8.2 Predictions

The simulation for the prediction of future groundwater situations and land subsidence was carried out by using each scenario's pumpage data as input to the calibrated 3-D model. Since an accurate land subsidence prediction requires a time-step shorter than one (1) year, a quarterly pumpage data set of 100 time-steps from year-1993 to year-2017 was prepared for each scenario. This quarterly data was prepared using the QGPC. The initial piezometric heads for the future simulation were assumed the same as the final computed heads of the historical calibration.

Future piezometric heads at each time-step were computed and made as input for the future land subsidence simulation. The predicted subsidence value was obtained as the total of each layer's compression from the beginning of year-1993 (the start of the simulation).

8.2.1 Scenario 1

Computed piezometric levels gradually drop in the whole modeled area from year-1993 to year-2017. Simulated piezometric heads at the JICA monitoring stations are shown in Figure 8.2.1. At Site-A (Lat Krabang, Bangkok), the simulated heads of NL Aquifer and NB Aquifer are below -80 masl by year-2017. The piezometric level of NL Aquifer at Site-B (AIT, Pathum Thani) drops below -190 masl in year-2017. The piezometric levels of NL and NB Aquifers at Site-C (Samut Sakhon) also drop linearly between -170 and -180 masl in year-2017.

Figure 8.2.2 shows the simulated land subsidence at the JICA monitoring stations and the DMR office (central Bangkok). Severe land subsidence occurs at all stations over the simulation period. The cumulative subsidence from year-1993 to year-2017 exceeds 200 cm at Site-C. The predicted land subsidence map by year-2017 (Figure 8.2.3) shows a wide section of the Study Area will subside more than 50 cm. Subsidence of more than 100 cm occurs in Samut Prakan, Bangkok, Pathum Thani, Samut Sakhon, and part of Nakhon Pathom. More than 150-cm subsidence are found in Samut Prakan and Samut Sakhon.

8.2.2 Scenario 2

Piezometric levels in the MWA service area (Bangkok, Nonthaburi, and Samut Prakan) recover from 1998 due to the reduction of pumpage, following the MWA Master Plan. Figure 8.2.4 shows that the piezometric level of NL aquifer at Site-A recovers about 15m from year-1998 to year-2017. In Pathum Thani, the piezometric levels recover when enough surface water is supplied to the area, however, the piezometric levels again drop due to the increase in groundwater demand. The simulated piezometric heads at Site-C exhibit a drop similar to Scenario 1, because Samut Sakhon is not covered by any surface water supply project. The piezometric heads of NL and NB Aquifers range between -160 and -170 masl in year-2017.

Figure 8.2.5 shows that subsidence at Site-A and DMR office will almost stop from year-1998. At Site B, subsidence becomes gentle from year-1997 to year-2003 with small rebound in years-1997 and 2002 due to the changes in piezometric level. However, subsidence will recur from year-2004 with subsidence rate of more than 3 cm/year. The subsidence at Site-C continues linearly, reaching 170 cm by year-2017.

In Figure 8.2.6, subsidence of more than 50 cm by year-2017 is not seen in major parts of Bangkok and Samut Prakan. The subsidence in central Pathum Thani ranges from 50 cm to 75 cm, which is considered small in comparison with that in Scenario 1. Subsidence in Samut Sakhon is still severe at more than 150 cm in its central area.

8.2.3 Scenario 3

The decline of piezometric levels in the present critical zones 1 and 2 will stabilize from year-1998 to year-2008 as shown in Figure 8.2.7. However, the piezometric levels at Site-B and Site-C drop straightly because these areas are not covered by the present critical zone. The drop in piezometric levels at Site-A will recur after year-2008 even when pumpage is maintained at constant level. This is due to the influence of the expansion of the cone of depression at Pathum Thani where pumpage increases as mentioned in Scenario 1.

Subsidence graphs at Site-A and DMR office in Figure 8.2.8 show gentle subsidence rates between years 1998 and 2008, which however, increase again from year-2009. The subsidence at Site-B and Site-C will continue until year-2017.

In Figure 8.2.9, most parts of the present critical zones 1 and 2 subside more than 50 cm by year^2017. Severe subsidence ranging from 50 cm to 190 cm is predicted in Pathum Thani and Samut Sakhon.

8.2.4 Scenario 4

The reduction of pumpage in the present critical zones 1 and 2 results in the recovery of piezometric levels at Site-A from year-2002 as shown in Figure 8.2.10. The piezometric levels of the main aquifers will be higher than the present levels. However, the piezometric levels of NL Aquifer at Site-B and Site-C drop by -187 masl and by -170 masl, respectively, in year-2017.

Subsidence at Site-A and DMR office will stop from year-2001 with a slight rebound a period from year-2001 to year-2012, as shown in Figure 8.2.11. However, subsidence at Site-B and Site-C continues as in Scenario 1.

The simulated land subsidence distribution by year-2017 is shown in Figure 8.2.12. This scenario is effective in the present critical zone, with a subsidence of around 25 cm by year-2017. But, a severe subsidence of more than 100-cm is predicted.in Pathum Thani and Samut Sakhon.

8.2.5 Scenario 5A

With this pumpage scenario, the decline of piezometric levels in the Study Area can be controlled after year-2000. As shown in Figure 8.2.13, the piezometric levels at Site-A slightly recovers from year-2000, whereas the rates of piezometric level declines at Site-B and Site-C become smaller after year-2000. The piezometric levels of NL Aquifer at Site-A, Site-B, and Site-C in 2017 are -59 masl, -114 masl, and -111 masl, respectively.

As shown in Figure 8.2.14, the rates of land subsidence at the observation points decrease from year-2001. Hence, land subsidence does not cease with this pumpage scenario. By end of year-2017, the predicted subsidences are 96 cm at Site-C, 58 cm at DMR office, 56 cm at Site-B, and 30 cm at Site-A.

Areas with more than 100 cm subsidence by year-2017 are no longer existing in Pathum Thani and Samut Sakhon as shown Figure 8.2.15. However, more than 50-cm subsidence is widely distributed even in the new critical zone.

8.2.6 Scenario 5B

The recovery of piezometric levels from year-2001 is clearly observed at the JICA monitoring stations (Figure 8.2.16). The simulated piezometric heads of NL Aquifer in year-2017 are -33 masl at Site-A, -65 masl at Site-B, and -62 masl at Site-C, respectively.

Figure 8.2.17 shows that the subsidence at the observation points stops in year-2001 and then rebounds slightly from year-2011 to year-2013 due to the recovery of groundwater levels. By the end of year-2017, subsidence is 66 cm at Site-C, 36 cm at Site-B, 32 cm at DMR office, and 18 cm at Site-A.

In Figure 8.2.18, subsidence of more than 50 cm by year-2017 is sporadically distributed in Bangkok, Pathum Thani, Samut Prakan, and Samut Sakhon. In the new critical zone, subsidence of more than 50 cm by year-2017 will occur only in Samut Sakhon.

8.2.7 Scenario 5C

Due to a smaller pumpage reduction rate (Figure 8.2.19) from year-2001 to year-2010, the piezometric heads recover less than that of Scenario 5B. The simulated piezometric heads of NL Aquifer at Site-A are -60 masl in year-2001 and -47 masl in year-2017. Similarly, the piezometric level of NL Aquifer at Site-B drops to -116 masl in year-2001 and then recovers to -90 masl in year-2017. At Site-C, the piezometric head of NL Aquifer drops to -103 masl in year-2001, and then recovers to -88 masl in year-2017.

The simulation results show that the subsidence at Site-A will cease from year-2001 to year-2011 (Figure 8.2.20). At Site-B, Site-C, and DMR office, the subsidence rates are within 0.5 cm/year from year-2001 to year-2010, and then the rates range from 0.5 cm/year in year-2011 to 1.0 cm/year in year-2017.

Subsidence of more than 50 cm by year-2017 is predicted in Samut Prakan, western Bangkok, part of Pathum Thani, and central Samut Sakhon as shown in Figure 8.2.21.

8.2.8 Scenario 6

In this scenario, the reduced rate of pumpage increase from year-1995 to year-2000 results in a drawdown smaller than that in Scenario 5C as shown in Figure 8.2.22. The simulated piezometric heads of NL Aquifer at Site-A are -57 masl in year-2001 and -41 masl in year-2017. Similarly, the head of NL Aquifer at Site-B drops to -87 masl in year-2001 and then recovers to -73 masl in year-2017. At Site-C, the head of NL Aquifer drops to -88 masl in year-2001 and then recovers to -72 masl in year-2017.

Accordingly, the simulated land subsidence by year-2001 decreases as compared with that in Scenario 5C. Figure 8.2.23 shows the subsidence at Site-C by end-2001 as 42 cm, which will be 48 cm by end-2017. Subsidence at Site-A, Site-B and DMR office can be controlled within 20 cm by year-2000 in this pumpage scenario.

The year-2017 subsidence map (Figure 8.2.24) shows that no area will subside more than 50 cm in the new critical zone.

8.2.9 Scenario 7

Compared with Scenario 6, Scenario 7 results in a more reduced drawdown by year-2000 in the new critical zone, as shown in Figure 8.2.25. The simulated piezometric heads of NL Aquifer at Site-A are -55 masl in year-2001 and -38 masl in year-2017. Similarly, the piezometric head of NL Aquifer at Site-B drops to -80 masl in year-2001 and then recovers to -68 masl in year-2017. At Site-C, it drops to -80 masl in year-2001 and then recovers to -66 masl in year-2017.

As a result, the simulated land subsidence by year-2001 reduces further as compared with that in Scenario 6. Figure 8.2.26 shows the subsidence at Site-C to be 31 cm by end of year-2001 and 36 cm by end of year-2017. The subsidence at Site-A, Site-B, and DMR office can be controlled within 30 cm in 25-year period up to year-2017.

Figure 8.2.27 indicates that subsidence up to year-2017 can be controlled within 30 cm in most parts of the Study Area. Areas having more than 30 cm of subsidence by year-2017 can be seen at western Samut Prakan, western Bangkok, central Bangkok, and parts of Pathum Thani and Ayutthaya.

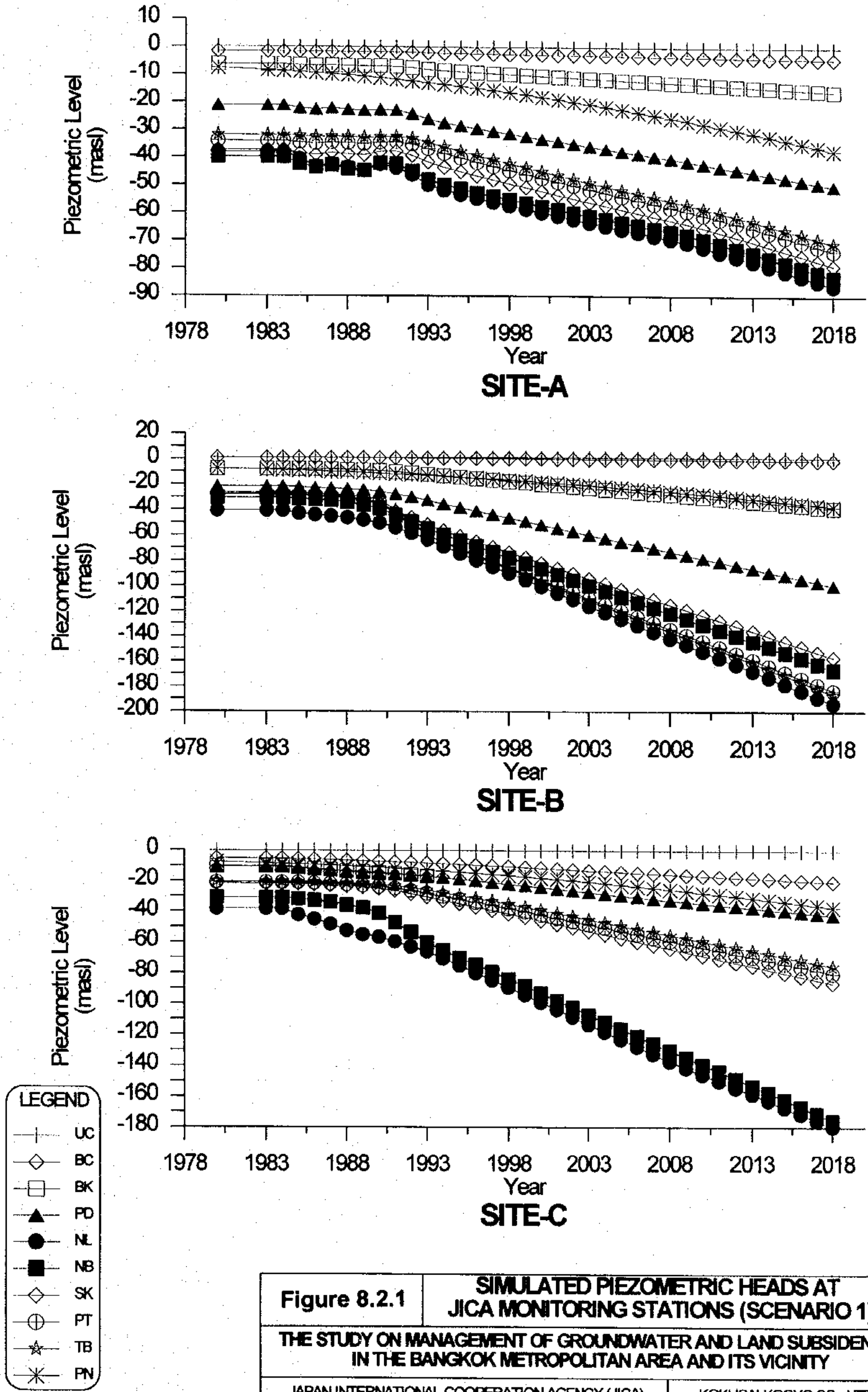


Figure 8.2.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 1)

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.

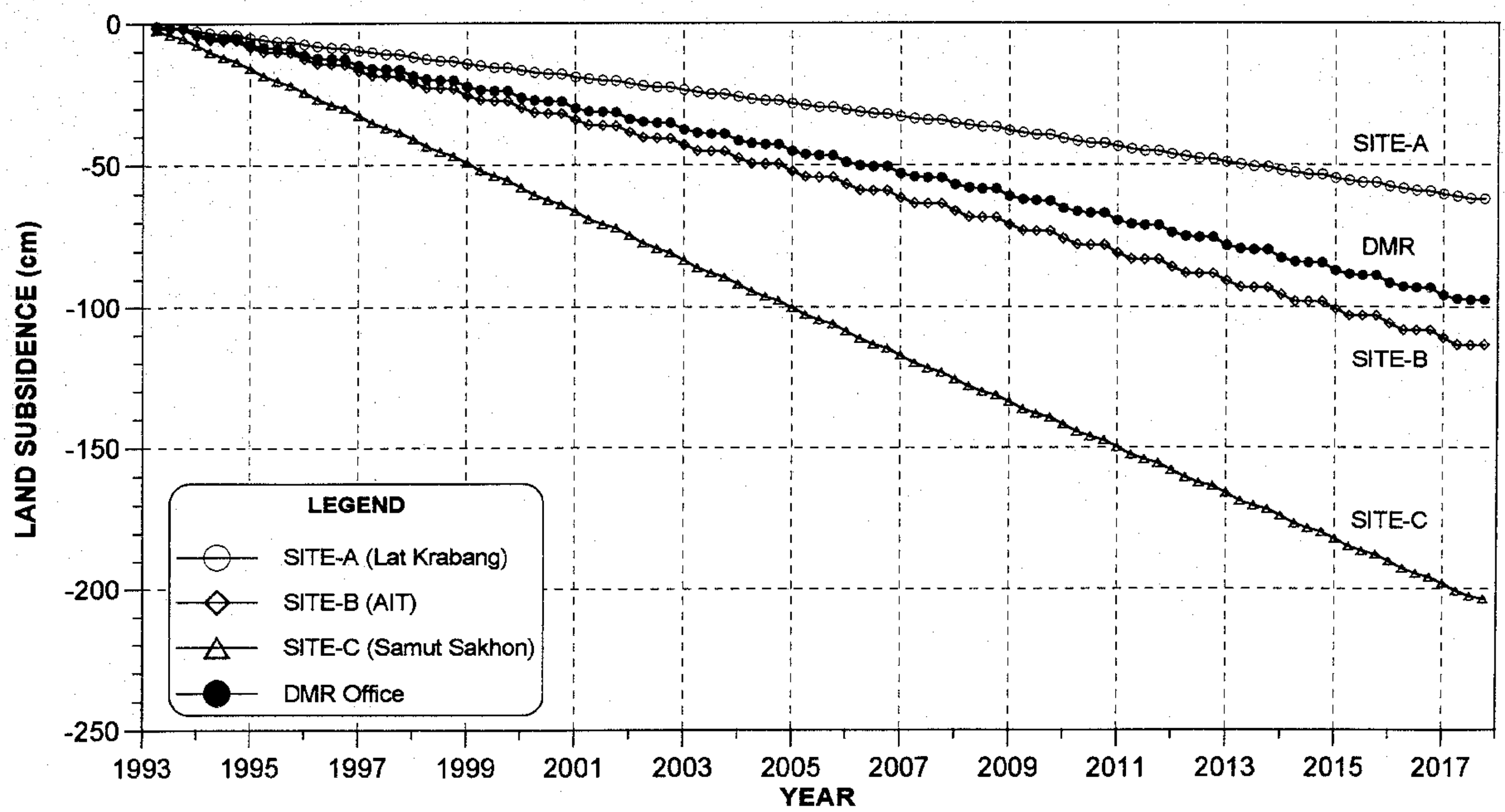
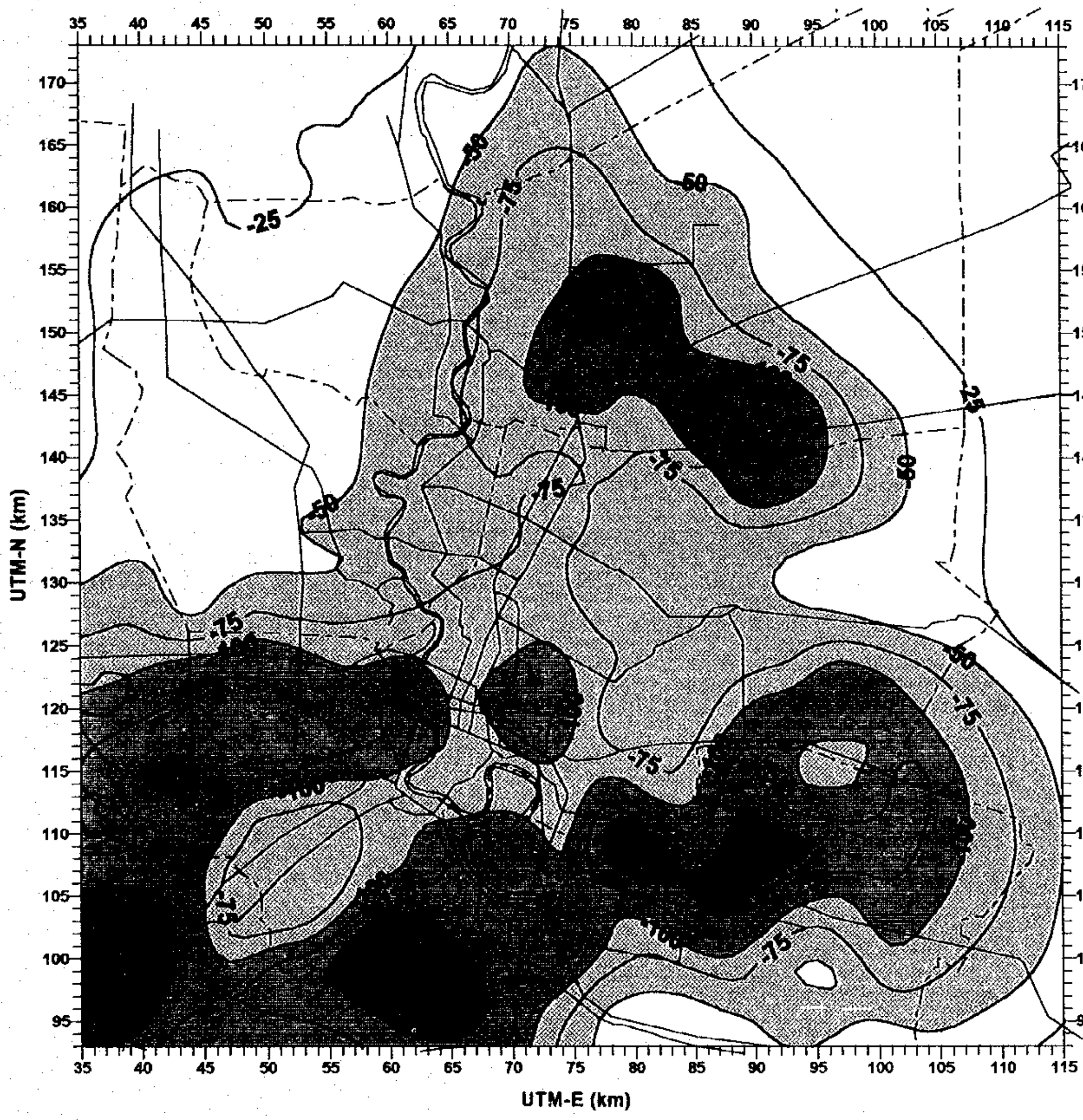


Figure 8.2.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 1)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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

Figure 8.2.3	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.

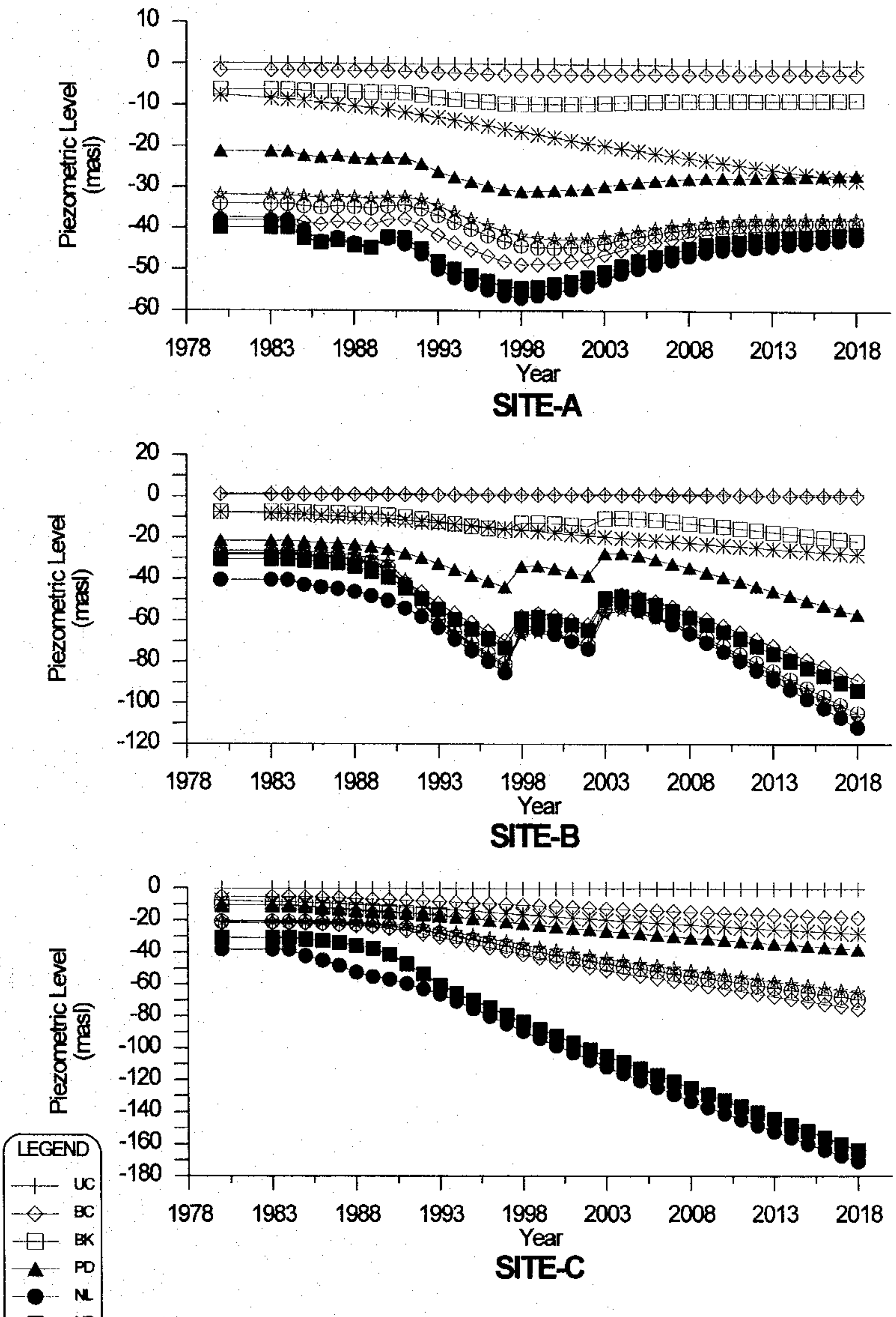


Figure 8.2.4	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 2)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

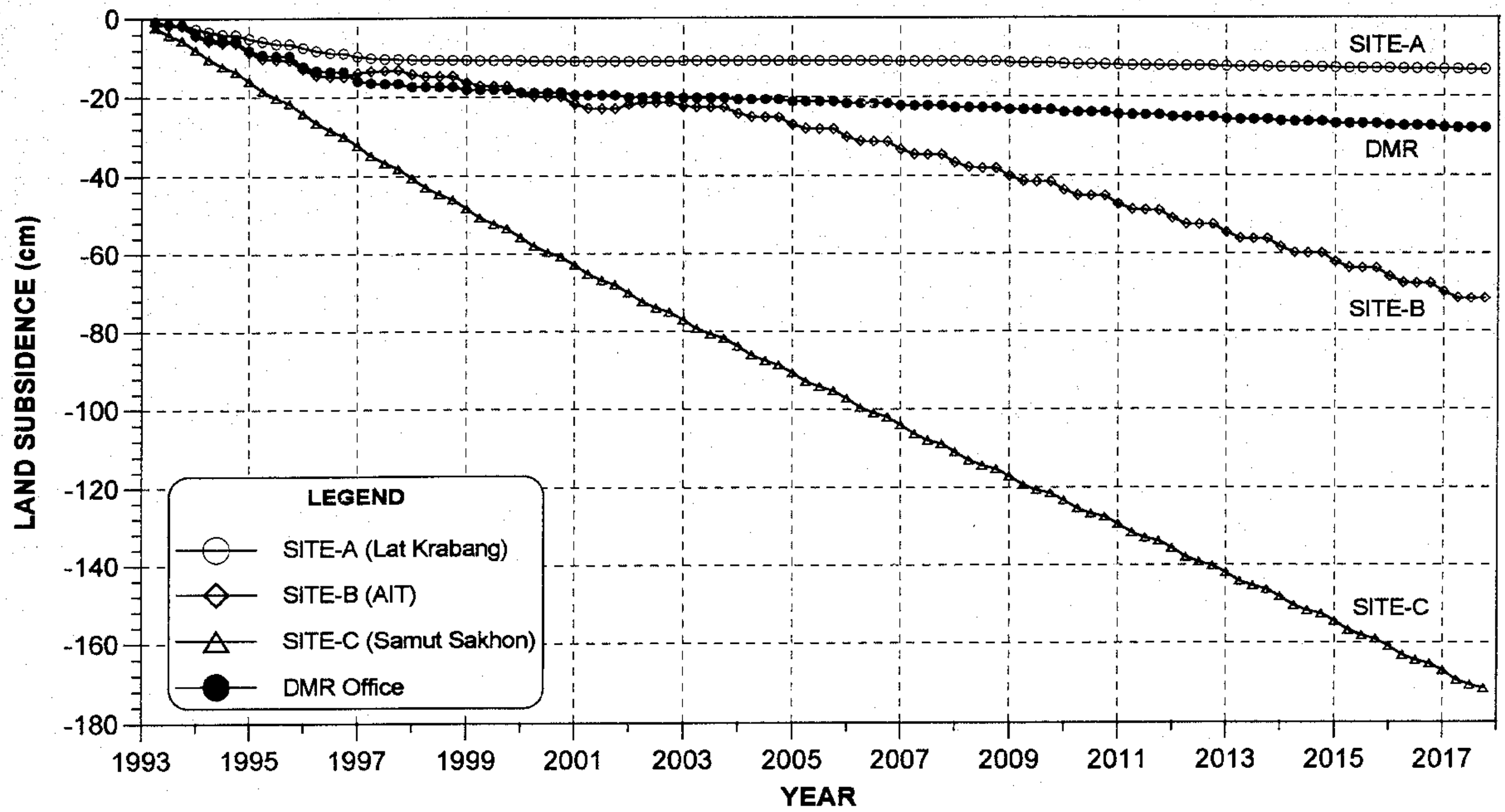
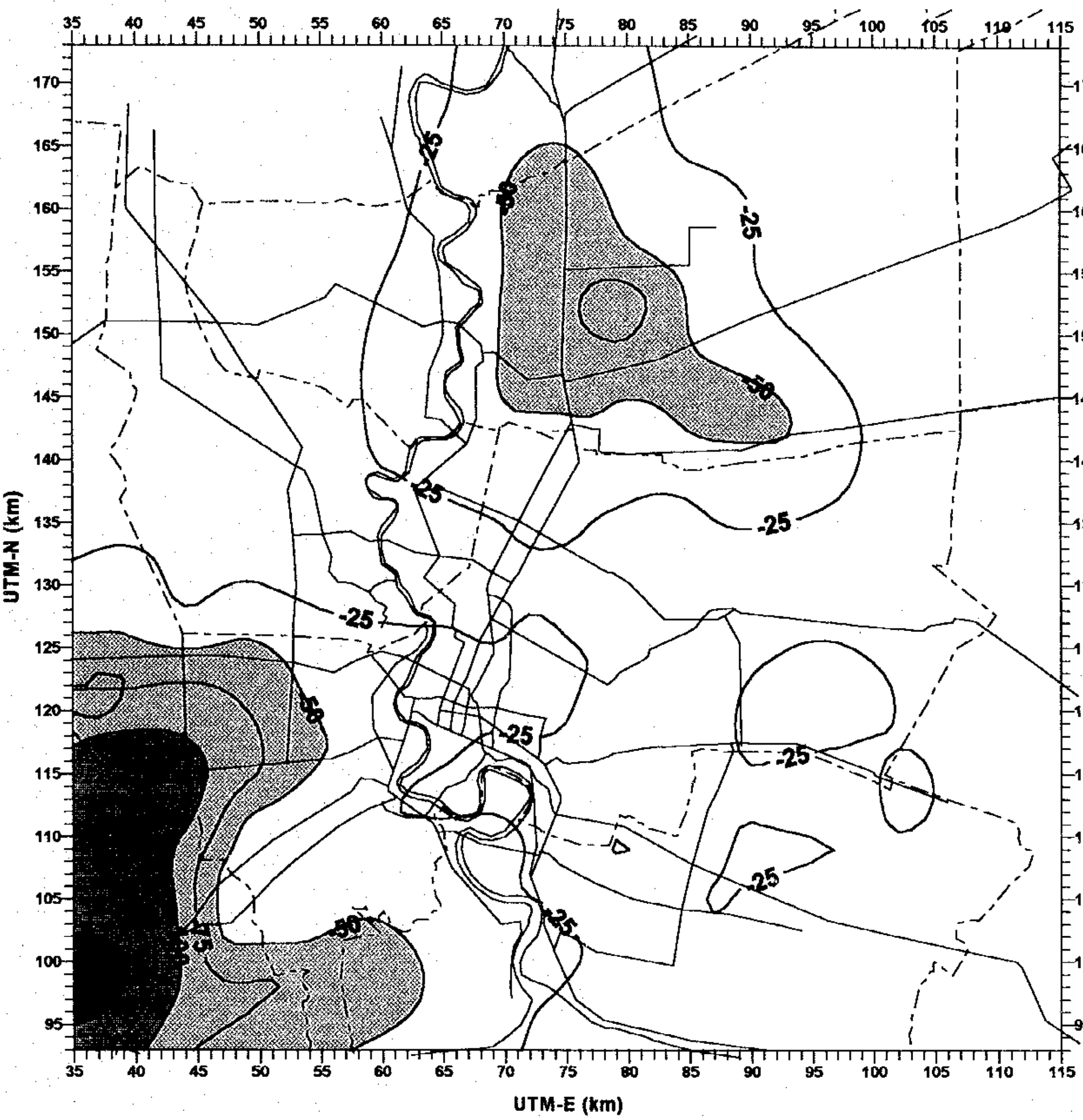
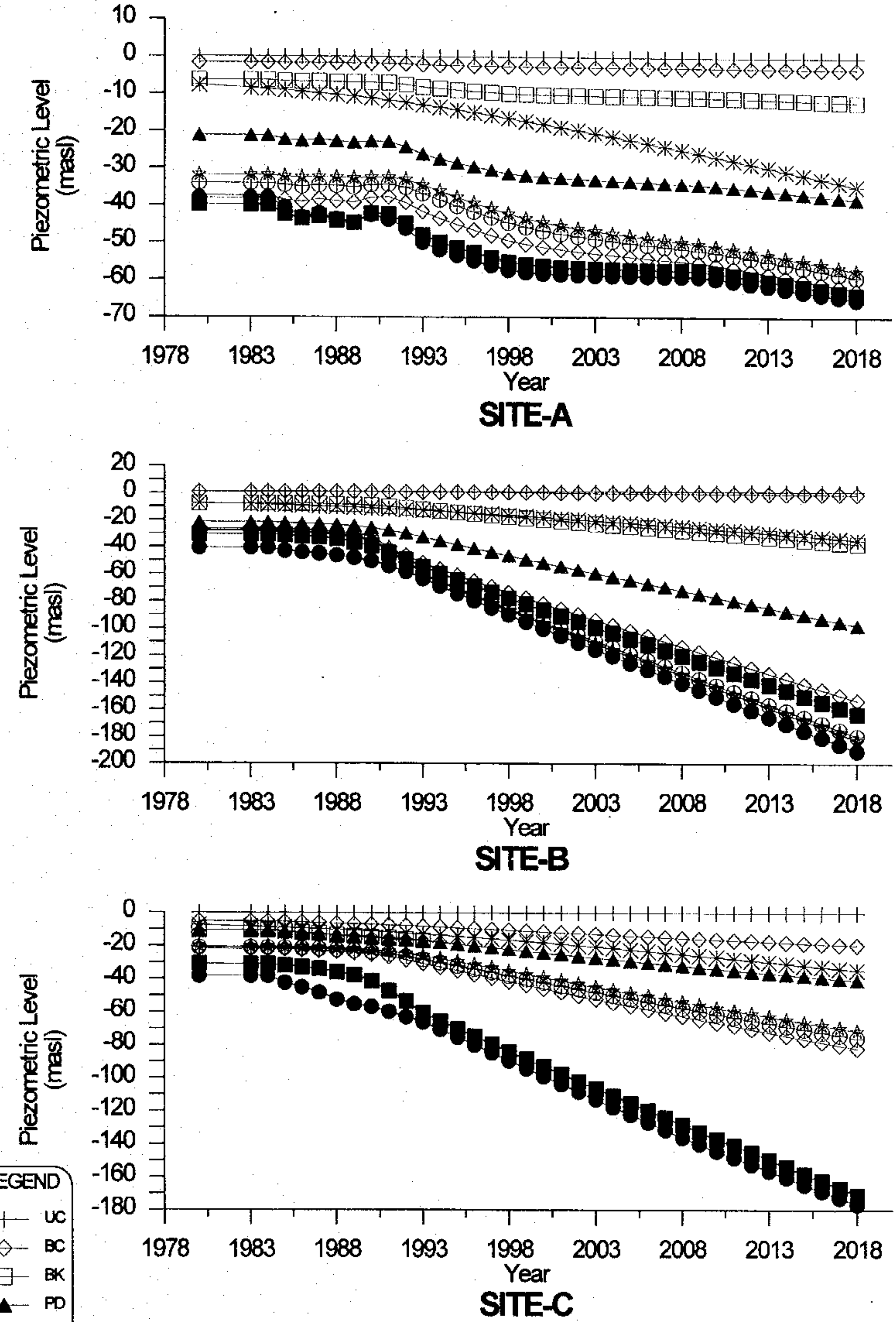


Figure 8.2.5	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 2)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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

Figure 8.2.6	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.



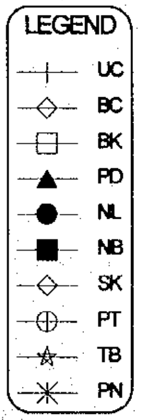


Figure 8.2.7	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 3)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

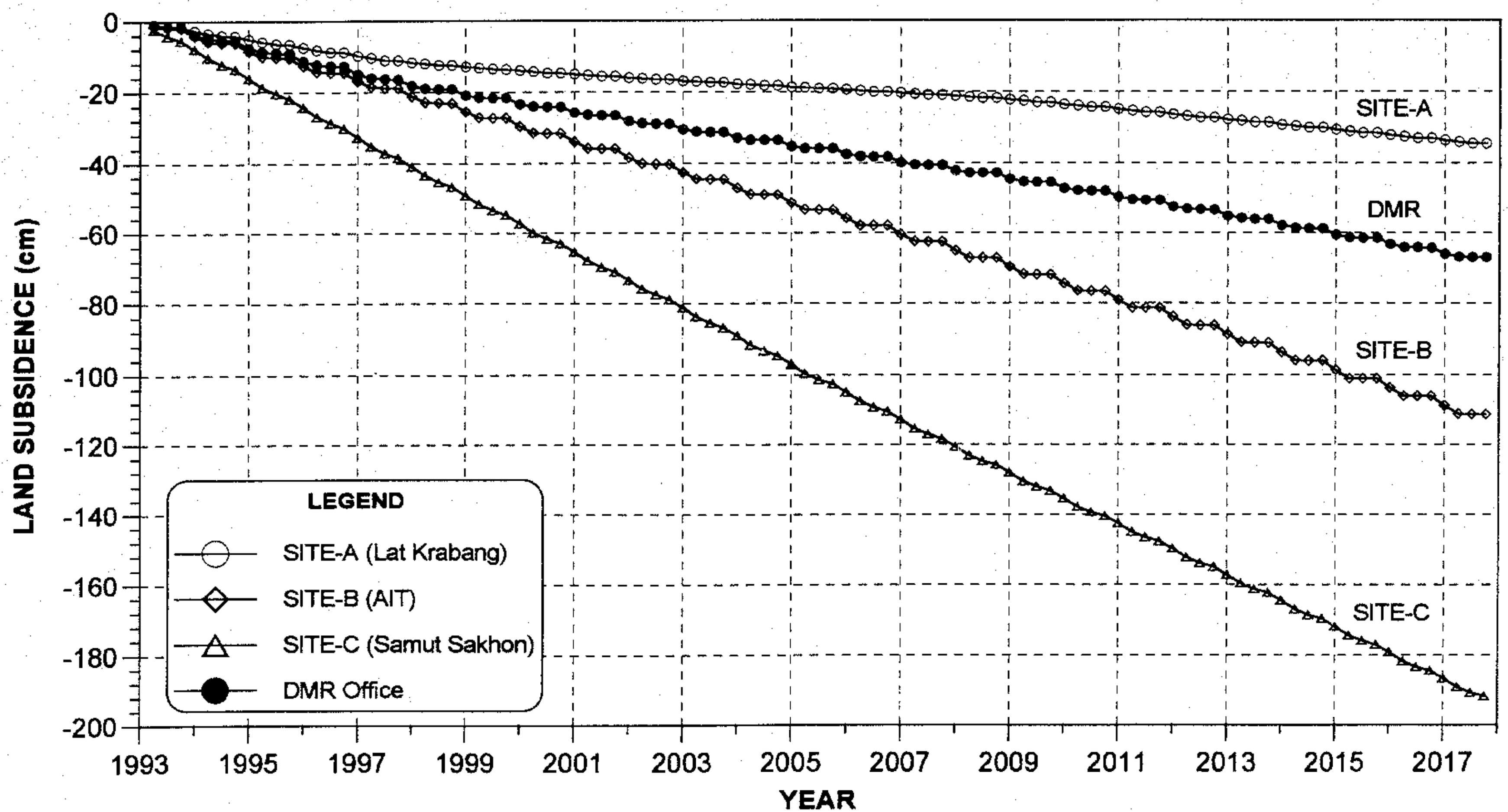
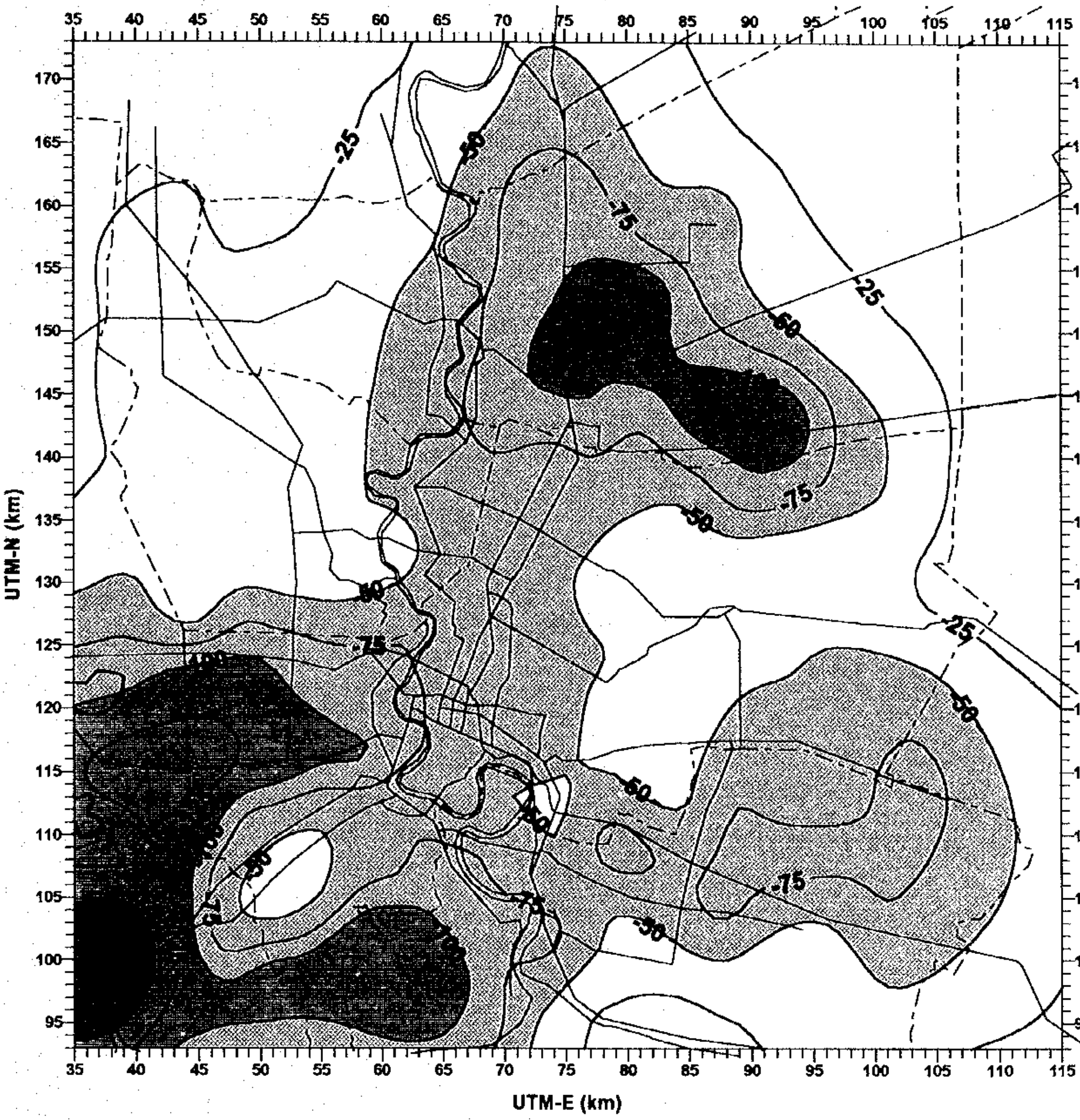
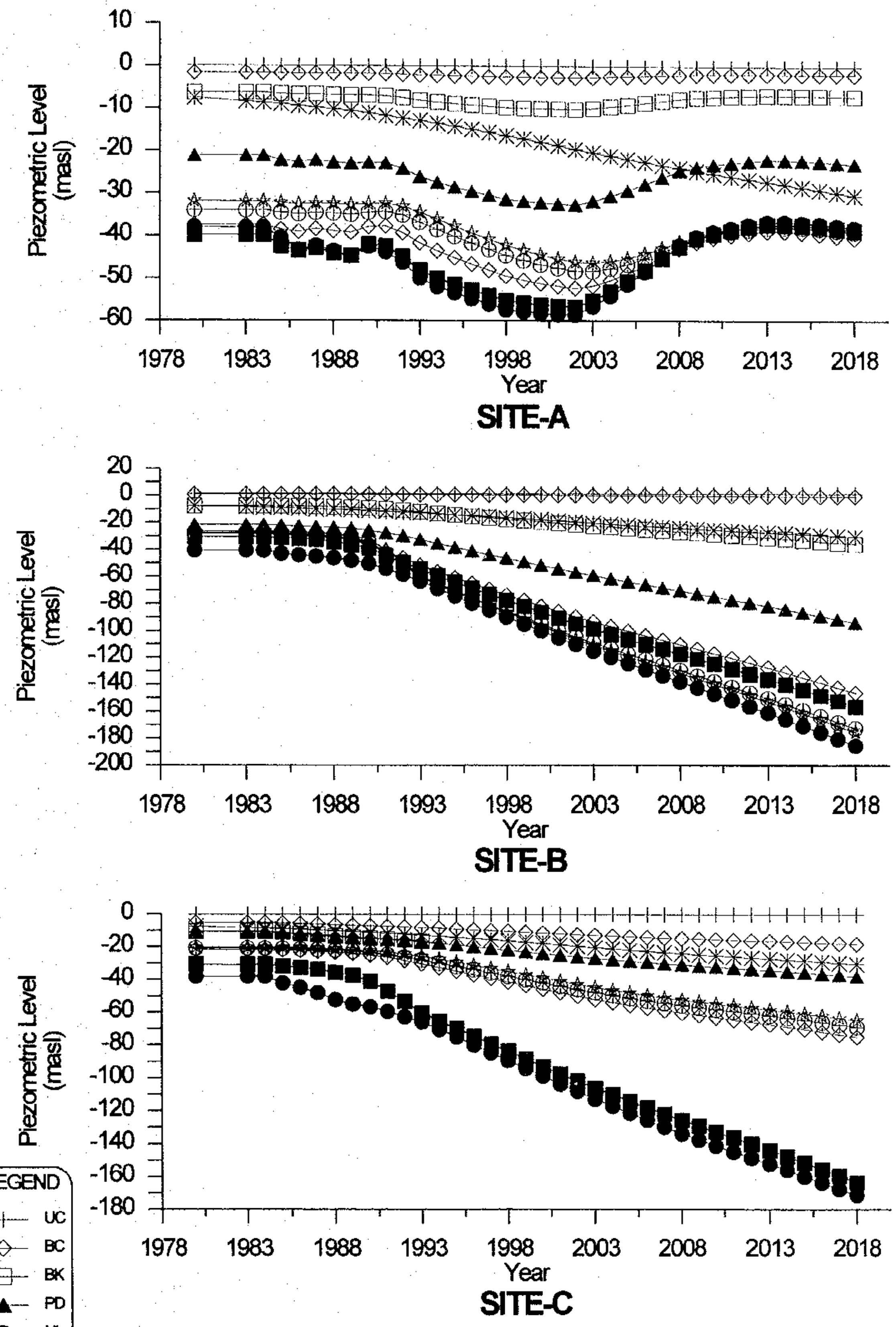


Figure 8.2.8	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 3)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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

Figure 8.2.9	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.



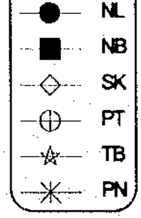


Figure 8.2.10	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 4)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

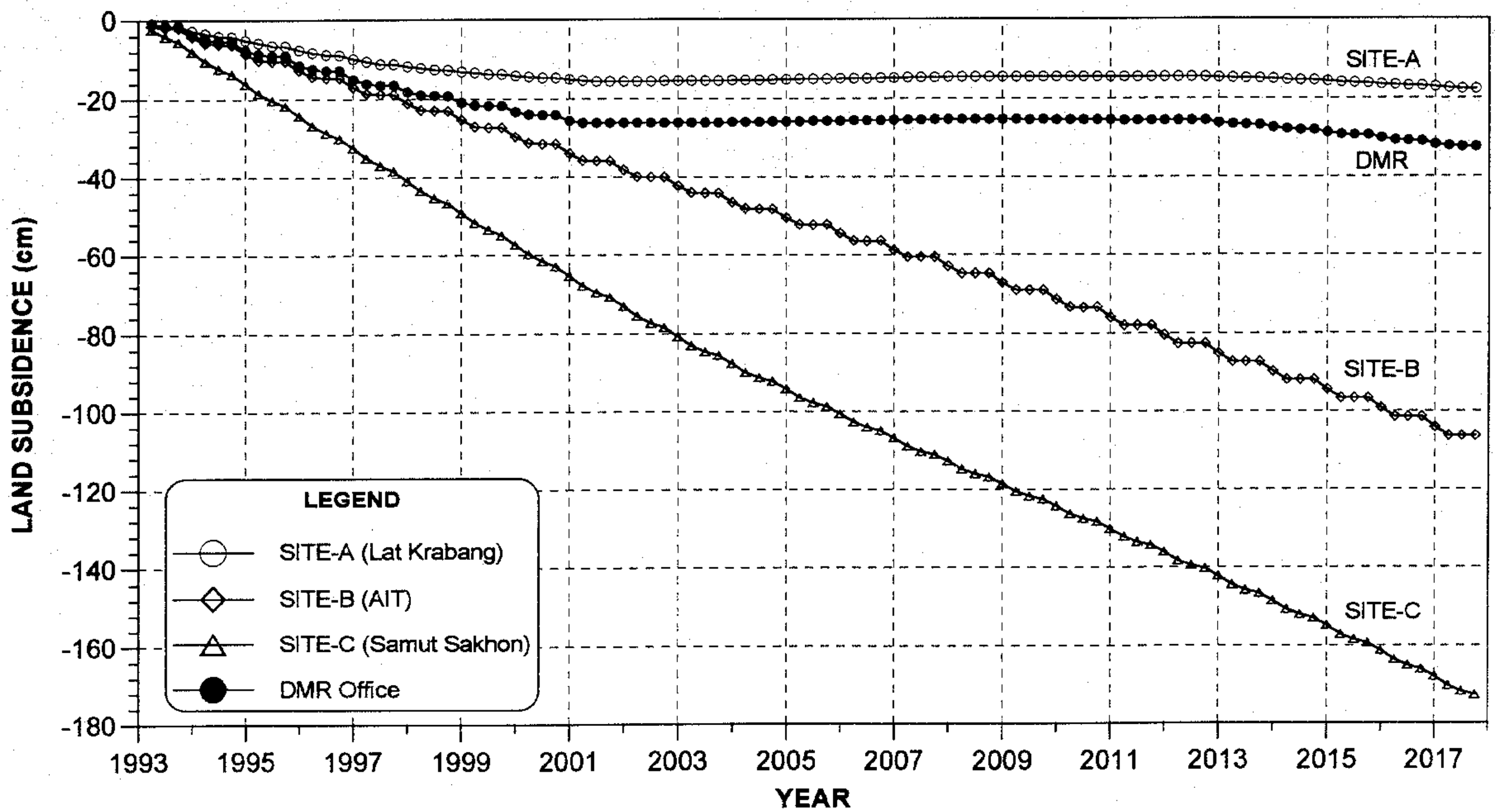
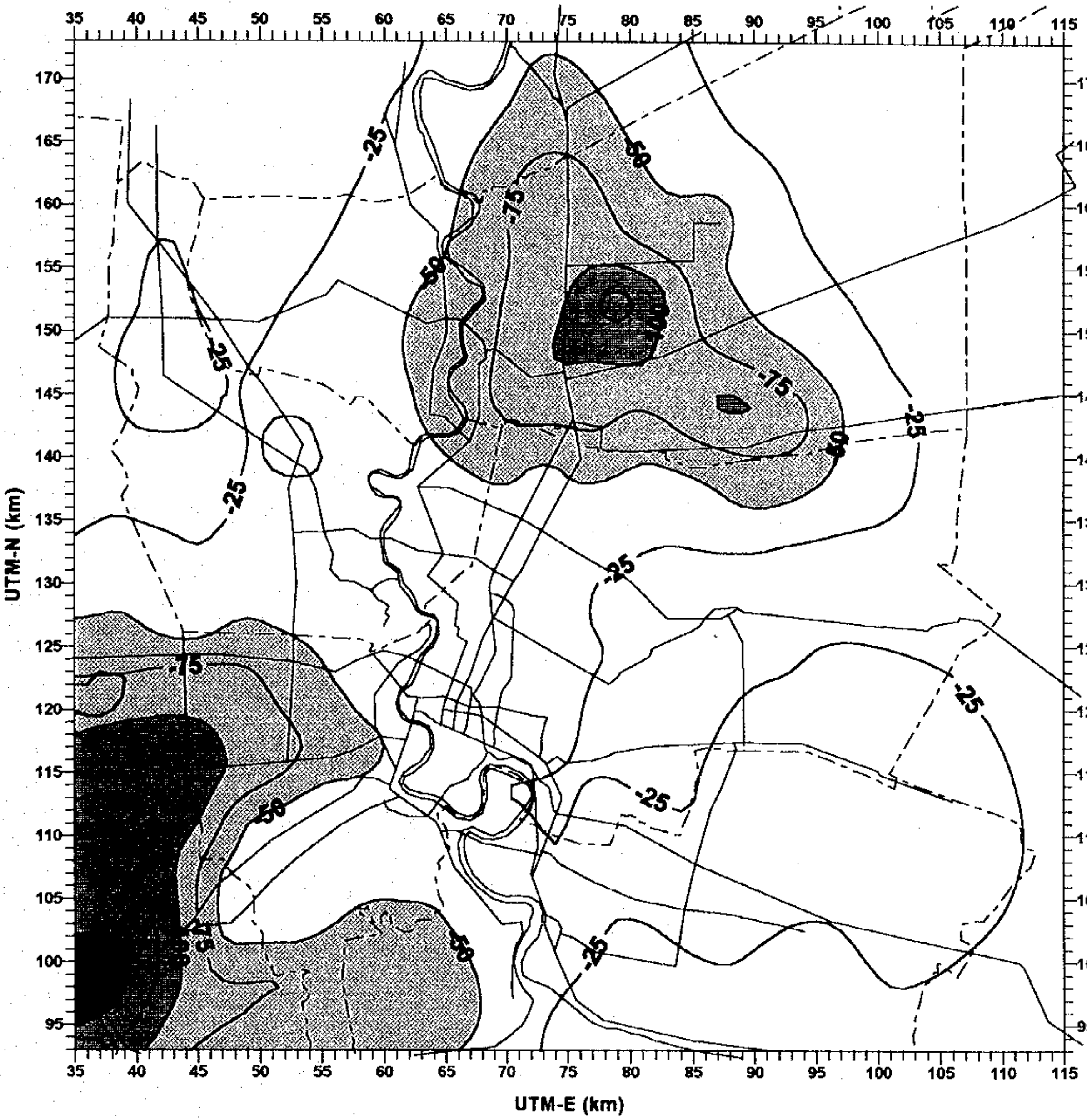


Figure 8.2.11	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 4)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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

Figure 8.2.12	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.

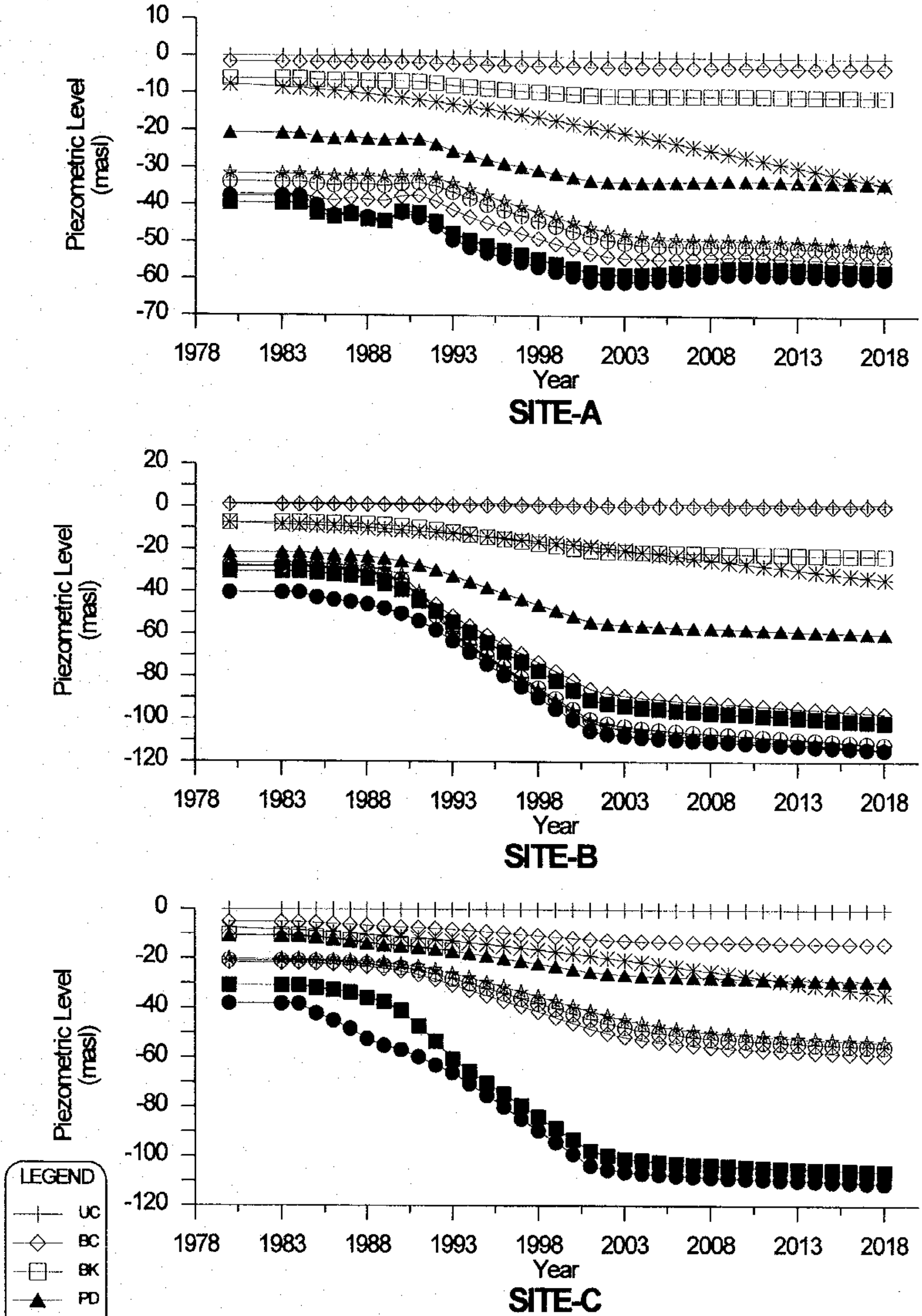


Figure 8.2.13	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 5)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

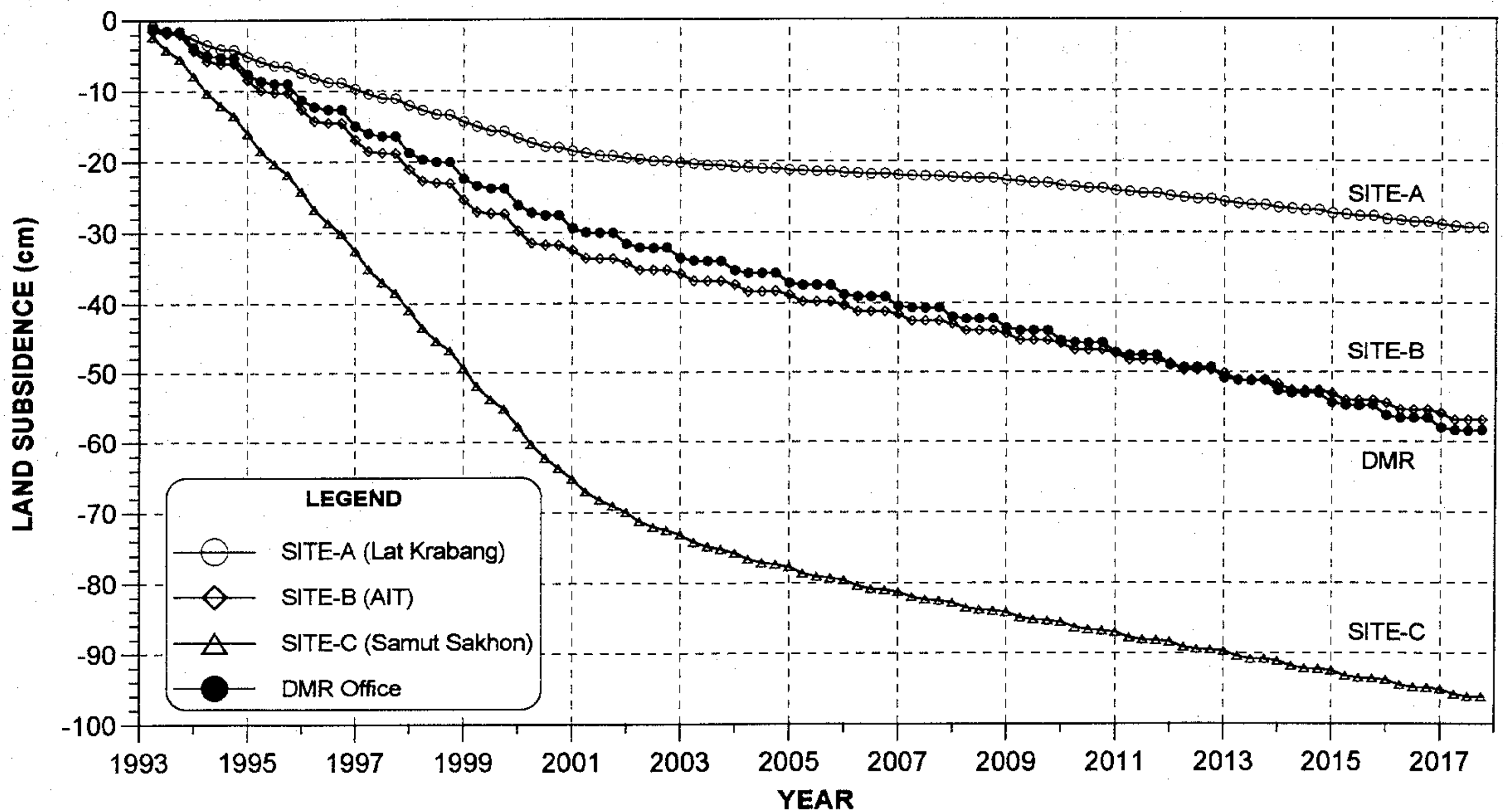
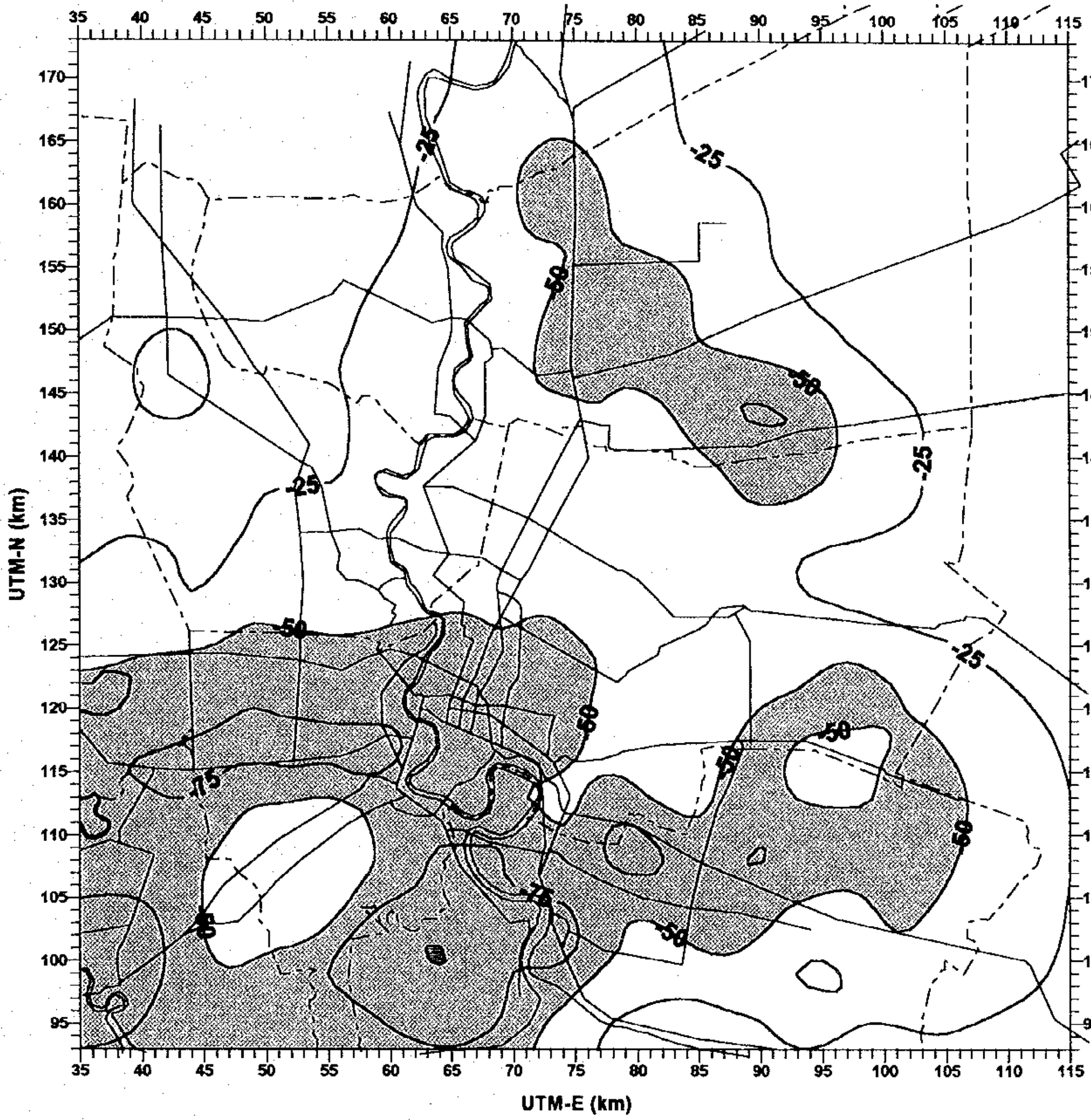


Figure 8.2.14	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 5A)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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

Figure 8.2.15	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.

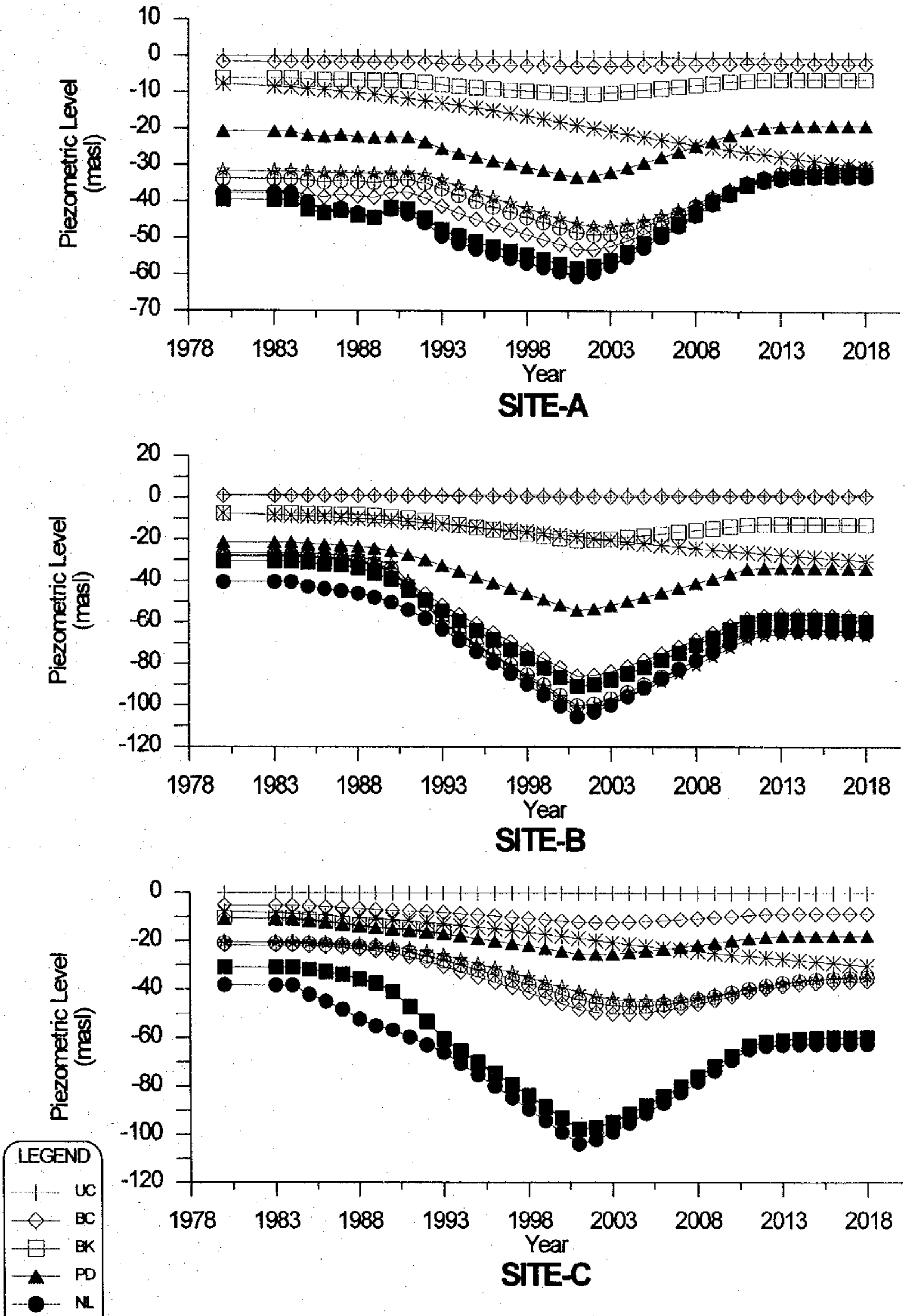


Figure 8.2.16	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 5B)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

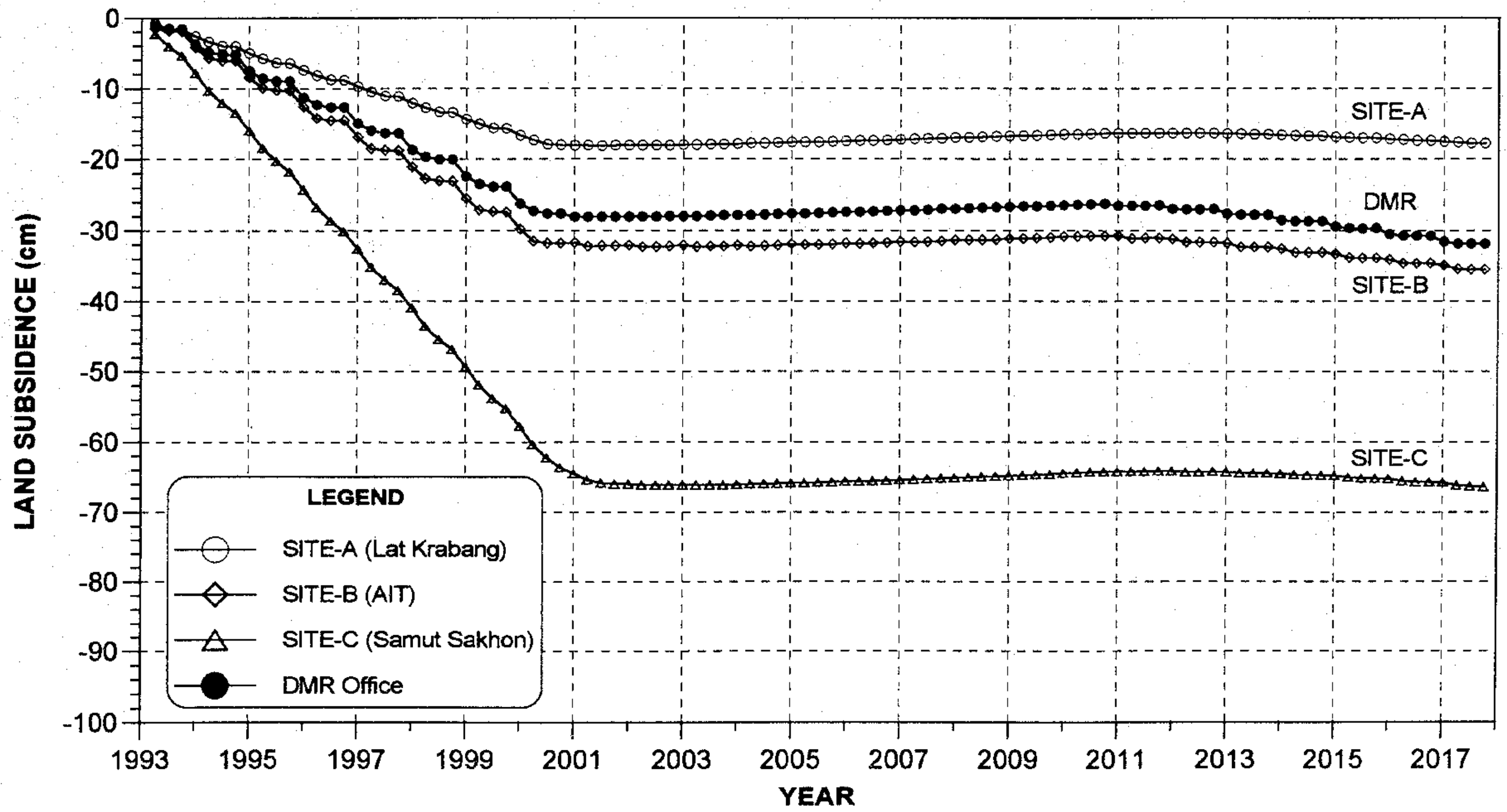
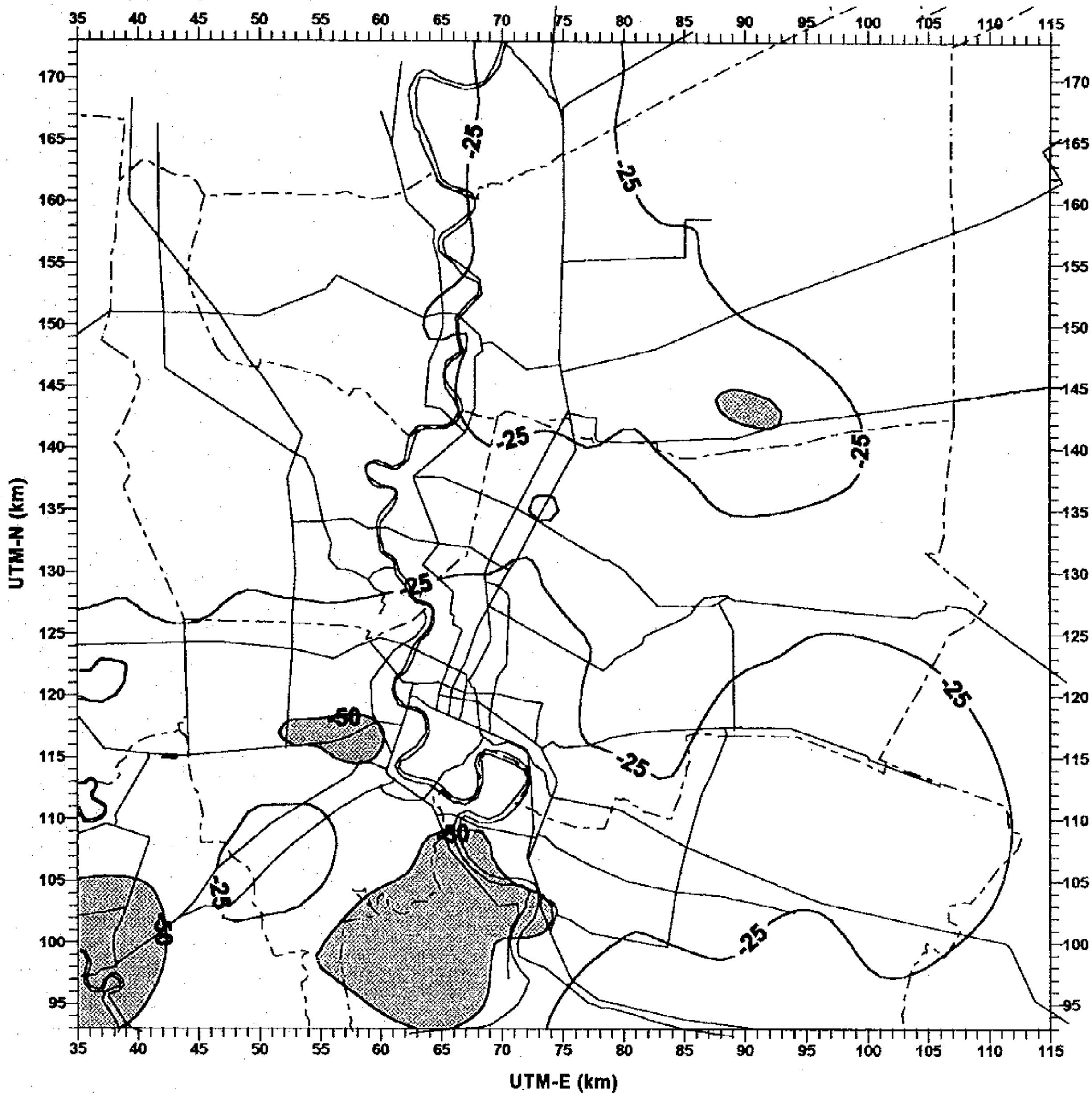
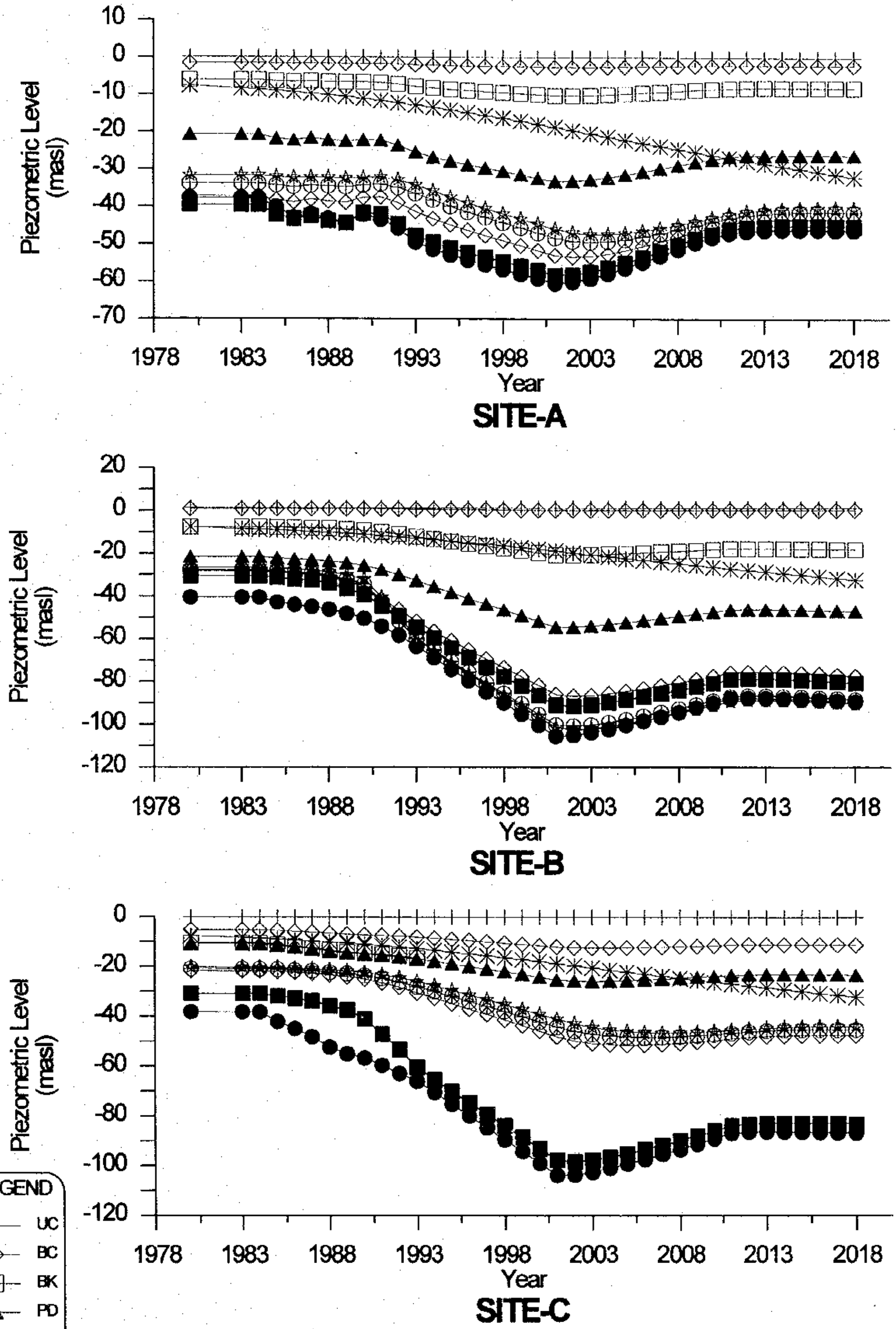


Figure 8.2.17	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 5B)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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

Figure 8.2.18	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.



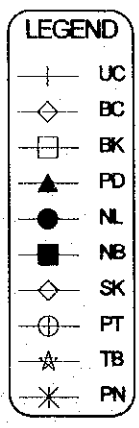


Figure 8.2.19	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 5C)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

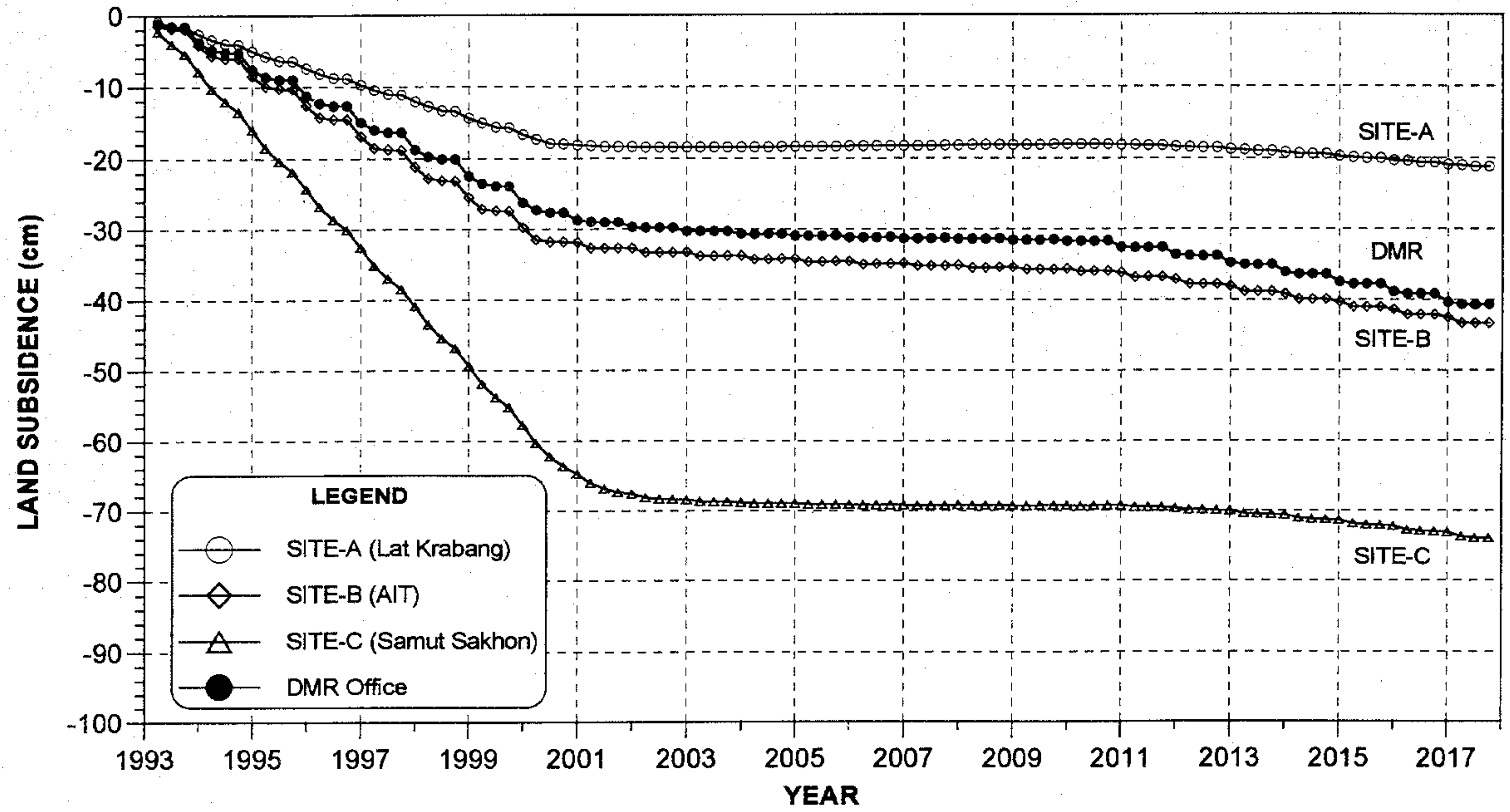
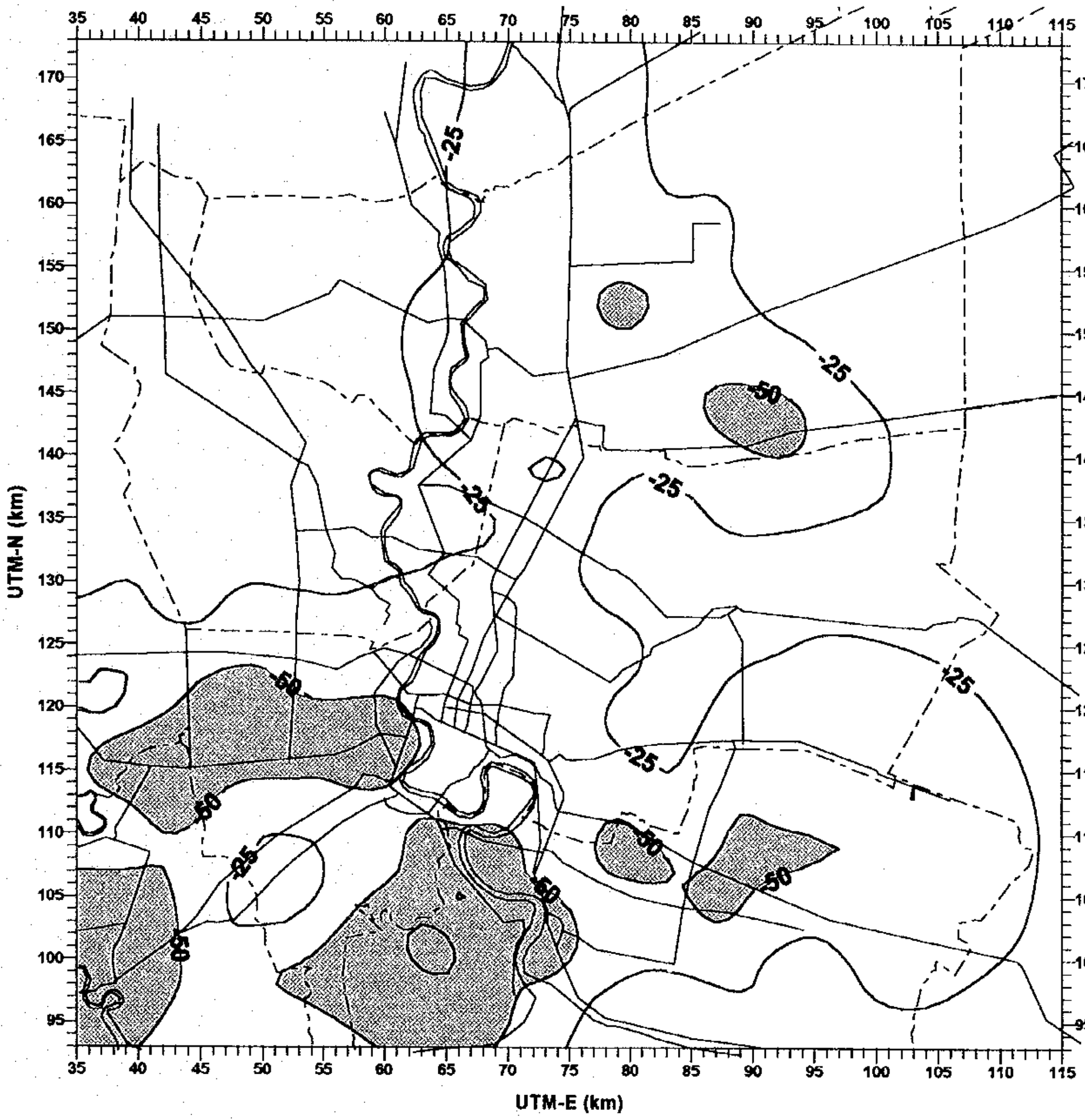
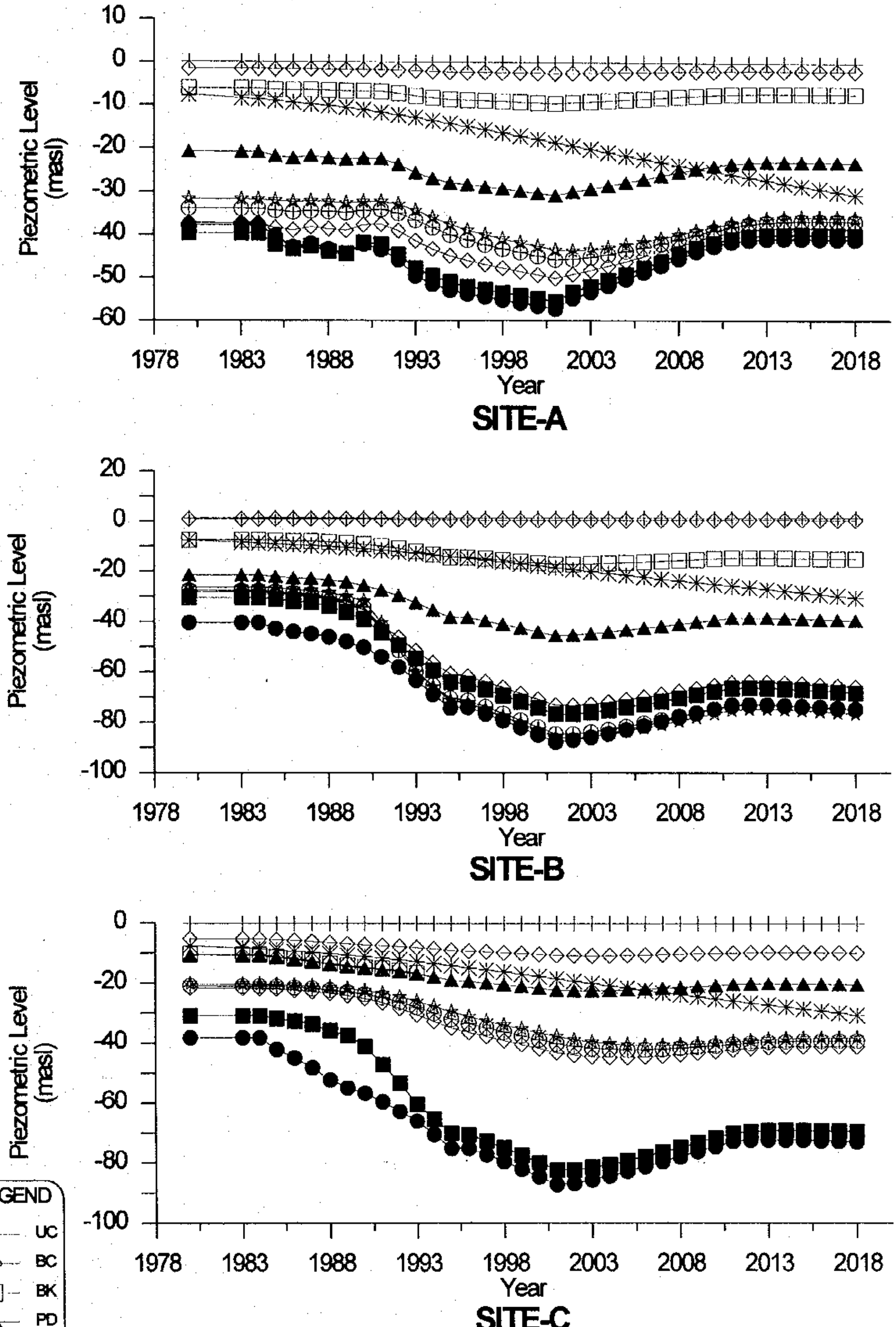


Figure 8.2.20	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 5C)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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

Figure 8.2.21	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.



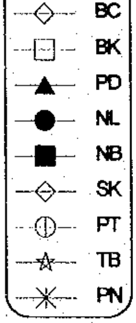


Figure 8.2.22	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 6)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

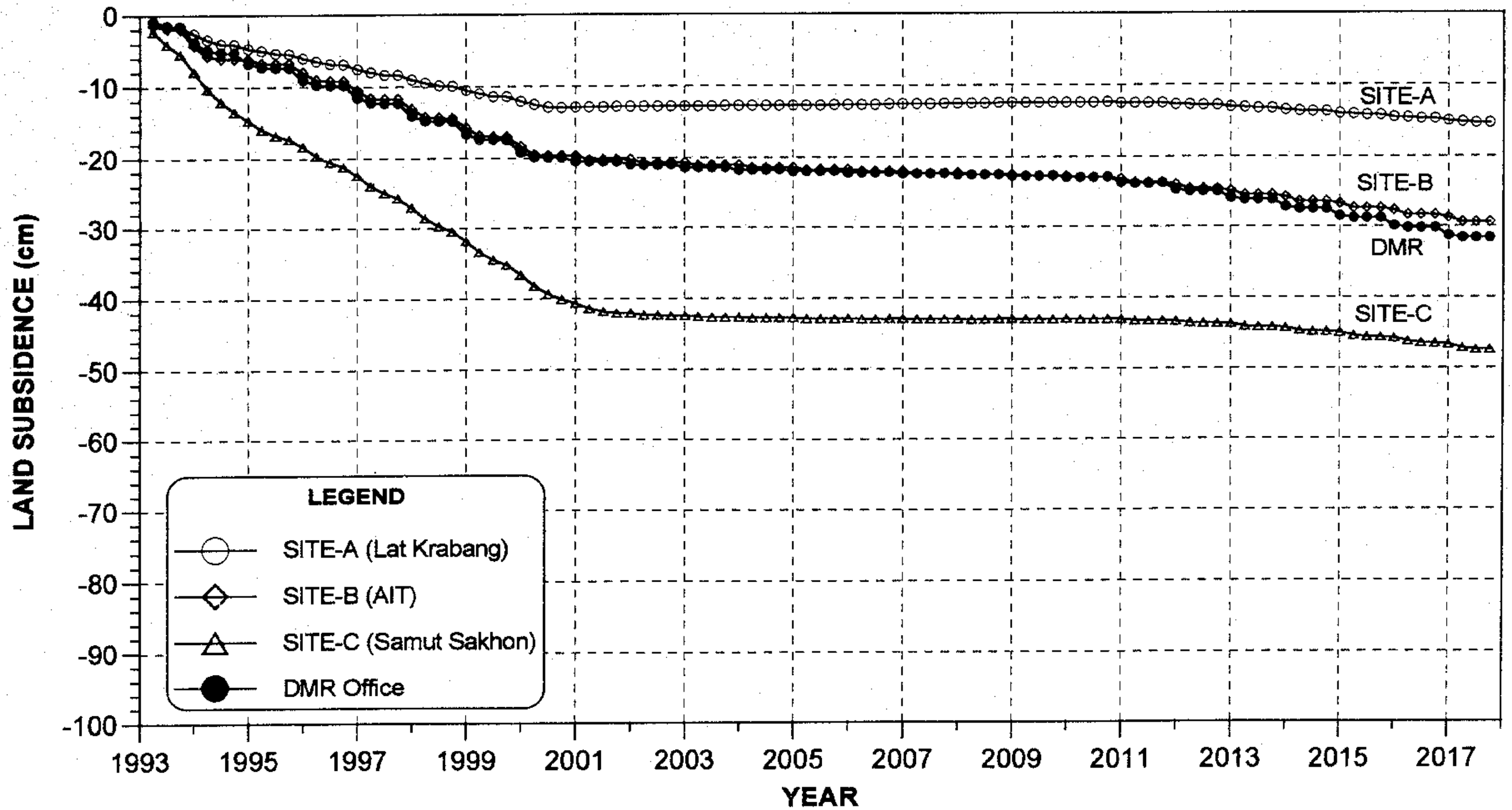
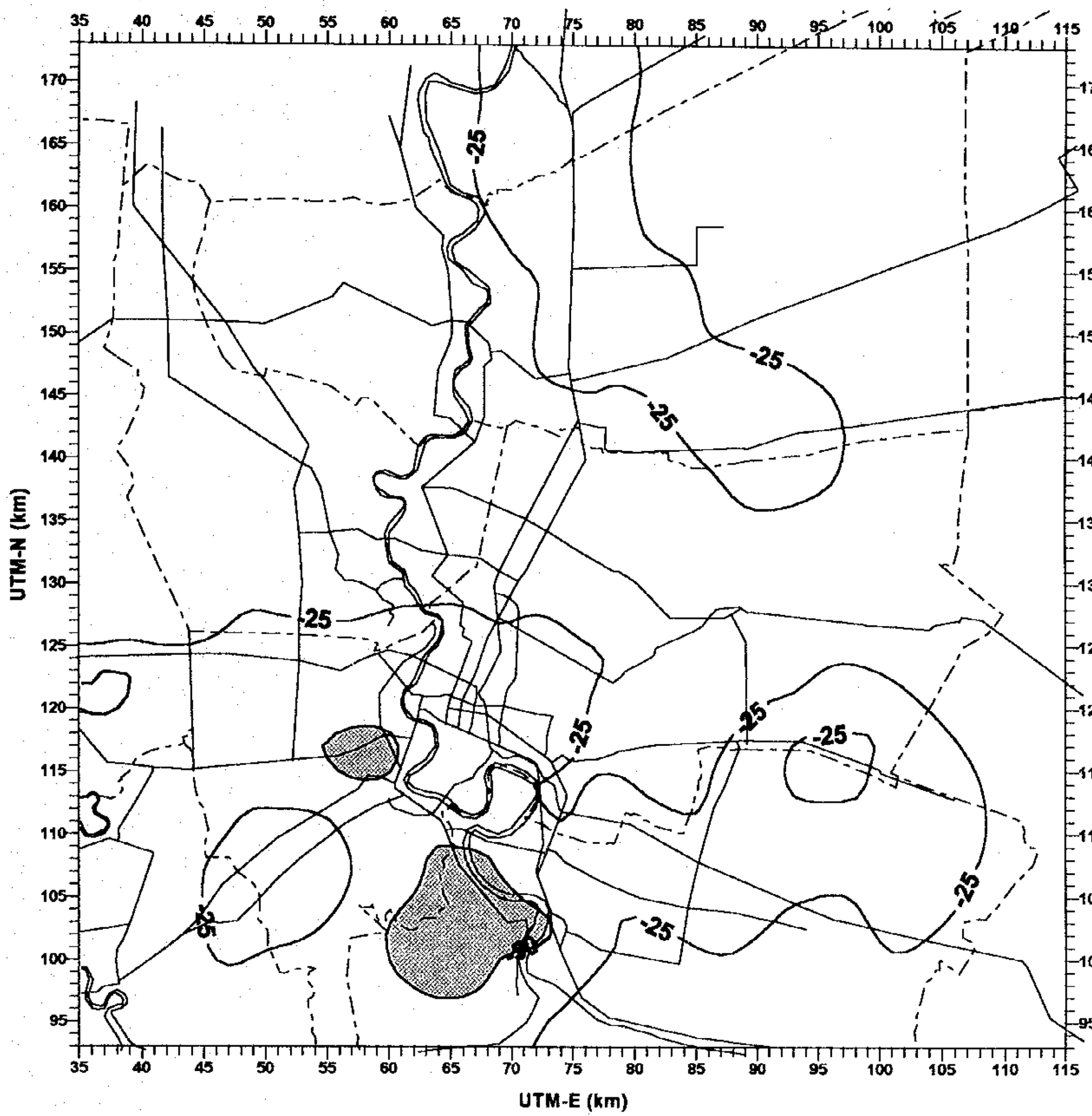
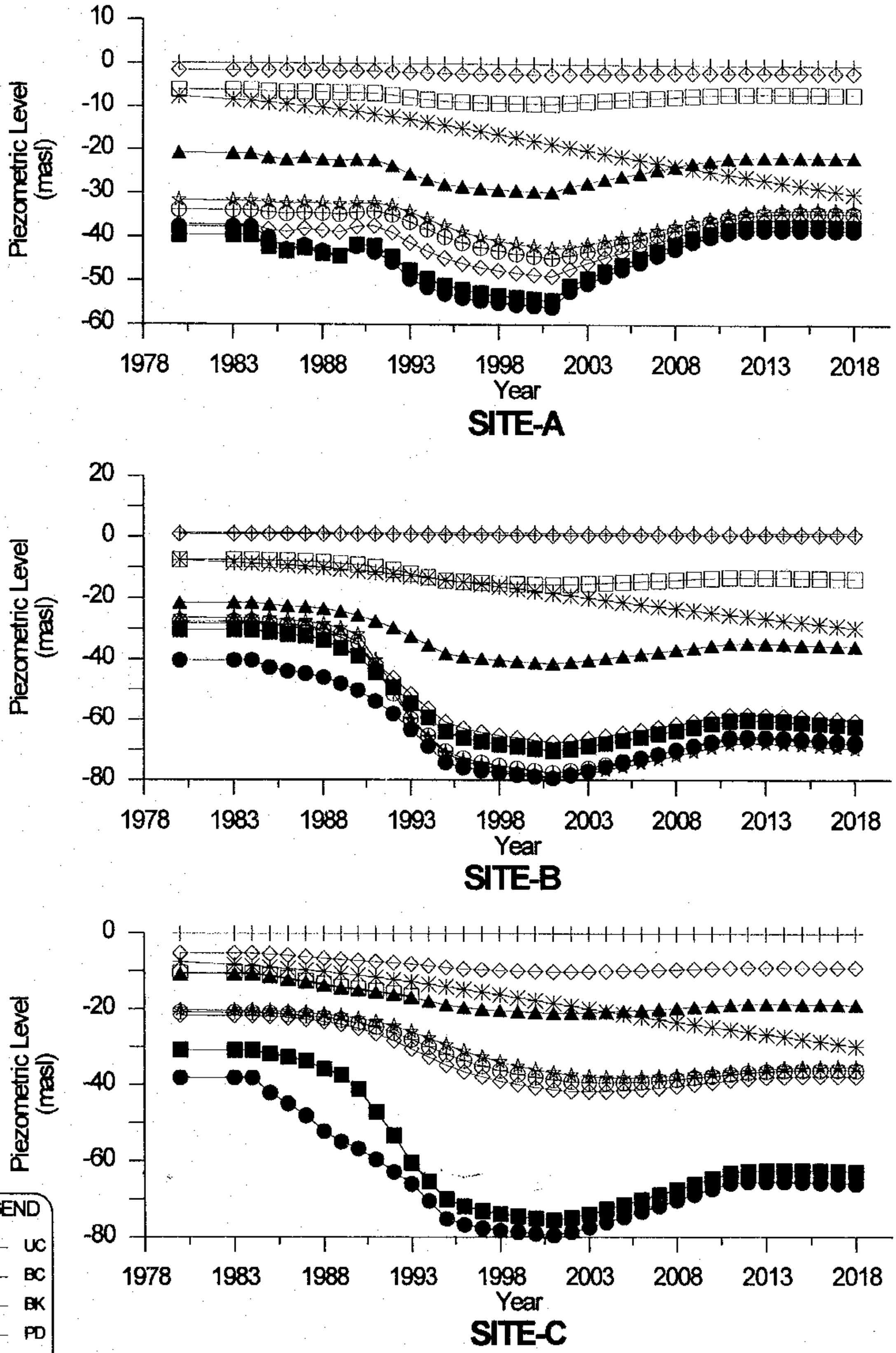


Figure 8.2.23	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 6)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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

Figure 8.2.24	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.



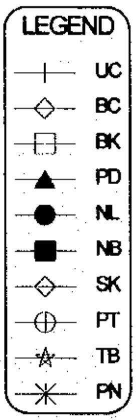


Figure 8.2.25	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 7)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

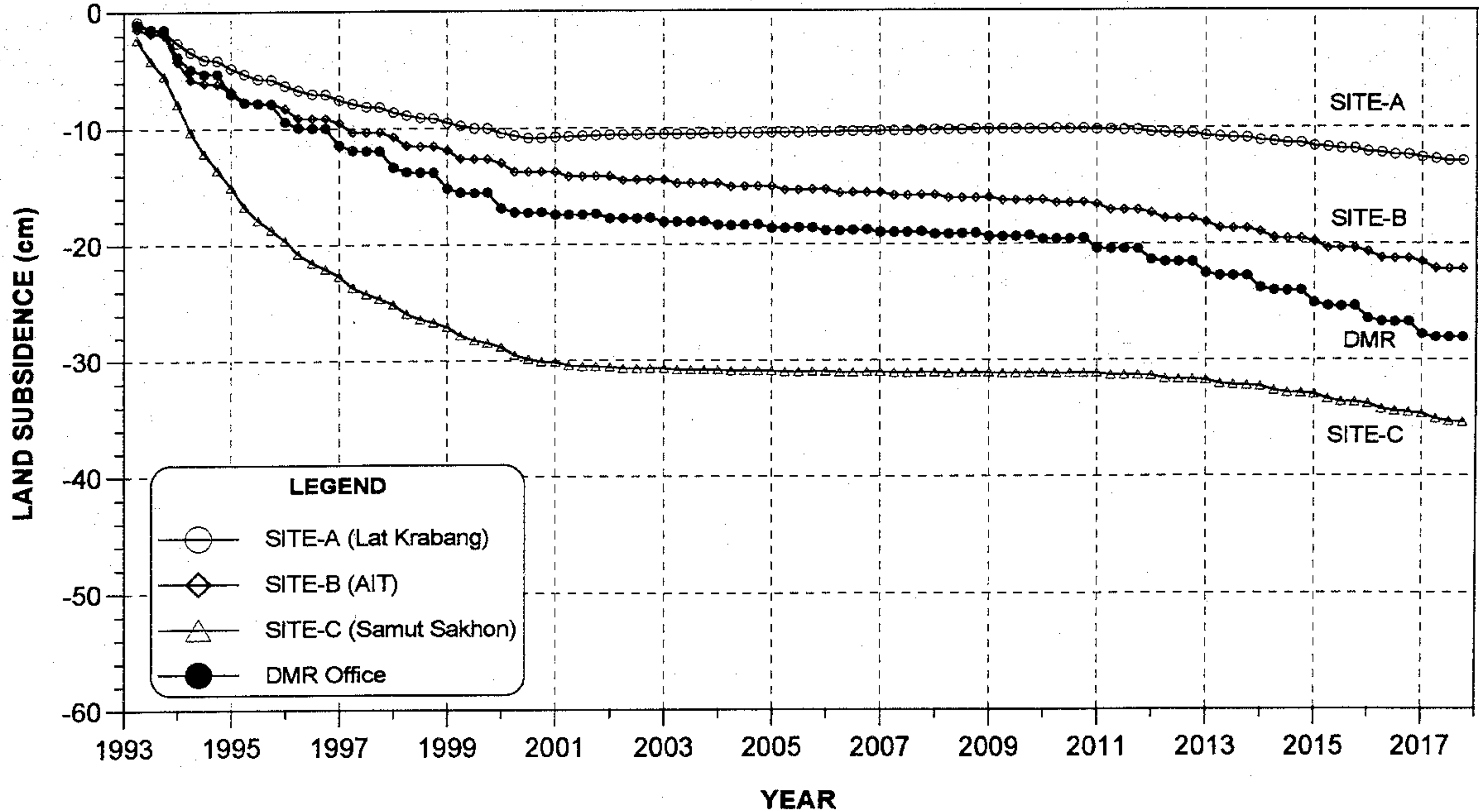
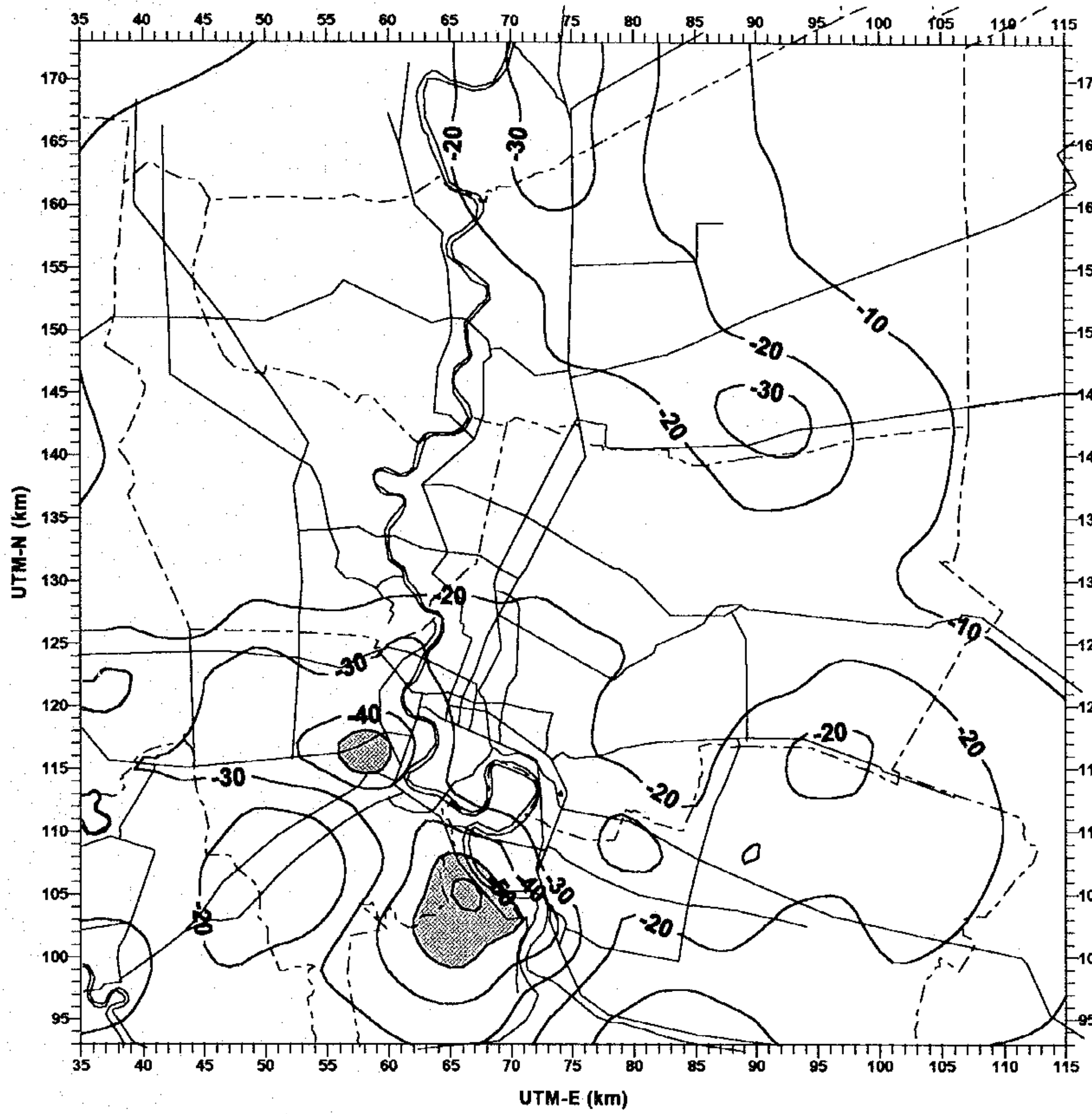


Figure 8.2.26	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 7)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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

Figure 8.2.27	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.

CONTENTS

LIST OF TABLES

CHAPTER 9 ASSESSMENT OF PERMISSIBLE YIELD

9.1 Concept of Safe Yield

At present, there is still no definite concept of permissible limit of basin-wide groundwater development and conservation. Since the first discussion on safe yield of groundwater basin was held in USA in 1910, there had been several related definitions suggested as shown below.

9.1.1 Sustained yield

Sustained yield is defined as the groundwater pumping discharge which can be taken continuously from the groundwater basin without any undesirable results. The term **sustained yield** is used as a synonym for **safe yield** (Meinzer, 1923).

Undesirable results will mean the groundwater level decline, sea water intrusion and land subsidence. Increase of pumping cost due to the lowering of groundwater level is also an undesirable result. The definition given above implies a perennial water balance. However, it also suggests no economic risk nor limitation on the use and development of groundwater.

The sustained yield can be classiffied into two:

1) **Maximum sustained yield** is defined as the maximum discharge that can be withdrawn perennially from the groundwater basin; and

2) **Permissible sustained yield** is the maximum discharge that can be withdrawn perennially and economically for useful purposes without any undesirable results.

The definition given above may suggest a socio-economic meaning to the concept of "permissible".

9.1.2 Mining yield

Mining yield is defined from the viewpoint that groundwater is an exhaustible resource like crude oil, natural gas, etc. This definition can be applicable if groundwater occurs in a closed non-leaky artesian aquifer system. Also the concept of "perennial" does not apply. However, it emphasizes the importance of socio-economic factors in evaluating groundwater yield.

The mining yield can be classified into two:

1) **Maximum mining yield** is the total recoverable groundwater volume from a groundwater basin; and

2) **Permissible mining yield** is the total groundwater volume that can be withdrawn under regulation for useful purposes without any undesirable results.

9.1.3 Safe yield

The **safe yield** of a groundwater basin is defined as the amount of groundwater which can be withdrawn from it annually without producing undesired results. Determination of safe yield of a groundwater basin requires identification of undesired results which may occur if the safe yield is exceeded (Todd, 1959).

Four (4) factors are generally considered, to wit:

1) Recharge to the basin;

2) Economics of pumpage from the basin;

3) Quality of the groundwater; and

4) Water rights in and near the basin.

9.1.4 Permissible yield

The **permissible yield** of a groundwater basin is the amount of groundwater which can be withdrawn permissibly from it considering the benefits and risks of the inhabitants living in the basin area and using groundwater (Water Balance Research Group, 1976).

Permissible yield is relative and has a social, scientific concept. A yield to be permissible must consider water balance and merits/demerits of groundwater use. The permissible yield may be determined individually for each groundwater basin considering its natural and socio-economic conditions.

The concept of permissible yield is quite similar to that of the permissible limit employed in environmental problems such as water pollution, air pollution, etc. Generally, "permissible limit" does not always mean "safe limit". In this context, "permissible yield" instead of "safe yield" may be suitable for groundwater management.

The term **permissible critical water level** is also proposed instead of the use of the term **permissible yield**. In this case, the permissible yield is the volume of water that can be withdrawn from the groundwater basin, constrained by the permissible critical water level.

Groundwater levels can be measured in monitoring wells as well as in existing wells distributed over the entire groundwater basin. If the permissible critical water level is established in the basin, then pumpage can be easily controlled.

9.2 Impact of Land Subsidence

9.2.1 Damages caused by land subsidence

In the Study Area, damages caused by land subsidence could be observed in many places. Attached facilities of some buildings could be seen either detached or cracked due to land subsidence. Buildings resting on deep foundations could be found standing up against the surrounding subsiding ground surface, and well casings could also be observed protruding. These protrusions of deep well casings and buildings however could indicate directly some regional land subsidence rates.

Some minor damages might have taken place because of land subsidence but could not be directly evaluated, especially those related to the physical properties of the uppermost clay layer, the quality of construction works, the variation in geologic conditions, the design of the facilities, the decrepit of the facilities and the propriety of operation and maintenance.

No report has been made so far by any government agency regarding the visible damages to road facilities, control gates, pumping stations and irrigation canals, which are thought of resulting from land subsidence.

Table 9.2.1 shows the results of the field investigations and questionnaire surveys on the damages caused by land subsidence in the industrial estates and other industrial areas. Damages on the facilities in old factories are found more severe than those in newly constructed ones. None or only minor damages were observed in the newly constructed factories.

Land subsidence could aggravate flooding, drainage and sewerage problems. Bangkok with its progressing land subsidence problem due to extensive groundwater withdrawal is susceptible to submergence and flooding. In recent years, the flooding in Bangkok has spread extensively. One of the recent floods, the year-1983 flood, was devastating in terms of damages which amounted to an estimated 6,600 million bahts.

The 1983 flood occurrence in Bangkok and its vicinity was brought about by many unfavorable coincidences, to wit:

a) High stage of flow in the river of about 2.5 meters above MSL and low flow rate of 3,600 m/sec, spilling over floodwaters into the subsiding areas of the city.

b) Widespread overland flow due to the broad flood plain and the big catchment areas around Bangkok's vicinity.

c) Direct rainfall of up to 280 mm per day over the low-lying, subsiding areas of the city.

d) High tide from the estuary, rising up to 2.1 meters above MSL.

The flood problem in the low-lying, subsiding areas of Bangkok during high tide in the monsoon season is a major one that must be remedied by the government.

9.2.2 Flood damages

Several agencies and consultants have reported estimates of damages caused by past floods in Bangkok area (Table 9.2.2).

In JICA (1985) and NEDECO (1984), the flood damages were classified as either "Direct" and "Indirect" monetary damages. Direct monetary damages are the cost of repairs or replacements of goods. Indirect damages are the value of lost business and services, the cost of alleviating hardship, safeguarding health, rerouting traffic, delay in completing activities, etc.

In an attempt to apply these unit monetary values, the AIT flood plain model was used to determine the depth and duration of flooding in each of some 250 computational cells. Each cell represented a specific geographical area. For each cell, the number of factories, commercial establishments and households were estimated. These estimates intended to use the land use maps prepared by the Department of Town and Country Planning (DTCP). Detailed land use maps which were required to yield meaningful data, however, were not available.

Table 9.2.2 Flood damage estimates from 1975 to 1983 (after Thavivongse Sriburi, 1989)

Year	Total Damage (million bahts)	Damaged Area (km^2)	Approximate Damage (million bahts/km^2)
1975	1,110/1	1,568	0.7
1978	280/2	1,568	0.18
1982	1,093/3	600	1.83
1983	6,600/4	1,568	4.2

Note:

/1 NESDB (National Economic and Social Development Board) Flood Damage Report, 1976

/2 Collected from various sources in BMA (Bangkok Metropolitan Authority) and RID (Royal Irrigation Department)

/3 NEDECO: Bangkok Flood Control & Drainage Project (City Core), 1984 and JICA: Feasibility Study on Flood Protection /Drainage Project in Eastern Suburban-Bangkok, 1985

/4 NSO (National Statistical Office), 1984

The direct flood damages in the private sectors, including households and companies, were estimated using the determined inundation depth and duration of flooding on the basis of the following equation:

$$D = A_0 + A_1 H + A_2 L$$

D: amount of flood damages and losses per household or establishment; H: flood depth (cm); L: flood duration (month); and A_0, A_1, A_2: parameters.

The damages and losses in the public sectors, including government offices, schools and other public corporations, were estimated based on the public expenditures for direct damages to the buildings. The medical expenditure was assumed to be 10 percent of the total flood damages from past flood damage surveys.

Among public corporations, the damage to the Bangkok Mass Transit Authority (BMTA) was recognized as fairly large. The amount of this damage was estimated based on the City Core Study (NEDECO, 1984). The estimation method used was as follows:

a) Repair and maintenance cost for flood damage (D)

$$D = 1.0 \times 8.020 \times (4{,}285 \times r \times 0.35 \times L)$$

b) Large repair cost and damage (D)

$$D = 0.5 \times 6{,}100 \times (4{,}285 \times r \times 0.35 \times L)$$

c) Extra fuel cost (D)

$$D = 1{,}000 \times (4{,}285 \times r \times 0.35 \times L)$$

r: percentage of buses operated in the Project Area, assumed to be 0.25, which was based on the population rate of the City Core Area and the Project Area; and L: flood duration around Sukhumvit Road in Bang Na, when buses became inaccessible due to flooding.

In JICA (1985), the flood damages were estimated for both "with project" and "without project" cases in both year-1985 and year-2000 using the above mentioned formulas coupled with the estimated case-wise, year-wise, probability-of-rainfall-wise and mesh-wise input data of inundation depth and duration and the year-wise input data of numbers of households and commercial and industrial establishments.

JICA (1985) showed the year-1985 estimates of 441 million bahts for the average annual damages under "without project", 187 million bahts for the average annual damages under "with project" and 254 million bahts for the project benefits in the 360-km^2 Eastern Suburban Bangkok Area.

9.2.3 Estimation of social cost

Economic activities of both private or public enterprises sometimes aggravate the environment. As they would require water for their economic activities, abstractions of groundwater could cause land subsidence. Land subsidence is an environmental impact of overexploitation of groundwater, which could aggravate inundation problems. Although several factors contributed to the major flood that occurred in Bangkok area in 1983 as enumerated above, land subsidence was considered as the most significant factor that intensified the inundation. Consequently, the repair or rehabilitation of the deteriorated or impacted environment would be charged to social cost.

After the 1983 flood, various measures for the flood protection and improvement of drainage facilities were proposed. Several plans were implemented by the government, and some of the completed projects are listed in Tables 9.2.3 to 9.2.5. These flood protection and drainage projects are regarded as social costs for the repair and rehabilitation of the impacted environment.

Meanwhile, the expenditures for the repair of minor damages caused by land subsidence, such as the settlement of building foundations, cracks in building facilities or pavements could not be estimated.

The cost estimates for the various schemes proposed in previous studies were based on various price levels which were in effect at the time of the studies. In order to make a more reasonable comparison of costs, they were escalated to a common reference year, 1993.

The method of escalating the orginal estimate was to assume that the costs have risen by 6% per year since the period of the original estimate (average annual rate assumed by JICA was 5%; NEDECO used varying rates which averaged 7.6% per year).

The escalation factor to be applied to the original estimate, therefore, is:

$$\textit{Escalation Factor} = (1 + i)^n$$

I: 6% per year and *n*: number of years from period of original estimate to 1993.

The escalated cost therefore becomes:

$$\textit{Escalated cost} = \textit{Original cost} \times (1.06)$$

The escalated costs are presented in Table 9.2.6.

Escalated costs in the year-1993 totaled 43,676 million bahts (around 43,700 million bahts). However, the present polder design criteria requires that khlong water levels be maintained at a high level between polders and dikes. If land subsidence still progresses in Bangkok area, the cost therefore will increase correspondingly.

The BMA also evaluated the existing cost figures and showed that in the case of using polder system, the 1,500 km perimeter in Bangkok will require 45,000 million bahts for investment, 1,500 million bahts per year for operation and 500 million bahts per meter lift per year (Suwarnrat, K., 1993).

Table 9.2.1 Damages due to Land Settlement at Several Factories in the Suburbs of Bangkok

Name of Industrial zone	Name of Manufactures	Damaged Facilities in a Factory
1.Bangchan Industrial Estate	1.Union Plastic Co.,Ltd.	unknown
	2.Honda Motors (Thailand) Co.,Ltd.	unknown
	3.Chinsan Electronic Industrial (Thailand) Co.,Ltd.	non
	4.Hanami-Tohato Co.,Ltd.	12cm/4year protrusion of building damages of drainage pipe
	5.National Adhesive Co.,Ltd.	non
2.Lat Krabang Industrial Estate	1.Thailand Honda Manufacturing Co.,Ltd.	5cm settlement of ground at the base of building
(along road)	3.Yarrapund Co.,Ltd.	30cm more or less settlement at the base of press machineries
3.Bang Plee Industrial Estate	1.Goshu Chemical Co.,Ltd.	10cm more or less protrusion of pumping house
4.Nava Nakorn Industrial Estate	1.Sun Food Co.,Ltd.	non
	2.Mizuki Electric Co.,Ltd.	20 to 30cm settlement at the base of building due to earth sliding toward canal
5.Samut Prakarn Industrial Zone	1.NHK Spring (Thailand) Co.,Ltd.	30cm more or less settlement at the base of press machineries
6.Bang Poo Industrial Estate	1.Nas Toa Co.,Ltd.	7 to 8cm protrusion of building installing concrete piles
7.Samut Sakorn Industrial Zone (along road)	1.Fuji Metal Co.,Ltd.	non
	2.East Asia Textile Co.,Ltd.	non
	3.Petahkasen Weaving Co.,Ltd.	non
	4.Thai Nam Plastic Co.,Ltd.	100cm more or less settlement during 22years at the base of heavy machineries
8.Bang Kadi Industrial Park	1.Toshiba semiconductor Thailand Co.,Ltd.	non
9.Hi-Tech Industrial Estate	1.Ajinomoto Frozen Food Co.,Ltd.	non

Table 9.2.3 SUMMARY OF BUDGET BY PROJECT FOR FLOOD CONTROL IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY BY BMA

Year	Project	Goal of Project	Detail of Works	Construction agency	Budget (Million Baht)		
					1984	1985	TOTAL
1984	Drain flood water-to the eastern coast-of Bangkok after - the edict of King	-Accelerate drainage of-flood water to the-eastern coast line -Promote flood - water control -Magnify railway - and highway against-waterlogging	-Build a dike- Total a year (45.100) Km. -Dig and extend canal- Total a year (173.5) Km. -Building to control - gate (43) m^2. -Magnify railway- bridge (2) m^2. -Magnify Highway - bridge (2) m^2.	Department of-Irrigation Department-of Highways State Railway - of Thailand	194.5	181.5	376.0
	Construction for-drainage of flooded-water in the Chanwat-Samut Prakan	-Drain off flood water-in the Municipality-Muang Samut Prakan	-Upgrade road KSN.- Total a year (1,600) m. -Improvement dike KSN.- Total a year (354) m. -Improvement drainage - Total a year (1,266) m. -Construction of - sluice gate (3) m^3.	Department-of Public Works	62.7	59.4	122.1
	Alleviation of-flooding intensity-in the coast of-castern Bangkok after-the edict of King	-Dredge Khlong Sam-Rong and Khlong-Saha	-Improvement by dredging-of Khlong Sam Rong-and Khlong Chek - 15 Khlong Total 16 Khlong	Chanwat Samut-Prakan	80.8	-	80.8
		TOTAL 3 AMOUNT			338.0	240.9	578.9

Table 9.2.4 SUMMARY OF BUDGET BY PROJECT FOR FLOOD CONTROL IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY BY BMA

Year	Project	Goal of Project	Detail of Works	Construction agency	Budget (Million Baht)		
					1984	1985	TOTAL
1984	Improvement Khlong Phra Kha Nong Khlong Sam Rong Khlong Bang khen	-Increase an ability- of drainage using - pump and sluice gate	-Improvement of sluice- gates Total 3 m. -Magnify drain - pipes 1 m. -Install pump - Total 32 tools.	Department of- Irrigation	140.0	-	140.0
	Improvement Khlong Bang su- Khlong Sam San- Khlong Chek- Khlong Bang O- Khlong Bang Na- Khlong Phra Kha Nong- Khlong Saen Saeb	-Increase an ability- of drainage using - pump and sluice gate -Magnify an ability- of much drainage	-Improvement of sluice- gates Total 6 m. -Install pump stations- Total 27 tools -Construct dike- KSL. Length 2,211 m. -Construct flood Wall- Length 1,756 m.	Bangkok	187.0	-	187.0
	Improvement by - dredging of Khlong- in Chanwat Samut- Prakan	-Magnify an ability- of much drainage- through Khlong lines	-Khlong improvement by- dredging Total 4 lines	Chanwat Samut- Prakan	14.0	-	14.0
		TOTAL 3 AMOUNT			341.0	-	341.0

Table 9.2.5 SAMUT PRAKAN FLOOD PROTECTION AND DRAINAGE PROJECT BY DPW

Project Name	Project Area	Construction Period	Project Budget (Million Baht)	
Samut Prakan Flood Protetion and Drainage Project (Phase)	376 Km	1986-1996		
			1. Study and Detail Design	42.74
			2. land (East Bank)	368.65
			3. Construction (East Bank)	1,428.16
			4. Land (West Bank)	60.0
East Bank Area :	257 Km		5. Construction (West Bank)	959.8
			Phase Total	2,854.35
1. Khlong Sam Rong	(30)			
2. Bang Nang Kreng	(21.5)			
3. Muang Pak Nam	(15.5)			
4. Alleviating area	(190)			
West Bank Area :	119 Km			
1. Rat Bur Rana	(12)			
2. Tung Khlong	(12)			
3. Khlong Tra Kaweun	(7.5)			
4. Bang Kra Chao	(17.5)			
5. Alleviating area	(70)			

Table 9.2.6 Escalated Construction Costs of Various Schemes for Flood Protection and Drainage in Bangkok and its Vicinity

Scheme	Original Estimate (million bahts)	Period of Original Estimate	Escalation Period up to 1993	Escalation Factor	Escalated Construction Cost (million bahts)
Additional East Bank Dikes	237	84/85	9/8	1.69/1.59	396
City Core	1,676	84	9	1.69	2,832
East Suburbs	247	85	8	1.59	393
East Bank Dikes + City Core	1,724	84/85	9/8	1.69/1.59	2,909
East Bank Dikes + East Suburbs	295	85	8	1.59	469
East Bank Dikes + City Cores + East Suburbs	1,933	84/85	9/8	1.69/1.59	3,241
Chao Phraya 2	20,100	86	7	1.5	30,150
Additional West Bank Dikes	368	84	9	1.69	622
Tawee Wattana	510	84	9	1.69	862
Thonburi and Samut Prakan West Phase I	1,269	87	6	1.42	1,802
				Total	43,676

9.3 Tentative Permissible Yield

9.3.1 Consideration of permissible water level

Based on the observation of land subsidence in Osaka, Japan, Wadachi and Hirono (1939) pointed out the cause of land subsidence. They explained that land subsidence occurs due to the consolidation of shallow soft clay bed as a result of the artificial decline of piezometric heads of underlying aquifers.

Their theory has been proven by facts that indeed subsidence could decrease or stop, or there could be a slight upheaval, as observed in some places in Japan at the end of World War II when groundwater pumpage decreased.

Wadachi and Hirono (1939) made the following observations:

1) Land subsidence stops if groundwater level is recovered artificially.

2) Even if land subsidence stops, the ground surface does not return to its original level. Prompt action to prevent land subsidence is therefore needed.

3) Control of pumpage and artificial recharge of aquifers are thought to be effective measures against land subsidence.

These observations made in 1939 are quite reasonable from today's viewpoint. They proposed the following equation to determine the critical water level to prevent land subsidence.

$$-ds/dt = k\,(p_0 - p)$$

where $-ds/dt$ represents the velocity of land subsidence, p_0 is the standard groundwater pressure, p is the present groundwater pressure in underlying aquifer and k is a constant.

This equation indicates that land subsidence stops if $p_0 \geq p$. Thus, the standard groundwater pressure p_0 could be considered as the permissible critical groundwater level for the prevention of land subsidence.

However, as pointed out by many researchers, the standard groundwater pressure p_0 is not a constant value. It increases as land subsidence progresses, and it changes when groundwater level fluctuates.

In some cases, the standard groundwater pressure p_0 can be found by analyzing the relationship between land subsidence and groundwater level in the monitoring wells. But in many cases, p_0 could not be obtained accurately from the monitoring well data. However, the following results obtained from past land subsidence studies conducted in Japan may be useful in considering the permissible critical water level or the permissive yield of a groundwater basin.

1) If groundwater level is stable, land subsidence gradually stops.

2) If groundwater level becomes stable, however, residual subsidence may continue for a long time.

3) Recovery of groundwater level is needed to stop land subsidence which is an irreversible process.

An objective of groundwater management in Bangkok Metropolitan Area and its vicinity is to sustain the use of groundwater with land subsidence being prevented. Thus, the permissive yield must be determined by giving importance to the rate of land subsidence.

9.3.2 Evaluation of model response

As mentioned in Chapter 8, nine (9) future pumpage scenarios were prepared as input to the 3-D model. The 3-D model covering the Lower Central Plain approximates the natural conditions of the aquifer system such as the structures of the groundwater basin and the hydrogeologic characteristics of each aquifer unit. Also it considers the present groundwater flow system in the historical calibration. The present groundwater flow regime is formed not only by the natural hydrogeologic characteristics but also by the groundwater pumpage which reflects human activities. The subsidence model considered the mechanism of land subsidence caused by the lowering of piezometric levels. Therefore, evaluation of model response could suggests the future groundwater management options in the Bangkok Metropolitan Area.

The historical calibration of the model reproduced the past changes in piezometric levels in the Study Area. For example, the model simulated the recovery of the piezometric levels from 1985 to 1990 in NL Aquifer in central Bangkok. This recovery could be explained by the reduction of the MWA's pumpage input to the model. The input total pumpage in the Study Area is 1.48 MCMD, the year-1992's total.

If the pumpage in the Study Area increases to 2.02 MCMD in year-2000 and further to 3.05 MCMD in year-2017, as assumed in Scenario 1, the piezometric level drops and the land subsidence rates will be the worst that could happen. For all the scenarios, it is assumed that MWA's pumpage would be phased out by year-2007 stepwise starting from year-1993. Therefore, the future piezometric levels will drop more unless the reduction started in year-1993.

In Scenario 2, pumpage in the Study Area will be 1.66 MCMD in year-2000 and 1.73 MCMD in year-2017. This scenario offers an effective control of land subsidence in MWA's service area. In Pathum Thani, the implementation of PWA's project can control land subsidence up to year-2003. But after year-2003, the subsidence will recur at a rate of more than 3.5 cm/year because of the further increase in water demand. Hence, measures other than the present PWA's plan are needed to decrease projected groundwater abstractions in Pathum Thani.

The simulation results using Scenarios 3 and 4 suggested that land subsidence in the present critical zones 1 and 2 can be slowed down if pumpage is regulated. However, Scenario 3 indicates that a constant pumpage rate from year-1997 to year-2000 is not enough to stop subsidence, while Scenario 4 can stop the subsidence in the present critical zones, with pumpage regulation of 1.94 MCMD in year-2000 and 1.81 MCMD in year-2010 in the Study Area. Model response to Scenario 4 reveals severe land subsidence in Pathum Thani and Samut Sakhon, which cannot be controlled even when enforcing the strictest regulation in the present critical zones.

Therefore, it is crucial to establish a new critical zone that covers not only the present critical zones 1 and 2 but also the heavily pumped areas of Bangkok, Nonthaburi, Pathum Thani, Samut Prakan, and Samut Sakhon. The simulation results using Scenarios 5A to 5C show that land subsidence rate can be controlled within 1cm/year in the new critical zone if pumpage is reduced at a rate of 2.5% annually from year-2000 to year-2010. If pumpage is maintained constantly at the year-2000 pumpage level as assumed in Scenario 5A, the subsidence rate exceeds 1 cm/year. Though the annual piezometric level may be constant, its seasonal fluctuation causes this land subsidence. Furthermore, the piezometric levels will continue to decline even after the regulation because it will take some time to reach the equilibrium condition. Also, withdrawals outside the new critical zone contunue to increase.

Before year-2000, immediate actions are urgently needed to control groundwater pumpage, because for a seven-year period from year-1993 to year-2000, the simulated land subsidence reaches 50cm if pumpage of 2.02 MCM/day is allowed by year-2000. This Scenario 5C-pumpage is not permissble in terms of the rate of land subsidence. Consequently, Scenarios 6 and 7 assume that the pumpage is regulated in this seven-year period.

From year-1995 to year-2000, Scenario 6 assumes that pumpage increases annually at 50% of the annual rate assumed in Scenario 1. Thus, the pumpage is 1.79 MCMD in year-2000, 1.49 MCMD in year-2010, and 1.55 MCMD in year-2017. With this scenario, subsidence will be about 2/3 of that in Scenario 5C by year-2000, and the total subsidence up to year-2017 can be controlled to within 50 cm in most parts of the Study Area.

Among the nine (9) scenarios, Scenario 7 is the best future pumpage plan for controlling land subsidence. However, this plan is difficult to implement because pumpage must be maintained at year-1994 level from year-1995 to year-2000. In this scenario, pumpage will be 1.68 MCM/day in year-2000, 1.39 MCM/day in year-2010, and 1.45 MCM/day in year-2017.

If the 50 cm total land subsidence for a period of 25 years (from year-1993 to year-2017) is permissible, then Scenario 6 will be the best option. The simulation results also indicated that the total pumpage of about 1.60 MCM/day could slow down the land subsidence within 1cm/year. There will be many more pumpage options, however, based on the simulation results using the nine scenarios alone, Scenario 6 can be taken as a tentative permissible yield *in terms of allowable land subsidence rate* for the Study Area.

CONTENTS

LIST OF FIGURES