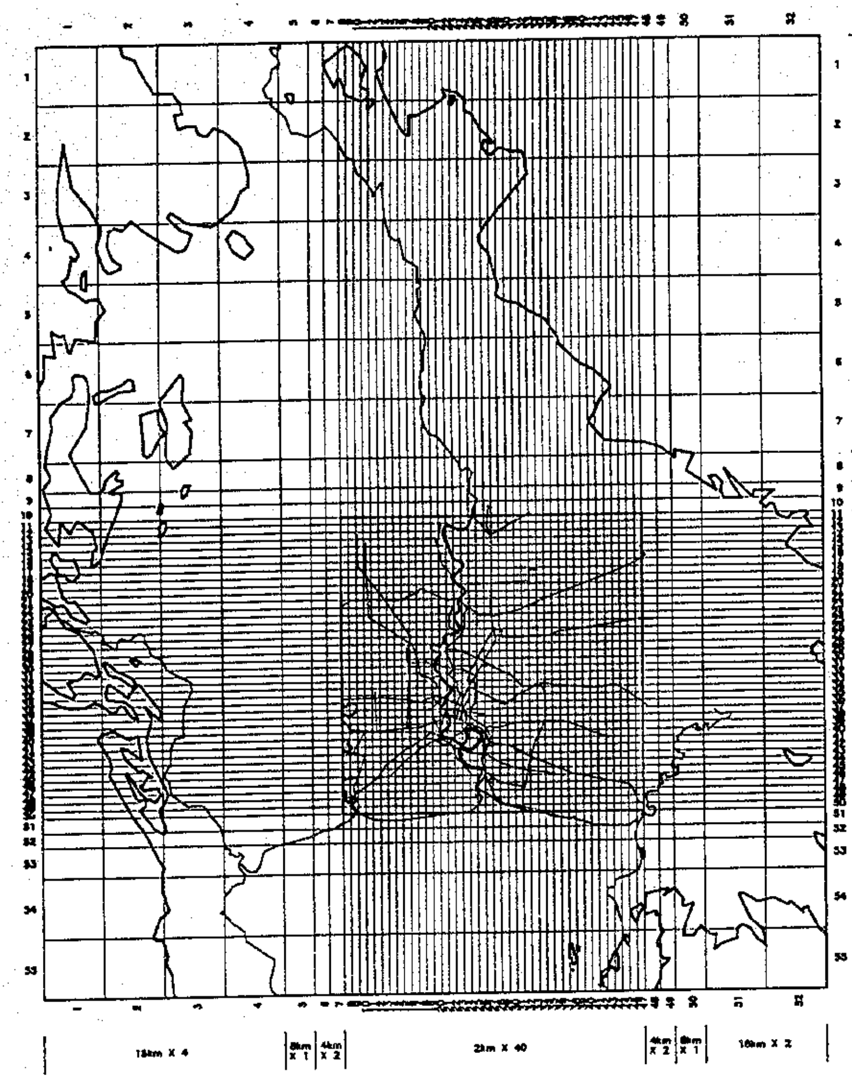
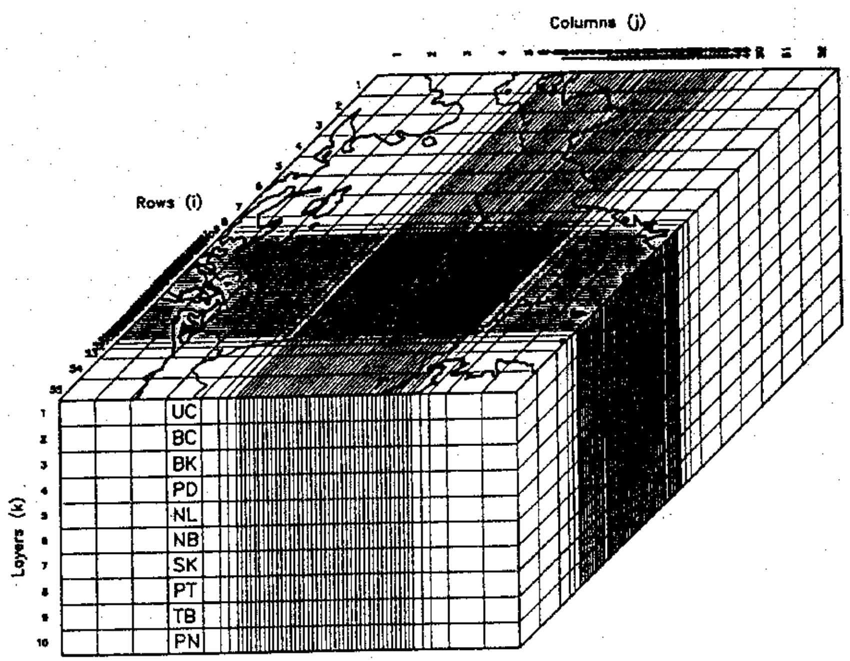


Figure 7.1.1 GRID FOR 3-D MODFLOW MODEL

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.



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 7.1.2 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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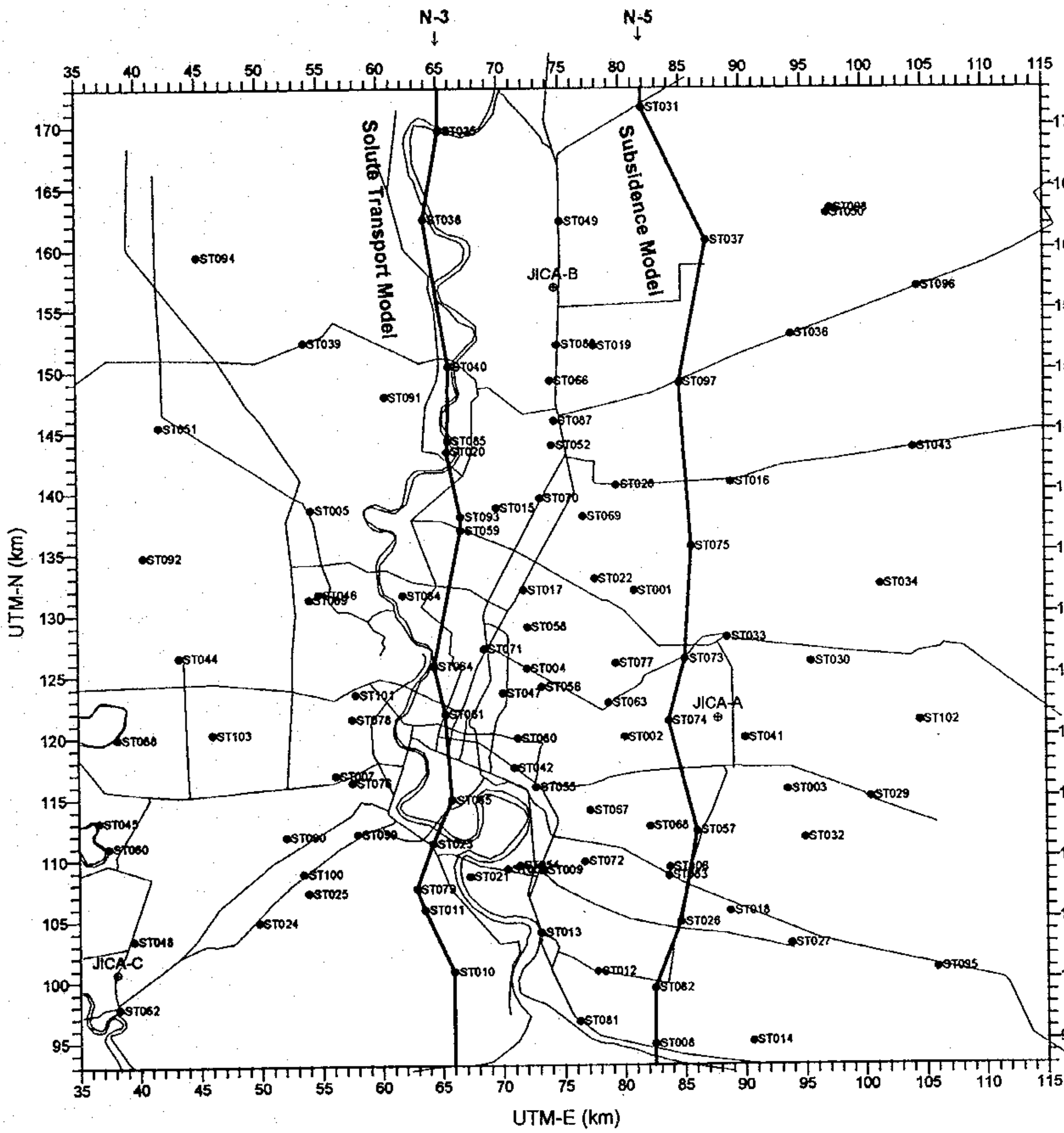

LEGEND

———	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	**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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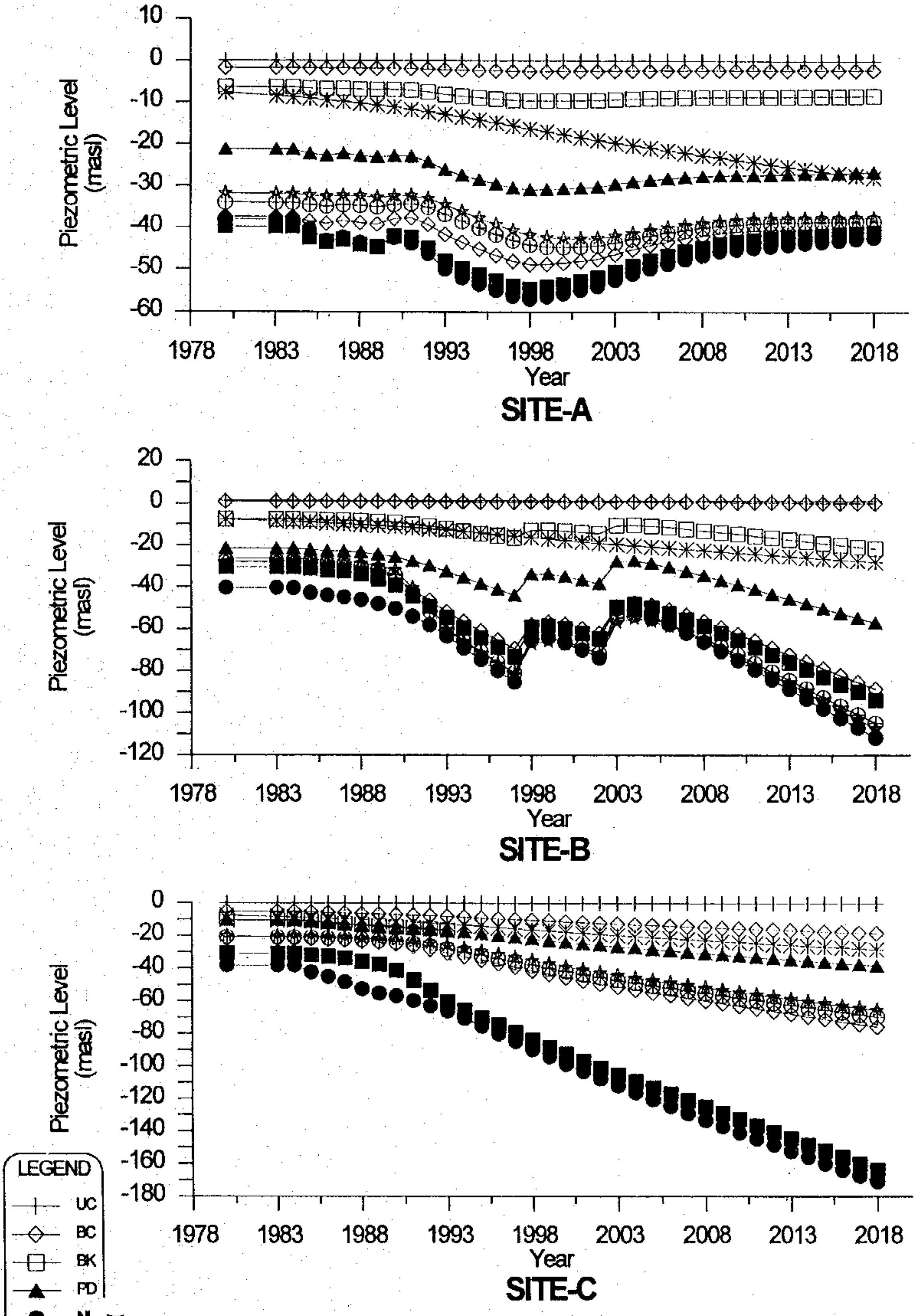

図 8.2.1 JICAモニタリング井周辺の地下水位変化予測値（シナリオ2）

SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 2)

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.

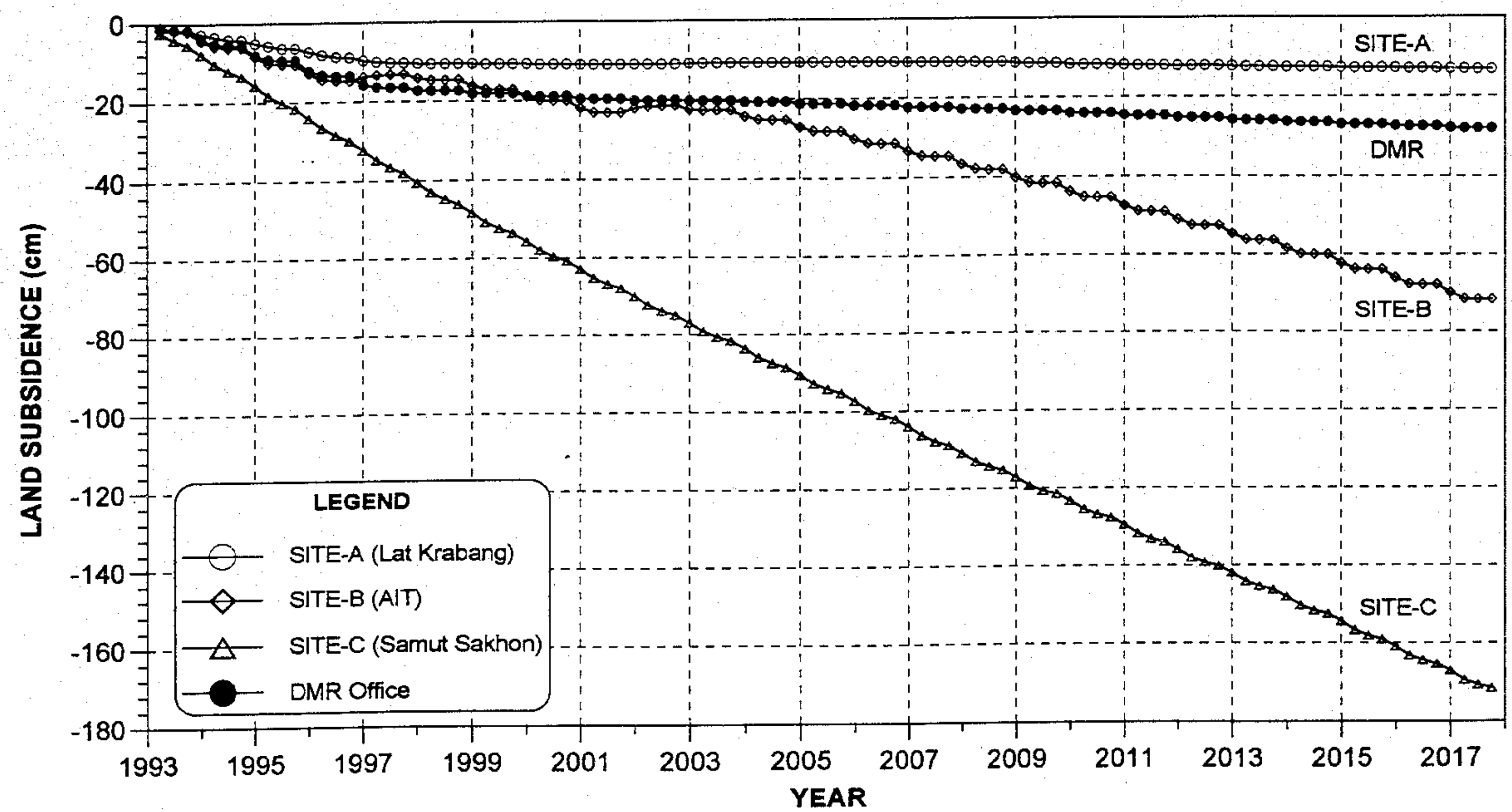

Figure 7.2.75	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 2)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

図　8.2.2　JICAモニタリング井周辺の地盤沈下予測値（シナリオ2）

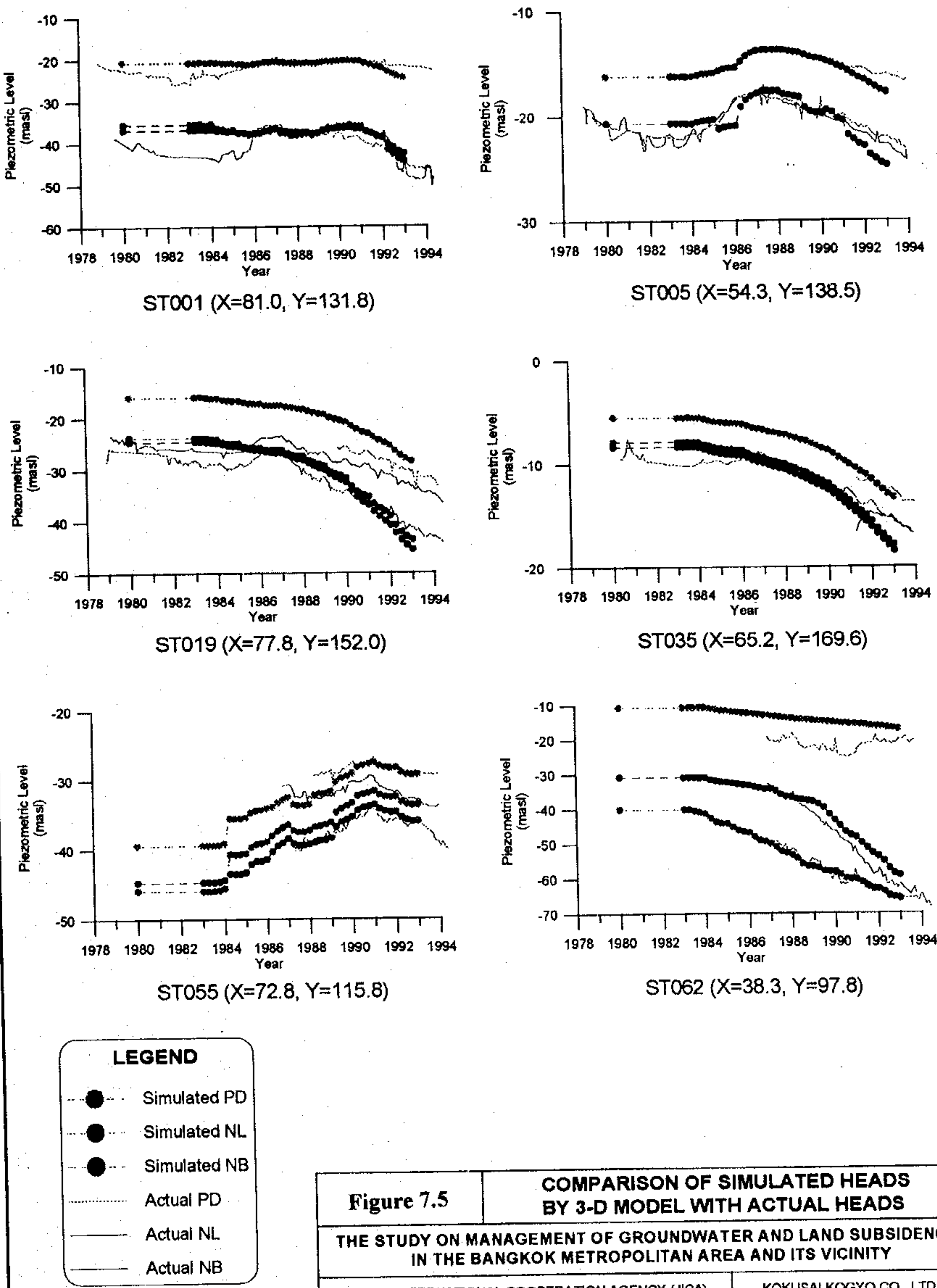

Figure 7.5	COMPARISON OF SIMULATED HEADS BY 3-D MODEL WITH ACTUAL HEADS
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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CHAPTER 8 PREDICTION OF LAND SUBSIDENCE

CHAPTER 8 PREDICTION OF LAND SUBSIDENCE

In order to predict future land subsidence, nine (9) future pumping scenarios were prepared by considering several conditions and constraints. A 25-year prediction period was taken from 1993 to 2017. Each scenario was prepared based on the actual pumpage in 1992 (Tables 8.1 and 8.2).

SCENARIO 1

Pumpage of the private and public wells (except MWA wells) will increase according to the trend. The MWA wells are stepwise phased out by 2007. The future production of IEAT wells will be according to plan and available facilities.

The computed piezometric levels will drop abruptly in the whole area from 1993 to 2017. Water levels of main aquifers will decline from 8 m to 180m in 2017 in the heavily pumped area, such as Lat Krabang, Pathum Thani and Samut Sakhon.

Land subsidence will occur severely in the whole area. The cumulative subsidence from 1993 to 2017 will exceed 200 cm in Samut Sakhon. Most of the Study Area will subside more than 50 cm. The subsidence of more than 100 cm will occur in Samut Prakan, Bangkok, Pathum Thani, Samut Sakhon, and part of Nakhon Pathom. Areas of subsidence with more than 150 cm will be found in Samut Prakan and Samut Sakhon (Figures 8.1.1 to 8.1.3).

SCENARIO 2

In the MWA service area, the MWA wells will be phased out by 2007 and private wells will be replaced by piped water supply. In Pathum Thani, the PWA wells will be gradually phased out from 1997 to 2001. Private wells will decrease and will be replaced by other water source. The future production of IEAT wells will be according to plan and available facilities. In Samut Sakhon, Ayutthaya and Nakon Pathum, the pumpage will be the same as that of Scenario 1.

The piezometric levels of the NL Aquifer will recover about 15 m from 1998 to 2017 in Lat Krabang area. In Pathum Thani, the piezometric levels will recover when surface water will be supplied to the area, however, the piezometric levels will again drop. Since Samut Sakhon area is not covered by any water supply project, water levels will decline 160 m to170 m below mean sea level similar to that of Scenario 1.

The subsidence of the central and eastern Bangkok almost stopped from 1988. In northern Bangkok, the subsidence will become mild from 1997 to 2003 with small rebound. However, subsidence will again occur from 2004 at the rate more than 3 cm/year. The subsidence will continue in Samut Sakhon and the total subsidence will reach to 170 cm in the year 2017. In Bangkok and Samut Prakan, the total land subisidence will be less than 50cm in the year 2017 (Figures 8.2.1 to 8.2.3).

SCENARIO 3

All types of pumpage will be regulated from 1997 at at that year's amount in the present critical zone. The pumpage outside of the critical zone is the same as that of Scenario 1.

The decline of piezometric levels in the present critical zones 1 and 2 will stabilize. However, the piezometric levels at Site-B (AIT) and Site-C (Samut Sakhon) will drop abruptly because these areas are not included in the present critical zone. The piezometric levels at Site-A (Lat Krabang) will again drop after 2008 even if the pumpage is maintained at a constant rate because of the pumpage increase in Pathum Thani.

The land subsidence in central and northern Bangkok will become mild from 1998 to 2008. However, the rate will increase again from 2009. The subsidence in Lat Krabang and Samut Sakhon will significantly continue until 2017.

Most of the areas under the present critical zones 1 and 2 will subside more than 50 cm by 2017. Severe subsidence will occur in Pathum Thani and Samut Sakhon. The total subsidence will reach from 100cm to 175cm (Figures 8.3.1 to 8.3.3).

SCENARIO 4

In the present critical zones 1 and 2 (in Bangkok, Nonthaburi and Samut Prakan), all types of pumpage from 1997 to 2001 will be regulated at 1997's amount (Figure 8.10.1). In the critical zone 3, all types of pumpage from 2000 are regulated at 2000's amount. However, the outside of the critical zone follows that of Scenario 1.

The piezometric levels at Site-A (Lat Krabang) will clearly recover from 2002 due to the reduction of pumpage at the present critical zones 1 and 2. The piezometric levels of the main aquifers will be higher than those at present. However, the piezometric levels of NL Aquifer at Site-B (AIT) and Site-C (Samut Sakhon) will drop abruptly by -187 masl and by -170 masl, respectively, in the year 2017.

The land subsidence in central and eastern Bangkok will stop from the year 2001, then slight rebound will occur. However, the subsidence at Site-B and Site-C will significantly continue like Scenario 1. The scenario will be effective in the present critical zone. The subsidence in 2017 will reach to about 25 cm in the area. But in Pathum Thani and Samut Sakhon, more than 100 cm of severe subsidence is predicted (Figures 8.4.1 to 8.4.3).

SCENARIO 5A

The new critical zone covers Bangkok, Nonthaburi,Pathum Thani,Samut Prakan and Samut Sakhon (Figure 8.10.2). In the new critical zone, all types of pumpage will be kept at 2000's amount. Outside of the new critical zone, the pumpage is the same as in Scenario 1.

The piezometric levels at Site-A will slightly recover from the year 2000 and the rate of decline at Site-B and Site-C will become small after the year 2000. The piezometric levels of NL Aquifer at Site-A, Site-B, and Site-C in 2017 will be 59 m, 114 m and 111m below mean sea level, respectively.

The total subsidence in the year 2017 is predicted as 96 cm at Site-C, 58 cm at central Bangkok, 56 cm at Site-B, and 30 cm at Site-A. The area will subside more than 100 cm in the year 2017 but no subsidence of more than 100 cm will occur in Pathum Thani and Samut Sakhon. More than 50 cm of land subsidence will be widely distributed even in the new critical zone (Figures 8.5.1 to 8.5.3).

SCENARIO 5B

The pumpage increase will be the same as that of Scenario 1 until the year 1999 in the new critical zone. From 2000 to 2010, all types of pumpage will stepwise be reduced from 100% to 50% of 2000's amount. From the year 2011 to 2017, the pumage will be kept constant at 50% of the year 2000's amount. Pumpage outside of the new critical zone is the same as in Scenario 1.

The recovery of piezometric levels from the year 2001 will be reflected in every monitoring station. The piezometric heads of NL Aquifer will recover 33 m at Site-A, 65 m at Site-B, and 62 m at Site-C.

Subsidence will stop in the year 2001 then slightly rebound until 2011 to 2013 due to the recovery of the piezometric heads. The total subsidence in the year 2017 will be 66 cm at Site-C, 36 cm at Site-B, 32 cm at the DMR office, and 18 cm at Site-A. Land subsidence of more than 50 cm by 2017 will be sporadically distributed in Bangkok, Pathum Thani, Samut Prakan, and Samut Sakhon. In the new critical zone, subsidence of more than 50 cm by 2017 will occur only in Samut Sakhon (Figures 8.6.1 to 8.6.3).

SCENARIO 5C

The pumpage increase will be the same as in Scenario 1 until 1999 in the new critical zone. From 2000 to 2010, all types of pumpage will stepwise be reduced from 100% to 75% of 2000's amount. From 2011 to 2017, the pumpage will be kept constant at 75% of 2000's amount. Outside of the new critical zone, the pumpage is the same as Scenario 1.

The recovery of piezometric heads from 2001 to 2010 will be smaller than that of Scenario 5B. The piezometric head of NL Aquifer at Site-A will be 60 m in 2001 and 47 m below MSL in 2017. Similarly, the head of NL Aquifer at Site-B will drop to 116 m in 2001 and then will recover to 90 m in 2017. At Site-C, the head of NL Aquifer will drop to 103 m in 2001, then will recover to 88 m in 2017.

The subsidence at Site-A will stop from the year 2001 to 2011. At Site-B, Site-C, and the center of Bangkok, the rates of subsidence will become within 0.5 cm/year from 2001 to 2010, then the rates will slightly increase from 0.5 cm/year to 1.0 cm/year from 2011 to 2017. The land subsidence of more than 50 cm by 2017 is predicted in Samut Prakan, western Bangkok, part of Pathum Thani, and central Samut Sakhon (Figures 8.7.1 to 8.7.3).

SCENARIO 6

From 1993 to 1994, the pumpage increase will be the same as in Scenario 1. From 1995 to 2000, the rate of increase will be reduced to 50% of Scenario 1. From 2001 to 2010, all types of pumpage will stepwise be reduced from 100% to 75% of 2000's amount. Outside of the new critical zone, the pumpage will be kept constant at 2000's amount.

The decline during the eight (8) years from the year 1993 to 2001 will become smaller than that in Scenario 5C. The piezometric head of NL Aquifer at Site-A will be 57 m below MSL in 2001 and 41 m in 2017. Similarly, the head of NL Aquifer at Site-B will drop to 87 m below MSL in 2001 and then recovers to 73 m in 2017. At Site-C, the head of NL Aquifer will drop to 88 m in 2001, then will recover to 72 m in 2017.

Land subsidence in the year 2001 will decrease comparing with that of Scenario 5C. The total subsidence in the year 2001 will be 42 cm. It will become 48 cm in the year 2017. The total subsidence at Site-A, Site-B, and the central Bangkok will be controlled within 20 cm in the year 2000. Land subsidence of more than 50 cm will no longer exist in the new critical zone (Figures 8.8.1 to 8.8.3).

SCENARIO 7

From 1993 to 1994, the pumpage will be the same as in Scenario 1. From 1995 to 2000, the pumpage will be regulated at 1994's amount. From 1995 to 2000, the total pumpage will be regulated at 1994's amount. From 2001 to 2010, all types of pumpage will stepwise be reduced from 100% to 75% of 2000's amount. From 2011 to 2017, the pumpage will be kept at 75% of 2000's amount. The pumpage in other area follows that of Scenario 1.

The piezometric head of major aquifers will recover after the year 2001. At Site-A, the piezometric head of NL Aquifer will be 55 m below MSL in the year 2001 and 38 m in 2017. Similarly, the head of NL Aquifer at Site-B will drop to 80 m in 2001 and then will recover to 68 m in 2017. At Site-C, the head of NL Aquifer will drop to 80 m in 2001, then will recover to 66 m in 2017.

The total land subsidence in the year 2001 will decrease comparing with that of Scenario 6. The subsidence at Site-C in the year 2001 will be 31 cm. It will become 36 cm in the end of 2017. The subsidence at Site-A, Site-B, and central Bangkok will be controlled within 30 cm in the year 2017.

The subsidence in most of the Study Area will be controlled within 30 cm in 2017. Land subsidence of more than 30 cm in the year 2017 is predicted at western Samut Prakan, western Bangkok, central Bangkok, part of Pathum Thani, and part of Phra Nakhon Si Ayutthaya (Figure 8.9.1 to 8.9.3)

Table 8.1 SUMMARY OF FUTURE PUMPAGE SCENARIOS

SCENARIO	ASSUMPTION
Scenario 1	Private wells and public wells (except IEAT and MWA wells) = Past 5 years trend extrapolated to the future. IEAT wells = Each industrial estate's plan. MWA wells = Stepwise phased out by 2007 from 1993.
Scenario 2	MWA responsible area (BKK, NTB, SPK) = MWA wells stepwise phased out by 2007 from 1993. Decrease private pumpage by MWA Master Plan. Pathum Thani = PWA wells phased out by 2001 from 1997. Supply surface water by PWA's plan. IEAT wells = Each industrial estate's plan. SSK, AYT, and NPT = Same as Scenario 1.
Scenario 3	Present Critical Zones 1&2 (in BKK and SPK) = Regulate all types of pumpage (except MWA) from 1998 at 1997's amount. MWA wells = Same as Scenario 1. Outside of Present Critical Zones 1&2 = Same as Scenario 1.
Scenario 4	Present Critical Zones 1&2 (in BKK and SPK) = Regulate all types of pumpage (except MWA) from 1998 to 2001 at 1997's amount. Stepwise reduction from 2002, 50% in 2007, 35% in 2012. Maintain 35% of 1997's pumpage from 2013 to 2017. Present Critical Zone 3 (BKK, NTB, and SPK) = Regulate all types of pumpage (except MWA) from 2001 at 2000's amount. MWA wells = Same as Scenario 1. Outside of Present Critical Zones = Same as Scenario 1.
Scenario 5A	New Critical Zone (in BKK, NTB, PTM, SPK, and SSK) = By 2000: Same as Scenario 1 From 2001 to 2017: Regulate all types of pumpage (except MWA) at 2000's amount. MWA wells = Same as Scenario 1. Outside of New Critical Zone = Same as Scenario 1.
Scenario 5B	New Critical Zone (in BKK, NTB, PTM, SPK, and SSK) = By 2000: Same as Scenario 1 From 2001 to 2010: Reduce all types of pumpage (except MWA) from 100% to 50 % of 2000's amount. From 2011 to 2017: Maintain 50% of 2000's amount. MWA wells = Same as Scenario 1. Outside of New Critical Zone = Same as Scenario 1.
Scenario 5C	New Critical Zone (in BKK, NTB, PTM, SPK, and SSK) = By 2000: Same as Scenario 1 From 2001 to 2010: Reduce all types of pumpage (except MWA) from 100% to 50 % of 2000's amount. From 2011 to 2017: Maintain 75% of 2000's amount. MWA wells = Same as Scenario 1. Outside of New Critical Zone = Same as Scenario 1.
Scenario 6	New Critical Zone (in BKK, NTB, PTM, SPK, and SSK) = From 1993 to 1994: Same as Scenario 1. From 1995 to 2000: Reduce pumpage increasing rate at 50% of Scenario 1. From 2001 to 2010: Reduce all types of pumpage (except MWA) from 100% to 75% of 2000's amount. From 2011 to 2017: Maintain 75% of 2000's amount. MWA wells = Same as Scenario 1. Outside of New Critical Zone = Same as Scenario 1.
Scenario 7	New Critical Zone (in BKK, NTB, PTM, SPK, and SSK) = From 1993 to 1994: Same as Scenario 1. From 1995 to 2000: Regulate all types of pumpage (except MWA) at 1994's amount. From 2001 to 2010: Reduce all types of pumpage (except MWA) from 100% to 75% of 2000's amount. From 2011 to 2017: Maintain 75% of 2000's amount. MWA wells = Same as Scenario 1. Outside of New Critical Zone = Same as Scenario 1.

Table 8.2 RESULTS OF FUTURE SIMULATION

SCENARIO No.	RESULTS		REMARKS
	WATER LEVEL	LAND SUBSIDENCE	
1	Straight drop in all area. Lowest W.L. = -190m in 2017.	Sharp increase in all area. Max. L.S. = 200cm by 2017.	Worst scenario.
2	Recovered from 1998 in BKK, NTB, SPK. Step rise and drop in PTM. Drop continues in SSK. Lowest W.L. = -170m in 2017.	Stabilize from 1997 in BKK, NTB, SPK. Increase rate from 2004 in PTM. Sharp increase in PTM and SSK. Max. L.S. = 175cm by 2017.	Effective in BKK, NTB, and SPK. Better than Scn. 1 in PTM. Severe in SSK.
3	Stabilize then drop in critical zone. Straight drop in PTM and SSK. Lowest W.L. = -190m in 2017.	Slightly decrease rate in critical zone. Sharp increase in PTM and SSK. Max. L.S. = 190cm by 2017.	Still worse in critical zone. Severe in PTM and SSK.
4	Clear recovery in critical zone. Straight drop in PTM and SSK. Lowest W.L. = -187m in 2017.	Stabilize then slightly rebound in critical zone. Sharp increase in PTM and SSK. Max. L.S. = 175cm by 2017.	Effective in critical zone. Severe in PTM and SSK.
5A	Slight recover then slight drop in BKK, NTB, and SPK. Decrease drop rate in PTM and SSK. Lowest W.L. = -114m in 2017.	Decrease rate in new critical zone from 2001. Max. L.S. = 96cm by 2017.	Subsidence by 2017 is less than 100cm in the Study Area, but more than 50cm in BKK, PTM, SPK, and SSK.
5B	Clear recovery from 2001 in new critical zone. Lowest W.L. = -65m in 2017.	Stop then slightly rebound in new critical zone. Max. L.S. = 66cm by 2017.	Subsidence by 2017 is less than 50cm in eastern area, but more than 50cm in south-western area.
5C	Gentle recover from 2001 in new critical zone. Lowest W.L. = -103m in 2017.	Almost stop from 2001 in new critical zone. Max. L.S. = 74cm by 2017.	2.5% of annual pumpage decrease is still effective to stop land subsidence. Large subsidence occurs by 2000.
6	Drop rate decreases from 1995 to 2000. Lowest W.L. = -87m in 2017.	Subsidence rate by 2001 become 2/3 compared with Scenario 5C. Max. L.S. = 48 cm by 2017.	Reduction of pumpage increasing rate is effective. Less than 50cm subsidence in SSK.
7	Drop rate become smaller from 1995 to 2000 Lowest W.L. = -80m in 2017.	Subsidence rate by 2001 become 1/2 compared with Scenario 5C. Max. L.S. = 36cm by 2017.	Most effective scenario. Subsidence by 2017 is mostly 10cm to 30cm.

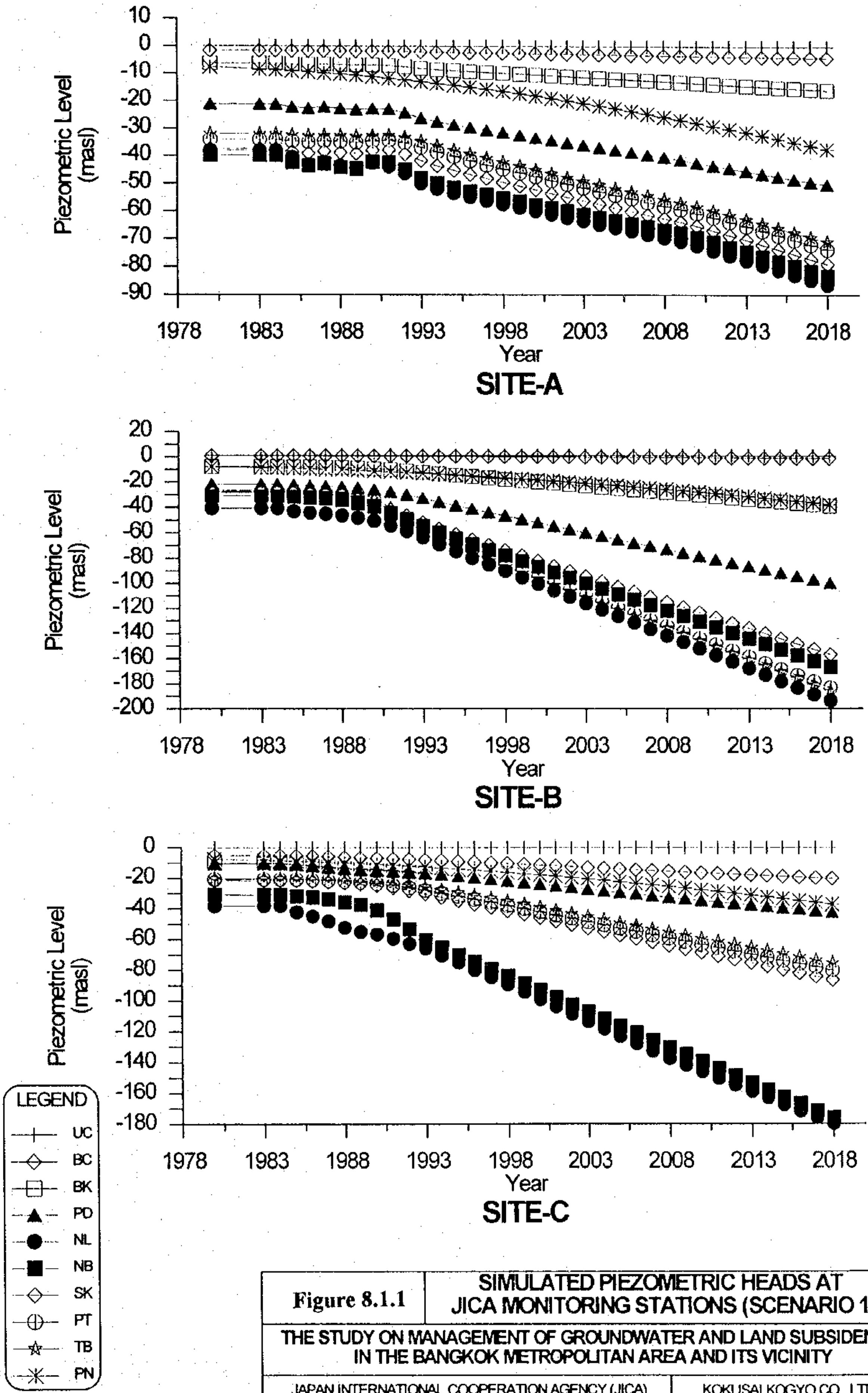


Figure 8.1.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 1)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

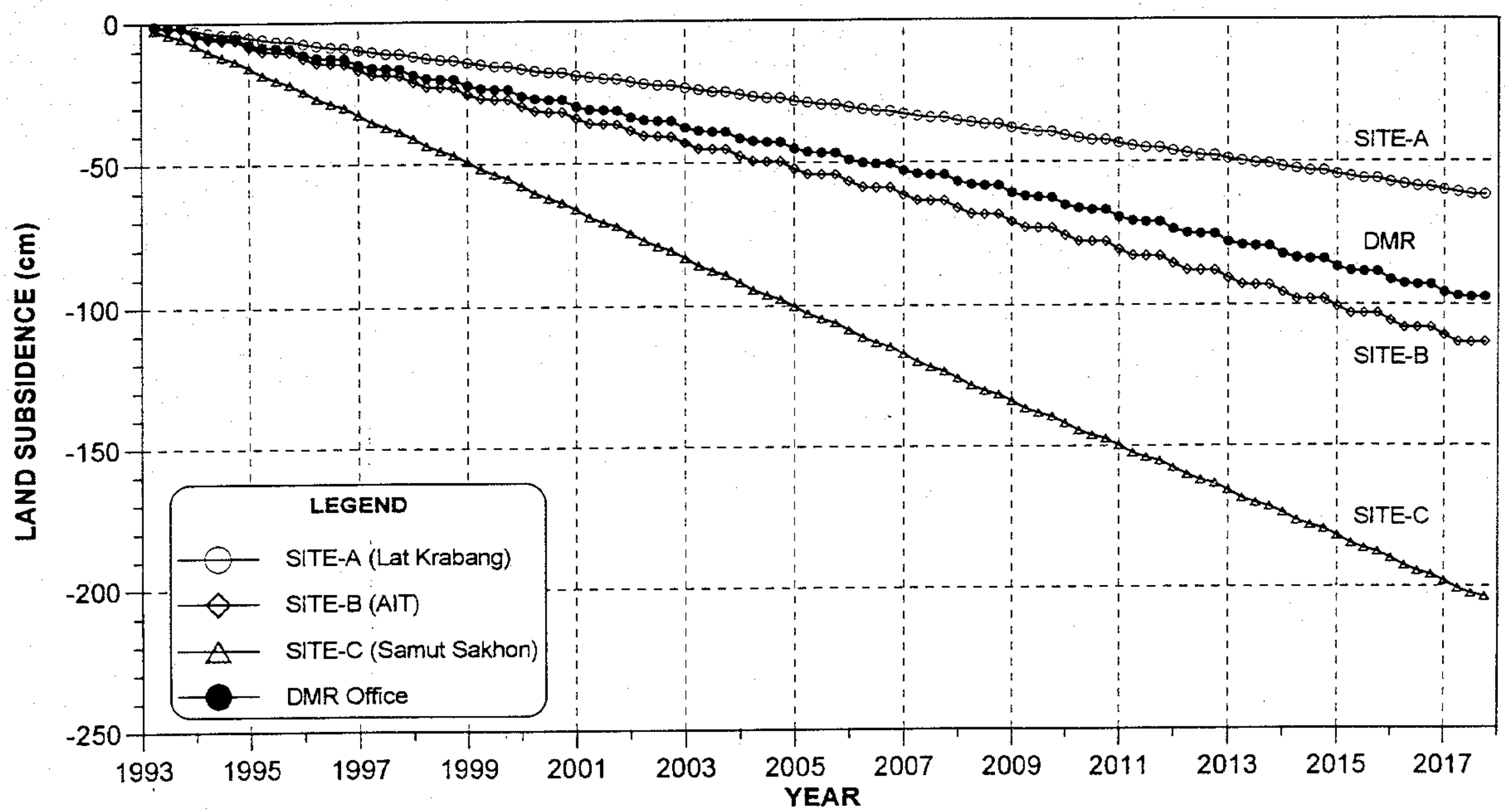
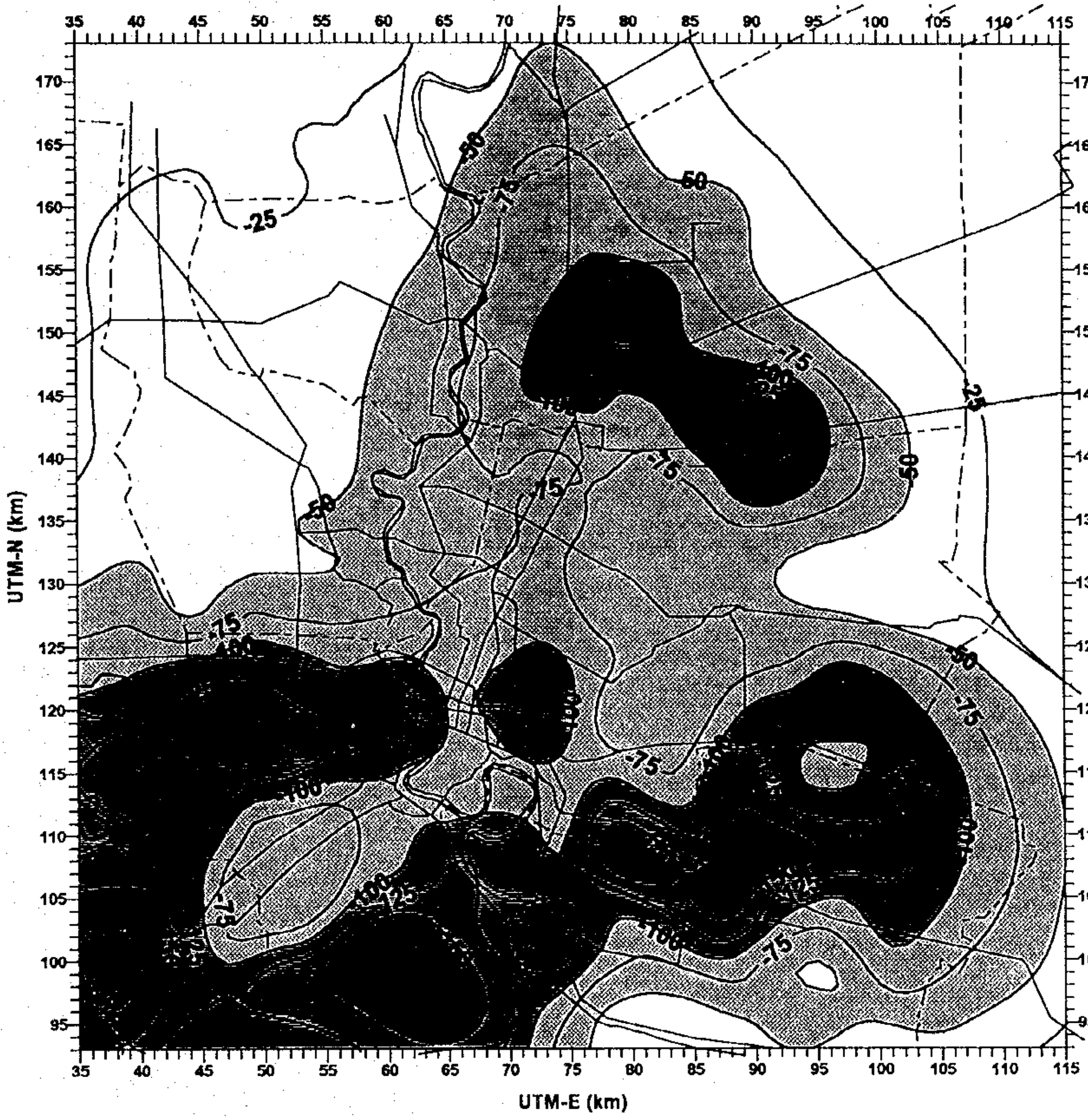
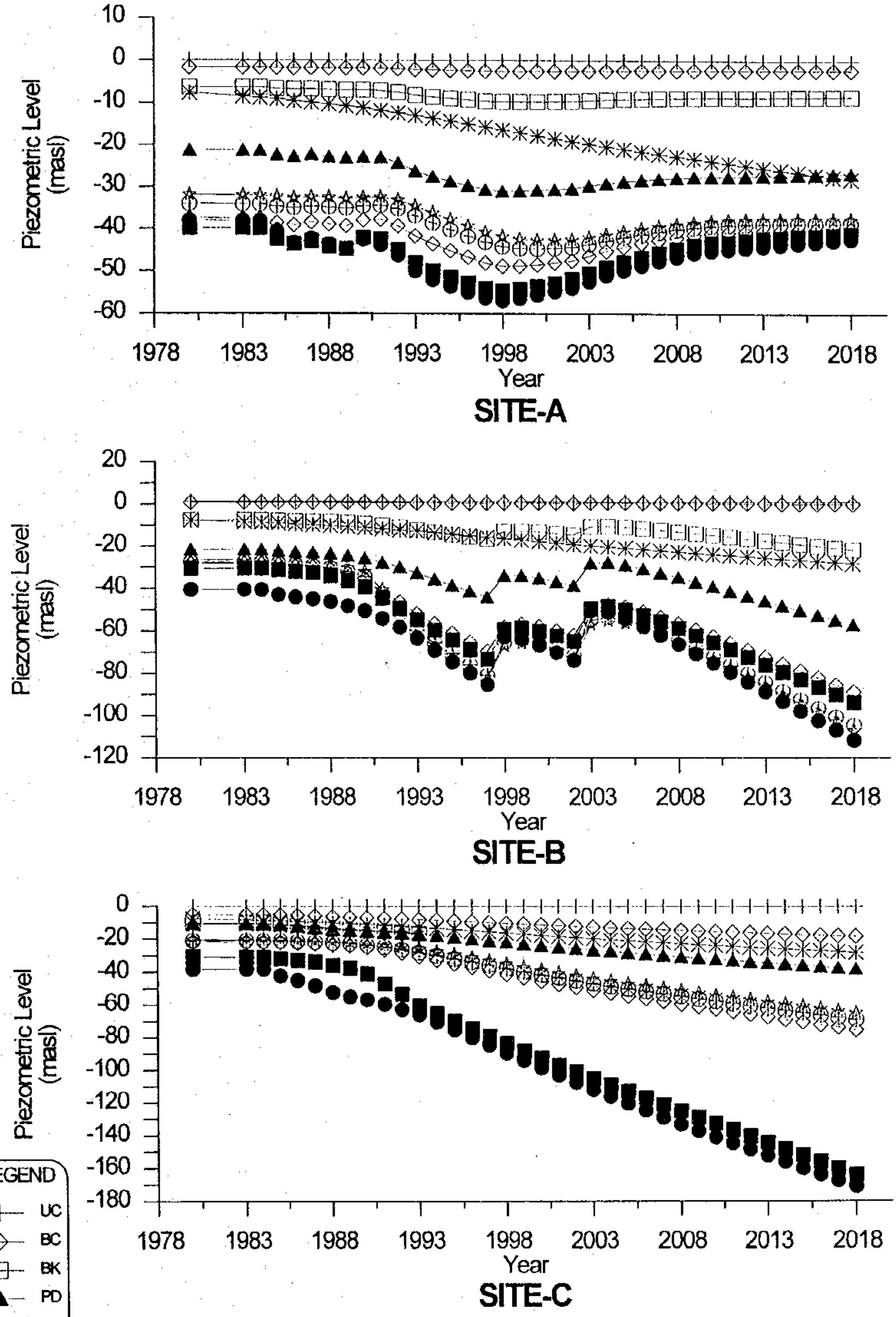


Figure 8.1.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 1)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



SIMULATED LAND SUBSIDENCE (cm)
FROM 1993 TO 2017 (25 years)
BY FUTURE SCENARIO 1

Figure 8.1.3	SIMULATED LAND SUBSIDENCE BY FUTURE SCENARIO 1
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.



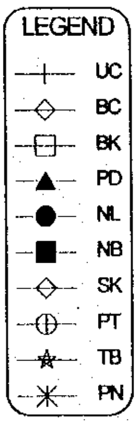


Figure 8.2.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 2)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

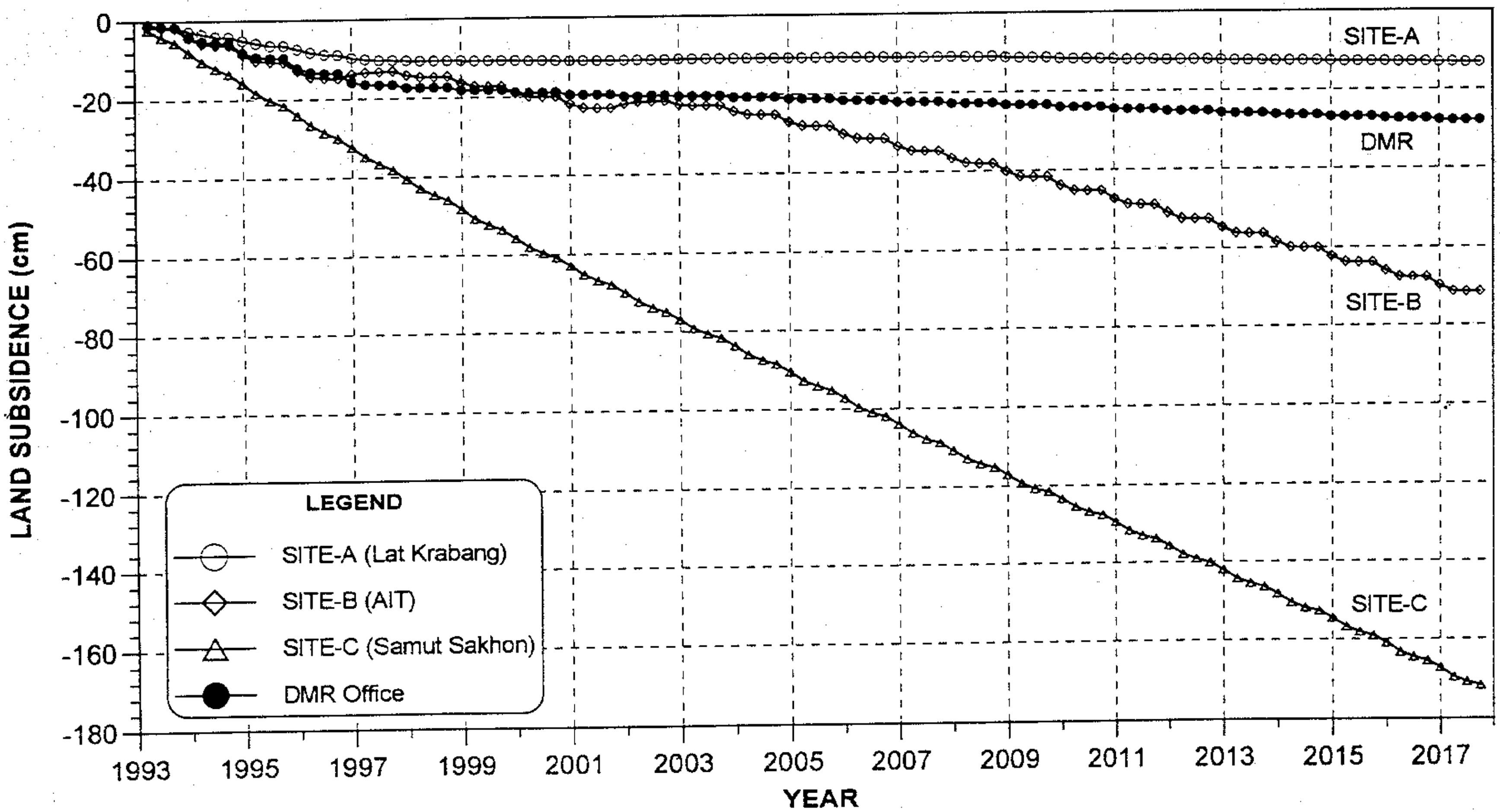
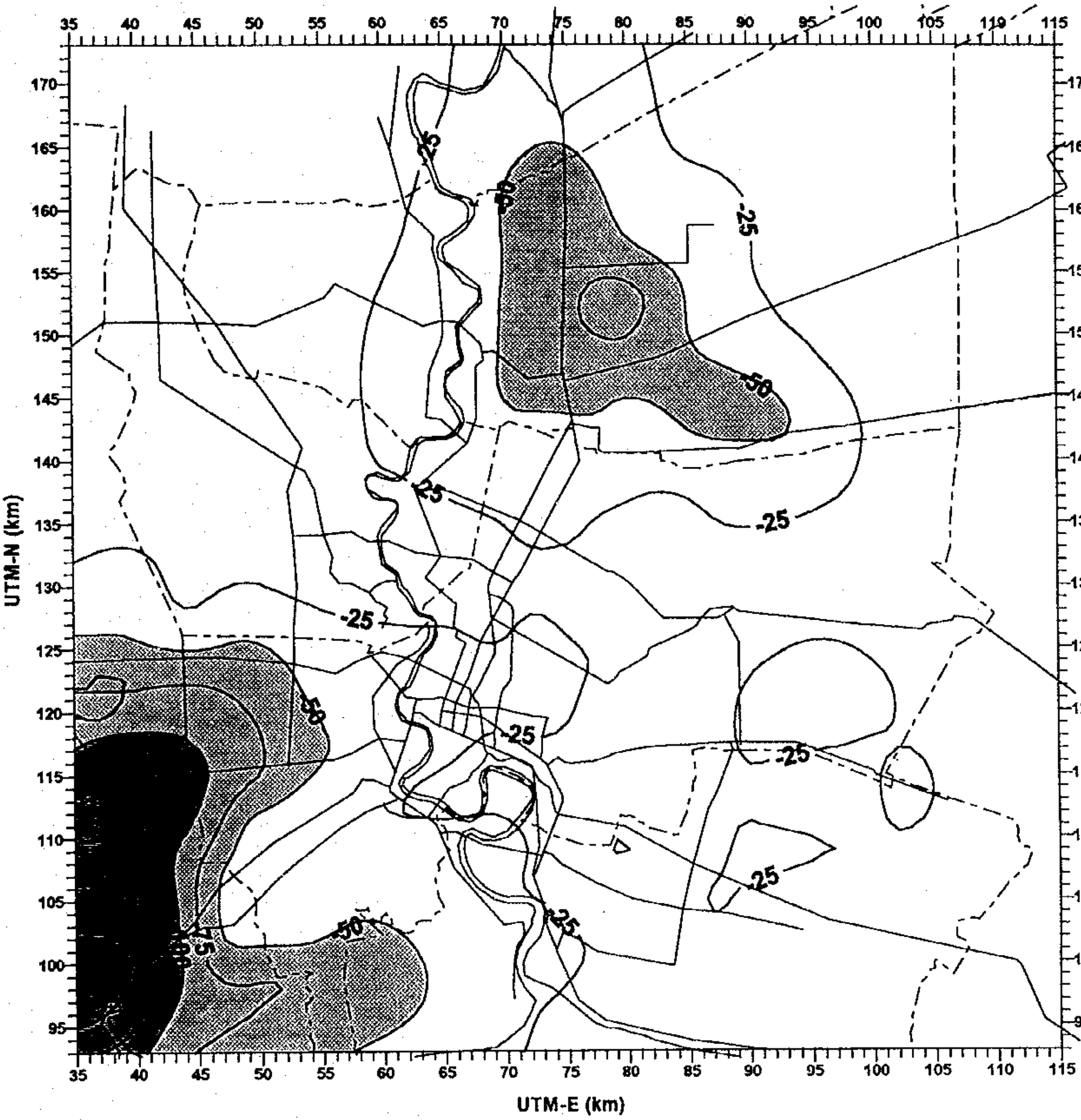


Figure 8.2.2 SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 2)

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.



SIMULATED LAND SUBSIDENCE (cm)
FROM 1993 TO 2017 (25 years)
BY FUTURE SCENARIO 2

Figure 8.2.3	SIMULATED LAND SUBSIDENCE BY FUTURE SCENARIO 2
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.

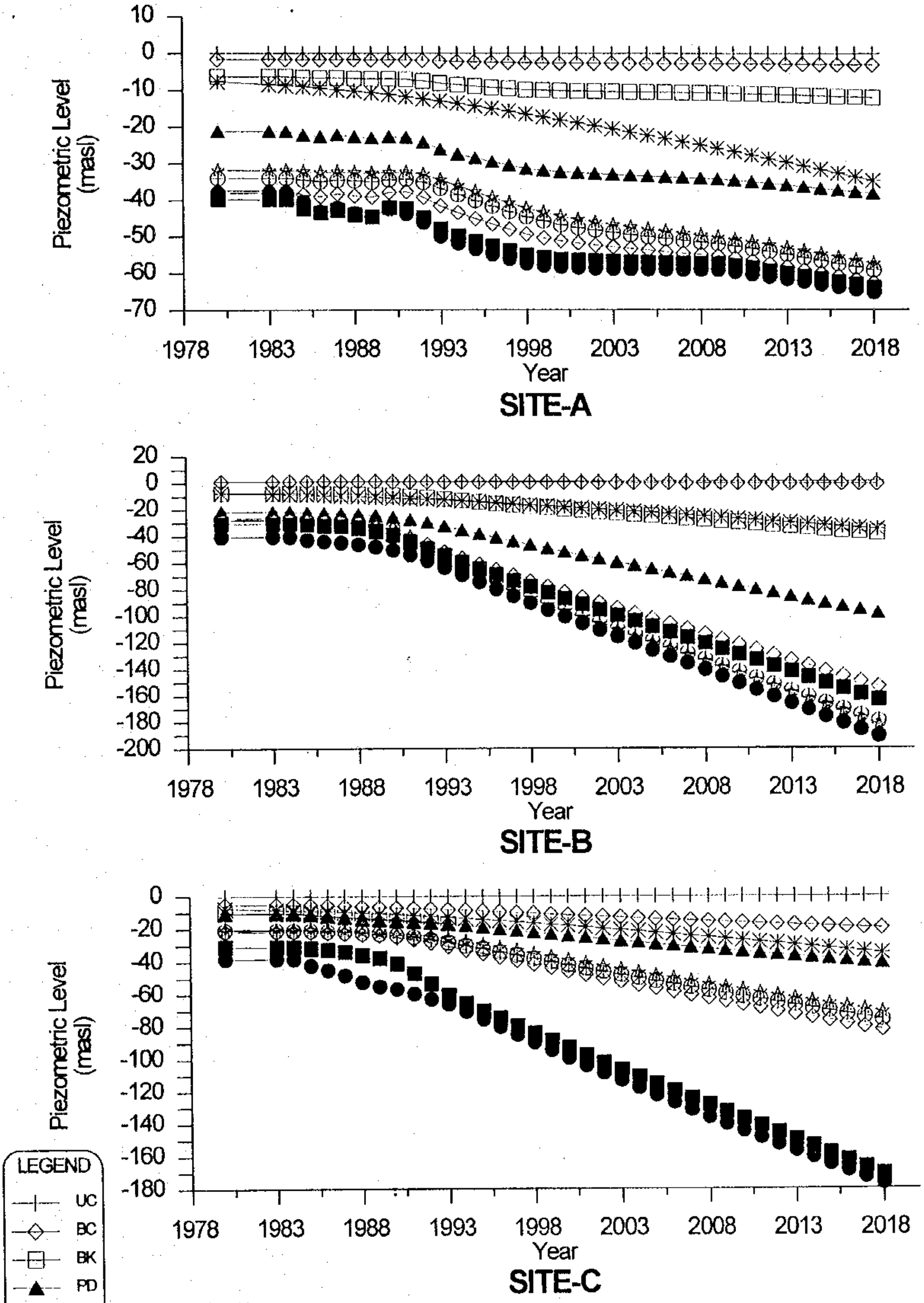


Figure 8.3.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 3)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

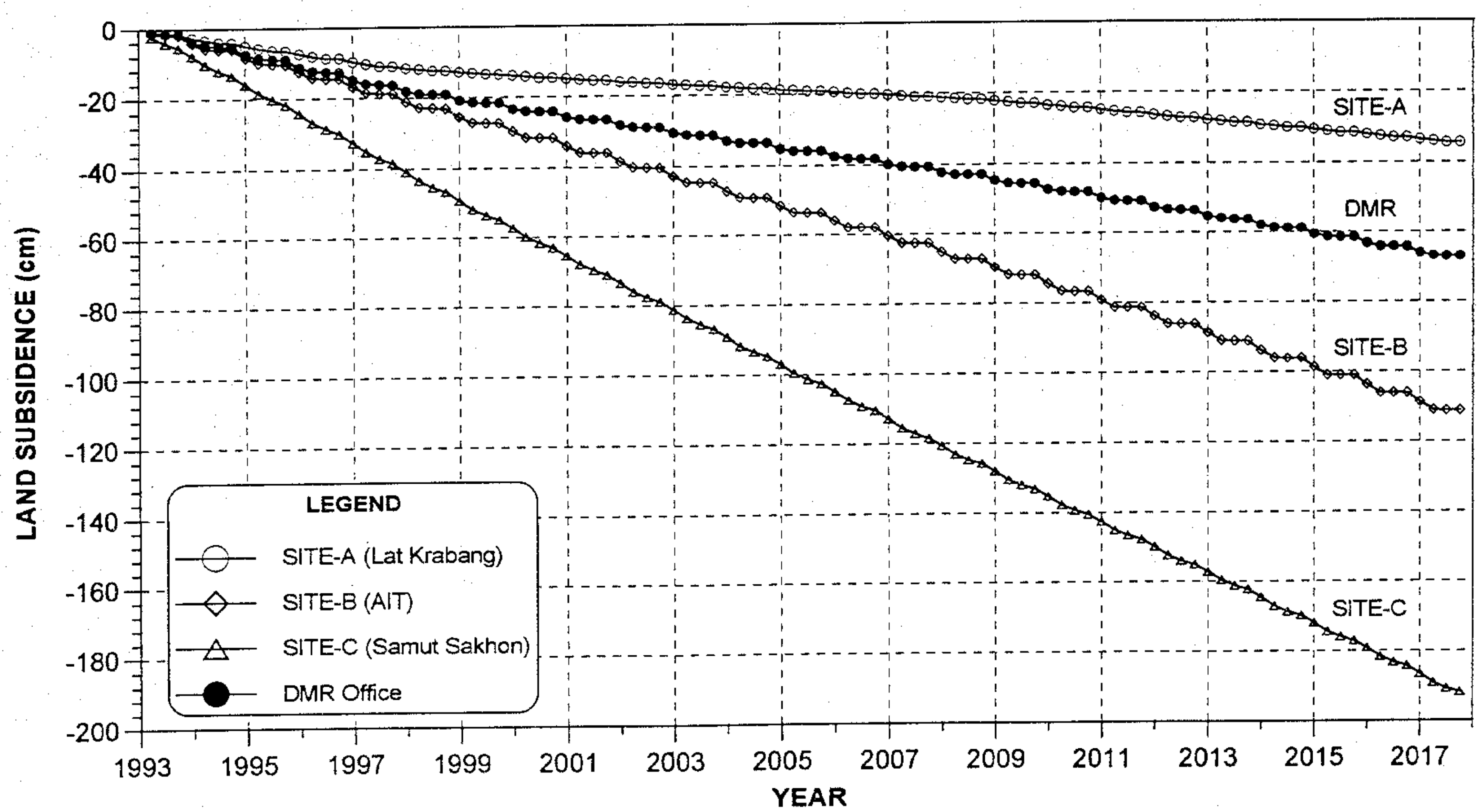
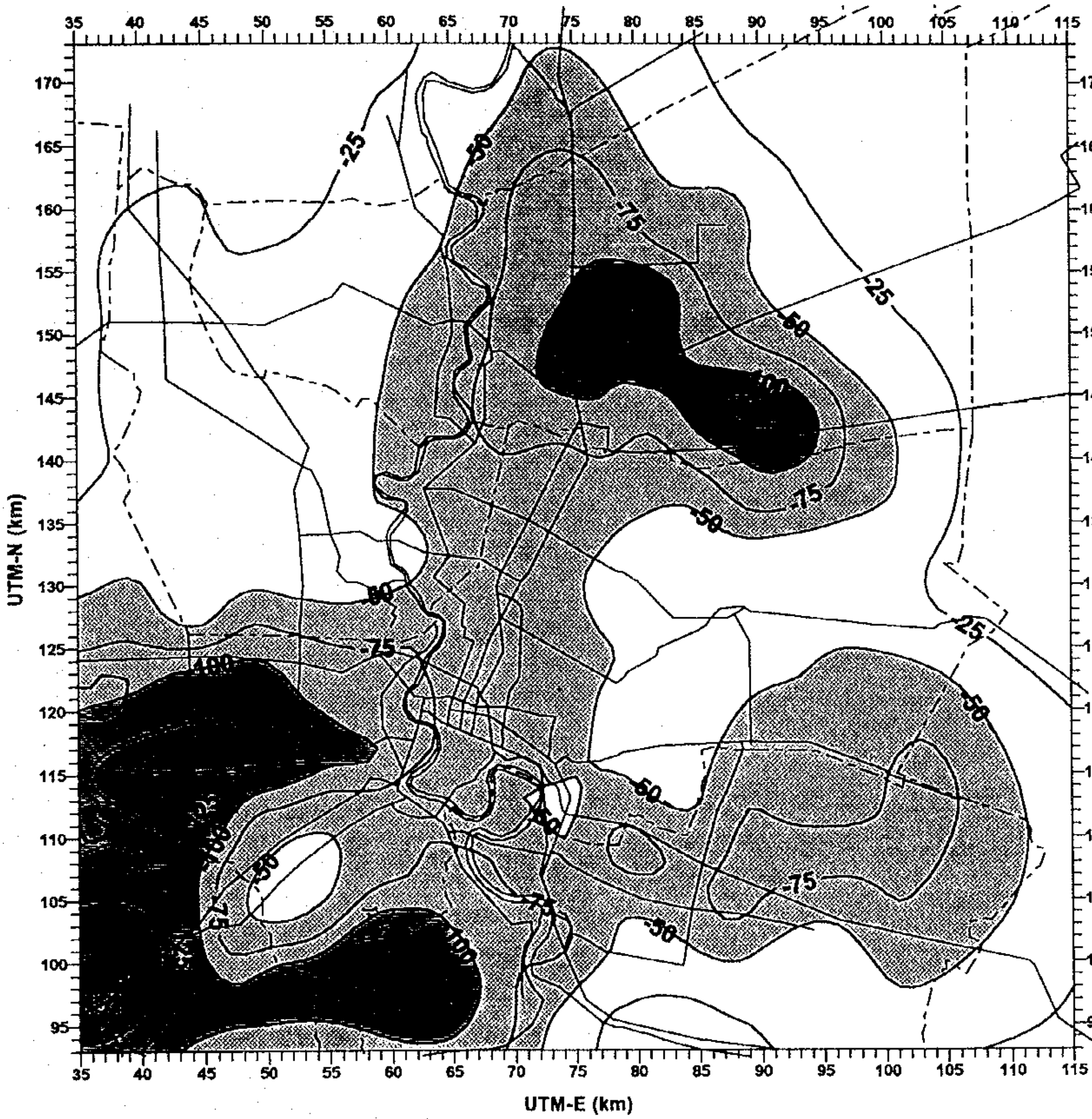
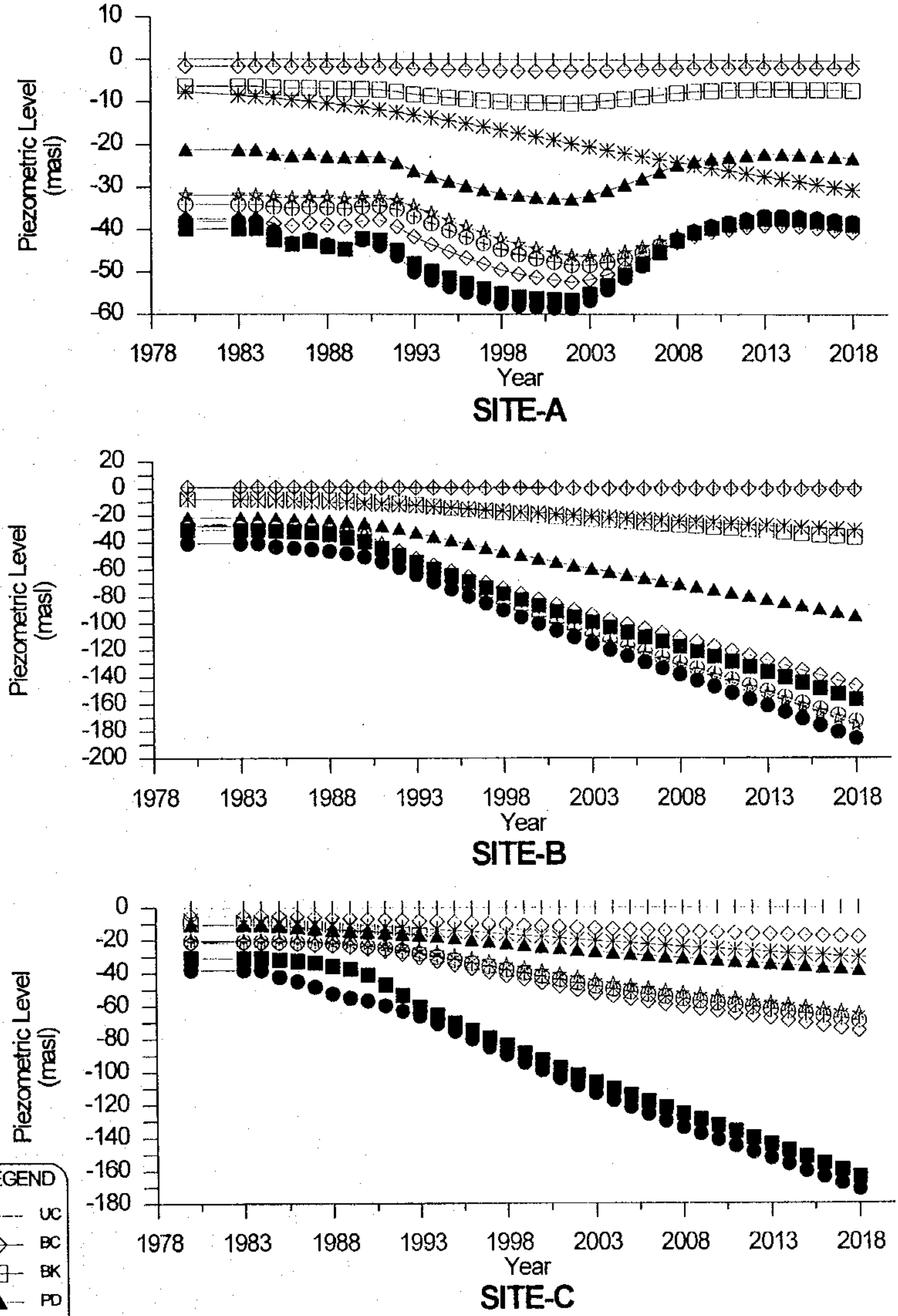


Figure 8.3.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 3)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



SIMULATED LAND SUBSIDENCE (cm) FROM 1993 TO 2017 (25 years) BY FUTURE SCENARIO 3

Figure 8.3.3	SIMULATED LAND SUBSIDENCE BY FUTURE SCENARIO 3
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.



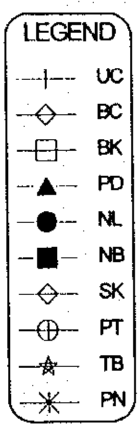


Figure 8.4.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 4)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

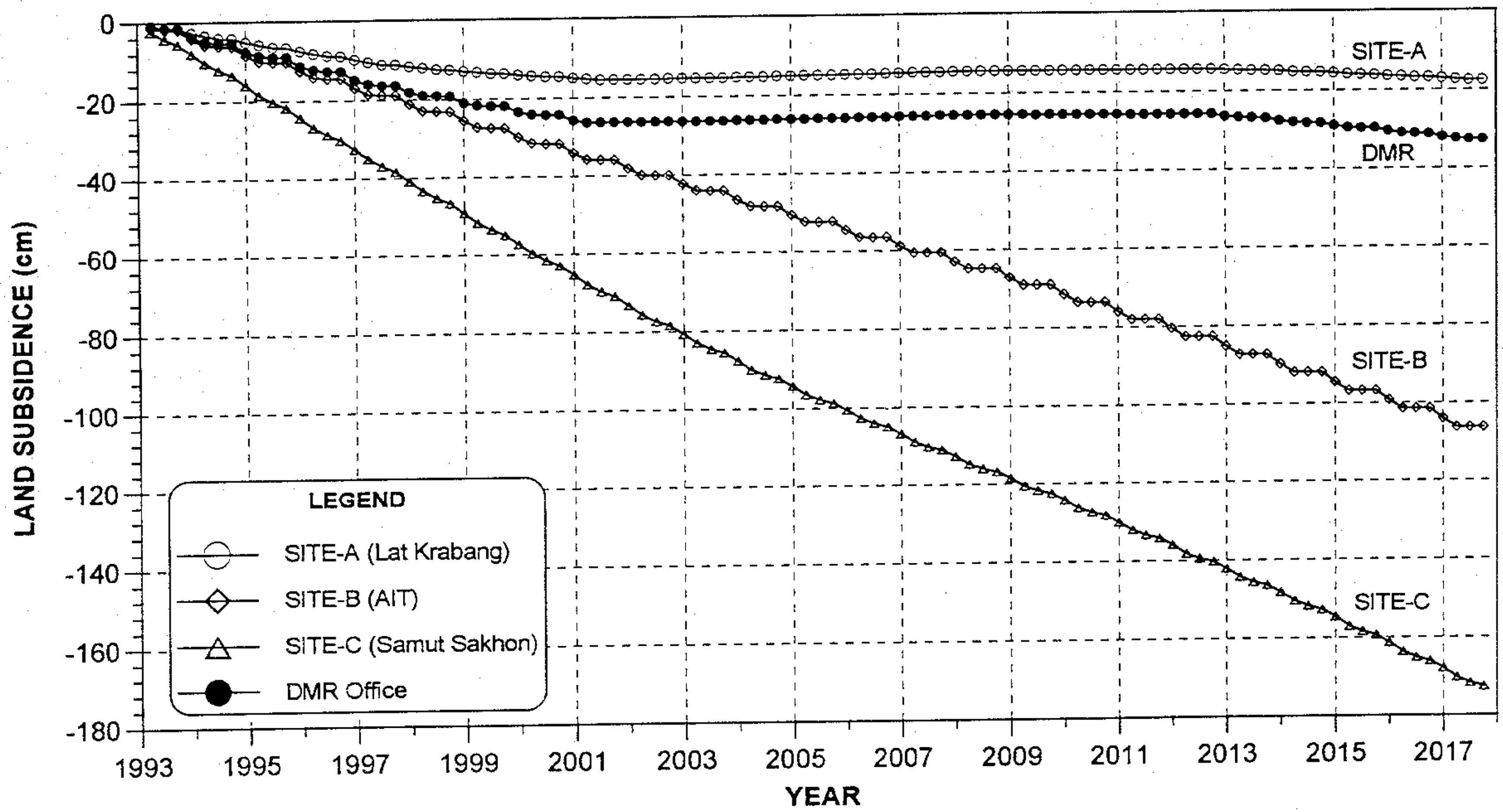
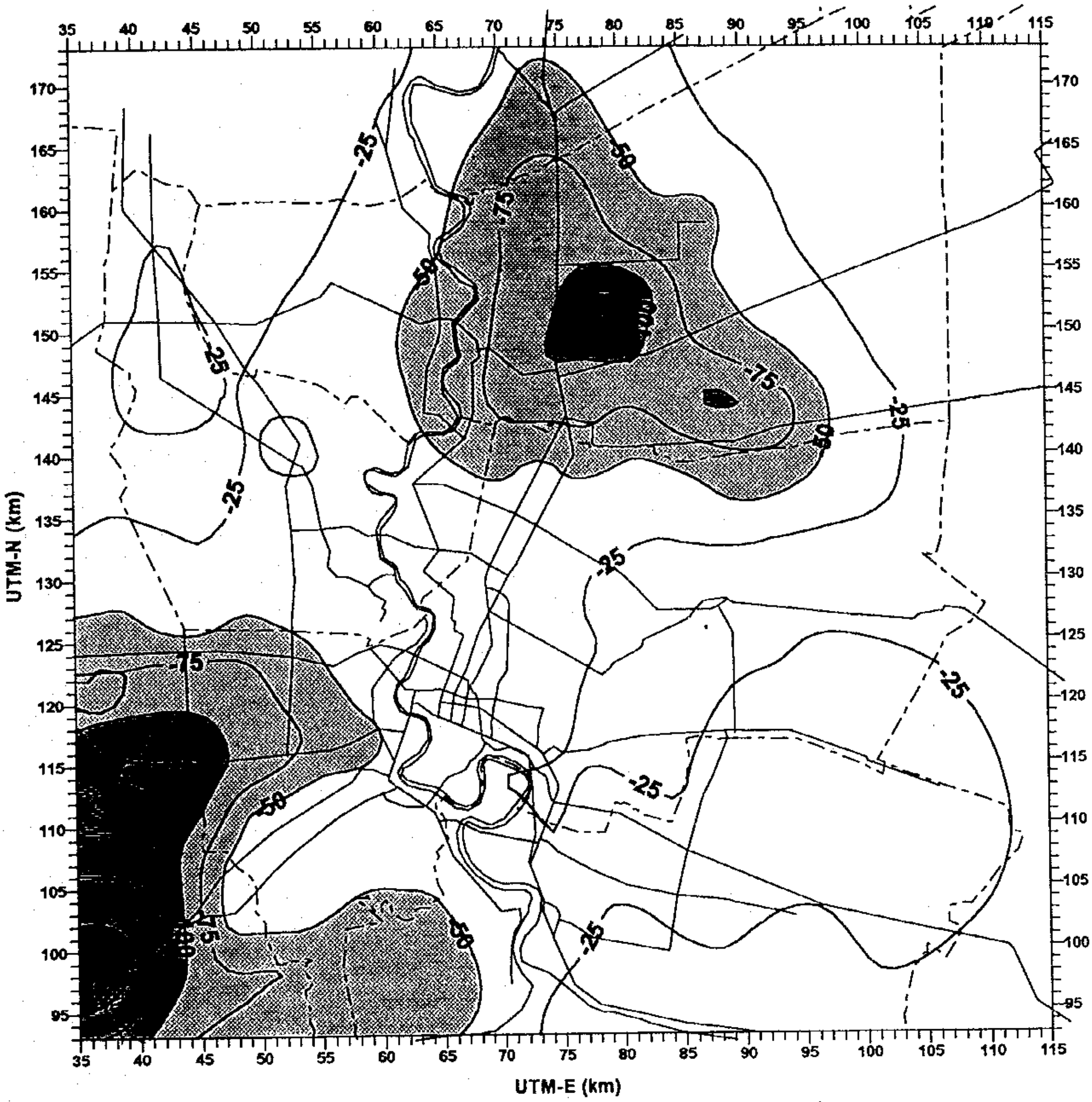
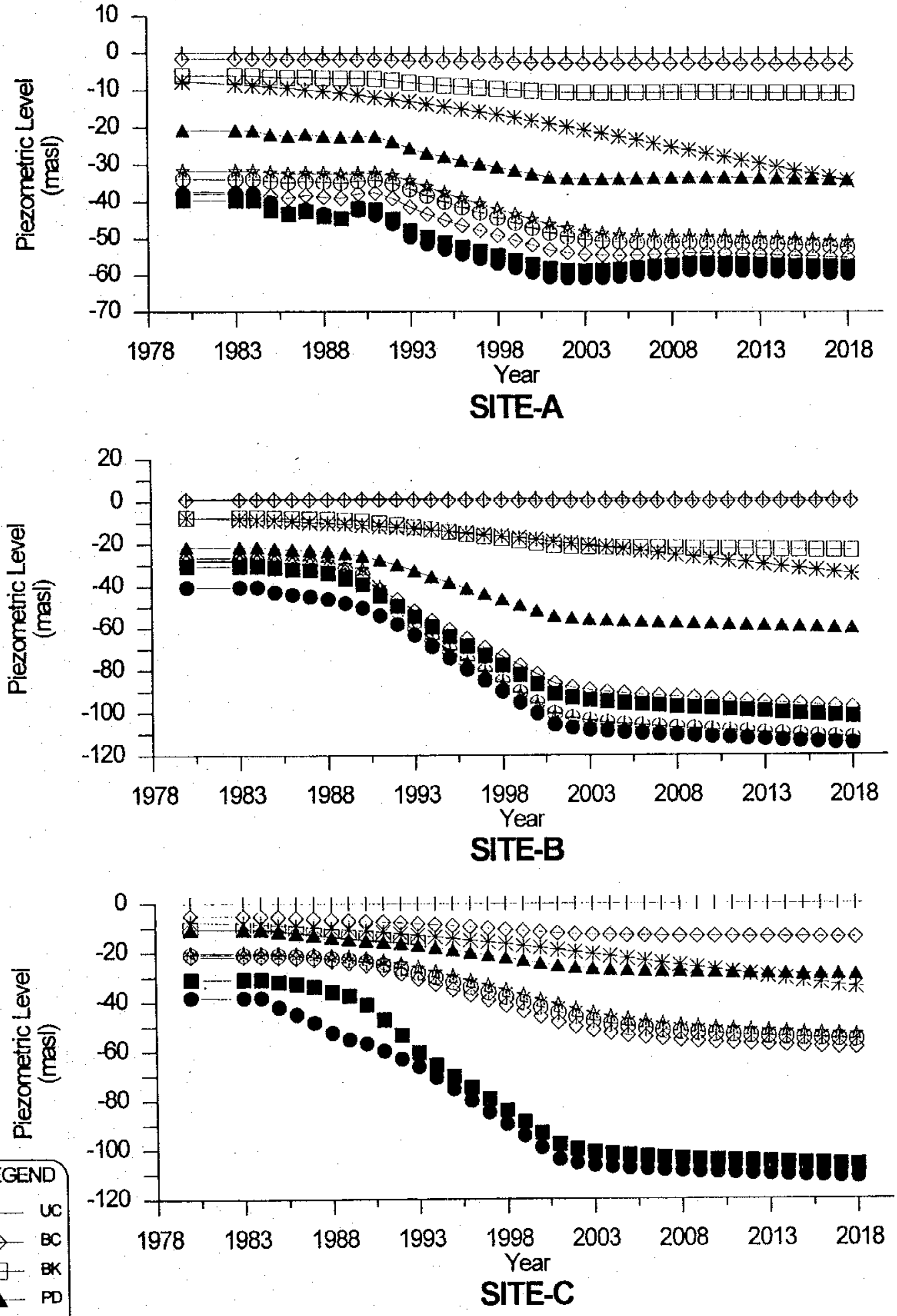


Figure 8.4.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 4)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



SIMULATED LAND SUBSIDENCE (cm)
FROM 1993 TO 2017 (25 years)
BY FUTURE SCENARIO 4

Figure 8.4.3	SIMULATED LAND SUBSIDENCE BY FUTURE SCENARIO 4
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.



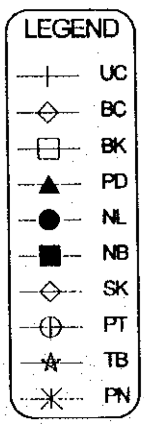


Figure 8.5.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 5)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

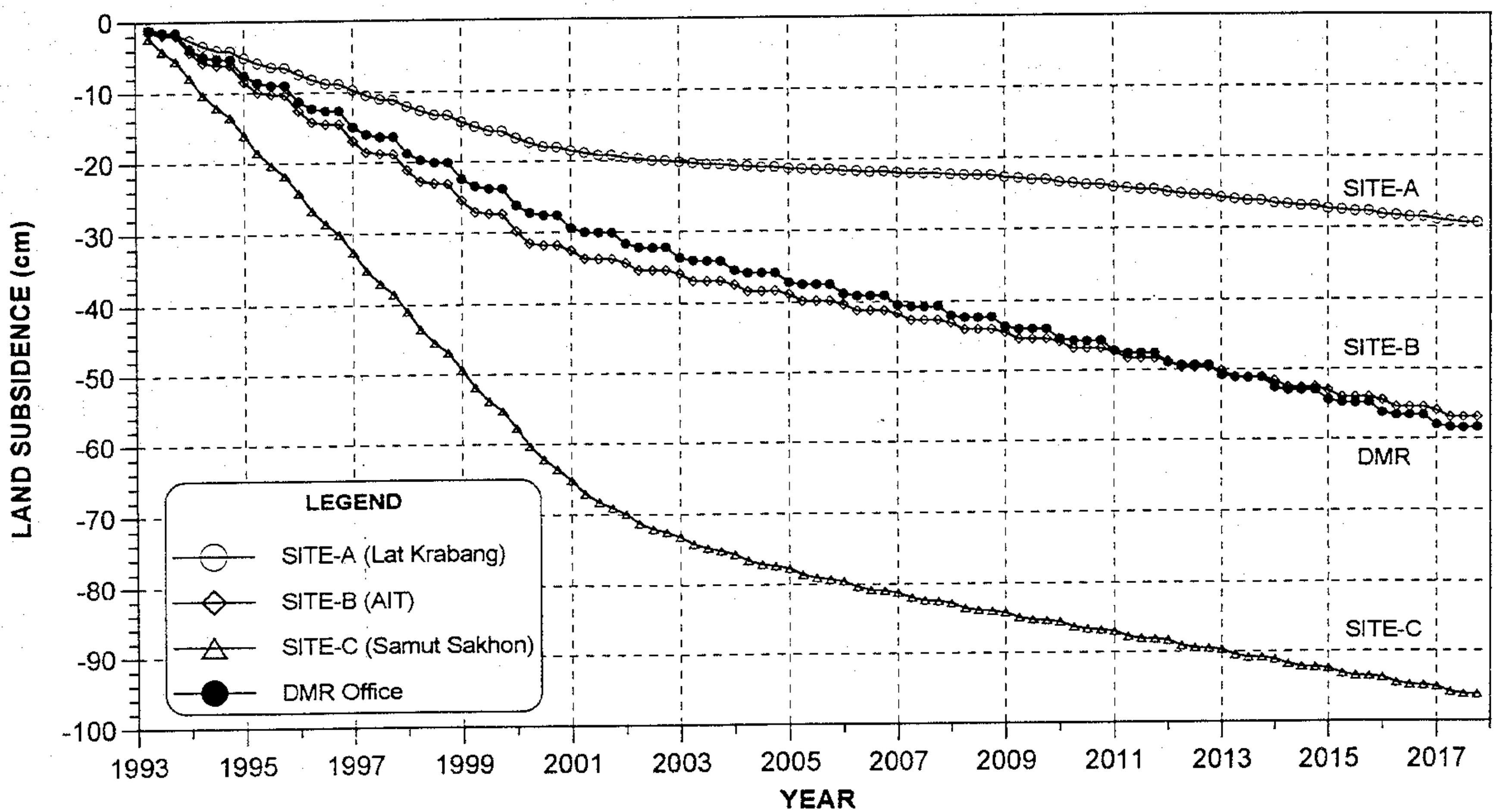
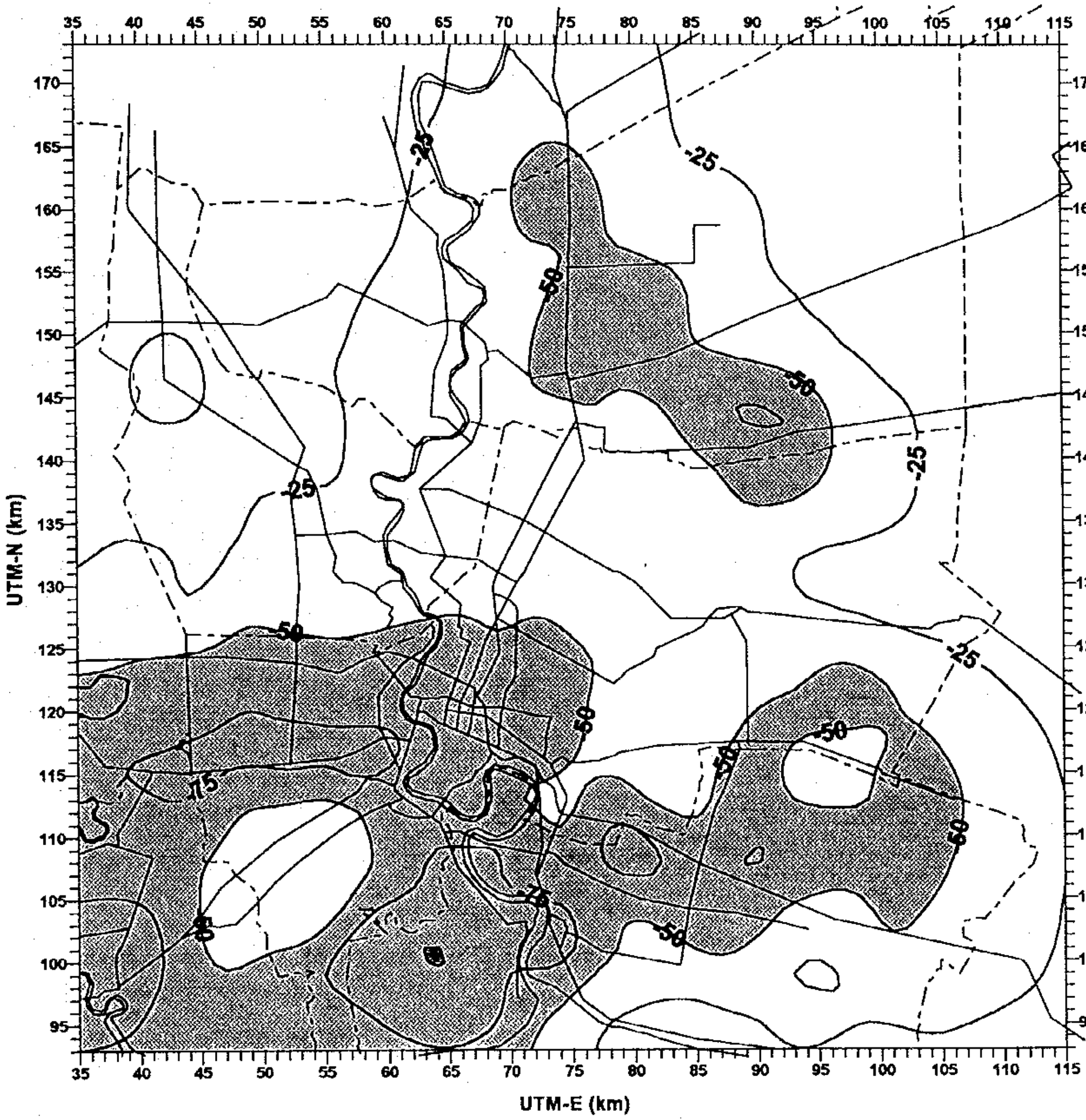


Figure 8.5.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 5A)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



SIMULATED LAND SUBSIDENCE (cm)
FROM 1993 TO 2017 (25 years)
BY FUTURE SCENARIO 5A

Figure 8.5.3	SIMULATED LAND SUBSIDENCE BY FUTURE SCENARIO 5A
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.

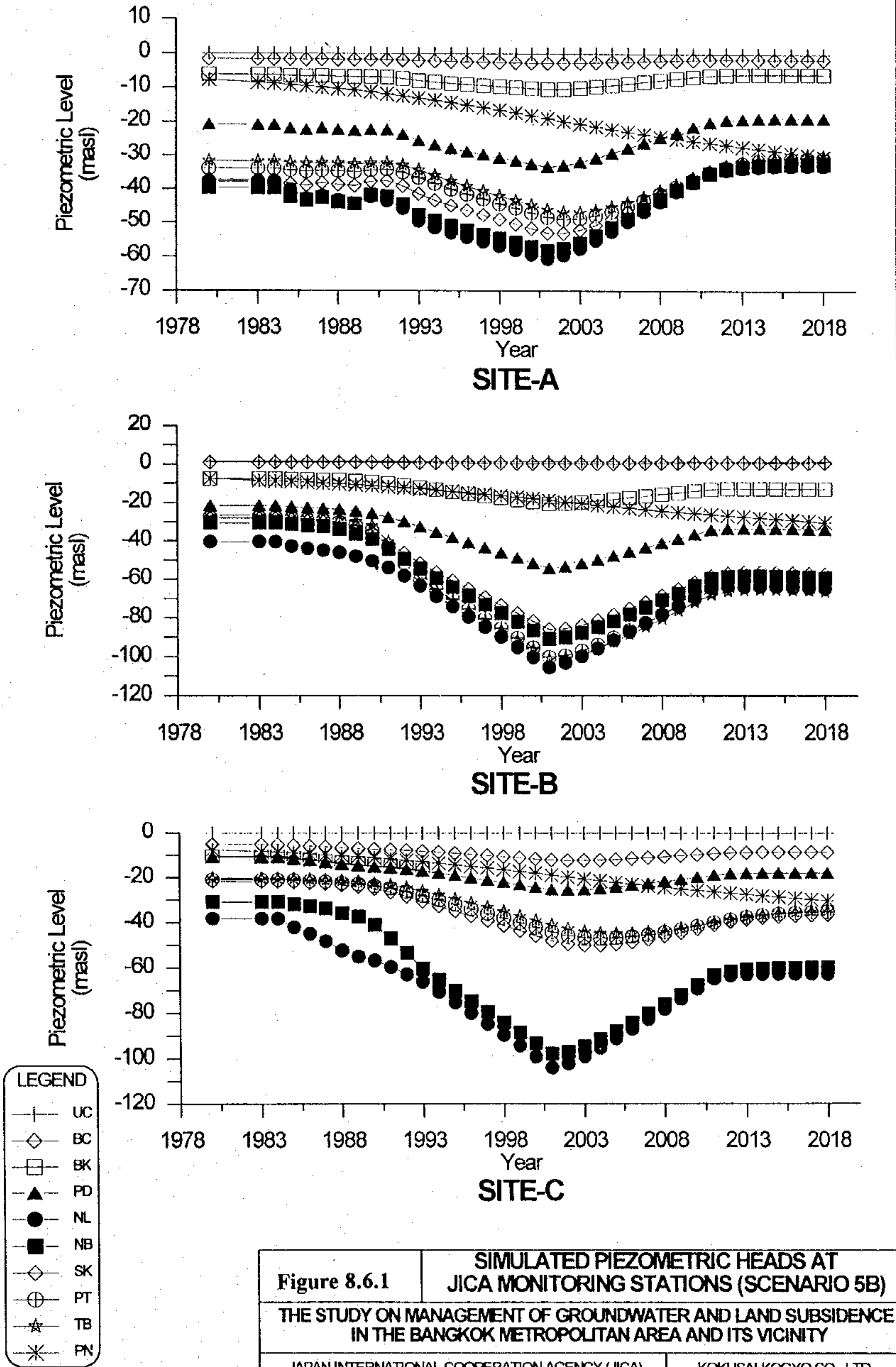


Figure 8.6.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 5B)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

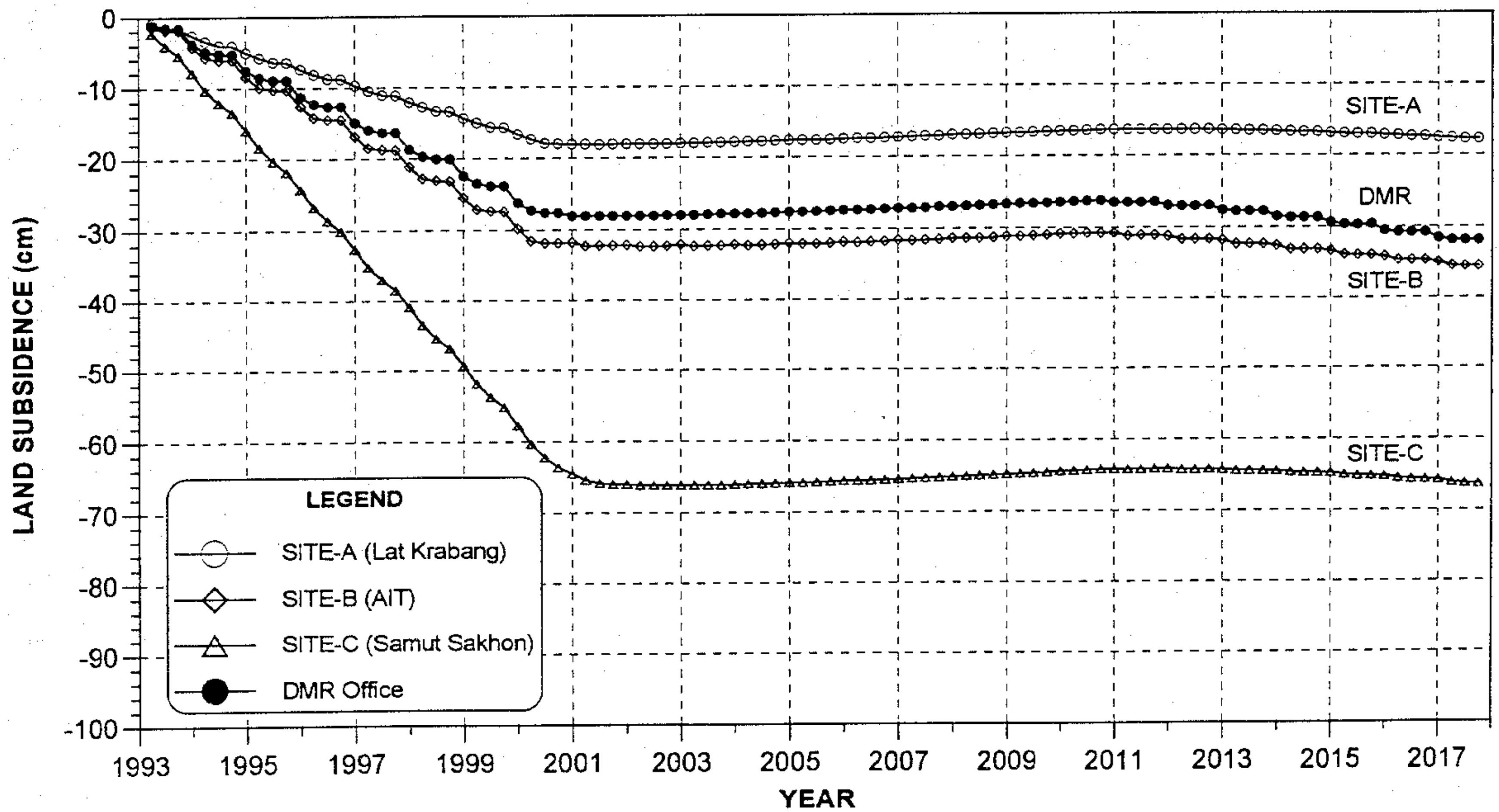
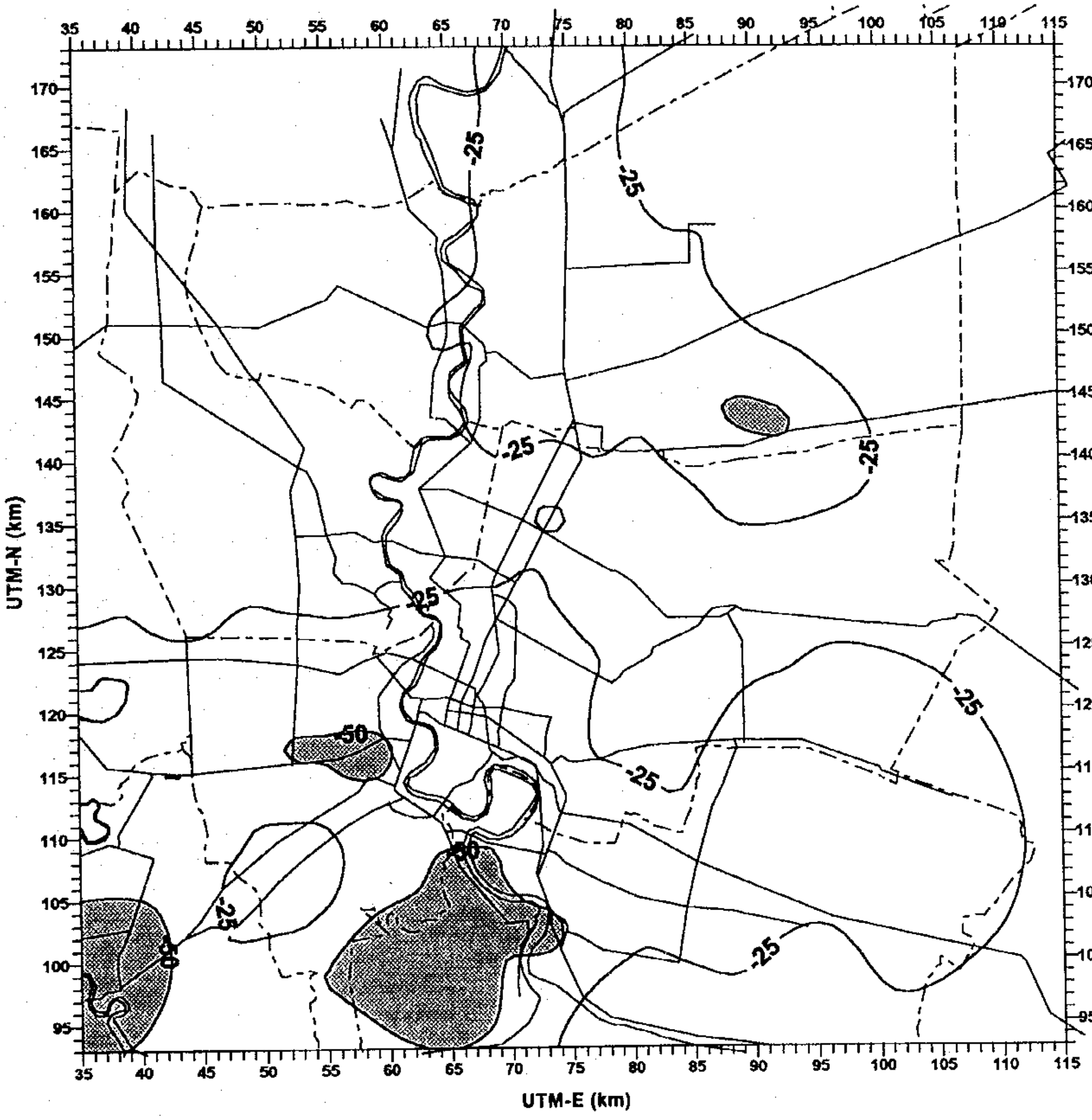


Figure 8.6.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 5B)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



SIMULATED LAND SUBSIDENCE (cm)
FROM 1993 TO 2017 (25 years)
BY FUTURE SCENARIO 5B

Figure 8.6.3	SIMULATED LAND SUBSIDENCE BY FUTURE SCENARIO 5B
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.

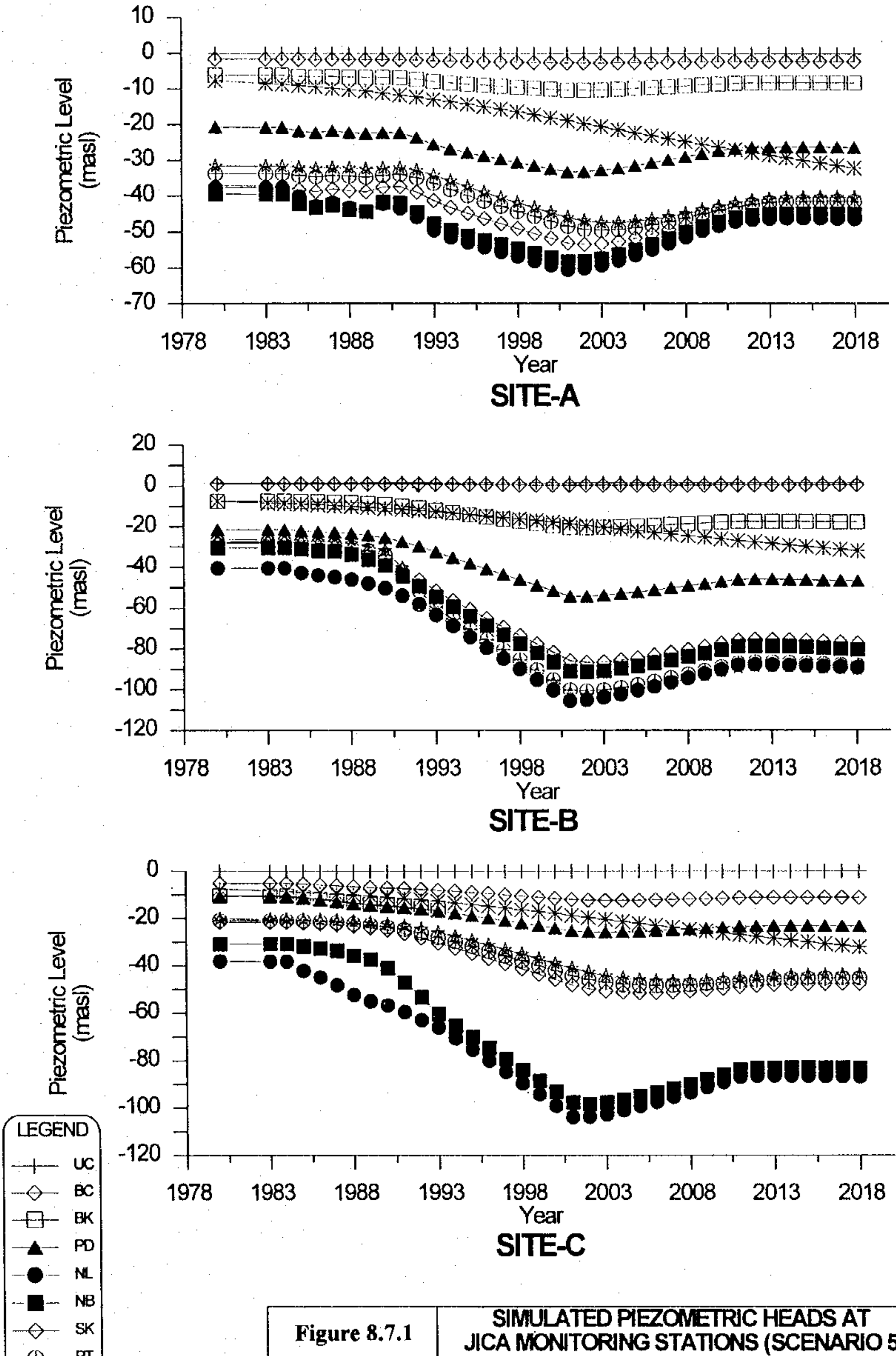


Figure 8.7.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 5C)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

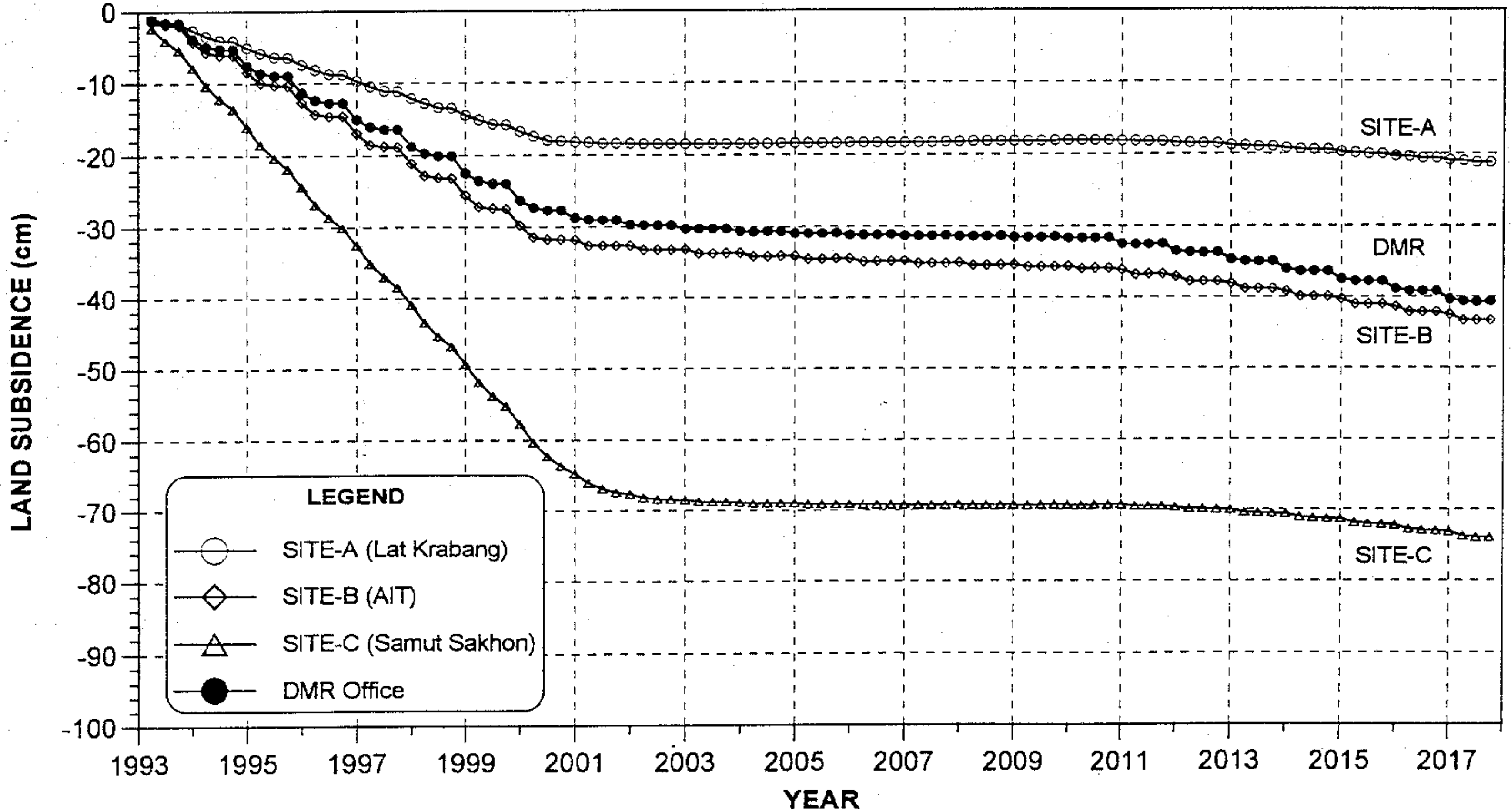
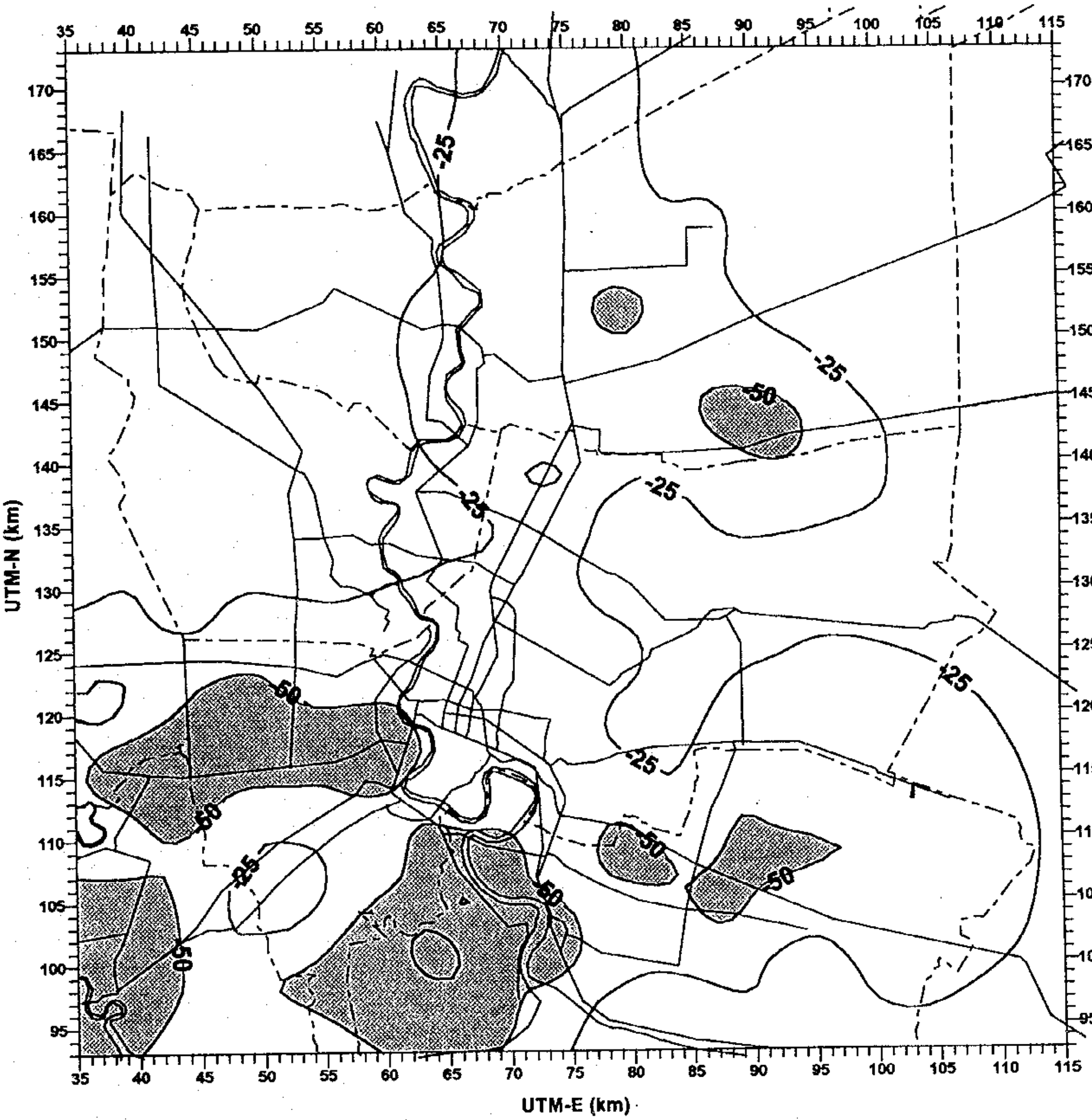
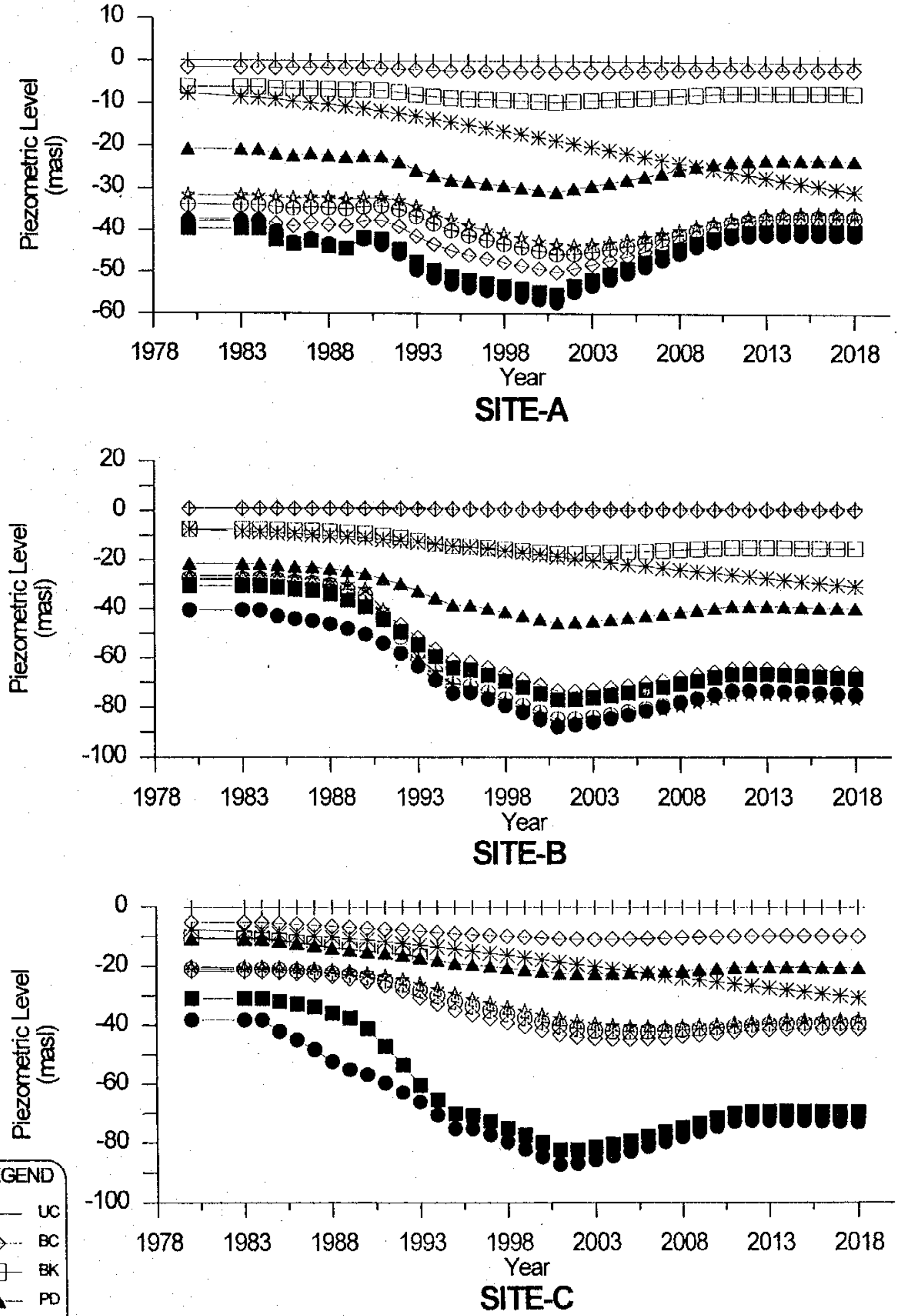


Figure 8.7.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 5C)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



SIMULATED LAND SUBSIDENCE (cm) FROM 1993 TO 2017 (25 years) BY FUTURE SCENARIO 5C

Figure 8.7.3	SIMULATED LAND SUBSIDENCE BY FUTURE SCENARIO 5C
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.



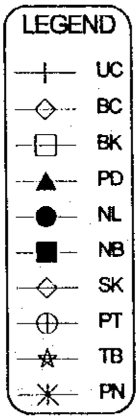


Figure 8.8.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 6)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

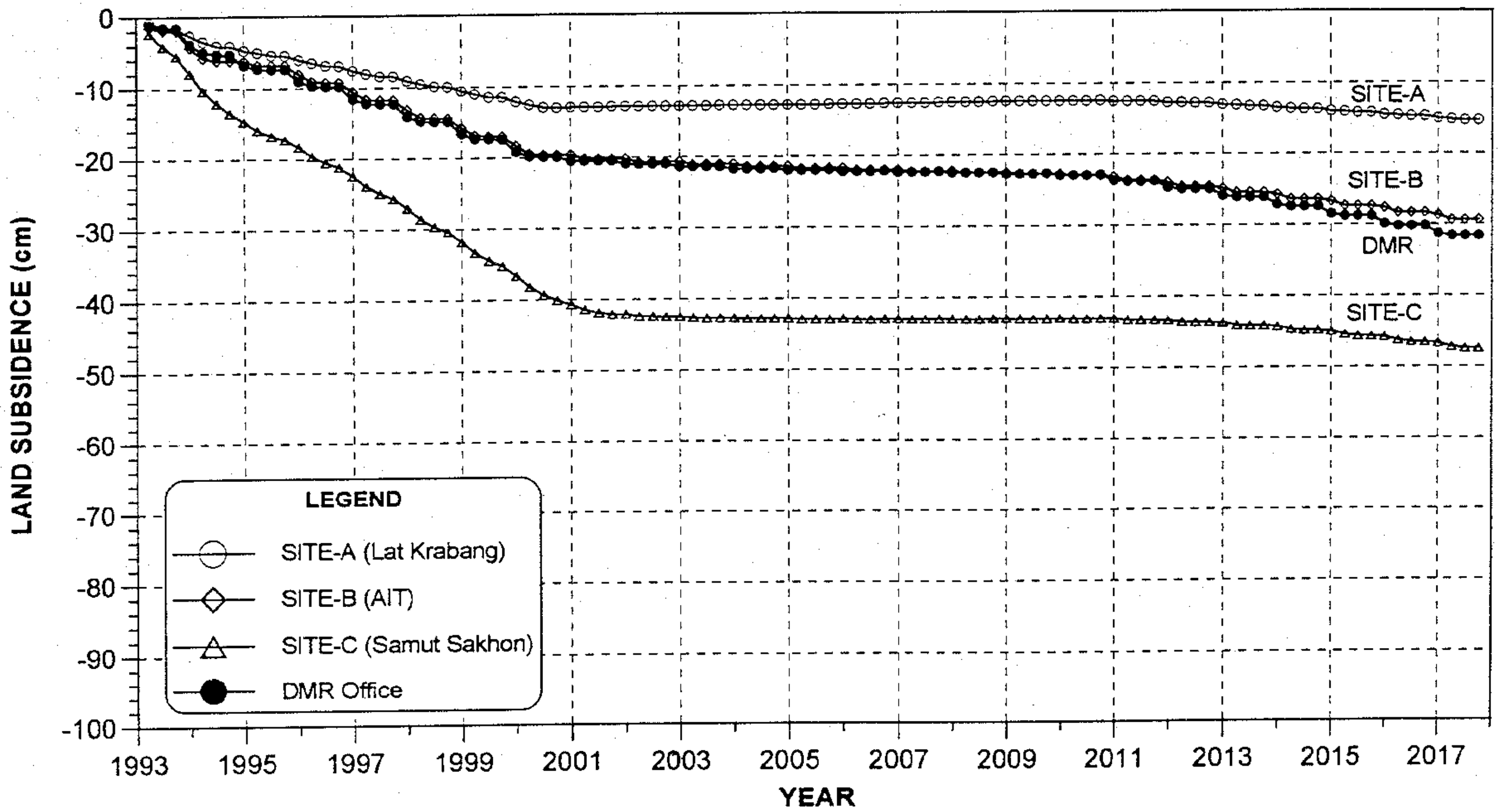
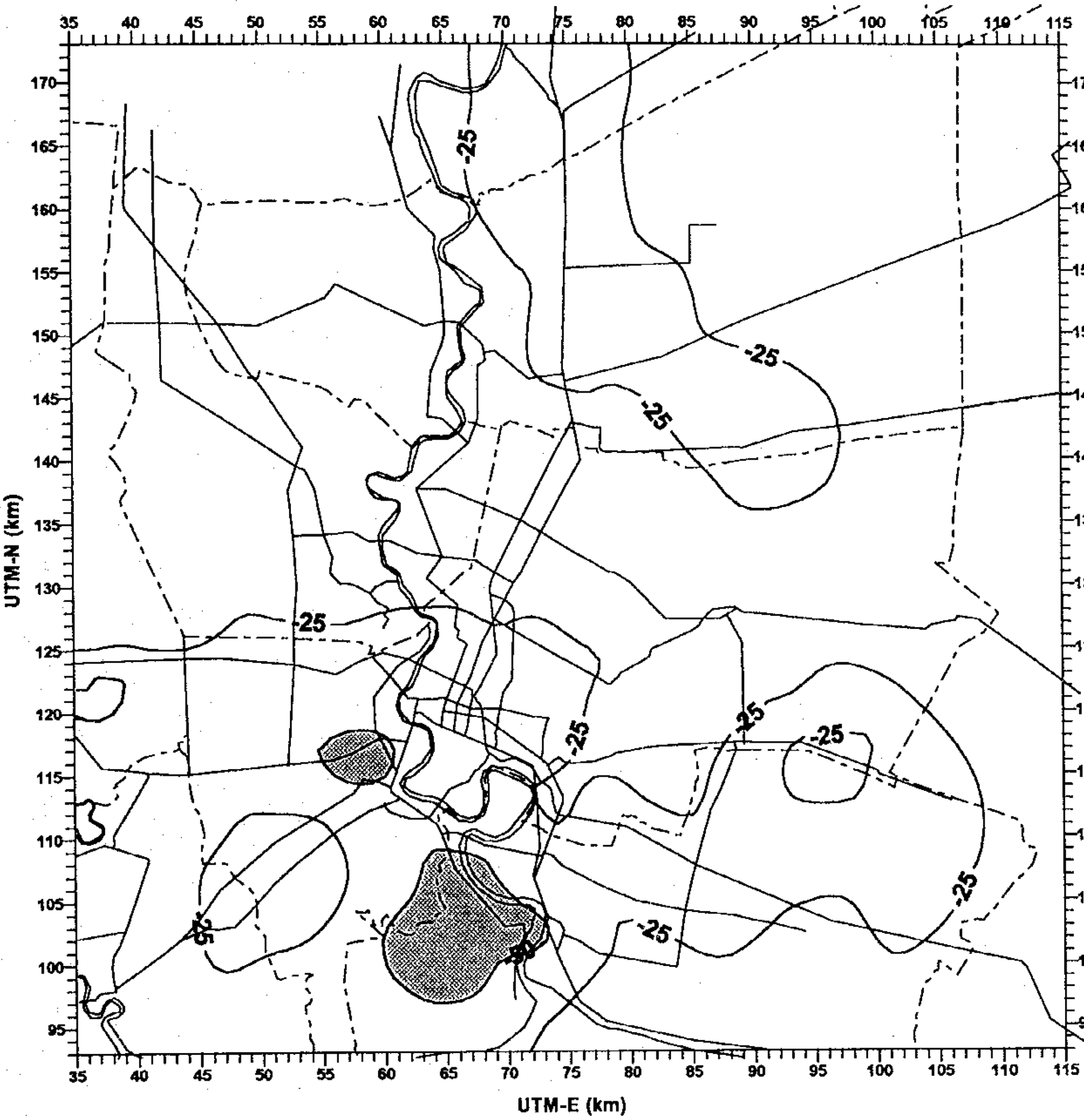
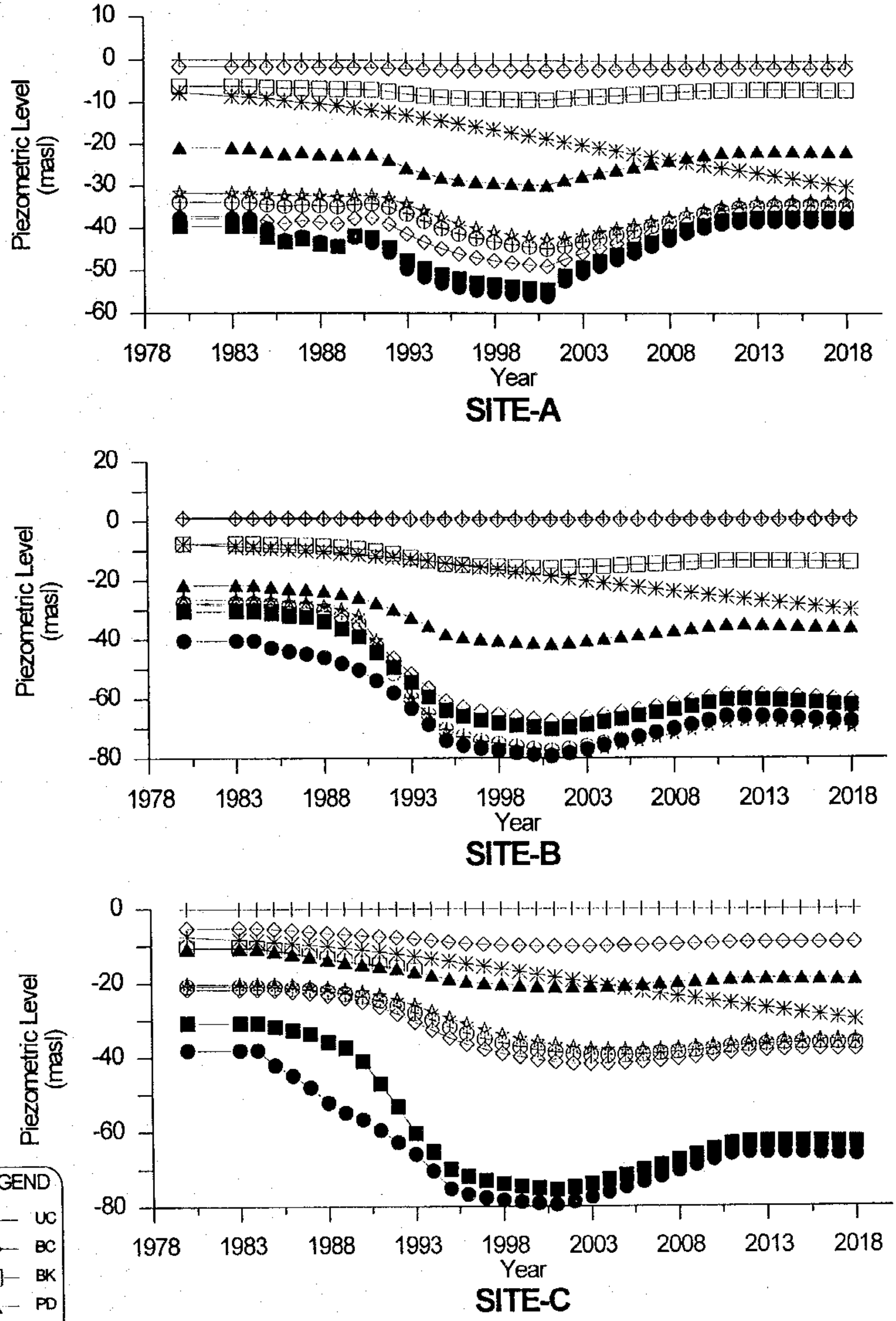


Figure 8.8.2	**SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 6)**
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



SIMULATED LAND SUBSIDENCE (cm)
FROM 1993 TO 2017 (25 years)
BY FUTURE SCENARIO 6

Figure 8.8.3	SIMULATED LAND SUBSIDENCE BY FUTURE SCENARIO 6
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.



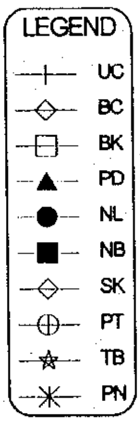


Figure 8.9.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 7)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

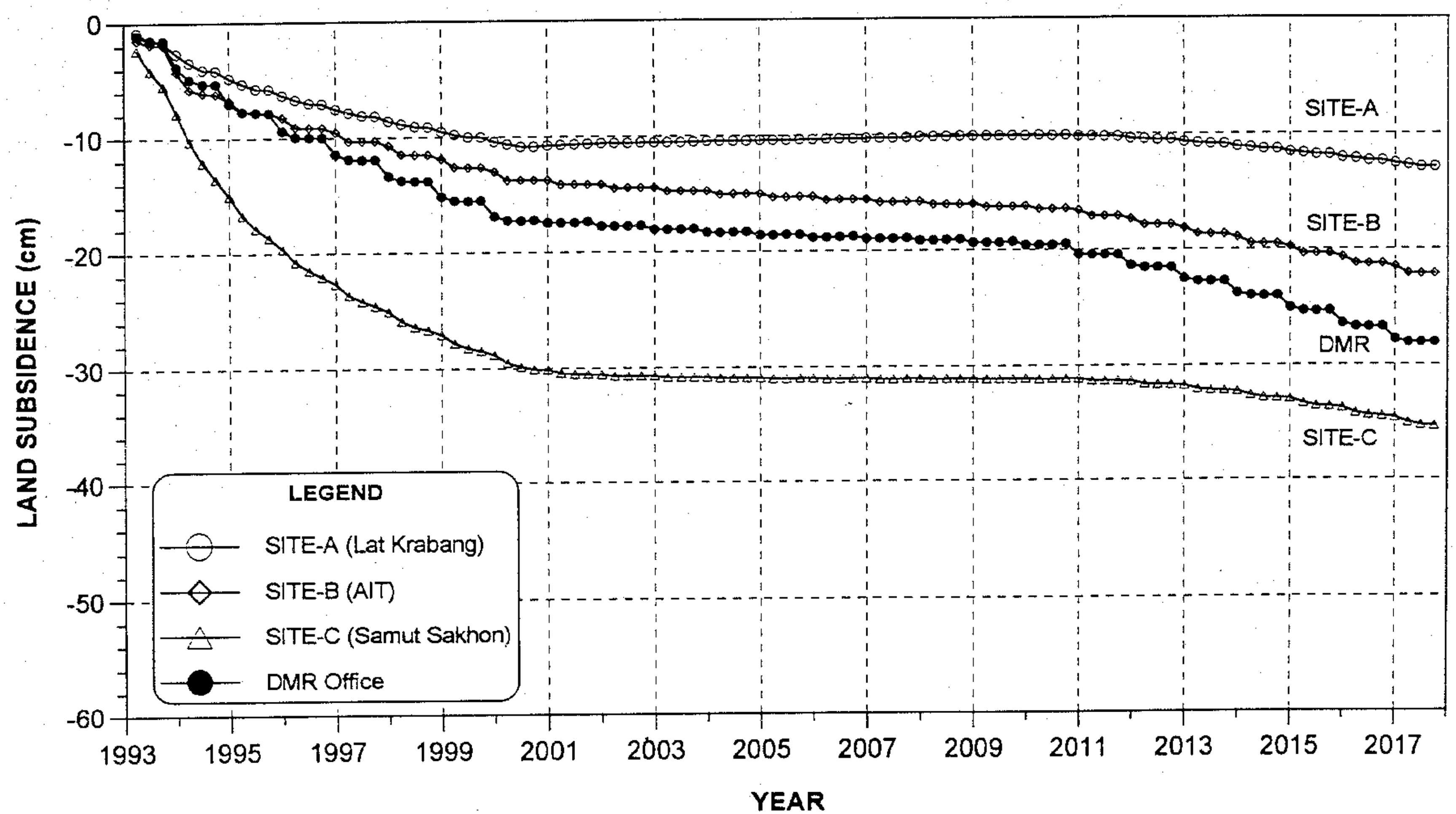
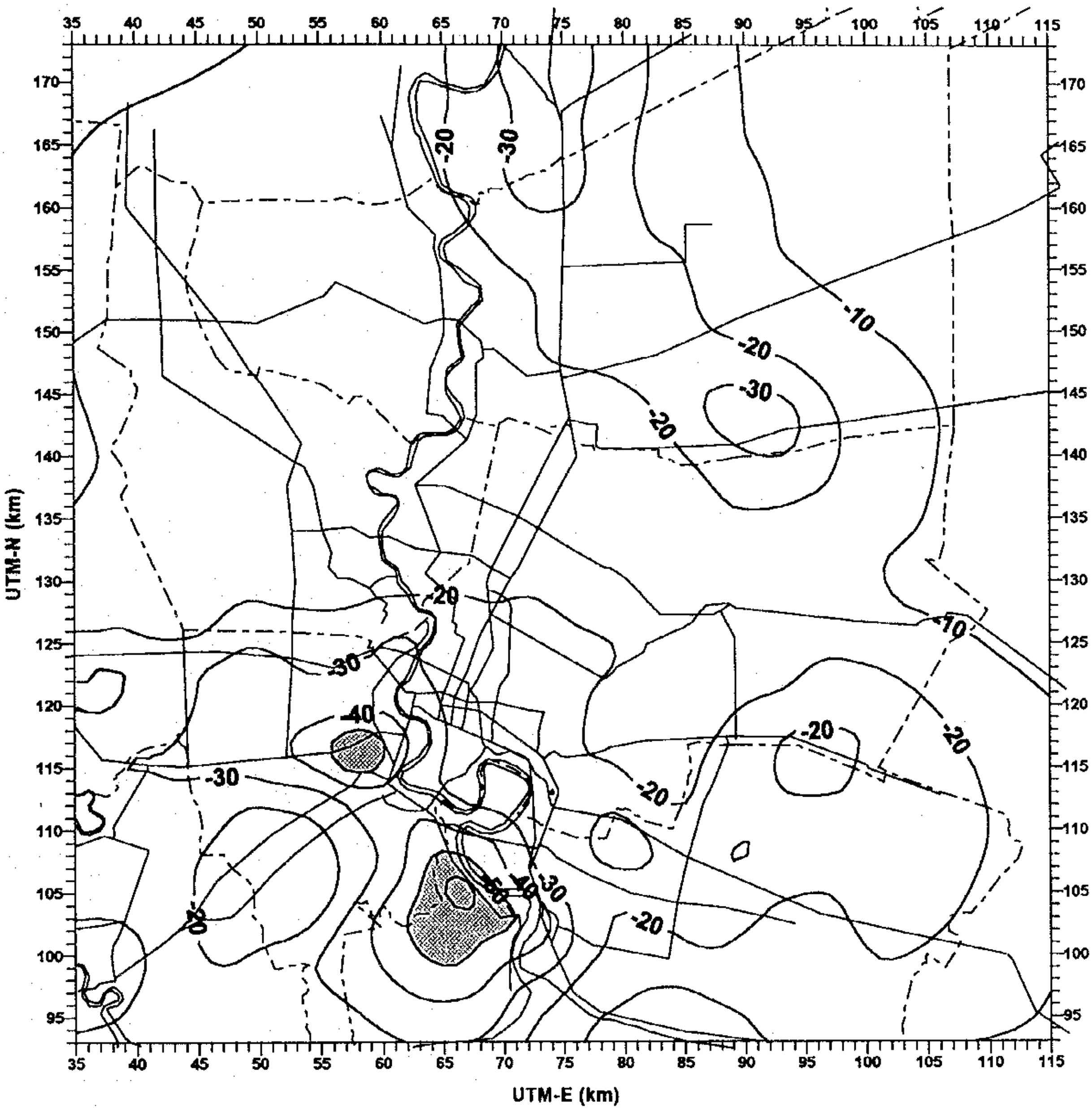


Figure 8.9.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 7)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



SIMULATED LAND SUBSIDENCE (cm)
FROM 1993 TO 2017 (25 years)
BY FUTURE SCENARIO 7

Figure 8.9.3	SIMULATED LAND SUBSIDENCE BY FUTURE SCENARIO 7
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.

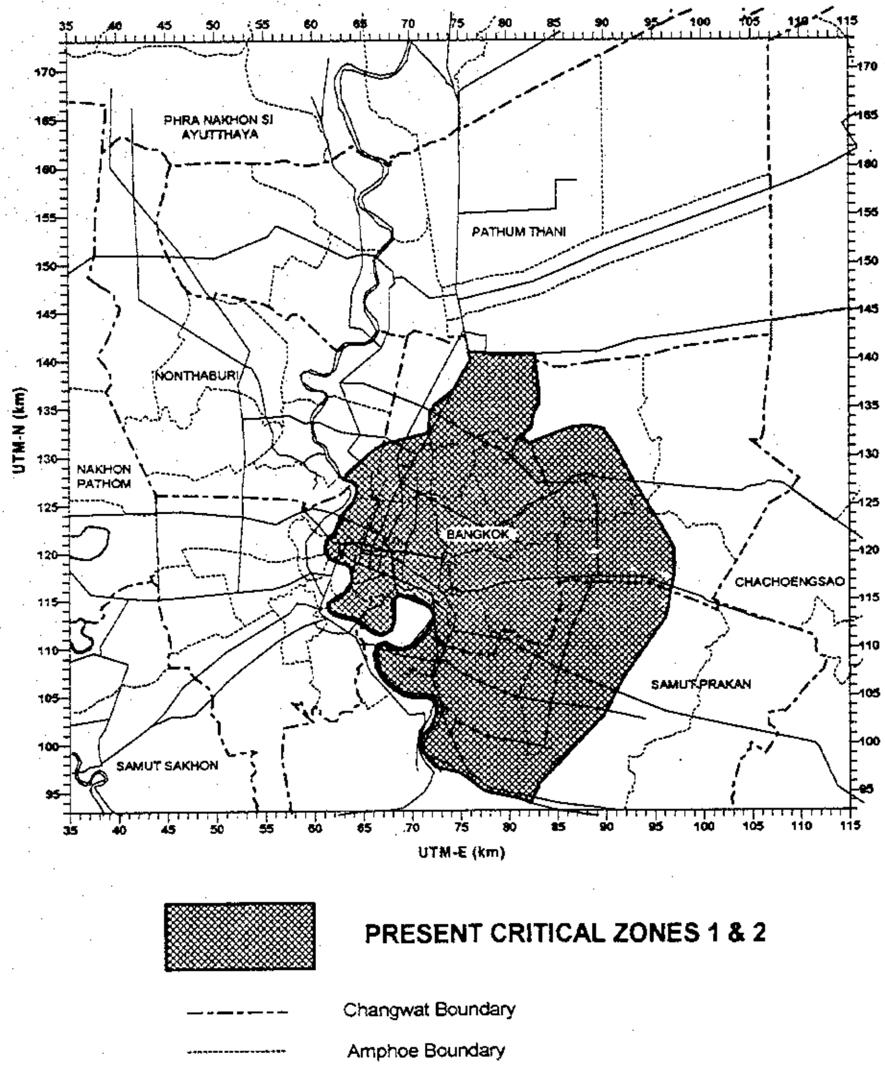


Figure 8.10.1	PRESENT CRITICAL ZONES 1 & 2
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

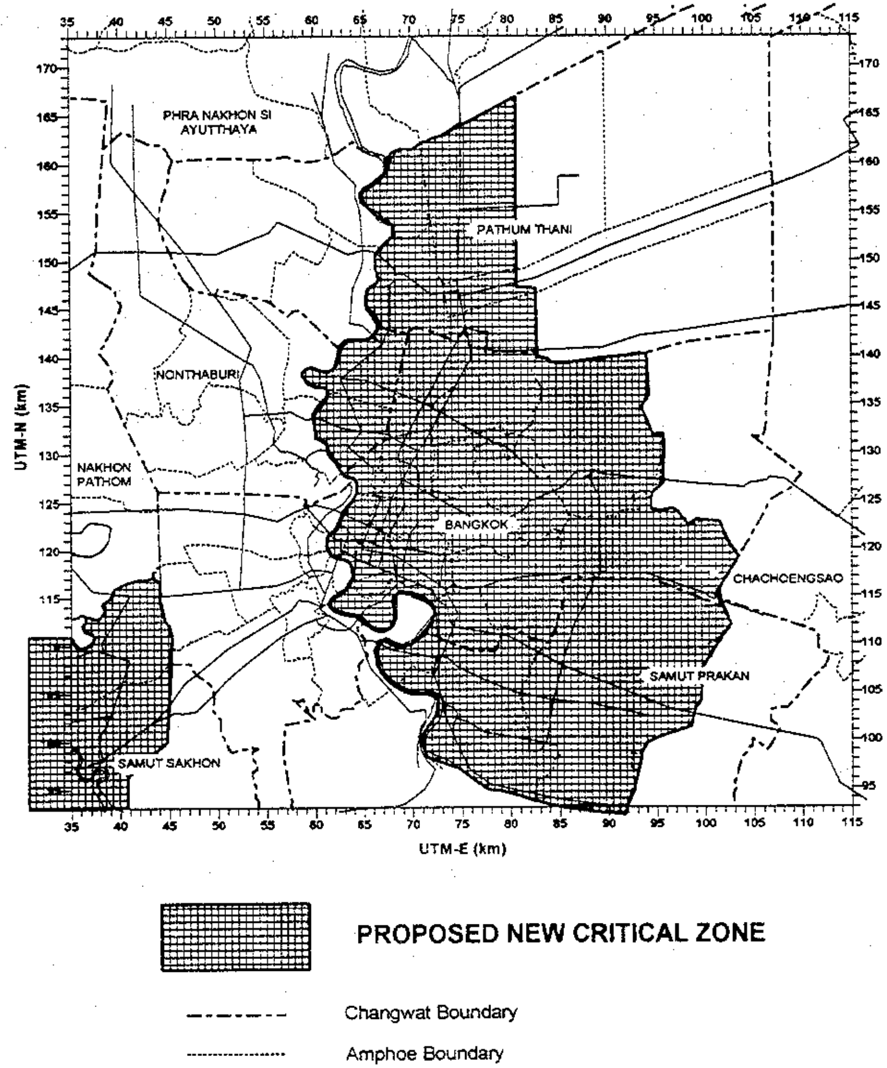


Figure 8.10.2	PROPOSED NEW CRITICAL ZONE
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

CHAPTER 9 ASSESSMENT OF PERMISSIBLE YIELD

CHAPTER 9 ASSESSMENT OF PERMISSIBLE YIELD

9.1 Concept of Permissible Yield

The "Permissible Yield" is defined as the amount of water which can be permissibly withdrawn from the basin considering the benefit and risk for the inhabitants who are living there and using groundwater (Water Balance Research Group, 1976). The permissible yield is a relative and a socially related scientific concept. A yield to be permissible must consider water balance and merit/demerit of groundwater use.

9.2 Impact of Land Subsidence

Damages caused by land subsidence can be observed in many places in the Study Area. The regional land subsidence will aggravate flooding, drainage and sewerage. The extent of flooding has increased over recent years, as evidenced by the flood in 1983 the damage of which was estimated as much as 6,600 million baht.

The flood protection and drainage project costs are regarded as social cost for repairing and rehabilitating the environment due to degradation, especially the problem of storm water runoff. However, the escalated costs of these projects in the year 1993 were evaluated to be in the total of about 43,700 million baht.

The cost of repairing minor damages caused by subsidence such as the settlement at the base of buildings, cracking of building facilities or pavements could not be estimated.

9.3 Tentative Permissible Yield

The objective of groundwater management is to sustain the use of groundwater, simultaneous with the prevention of land subsidence in Bangkok Metropolitan Area. Thus, the permissible yield may be determined by giving importance to the rate of land subsidence considering the factors defined in the concept.

Assessing the response of the groundwater models carefully, Scenario 6 could decrease land subsidence at about 2/3 of that of Scenario 5C by the year 2000. The total subsidence up to the year 2017 can also be controlled within 50 cm in most parts of the Study Area.

Scenario 7 is the best future pumpage plan for control of land subsidence among the nine (9) scenarios. However, such plan is difficult to implement because the pumpage must be maintained at the 1994's amount starting from 1995.

If the total land subsidence of 50cm from 1993 to 2017 is permissible, Scenario 6 may be the best option among the nine (9) scenarios. The simulation responses also indicated that the total pumpage of about 1.60 MCM/day could slow down the land subsidence within the rate of 1cm/year. There will be many pumpage options, however, based on the simulation of the nine (9) scenarios, Scenario 6 can be taken as a tentative permissible yield with respect to land subsidence.

CHAPTER 10 GROUNDWATER BASIN MANAGEMENT

CHAPTER 10. GROUNDWATER BASIN MANAGEMENT

10.1 Immediate Management Actions

10.1.1 Setting of Permissible Yield as Target

Groundwater management must be forwarded under a pertinent selection of management objective. The objective , in other word, "target" of the management may be represented by the "permissible yield".

Since water supply in the Bangkok Metropolitan Area shall still for a long time depend on groundwater sources, not only for domestic use but also for commercial and industrial uses, groundwater must be sustainably used with land subsidence in Bangkok Metropolitan Area being prevented. Thus, the permissible yield may be determined by giving importance to *the rate of land subsidence.*

Response of the 3-D simulation model suggests that Scenario 6 is permissible in terms of the rate of the land subsidence. Scenario 6, however, allows increase of pumpage from 1995 to 2000 at the rate of about 2.5% of the 1992 pumpage. This is unavoidable considering the economic growth. Therefore, 1.79 MCMD of the pumpage is being proposed as a tentative target in the year 2000 and 1.62 MCMD in the year 2005.

10.1.2 New Critical Zone and Pumpage Regulation

In order to achieve the target, it is necessary to designate a new critical zone as follows.

The regulation of pumpage must be started from 1995 in the new critical zone. As assumed in Scenario 6, pumpage in the Study Area will be regulated to 1.79 MCMD in the year 2000. New application of water permits in the critical zone must be carefully investigated and the number of water permits will be reduced to control total pumpage in the new critical zone. After the year-2000, the target regulated pumpage will be reduced to 1.62 MCMD in the year 2005 and 1.49 MCMD by the year-2010.

10.1.3 Expansion of Monitoring System

In order to monitor the effects of regulation, the montoring network shall be extended to the surrounding areas, i.e., Pathum Thani, Lat Krabang and Samut Sakhon. A set of observation wells---from Bangkok to Pak Nam Aquifers--- shall be constructed per monitoring location.

Since pumpage is the basis of the management target, in the long run, it must be estimated from the records of water meter installed in all of the wells in the basin. Pumpage data of other agencies shall be gathered, stored and processed in the database established in the DMR together with land subidence and water quality data.

The groundwater monitoring system, in conjunction with the groundwater database and the simulation models shall be used as a regular tool of groundwater basin management. The tentative permissible yield may be re-evaluated through analysis and evaluation of the monitored data and application of groundwater models.

10.2 Comprehensive Measures for Land Subsidence

10.2.1 Substitutional Water Supply

The substitutional water supply system must be constructed in the regulated areas prior to the enforcement of the relevant implementing regulations. Measure for the substitutional water supply is the development of surface water in Mae Klong River as mentioned in the MWA's Master Plan.

In the north of Bangkok, the PWA is going to implement an expansion project which will construct a new intake at Samkho point along Chao Phraya River, Pathum Thani. Its production capacity will be expanded to 155,650 CMD in the year 1995 and 311,300 CMD in the year 2001. These substitutional water supply projects must be implemented on schedule or completed earlier than planned.

10.2.2 Rational Use of Groundwater

Considering the slow phase of developing water supply projects, it is difficult to depend only on the substitutional water supply. Saving and rational use of groundwater should be targetted in the industrial use and the domestic use.

Technical Measures

1) Saving water by means of design improvement of sanitary and plumbing fixtures, etc.
2) Stepwise or cascade utilization by means of rearrangement of water supply and drainage facilities
3) Recycling water by means of installing water treatment plant

Institutional Measures

1) Generation of pubic consciousness for saving water through campaigns
2) Enactment of rules and regulations for water users

10.2.3 Artificial Recharge

Artificial recharge of groundwater is a technical measure for the recovery of water levels and reduction of land subsidence. This method shall be promoted in conjunction with other measures, such as regulation of pumpage, construction of substitutional water supply system, etc.

The Study Area consists of a multiple confined aquifer system and water levels of main aquifers, Phra Pradaeng, Nonthaburi and Nakhon Luang Aquifers, have declined to 50 to 60 m below mean sea level. Direct injection by using recharge well method is expected to recover groundwater levels and reduce the rate of land subsidence.

Surplus water in the rainy season could be stored in the underground aquifers. Recharge water may possibly be taken from the Chao Phraya River but has to be treated because of its high turbidity. A pilot recharge project is necessary to assess the potential of the recharge scheme in Bangkok.

The recharge scheme must first be assessed not only from the technical aspect but also from the economical and legal points of view, since a recharge project needs huge amount of investments when implemented on a large scale.

10.2.4 Price Policy

Groundwater is privately or commercially utilized at relatively cheap cost comparing with the external social cost. Therefore, a policy that makes its price the same as the water tariff charged by the public waterworks may be needed.

Presently, the MWA charges water fee at 4.0 Baht/m^3 at water consumption less than 10 m^3/month, while the groundwater fee, which was just raised in 1994, is 3.5 Baht/m^3 without any consumption limit. Therefore, the revision of groundwater tariff is necessary.

10.2.5 Legal and Organizational Measures

As a legal measure against land subsidence, the Government enforced the Groundwater Act B.E. 2520 in July of 1978. The Groundwater Committee was organized to advise the Minister of Industry in establishing regulations and in making recommendations. Under this Act, groundwater utilization, exploitation, development, conservation and protection is controlled by the government through the DMR.

With regard to monitoring of groundwater levels and land subsidence, a sub-technical committee should be organized under the Groundwater Committee. Data collected by the related agencies should be gathered, processed, analyzed and evaluated at this sub-committee. The DMR shall also act as the center of groundwater data and information.

CHAPTER 11 CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 11 CONCLUSIONS AND RECOMMENDATIONS

11. 1 Conclusions

The Study which was conducted for 33 months from July 1992 to March 1995 had established the following major pillars for the management of groundwater and land subsidence in the Bangkok Metropolitan Area and its vicinty.

1) Development and Installation of Groundwater Database System
2) Construction of Monitoring Stations at Lat Krabang, AIT and Samut Sakhon
3) Groundwater Modeling and Predictions

From the data collected, processed and analyzed throughout the Study, the following conclusions were derived.

(1) Groundwater Use

Groundwater is being pumped out from the aquifer system in Bangkok Metropolitan Area and its vicinity for domestic, institutional, commercial and industrial uses. The total groundwater pumpage of the Whole Area, which is including wholly the eight provinces, was estimated from the well inventory database at 1.80 MCMD ,while the total pumpage of the Study Area which is inside the Whole Area, was estimated at 1.48 MCMD. Pumpage is recently increasing in Bangkok's vicinity, e.g., Lat Krabang, Pathum Thani and Samut Sakhon, but has decreased in the central part of Bangkok Metropolis as a result of the regulations.

(2) Groundwater Levels

Piezometric levels of main aquifers, i.e., Phra Pradaeng, Nakhon Luang and Nonthaburi, have declined from 30m to 60m below MSL in Pathum Thani, Samut Sakhon and from eastern Bangkok to Samut Prakan. In these places, the rate of piezometric level decline of 1.0 to 2.0m/year was observed in Phra Pradaeng Aquifer, 3.0 to 5.0m/year in Nakhon Luang Aquifer and 3.0m/year in Nonthaburi Aquifer. In the central area of Bangkok, groundwater level recovered significantly since 1983, but recently it is lowering because of the effect of the regional decline of groundwater level caused by overpumping in its vicinity.

(3) Land Subsidence

Land subsidence occurs at more than 20mm/year in Bangkok Metropolis, Samut Prakan, Samut Sakhon, central part of Pathum Thani, and part of Nonthaburi. High land subsidence rate is observed in areas where groundwater levels have dropped extensively. Subsidence of 50mm/year to 60mm/year were recorded in Samut Prakan, 40mm/year to 55mm/year in Min Buri and Lat Krabang areas, 30mm/year to 40mm/year in Pathum Thani and Samut Sakhon. Recently land subsidence has slowed down in the central part of Bangkok.

(4) Chloride Concentration

High chloride concentrations were observed from Samut Sakhon to Pathum Thani along the Chao Phraya River and in the coastal areas of Samut Prakan. Concentrations partly exceeding 5,000 mg/L were detected in Phra Pradaeng Aquifer. High chloride concentrations ranging from 3,000 to 16,000 mg/L were observed in Nakhon Luang Aquifer and 2,400 to 13,000 mg/L in Nonthaburi Aquifer.

(5) Monitoring Stations

New land subsidence and groundwater level monitoring station was constructed in Lat Krabang (Site A; 8 wells), at AIT (Site B; 5 wells) and in Samut Sakhon (Site C; 5 wells). Each observation well automatically records the groundwater level and land subsidence in the different aquifers. Data were processed and stored in the groundwater database system which was established during the Study. Together with the DMR's existing 103 monitoring stations (258 wells), the new monitoring stations would be utilized for the groundwater management.

(6) Groundwater Modeling

Groundwater flow and land subsidence models were made for the prediction of future groundwater level and land subsidence. A solute transport model was also prepared for the analysis of saltwater intrusion.

The groundwater models have shown that the groundwater flows towards the piezometric level depression zone both laterally and vertically. Downward and upward leakages resulted from squeezing of clayey layers. Subsidence mainly occurred at the Bangkok Soft Clay due to downward leakage. Deep clayey layers also contribute significantly to land subsidence.

(7) Prediction of Groundwater Levels and Land Subsidence

Calibrated groundwater flow and land subsidence model was used to predict future groundwater levels and land subsidence up to year-2017 using different future pumping scenarios.

Using the worst scenario, which assumed that groundwater pumpage would continue to rise at the present rate, the model predicted that land subsidence would reach a maximum of 200cm by year-2017 and groundwater levels would lower extensively in the entire groundwater basin.

On the other hand, the best scenario assumed that groundwater pumpage would be regulated and reduced starting year-1995 in the proposed new critical zone, and using this scenario, the model predicted that the maximum total land subsidence would be 35cm and the present lowest groundwater level would decline further to 80m below MSL by year-2001 but would recover to 70m below MSL by year-2017.

(8) Tentative Permissible Yield

A tentative permissible yield was determined by giving importance to the rate of land subsidence. The response of the models was carefully reviewed and assessed. This assessment concluded that the tentative permissible yield for the Study Area would be 1.60

MCMD (PD Aquifer: 355,000 CMD, NL Aquifer 693,000 CMD, NB Aquifer 427,000 CMD and Others :125,000 CMD).

(9) Groundwater Basin Management

The tentative permissible yield that was determined in the Study is a management target. In order to achieve this target, it is necessary to expand the present critical zone and regulate the groundwater pumpage. Monitoring of groundwater level, land subsidence and groundwater pumpage coupled with the use of the groundwater database and simulation models are prerequisite to an effective implementation of the groundwater basin management.

11. 2 Recommendations

11.2.1 Groundwater Management

(1) Expansion of the Critical Zone

Groundwater level has been declining heavily, and land subsidence is progressing in Lat Krabang, Pathum Thani and Samut Sakhon areas. It is predicted that by year-2017 the total land subsidence will reach more than 180cm/year and the groundwater level will drop to 170m to190m below MSL. To mitigate such situations, it is therefore necesssary to expand the present existing critical zone to cover those areas.

(2) Regulation of Pumpage

In the medium-term, the tentative permissible yields (target pumpage) in the Study Area are 1.79 MCMD in year-2000 and 1.62 MCMD in year-2005 (Scenario 6). In order to achieve this target, the pumpage must be regulated according to the following schedule.

1995-2000: Regulate pumpage within 2.5% increase annually
2000-2010: Reduce pumpage stepwise at 5% decrease annually
2010-2017: Keep pumpage constant at year-2010 level

(3) Construction of New Monitoring Stations

Monitoring of groundwater level and land subsidence is necessary not only to assess the effectiveness of regulations but also to obtain accurate groundwater data to be used in improving the groundwater models for the evaluation of the permissible yield of the basin. The monitoring system constitutes an essential component of the groundwater basin management, and it is therefore recommended that more new monitoring stations be constructed in Pathum Thani, Samut Prakan and Samut Sakhon where groundwater level continues to decline and land subsidence is progressing.

(4) Leveling of Benchmarks

Leveling surveys are conducted by RTSD, BMA and DMR. However, the date and frequency of their levelings must be coordinated, and their data must be integrated to prepare an authoritative, uniform land subsidence contour map.

(5) Installation of Water Meter

Estimation of pumpage is also an important part of the groundwater basin management. In the Study, the pumpage of private wells was estimated from the water rights records stored in the well inventory database and actual pumpage records of about 2500 wells installed with water meters. Since pumpage estimates were used to set the tentative permissible yield, they must therefore be estimated as accurate as possible in the future evaluation of permissible yield.

Presently, the water permit applicants are obliged to install water meters for industrial and commercial uses of groundwater. This requirement must be extended to other users of groundwater so that a more accurate pumpage estimate can be obtained using the actual groundwater consumption readings from the water meters.

(6) Application of the Groundwater Database System

The groundwater database system established in DMR processes groundwater levels, land subsidence, water quality data, well inventory, etc. These data must be stored continuously in the future. Particularly, the well inventory database must be used, operated and maintained conjunctively with the water permit registration records of DMR.

(7) Improvement of Groundwater Models

The accuracy and reliability of groundwater models established in DMR must be improved in the future. This may be achieved by a more accurate pumpage estimates, by collection and analysis of a more accurate aquifer parameters, and by continuous monitoring of groundwater levels, land subsidence and water quality, etc.

(8) Model Applications and Permissible Yield

The groundwater models jointly with the groundwater database and monitoring systems shall be applied as tools in groundwater management, i.e., in assessing and predicting groundwater levels, land subsidence and water quality and in evaluating the permissible yield of the basin. Since the permissible yield is the management target, it must be re-evaluated according to the monitored data. It is, therefore, recommended to modify the tentative permissible yield and set a more accurate and updated target according to the future monitored groundwater conditions.

(9) Hydrogeological Investigations

The Study Area is located only at the southern part of the Lower Central Plain which itself constitutes a huge groundwater basin, while recent urbanization tends to move towards north and east of Bangkok Metropolitan Area. Hydrogeology of the entire groundwater basin has not been investigated in detail yet, though several studies had been conducted and data had been gathered in the past. It is, therefore, recommended to expand the Study Area to cover the entire groundwater basin and to investigate the long-term prospect of its development.

11.2.2 Comprehensive Measures

(1) Substitutional Water Supply

Since the supply of surface water is a necessary condition for implementing the pumpage regulation, the MWA and the PWA should therefore implement their expansion projects on schedule. It is strongly recommended that waterworks for industrial water use be constructed, particularly, in Samut Sakhon area. The lack of water supply may become a factor obstructing investments in industries, which will finally affect the regional economy.

(2) Rational Use of Water

Technical and institutional measures should be undertaken to save groundwater. In order to find out technical measures in commerce and industry, investigation on the rational use of groundwater is recommended. In addition, campaign to save water should be done vigorously through media and through distribution of leaflets.

(3) Groundwater Fee

Groundwater fee is presently 3.5 bahts/m^3. This rate should be raised to the same price level charged by MWA and PWA. Payment should also be based on the volume of groundwater actually consumed. In addition, groundwater fee should be implemented to other heavily pumped areas as well, not only limited to the present six groundwater areas designated by the Groundwater Act.

(4) Artificial Recharge

One of the measures for recovering groundwater levels and mitigating land subsidence is artificial recharge. However, a pilot artificial recharge well system is recommended to be implemented first before constructing a large one. During the piloting, the main technical as well as economic and legal issues must be investigated and assessed thoroughly through experiments.

(5) Strengthening of the Technical Sub-Committee

To be tasked with assisting the Groundwater Committee in assessing the groundwater situations, the function of the technical sub-committee is recommended to be strengthened within the organization. The sub-committee should deal with the preparation of the groundwater management options from the basin-wide hydrogeological viewpoints.

(6) Organization

The Groundwater Division and the MGL Project of the DMR is tasked to conduct the investigation, observation, analysis and evaluation of groundwater and land subsidence in Bangkok Metropolitan Area. Aside from this, the DMR is deputized by the Minister to investigate and assess water permit applications. Considering the importance of the role of the Groundwater Division and the MGL Project in the management of groundwater and land subsidence in Bangkok Metropolitan Area, it is important that these organizations be strengthened by beefing up their manpower.