JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)

DEPARTMENT OF MINERAL RESOURCES
MINISTRY OF INDUSTRY
AND
PUBLIC WORKS DEPARTMENT
MINISTRY OF INTERIOR
THE KINGDOM OF THAILAND

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

SUMMARY REPORT

MARCH 1995

KOKUSAI KOGYO CO., LTD.
TOKYO, JAPAN

PREFACE

In response to a request from the Government of the Kingdom of Thailand, the Government of Japan decided to conduct a study on the Management of Groundwater and Land Subsidence in the Bangkok Metropolitan Area and Its Vicinity and entrusted the study to the Japan International Cooperation Agency (JICA).

JICA sent to Thailand a study team headed by Dr.Akira KAMATA, Kokusai Kogyo Co.,Ltd., 7 times between July 1992 and February 1995.

The team held discussion with the officials concerned of the Government of Thailand, and conducted field surveys at the study area. After the team returned to Japan, further studies were made and the present report was prepared.

I hope that this report will contribute to the promotion of the project and to the enhancement of friendly relations between our two countries.

I wish to express my sincere appreciation to the officials concerned of the Government of the Kingdom of Thailand for their close cooperation extended to the team.

March 1995

Kimio Fujita

Kimio Fujita
President
Japan International Cooperation Agency

March 1995

Mr.Kimio Fujita
President
Japan International Cooperation Agency

LETTER OF TRANSMITTAL

Dear Sir,

We are pleased to submit the final report of "The Study on Management of Groundwater and Land Subsidence in the Bangkok Metropolitan Area and Its Vicinity ". This report has been prepared based on the field survey and the study conducted during the period from July 1992 to March 1995.

The report contains the study results on the hydrogeology, the groundwater database, the groundwater quality and the prediction of future groundwater levels and land subsidence by computer modeling as well as the details of the three new monitoring stations. A target pumpage for the management of groundwater and alleviation of land subsidence is presented based on the predictions.

We hope that the implementation of the groundwater management plan would greatly contribute to the mitigation of land subsidence in the Bangkok Metropolitan Area.

All the members of the Study Team wish to express their sincere thanks to the personnel of your Agency, the Embassy of Japan in Thailand and the officials and personnel of the Department of Mineral Resources and the Public Works Department, the Government of Thailand for the assistance extended to them.

Very truly yours,

鎌田 烈

Akira KAMATA
Team Leader
The Study on Management of Groundwater and Land Subsidence in the Bangkok Metropolitan Area and Its Vicinity

The Study on Management of Groundwater and Land Subsidence in the Bangkok Metropolitan Area and Its Vicinity

Study Period:	July 1992 to March 1995
Counterpart Agencies:	Department of Mineral Resources Public Works Department

Abstract

1. Background

The recent economic development of Thailand has brought about increases in water demands for industrial, commercial and domestic purposes, particularly in the Bangkok Metropolitan Area. In order to meet the growing water demands, groundwater is pumped heavily, causing increased and more widespread land subsidence and saltwater intrusion in the area. Though land subsidence has slowed down in the central part of Bangkok due to regulations undertaken in the early 80's, it is still progressing in the vicinity of the Bangkok Metropolitan Area. The land subsidence not only damages roads, bridges, buildings and canals but also causes flood in the low lands, which has brought huge economic losses. It is therefore urgently needed to establish a sound groundwater management plan and implement comprehensive measures against land subsidence.

2. Study Objectives

The Study aims at achieving the following:

(1) To establish groundwater management system
(2) To prepare alleviation plans against land subsidence and saline water intrusion
(3) Technical transfer through out the Study

3. Study Area

The 5,600-km^2 Study Area covers the Bangkok Metropolis and its vicinity, comprising wholly or partly the following eight (8) provinces, namely:

whole of BANGKOK, NONTHABURI, SAMUT PRAKAN, PATHUM THANI and parts of CHACHOENGSAO, SAMUT SAKHON, NAKHON PATHOM, PHRA NAKHON SI AYUTTHAYA

4. Study Results

The Study 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

Based on the data collected, processed and analyzed throughout the Study, the following results were obtained.

4.1 Groundwater Use

The Study Area's total groundwater pumpage in 1992 was estimated from the well inventory database at 1.48 MCMD. Pumpage is recently increasing in Bangkok's vicinity, e.g., Lat Krabang, Pathum Thani and Samut Sakhon.

(2) Groundwater Levels

Piezometric levels of the main aquifers have declined from 30m to 60m below MSL. In the central area of Bangkok, groundwater level is again lowering because of the effect of the regional decline of groundwater level caused by overpumping in the vicinity.

(3) Land Subsidence

Land subsidence occurs widely at more than 20mm/year in the Bangkok Metropolitan Area. Subsidence of 50mm/year to 60mm/year were recorded in Samut Prakan, 40mm/year to 55mm/year in Min Buri and Lat Krabang, 30mm/year to 40mm/year in Pathum Thani and Samut Sakhon.

(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. High chloride concentrations ranging from 3,000 to 16,000 mg/L were observed in the main aquifers.

(5) Monitoring Stations

The new land subsidence and groundwater level monitoring stations were constructed in Lat Krabang, AIT and Samut Sakhon. Each observation well automatically records the groundwater level and land subsidence of the different aquifers. Together with the DMR's existing monitoring stations, the new monitoring stations would be utilized for the groundwater management, conjunctively with the database and the groundwater models.

(6) Groundwater Modeling

Groundwater flow and land subsidence models were made to predict the future groundwater levels and land subsidence. A solute transport model was also prepared to analyze saltwater intrusion. These models have shown the mechanism of land subsidence and saltwater intrusion.

(7) Prediction of Groundwater Levels and Land Subsidence

Groundwater flow and land subsidence models were used to predict the future groundwater levels and land subsidence up to year-2017 using different future pumping scenarios. Using the worst scenario, the models predicted that land subsidence would reach a maximum of

200cm by year-2017. While, using the best scenario, the models predicted that the maximum total land subsidence would be 35cm 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. It was concluded that the tentative permissible yield for the Study Area would be 1.60 MCMD.

(9) Groundwater Basin Management

The groundwater basin management is implemented by targeting the tentative permissible yield in year-2005. The expansion of the present critical zone and the regulation of groundwater pumpage are concurrently implemented. Groundwater level, land subsidence, water quality and groundwater pumpage are monitored and used conjunctively with the database and groundwater models.

5. Recommendations

(1) Groundwater Management

Expansion of the Critical Zone
Regulation of Pumpage
Construction of New Monitoring Stations
Leveling of Benchmarks
Installation of Water Meter
Application of the Groundwater Database System
Improvement of Groundwater Models
Model Applications and Permissible Yield
Hydrogeological Investigations

(2) Comprehensive Measures

Substitutional Water Supply
Rational Use of Water
Groundwater Fee
Artificial Recharge
Strengthenning of the Technical Sub-Committee
Organization

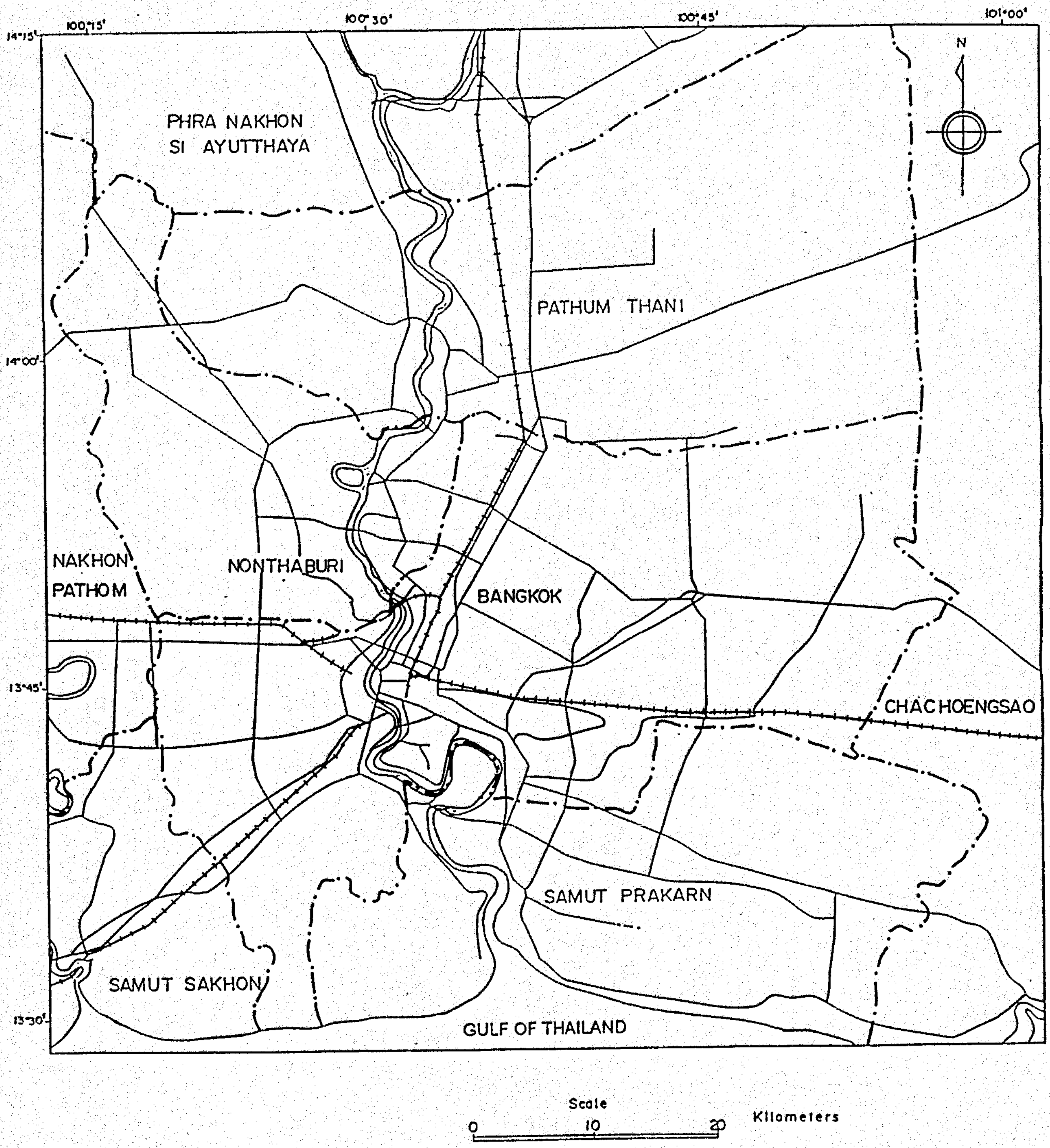

Figure 1.1	LOCATION MAP OF THE STUDY AREA
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

TABLE OF CONTENT

CHAPTER 1 INTRODUCTION

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1.1 Background of the Study

The Bangkok Metropolitan Area is the capital of the Kingdom of Thailand and the biggest city among the capital cities in Southeast Asia. It is situated at the southern edge of alluvial plain in the downstream of the Chao Phraya River. It has a total population of 8.2 million including its vicinity. Because of rapid urbanization, the said metropolitan area and its suburbs are confronted with serious problems in water supply, sewerage, transportation, housing, waste disposal and other related problems.

Waterworks of the Bangkok Metropolitan Area is being operated and managed by the Metropolitan Waterworks Authority (MWA). The Chao Phraya River is the main source of water supply. However, the present water supply can not meet the increasing domestic and industry water demand brought about by rapid economic growth. Areas not covered by the MWA's water supply networks resort to groundwater for their water supply.

In early 1970, uncontrolled development and excessive withdrawal of groundwater resulted in the decline of groundwater levels and land subsidence. A maximum total land subsidence was recorded at 75 cm during the 10 year period between 1978 and 1987. Land subsidence damaged various private and government infrastructures such as buildings, roads and bridges. It also caused flood in the low land and brought huge economic loss and risk of disaster.

In order to overcome such situations, the Department of Mineral Resources (DMR) and other governmental agencies initiated the investigations of groundwater and land subsidence in Bangkok in collaboration with the Asian Institute of Technology (AIT) since late 1970's. Based on these studies, the Cabinet issued a resolution on "Mitigation of Groundwater Crisis and Land Subsidence in Bangkok Metropolis" in March 1983.

In 1985, the Ministerial Regulations were issued according to the Groundwater Act, B.E.2520 which was enforced in 1978. These regulations specified "the Bangkok Groundwater Area" which covers six (6) provinces located at the downstream of the Chao Phraya River. Several initiatives were adopted and carried out such as the phase out program of MWA wells, control of groundwater use, collection of water fee, etc.

Inspite of such efforts, the decline of groundwater levels and land subsidence still continue in the industrial areas located along the main roads at the eastern, southern and western suburbs of Bangkok. However, they have been reduced in the central Bangkok area. The problem is further aggravated by groundwater salinity which is spreading to the west and south of the Bangkok Metropolitan Area.

In the light of the foregoing, the Government of the Kingdom of Thailand requested the Government of Japan for technical assistance on "The Study on Management of Groundwater and Land Subsidence in the Bangkok Metropolitan Area and Its Vicinity" in October 1989 and March 1990.

The request was favorably considered and a preliminary survey mission was sent by the Government of Japan to clarify the background and specifics of the request. An agreement was reached between the Counterpart Agencies -- the DMR and the Public Works Department (PWD) and JICA on the Scope of Work (SW) for the Study.

1.2 Study Objectives and Area

Study Objectives

The Study aims at achieving the following:

(1) To establish groundwater management system
(2) To prepare alleviation plans against land subsidence and saline water intrusion

Study Area

The Study Area covers the Bangkok Metropolis and its vicinity. As shown in Figure 1.1, the Study Area comprises wholly or partly the following eight (8) provinces, namely:

whole of BANGKOK, NONTHABURI, SAMUT PRAKAN, PATHUM THANI and parts of CHACHOENGSAO, SAMUT SAKHON, NAKHON PATHOM, PHRA NAKHON SI AYUTTHAYA

1.3 Study Framework

The Study commenced in July, 1992 and lasted for 33 months until March, 1995. The Study period is divided into three (3) stages:

Stage I - Basic Survey
Stage II - Detailed Survey
Stage III - Analysis and Planning

Stage I: Basic Survey

This stage involved the review and analysis of existing studies and data, field geological reconnaissance, arrangement of existing well inventories, questionnaire survey on groundwater utilization, preparation of the groundwater database, and appraisal survey on the availability and capability of local drilling contractors.

Stage II: Detailed Survey

The Study in this stage included the reviews of artificial recharge, existing water supply systems, urban planning, preliminary environmental impact survey, core drilling and soil testing, construction of observation stations, survey on groundwater utilization and completion of well inventories and groundwater database. After the construction of new observation stations, long-term measurements of groundwater level and land subsidence were conducted. Groundwater samples were collected and analyzed. The various data obtained throughout Stage II were arranged for Stage III.

Stage III: Analysis and Planning

The Study at Stage III concerned the prediction of land subsidence and saltwater intrusion, the planning for the mitigation of land subsidence, and the groundwater management system in Bangkok Metropolitan Area and its vicinity.

1.4 Organization of the Study

The Study was carried out jointly by the JICA Study Team, the DMR Team and the PWD Team:

JICA STUDY TEAM

Akira KAMATA	Team Leader/Hydrogeologist
Shoichi OHMORI	Geologist
Reynaldo R. MEDINA	Hydrologist
Mutsuo ASANO	Soil Engineer
Yoshinao MIURA	Drilling Supervisor
Chujiro TAKAHASHI	Drilling Supervisor
Naoaki SHIBASAKI	Hydrogeologist
Masaharu KINA	Urban Planner
Eiji TAKEMORI	Water Supply Engineer
Hajime TAKAHASHI	Socio-economist
Presha CHUNTAKORN	Coordinator

DMR Team

Vachi RAMANARONG	Research Expert, Director of the Mitigation of Groundwater Crisis and Land Subsidence in Bangkok (MGL Project)
Somkid BUAPENG	Chief of Groundwater Data Center, Groundwater Division
Samrit CHUSANATHAS	Hydrogeologist
Aranya FUANGSWASDI	Hydrogeologist
Suchai SHINPOOL-ANANT	Hydrogeologist
Paisal LAKANANURAK	Hydrogeologist
Oranuj LORPHENSRI	Hydrogeologist
Sanguansak SUNGKABUN	Hydrogeologist

PWD Team

Nathanwuth USOMBOON	Chief, Deep Well Drilling and Development Division
Posit NIPPITAWASIN	Senior Hydrogeologist
Roongroj KIATPANICHKIT	Hydrogeologist
Chaiporn SIRIPORNPIBUL	Hydrogeologist

CHAPTER 2 THE STUDY AREA

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2.1 Natural Conditions

(1) Topography

The main physiographic features of Thailand can be divided into seven (7) regions, namely, the Central Plain, the West Continental Highlands, the North Continental Highlands, the Central Highlands, the Northeast Plateau, the Southeast Coast and the Peninsular Thailand (Figure 2.1). The widest lowland area is the Central Plain which stretches from the Gulf of Thailand to as far as Uttaradit in the north, over 500 km long and 100 to 200 km wide.

Three (3) big rivers, namely, the Ping, the Yom and the Nan, whose source lies in the northern mountainous regions traverse the plain and join together at Nakhon Sawan to form the Chao Phraya River. The Central Plain is divided into two (2) plains, namely, the Upper Central Plain and the Lower Central Plain at Nakhon Sawan area, where the width of the plain narrows.

The Lower Central Plain is a large and flat plain consisting of young fluvial and marine deposits. From Chai Nat, the Chao Phraya River branches out to smaller rivers, two (2) of which are the Tha Chin (or Suphan Buri) River and the Noi River which flow southward joining the Pasak River on the way. The Mae Klong River, draining the mountainous areas in the west, flows southeast and south through the plain. The Bang Pakong River enters the Lower Central Plain from the east and flows southward to the Gulf of Thailand.

The Study Area is situated in the Lower Central Plain and is bounded on the west by Tha Chin River, on the east by Bang Pakong River, and on the south by the Gulf of Thailand. It has an area of about 5,600 km^2 and geomorphologically comprises the fan, the delta and the tidal zone (Figure 2.2) with the natural ground elevations ranging from one (1) to three (3) meters above MSL. Recently, land subsidence caused certain areas to be below MSL.

(2) Climate

The Study Area is located in the monsoonal region which has a distinct dry season from December to April and a rainy season from May to November. About 85% of the rainfall occurs in the rainy season. The mean annual rainfall is about 1,500 mm in Bangkok and averages 1,300 mm in the Study Area (Figure 2.3). The mean monthly temperature varies from 25.4°C to 29.7°C and the average monthly minimum and maximum temperature are 20.6°C and 34.9°C in Bangkok, respectively.

(3) Hydrology

The Chao Phraya River is a big river which has a total drainage area of 160,000 km^2. The annual mean flow of the Chao Phraya River at RID's Sta. C.2 in Nakhon Sawan is 683.62 m^3/sec. About 100 km downstream from Nakhon Sawan near Chai Nat Province, the Chao Phraya Dam was constructed to divert the river flow for irrigation. The flow of the Chao Phraya River downstream of this dam at RID's Sta. C.13 has decreased to 336.10 m^3/sec.

Downstream of Chai Nat Province many effluent branches come off from the main river. The discharge of the Chao Phraya River before it reaches the city of Ayutthaya as observed at RID's Sta. C.7A averages 358.02 m^3/sec.

River flow fluctuates sharply according to the season. For instance, the discharge of the Chao Phraya River at Sta. C.7A varies from 495.8 to 835.3 m^3/sec in the period from January to August, while the discharge in the period from September to December exceeds 1,000 m^3/sec. The capacity of the river is only 1,500 m^3/sec near Ayutthaya and the excess water will overflow and flood the low-lying areas including the Study Area (Figure 2.4).

(4) Hydrogeology

Pre-Cambrian, Paleozoic and Triassic rocks are distributed in the highlands west and north of Thailand and southern Peninsula. The highlands on the east and south consist of Triassic rocks. In the plateau situated in the northeast of Thailand, Mesozoic rocks from Jurassic to Cretaceous ages are extensively distributed. The Central Plain consists mainly of Neogene and Quaternary sediments.

The basement of Neogene and Quaternary sediments in the Central Plain is divided into several blocks which constitute the grabens. The basement depth was estimated to be more than 1,800 m according to the oil exploratory drilling, aero-magnetic and seismic data. Geology of Neogene sediment is still not clarified yet. Quaternary sediment consists of the terrace deposit, the alluvium and the laterite.

The hydrogeology of the Study Area was investigated using lithologic logs of production wells and shallow borings. The ground surface of Bangkok is entirely underlain by blue to grey marine clay, 15 m to 30 m in thickness, known as the Bangkok Clay. Unconsolidated and semi-consolidated sediments underlying the Bangkok Clay consist of sand, gravel and clay of Pleistocene to Pliocene ages. From a detailed study of electrical logs, the DMR identified and named eight (8) aquifers within 550 m depth. These aquifers consist mainly of sand and gravel separated by clay beds.

1. Bangkok Aquifer (BK, 50 m zone)
2. Phra Pradaeng Aquifer (PD, 100 m zone)
3. Nakhon Luang Aquifer (NL, 150 m zone)
4. Nonthaburi Aquifer (NB, 200 m zone)
5. Sam Khok Aquifer (SK, 300 m zone)
6. Phaya Thai Aquifer (PT, 350 m zone)
7. Thon Buri Aquifer (TB, 450 m zone)
8. Pak Nam Aquifer (PN, 550 m zone)

Among the eight (8) aquifers, Phra Pradaeng, Nakhon Luang and Nonthaburi Aquifers are the most developed and extensively used for water supply (Figure 2.5).

2.2 Socio-Economy

(1) Economic Development in Thailand

Economic growth in Thailand over the past decade was one of the highest and steadiest among the developing countries. Beginning 1986, the economy began a period of very rapid growth brought about by increase in exports, capital inflows, as well as tourism. The growth in GDP during the last three (3) years had been remarkable, averaging over 10 percent per annum (Table 2.1).

The Bangkok Metropolitan Area and its Vicinity and the Central Region served as the core of Thailand's economy and contributed one half of the country's GDP. Recently, the annual growth rate of the Bangkok Metropolitan Area exceeded 20% .

The concentration of economy in the Bangkok Metropolitan Area lured the rural populace to migrate to the urban areas. The heavy influx to the metropolis caused severe environmental problems, such as traffic congestion, shortage of housing facilities and water supply systems, air and water pollution, etc.

(2) Population

According to Thailand's population census, the population of Thailand was 56.3 million in 1990 with Bangkok having 5.62 million. The population of Bangkok and the adjoining 7 provinces reached 9.98 million. Considering the number of unaccountable migrants, Bangkok's population may exceed 8 million (Table 2.2).

(3) Transportation and Electric Power Supply

Thailand's transportation network is characterized mainly by highways and roads. These highways and roads are well consolidated. However, the present rate of construction of new highways can not meet the demand of rapid mobilization in the Bangkok Metropolitan Area. Serious and chronic traffic congestion hinders daily urban activities. Alternate means of transportation, such as the subways and the elevated rail road projects have been planned but are yet to be implemented.

Almost 100% of the Bangkok Metropolis and 90% of its adjoining provinces have electricity.

2.3 Water Supply

(1) Water Supply Organizations

In the Study Area, the MWA supplies water to the Bangkok Metropolis and the provinces of Samut Prakan and Nonthaburi. The PWA serves the Pathum Thani Province through its Regional Office III in Bangkok. Groundwater is used for domestic purpose in areas not covered by the MWA and PWA water distribution networks.

Four (4) goverment agencies, namely, the Office of Accelerated Rural Development (ARD), the Public Works Department (PWD), the Department of Mineral Resources (DMR) and the Department of Health (DOH) are involved in well constructions for the use of groundwater in the rural areas. The Industrial Estate Authority of Thailand (IEAT) supplies water from its own deep wells to the factories located in its industrial estates.

More than 10,000 private deep wells were constructed in the Study Area mainly for domestic and industrial consumptions. Drilling of these private wells and use of groundwater are controlled by the DMR.

(2) MWA

The MWA's water supply service in 1991 covered an area of 710 km^2 which is about 22% of the MWA's total service area (3,195 km^2) and 5.6 million of the service population which is about 78% of the total population (7.2 million) (Figure 2.6). The total water production in 1991 was 1,143.4 MCM (3.13 MCMD). About 97% of the total production, 1,109.2 MCM (or 3.04 MCMD), came from the Chao Phraya River. The rest, which amounted to about 34.2 MCM (or 93,000 CMD), about 3% of the total , came from groundwater pumped from its 41 deep wells. The total pumpage of the MWA wells amounted to 142.4 MCM (390,000 CMD) in 1983 (Table 2.3). However, since then, the MWA is phasing out its wells according to the Cabinet Resolution in order to alleviate land subsidence.

(3) PWA (Pathum Thani)

Pathum Thani Province is located north of Bangkok Metropolis. The PWA Regional Office III in Bangkok manages the waterworks system in Pathum Thani province. This system relies on 20 deep wells. In 1992, PWA's service area covered about 180 km^2 and about 6.27 MCM of groundwater was produced. About 98,000 people were served, which is about 21% of the province's total population.

(4) Private and Public Wells

Private wells are registered at the DMR as required by the Groundwater Act of Thailand. At present, the DMR charges water fee at 3.5 baht/m^3 for these wells.

Public wells numbering about 12,600 have been constructed by government agencies, such as PWD, DOH, ARD and DMR. Pumpage from these wells is estimated at 1.4 MCMD (see Chapter 5).

(5) IEAT

There are presently nine (9) industrial estates in the Study Area. The total pumpage from the eighty (80) deepwells located in these estates amounted to 33 MCM in 1992 (Figure 2.7).

2.4 Review of Land Subsidence in Bangkok

(1) Brief History

In 1969, land subsidence in Bangkok caught public attention when its evidence, such as protrusions of well casings and foundations of buildings, were observed in many places. A seminar organized in 1979 recognized the major cause of land subsidence as due to excessive withdrawal of groundwater. Consequently, the DMR and the AIT started research projects on the management of groundwater and mitigation of land subsidence in Bangkok. The ground surface leveling revealed that Lat Phrao, Bang Kapi, Hua Mak, Phra Khanong and Bang Na areas subsided more than 10 cm/year and the center of land subsidence coincided with the center of depression of artesian pressure.

(2) Groundwater Use

Groundwater is used as supplemental source of the MWA water supply systems. Groundwater is used mainly for residential, commercial and industrial water supplies in areas not covered by the MWA distribution networks. The Groundwater Act requires groundwater users to secure permit for drilling of wells and usage. Likewise, installation of water meter was required since 1985. As a result, groundwater pumpage can be estimated. The total estimated pumpage of groundwater of the private wells and MWA's wells increased from 1.12 to 1.48 MCMD in the Study Area (see Chapter 5).

(3) Groundwater Level and Land Subsidence

Groundwater levels in the Phra Pradaeng (PD), the Nakhon Luang (NL), and the Nonthaburi (NB) Aquifers declined through late 60's to 70's. They declined to a maximum of between 40 m to 50 m in each aquifer in early 80's. However, groundwater level recovered at the central area of Bangkok since 1985 due to the control of groundwater pumpage by the Ministerial Regulations. On the other hand, groundwater levels continued to decline in the vicinity of Bangkok, such as Lat Krabang, Pathum Thani and Samut Sakhon areas. Groundwater pumpage in these areas increased yearly due to continuous construction of factories and housing. This has caused the steep decline of groundwater levels.

Leveling surveys for land subsidence have been conducted by the Royal Thai Survey Department (RTSD), Bangkok Metropolitan Authority (BMA), and DMR. Based on the RTSD's data, a maximum subsidence of 75 cm occurred during the 10 year period between 1978 and 1987. It can be estimated that a maximum subsidence of over 160 cm had occurred in 45 years based on the old leveling survey data.

As mentioned above, land subsidence rate in early 80's was 5 to 10 cm/year in central Bangkok. It decreased to less than 2 cm/year accompanied with a recovery of groundwater level. Meanwhile, Bang Phli, Samut Prakarn and Samut Sakhon, located at the east, at the south and at the southwest of Bangkok Metropolitan Area, respectively, suffered from extreme land subsidence at the rate of over 5 cm/year.

(4) Legal Aspect

To conserve groundwater and minimize land subsidence, the Government of Thailand enforced the Groundwater Act B.E. 2520 in 1978. Under this Act, permits for drilling of groundwater, for use of groundwater and for disposal of water into wells must be secured by the user.

As a result of the promulgation of said law, Bangkok and five (5) adjoining provinces were designated as the Bangkok Groundwater Area and users of wells in these areas were charged groundwater fee.

(5) Mitigation of Groundwater Crisis and Land Subsidence

Based on the DMR and AIT joint study on "Groundwater Resources in Bangkok Area: Development and Management", the Cabinet issued a resolution on the "Mitigation of Groundwater Crisis and Land Subsidence in Bangkok Metropolis" in March 1983. The resolution aimed at controlling the groundwater pumpage to recover the piezometric levels in the three (3) heavily used aquifers to as high levels as possible and to slow down the rate of land subsidence .

In this resolution, a control area of groundwater use was designated and the area was divided into three (3) critical zones according to the rate of subsidence, rate of water level decline and water levels. The MWA wells were planned to be phased out. The rate of private pumpage was regulated in the critical zones by the target year (Figure 2.8).

From 1983 to 1987, groundwater recovery was observed and the rate of land subsidence was reduced in the central area of Bangkok due to the instituted control measures. Unfortunately, annual private pumpage kept on increasing since 1988 because of the unexpected rapid national economic growth. This phenomenon caused an upsurge in water demand and hastened the decline of water levels as well as the rate of land subsidence. It is in this light that groundwater control and management programs should be reassessed to be more responsive to the present situation.

Table 2.1 Growth of Real GDP and Per Capita GNP

Year	Real GDP	Agricul–ture	Industry	Services	Real per Capita GNP
60 – 65	7.2	4.8	11.5	7.2	–
65 – 70	8.6	6.0	10.4	9.5	–
70 – 75	5.6	3.8	7.3	5.6	2.9
75 – 80	7.9	4.0	10.6	8.2	5.3
80 – 85	5.6	4.9	5.0	6.3	3.5
86	4.5	0.2	7.1	4.6	2.6
87	9.5	–0.2	12.8	11.1	7.7
88	13.2	10.2	17.4	11.6	11.4
89	12.0	6.6	16.2	11.1	10.5
90	10.0	–1.8	15.8	10.0	8.5

Source : National Economic and Social Development Board (NESDB)

Table 2.2 NUMBER OF POPULATION BY PROVINCE 1980-1991

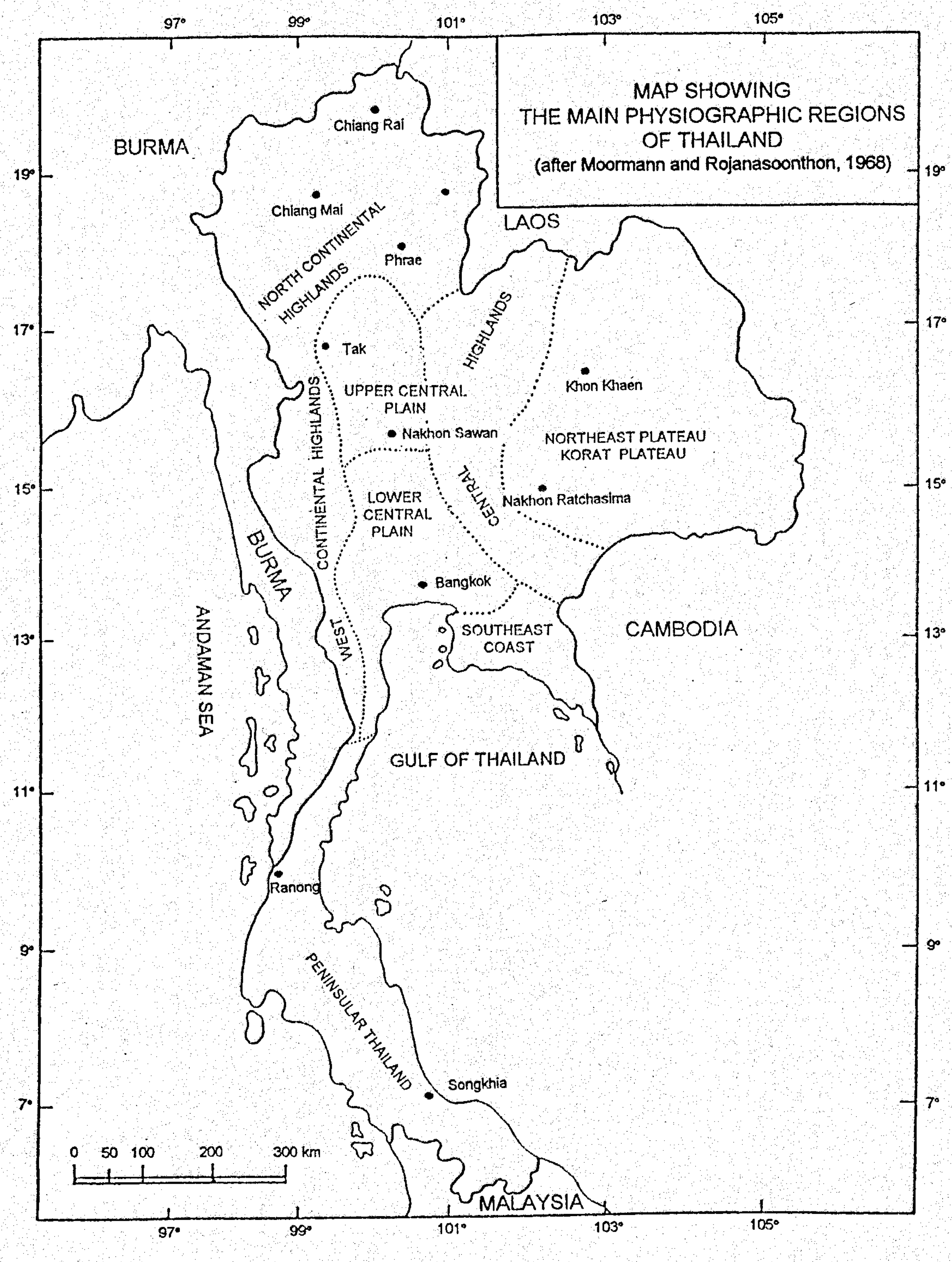
PROVINCE	1980	1981	1982	1983	1984	1985	
WHOLE KINGDOM	44,824,540	47,875,002	48,846,927	49,515,094	50,583,105	51,795,651	
Bangkok	4,697,071	5,331,402	5,468,286	5,018,327	5,174,682	5,363,378	
Nonthaburi	369,777	403,809	422,392	456,588	478,199	504,424	
Pathum Thani	319,674	332,111	341,336	357,809	366,767	384,713	
Samut Prakarn	484,829	557,292	585,320	623,514	640,316	662,612	
Samut Sakhon	247,168	270,744	278,949	296,714	301,631	315,373	
Ayutthaya	602,021	626,590	631,285	630,799	637,845	652,977	
Nakhon Pathom	525,906	569,649	590,588	585,931	596,257	609,316	
Chachoengsao	445,000	498,092	507,422	503,184	510,308	525,717	
TOTAL	7,691,446	8,589,689	8,825,578	8,472,866	8,706,005	9,018,510	
PROVINCE	1986	1987	1988	1989	1990	1991	Av.Annual Grow.Rate 1980.1991
WHOLE KINGDOM	52,969,204	53,873,172	54,960,917	55,888,393	56,303,273	56,961,030	2.20
Bangkok	5,468,915	5,609,352	5,716,779	5,832,843	5,546,937	5,620,591	1.65
Nonthaburi	525,475	571,871	596,381	627,667	668,760	703,187	6.02
Pathum Thani	402,080	415,193	435,409	441,930	452,693	465,968	3.48
Samut Prakarn	689,631	741,905	789,060	829,412	854,883	882,164	5.59
Samut Sakhon	327,677	334,170	340,952	349,680	358,155	365,274	3.61
Ayutthaya	664,245	668,611	677,626	680,100	685,394	691,075	1.26
Nakhon Pathom	617,596	619,518	630,805	646,803	657,182	664,190	2.14
Chachoengsao	540,864	550,787	569,411	575,731	582,783	589,829	2.59
TOTAL	9,236,483	9,511,407	9,756,423	9,984,166	9,806,787	9,982,278	2.40

Source : Department of Local Administration

Table 2.3 WATER SUPPLY ACHIEVEMENT OF MWA

Description	Unit	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
A. Total Water Production (Include Groundwater) B + Water Loss + I	M. m3	624.7	630.3	626.5	731.2	801.8	820.8	841.3	859.6	934.3	1049.3	1109.2
B. Water Sales 1)+2)	M. m3	334.2	340.8	360.7	423.4	477.4	485.0	523.0	570.3	628.2	718.7	781.5
1) Residence	M. m3	191.1	194.6	205.0	239.4	280.4	280.0	305.2	328.5	328.0	369.4	391.7
2) Business, Gove. Agencies	M. m3	143.1	144.3	162.3	182.7	195.4	204.0	216.2	240.3	298.7	347.9	377.7
C. Water Sales %, B/A	%	53.5	54.2	59.0	57.9	59.5	59.1	62.2	66.4	67.4	68.5	70.5
D. Total Customers, No.	1000	423	445	468	520	602	660	721	790	867	949	1028
E. Population Responsible Area, Person	1000	6292.5	6476.0	6098.4	6293.2	6530.4	6684.0	6923.2	7102.2	7289.9	7070.6	7205.9
F. Water Consumption Ratio, ℓ/Person/day	ℓ	148	142	148	163	178	169	172	172	164	188	190
G. Service Area	km2	315	330	350	390	430	475	520	580	625	680	710
H. Water Supply Ratio	%	56	58	62	64	66	68	70	74	75	76	78
I. Groundwater Supply Volume	M. m3	186.2	163.4	143.4	130.8	109.9	71.3	76.7	72.6	59.3	28.7	34.2
J. Groundwater Supply Ratio, I/A	%	29.8	25.9	22.8	17.9	13.7	8.6	9.1	8.4	6.3	2.8	3.1

Source : MWA   M. m3 =Million m3   Note: MWA service area is BKK Metropolis, Nonthaburi and SamutPrakarn.



modified Thiramongkol, 1983

Figure 2.1	**MAIN PHYSIOGRAPHIC REGIONS OF THAILAND**

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

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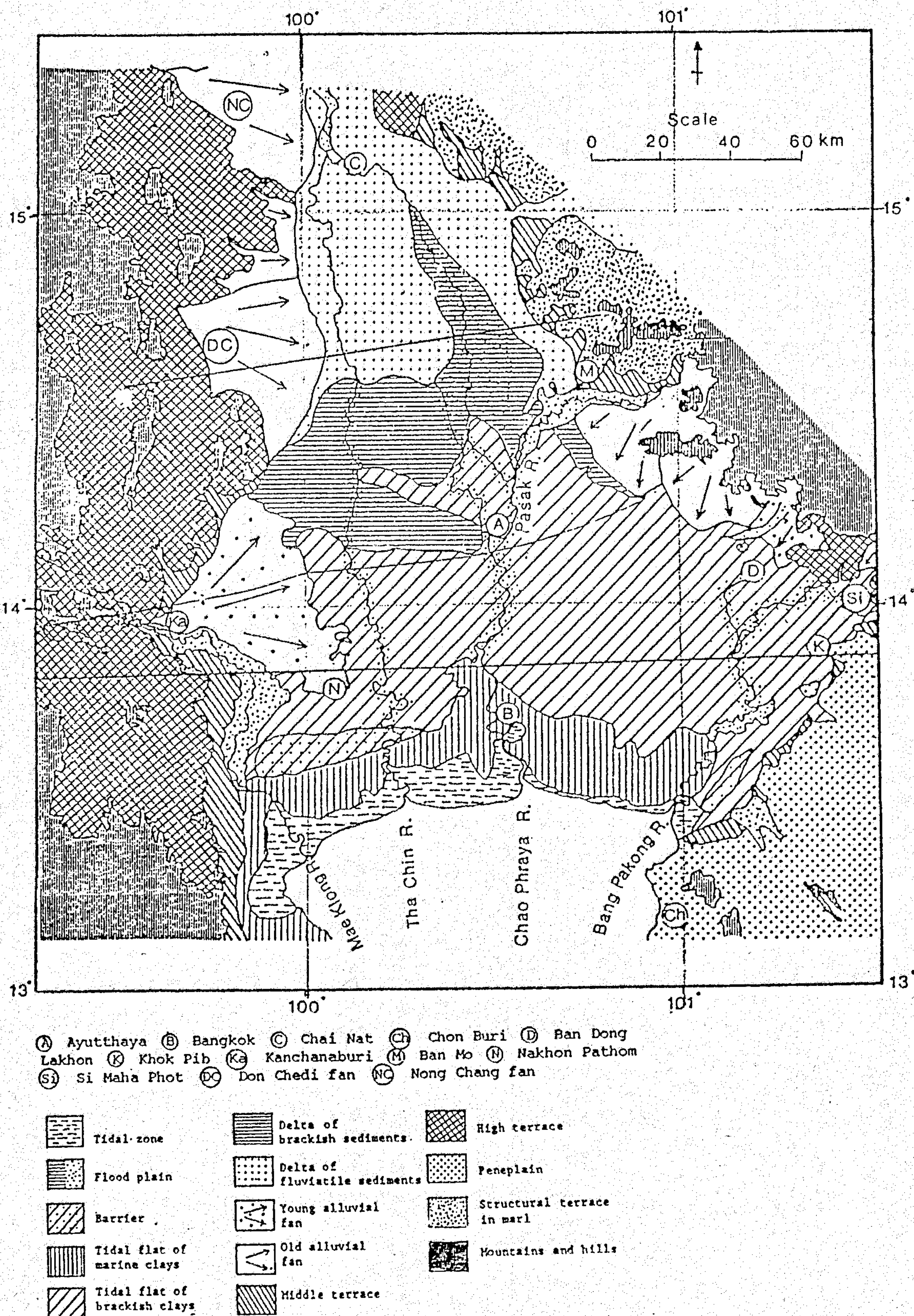

After Narong Thiramongkol (1983)

Figure 2.2	GEOMORPHOLOGICAL MAP OF THE LOWER CENTRAL PLAIN
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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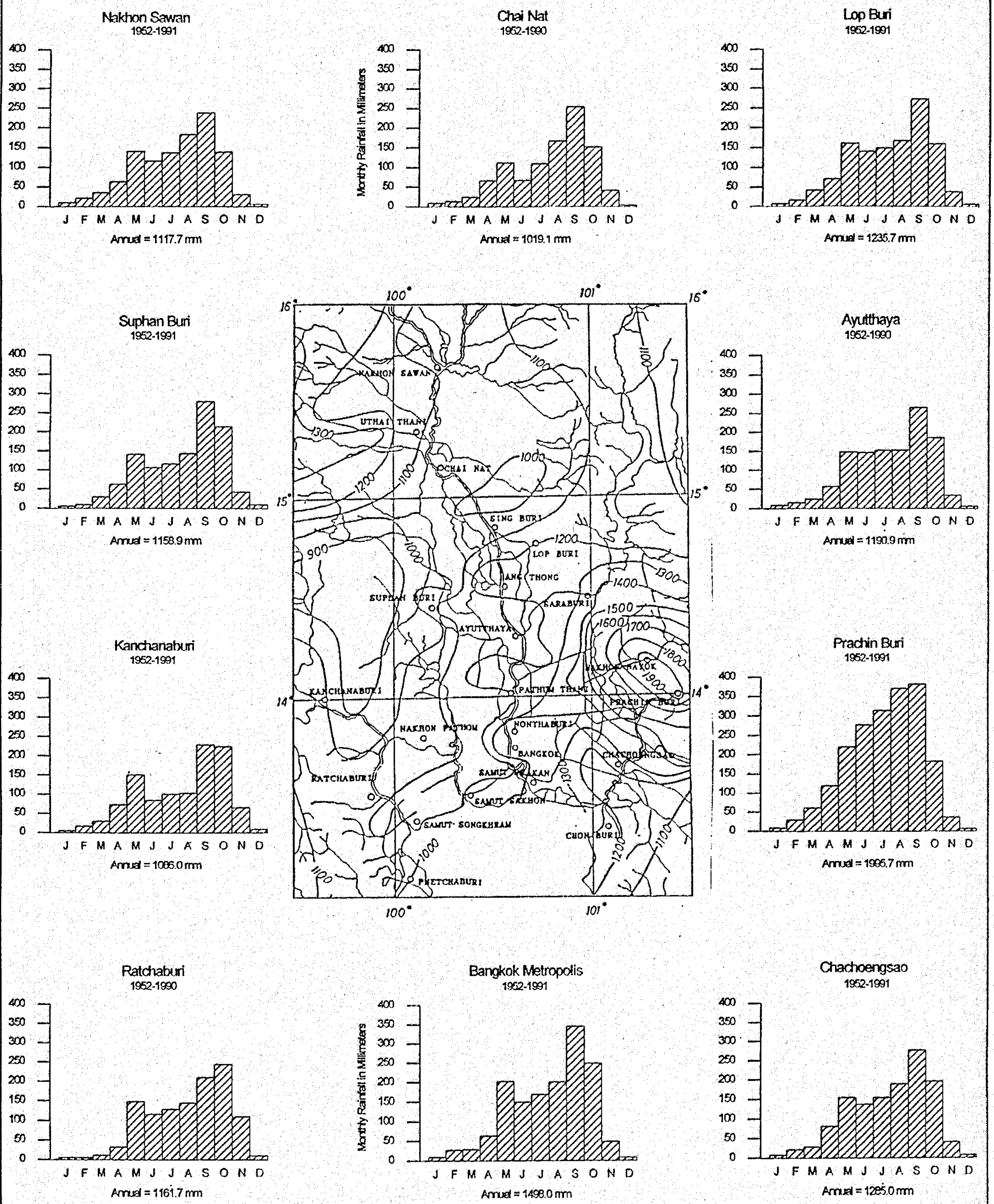

Figure 2.3	MEAN ANNUAL RAINFALL AND MEAN MONTHLY DISTRIBUTION OF RAINFALL IN THE LOWER CENTRAL PLAIN

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

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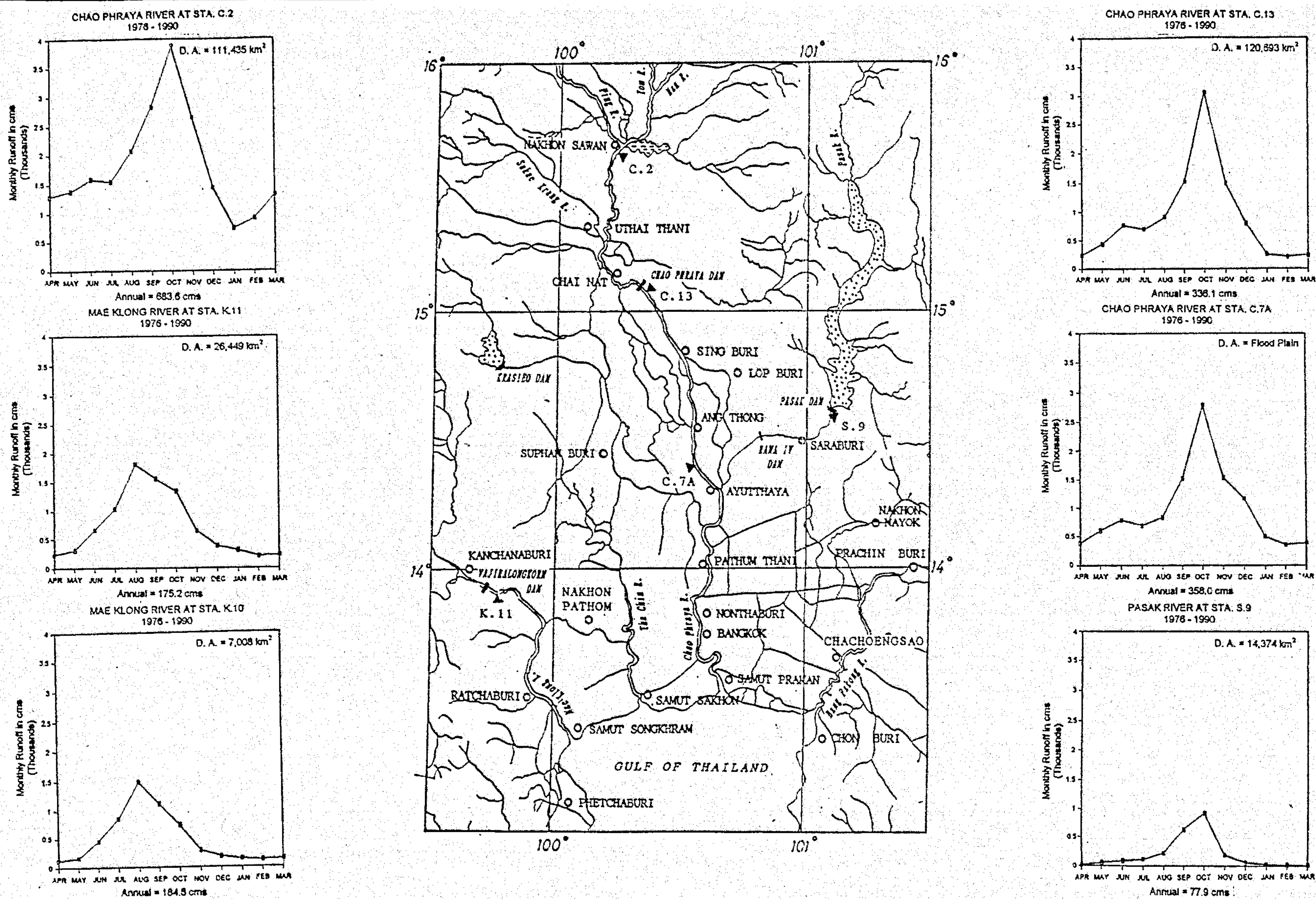

Figure 2.4 MEAN MONTHLY DISTRIBUTION OF RUNOFF OF THE CHAO PRAYA, PASAK AND MAE KLONG RIVERS

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

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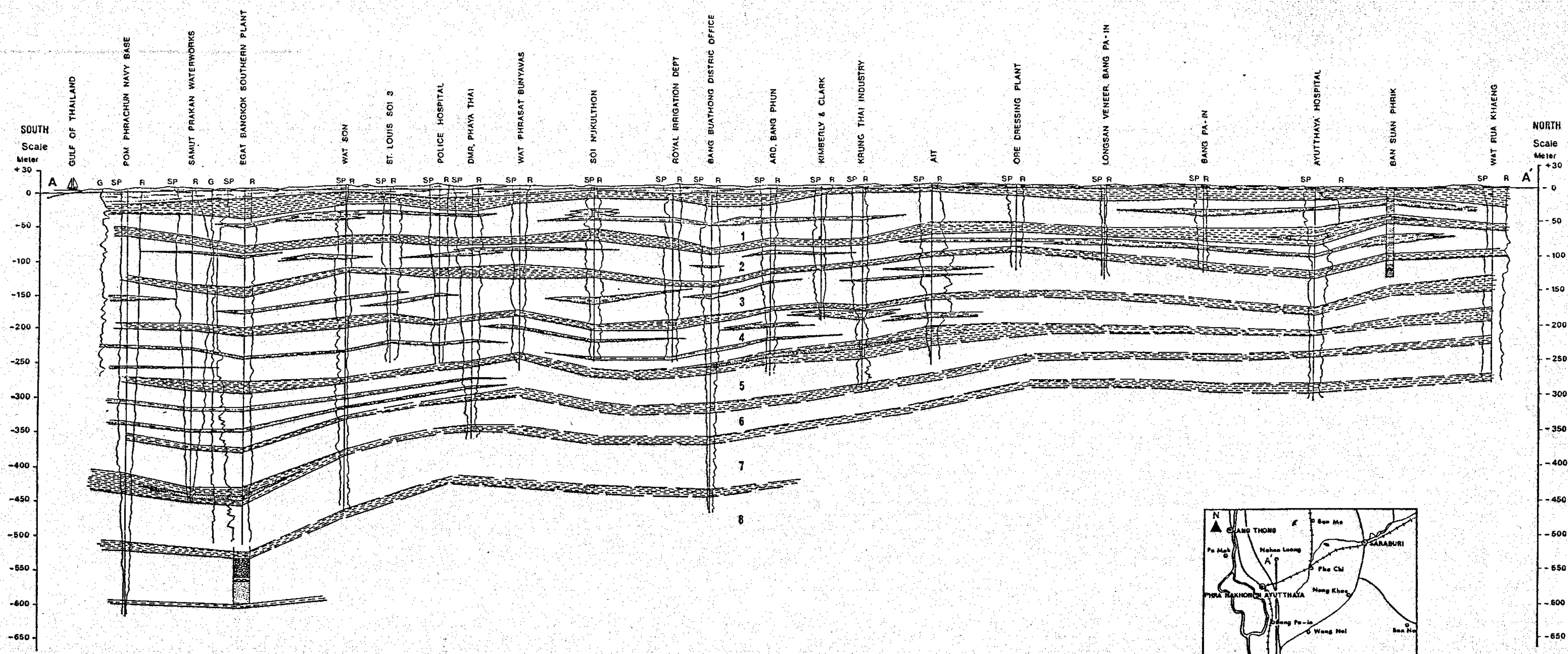


SP R — Electrical log, SP curve on the left, Resistivity (R) curve on the right

G — Gamma ray log (G)

Drilled log

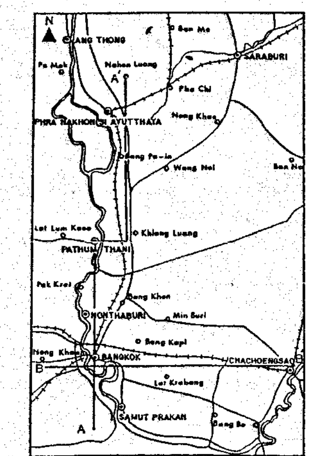
Top Clay: dark gray to black, very soft, known as "Bangkok soft clay"

Clay (confining bed) : consisted predominantly of stiff clay, with localized sandy clay or fine sand layers or lenses. Boundaries are correlated through electrical logs, and dashed where approximate.

Sand and gravel (aquifer) : consisted of sand and gravel of various sizes and colors, moderately to well sorted, subangular to rounded. The aquifers are commonly interbedded by clay layers and lenses.

Clay layer intercalating in the sand and gravel aquifer.

Sand layer intercalating in the confining clay bed.



INDEX MAP SHOWING PROFILE-LINE

Scale 1:1,000,000

A——A' Profile-line
∘ Amphoe (district)
⊙ Changwat (province)

DMR, 1979

Figure 2.5 HYDROGEOLOGICAL NORTH-SOUTH PROFILE OF THE LOWER CHAO PHRAYA BASIN

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

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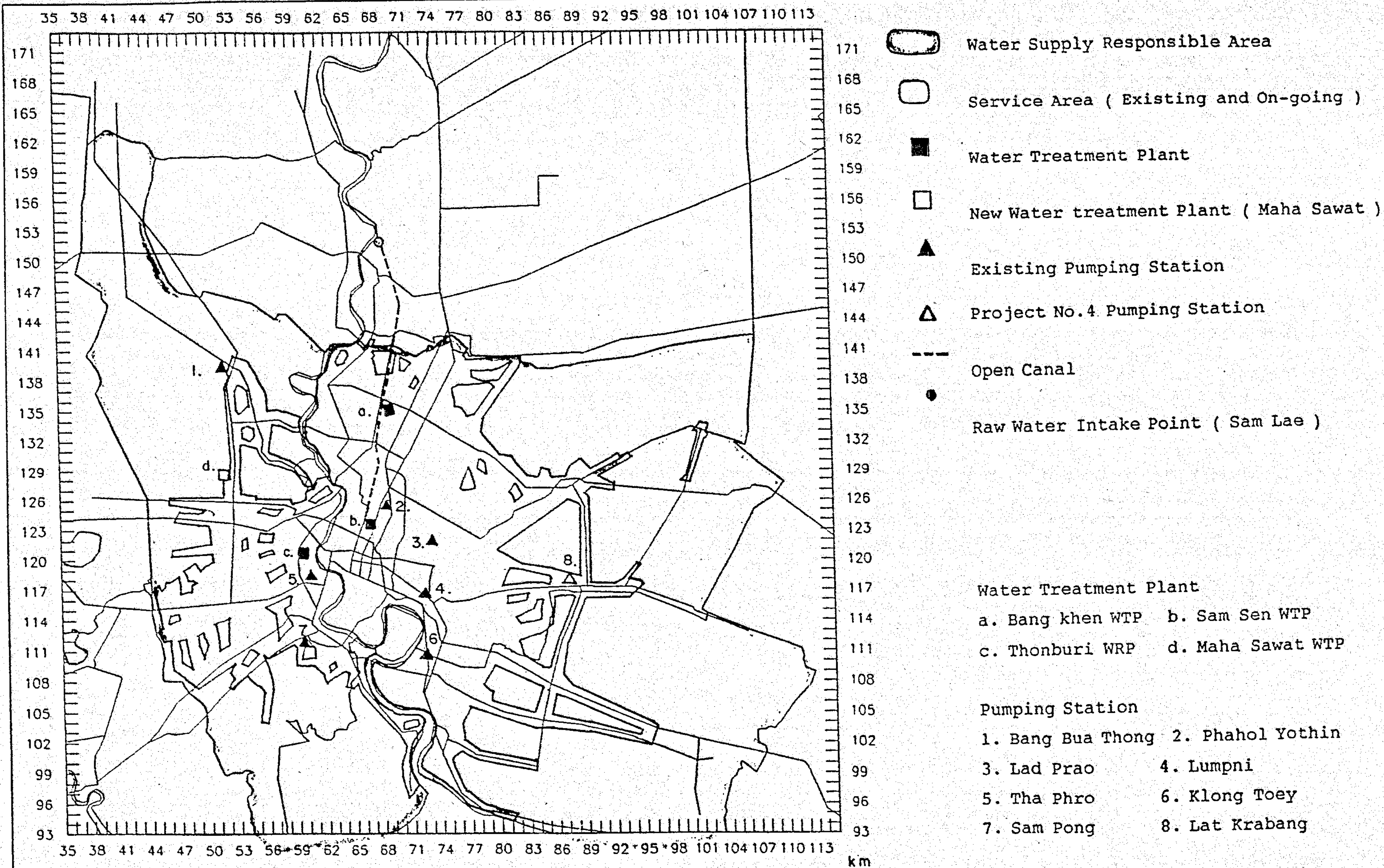

Figure 2.6 MWA WATER SUPPLY MAP

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

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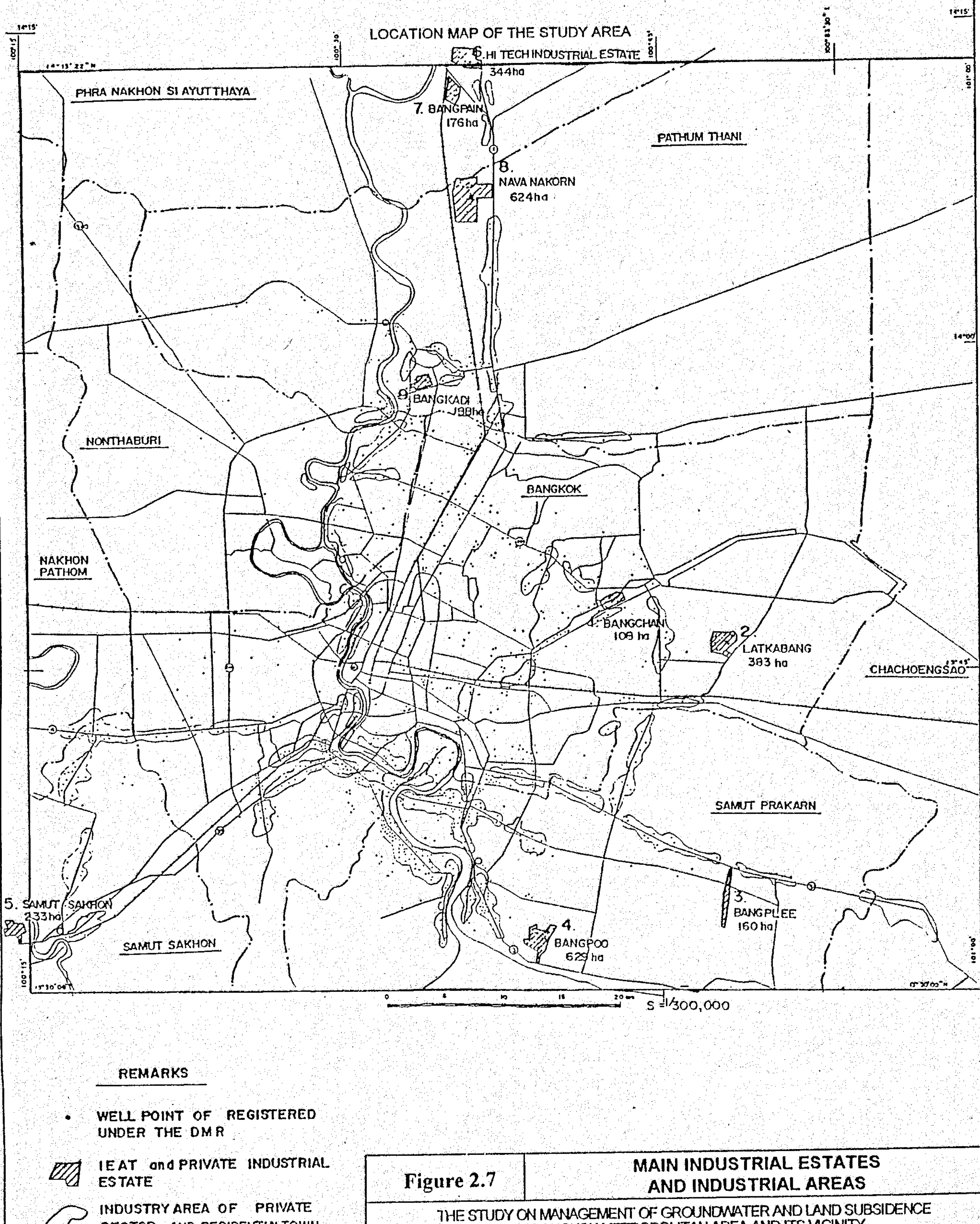

Figure 2.7	MAIN INDUSTRIAL ESTATES AND INDUSTRIAL AREAS
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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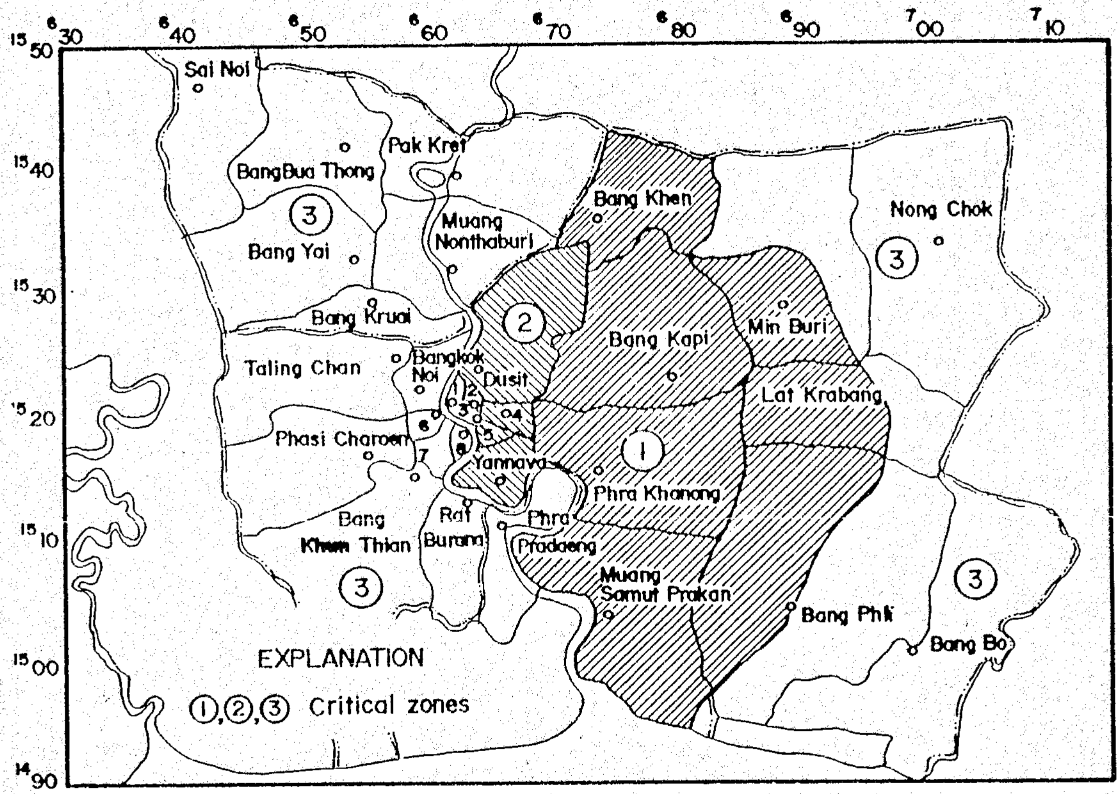


Figure 2.8 Present Critical Zones of Bangkok Metropolitan Area

CHAPTER 3 HYDROGEOLOGIC STRUCTURE

CHAPTER 3 AQUIFER SYSTEM

3.1 Topography and Geology

A schematic topographical and geological map of the Lower Central Plain is shown in Figure 3.1. Mountains are situated in the west and the east of the plain. High and middle terraces are distributed from the mountain foot to the plain. Old and young alluvial fans are located at the outlet of the rivers from the mountain. The plain consists of delta and tidal zone. The delta is composed of fluviatile sediments in the vicinity of Chai Nat and brackish sediments in Ayutthaya. Marine to brackish delta underlain by Bangkok Clay and tidal zone are distributed in the Bangkok Metropolitan Area. As the ^{14}C age of Bangkok Clay (soft clay) indicates 4,000 to 7,000 Y.B.P., the clay was deposited during the Holocene Transgression. Overlain by Bangkok Clay, Pleistocene to Pliocene sediments overlay the basement at the thickness of 500 to 1,800 m.

3.2 Core Borings

Core borings were conducted to investigate subsurface hydrogeological conditions as well as to collect core samples for core analyses and soil tests. Three (3) sites were selected to perform core borings and to construct observation wells.

Site-A: Rom Klao Village of NHA, Lat Krabang	: depth 600 m
Site-B: AIT Campus, Pathum Thani	: depth 300 m
Site-C: Ron Riang Wat Klong Kru, Samut Sakhon	: depth 325 m

(1) Hydrogeologic Classification

Site-A

Sixteen (16) facies units were identified based on the detailed lithologic logs and the results of geophysical loggings. Hydrogeological classification at Site-A is summarized as follows (Figure 3.2):

Hydrogeological Classification	Depth
Bangkok Clay (soft clay)	1.50 m to 17.20 m
Bangkok Clay (stiff clay)	17.20 m to 20.30 m
Bangkok Aquifer	20.30 m to 57.80 m
Phra Pradaeng Aquifer	57.80 m to 121.50 m
Nakhon Luang Aquifer	121.50 m to 178.28 m
Nonthaburi Aquifer	178.28 m to 280.80 m
Sam Khok Aquifer	280.80 m to 361.40 m
Phayathai Aquifer	361.40 m to 440.00 m
Thonburi Aquifer	440.00 m to 482.00 m
Pak Nam Aquifer	482.00 m to 600.00 m+

Site-B

Eleven (11) facies units were identified based on the detailed lithologic logs and the results of geophysical loggings. The hydrogeological classification at Site-B is summarized as follows:

Hydrogeological Classification	Depth
Bangkok Clay (soft clay)	2.00 m to 9.20 m
Bangkok Clay (stiff clay)	9.20 m to 15.80 m
Bangkok Aquifer	15.80 m to 49.00 m
Phra Pradaeng Aquifer	49.00 m to 126.25 m
Nakhon Luang Aquifer	126.25 m to 193.40 m
Nonthaburi Aquifer	193.40 m to 281.13 m
Sam Khok Aquifer	281.13 m to 300.00 m+

Site-C

Thirteen (13) facies units were identified based on the detailed lithologic logs and the results of geophysical loggings. The hydrogeological classification at Site-C is summarized as follows:

Hydrogeological Classification	Depth
Bangkok Clay (soft clay)	1.40 m to 14.50 m
Bangkok Clay (stiff clay)	14.50 m to 19.45 m
Bangkok Aquifer	19.45 m to 43.45 m
Phra Pradaeng Aquifer	43.45 m to 108.00 m
Nakhon Luang Aquifer	108.00 m to 170.00 m
Nonthaburi Aquifer	170.00 m to 281.00 m
Sam Khok Aquifer	281.00 m to 325.00 m+

(2) Analysis of Core Samples

Core samples were analyzed for the following items.

- ^{14}C dating
- Microfossils (Diatom and Foraminifera)
- Salt content

^{14}C Dating

The age of Bangkok Clay (soft clay) was estimated by ^{14}C dating. The results of dating ranged from 1,110±100 to 8,620±340 Y.B.P. at Site A (Lat Krabang) and Site B (AIT) indicating the deposits of the Alluvial Transgression.

Environments of Deposition

A few diatom and foraminifera are contained in the Bangkok Clay. Results of microfossil analysis indicated that the Bangkok Clay is deposited in a marginal sea environment.

Salt Content Analysis

Salt contents in the core samples showed high concentration at depth of 30 m to 90 m at Site A and 30 m to 50 m at Site B. These results indicated the salinity of the Bangkok Aquifer.

Soil Test

Undisturbed samples were taken by thin wall sampler and tested for physical properties and consolidation. Pleistocene sediments may also be consolidated. Therefore, core samples were taken at depth from 50 to 600 meter by wire line method and tested for physical properties and consolidation (some samples for high stress consolidation). Future land subsidence was predicted by using parameters obtained by the soil tests. Bangkok Clay is a consolidated bed which affects land subsidence.

3.3 Basement Structure

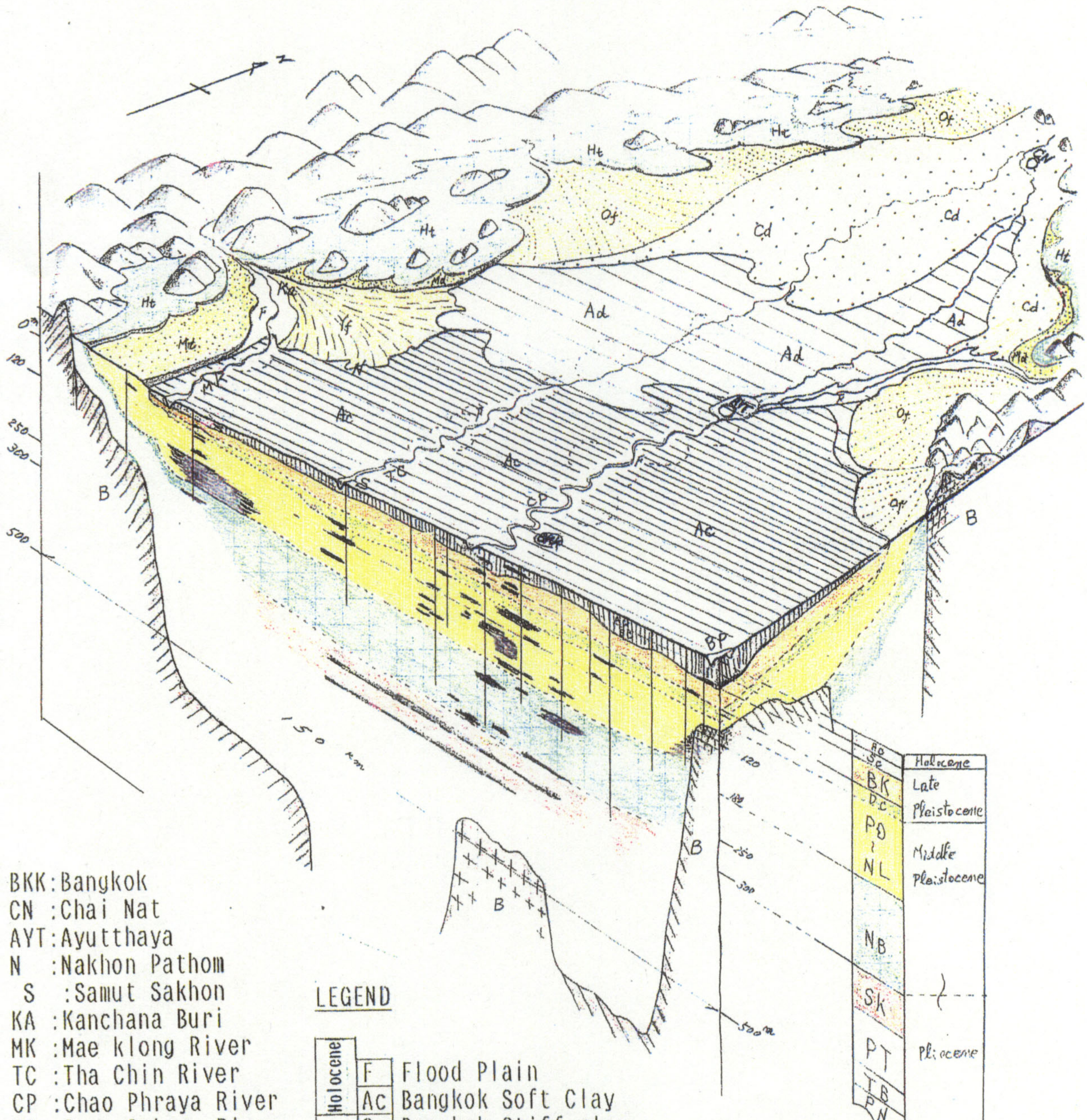
Based on previous studies and results of the core borings, the basement structure of the Lower Central Plain was delineated as shown in Figure 3.3. The depth of the basement was estimated at more than 1,000 m in the right bank of the Chao Phraya River. The depth of the basement is 385 m and 412 m at two (2) existing boreholes in the left bank near the river mouth. However, the core boring at Site A did not reach the basement at depth of 600m. Therefore, the depth of the basement of the entire left bank was estimated at 500 to 1,000 m.

3.4 Aquifer Unit

Based on the core boring data and the existing lithologic logs, the geology and hydrogeology of the Study Area were interpreted and analyzed. Figure 3.4 shows a representative profile of the Study Area. Eight (8) aquifer units were classified according to DMR's definition. The isodepth maps of main aquifers were prepared as shown in Figures 3.5.1, 3.5.2 and 3.5.3.

3.5 Construction of Monitoring Stations

Monitoring wells were drilled at Site A (Lat Krabang), B (AIT) and C (Samut Sakhon) for measurement of land subsidence and groundwater levels at different depths. Number of wells and their depths are shown in Figure 3.6. The set of subsidence equipment and water level recorders were installed at each monitoring well (Figure 3.7). Pumping tests were conducted to obtain aquifer parameters.



BKK : Bangkok
CN : Chai Nat
AYT : Ayutthaya
N : Nakhon Pathom
S : Samut Sakhon
KA : Kanchana Buri
MK : Mae klong River
TC : Tha Chin River
CP : Chao Phraya River
BP : Bang Pakong River

LEGEND

Holocene	F	Flood Plain
	Ac	Bangkok Soft Clay
Plio~Pleistocene	Sc	Bangkok Stiff clay
	Ad	Ayutthaya Delta(Brackish Sediments)
	Cd	Chai Nat Delta(FluviatileSediments)
	Yf	Young Alluvial Fan
	Of	Old Alluvial Fan
	Mt	Middle Terrace
	Ht	High Terrace
Pre-Tertiary	B	Bedrocks

Granule, Coarse Sand
Production Wells

Figure 3.1	**SCHEMATIC DIAGRAM OF THE LOWER CENTRAL PLAIN**

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

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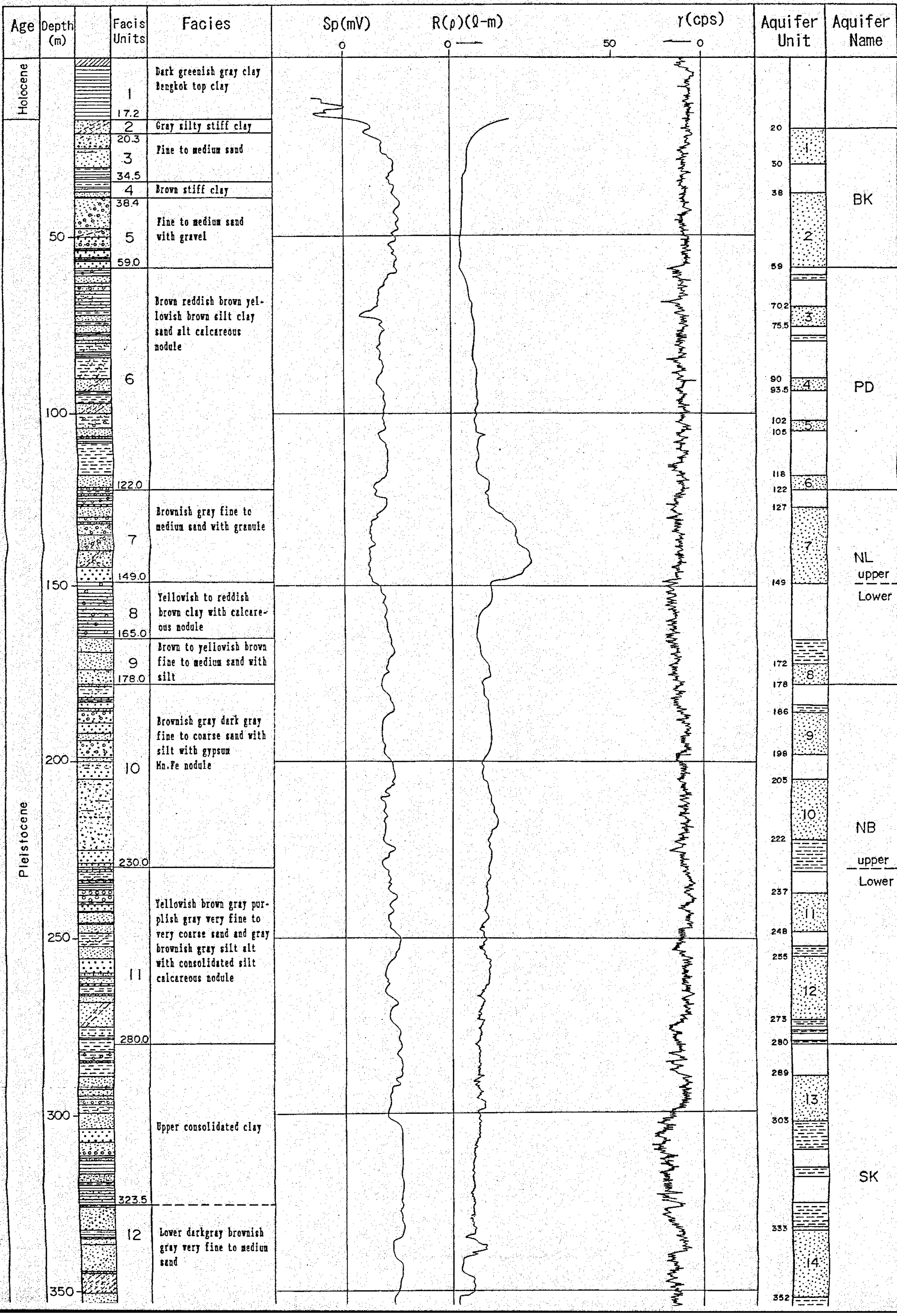
JICA-A LOGGING



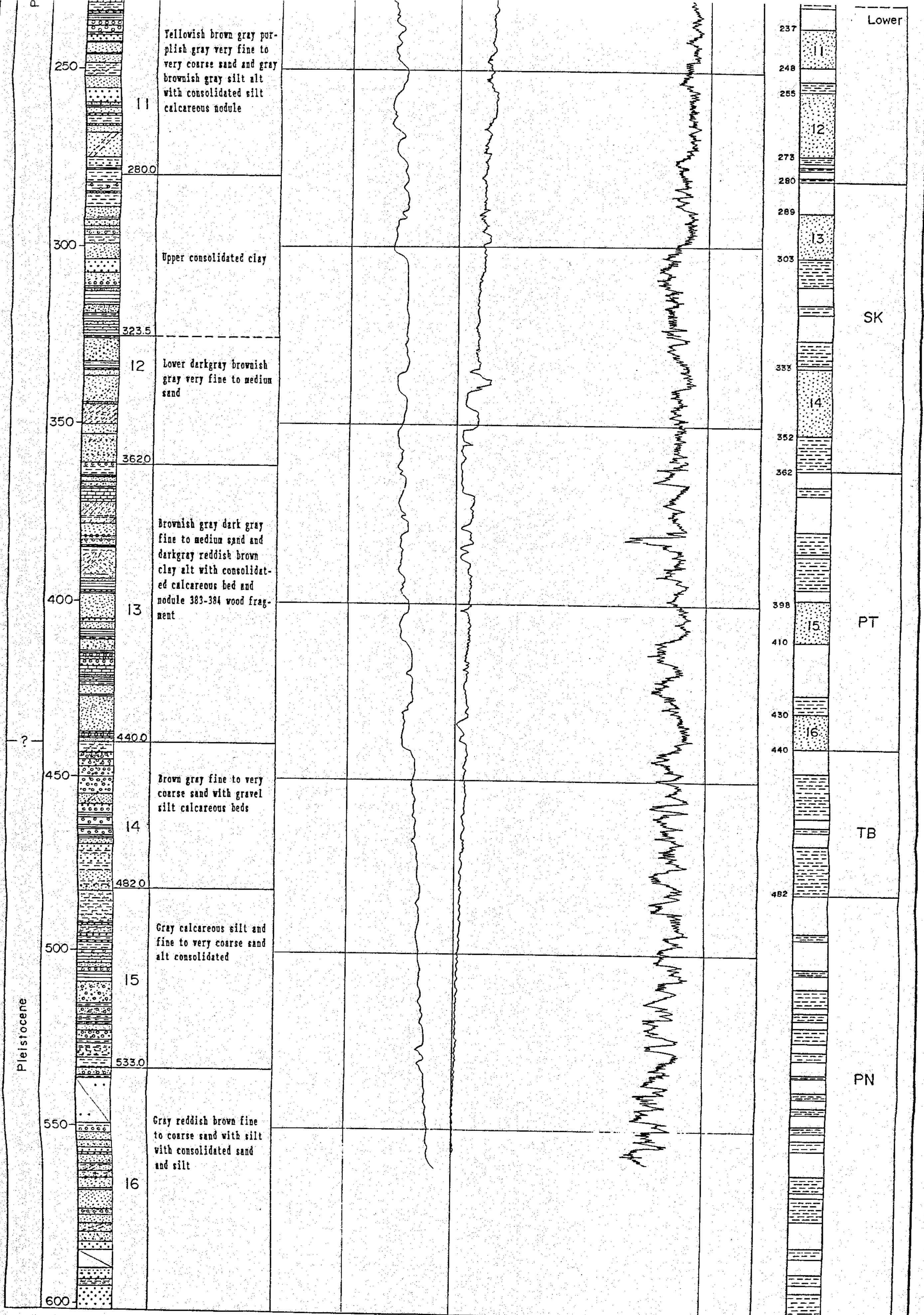


Figure 3.2	JICA - A Logging and Aquifer

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.

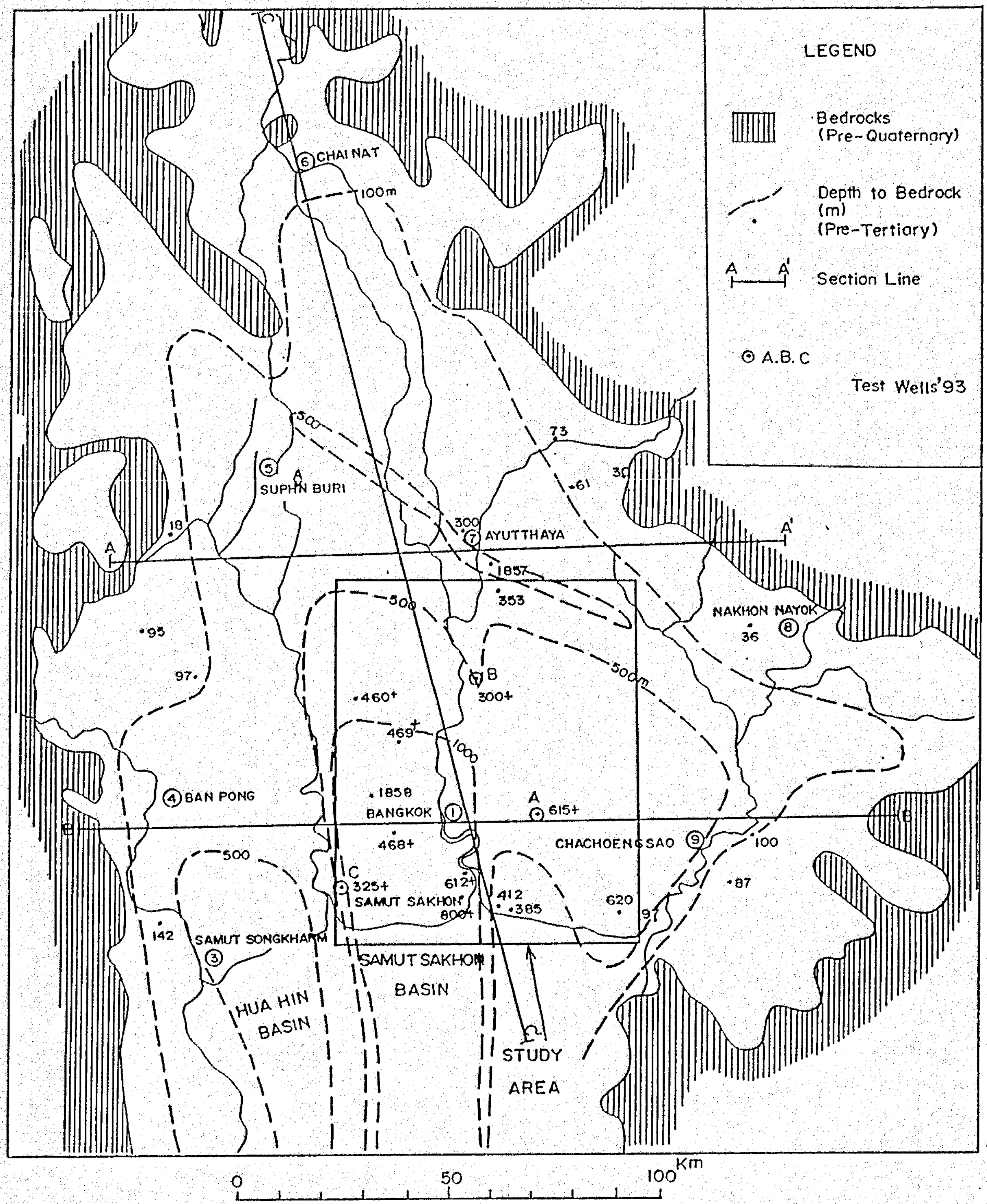
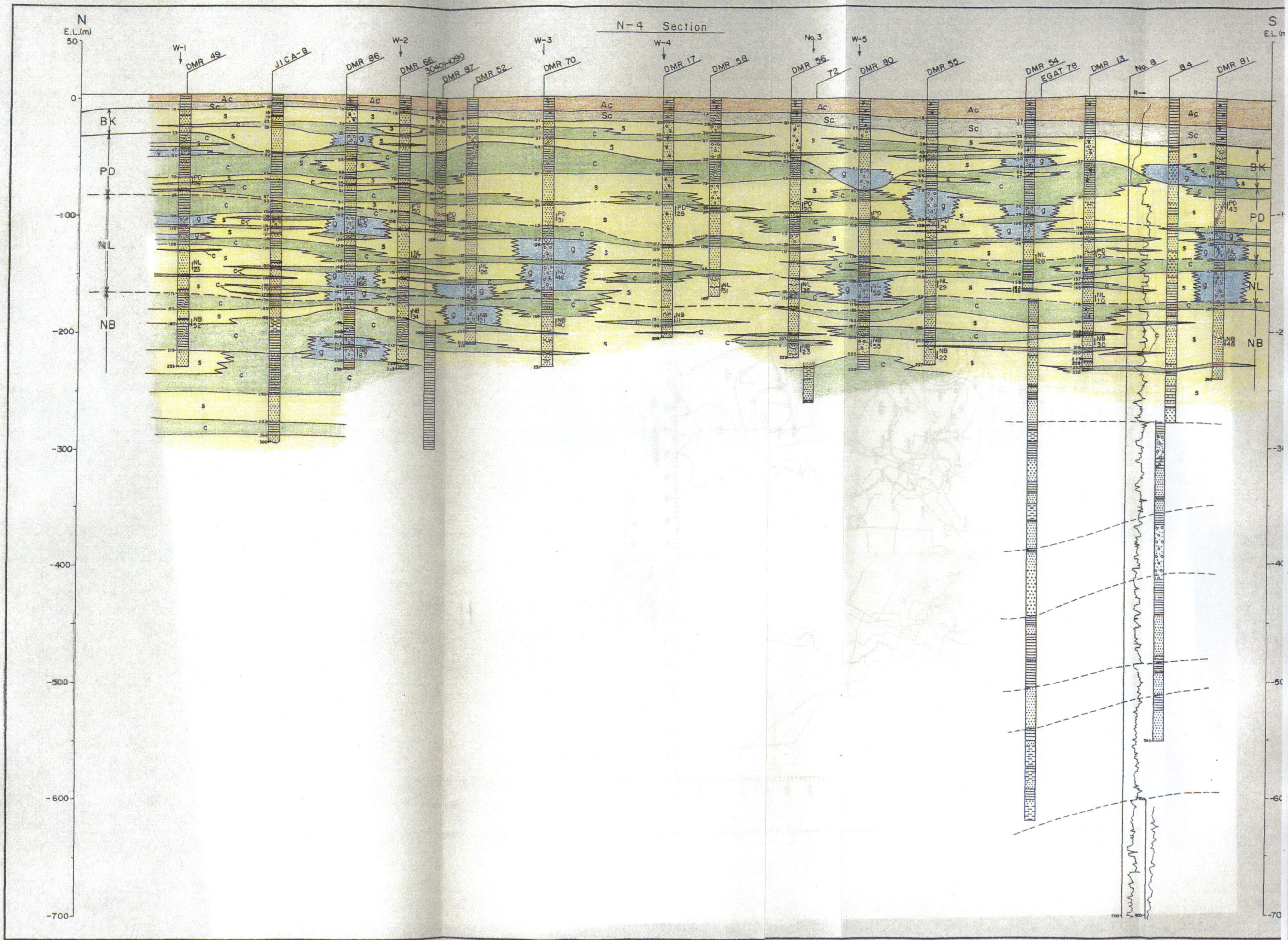


Figure 3.3	SEDIMENTARY BASIN OF THE LOWER CENTRAL PLAIN

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.



N-4 Section
N
S
E.L.(m)
50
0
-100
-200
-300
-400
-500
-600
-700
BK
PD
NL
NB
W-1
W-2
W-3
W-4
W-5
No.3
DMR 49
JICA-8
DMR 86
DMR 66
3040H099
DMR 87
DMR 52
DMR 70
DMR 17
DMR 58
DMR 56
72
DMR 80
DMR 55
DMR 54
EGAT 78
DMR 13
No. 8
84
DMR 81
Ac
Sc

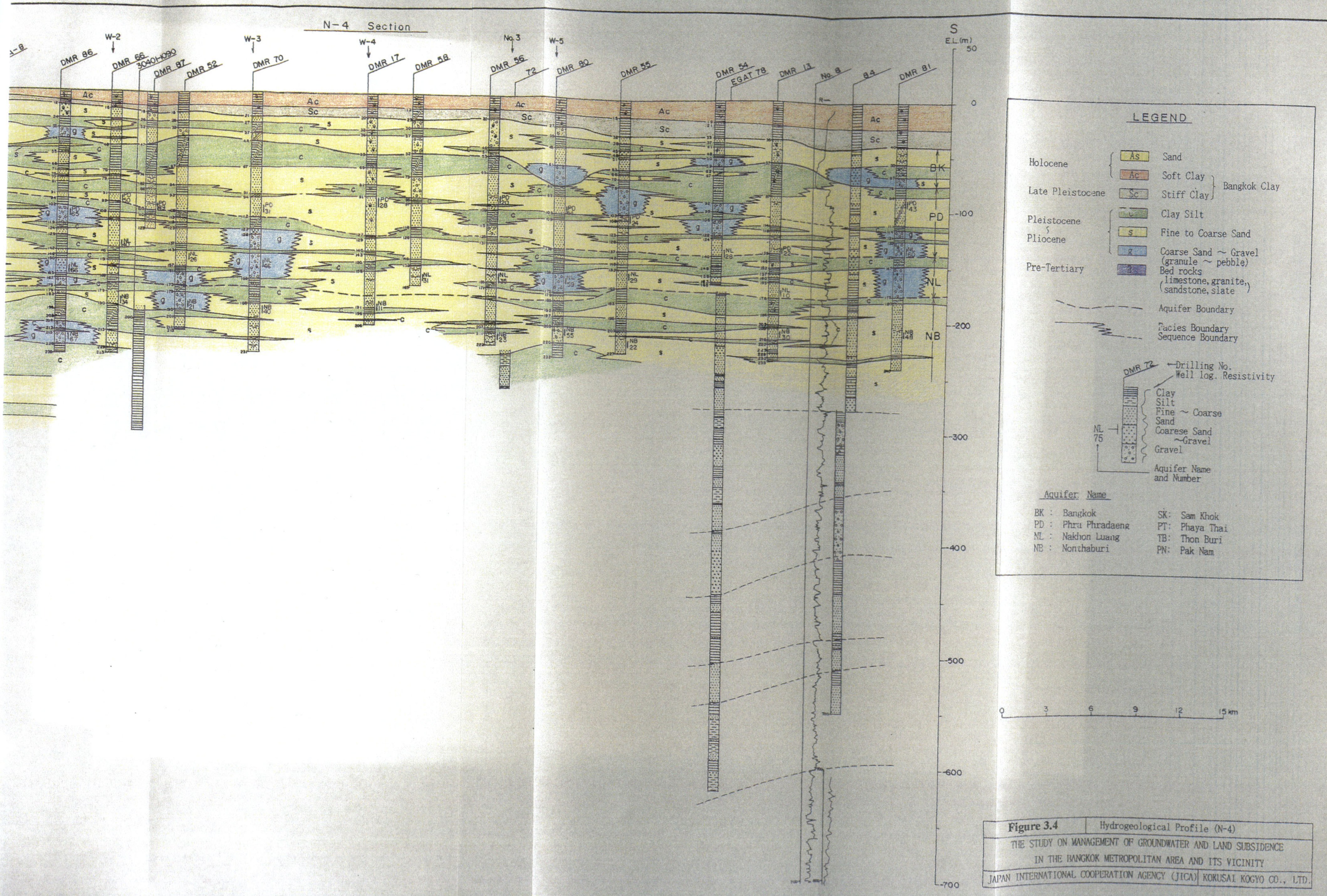


Figure 3.4 Hydrogeological Profile (N-4)

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

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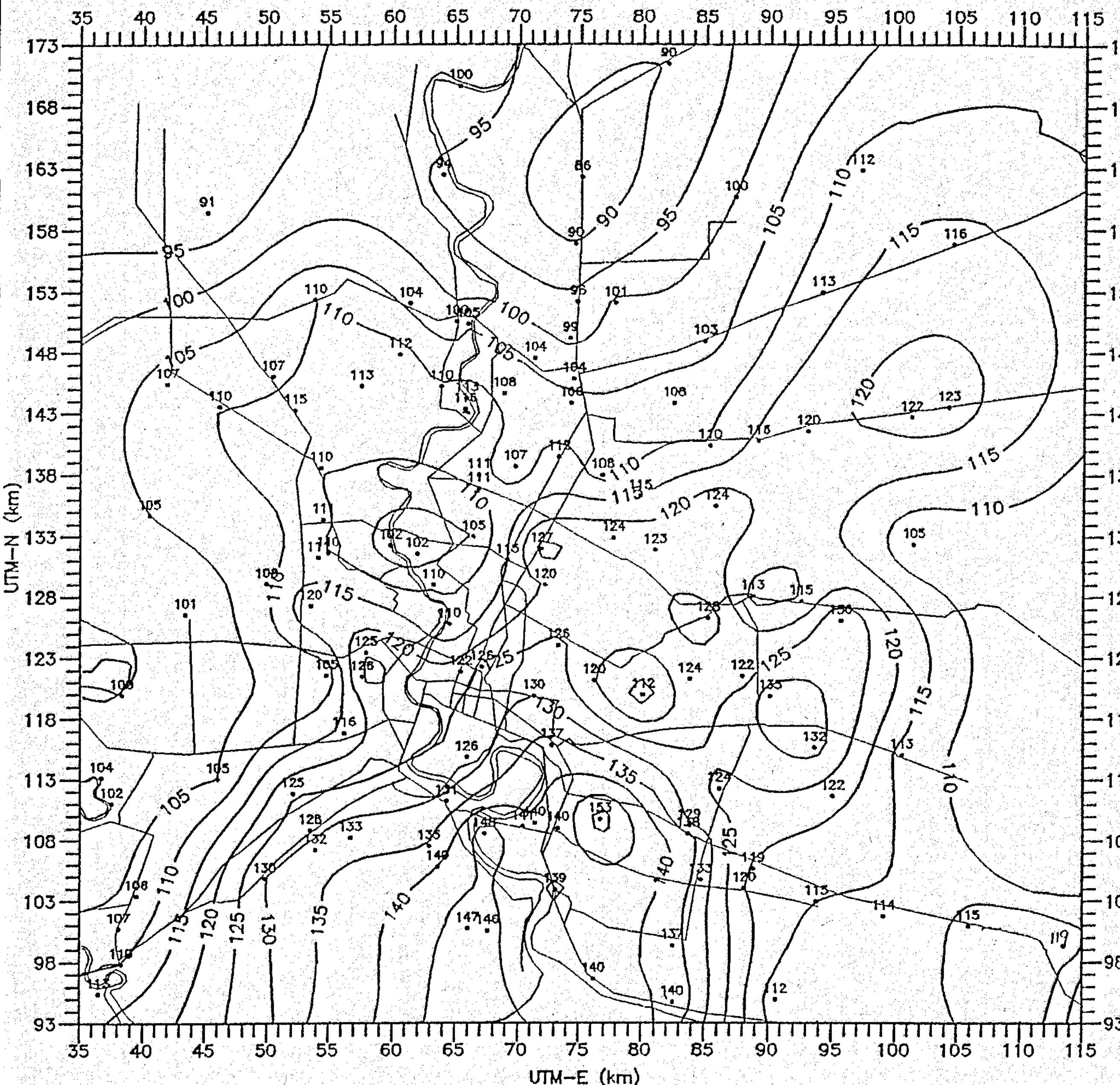

LEGEND

LINE OF EQUAL DEPTH TO AQUIFER BOTTOM
(m below ground surface)

120 INVESTIGATED WELL
WITH DEPTH TO AQUIFER BOTTOM
(m below ground surface)

Figure 3.5.1	**DEPTH TO THE BOTTOM OF PHRA PRADAENG AQUIFER (PD)**
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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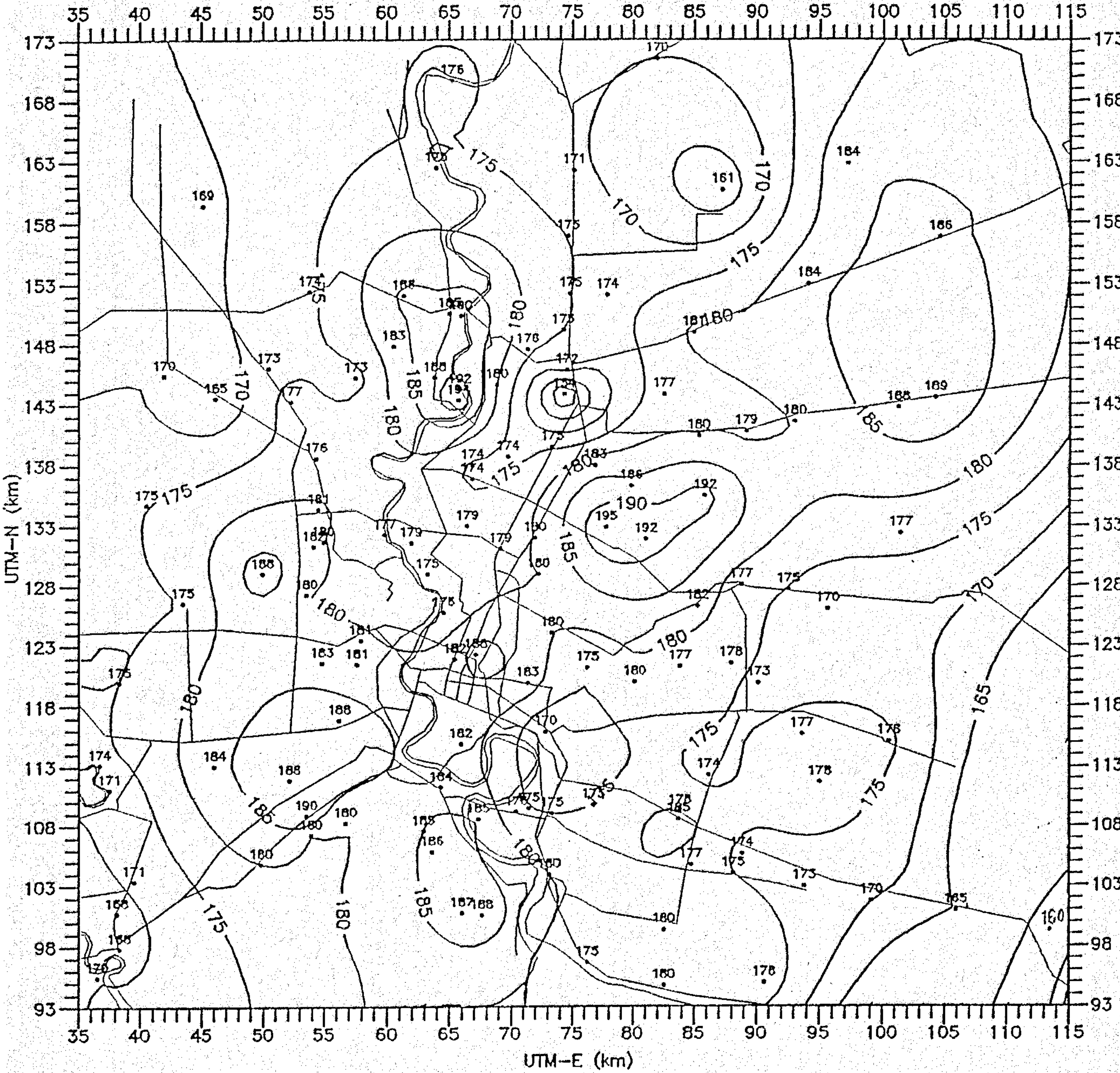
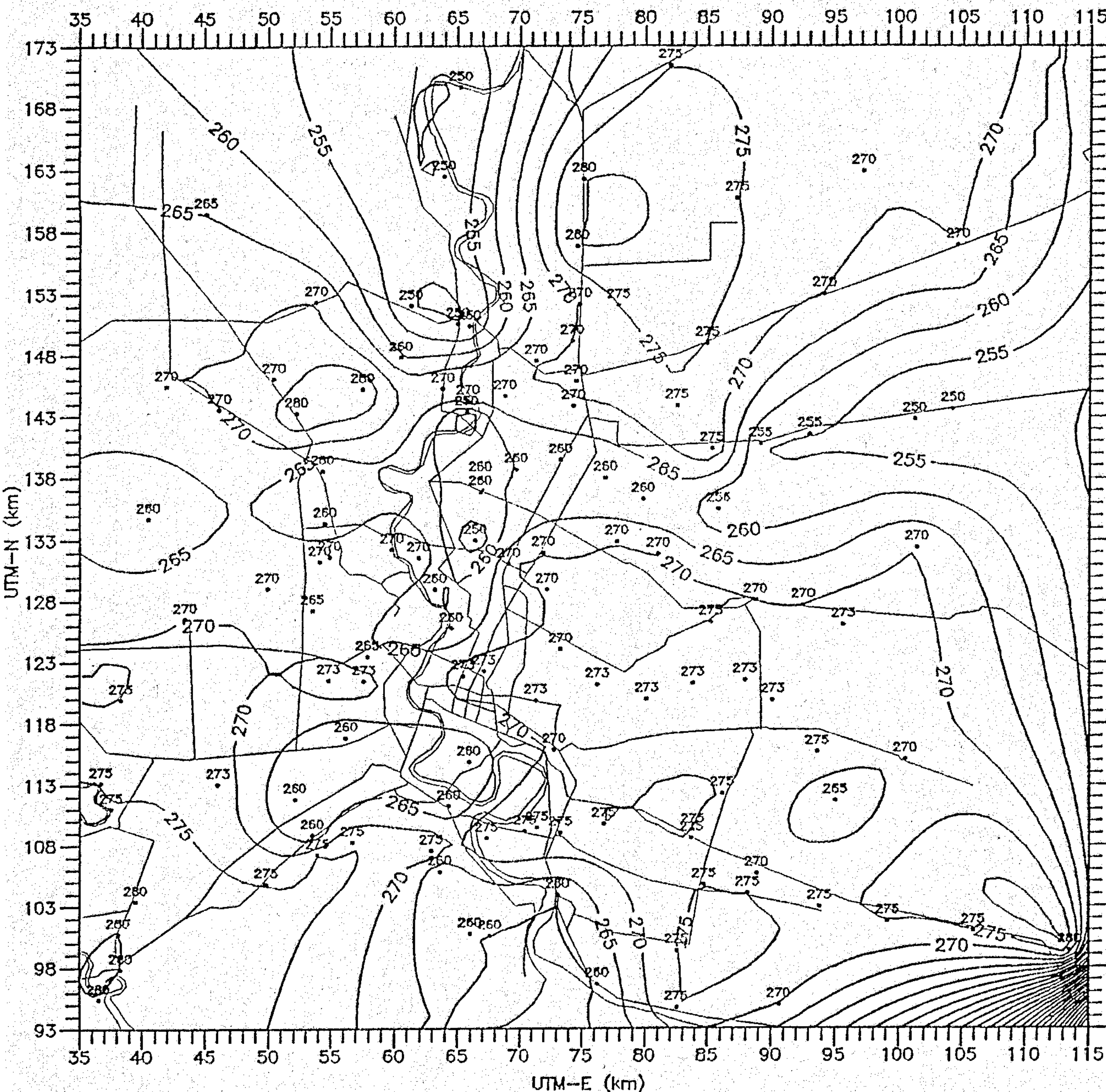


LEGEND

LINE OF EQUAL DEPTH TO AQUIFER BOTTOM (m below ground surface)

120 INVESTIGATED WELL WITH DEPTH TO AQUIFER BOTTOM (m below ground surface)

Figure 3.5.2	DEPTH TO THE BOTTOM OF NAKHON LUANG AQUIFER (NL)
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.



LEGEND

——— LINE OF EQUAL DEPTH TO AQUIFER BOTTOM (m below ground surface)

120 • INVESTIGATED WELL WITH DEPTH TO AQUIFER BOTTOM (m below ground surface)

Figure 3.5.3	DEPTH TO THE BOTTOM OF NONTHABURI AQUIFER (NB)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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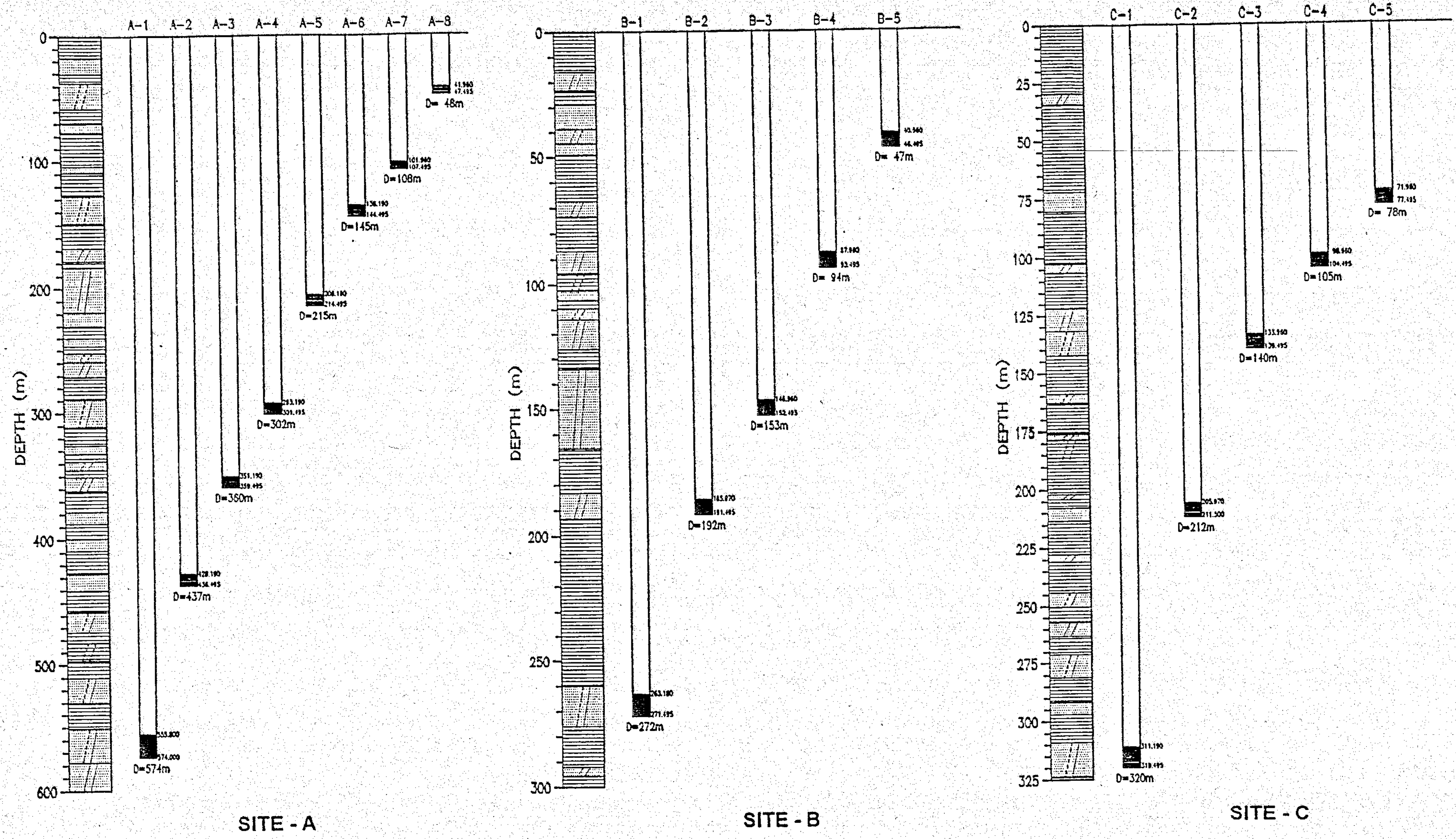

Figure 3.6	**SCHEMATIC DIAGRAM OF MONITORING WELLS**
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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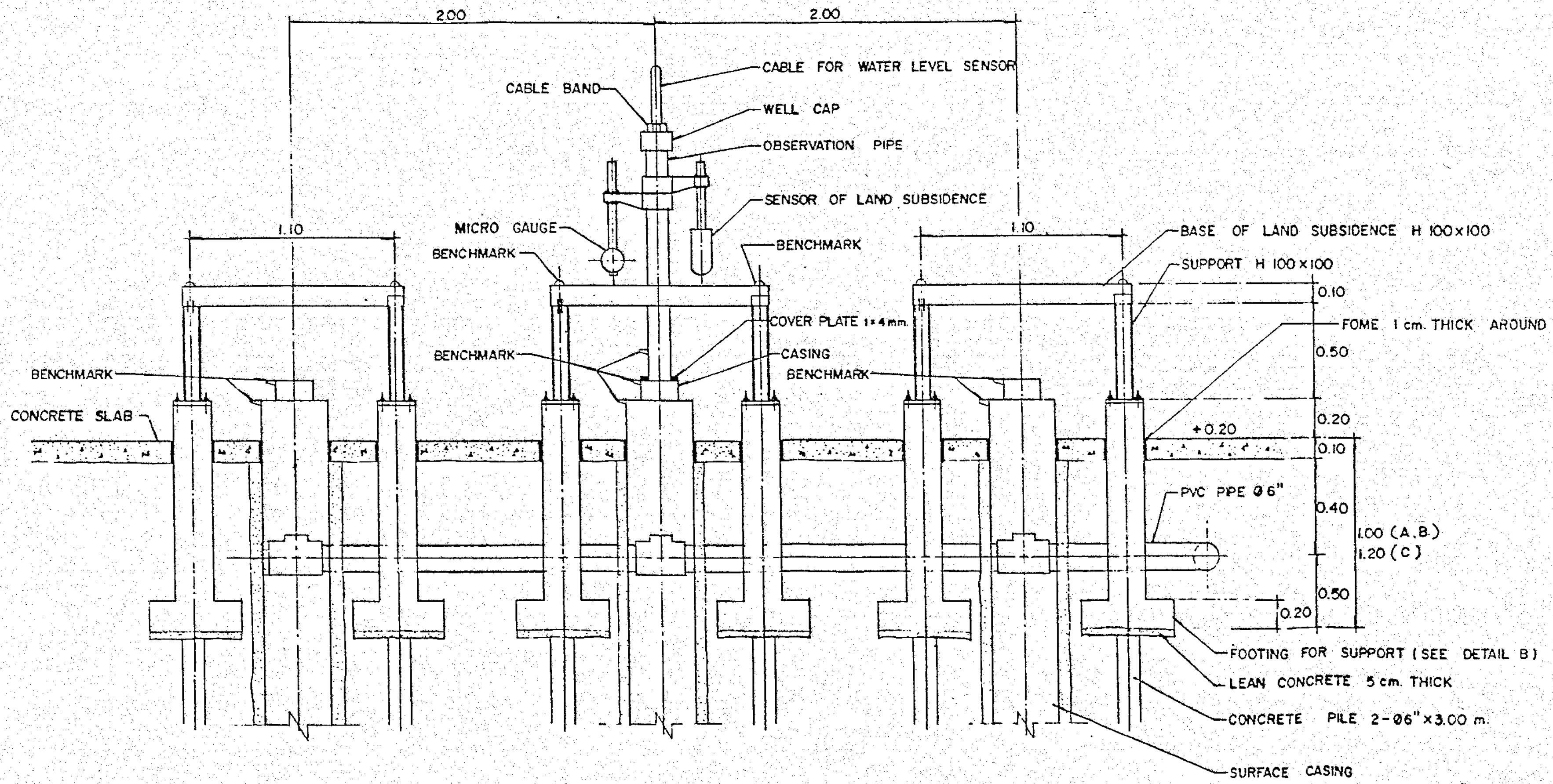
Figure 3.7 SCHEME DRAWING OF THE OBSERVATION UNIT



CHAPTER 4 GROUNDWATER QUALITY

CHAPTER 4 GROUNDWATER QUALITY

4.1 Water Quality of DMR Monitoring Wells

(1) Method of Sampling

A total of 237 groundwater samples from the DMR monitoring wells and 16 samples from production wells were collected and analyzed in the laboratory. The submersible pump was used to remove stagnant water from the well so as to collect reliable samples. Pumping was done for at least one (1) hour. Water level, discharge rate, electric conductivity, pH, and temperature were measured at an interval of 10 minutes during pumping.

(2) Distribution of Water Quality

DMR monitoring wells tapped three (3) major aquifers, i.e, Phra Pradaeng (PD), Nakhon Luang (NL) and Nonthaburi (NB) Aquifers. Groundwater of these aquifers were interpreted from the geochemical point of view.

Trilinear Diagram Analysis

The results of analysis were plotted on the trilinear diagram. The central diamond-shape area of the diagram was divided into 5 domains.

Domain I	$Ca(HCO_3)_2$ type
Domain II	$NaHCO_3$ type
Domain III	$CaSO_4$ or $CaCl_2$ type
Domain IV	Na_2SO_4 or NaCl type
Domain V	the middle

Groundwater chemically evolved along the path from domain III(V) to domain I, and from domain I to II(V). Most of PD Aquifer samples were plotted on domain III, IV and V. A few samples were plotted on domain I and II. NL Aquifer samples were also located in domain III, IV and V. More NL Aquifer samples were plotted on domain I and II than PD Aquifer samples. NL Aquifer samples were divided into two (2) groups: one at domain III and IV and the other at domain II and V. Fresh water was generally represented on domain I,II and V. Groundwater at domain IV was affected by sea water or fossil water (Figures 4.1.1 to 4.1.3).

Pattern Diagram Analysis

PD Aquifer samples were classified into two (2) groups: one was characterized by dominance of (Na+K) and the other was characterized by almost the same contents of (Na+K) and (Ca). The former group is in Samut Prakan and western Bangkok, while the latter group is distributed in northern Bangkok, Pathum Thani, and Nonthaburi.

NL Aquifer samples taken from the coastal area had high content of chloride and (Na+K) which could have originated from sea water. Samples taken from the inland area had higher content of calcium as well as (Na+K) in cations. This may indicate that the source of saline water in the inland area may be different from that in the coastal area.

NB Aquifer samples taken from the southern part of the Study Area were rich in chloride and (Na+K), similar to the water quality of NL Aquifer. The cause of salinity of the NB Aquifer may be the same as that of the NL Aquifer (Figures 4.2.1 to 4.2.3).

4.2 Water Quality of JICA Monitoring Wells

The results of analysis of groundwater collected from the 18 monitoring wells are summarized in Figure 4.3 and Table 4.1. BK Aquifer samples were plotted on domain IV or III because of high chloride concentration. Groundwater of PD and NB Aquifers were plotted on domain IV at Site A (Lat Krabang) and Site B (AIT), however, in Site C (Samut Sakhon), PD and NB groundwater not affected by salinity yet were plotted at domain V and I, respectively.

NL groundwater which was affected by salinity was plotted on domain IV at Site C (Samut Sakhon). At Site A (Lat Krabang) and B (AIT), it was plotted on domain IV to V and was not affected by salinity yet.

Groundwater of deep SK, PT and PN Aquifers at Site A (Lat Krabang) was moved to domain IV. At Site C (Samut Sakhon), it was still on domain I indicating fresh water.

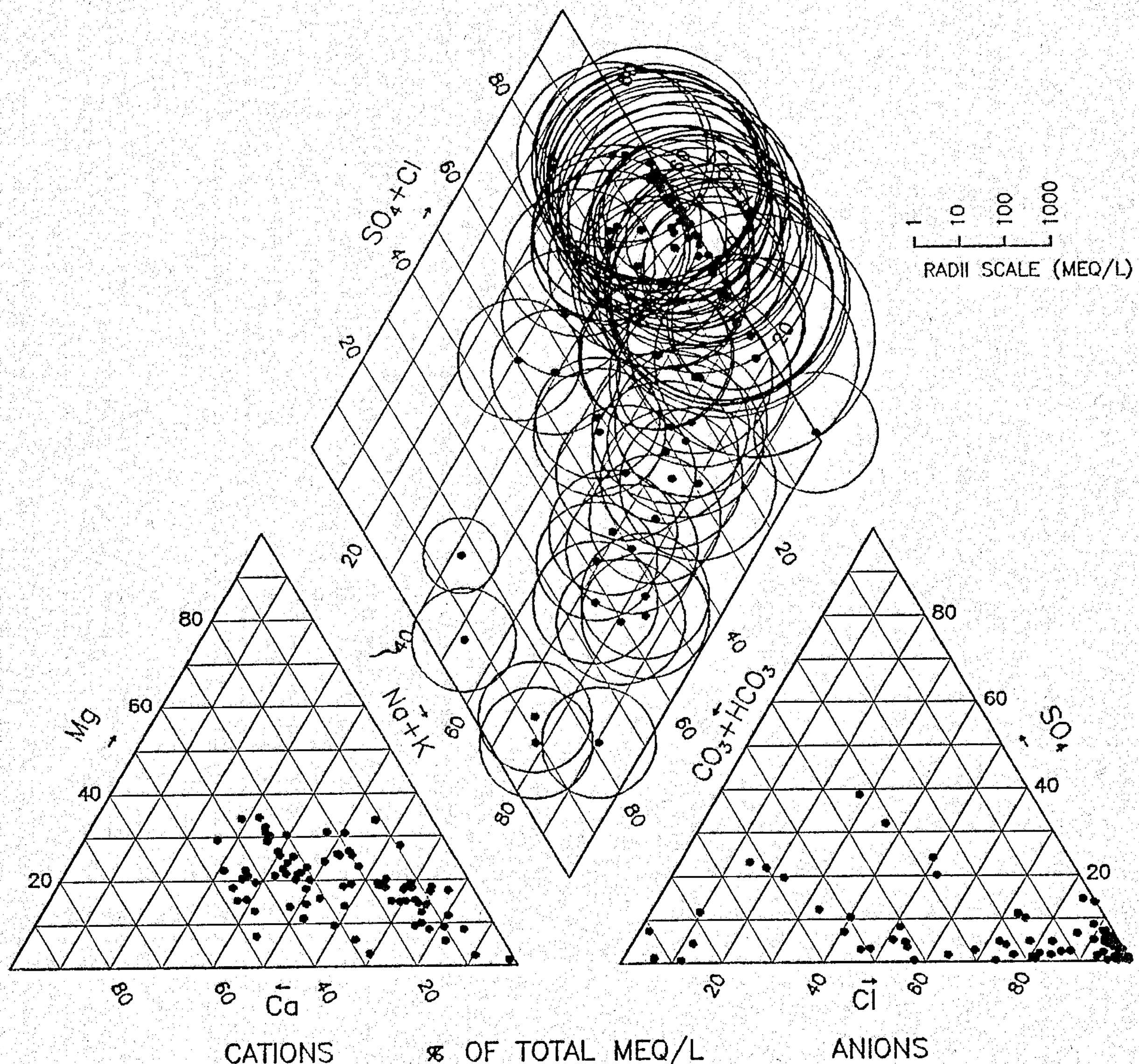
4.3 Salinity of Groundwater

In PD Aquifer, the area of high chloride concentration spread over the entire Study Area except the eastern part. On the other hand, in NL Aquifer, the area of concentration laid along the coast from Samut Sakhon to Samut Prakan and right bank of the Chao Phraya River. NB Aquifer showed more than 5,000 mg/l of chloride concentration in the areas at the mouth of the Chao Phraya River, Samut Sakhon, Samut Prakan and Pathum Thani (Figures 4.4.1 to 4.4.3).

Spatial distribution of chloride concentration suggested that the salinity of groundwater was brought about by downward leakage of fossil water from shallow BK Aquifer to deep aquifers. Leakage occurred due to depletion of the deep aquifer's artesian head which was heavily pumped. Aquifers deeper than PD Aquifer are possible to crop out at the bottom of the Gulf of Thailand. However, they may crop out several hundred kilometers far from the mouth of the Chao Phraya River. In addition, aquifers are overlain by Bangkok Clay in the coastal area. This indicates low possibility of direct sea water intrusion.

Table 4.1 CHEMICAL ANALYSES OF GROUNDWATER FROM MONITORING WELLS

Well No.	A-1	A-2	A-3	A-4	A-5	A-6	A-7	A-8	B-1	B-2	B-2	B-3	B-4	B-5	C-1	C-1	C-2	C-3	C-4	C-5
Well Depth (m)	574	437	215	302	215	145	108	48	272	192	192	153	94	47	320	320	212	140	105	78
Sampling Date	20-Jul-93	27-May-93	23-May-93	29-May-93	07-Jun-93	05-Jun-93	09-Jun-93	02-Jun-93	22-Feb-93	23-Mar-93	08-May-93	23-Apr-93	29-Apr-93	29-Apr-93	15-Mar-93	08-May-93	29-Jun-93	20-Jun-93	18-Jun-93	23-Jun-93
pH	9.04	8.45	8.13	7.96	8.57	7.65	7.55	5.67	7.88	7.71	7.60	7.64	7.59	6.35	7.50	7.34	7.45	7.89	7.89	7.48
Temperature (deg.C)		39.0	28.0	36.0	30.6	26.7	27.6	30.0	39.0	35.0	34.4	33.3	33.3	31.7	40.0	40.5	37.7	37.8	30.8	29.1
Electric Conductivity (us/cm)	1160	1540	975	1500	1180	749	1860	28400	981	865	858	783	1450	21900	477	486	560	1570	767	3000
Calcium Ion (ppm)	4.20	5.15	6.34	1.50	15.92	55.40	99.80	1519.70	24.13	27.13	26.10	30.50	71.20	76.50	40.21	45.00	39.60	21.70	11.70	41.30
Magnesium Ion (ppm)	0.79	0.27	0.31	0.03	3.10	6.78	24.21	39.75	4.43	5.49	6.06	21.38	15.06	122.60	14.18	15.19	3.85	51.49	22.00	131.45
Sodium Ion (ppm)	22.10	552.98	134.77	177.19	414.80	323.94	202.22	1910.40	46.40	303.14	110.63	95.22	212.73	329.70	29.44	37.57	50.63	180.58	190.16	236.70
Potassium Ion (ppm)	4.13	1.89	1.32	1.67	2.36	2.00	3.16	40.76	2.77	2.08	1.86	1.47	2.41	45.19	17.69	7.03	4.87	6.75	6.64	9.93
Manganese Ion (ppm)	0.17	ND	ND	0.16	0.17	0.06	0.45	198.73	0.02	<0.02	0.06	0.06	0.35	1.22	<0.02	0.06	0.07	ND	<0.02	0.67
Ammonium Ion (pmm)	0.56	ND	ND	ND	ND	ND	ND	1.74	ND	ND	0.25	0.17	0.17	1.54	ND	0.08	0.22	ND	ND	0.22
Bicarbonate Ion (ppm)	31.70	212.30	222.00	119.60	100.00	209.80	173.20	28.10	90.30	179.30	201.30	206.20	195.40	242.20	146.40	151.28	168.40	153.70	205.00	174.50
Sulfate Ion (ppm)	69.60	326.00	34.50	69.30	85.10	35.60	161.00	403.00	36.05	70.70	60.14	46.21	162.30	1923.00	7.24	6.33	16.00	34.30	61.40	17.34
Iron Ion (ppm)	1.64	0.12	0.16	0.17	1.60	0.13	0.10	2.23	0.02	<0.02	0.17	0.07	0.13	6.60	ND	0.07	0.01	0.10	0.21	0.43
Chloride Ion (ppm)	193.0	47.5	69.5	263.7	205.5	40.1	332.7	9686.4	203.0	80.7	78.3	34.2	210.4	7631.7	10.8	7.6	11.5	347.3	14.4	792.5
Bromide Ion (ppm)	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	1.09	1.10	1.60	1.20	1.80	0.60	<0.3	1.60	1.30	<0.3	ND	ND	0.09
Iodide Ion (ppm)	0.17	0.58	0.17	0.46	0.39	<0.1	ND	0.14	<0.2	<0.2	<0.2	<0.2	0.20	0.50	<0.2	<0.2	0.10	1.35	0.26	0.06
Nitrate Ion (ppm)	12.00	0.15	1.70	2.41	0.88	1.41	0.10	14.78	<1	<1	2.74	2.83	ND	7.73	<1	1.97	0.92	0.85	0.82	ND
Nitrite Ion (ppm)	40.80	5.30	NIL	NIL	10.40	NIL	NIL	20.80	<6	<6	8.90	11.80	20.80	26.10	ND	<6	10.20	11.90	8.90	11.90

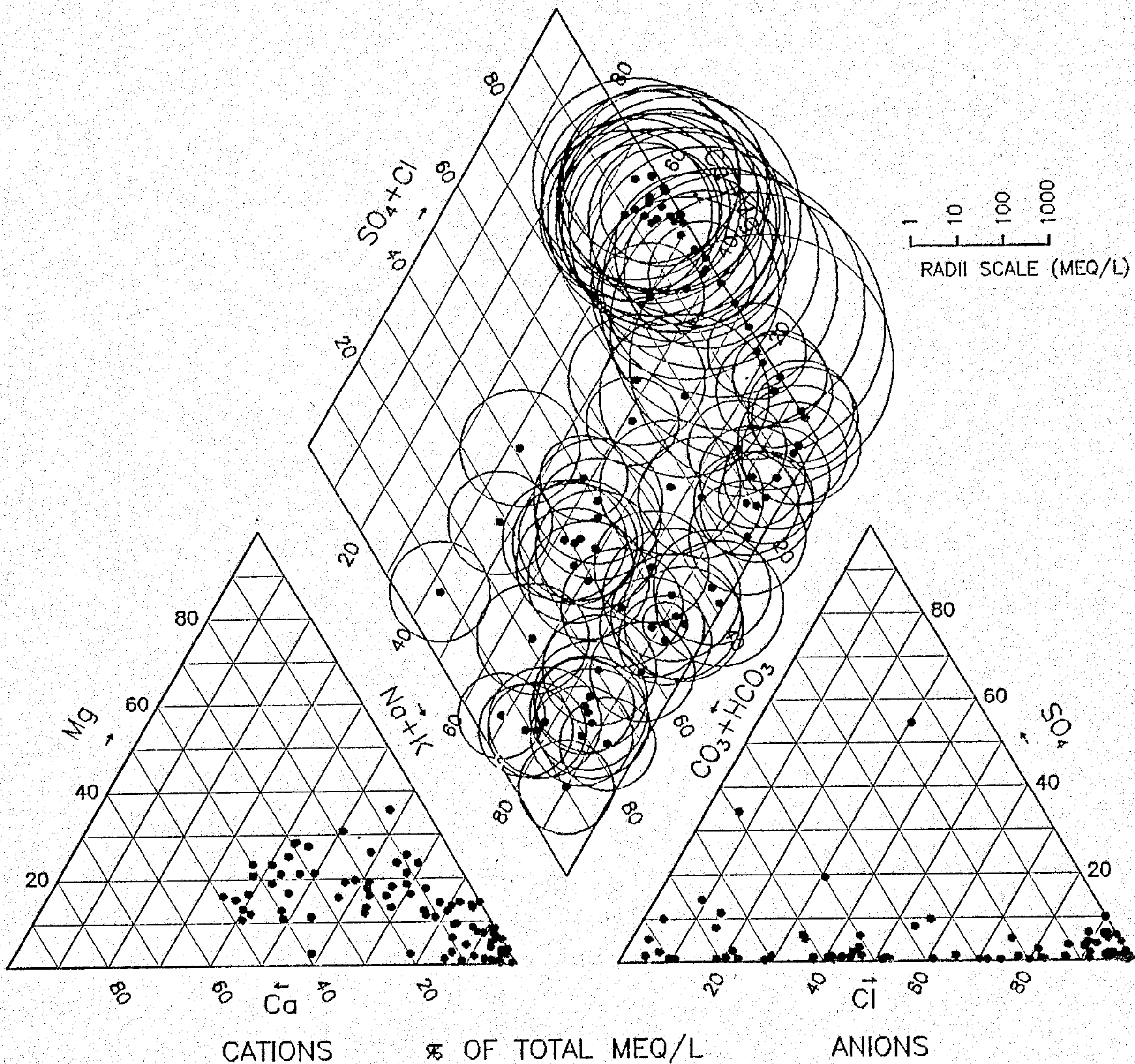


(Water samples were collected by the Study Team in 1993.)

Figure 4.1.1	TRILINEAR DIAGRAM OF PHRA PRADAENG AQUIFER

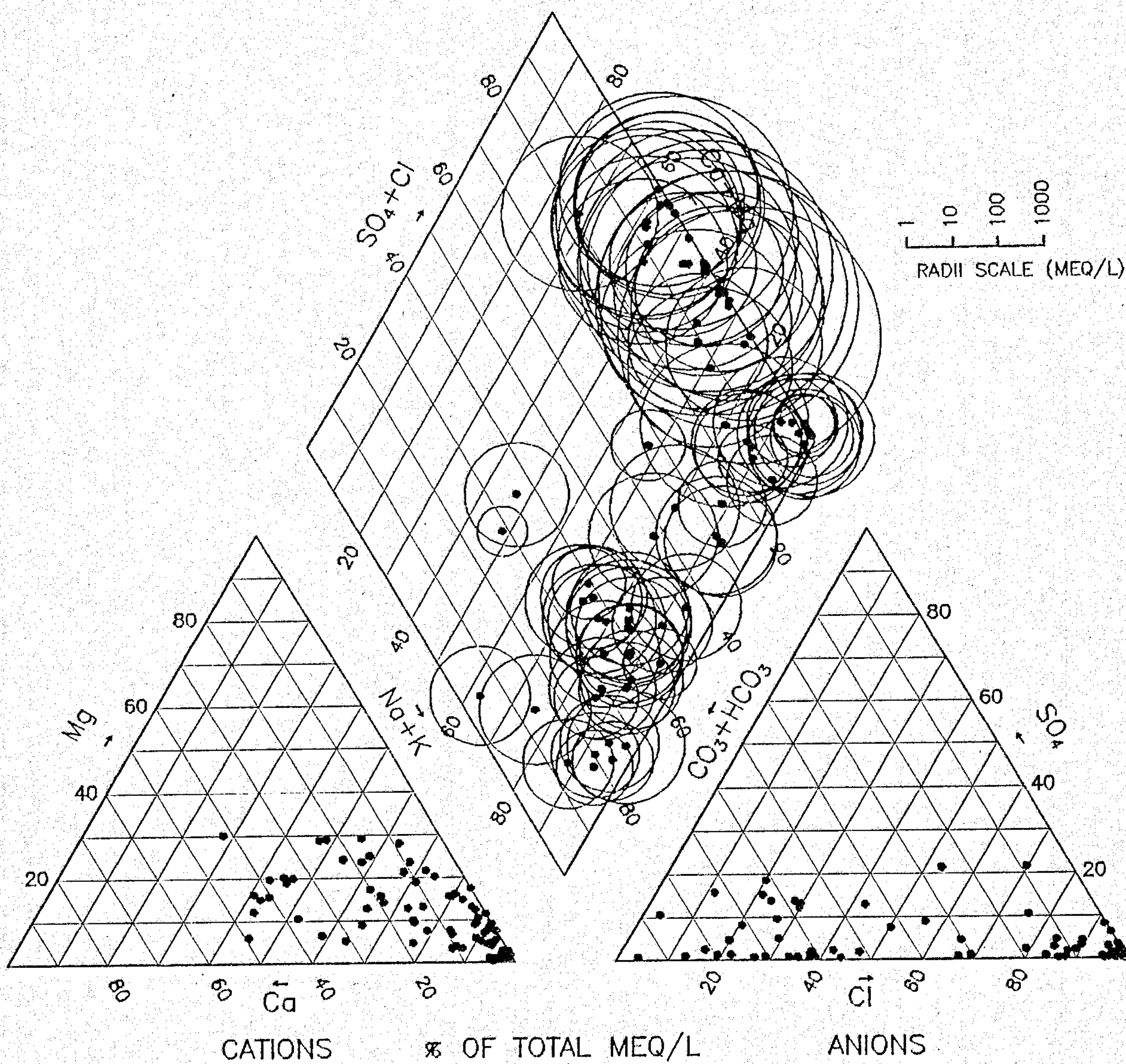
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA) | KOKUSAI KOGYO CO., LTD.



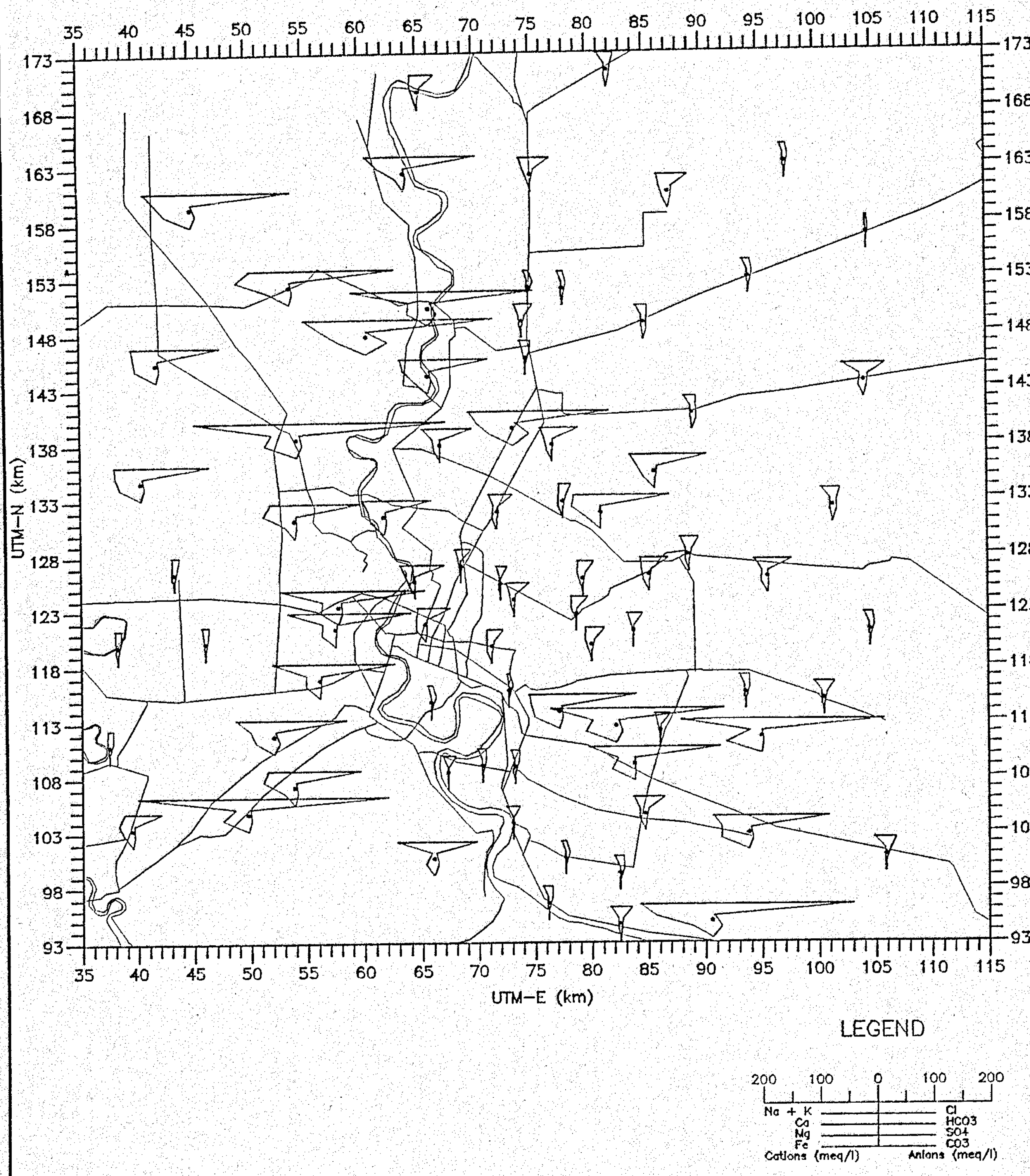
(Water samples were collected by the Study Team in 1993.)

Figure 4.1.2	TRILINEAR DIAGRAM OF NAKHON LUANG AQUIFER
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.



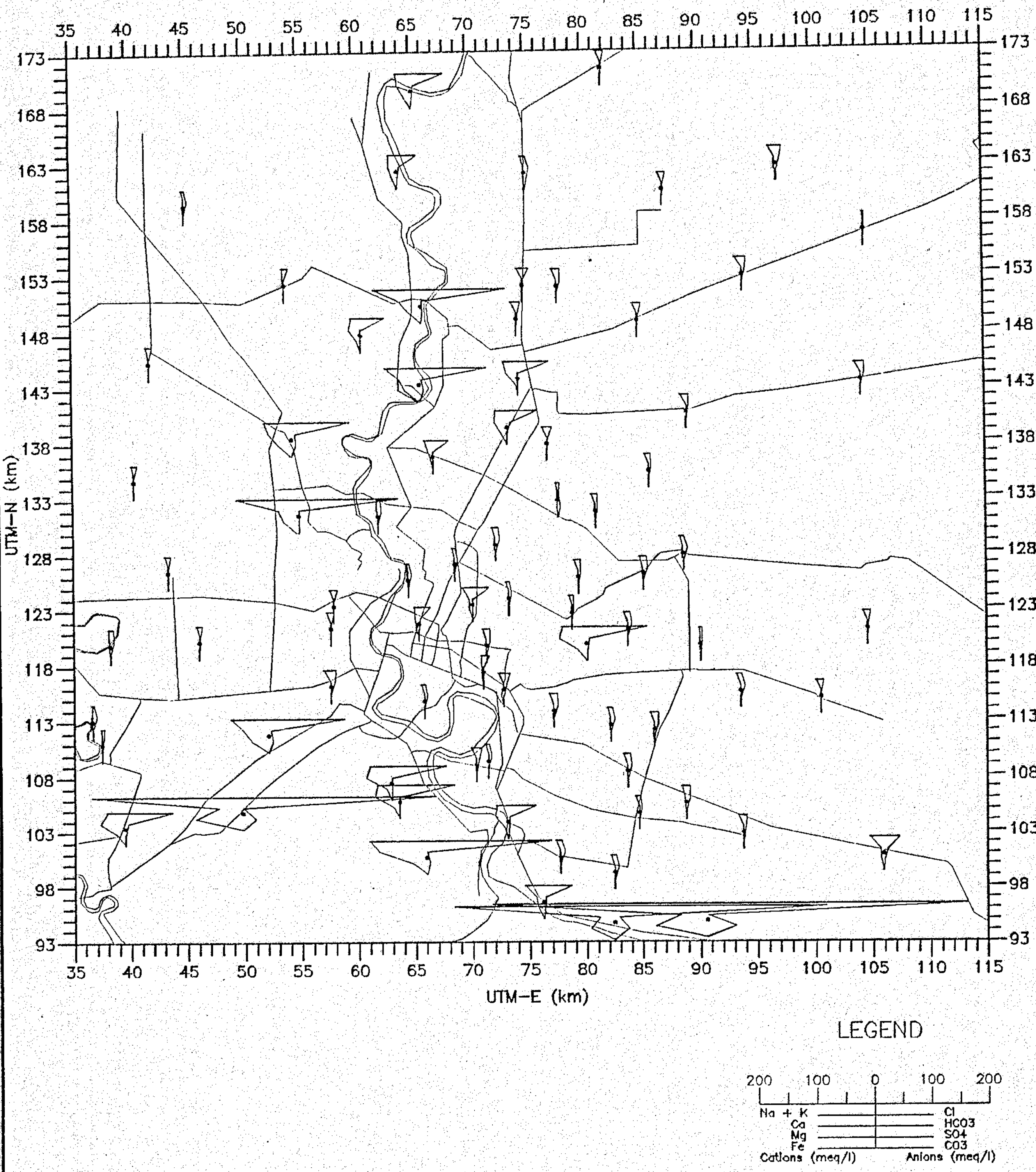
(Water samples were collected by the Study Team in 1993.)

Figure 4.1.3	TRILINEAR DIAGRAM OF NONTHABURI AQUIFER
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.



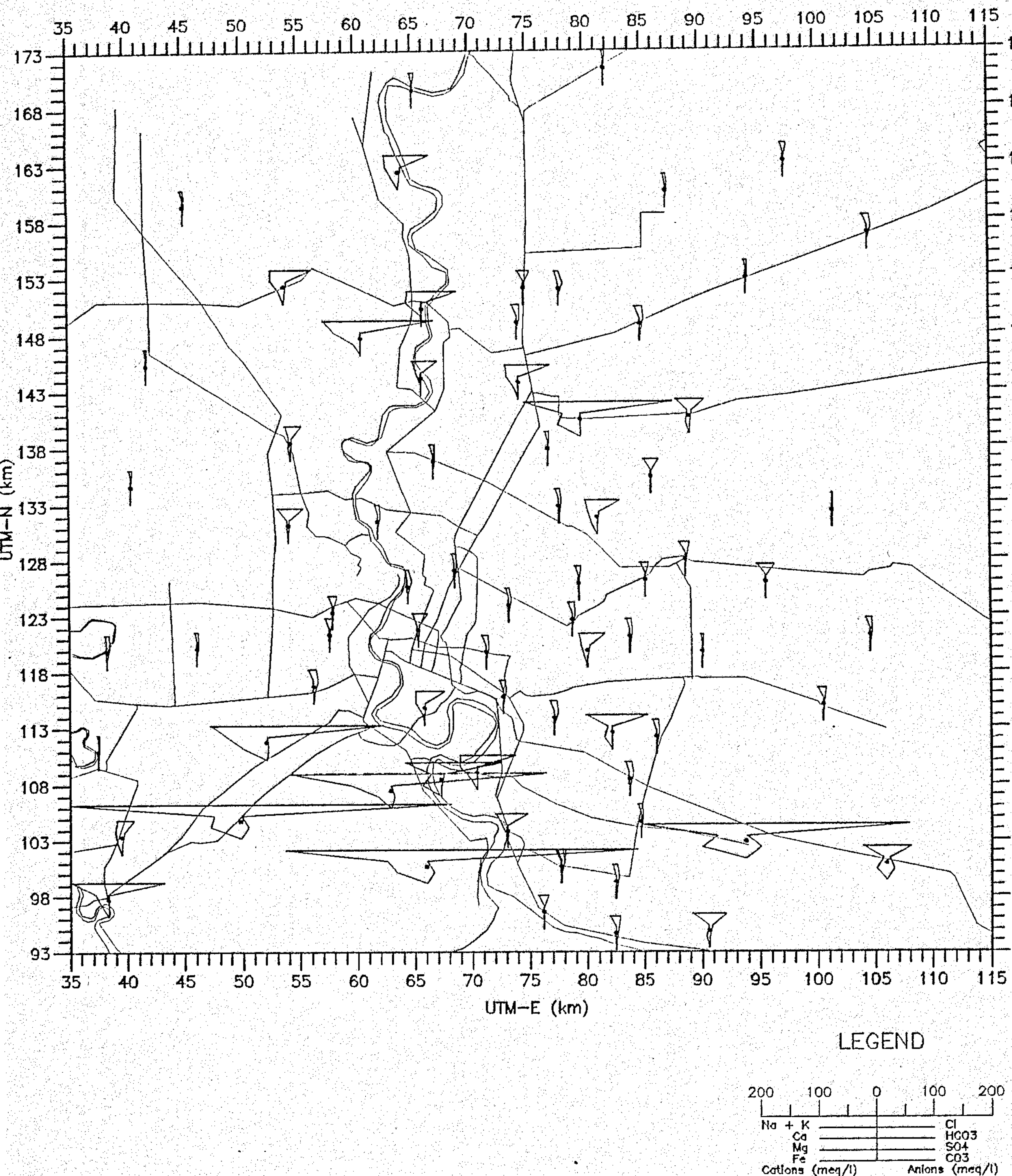
(Water samples were collected by the Study Team in 1993.)

Figure 4.2.1	STIFF DIAGRAMS OF PHRA PRADAENG AQUIFER
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.



(Water samples were collected by the Study Team in 1993.)

Figure 4.2.2	STIFF DIAGRAMS OF NAKHON LUANG AQUIFER
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.

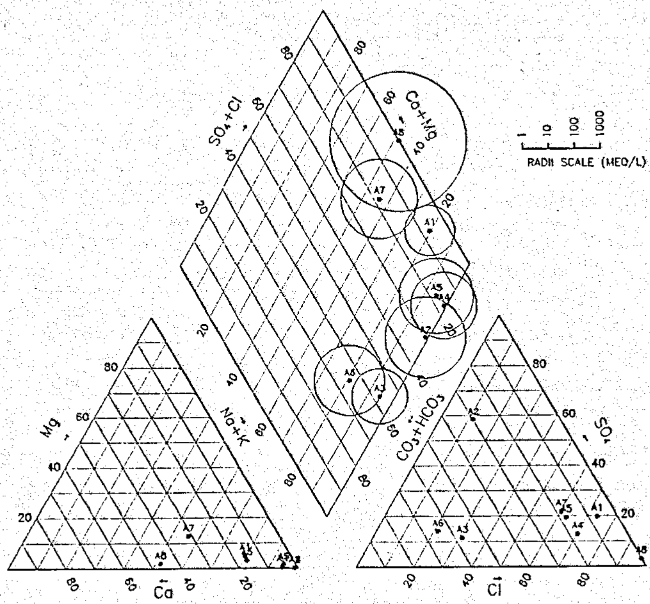


(Water samples were collected by the Study Team in 1993.)

Figure 4.2.3	STIFF DIAGRAMS OF NONTHABURI AQUIFER

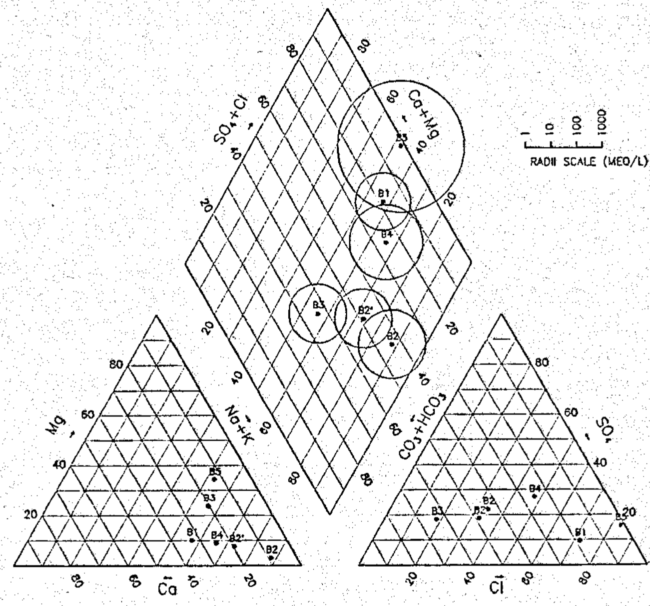
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY

JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



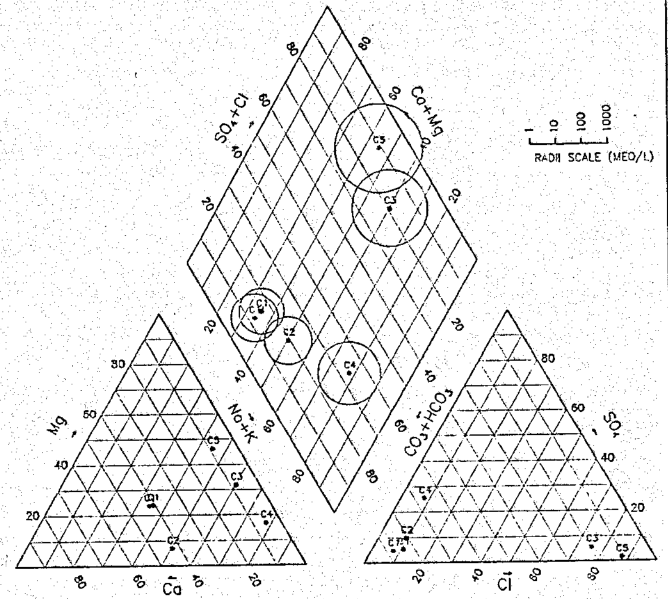
Label	Well No.	Well Depth (m)	Aquifer	Sampling Date
A1	A-1	574	PK	20-07-1993
A2	A-2	437	PT	27-05-1993
A3	A-3	360	SK	23-05-1993
A4	A-4	302	SK	29-05-1993
A5	A-5	215	NB	07-06-1993
A6	A-6	145	NL	05-06-1993
A7	A-7	108	PD	09-06-1993
A8	A-8	48	BK	02-06-1993

SITE - A



Label	Well No.	Well Depth (m)	Aquifer	Sampling Date
B1	B-1	272	NB	22-02-1993
B2	B-2	192	NL	23-03-1993
B2'	B-2	192	NL	08-05-1993
B3	B-3	153	NL	23-04-1993
B4	B-4	94	PD	29-04-1993
B5	B-5	47	BK	29-04-1993

SITE - B



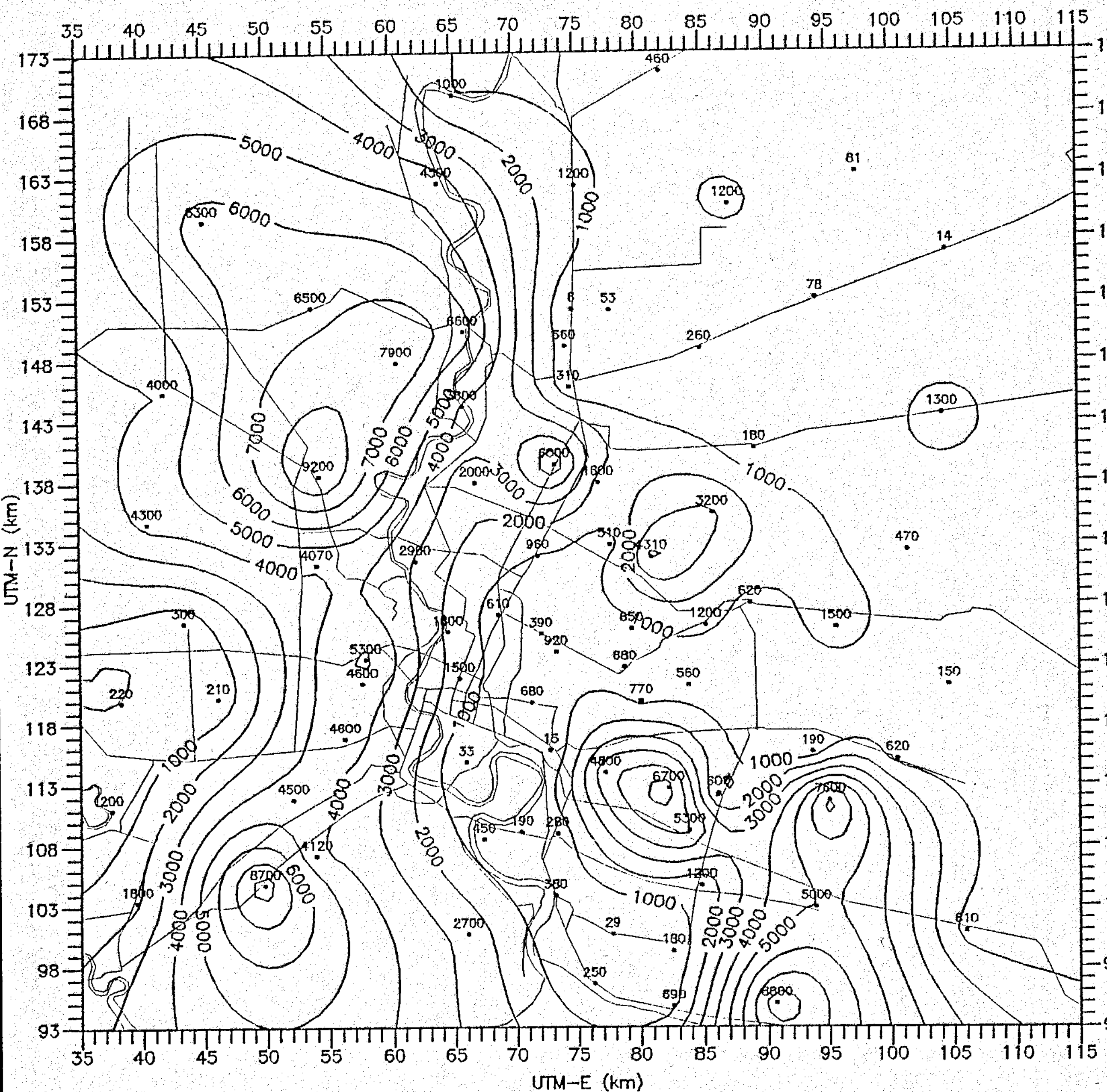
Label	Well No.	Well Depth (m)	Aquifer	Sampling Date
C1	C-1	320	SK	15-03-1993
C1'	C-1	320	SK	08-05-1993
C2	C-2	212	NB	29-06-1993
C3	C-3	140	NL	20-06-1993
C4	C-4	105	PD	18-06-1993
C5	C-5	78	PD	23-06-1993

SITE - C

Figure 4.3 TRILINEAR DIAGRAMS OF GROUNDWATER AT SITES - A, B & C

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.



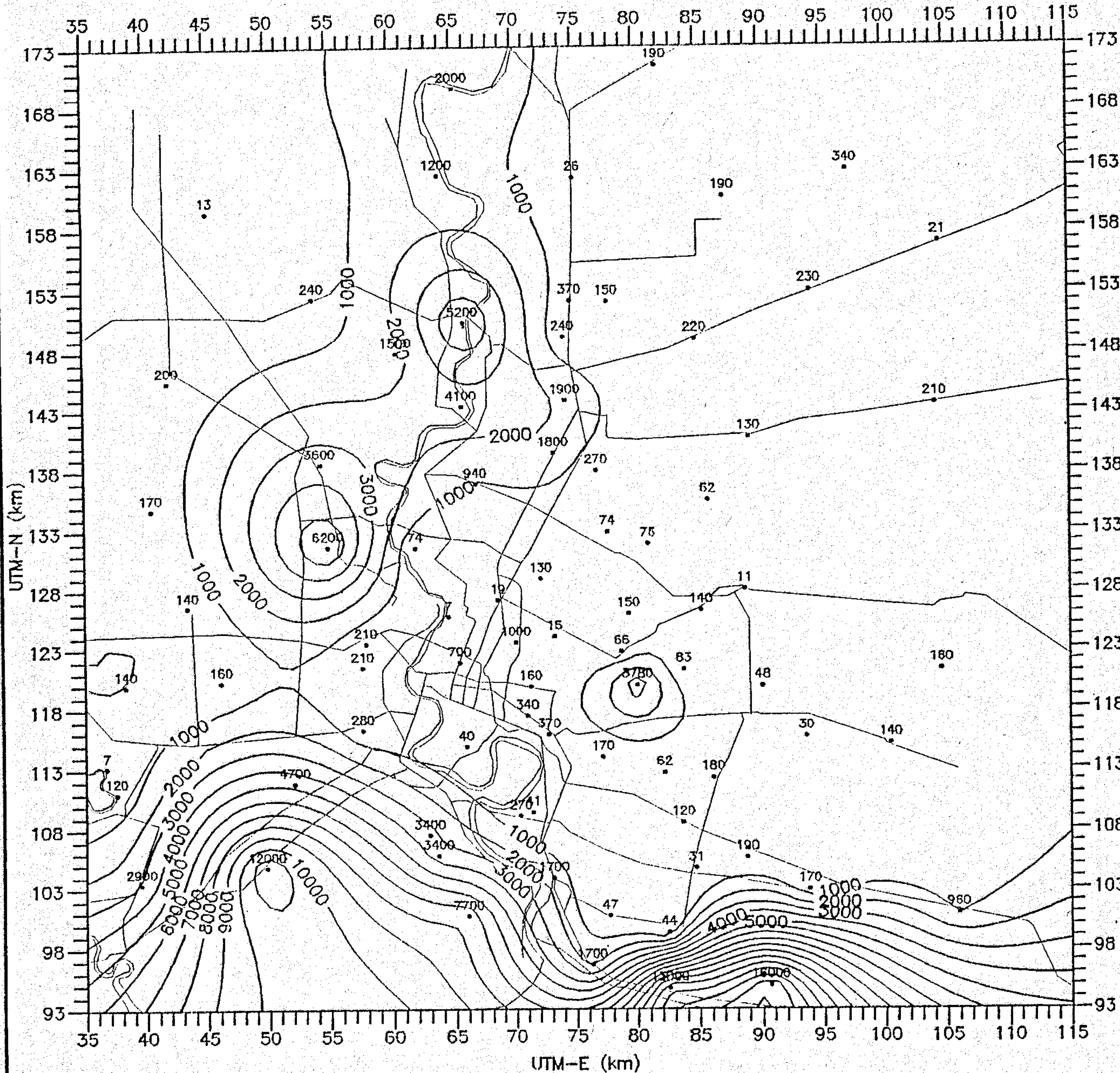
LEGEND

LINE OF EQUAL Cl^- CONCENTRATION (mg/L)

1500 DMR MONITORING WELL WITH Cl^- CONCENTRATION (mg/L)

(Water samples were collected by the Study Team in 1993.)

Figure 4.4.1	**CHLORIDE CONCENTRATION OF PHRA PRADAENG AQUIFER**
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.



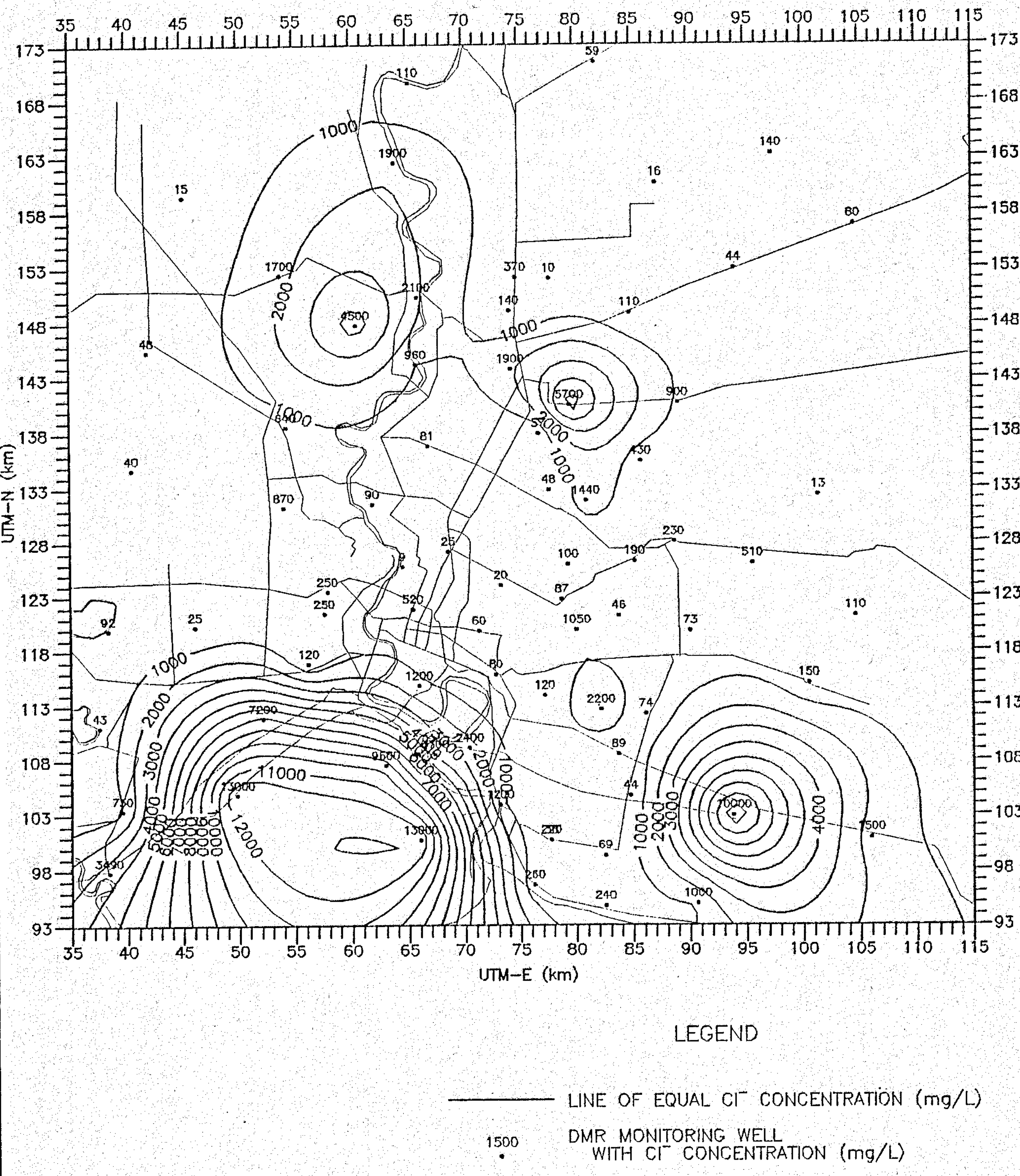
LEGEND

LINE OF EQUAL Cl^- CONCENTRATION (mg/L)

1500 DMR MONITORING WELL WITH Cl^- CONCENTRATION (mg/L)

(Water samples were collected by the Study Team in 1993.)

Figure 4.4.2	CHLORIDE CONCENTRATION OF NAKHON LUANG AQUIFER
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.



(Water samples were collected by the Study Team in 1993.)

Figure 4.4.3	**CHLORIDE CONCENTRATION OF NONTHABURI AQUIFER**
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 5 GROUNDWATER PUMPAGE

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5.1 Background

This chapter presents the results of the estimations of year-1992 groundwater abstractions and historical groundwater pumpage records (1983-1992) based on the compilation of well inventories of both private and public wells in the Bangkok Metropolitan Area and its vicinity.

Private wells are those wells registered at DMR for water rights, while **public wells** are those wells constructed or managed (or both) by DMR, PWD, MWA, PWA, DOH, ARD and IEAT. Meanwhile, the **Whole Area** shall include wholly the eight provinces containing the 11,222 private wells and 2,475 public wells. Inside the Whole Area is the **Study Area** which covers wholly Bangkok, Nonthaburi, Pathum Thani, and Samut Prakan and partly Samut Sakhon, Ayutthaya, Nakhon Pathum and Chachoengsao, i.e., between 35°E and 115°E and between 93°N and 173°N, and locates the 10,772 private wells and 884 public wells.

5.2 Well Inventory

The groundwater pumpage estimations basically relied on the Groundwater Database System prepared by the Study Team, specifically on the system's well inventory database which stores all the different well inventories collected from the said agencies during the Study. These well inventories contain 11,222 private wells, 2,475 public wells and 258 groundwater observation wells for a total of 13,955 wells as of 1992, encompassing active, inactive and abandoned wells.

As shown in Figure 5.2.1, of the 11,222 inventoried private wells, more than 75% of the private wells are located in Bangkok (4,853 wells) and Samut Prakan (3,669 wells), and more than 45% (5,140 wells), 37% (4,189 wells) and 14% (1,667 wells) are tapping Nakhon Luang, Phra Pradaeng and Nonthaburi Aquifers, respectively. Nakhon Luang Aquifer is giving out groundwater to 52.5% of the wells in Bangkok, 57.2% of the wells in Pathum Thani, 52.9% of the wells in Samut Sakhon and 72.4% of the wells in Ayutthaya. In Samut Prakan, 62.2% of the wells are tapping Phra Pradaeng Aquifer. More than 72.4% of the wells in Nonthaburi province are withdrawing from a deeper aquifer, Nonthaburi.

Around 45.3% (5,088 wells) of the 11,222 private wells are for domestic consumption. The distributions of the rest consist of 4.2% (478 wells) for institutional use; 10.6% (1,186 wells) for commercial use; and 39.8% (4,470 wells) for industrial use. Around 47% of the 5,088 domestic wells are abstracting from Nakhon Luang Aquifer, and 39.3% from Phra Pradaeng Aquifer. The largest number of industrial wells, 1,129, are pumping from Phra Pradaeng Aquifer in Samut Prakan. The second largest number (645 wells), which is also situated in Samut Prakan, is withdrawing groundwater from Nakhon Luang Aquifer.

As shown in Figure 5.2.2, of the 2,475 public wells, 1,019 (41.2%) were constructed by DMR, 932 (37.7%) by PWD, 157 (6.3%) by MWA, 111 (4.5%) by PWA, 83 (3.4%) by DOH, 93 (3.7%) by ARD, and 80 (3.2%) by IEAT. Wells constructed or managed (or both) by DMR, PWD, PWA, DOH, and ARD are specifically for domestic use. MWA well productions are largely for domestic consumption, while IEAT wells are utilized for industries.

More than 6.6% (163) of the 2,475 public wells are located in Bangkok, 3.2% (79) in Nonthaburi, 8% (198) in Pathum Thani, 7.1% (175) in Samut Prakan, 12.2% (303) in Samut

Sakhon, 34.3% (847) in Ayutthaya, 14.3% (355) in Nakhon Pathum and 14.3% (355) in Chachoengsao. There are 1,110 (44.8%) pumping out from Nakhon Luang Aquifer, 602 (24.3%) from Phra Pradaeng Aquifer, and 534 (21.6%) from Nonthaburi Aquifer.

Of the 11,222 private wells gathered from the DMR's Groundwater Division, 10,772 are located in the Study Area. More than 60.6% of the 884 inventoried public wells in the Study Area are located in Bangkok, Pathum Thani and Samut Prakan, and more than 46.4% were constructed by PWD. The combined total of the inventoried number of private and public production wells in the Study Area is 11,656. Of this total, public wells represent only 7.6%.

On the other hand, the number of private wells with active water permits was estimated at 4,141 for the year-1992 based on the years of the issuance, expiration and extension of water permits. Of this total, 4,132 wells are located in the Study Area.

5.3 Historical Groundwater Pumpage Estimations

The 1983-1992 historical groundwater pumpage records were estimated to provide basic data for groundwater simulation studies, i.e. for the calibration and verification of groundwater model, and also for generation of future pumpage scenarios.

Two (2) cases of historical daily groundwater pumpage estimates were considered for private wells:

Case 1: Assumes that all private wells with permits that have expired and have not been extended shall become inactive or abandoned. daily pumpage Estimates are based on the years of issuance, expiration and extension of water rights and the volume permitted stipulated in the water rights multiplied by the GPC. This GPC is the average ratio of the actual pumpage to the volume permitted.

Case 2: Considers that well owners shall continue using groundwater even after the expiration of their water rights for there is still an inadequate supply of surface water. Estimates are based on either the year of issuance of water permit or the year of completion of well construction and the volume permitted multiplied by the GPC.

For public wells, monthly discharge records stored in the well inventory database were used for the computation of historical groundwater pumpage. In the absence of actual pumpage records, historical daily pumpage was estimated using the well yield data obtained during pumping test, the number of hours of operation per day, and the year the well was constructed.

The results of estimations are as follows.

Private Wells *Case 1*: The year-to-year pattern of groundwater withdrawals for the Study Area is similar to that for the Whole Area, as shown in Figure 5.3.1. The groundwater withdrawals for the Whole Area increased steadily from 640,375 CMD (630,619 CMD for the Study Area) in 1980, peaked to 838,610 CMD (821,952 CMD) in 1988, started declining in 1989, and decreased abruptly between 1989 and 1990 by 22.1% (23.4% for the Study Area) mainly due to the supposed abandonment of wells with expired water permits. By the year-1992, the groundwater pumpage was estimated at 645,053 CMD for the Whole Area and 603,588 CMD for the Study Area.

Private Wells *Case 2*: The historical records of groundwater pumpage as calculated using *Case 2* for both Whole Area and Study Area had patterns similar to the one shown in Figure 5.3.2. The rate of increase in the total groundwater withdrawal is higher after 1987 (about 7.5%) than before 1987 (about 5%). This phenomenon after 1987 can be attributed to the fact that Thailand experienced an unexpected high economic growth.

The total groundwater withdrawals for the Whole Area increased from 640,375 CMD in 1983 to 1,171,321 CMD in 1992. In the Study Area, the total use of groundwater had increased 177.8% (or by 490,685 CMD) from 630,620 CMD to 1,121,305 CMD for the same period.

In Table 5.3.1, these statistics have shown that groundwater withdrawal is continuously increasing as assumed in *Case 2*. Since it was also in good agreement with the results of the groundwater simulation studies, *Case 2* therefore was considered as the most probable historical pattern of groundwater withdrawal in the Study Area.

Public Wells: For both the Whole Area and Study Area, the groundwater pumpage estimates for DMR, PWD, PWA, IEAT, DOH, and ARD showed a year-to-year increasing pattern, while MWA showed a historical decreasing trend. This is shown in Figure 5.3.3. Combined withdrawals of all public wells reflected the historical trend of that of MWA because its withdrawals as compared with those of other agencies were much larger. The historical decline of MWA pumpage was due to the Cabinet Resolution of March 1983 directing MWA to phase out all public wells in the defined Critical Zones 1 and 2 by the end of 1987.

Combined total groundwater pumpage of both private and public wells: The combined total historical groundwater withdrawals of both private and public wells were generated using *Case 2*. They are shown in Table 5.3.2 and Figure 5.3.4.

The historical patterns for the Whole Area and the Study Area showed a drop in groundwater withdrawal between 1985 and 1986 as influenced by the abrupt decline of MWA extraction in the same period for the reason mentioned above.

The total groundwater withdrawals for the Whole Area increased from 1,277,499 CMD in 1983 to 1,799,596 CMD in 1992. In the Study Area, the total use of groundwater had increased 132.6% from 1,117,028 CMD to 1,481,061 CMD for the same period.

5.4 Year-1992 Total Groundwater Pumpage in the Study Area

The combined year-1992 total pumpage of both private and public wells shows the approximate picture of the year-1992 groundwater pumpage in the Study Area.

The year-1992 pumpage level generated by private wells in the Study Area was 1,121,305 CMD as computed using *Case 2* in Table 5.4.1. Figure 5.4.1 shows the distributions of this total pumpage as 23.8% for domestic supplies, 4.3% for institutional uses, 6.9% for commercial purposes and 65% for industries. Around 728,755 CMD, which represented 65% of the total average daily pumpage in the Study Area, were used by industries. Of this amount of pumpage, textile industry got the biggest share at 30.6%, followed by food processing industry with 11.5%. The share of chemical industry amounted to 7% or 50,709 CMD and paper industry shared 5.9% or 42,739 CMD to the total industrial pumpage. On the other hand, the high pumpage shares of Samut Prakan, Bangkok and Pathum Thani could be attributed to the concentration of industries in these areas.

As presented in Table 5.4.1, the year-1992 groundwater production of public wells in the Study Area totaled 359,756 CMD. In Figure 5.4.1, this total was divided into 78.7% for domestic use and 21.3% for industrial use. For domestic use, public wells produced more groundwater than private wells (283,153 CMD against 267,570 CMD). While abstraction for industrial use by public wells represented only 10.5% of the total industrial production of private wells.

Combined total of the estimated groundwater withdrawals of private and public wells in the Study Area amounted to 1,481,061 CMD. Of this total, public wells used 24.3%.

The combined total withdrawals were distributed as: 550,723 CMD for domestic uses; 47,944 CMD for institutional uses; 77,036 CMD for commercial uses; and 805,358 CMD for industrial uses. Combined distributions were 37.2% for domestic supplies, 3.2% for institutional uses, 5.2% for commercial supplies and 54.4% for industries. This is shown in Figure 5.4.1. Figure 5.4.2 plots the spatial distribution of pumpage in the Study Area in year-1992.

Table 5.3.1 GROUNDWATER LEVEL STATISTICS FROM 84 DMR MONITORING STATI

Changwat	Recover* in 1990-91	Decline after 1987	Neither Recover nor Decline* after 1987	Total
Bangkok	14 (41%)	13 (38%)	7 (21%)	34 (100%)
Nonthaburi		5 (100%)		5 (100%)
Pathum Thani		15 (94%)	1 (6%)	16 (100%)
Samut Prakan	1 (5%)	17 (77%)	4 (18%)	22 (100%)
Samut Sakhon		1 (50%)	1 (50%)	2 (100%)
Ayutthaya		3 (100%)		3 (100%)
Nakhon Pathom		2 (100%)		2 (100%)
Total	15 (18%)	56 (67%)	13 (15%)	84 (100%)

*Decline after 1991

Table 5.3.2 COMBINED HISTORICAL PUMPAGE ESTIMATES FOR PRIVATE (USING CASE 2) AND PUBLIC WELLS

Changwat	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Bangkok	595,922	566,283	540,192	491,247	504,187	483,409	439,486	409,567	435,201	458,729
Nonthaburi	81,191	88,060	77,369	46,210	49,296	52,163	56,427	62,422	66,940	69,729
Pathum Thani	96,888	105,918	115,955	125,360	137,731	159,293	196,442	223,842	263,734	289,979
Samut Prakan	269,940	308,389	327,221	330,583	353,731	368,664	382,223	421,692	460,615	474,118
Samut Sakhon	89,145	104,795	117,434	129,061	144,421	156,876	172,497	186,303	205,009	220,611
Ayutthaya	121,149	133,866	139,696	154,469	173,394	185,921	195,609	208,334	238,179	249,583
Nakhon Pathom	22,568	23,294	23,282	24,467	24,036	24,206	25,988	27,554	29,096	31,478
Chachoengsao	697	992	1,387	2,171	2,545	2,901	3,092	3,787	4,559	5,367
WHOLE AREA	1,277,499	1,331,597	1,342,536	1,303,567	1,389,340	1,433,434	1,471,765	1,543,501	1,703,334	1,799,596
Bangkok	595,799	566,160	540,069	491,124	504,065	483,286	439,362	409,445	435,078	458,607
Nonthaburi	80,918	87,788	77,096	45,936	49,022	51,889	56,153	62,149	66,667	69,456
Pathum Thani	96,824	105,918	115,955	125,360	137,675	159,238	196,156	223,083	261,849	287,304
Samut Prakan	269,938	308,388	326,219	330,581	353,728	368,661	382,170	421,638	460,560	473,973
Samut Sakhon	61,470	69,234	77,246	85,377	94,516	102,518	115,533	128,542	144,165	154,231
Ayutthaya	10,717	12,182	14,470	17,250	17,167	18,475	21,743	25,950	32,042	35,425
Nakhon Pathom	1,362	1,362	1,471	1,638	1,629	1,624	1,624	1,756	1,863	1,979
Chachoengsao	0	5	66	66	66	66	77	77	86	86
STUDY AREA	1,117,028	1,151,037	1,152,592	1,097,332	1,157,868	1,185,757	1,212,818	1,272,640	1,402,310	1,481,061

UNITS: PUMPAGE IN CUBIC METERS PER DAY (CMD)

Table 5.4.1 YEAR-1992 COMBINED GROUNDWATER PUMPAGE ESTIMATES FOR PRIVATE AND PUBLIC WELLS IN THE STUDY AREA

Changwat	Type of User	Private Total	DMR	PWD	MWA	PWA	DOH	ARD	IEAT	Public Total	Combined Total
Bangkok	Domestic	141,628	2,516	4,110	79,937	0	0	0	0	86,563	228,191
	Institutional	34,318								0	34,318
	Commercial	42,867								0	42,867
	Industrial	134,755							18,476	18,476	153,231
	TOTAL	353,568	2,516	4,110	79,937	0	0	0	18,476	105,039	458,607
Nonthaburi	Domestic	22,542	750	20,300	5,197	0	0	0		26,247	48,789
	Institutional	2,211								0	2,211
	Commercial	2,270								0	2,270
	Industrial	16,186							0	0	16,185
	TOTAL	43,209	750	20,300	5,197	0	0	0	0	26,247	69,456
Pathum Thani	Domestic	41,902	2,391	19,765	0	19,487	0	0		41,643	83,545
	Institutional	5,373								0	5,373
	Commercial	12,431								0	12,431
	Industrial	157,355							28,600	28,600	185,955
	TOTAL	217,061	2,391	19,765	0	19,487	0	0	28,600	70,243	287,304
Samut Prakan	Domestic	47,020	2,699	33,945	20,892	0	0	0	0	57,536	104,556
	Institutional	4,300								0	4,300
	Commercial	13,256								0	13,256
	Industrial	322,734							29,127	29,127	351,861
	TOTAL	387,310	2,699	33,945	20,892	0	0	0	29,127	86,663	473,973
Samut Sakhon	Domestic	10,609	459	43,510	0	9,871	0	0	0	53,840	64,449
	Institutional	1,676								0	1,676
	Commercial	4,550								0	4,550
	Industrial	83,556								0	83,556
	TOTAL	100,391	459	43,510	0	9,871	0	0	0	53,840	154,231
Ayutthaya	Domestic	3,869	3,375	10,810	0	956	0	118		15,259	19,128
	Institutional	66								0	66
	Commercial	1,662								0	1,662
	Industrial	14,169							400	400	14,569
	TOTAL	19,766	3,375	10,810	0	956	0	118	400	15,659	35,425
Nakhon Pathom	Domestic		1632	0	0	211	136	0	0	1,979	1,979
	Institutional									0	0
	Commercial									0	0
	Industrial									0	0
	TOTAL	0	1,632	0	0	211	136	0	0	1,979	1,979
Chachoengsao	Domestic		86							86	86
	Institutional									0	0
	Commercial									0	0
	Industrial									0	0
	TOTAL	0	86	0	0	0	0	0	0	86	86
Study Area	Domestic	267,570	13,908	132,440	106,026	30,525	136	118	0	283,153	550,723
	Institutional	47,944	0	0	0	0	0	0	0	0	47,944
	Commercial	77,036	0	0	0	0	0	0	0	0	77,036
	Industrial	728,755	0	0	0	0	0	0	76,603	76,603	805,358
	TOTAL	1,121,305	13,908	132,440	106,026	30,525	136	118	76,603	359,756	1,481,061

Note: No private well was inventoried in Nakhon Pathom and Chachoengsao.
UNITS: PUMPAGE IN CUBIC METERS PER DAY (CMD)

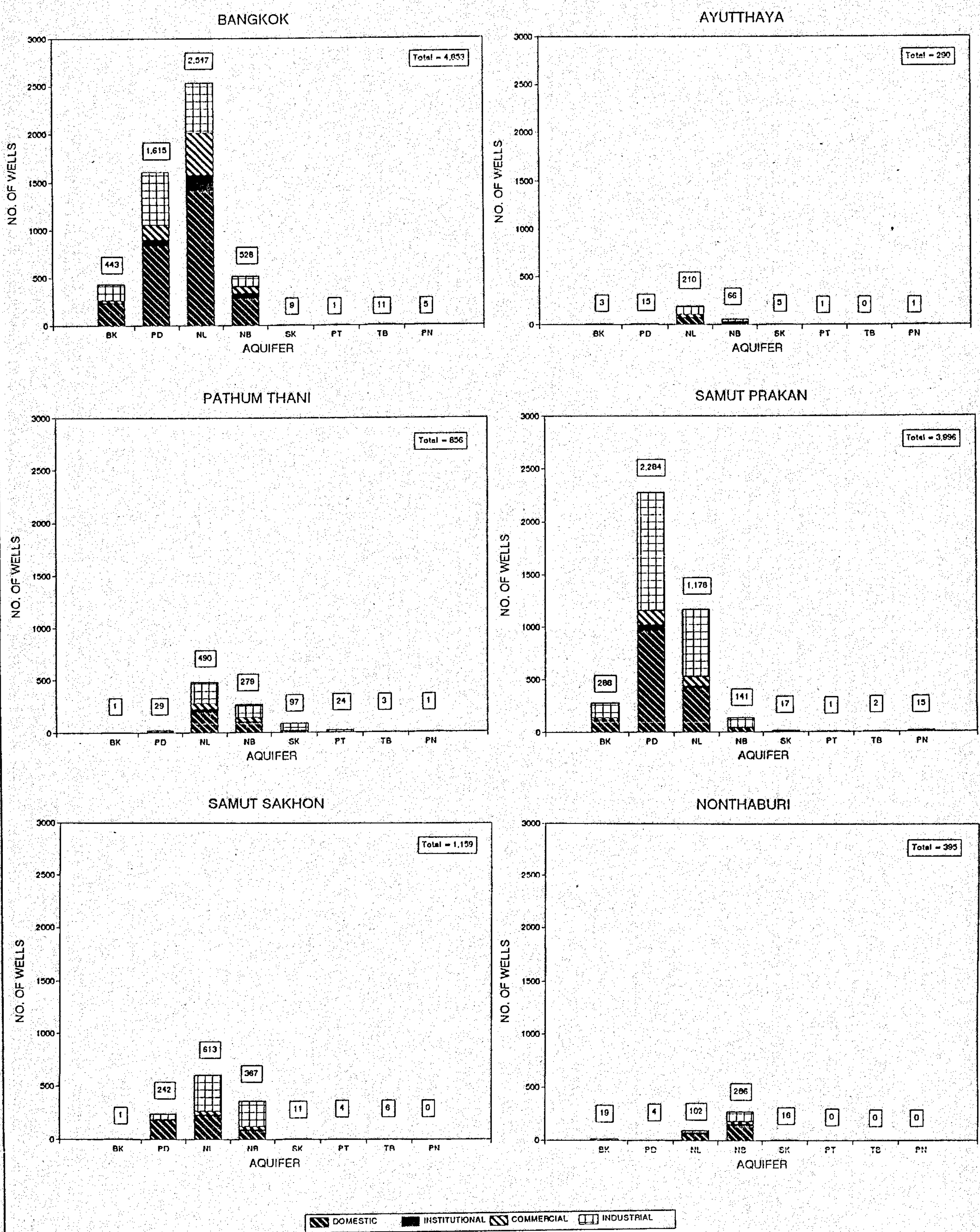
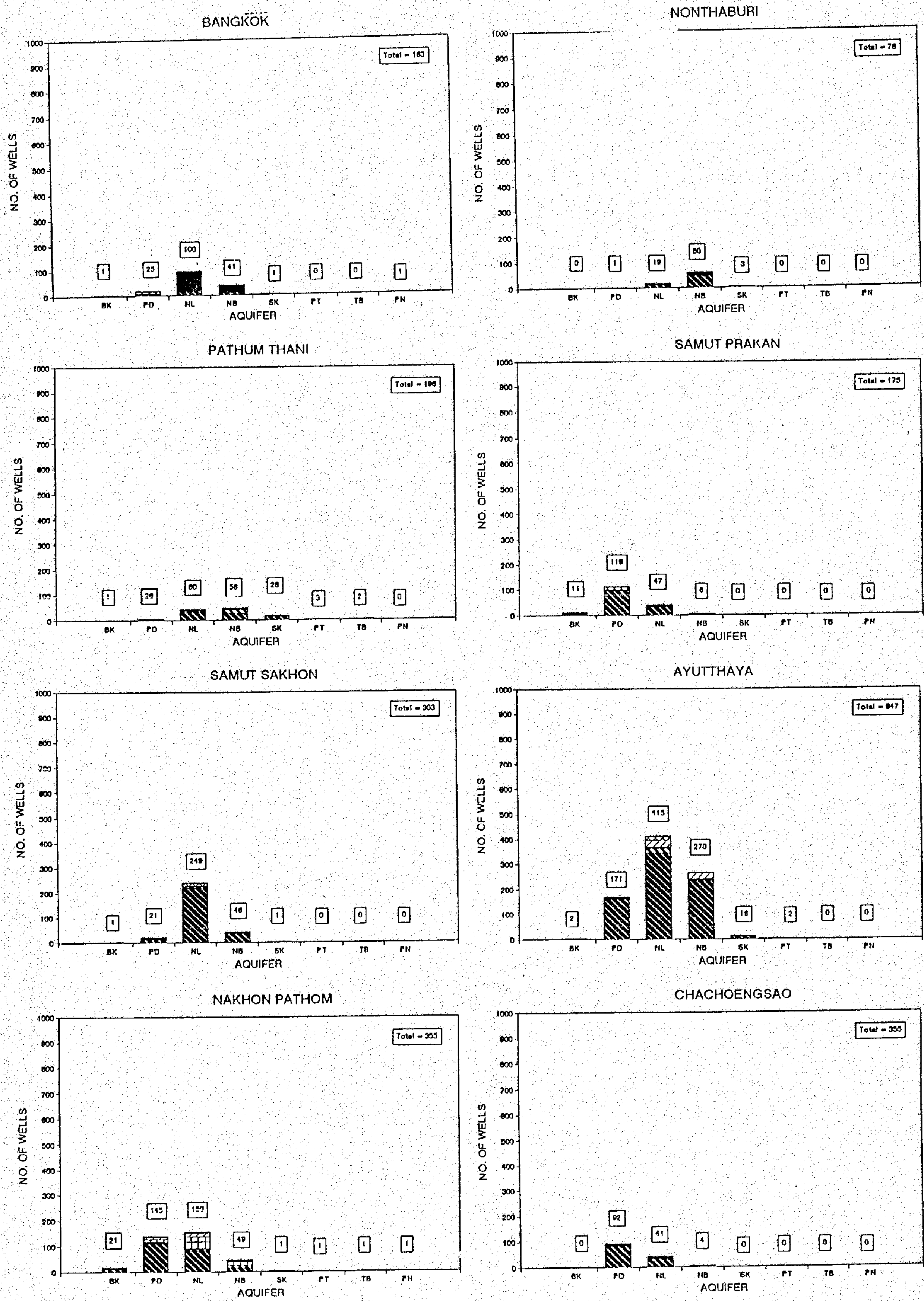


Figure 5.2.1	DISTRIBUTION OF PRIVATE WELLS IN THE WHOLE AREA
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



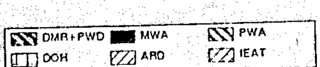


Figure 5.2.2	DISTRIBUTION OF PUBLIC WELLS IN THE WHOLE AREA
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

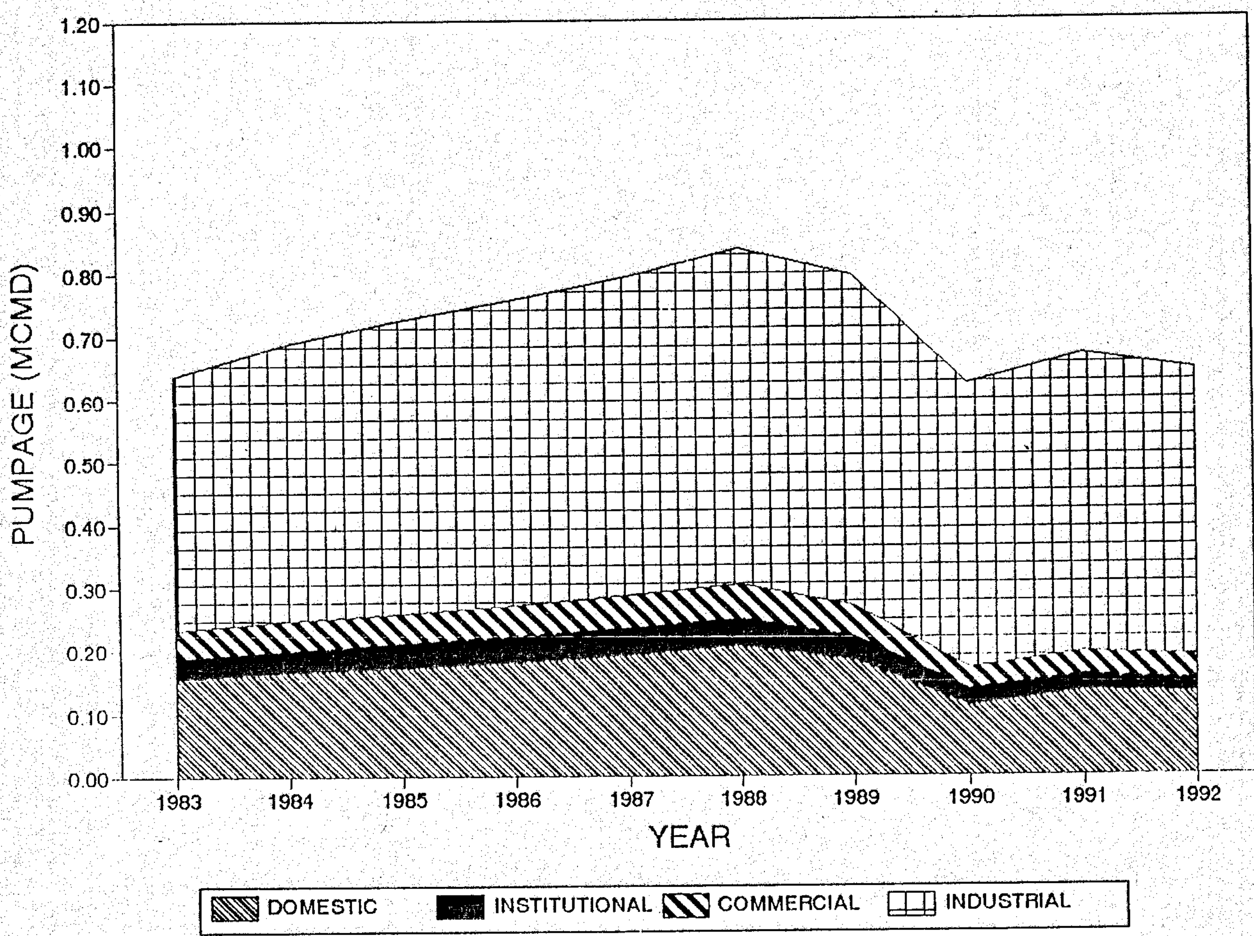


Figure 5.3.1	CASE 1 HISTORICAL PUMPAGE ESTIMATES FOR PRIVATE WELLS IN THE WHOLE AREA
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

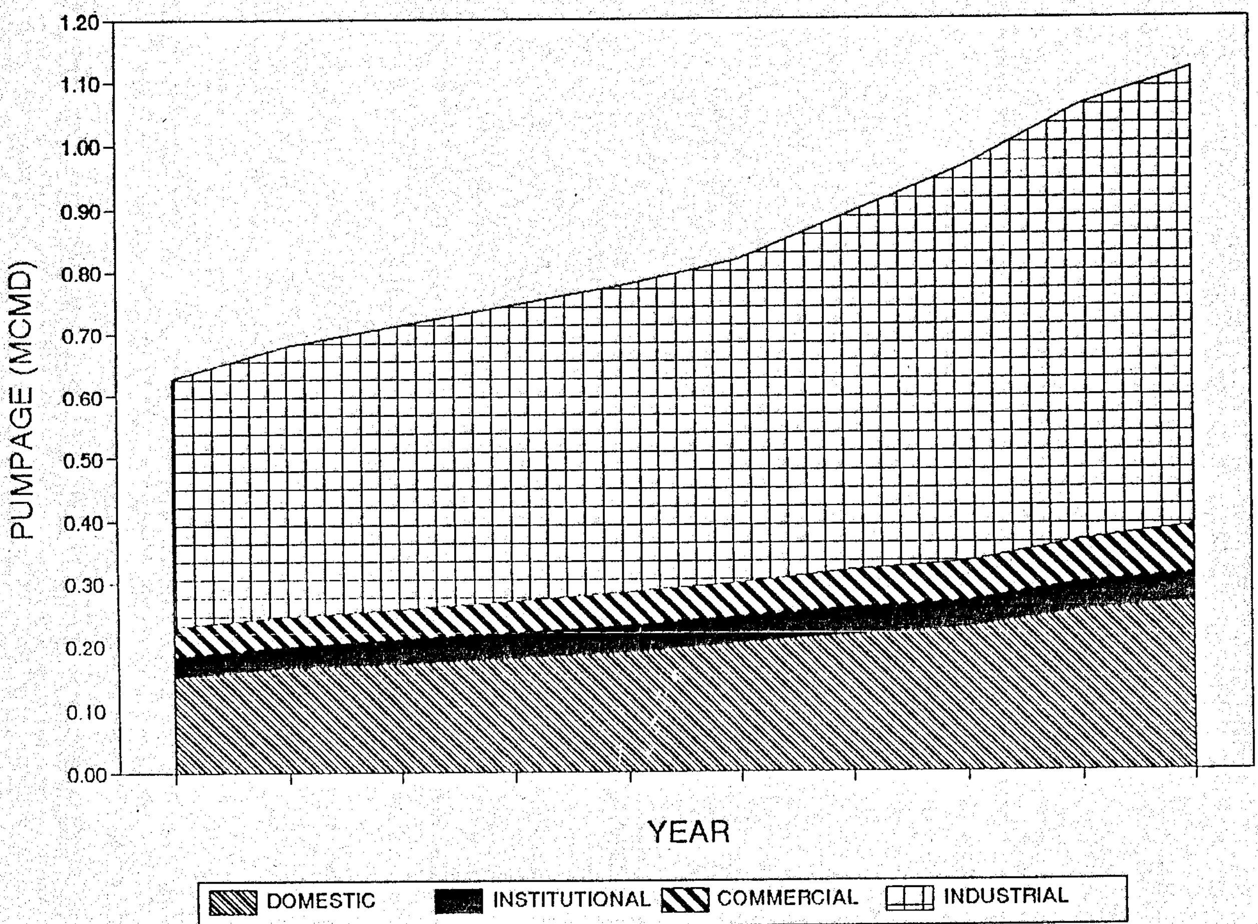


Figure 5.3.2	CASE 2 HISTORICAL PUMPAGE ESTIMATES FOR PRIVATE WELLS IN THE STUDY AREA
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

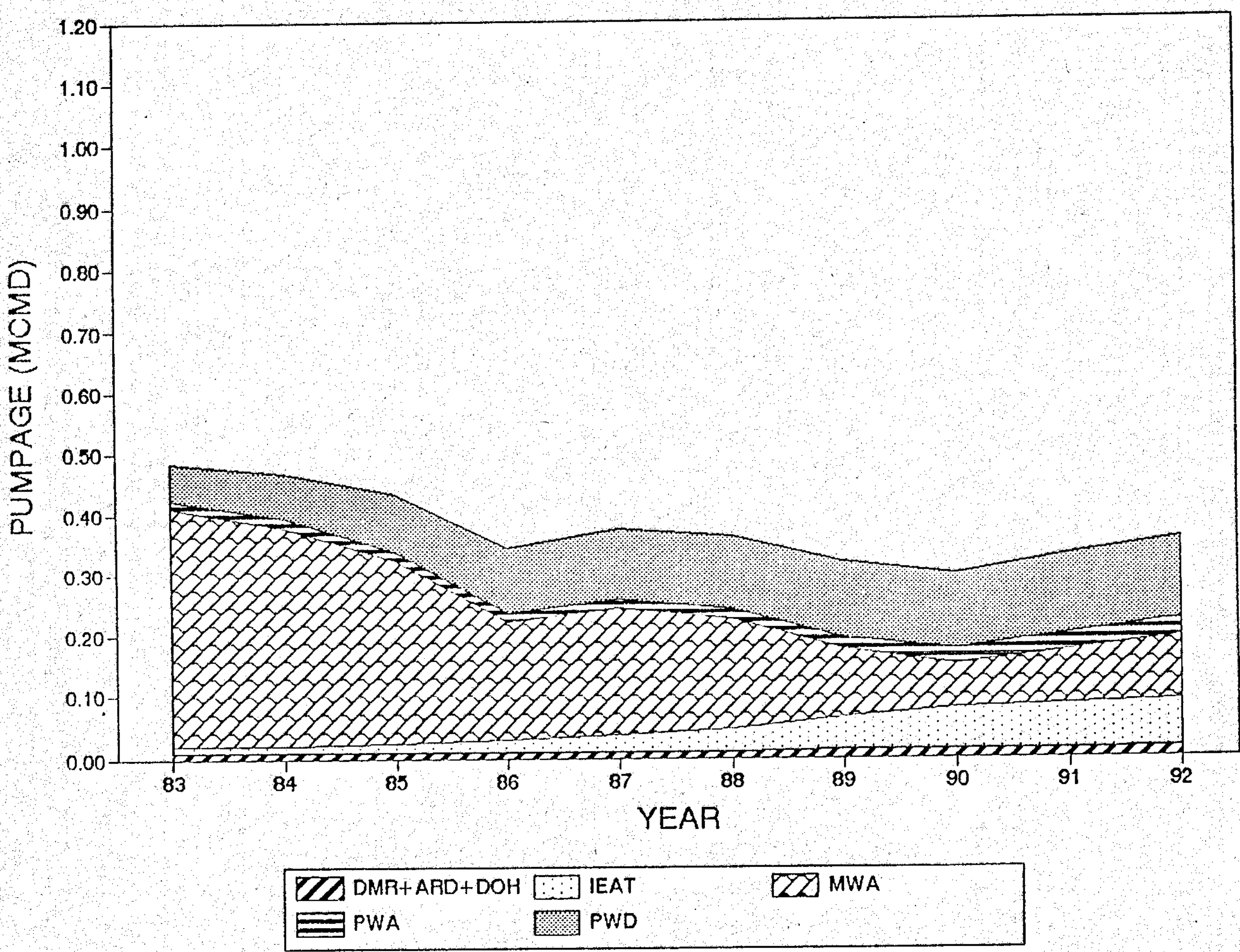


Figure 5.3.3	HISTORICAL PUMPAGE ESTIMATES FOR PUBLIC WELLS IN THE STUDY AREA
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

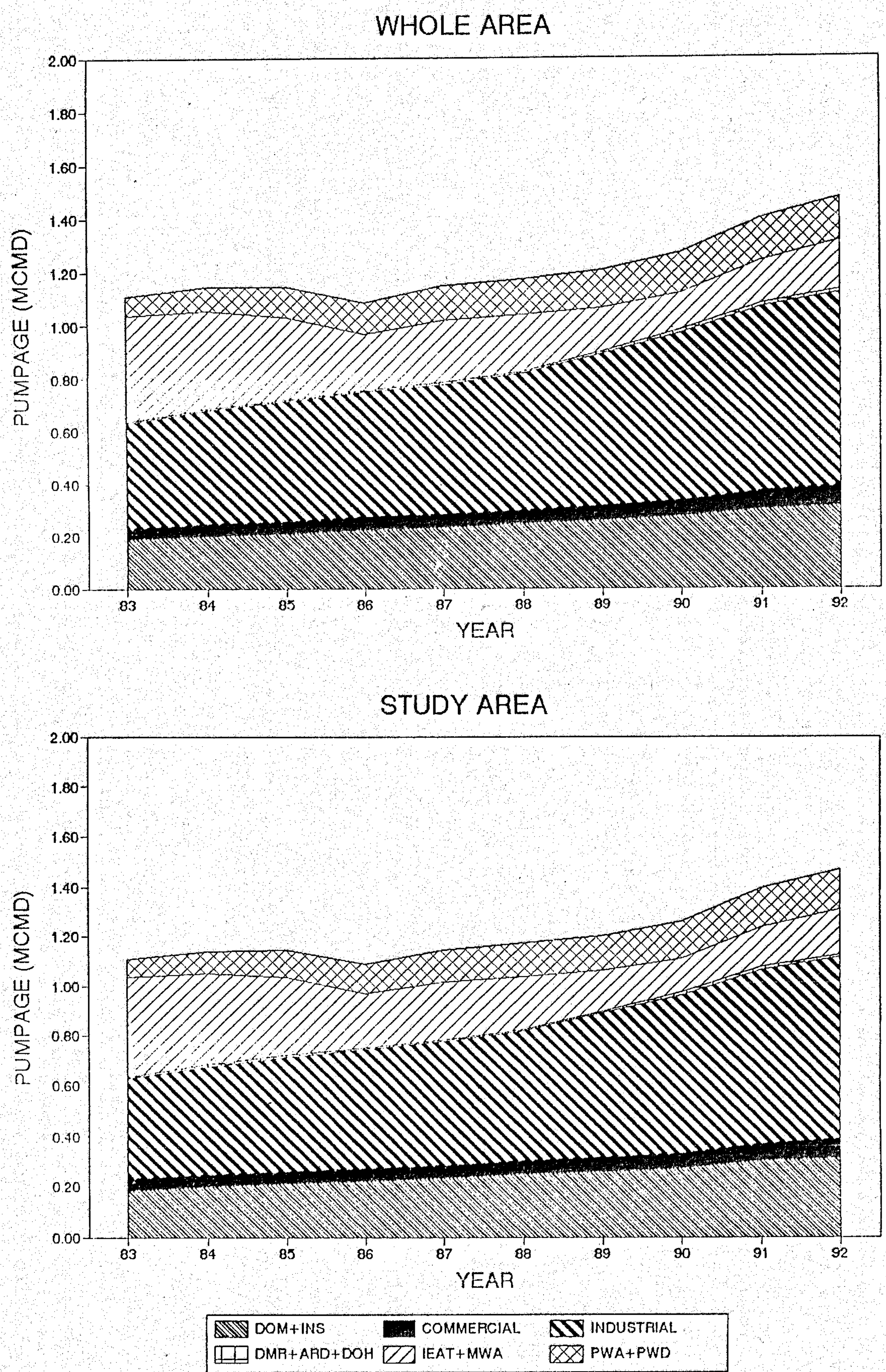
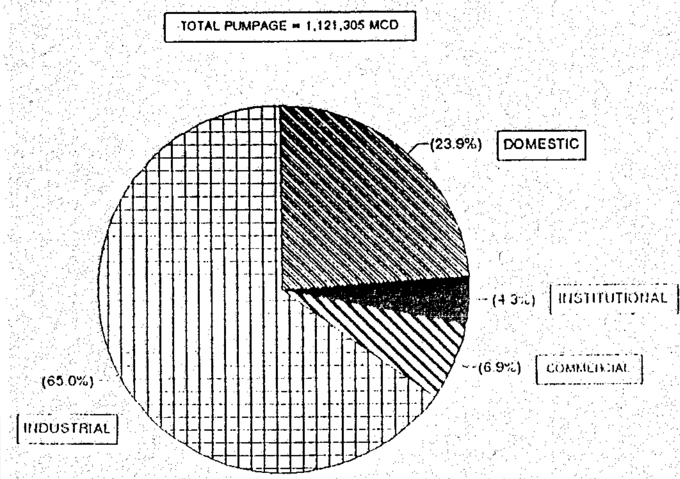
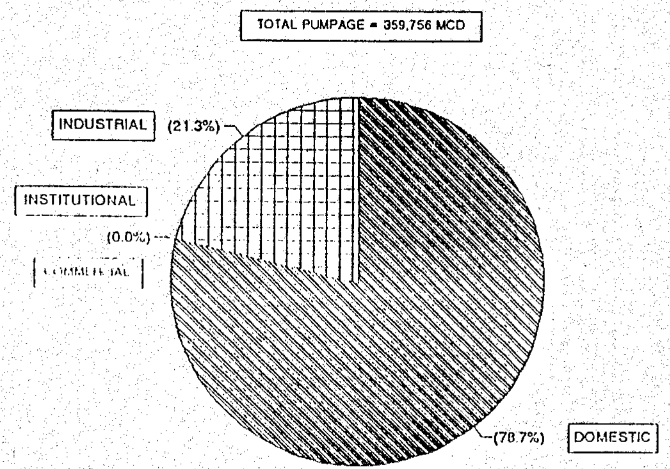


Figure 5.3.4	CASE 2 COMBINED HISTORICAL PUMPAGE ESTIMATES FOR PRIVATE AND PUBLIC WELLS
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

PRIVATE WELLS



PUBLIC WELLS



PRIVATE AND PUBLIC WELLS

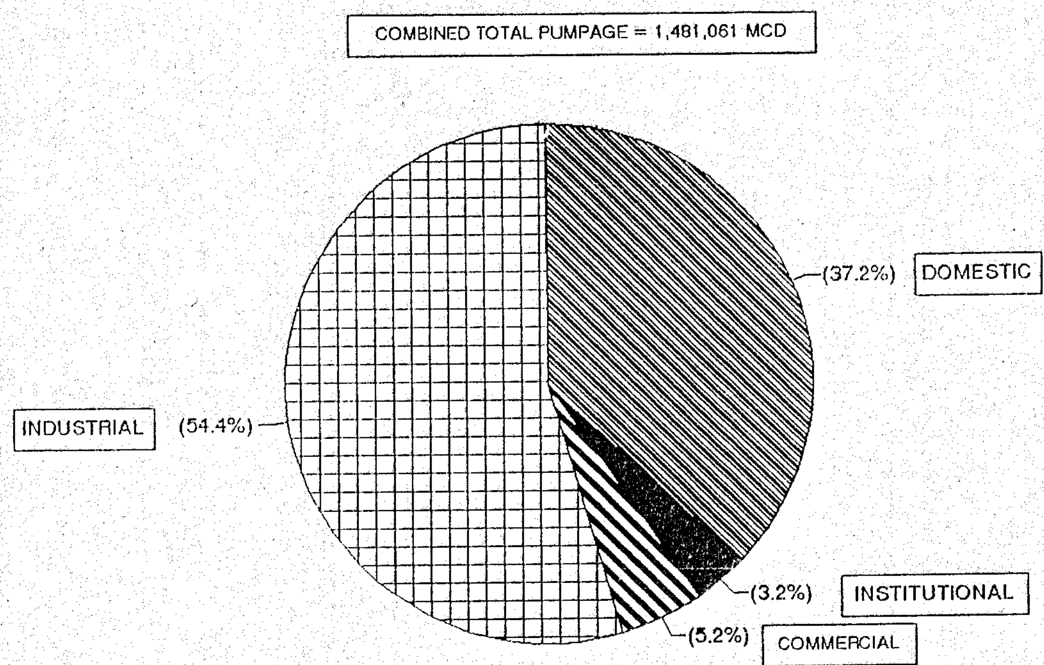
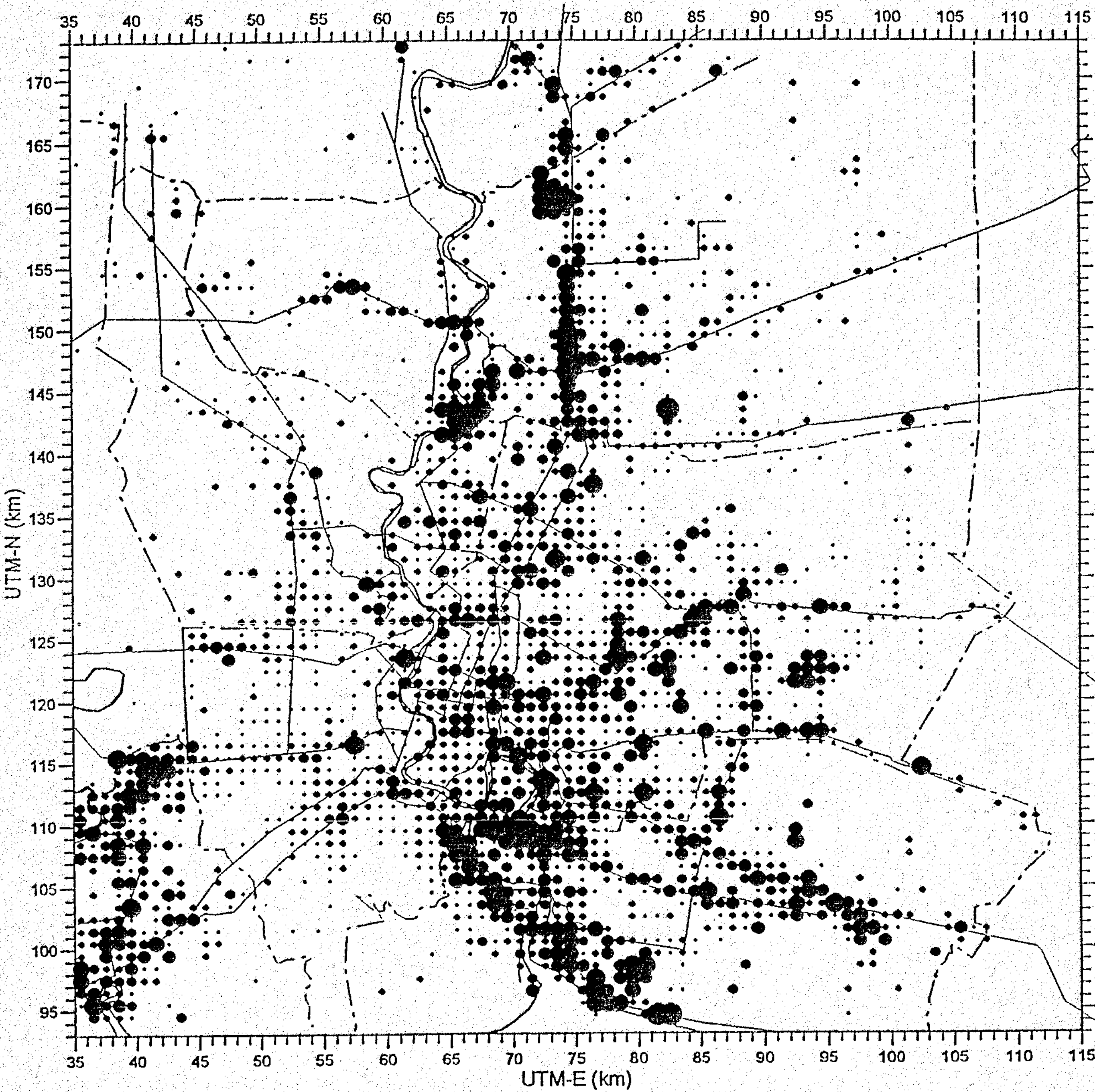


Figure 5.4.1	YEAR-1992 GROUNDWATER USE DISTRIBUTIONS OF PRIVATE AND PUBLIC WELLS IN THE STUDY AREA
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



LEGEND

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

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

Total Pumpage in Study Area in 1992 = 1,481,061 m^3/day

Figure 5.4.2	DISTRIBUTION OF GROUNDWATER PUMPAGE IN THE STUDY AREA IN 1992
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 6 GROUNDWATER LEVELS AND LAND SUBSIDENCE

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6.1 DMR Monitoring Stations

Groundwater levels in the Study Area are monitored by DMR through the groundwater monitoring network consisting of 258 observation wells in 103 stations. Of the 258 monitoring wells, 77 wells were installed with water level recorders. Groundwater levels in all monitoring wells are measured at least monthly (Figure 6.1).

(1) Groundwater Level Changes

The annual piezometric changes of main aquifers in the past 15 years in Lat Krabang, PathumThani, and Samut Sakhon are presented in Figure 6.2. Recent decline of groundwater levels and land subsidence were noticeable in these areas. In Pathum Thani, the piezometric levels declined almost continuously, though the levels temporarily recovered from 1985 to 1987 due to DMR's restriction on private pumpage. The annual decline of water levels were also significant in the other two (2) areas.

(2) Groundwater Contour

Phra Pradaeng Aquifer

From 1981 to 1985, piezometric level lowered yearly in the central Bangkok Metropolis but recovered slightly in 1987 due to restriction of pumpage. The cone of depression extended to the east and the deepest piezometric level of 53.0 m was observed in Bang Phli, Samut Prakan in 1993. The piezometric levels below 20 m were distributed in the entire Bangkok Metropolis, Samut Prakan, Samut Sakhon, and central Pathum Thani. The cone of depressions deeper than 30 m appeared isolately (Figure 6.3).

Nakhon Luang Aquifer

Peizometric levels lower than 40-50 m were observed from central to eastern portion of Bangkok in the beginning of 1980. The center of the depression moved toward east every year. The 1994 groundwater contour shows an elliptical depression zone extending from north to south at maximum depth of 60 m. The center of Bangkok is at the western edge of the depression zone showing 30 m to 35 m water level (Figure 6.4).

Nonthaburi Aquifer

The piezometric contour of Nonthaburi aquifer is similar to those of the above mentioned two (2) aquifers. From 1980 to 1984, the cone of depression was observed in the central Bangkok but moved gradually toward the east. A wide depression zone of 40 m to 50 m stretching from Pathum Thani, Samut Sakhon and Samut Prakarn appeared in 1994 (Figure 6.5).

6.2 JICA Monitoring Stations

Groundwater levels and land subsidence are monitored at the JICA monitoring stations in Lat Krabang (Site A), AIT (Site B) and Samut Sakhon (Site C) since July 1993. These monitoring wells measure groundwater levels and land subsidence at different depths, record data on the chart continuously and store them in the magnetic card every hour. These data are collected every month and processed on the micro-computer at DMR.

(1) Lat Krabang (Site-A)

The deepest groundwater level was observed at A-6 well (Nakhon Luang Aquifer) showing 63.0 m in July 1994. The decline since the beginning was about 5 m. The groundwater levels at A-5 well (Nonthaburi Aquifer) and A-7 well (Phra Pradaeng Aquifer) were lower than 50 m. Those at the deep monitoring wells, i.e., A-2 well (Phayathai Aquifer), A-3 well (Sam Khok Aquifer), A-4 well (Sam Khok Aquifer) and at the shallowest A-8 well (Bangkok Aquifer) ranged from 20 m to 27 m. The water level of the deepest A-1 well (Pak Nam Aquifer) has gradually recovered since its construction, and the present piezometric head is slightly higher than the ground elevation indicating an artesian condition.

The maximum land subsidence of 6.5 cm was recorded at A-2 well in July 1993. The subsidence rate which was evaluated considering the compaction of land fill was almost the same as the recorded subsidence rate based on the nearby benchmark. The annual compression from the surface to the bottom of A-8 well (48 m) which was considered subsidence of the shallow formations including Bangkok Clay represented only 40% of the total compression measured at A-1 well (574 m). The rest, 60% of the compression, occurred at deeper formations (Figure 6.6).

(2) AIT (Site-B)

Groundwater level was lowest at B-1 well (Nonthaburi Aquifer) and gradually increased as the depth decreased in the order of B-2, B-3 (both Nakhon Luang Aquifers), B-4 (Phra Pradaeng Aquifer) and B-5 (Bangkok Aquifer). The groundwater levels declined to 37 m, 32 m and 32 m at B-1, B-2 and B-3, respectively. The daily and weekly fluctuations of water levels were observed at B-2 and B-3 wells. These fluctuations were caused by the pumping of the industrial wells in the vicinity.

Slight land subsidence occurred at the above monitoring wells. A maximum subsidence was only 1.1 cm since the beginning. However, records showed the land slightly rebounded since May 1994. A rhythmic daily cycle of compression and rebound was observed. This corresponded with the daily fluctuation of the groundwater level (Figure 6.7).

(3) Samut Sakhon (Site -C)

The deepest groundwater levels were observed at C-2 well (Nonthaburi Aquifer) recorded at 71 m elevation and at C-3 well (Nakhon Luang Aquifer) recorded at 53 m elevation (July, 1994). The groundwater levels were affected by the pumping of wells in the vicinity and a rhythmic daily and weekly fluctuations were observed. C-4 and C-5 (both Phra Pradaeng Aquifers) and the deepest C-1 well (Sam Khok Aquifer) ranged from 17 m to 29 m in water levels. Fluctuations of groundwater levels were not observed.

A maximum subsidence of 12.6 cm was recorded at C-2 well (212 m) for about 1 year. C-4 well (105 m) recorded a minimum subsidence of 10 cm. The deepest C-1 well (320 m) also recorded about 12.0 cm and the shallowest C-5 (78 m) was 10.6 cm. Most of the compression occurred at the shallow formations. The site was excavated and filled with soil when it was constructed because it was situated at a low soft ground. A much longer time for evaluation of land subsidence on each well was necessary in view of the anticipated settlement of the land fill (Figure 6.8).

(4) Benchmarks

Two (2) kinds of benchmarks were constructed at each monitoring station in order to measure ground subsidence. One benchmark's foundation was placed at the depth of 1 m BGS without support. The other benchmark's foundation was supported by 3 m long concrete piles. The elevations of these benchmarks were determined by reliable leveling conducted by the Study Team in July 1993 and June 1994 using nearby existing DMR benchmarks as reference benchmark. The latest elevation of existing DMR benchmarks were not available at that time and so, their subsidence were calculated.

(5) Pore Water Pressure

Five (5) pore water pressure meters were buried from 5 m to 34 m depths at Lat Krabang (Site A). The pore water pressure of Bangkok Clay was measured once a month. The results indicated the hydrostatic pressure distribution up to a depth of 15 m. It was noted that the pressure lowered to $0.8 kgf/cm^2$ and $1.8 kgf/cm^2$ at 25 m and 34 m depths, respectively.

6.3 DMR and RTSD Benchmarks

A total of 1,243 benchmarks were constructed by DMR, RTSD, BMA and related agencies as of the year-1992. Some of these benchmarks were destroyed or lost (see Figure 6.9). There was no established standard date and time of leveling among these agencies. The following is discussed according to the RTSD and the DMR data:

(1) Subsidence at Representative Benchmarks

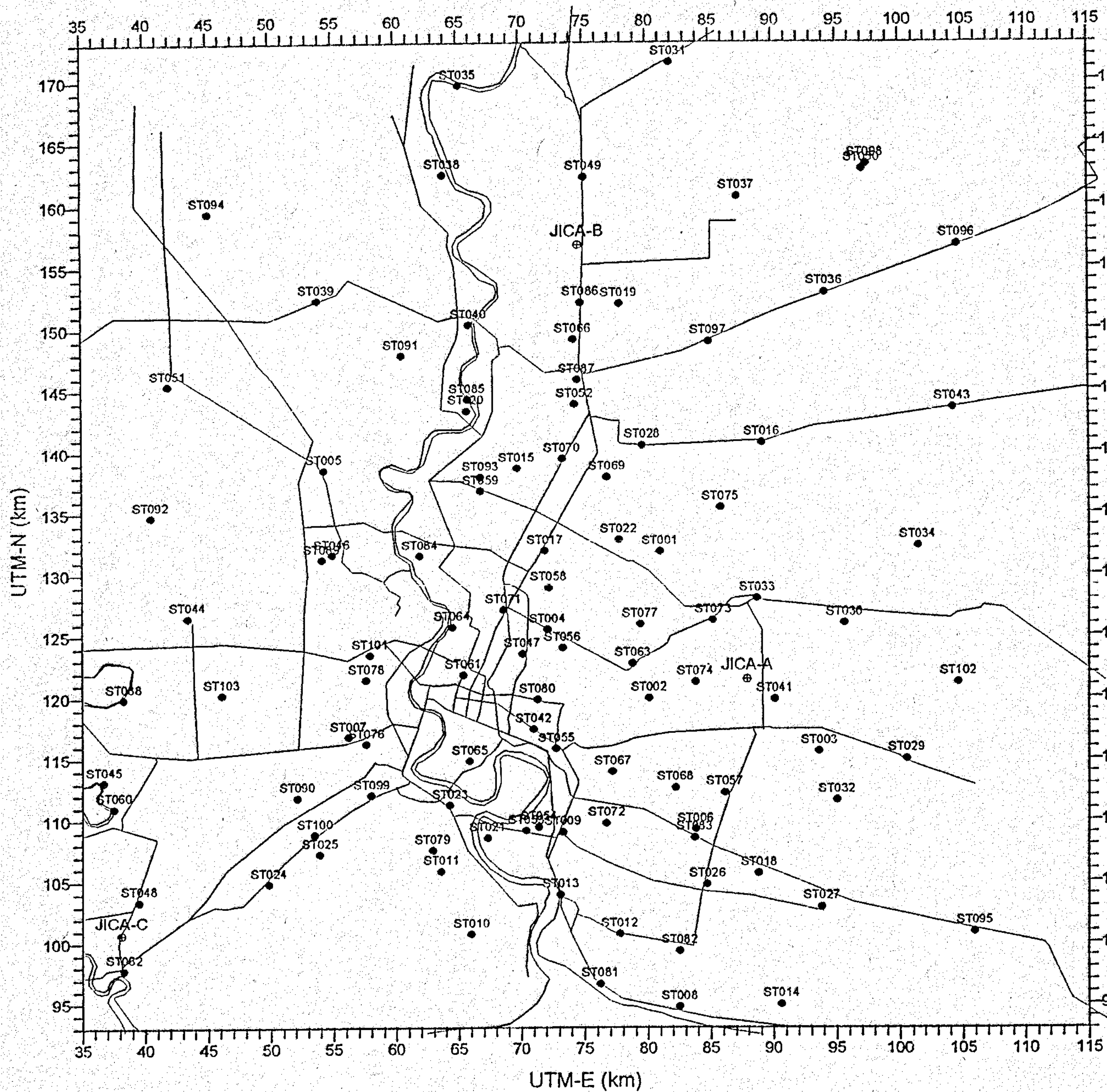
The land subsidence recorded at AIT-14 station's CI-1 benchmark (1 m depth) in Phra Khanong, Bangkok was 648.8 mm in 13 years from 1980 to 1993. AIT-08 station's CI-1 showed 225 mm in the same period. It is located at Chulalongkorn University in the center of Bangkok. AIT-25 station's CI-1 in Pathum Thani also recorded 75 mm in 8 years since 1986, however, it rebounded in 1990 and 1992 (Figure 6.10).

(2) Total Land Subsidence

Figure 6.11 shows the total subsidence distribution in twelve (12) years from 1980 to 1992 (1 m depth). A subsidence cone was located in the center of Bangkok indicating 62.6 cm maximum. The land subsidence area extends north-south direction from this center of the cone. The Study Area entirely subsided more than 10 cm. The total subsidence before 1986 formed the subsidence cone in the center of Bangkok, however, the cone gradually moved toward the east since 1986. The total subsidence in the southern and eastern areas, Samut Prakan and Lat Krabang, showed 20 to 25 cm in 6 years, while in the center of Bangkok was less than 15 cm.

(3) Land Subsidence Rate from 1992 to 1993

Figure 6.12 shows the annual rate of subsidence from 1992 to 1993. The map indicates significant land subsidence at more than 3 cm/year which occurred in Samut Prakan and Lat Krabang, south and east of Bangkok, respectively. The subsidence cone of 4-5 cm/year was observed locally in these areas. On the other hand, 1-2 cm/year of subsidence was observed at the center of Bangkok. It was less than 1 cm/year in the area along the Chao Phraya River.

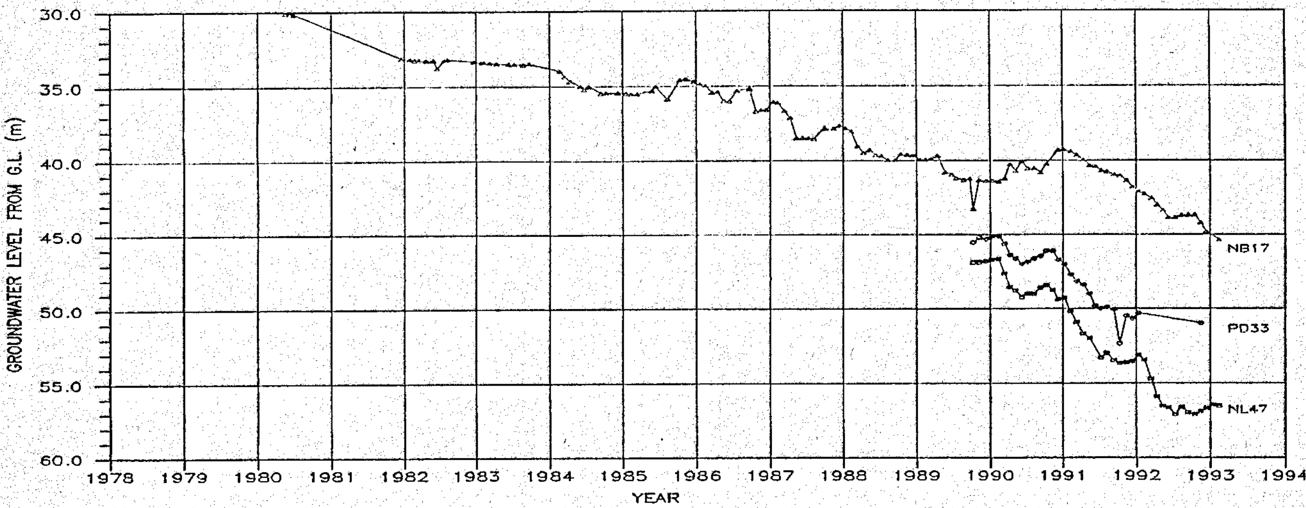


LEGEND

⊕ Location of JICA monitoring station

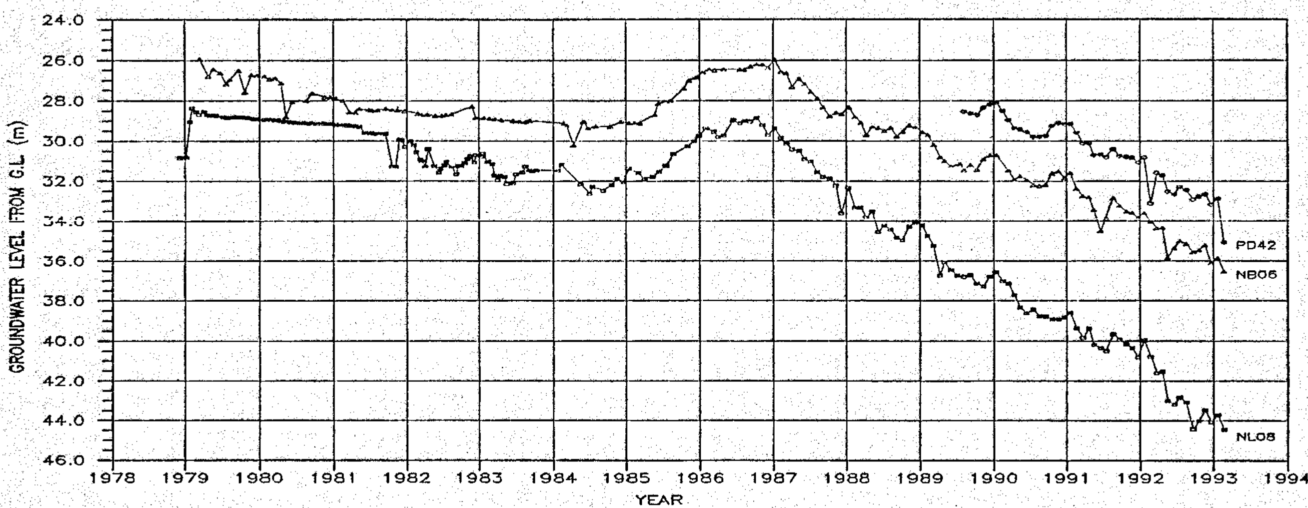
• Location of DMR monitoring station with station No.

Figure 6.1	LOCATION OF DMR MONITORING STATIONS
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.



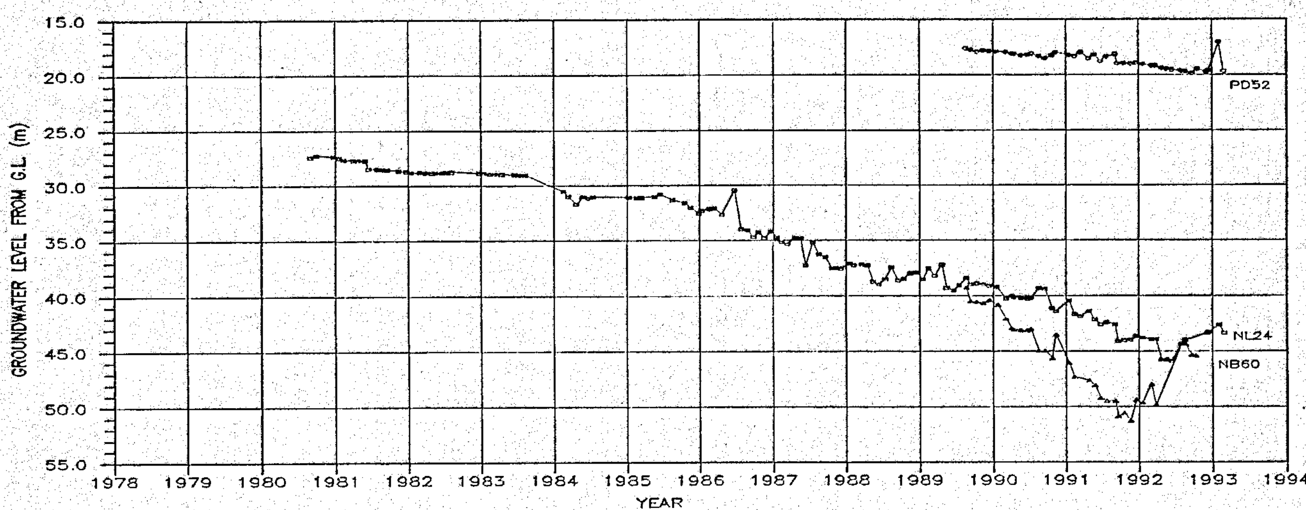
LOCATION	: Wat Bamrung Run	SCREEN DEPTH		
Tambon	: Khlong Sam Prawet	PD33	:	104.0–110.0m
Amphoe	: Lat Krabang	NL47	:	147.0–153.0m
Changwat	: Bangkok	NB17	:	183.0–189.0m
UTM Grid	: 901198			

STATION No. 41



LOCATION	: Wat Kla Cha-um	SCREEN DEPTH		
Tambon	: Khlong Song	PD42	:	107.0–113.0m
Amphoe	: Khlong Luang	NL08	:	122.3–128.3m
Changwat	: Pathum Thani	NB06	:	186.2–192.2m
UTM Grid	: 778520			

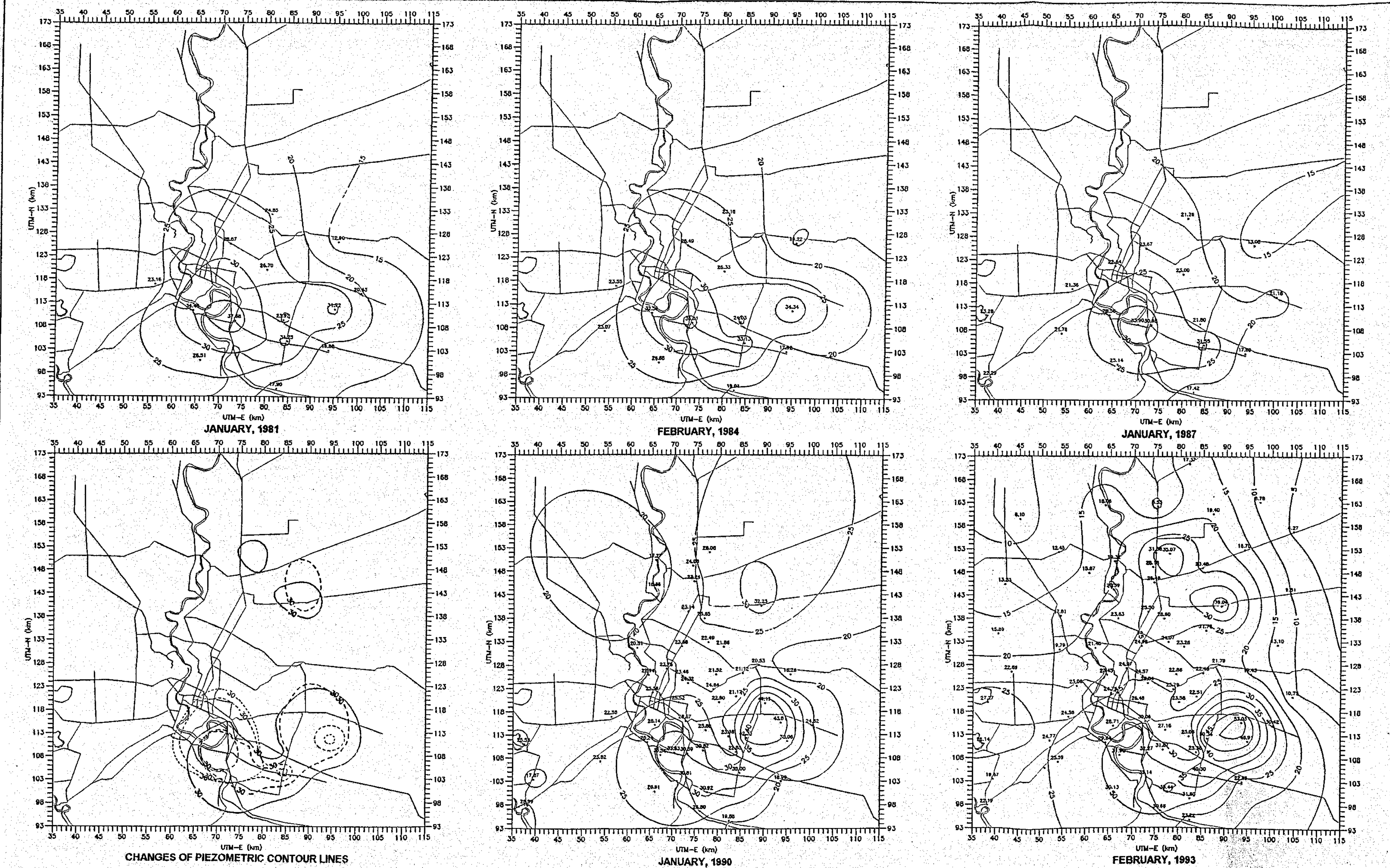
STATION No. 19



LOCATION	: Wat Bang Ping	SCREEN DEPTH		
Tambon	: Na Di	PD52	:	77.0–83.0m
Amphoe	: Muang Samut Sakhon	NL24	:	134.0–140.0m
Changwat	: Samut Sakhon	NB60	:	221.0–227.0m
UTM Grid	: 395034			

STATION No. 48

Figure 6.2	GROUNDWATER LEVEL CHANGES
	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.



LEGEND

- 30mbgs CONTOUR LINE IN JAN. 1981
- 30mbgs CONTOUR LINE IN FEB. 1984
- 30mbgs CONTOUR LINE IN JAN. 1987
- 30mbgs CONTOUR LINE IN JAN. 1990
- 30mbgs CONTOUR LINE IN FEB. 1993

(mbgs : m below ground surface)

LEGEND

- LINE OF EQUAL PIEZOMETRIC LEVEL (m below ground surface)
- 25.00 DMR MONITORING WELL WITH PIEZOMETRIC LEVEL (m below ground surface)

Figure 6.3	PIEZOMETRIC LEVEL OF PHRA PRADAENG AQUIFER
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.

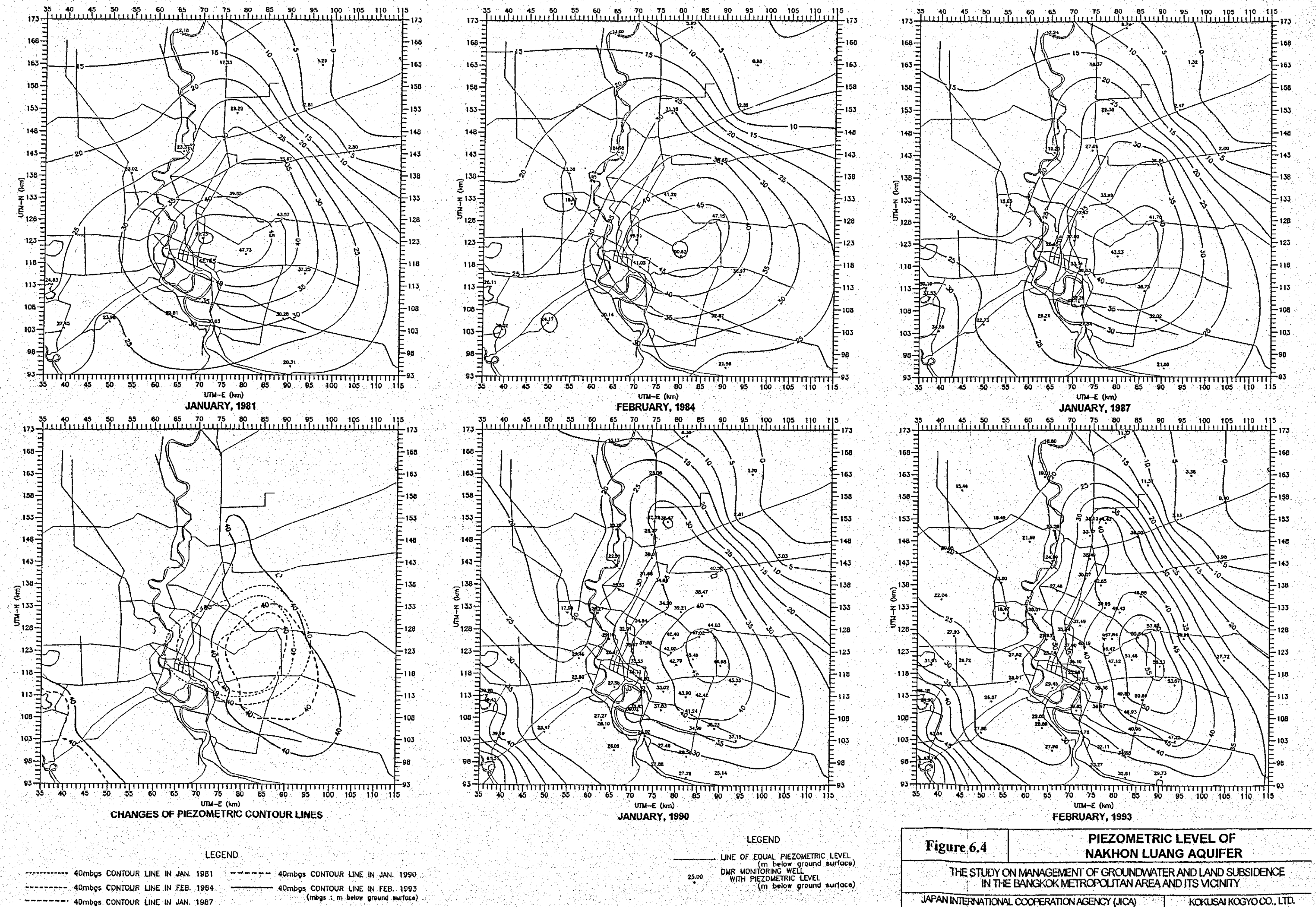


Figure 6.4	PIEZOMETRIC LEVEL OF NAKHON LUANG AQUIFER
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

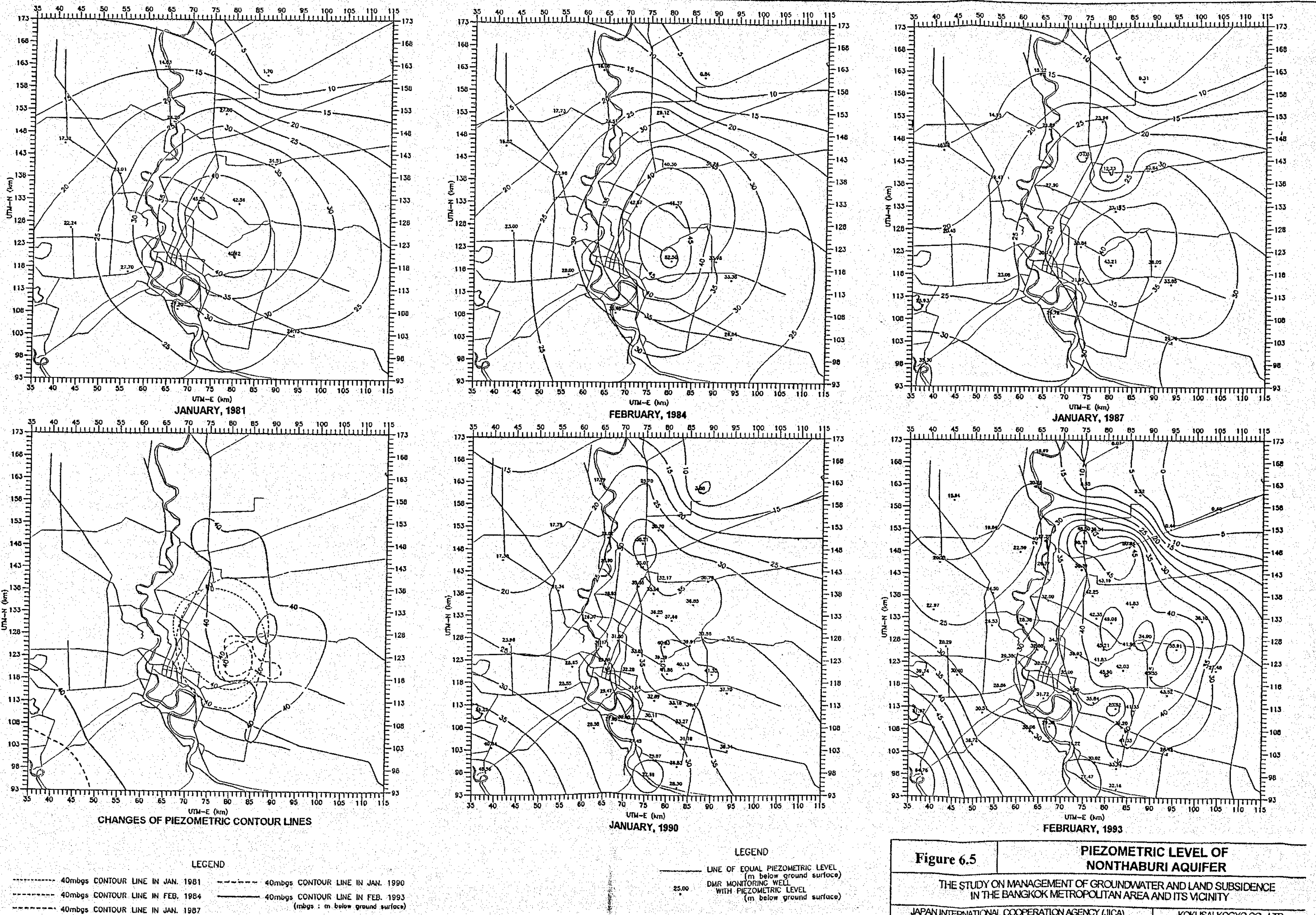


Figure 6.5	PIEZOMETRIC LEVEL OF NONTHABURI AQUIFER
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

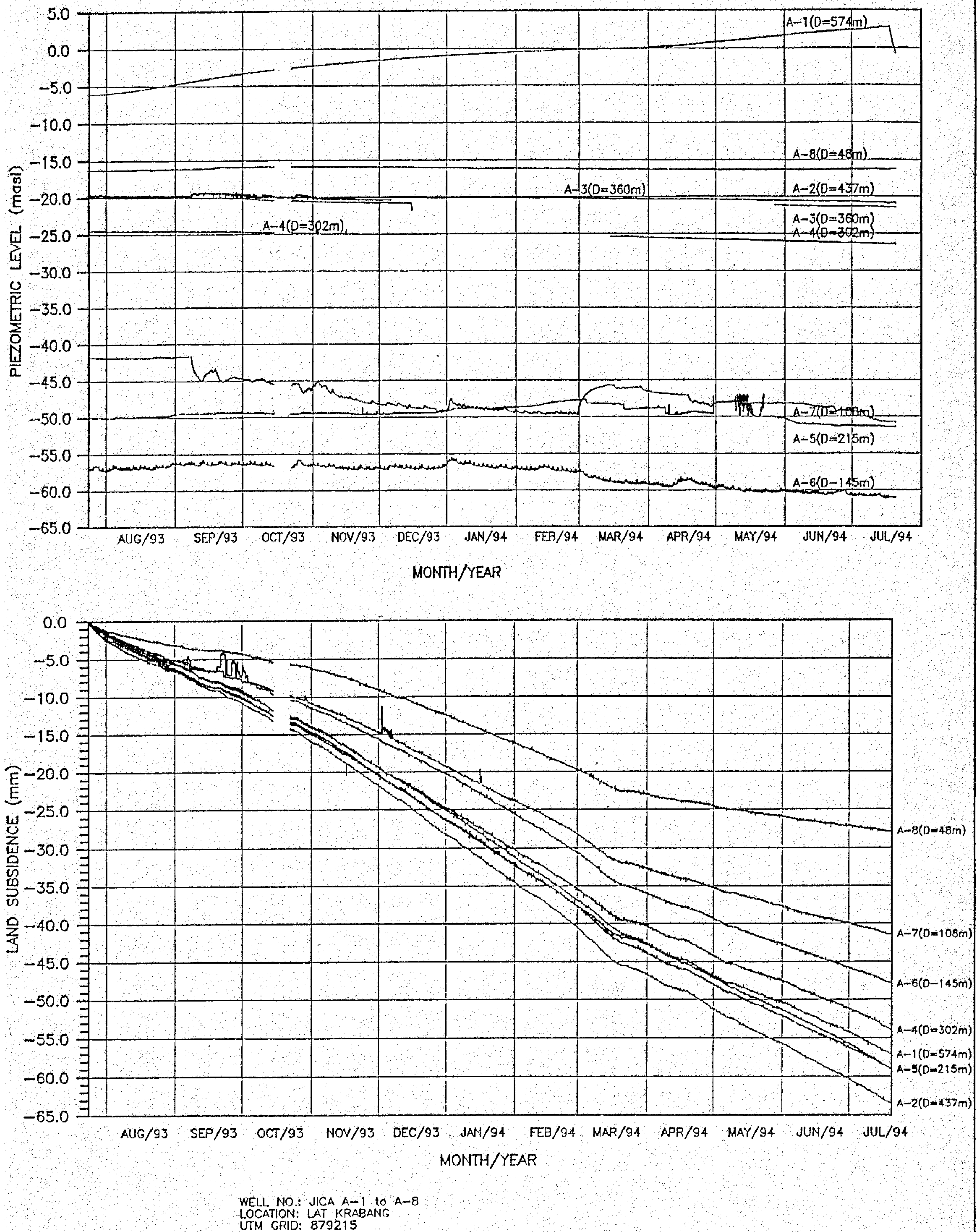
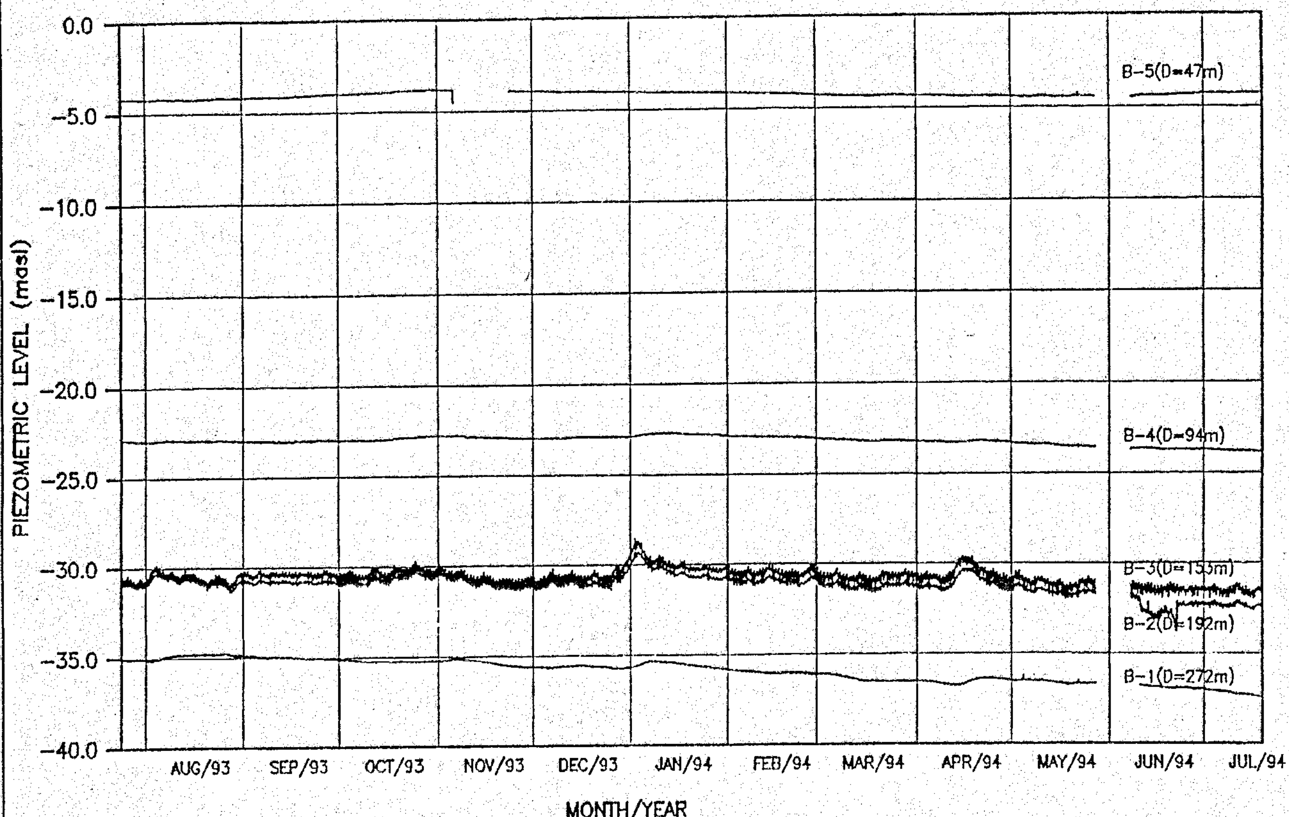
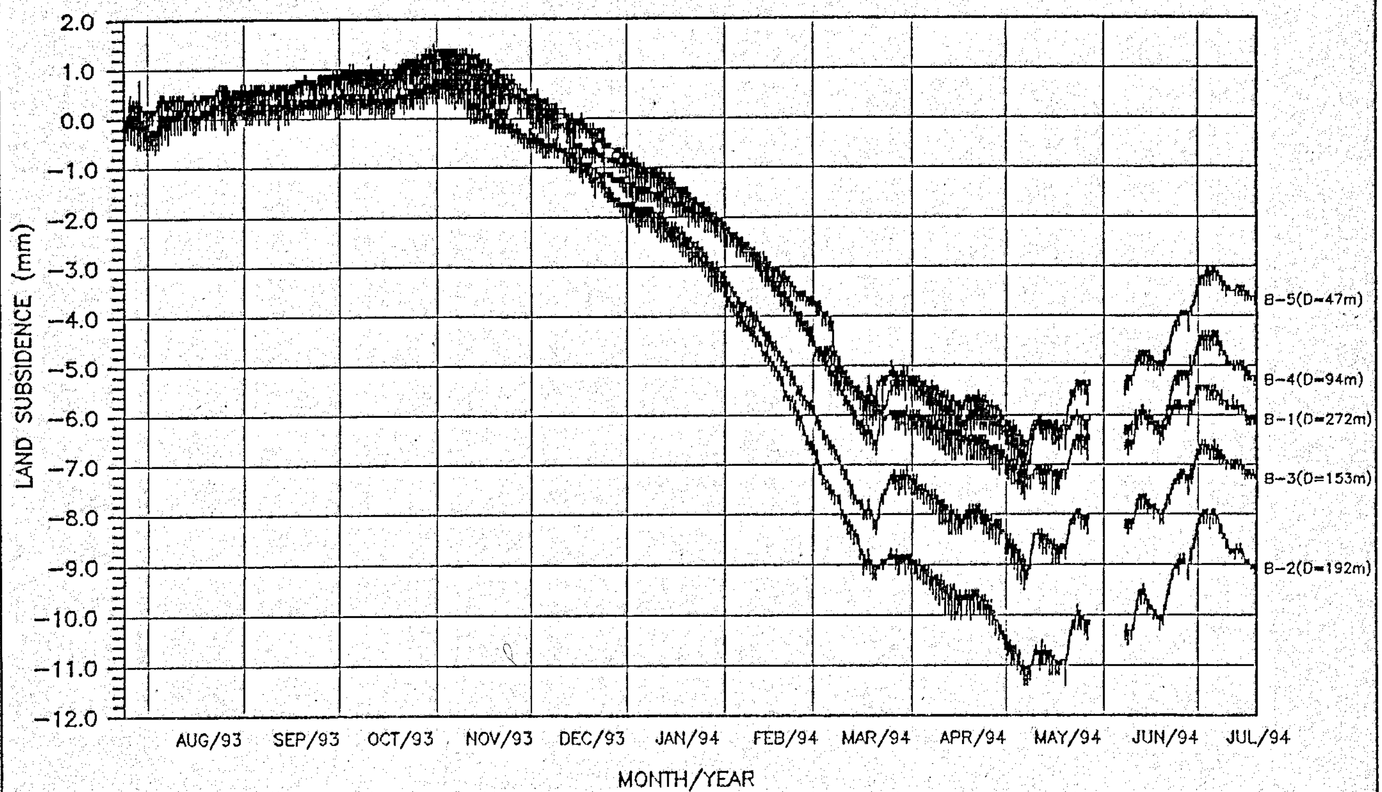


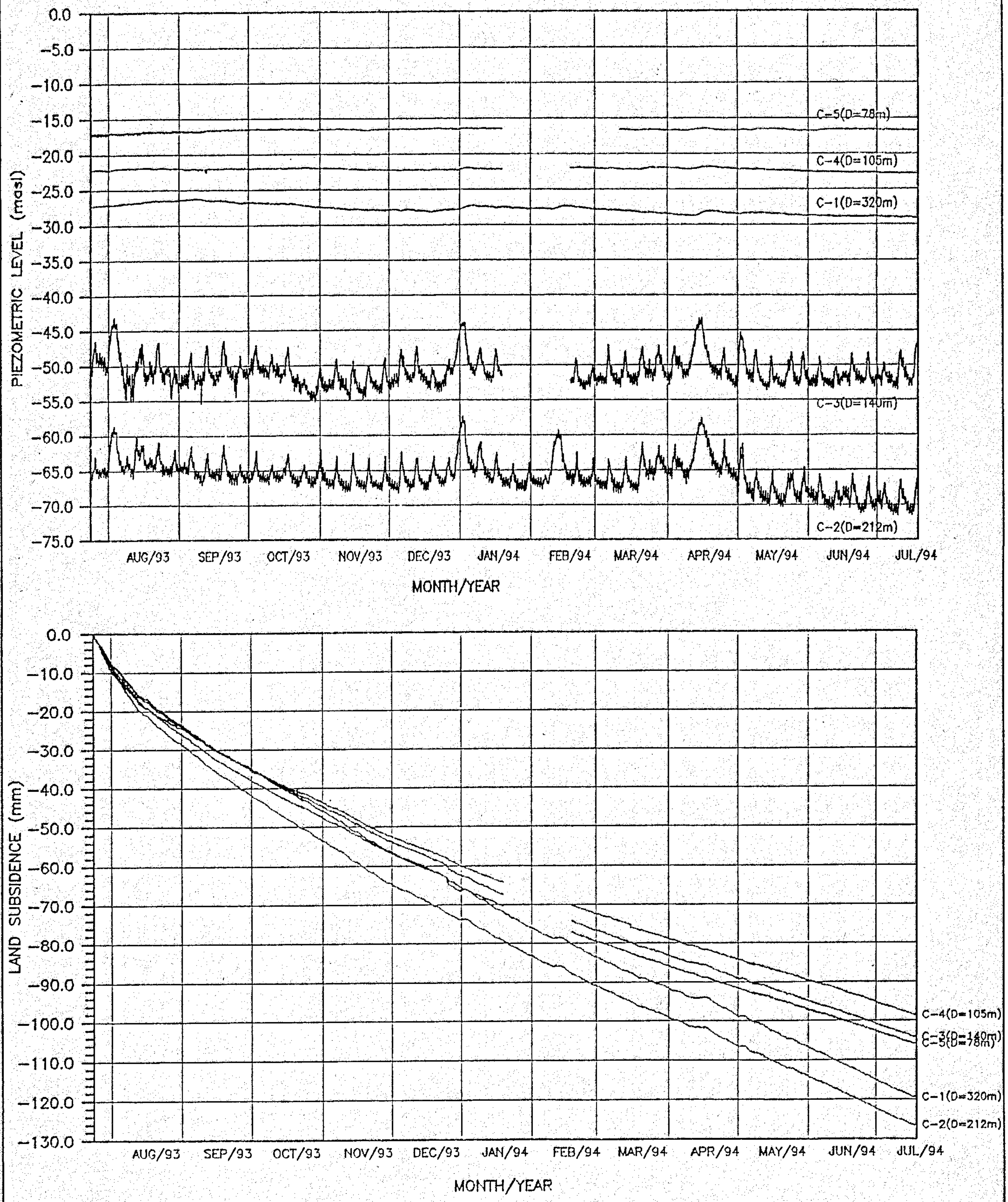
Figure 6.6	PIEZOMETRIC LEVELS AND LAND SUBSIDENCE AT SITE - A
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.





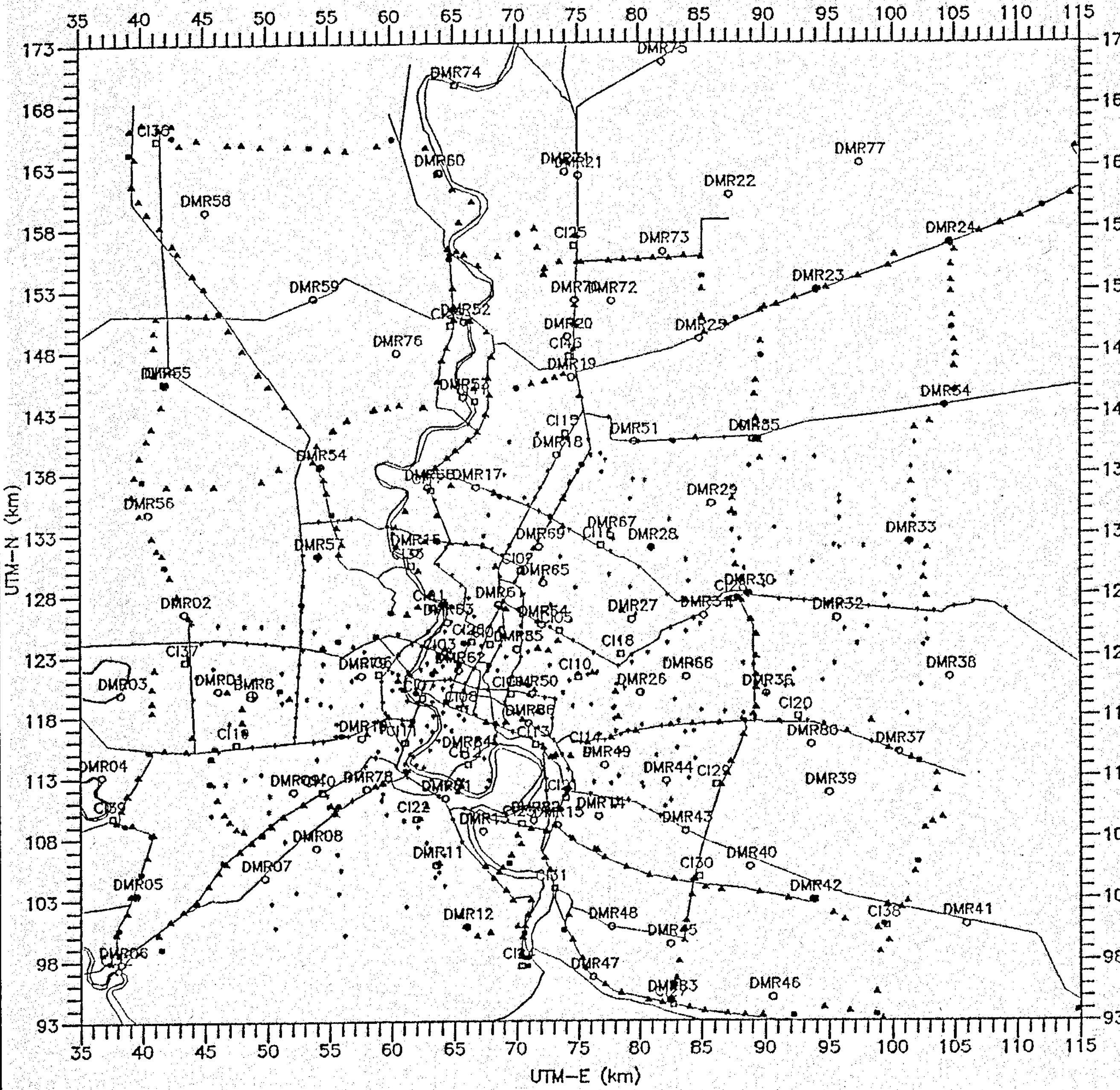
WELL NO.: JICA B-1 to B-5
LOCATION: AIT
UTM GRID: 746568

Figure 6.7	PIEZOMETRIC LEVELS AND LAND SUBSIDENCE AT SITE - B
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.



WELL NO.: JICA C-1 to C-5
LOCATION: SAMUT SAKHON
UTM GRID: 381007

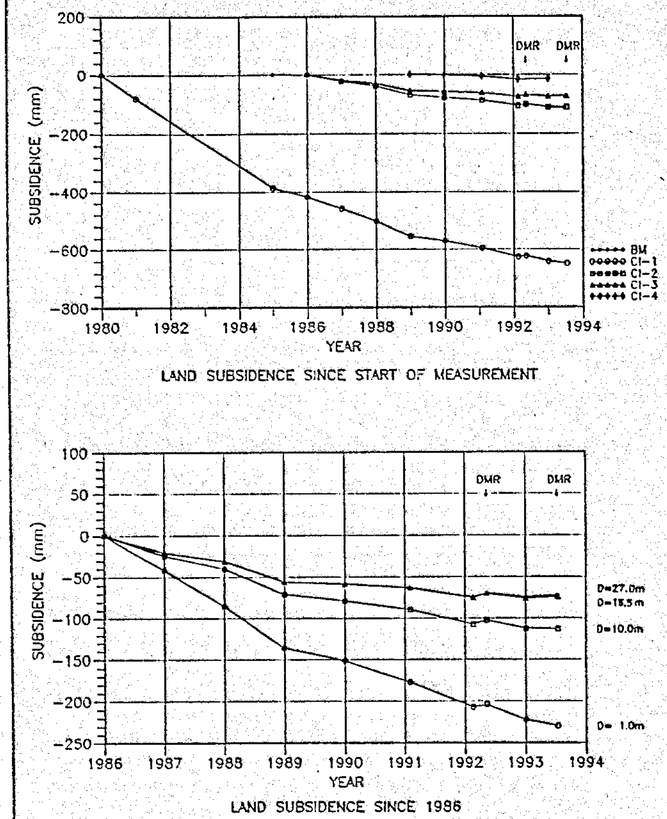
Figure 6.8	PIEZOMETRIC LEVELS AND LAND SUBSIDENCE AT SITE - C
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



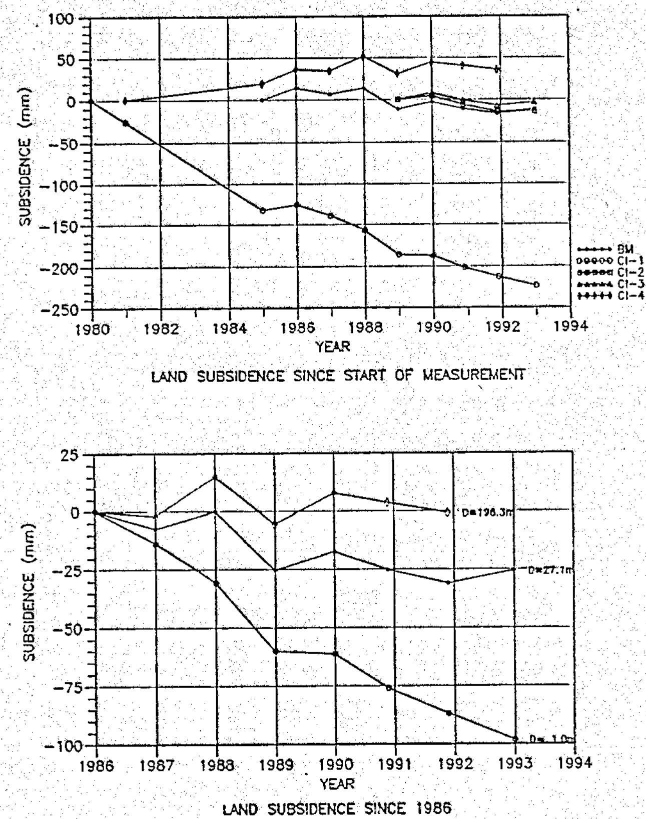
LEGEND

- ○ DMR Land Subsidence Station
- □ NEB Land Subsidence Station (CI Station)
- • RTSD BMP–series Benchmark
- ▲ RTSD BMS–series Benchmark
- ⋅ BMA Benchmark
- ⊕ RTSD BMR Benchmark

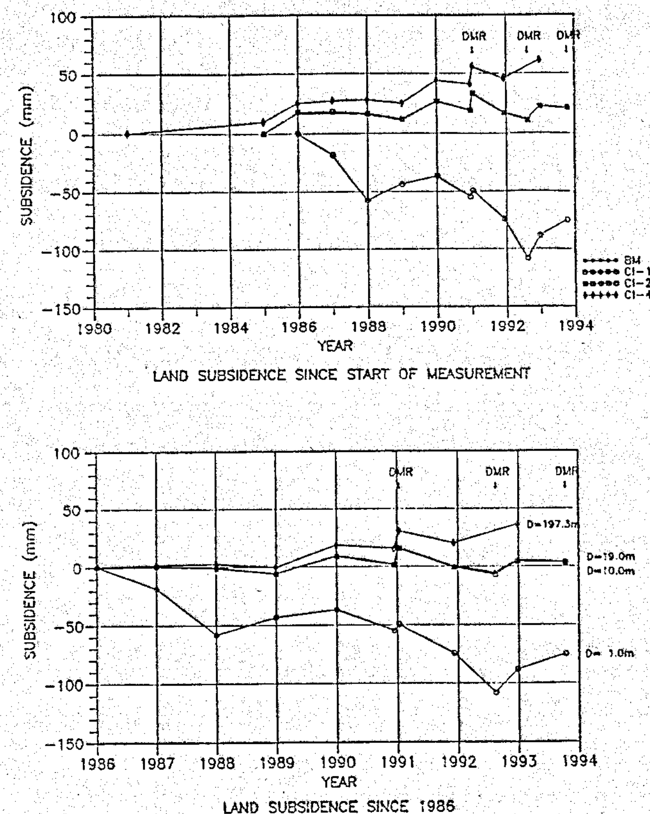
Figure 6.9	LOCATION OF LAND SUBSIDENCE STATIONS AND BENCHMARKS
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



a) AIT14 STATION



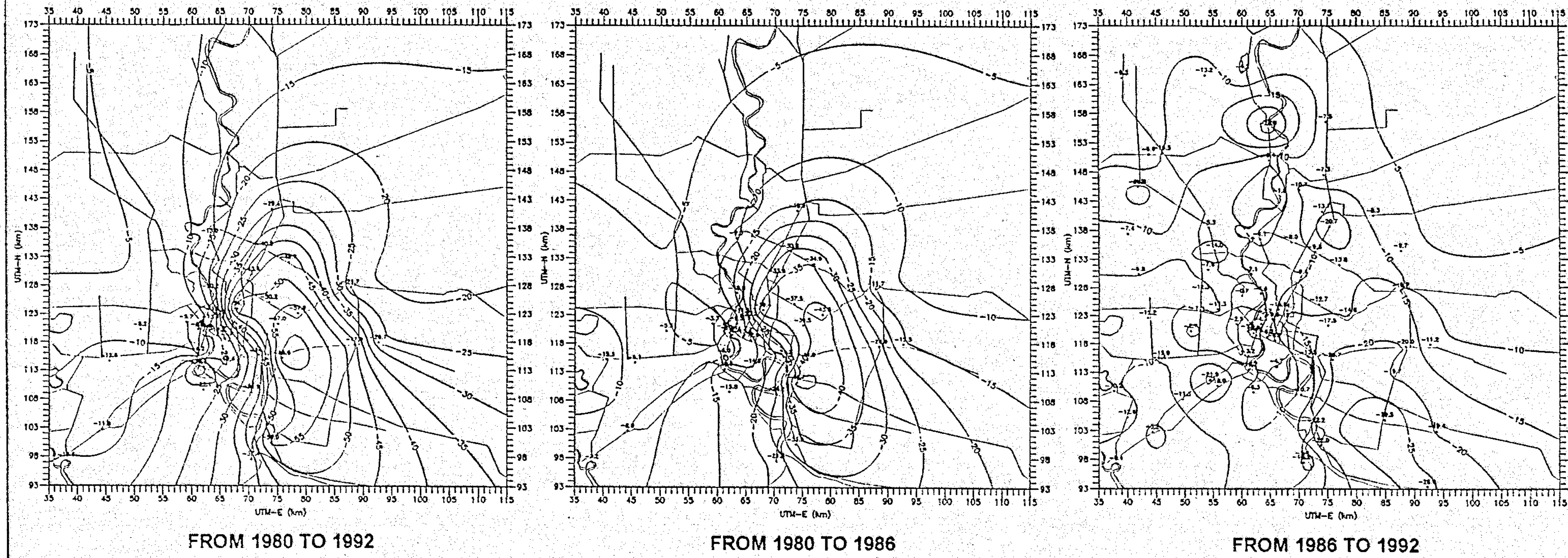
b) AIT08 STATION



c) AIT25 STATION

(DMR: Measured by DMR)

Figure 6.10	LAND SUBSIDENCE
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.



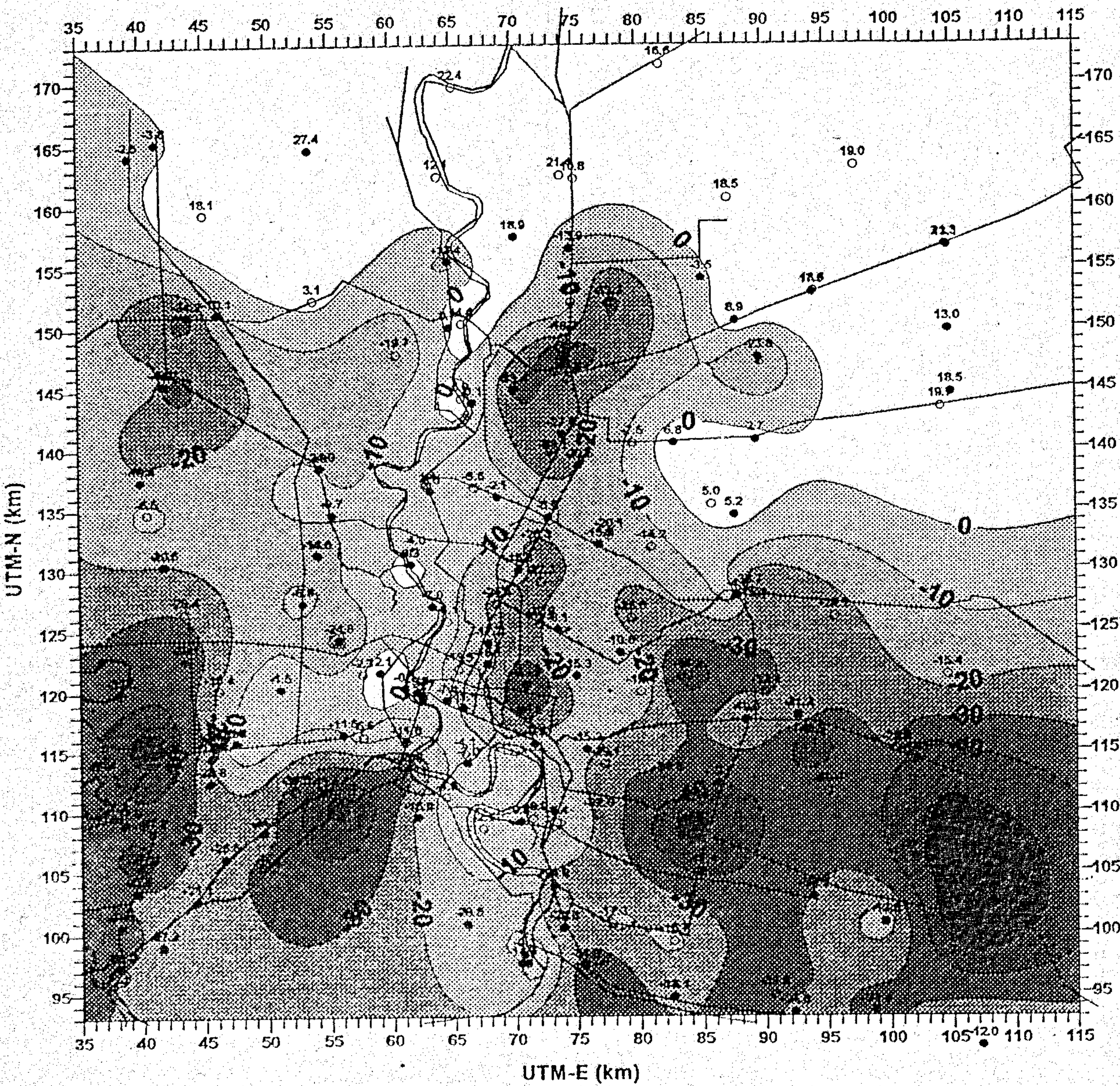
LEGEND

LINE OF EQUAL LAND SUBSIDENCE (cm/12years)

-20.0 LAND SUBSIDENCE STATION OR BENCHMARK WITH LAND SUBSIDENCE (cm/12years)

(Negative sign represents subsidence.)

Figure 6.11	LAND SUBSIDENCE MEASURED AT 1 m DEPTH BENCHMARKS
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.



LAND SUBSIDENCE (mm/year)

-70 -60 -50 -40 -30 -20 -10

○ DMR Benchmarks (1m depth)

● RTSD Benchmarks (1m depth)

Figure 6.12	LAND SUBSIDENCE FROM 1992 TO 1993 MEASURED AT 1m DEPTH BENCHMARKS
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 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).

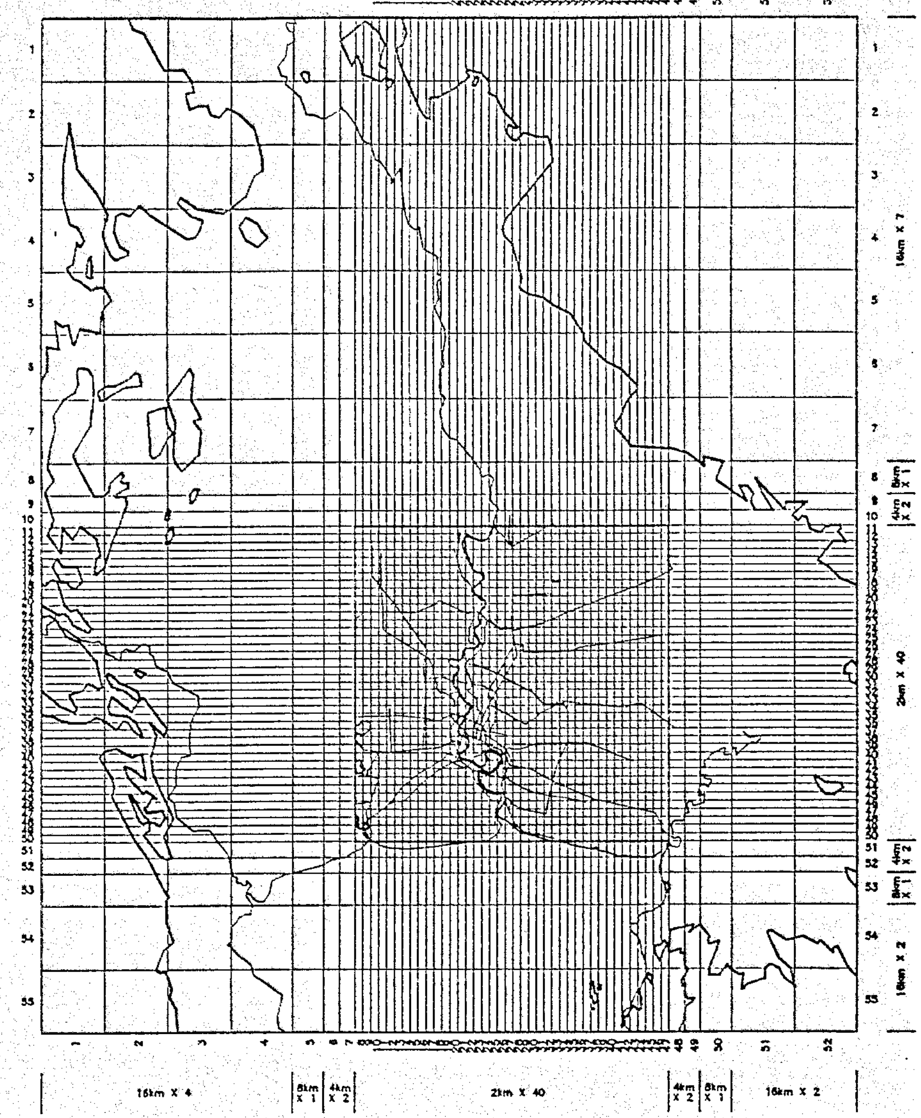


Figure 7.1.1 GRID FOR 3-D MODFLOW MODEL

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

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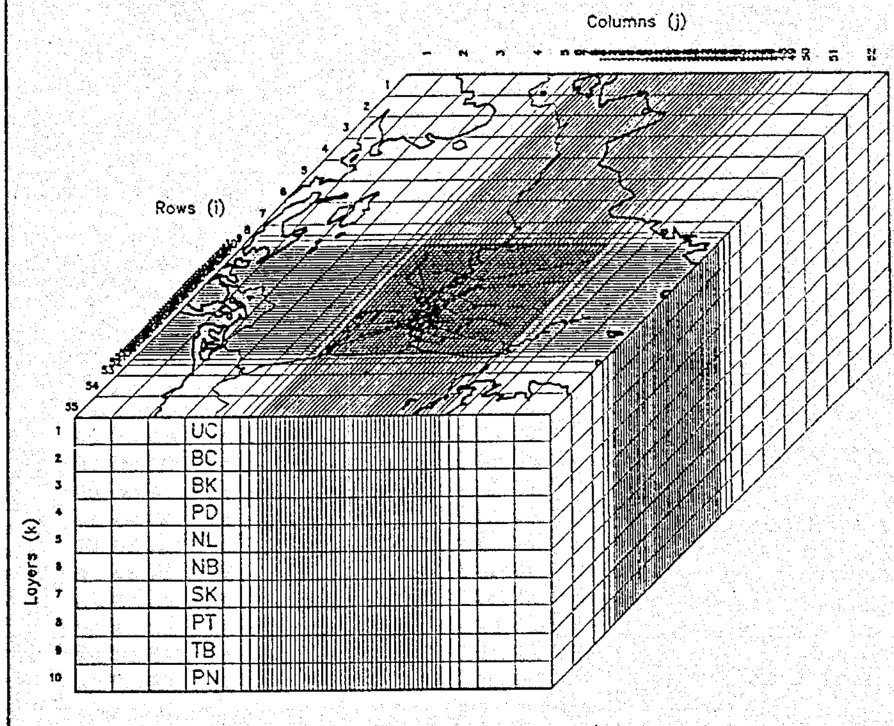

AQUIFER UNITS

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

Figure 7.1.2 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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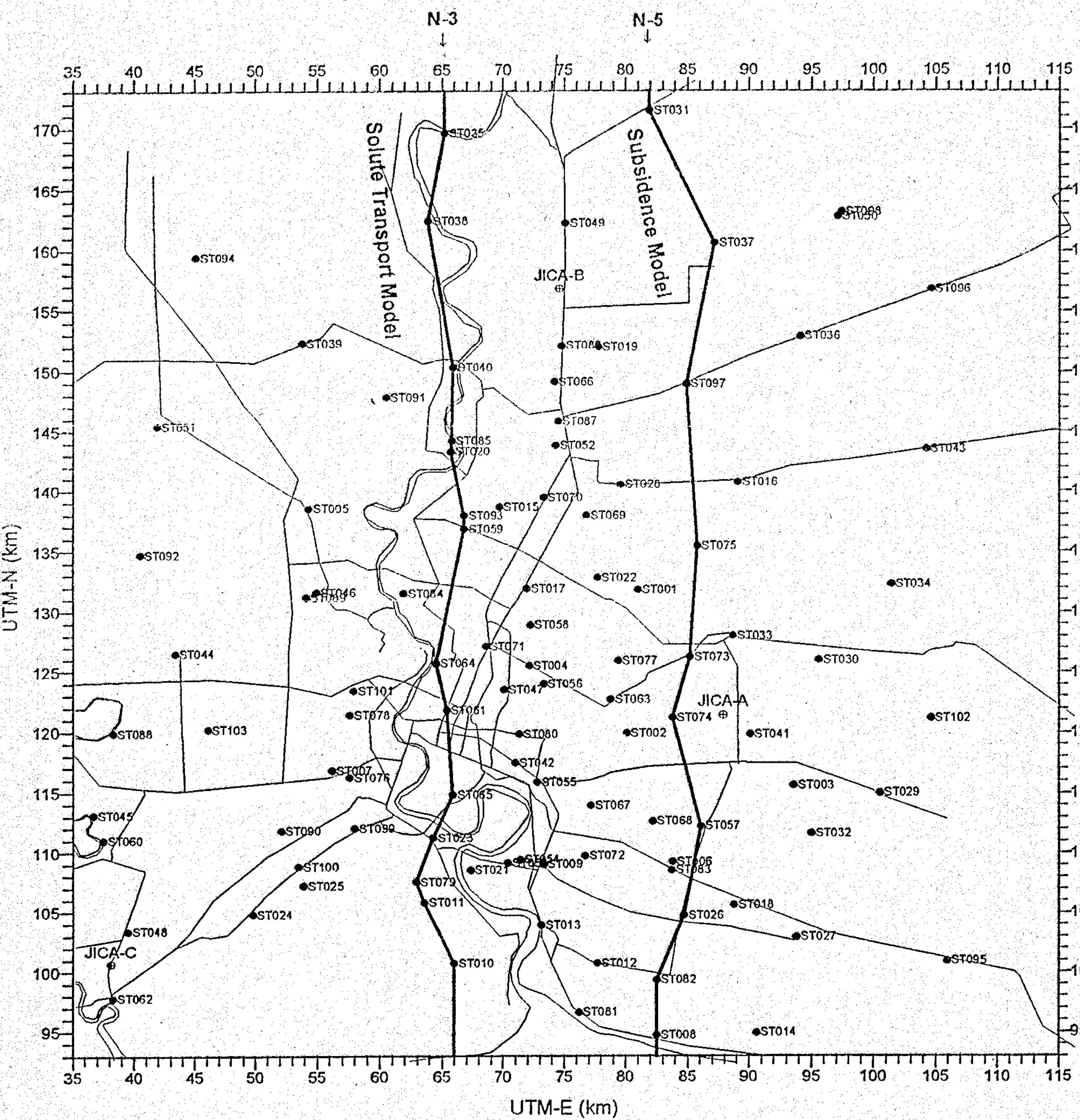
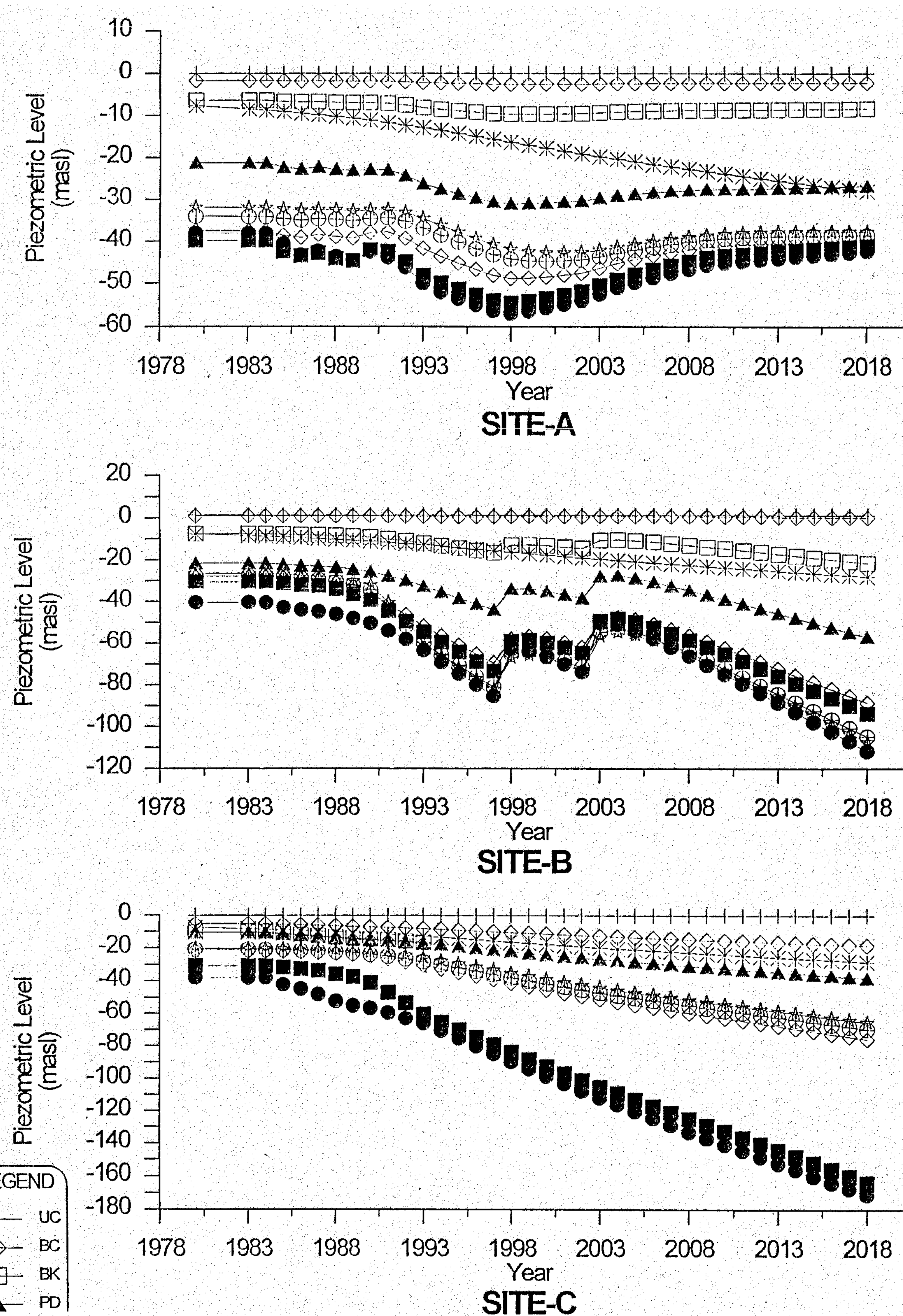


LEGEND

———	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	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



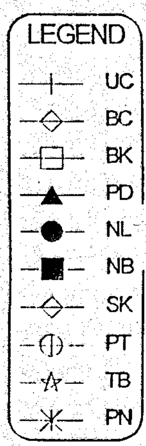


図　8.2.1 JICAモニタリング井周辺の地下水位変化予測値（シナリオ2）

	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.

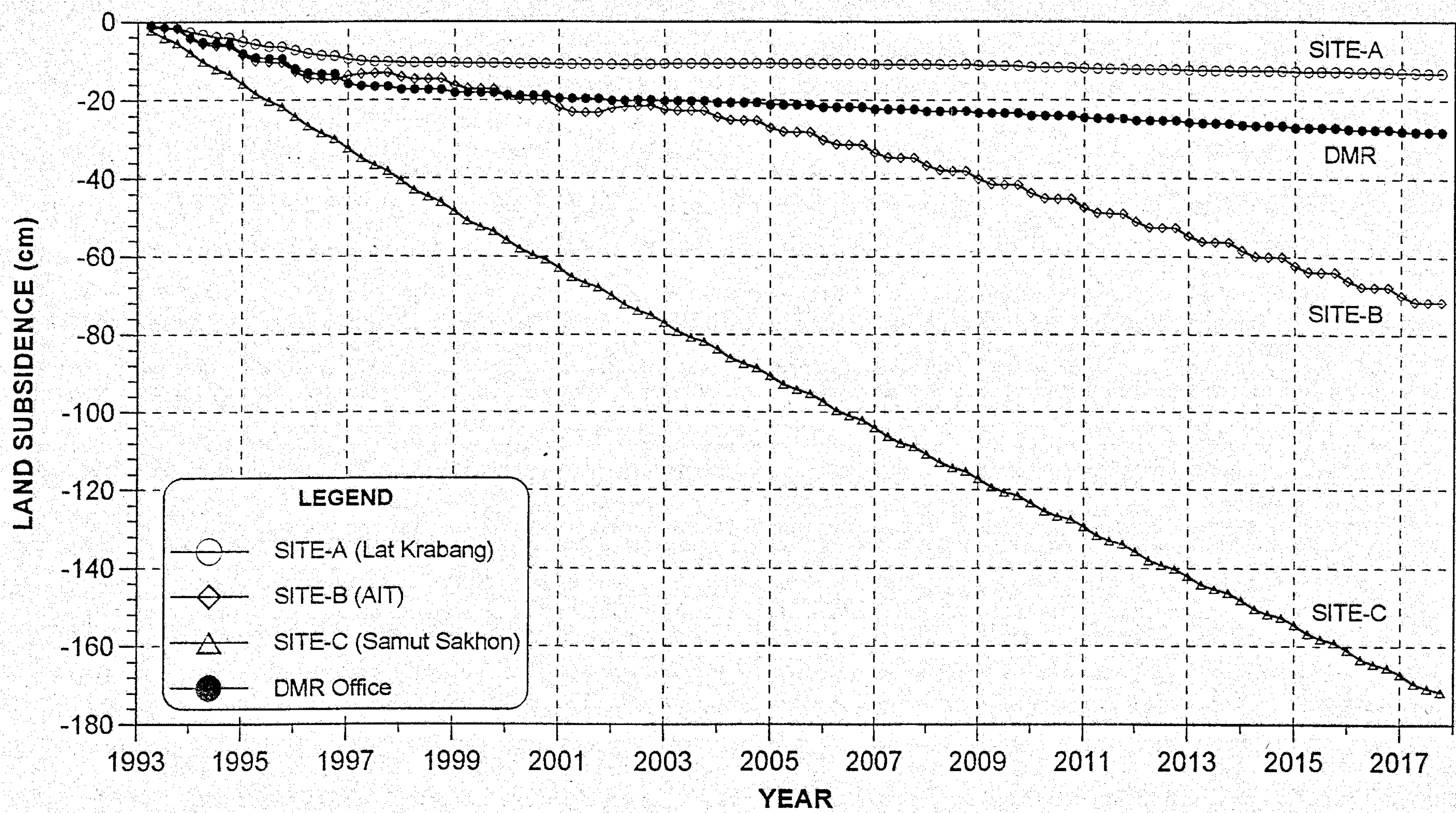
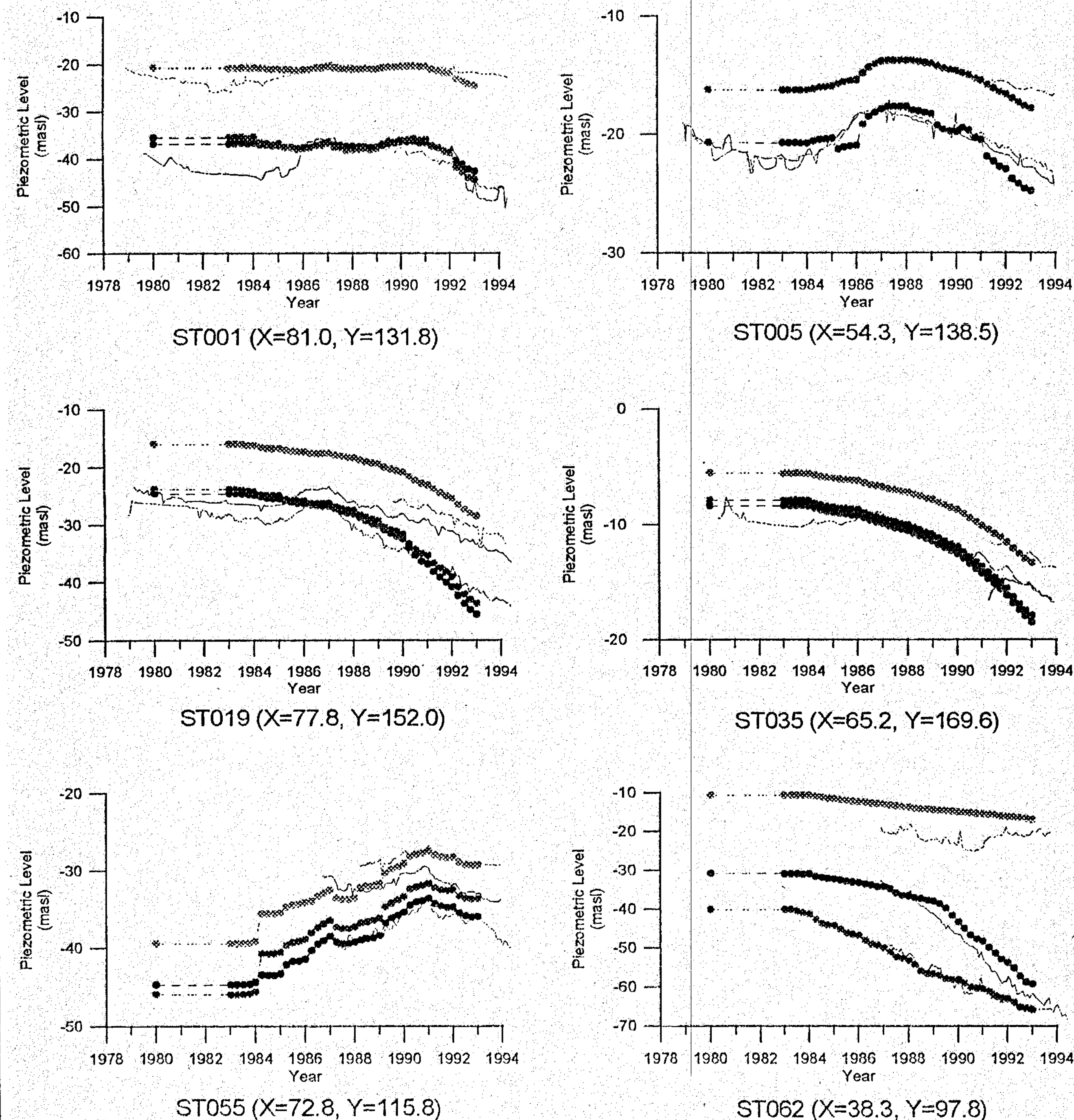


Figure 7.2.75	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 2)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

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）



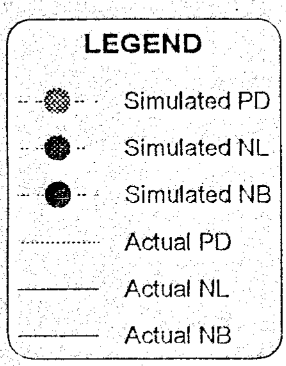


Figure 7.5	COMPARISON OF SIMULATED HEADS BY 3-D MODEL WITH ACTUAL HEADS
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

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.

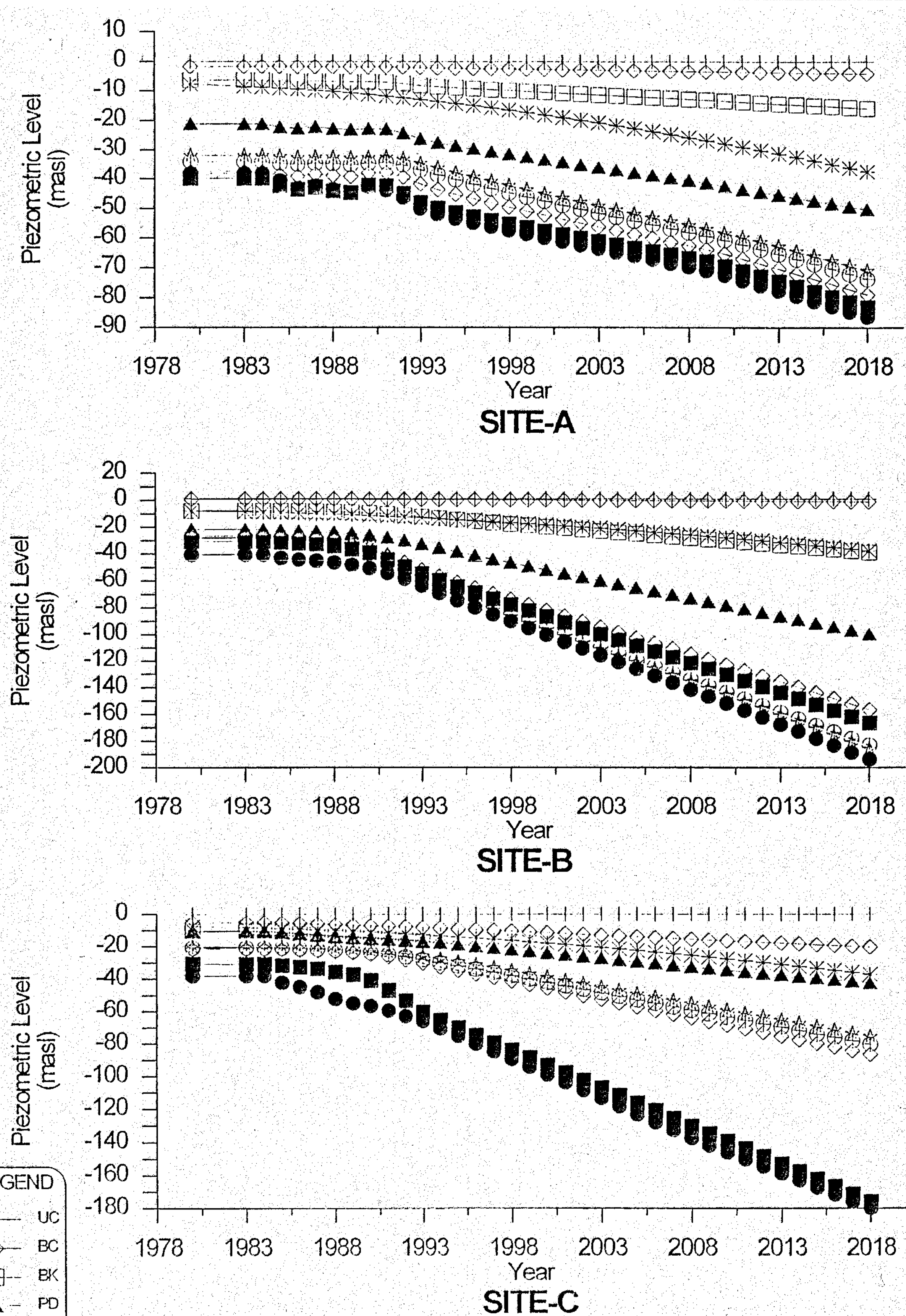
The subsidence in most of the Study Area will be controlled within 30 cm in 2017. Land subsidence of more than 30 cm in the year 2017 is predicted at western Samut Prakan, western Bangkok, central Bangkok, part of Pathum Thani, and part of Phra Nakhon Si Ayutthaya (Figure 8.9.1 to 8.9.3)

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 becme 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.



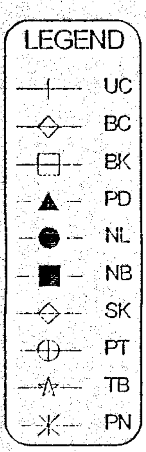


Figure 8.1.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 1)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

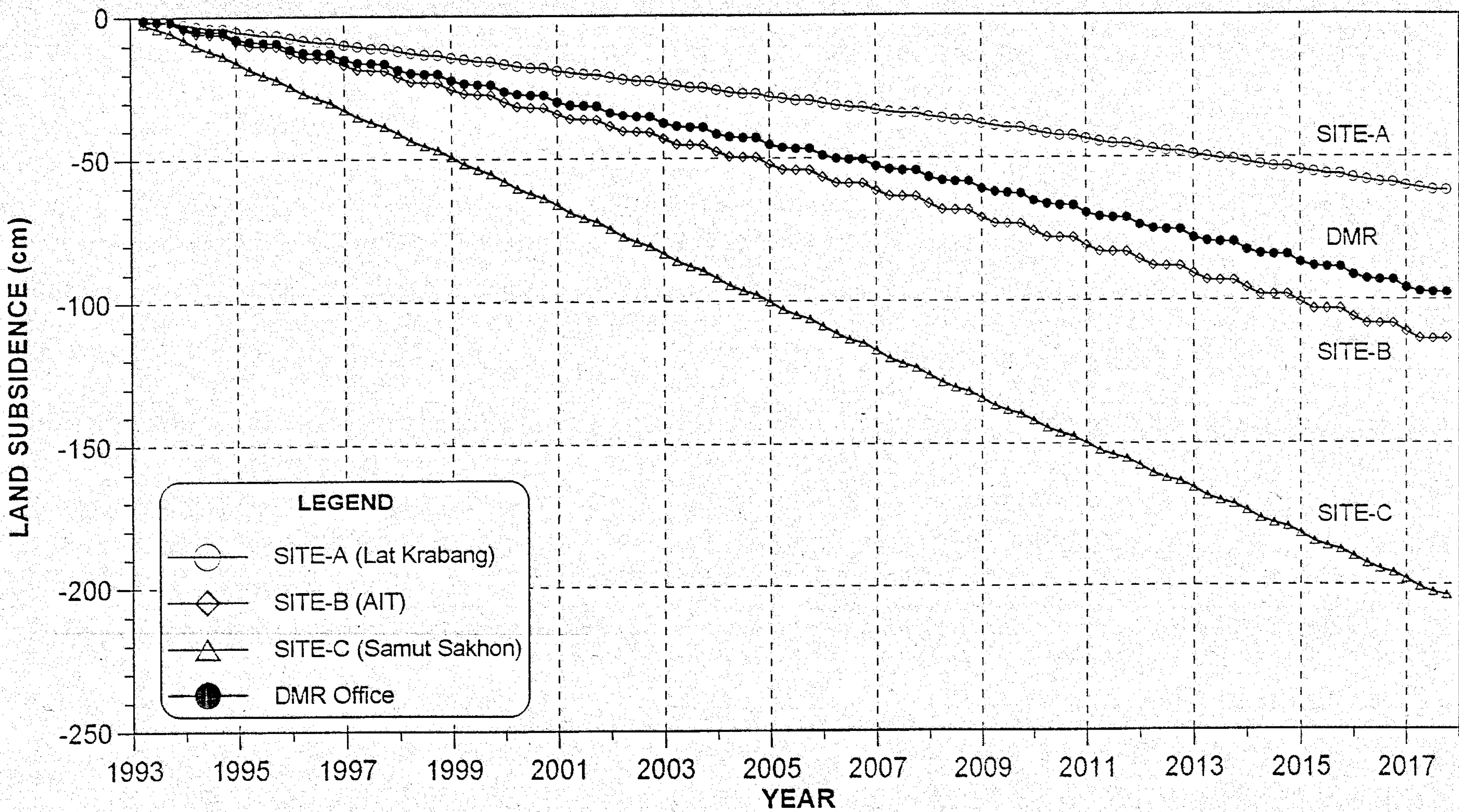
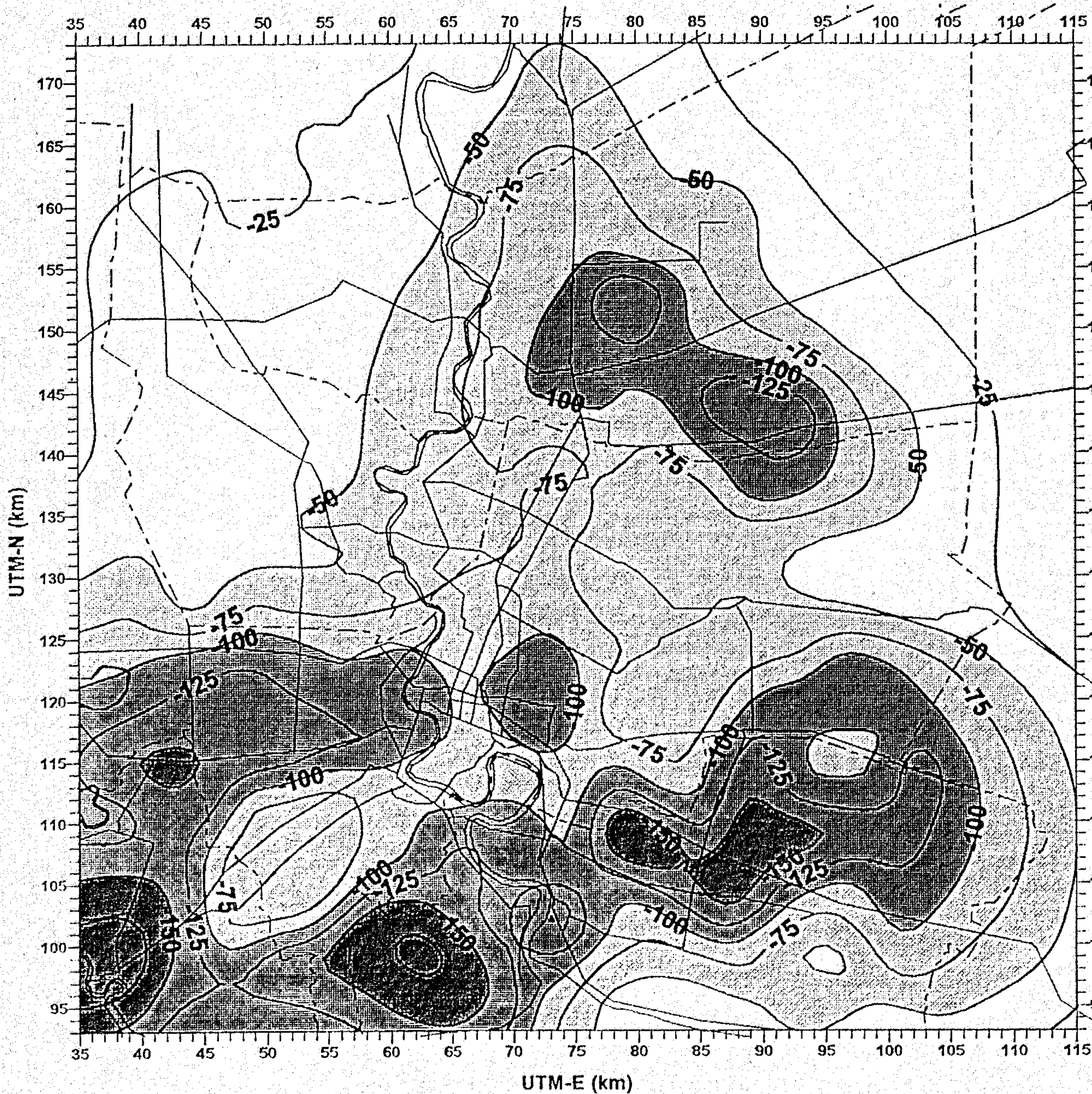


Figure 8.1.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 1)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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.

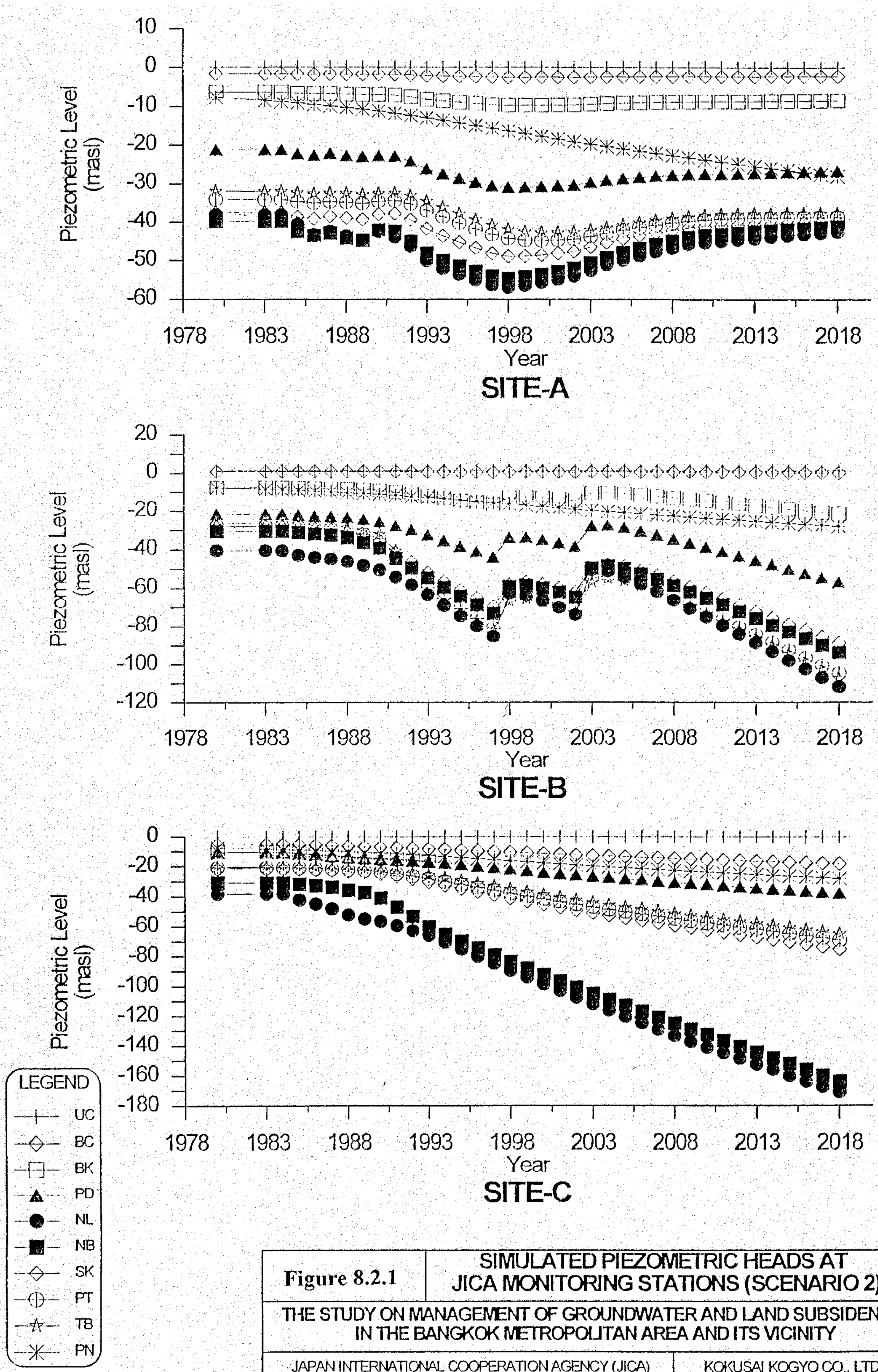


Figure 8.2.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 2)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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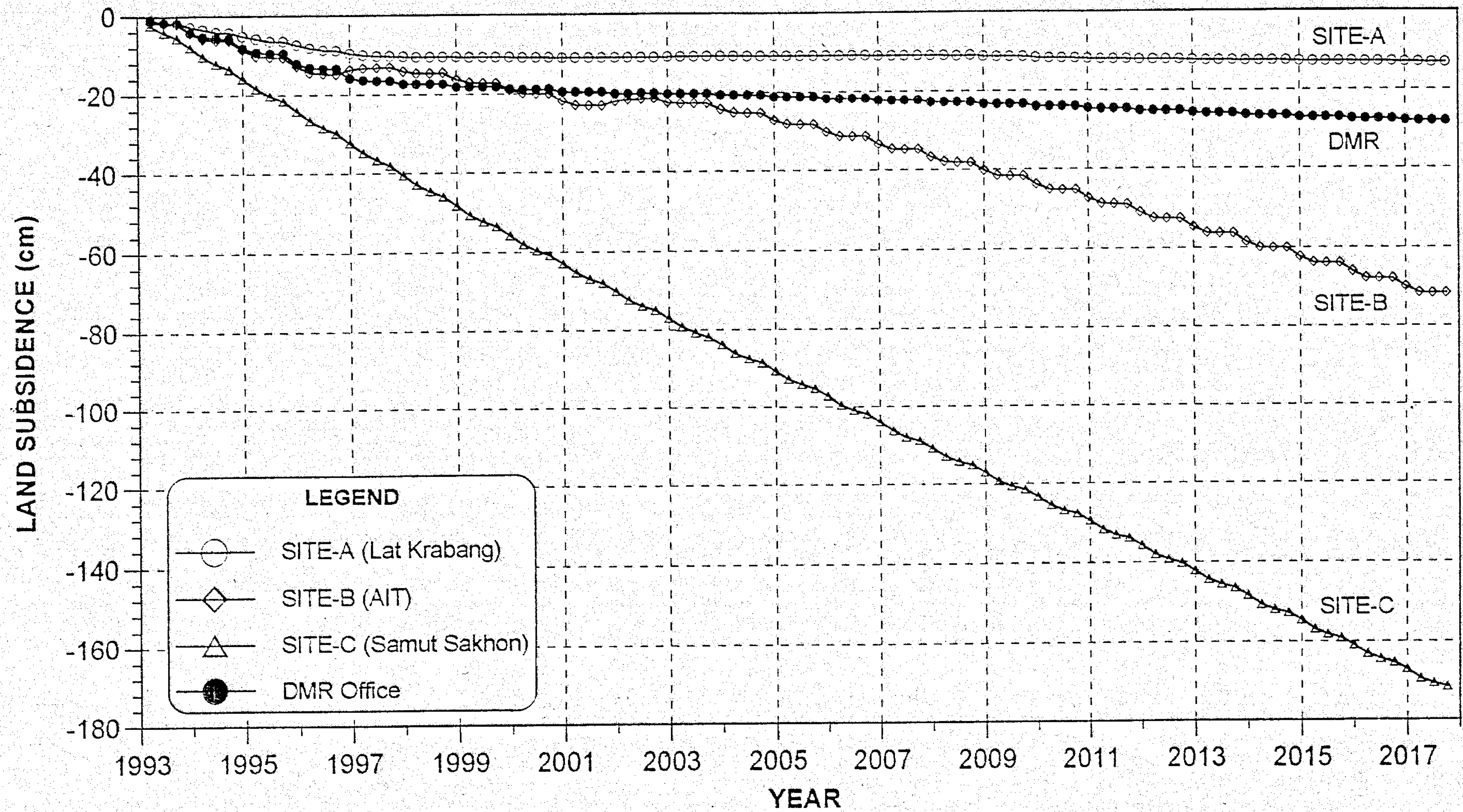
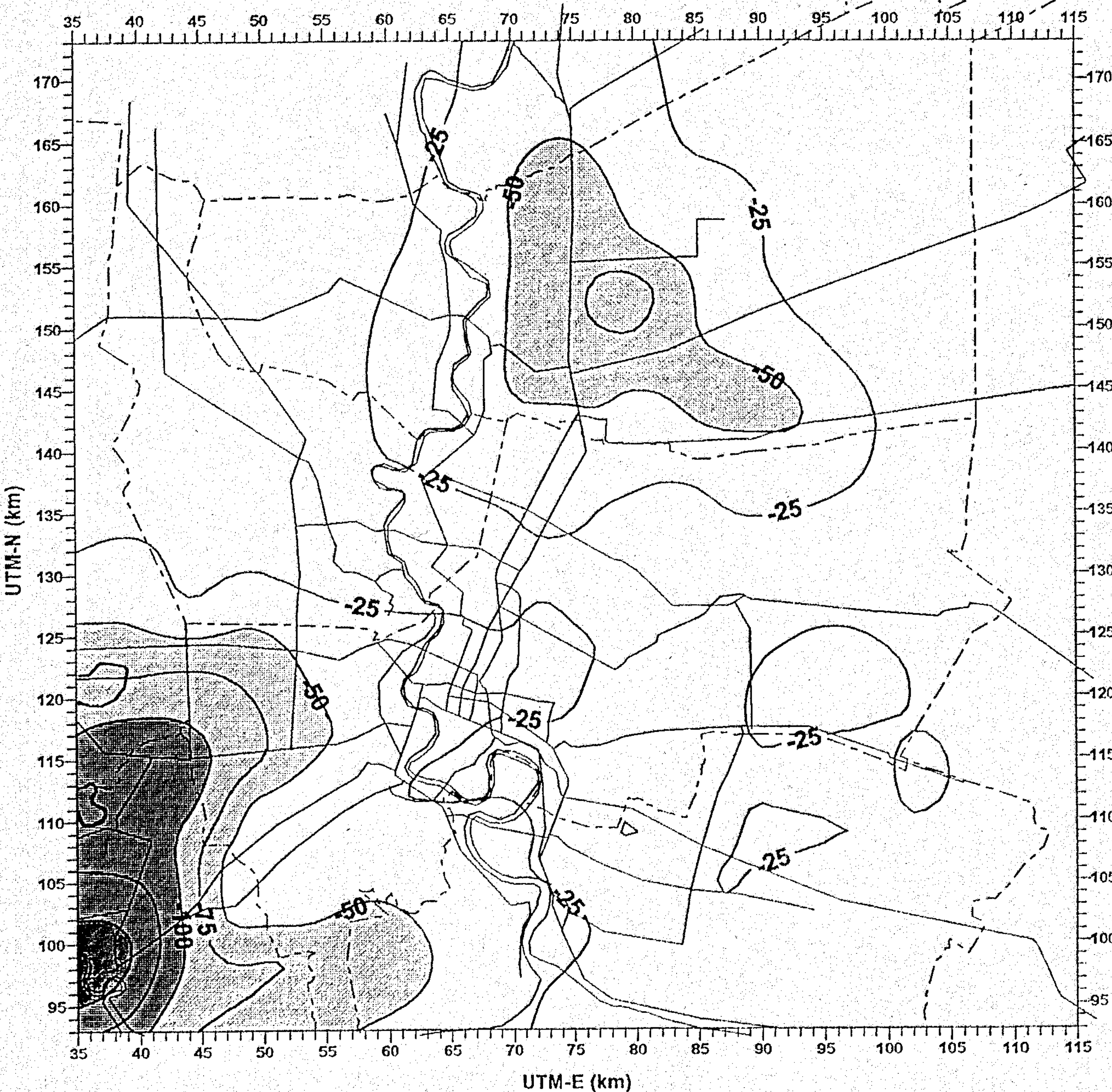
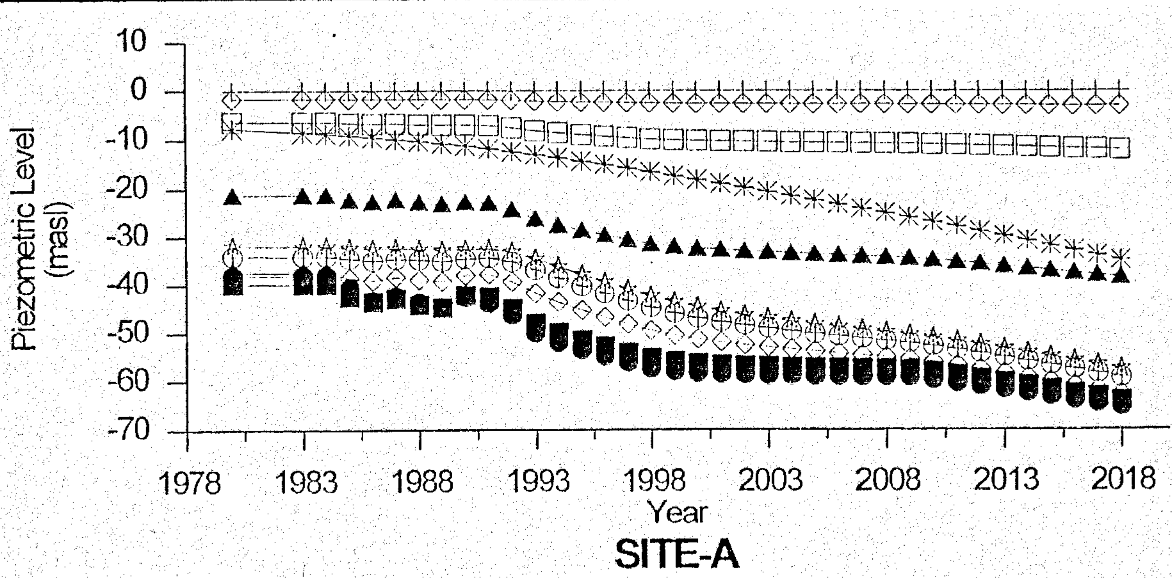


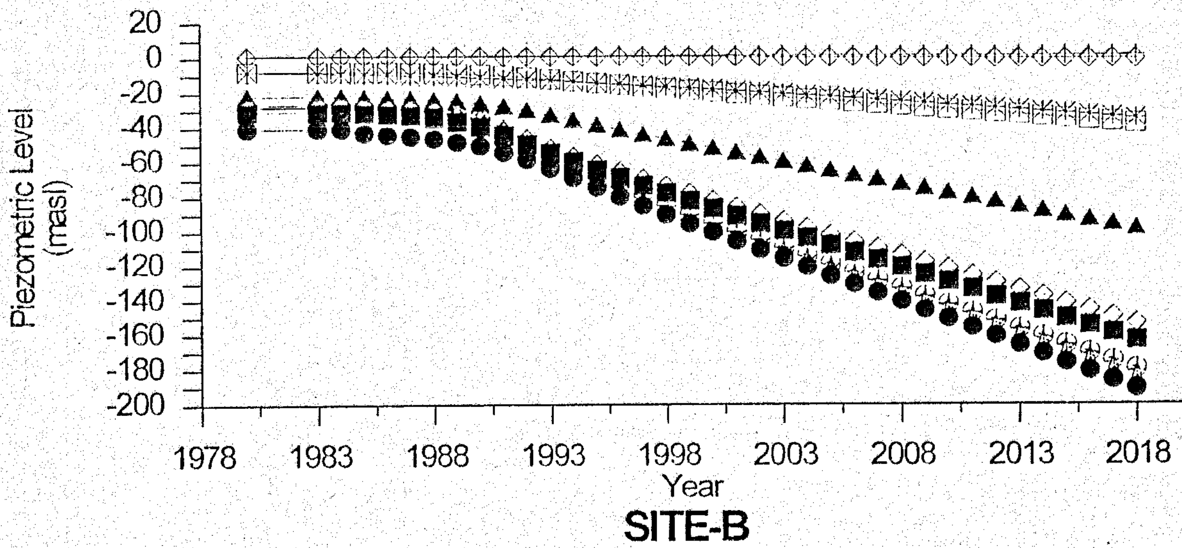
Figure 8.2.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 2)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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.





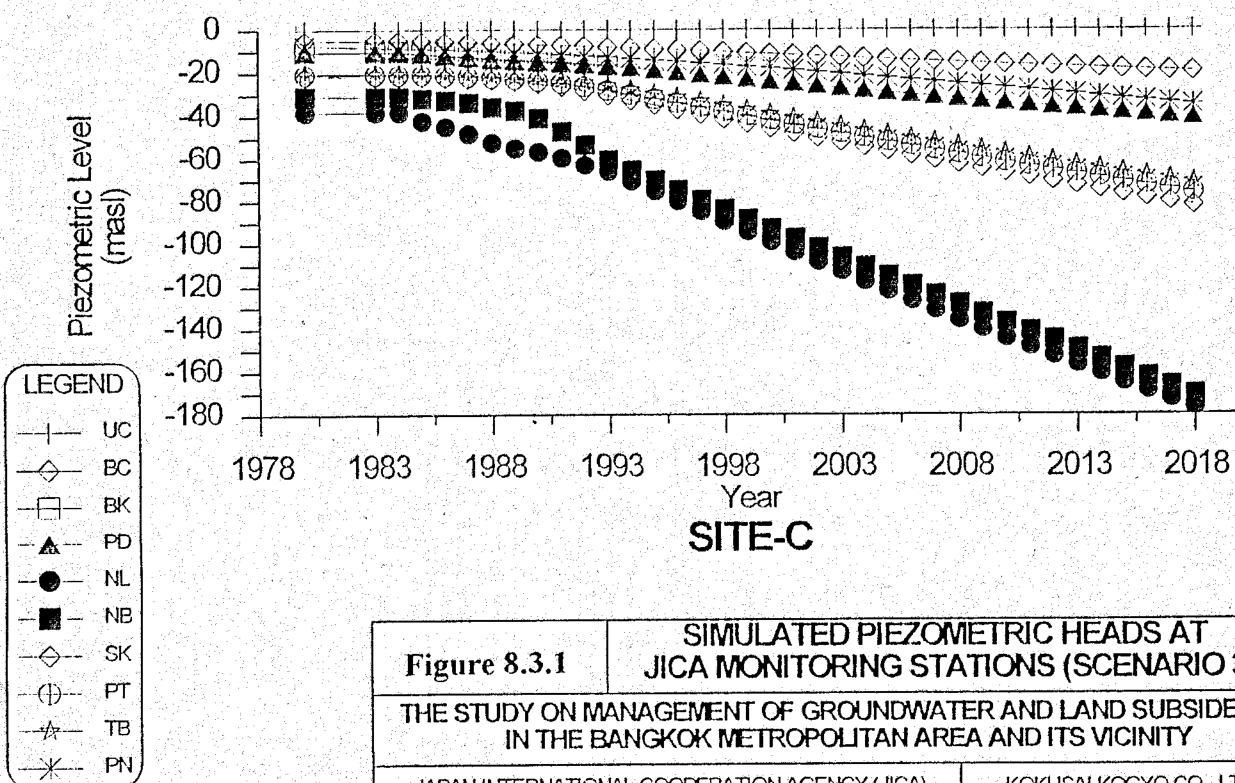


Figure 8.3.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 3)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

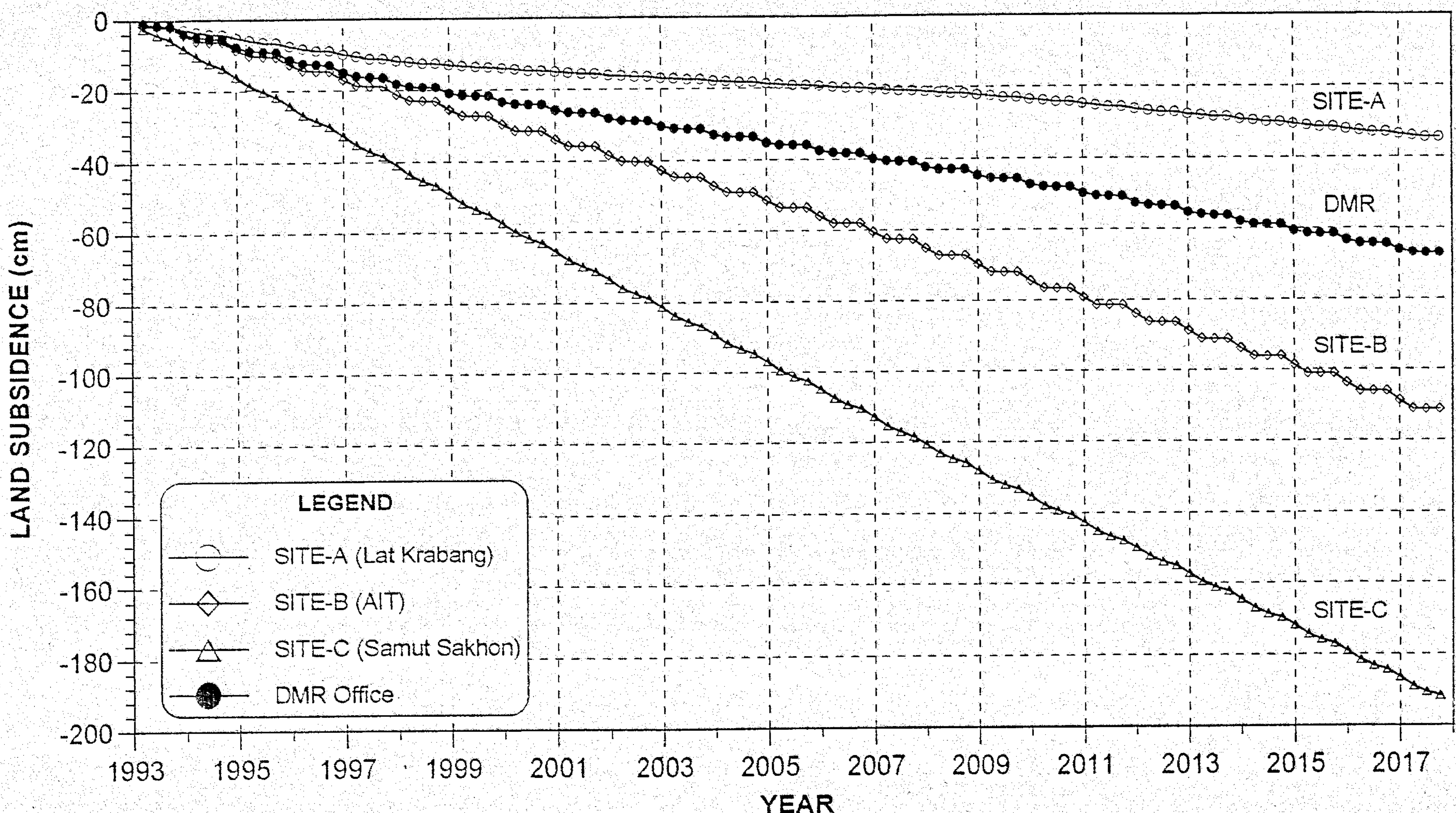
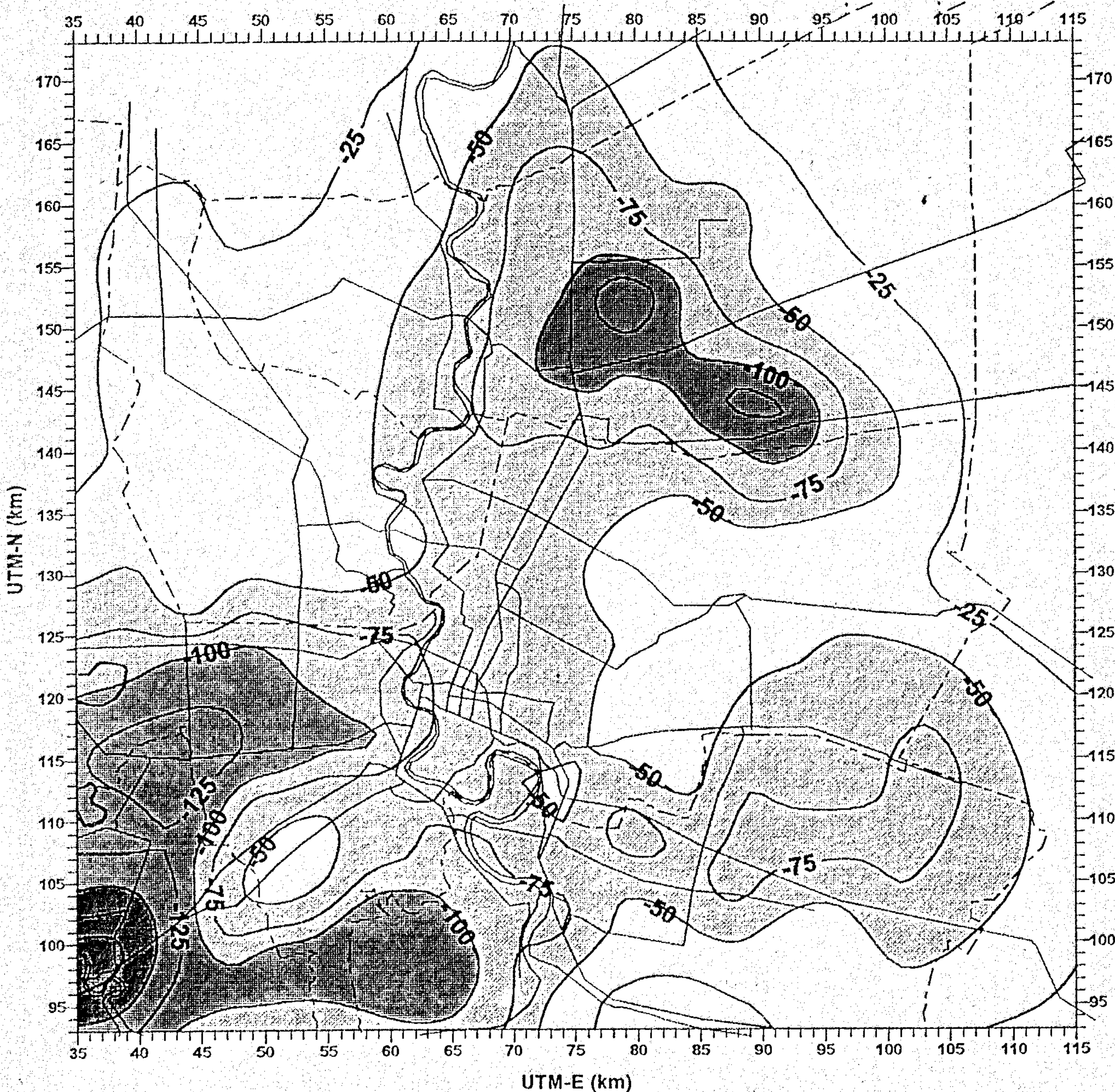
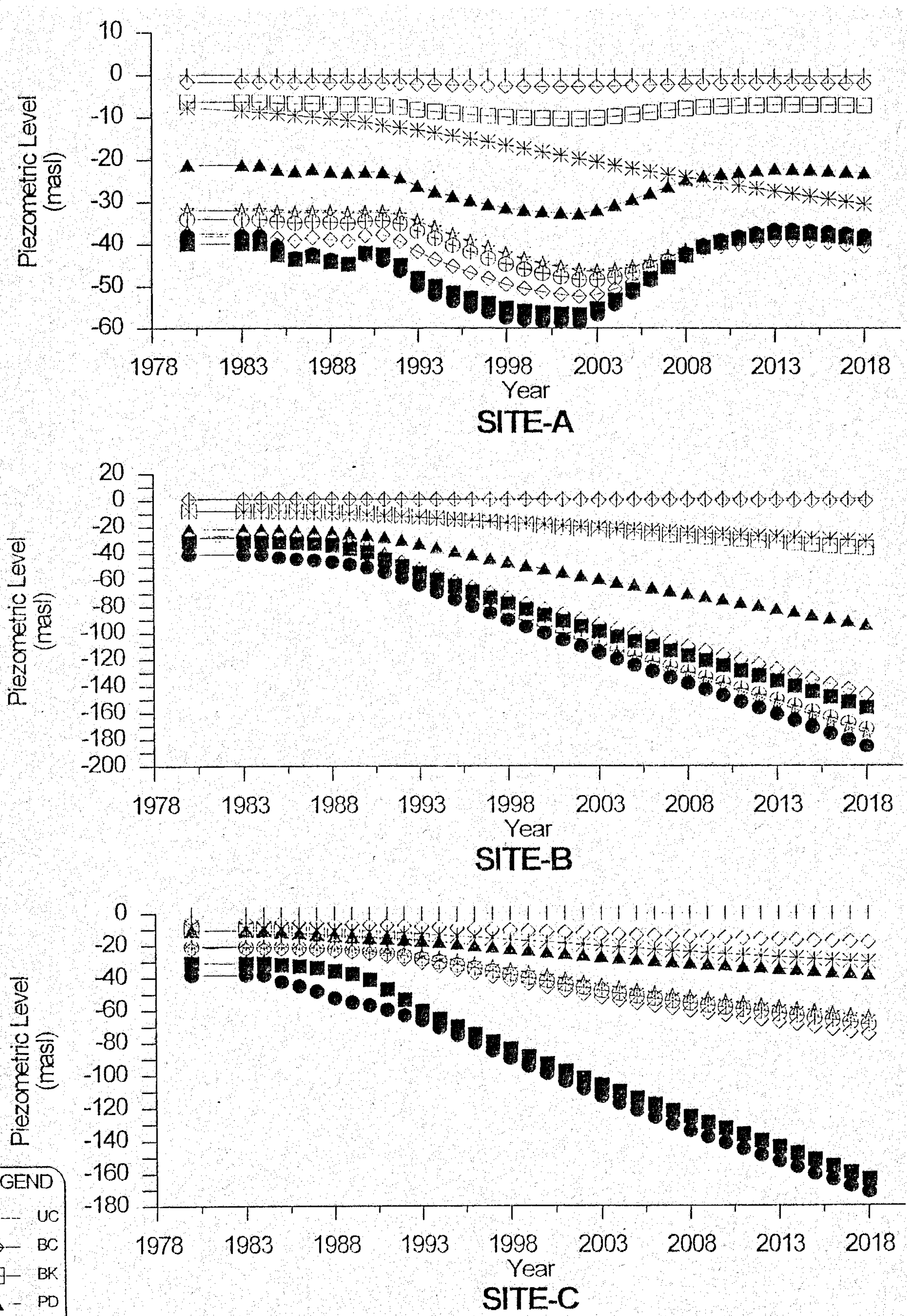


Figure 8.3.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 3)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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.



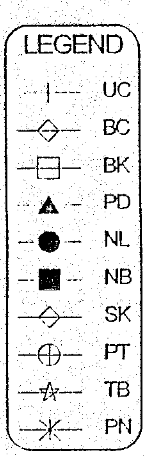


Figure 8.4.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 4)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

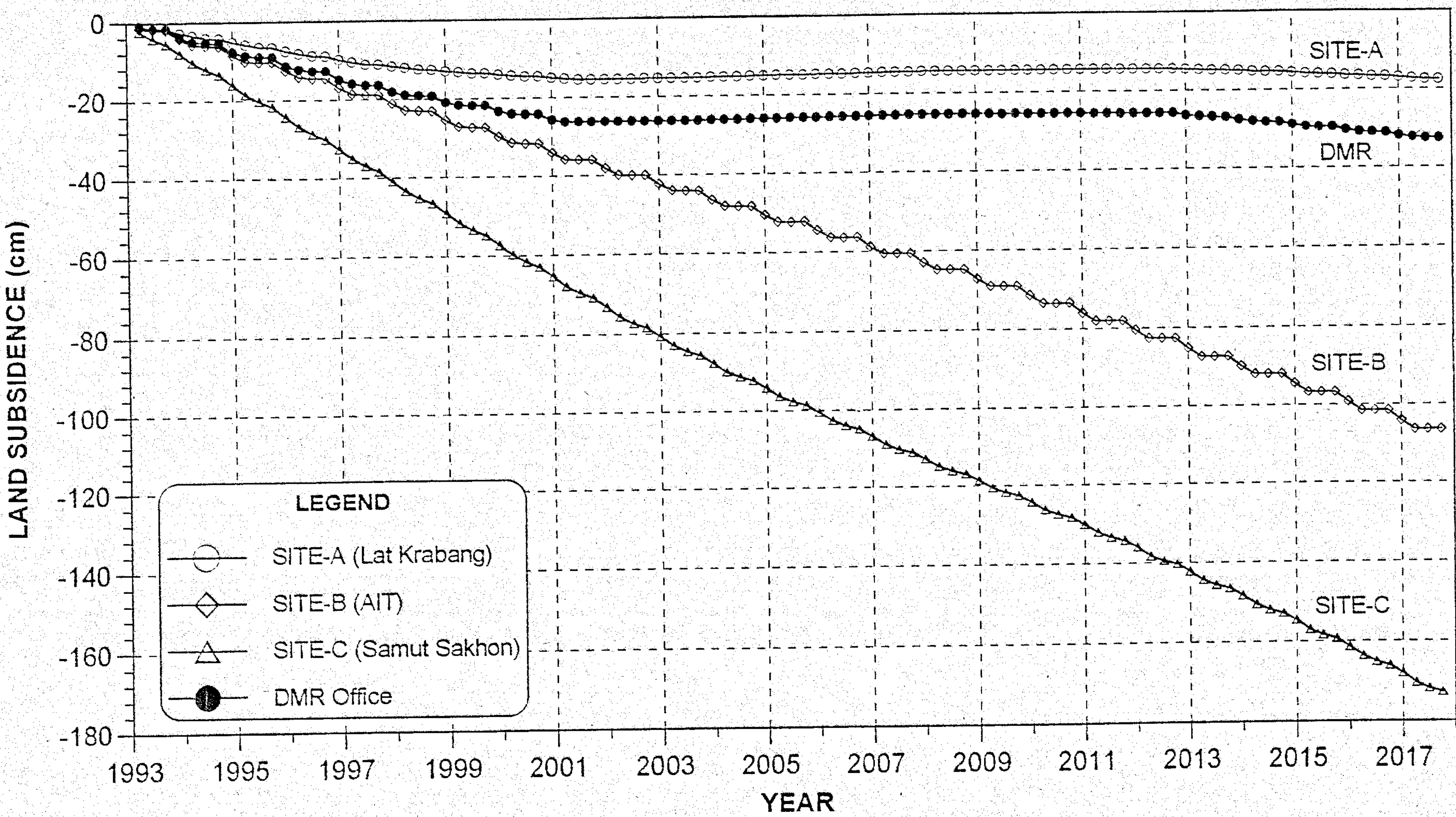
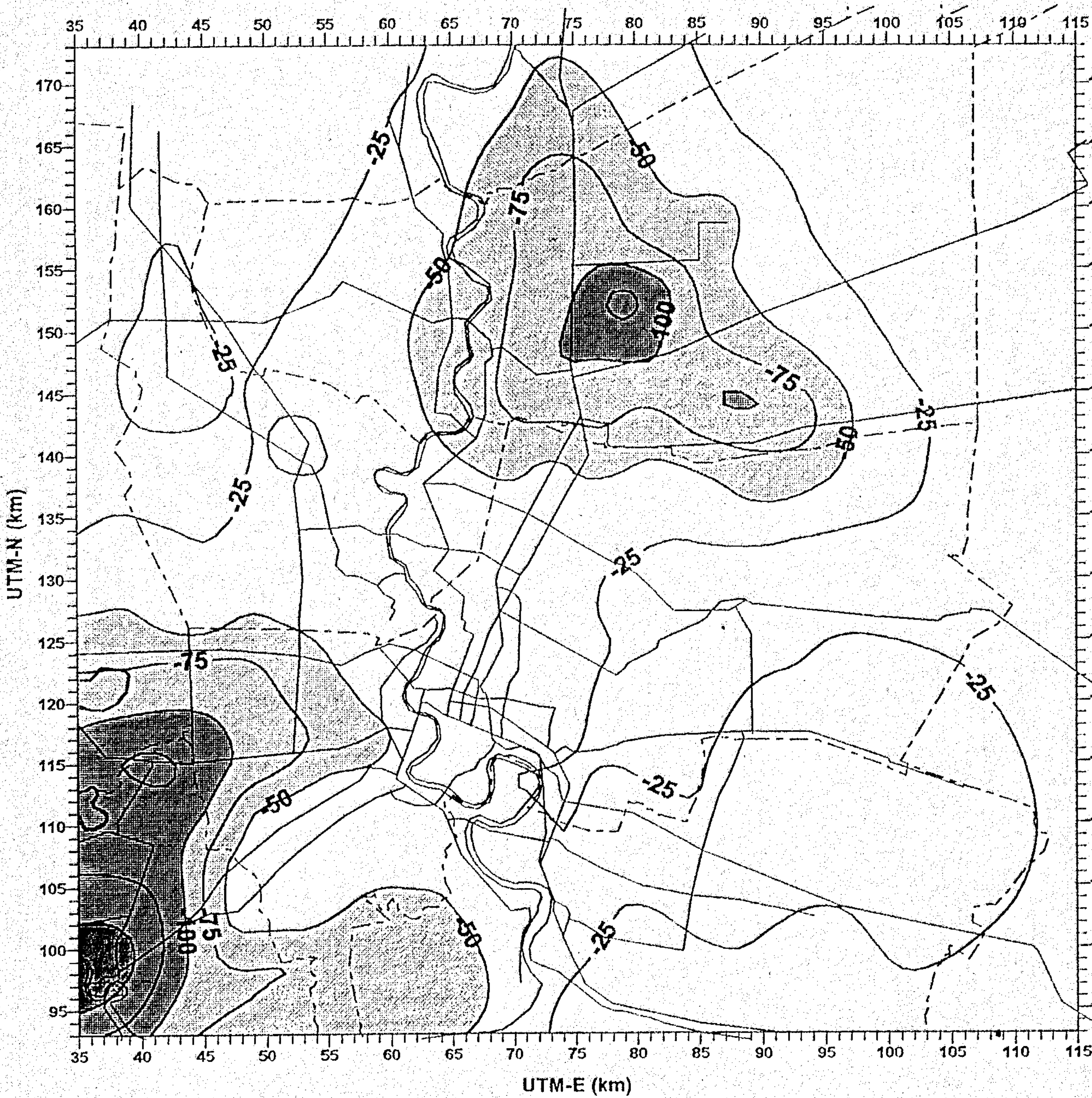


Figure 8.4.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 4)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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	
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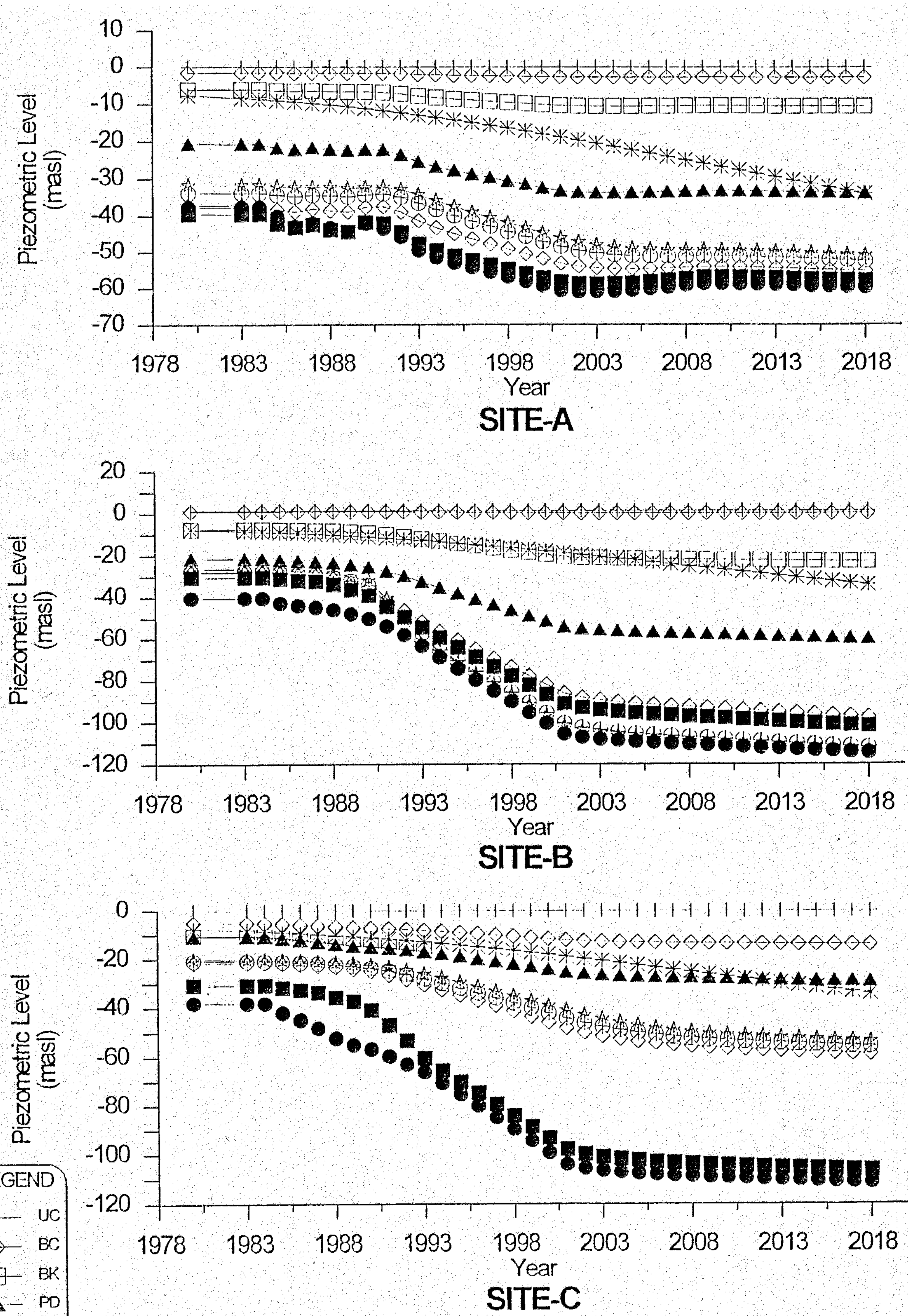


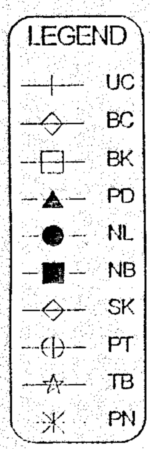


Figure 8.5.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 5)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

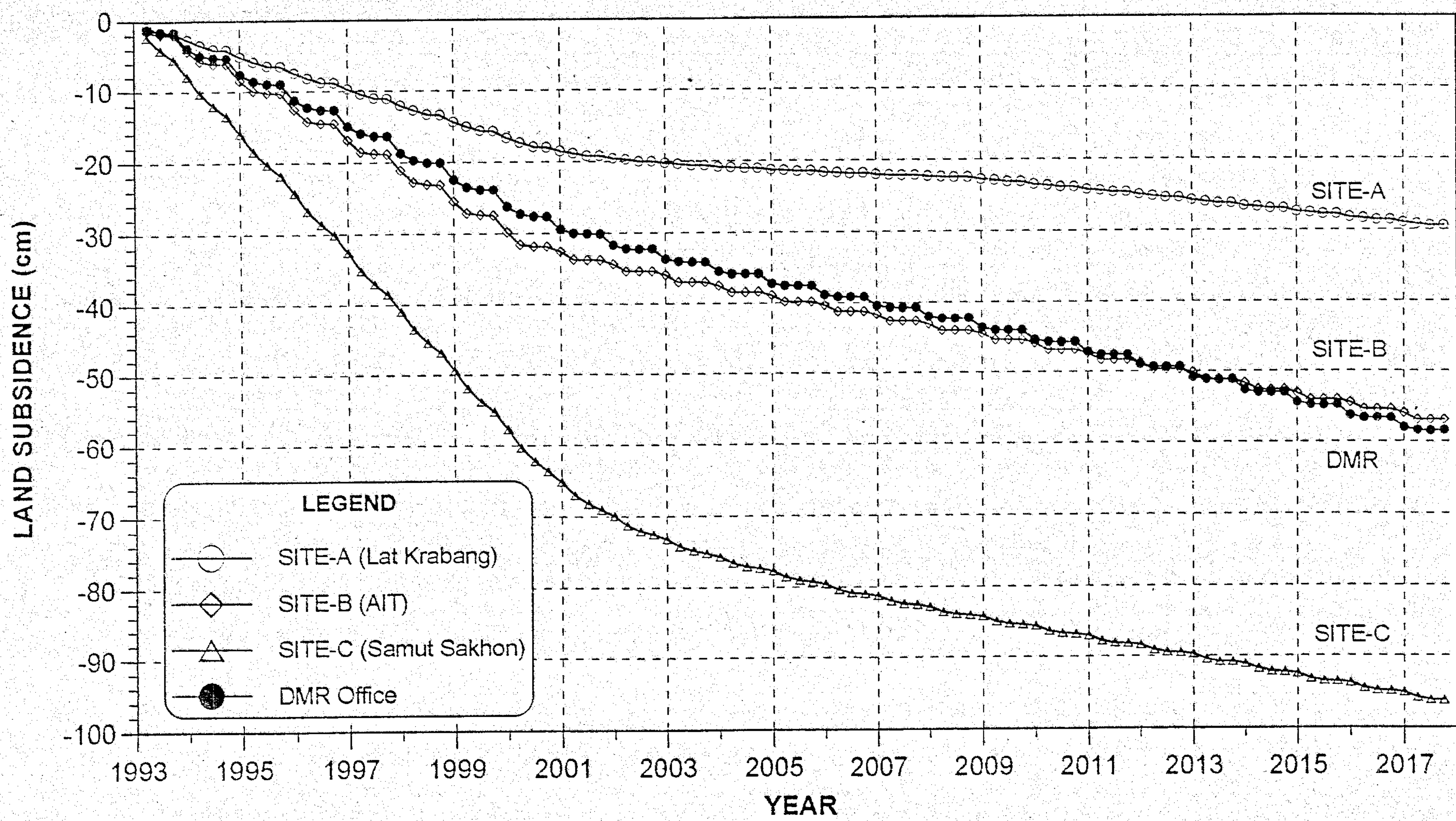
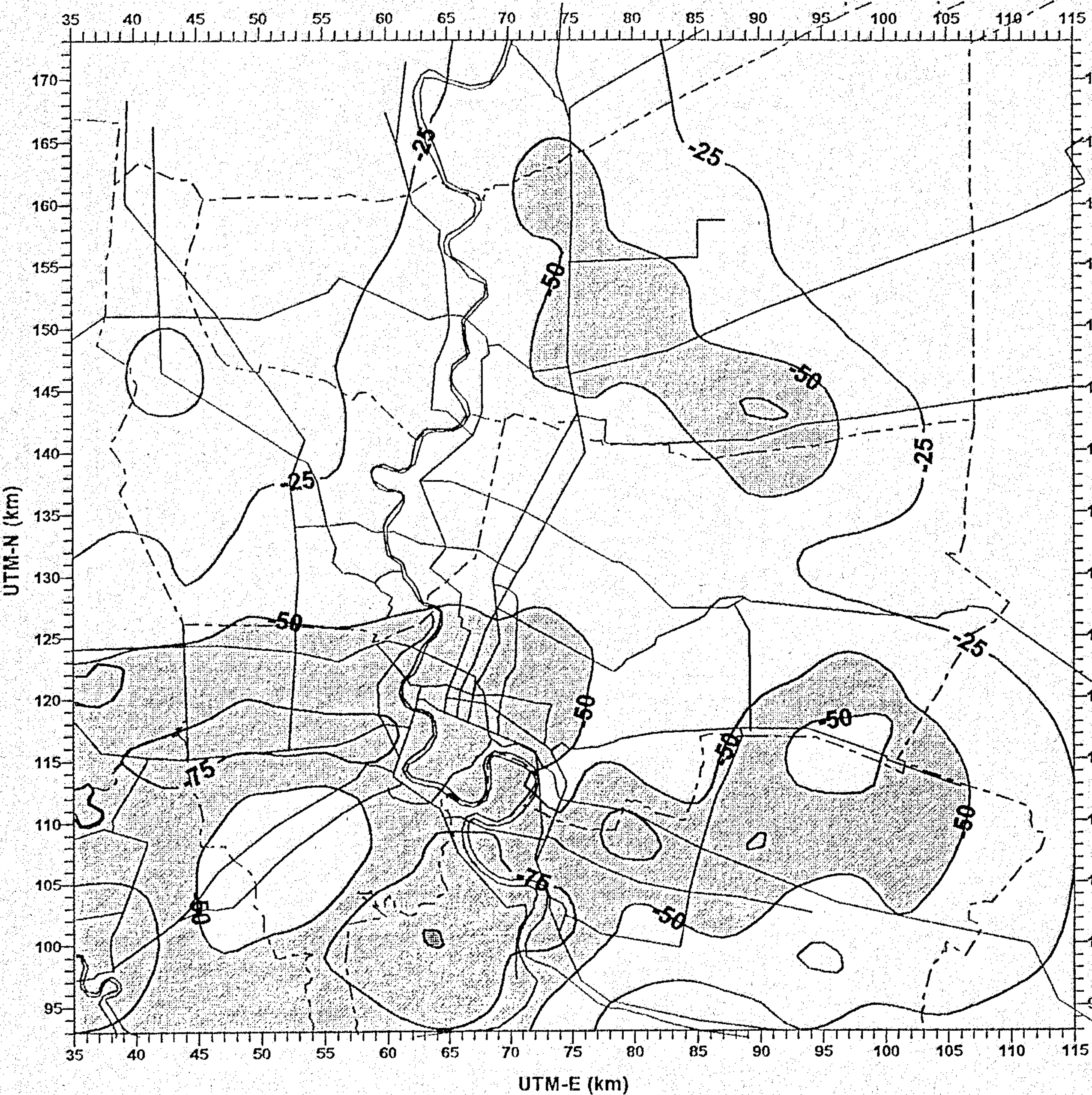


Figure 8.5.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 5A)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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	
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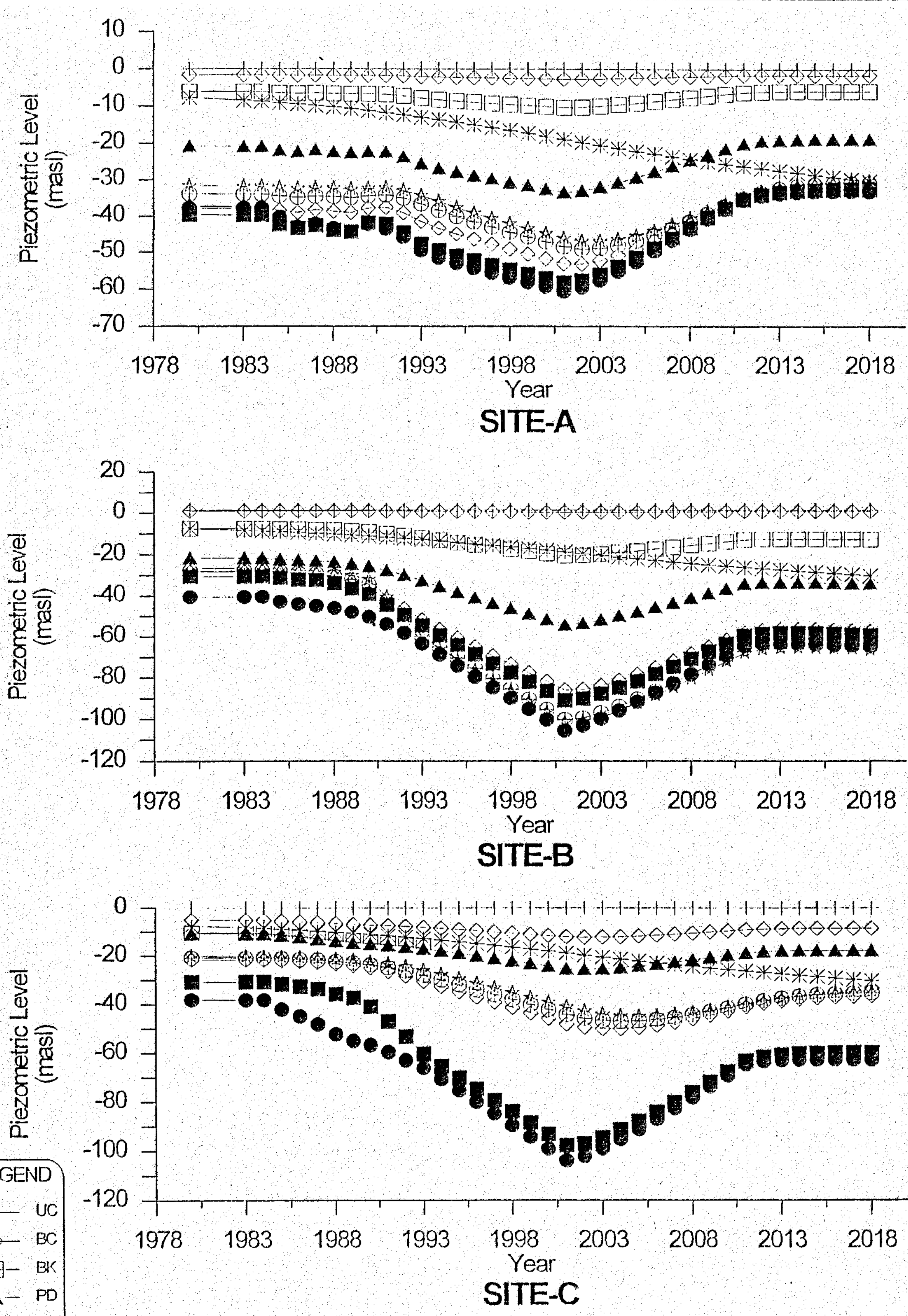

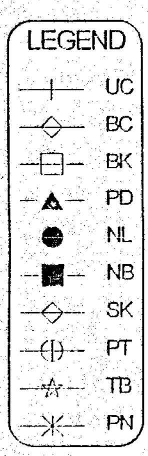

Figure 8.6.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 5B)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
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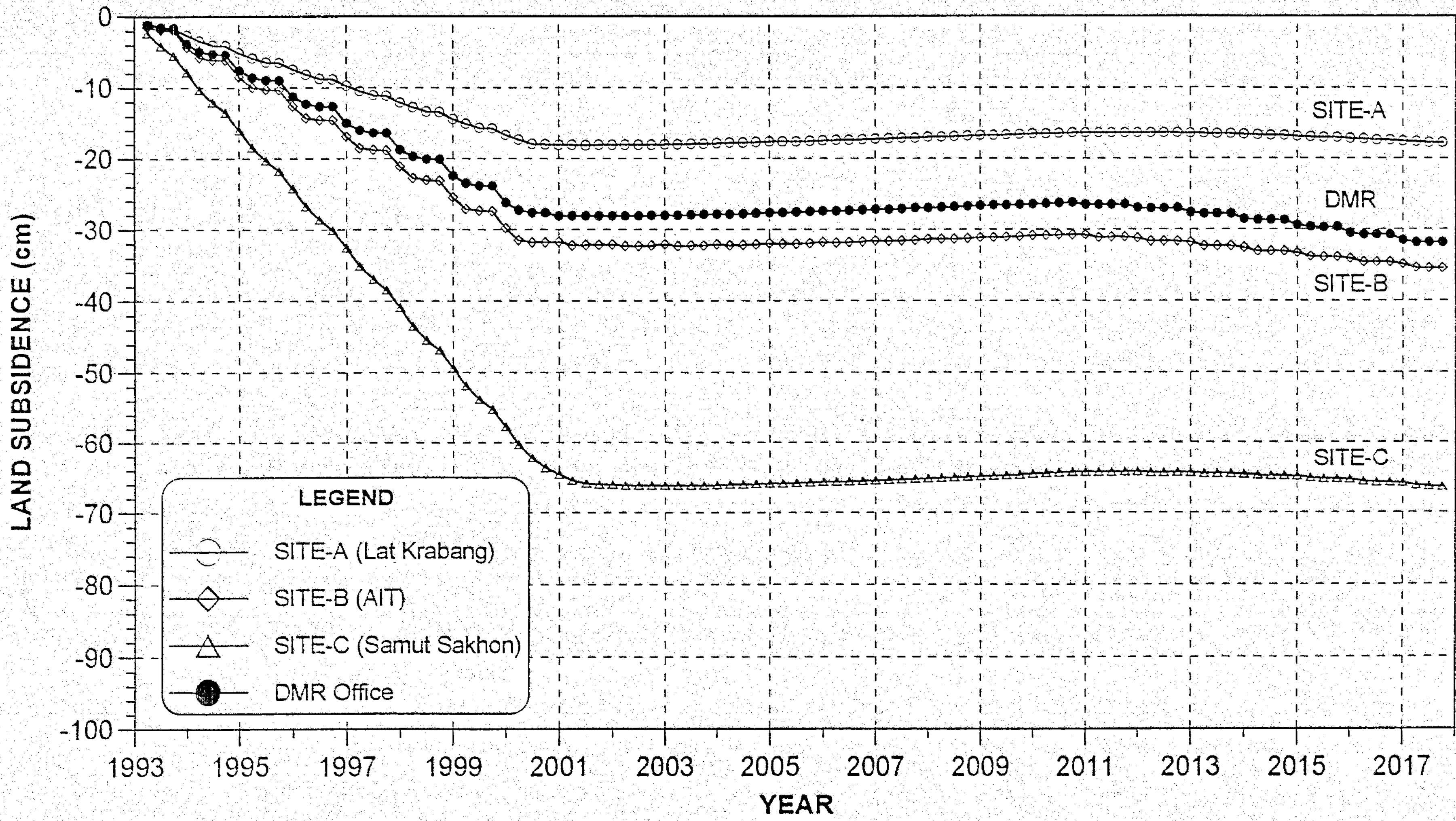
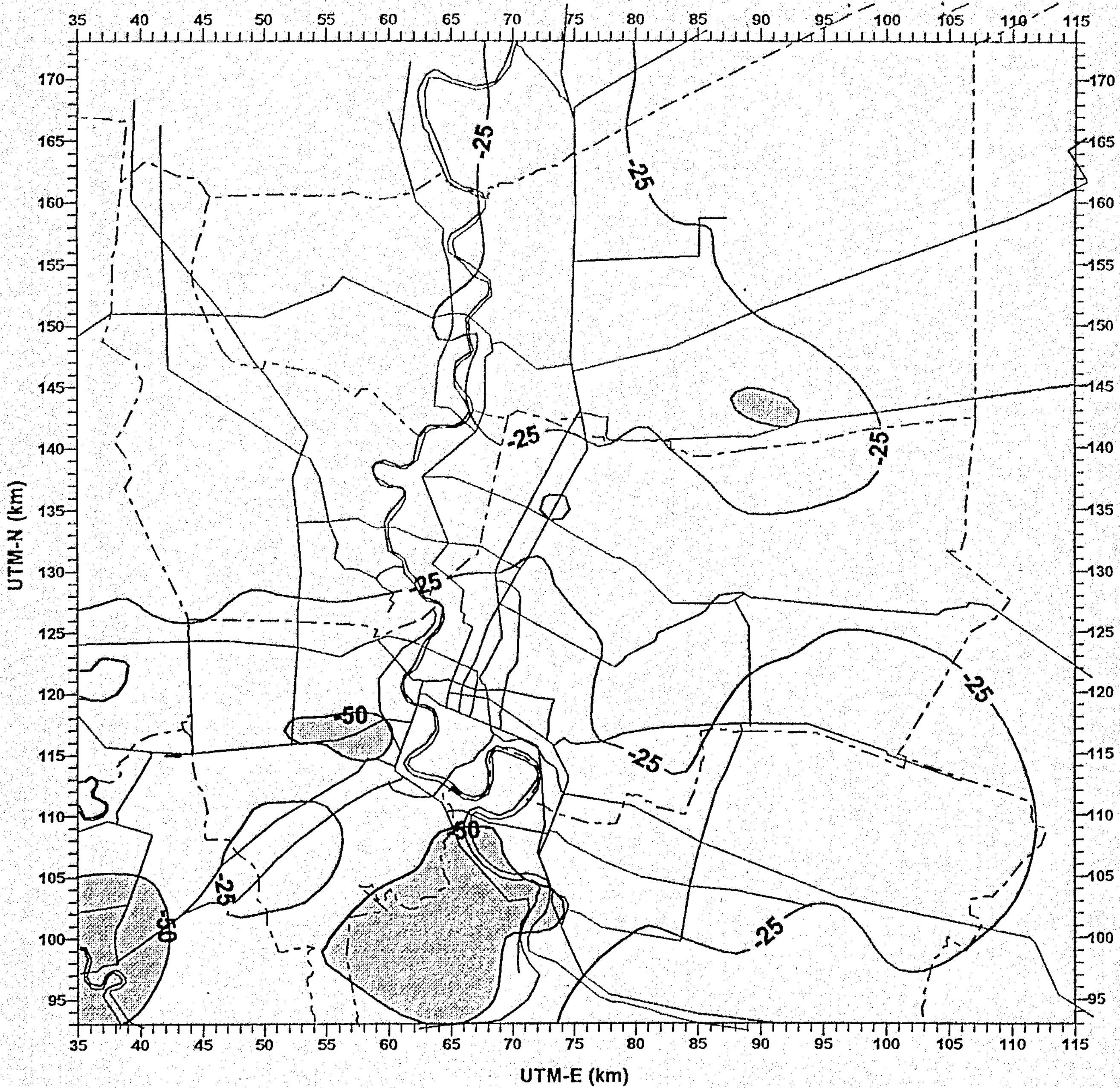


Figure 8.6.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 5B)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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	
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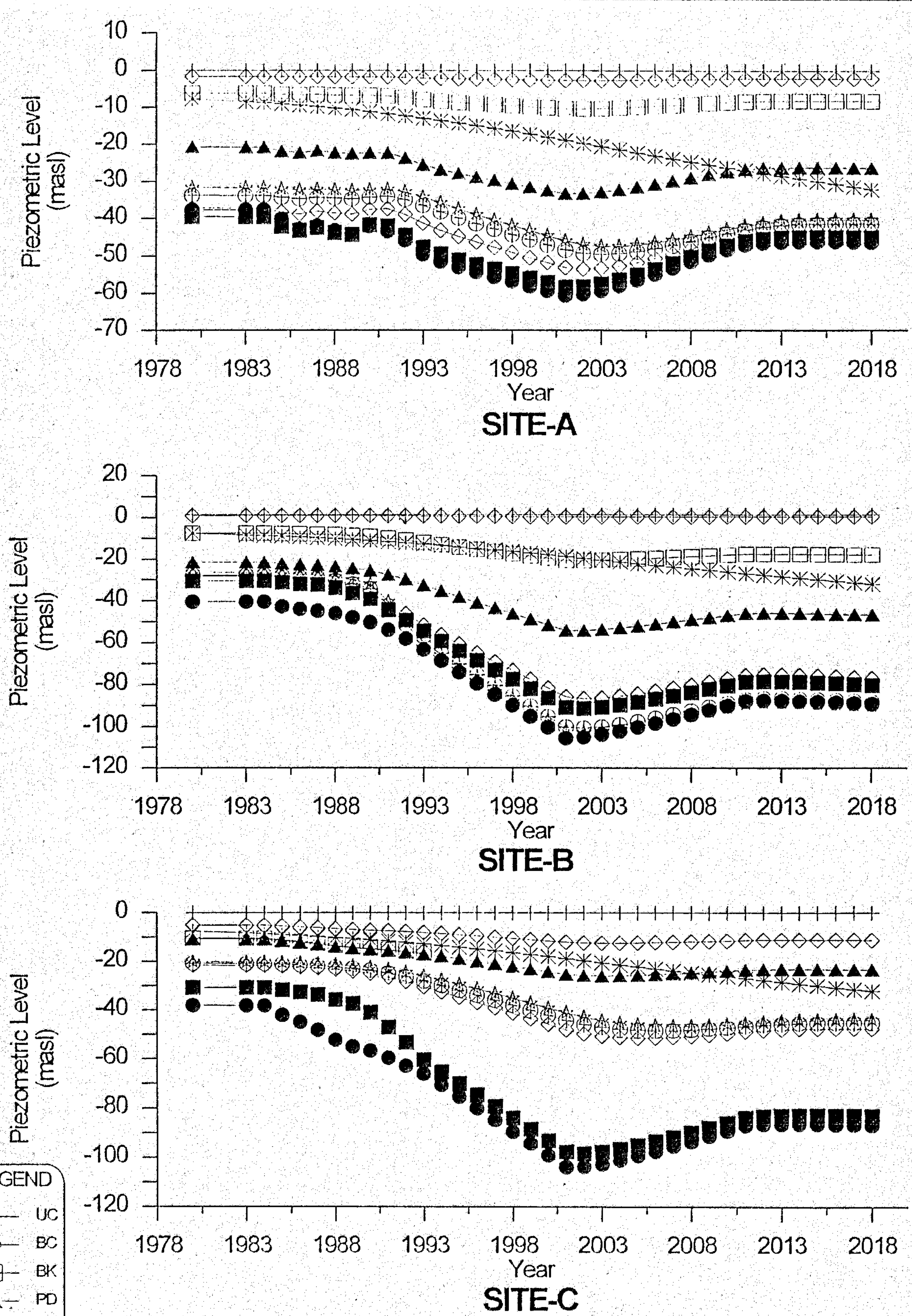


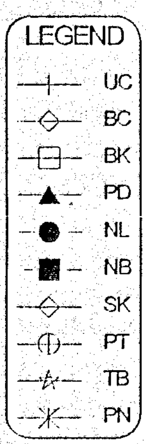


Figure 8.7.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 5C)

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.

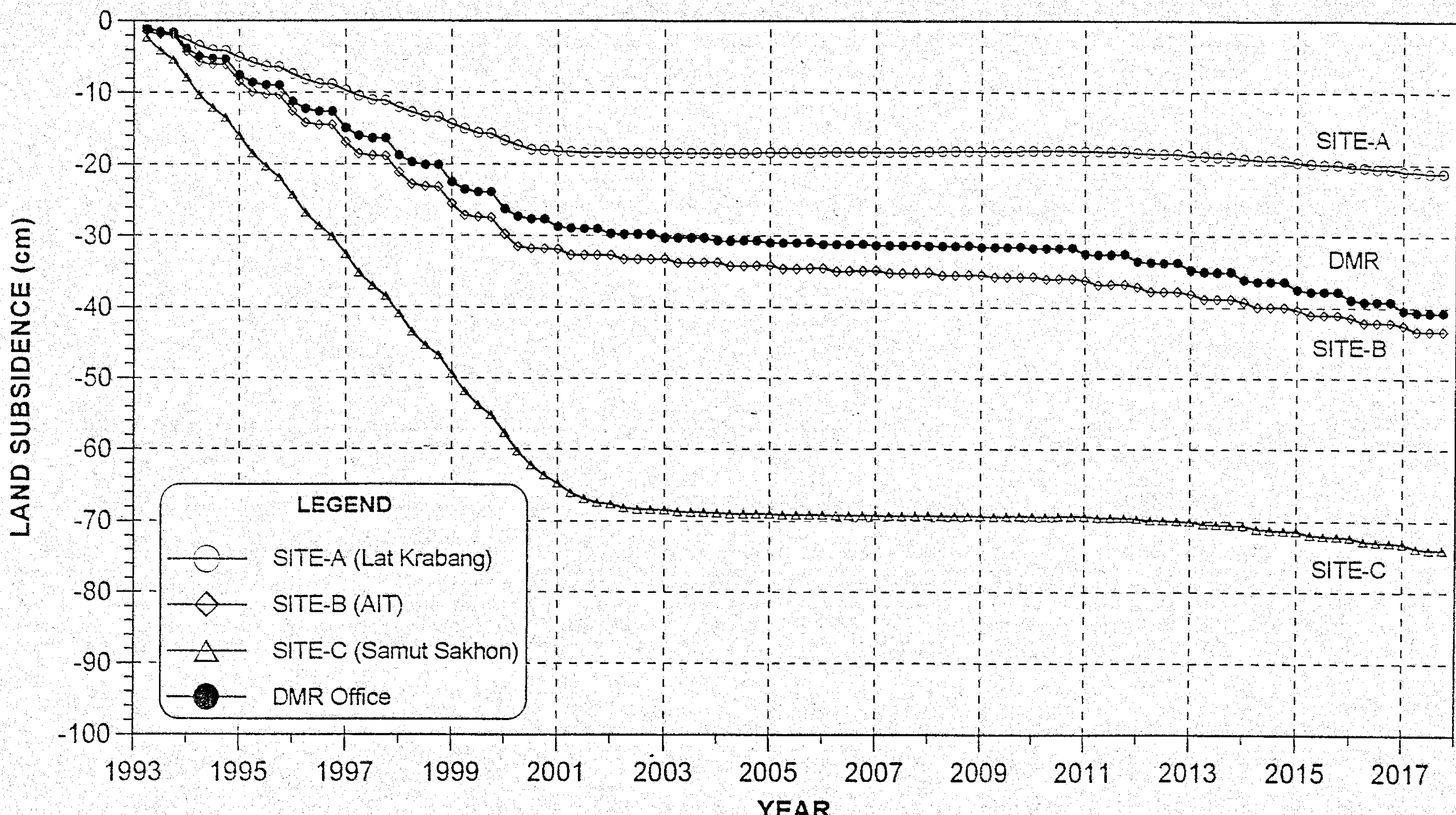
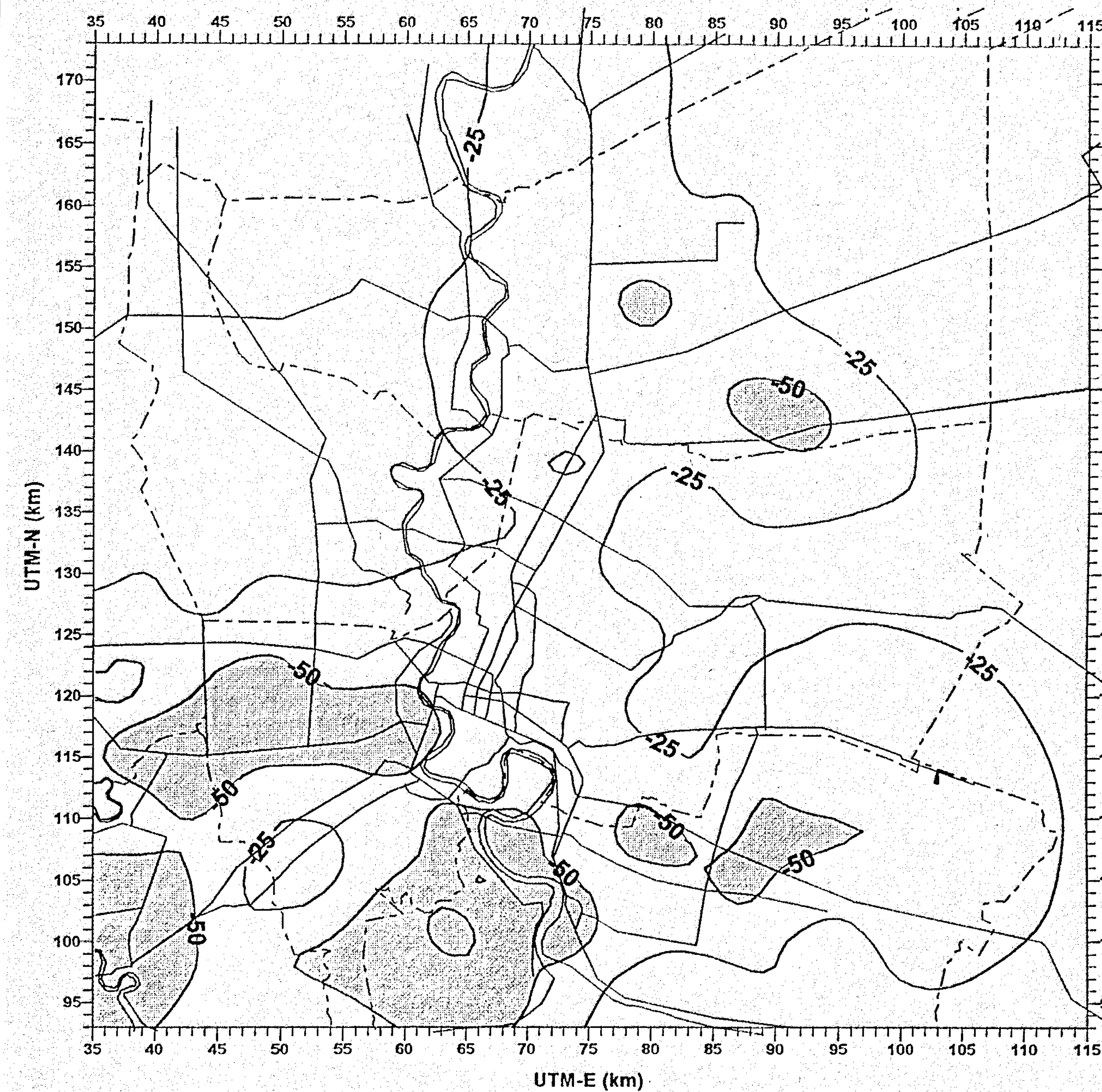


Figure 8.7.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 5C)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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.

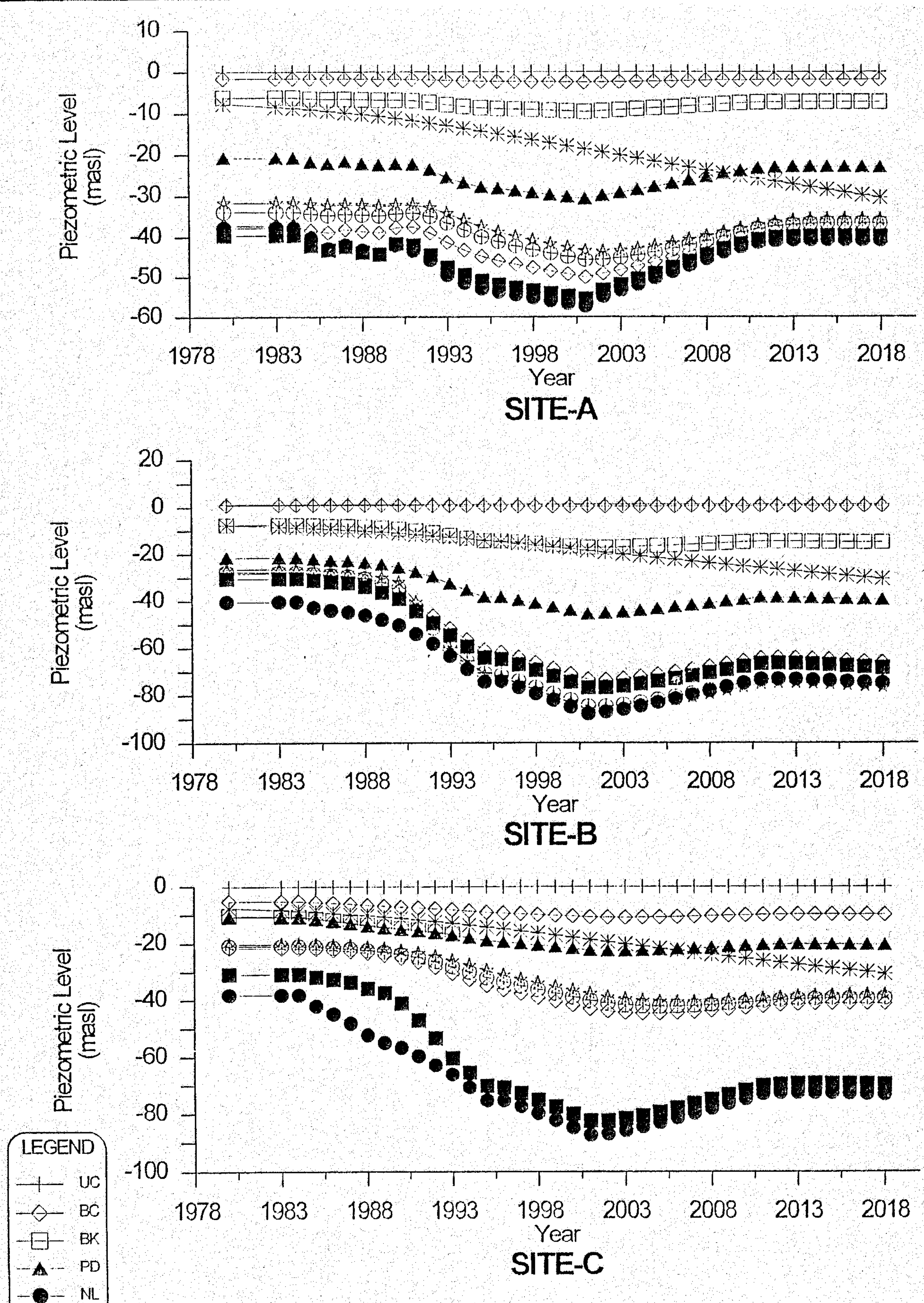


Figure 8.8.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 6)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

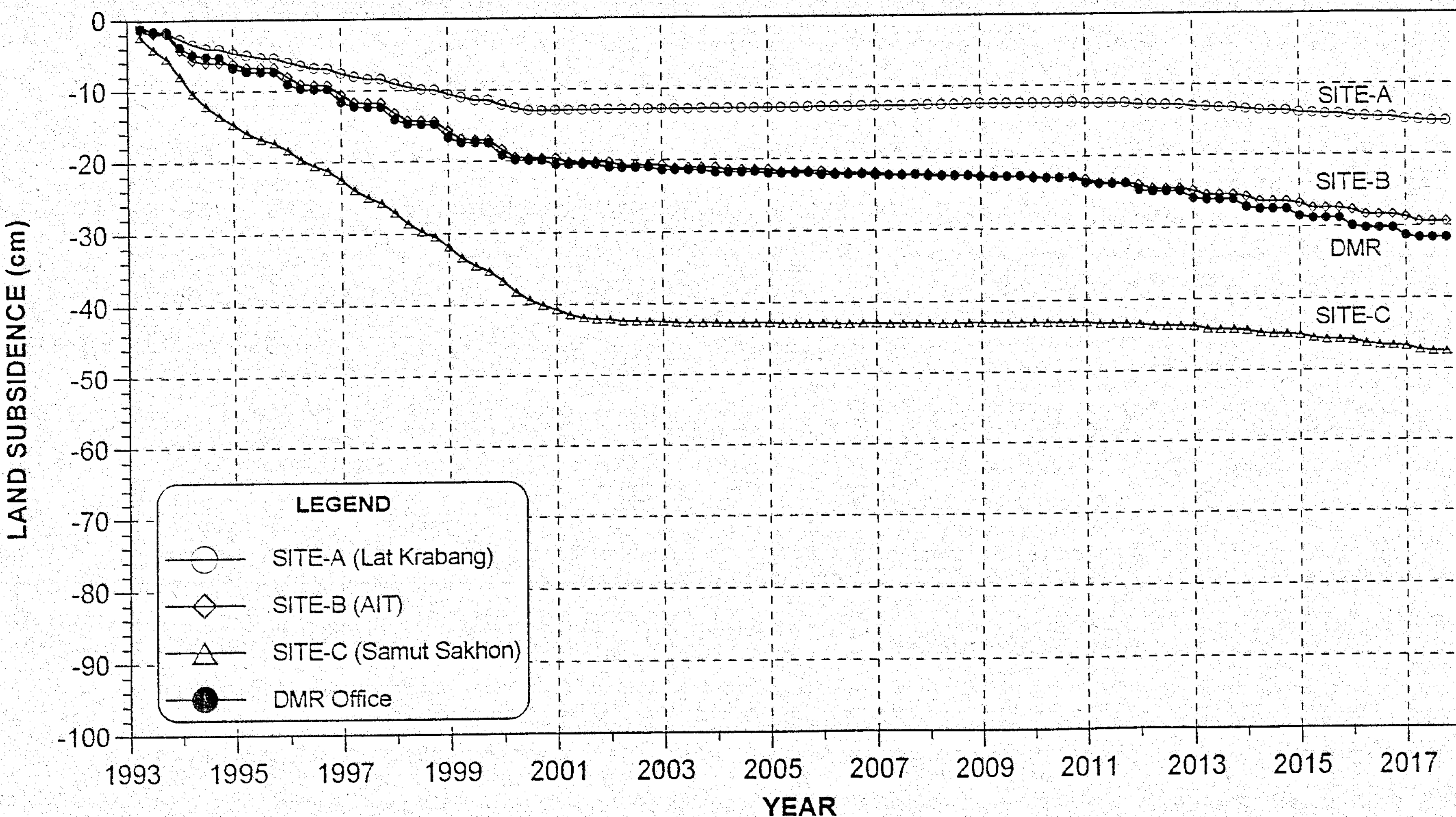
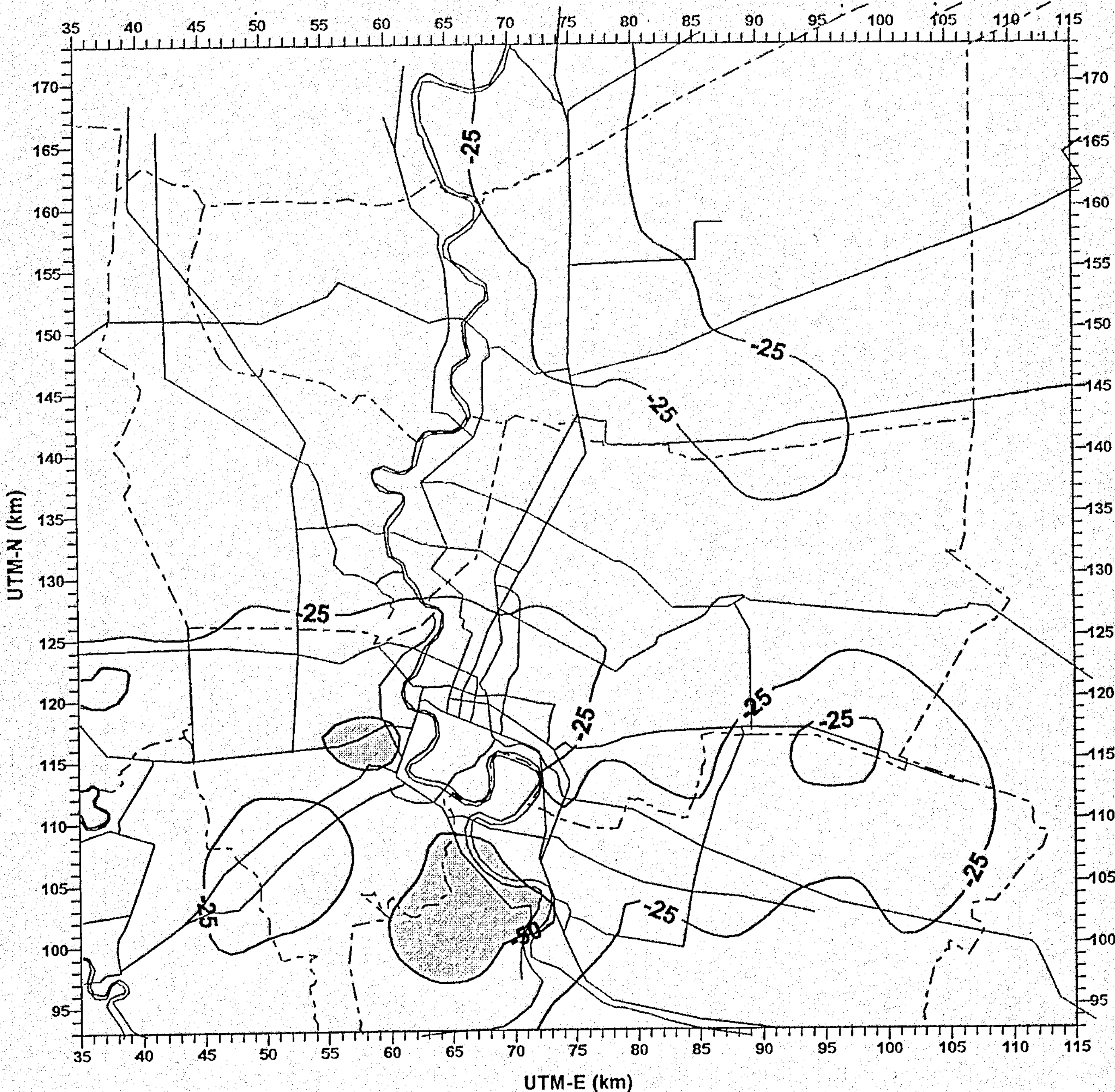


Figure 8.8.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 6)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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.

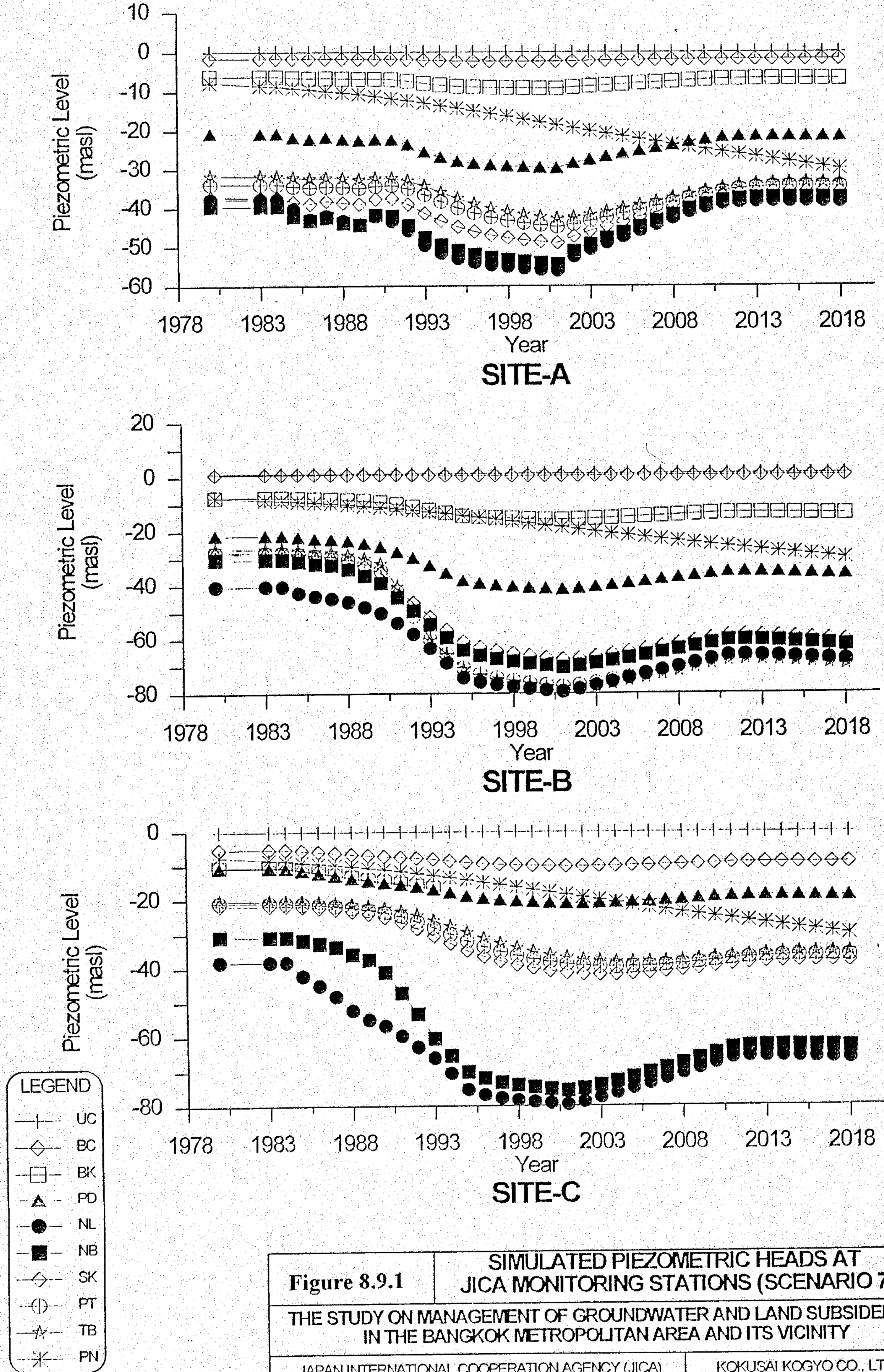


Figure 8.9.1	SIMULATED PIEZOMETRIC HEADS AT JICA MONITORING STATIONS (SCENARIO 7)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.

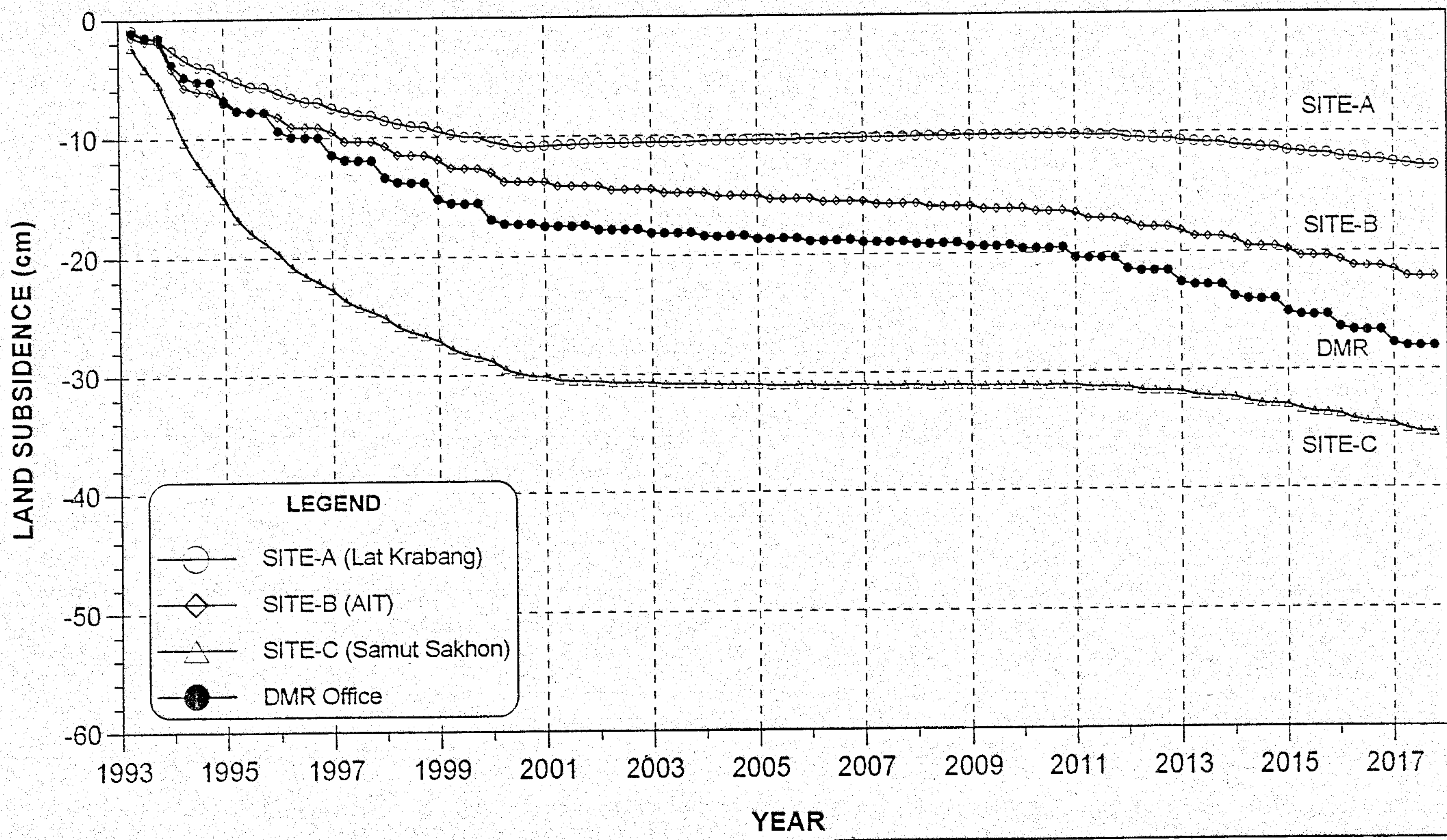
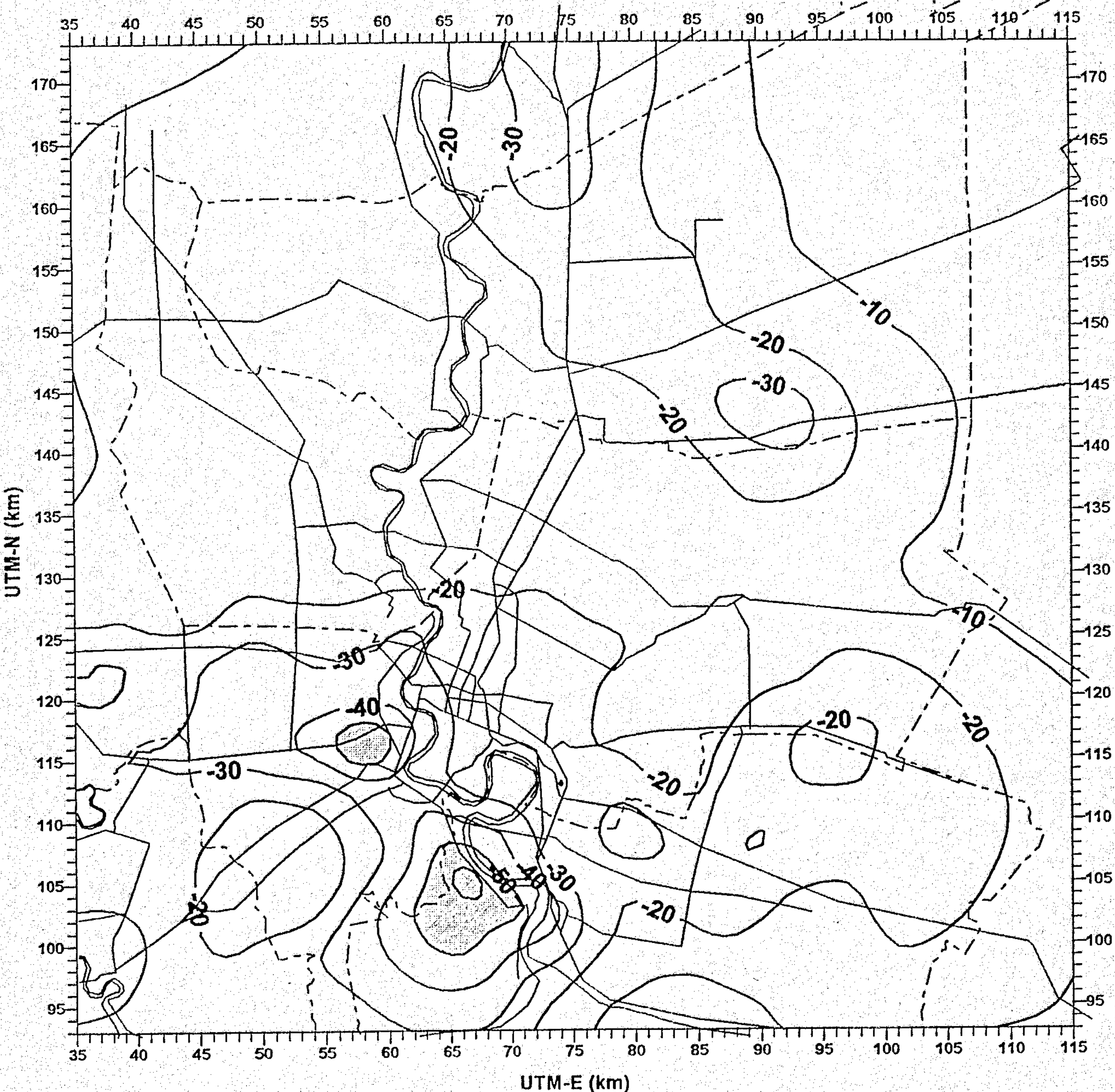


Figure 8.9.2	SIMULATED LAND SUBSIDENCE (FUTURE SCENARIO 7)
THE STUDY ON MANAGEMENT OF GROUNDWATER AND LAND SUBSIDENCE IN THE BANGKOK METROPOLITAN AREA AND ITS VICINITY	
JAPAN INTERNATIONAL COOPERATION AGENCY (JICA)	KOKUSAI KOGYO CO., LTD.



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.	

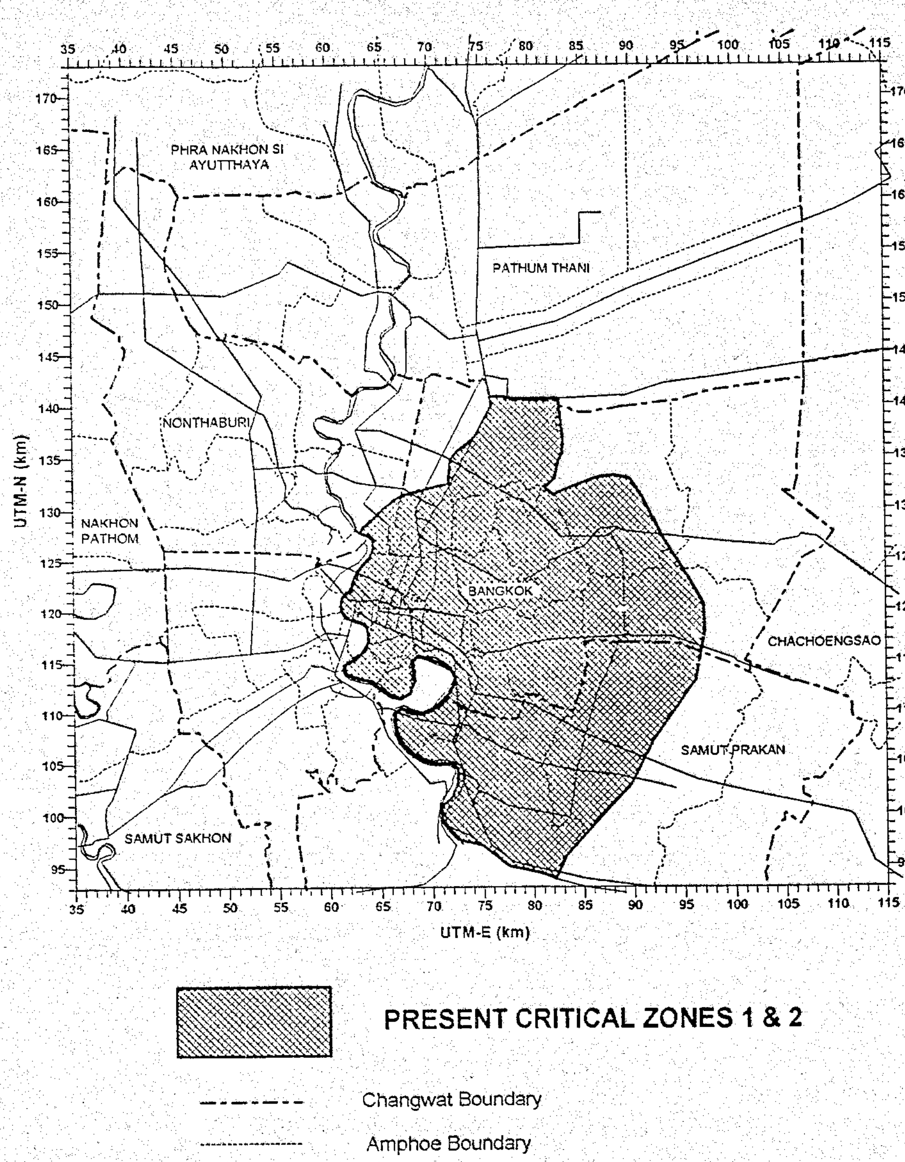


Figure 8.10.1	PRESENT CRITICAL ZONES 1 & 2
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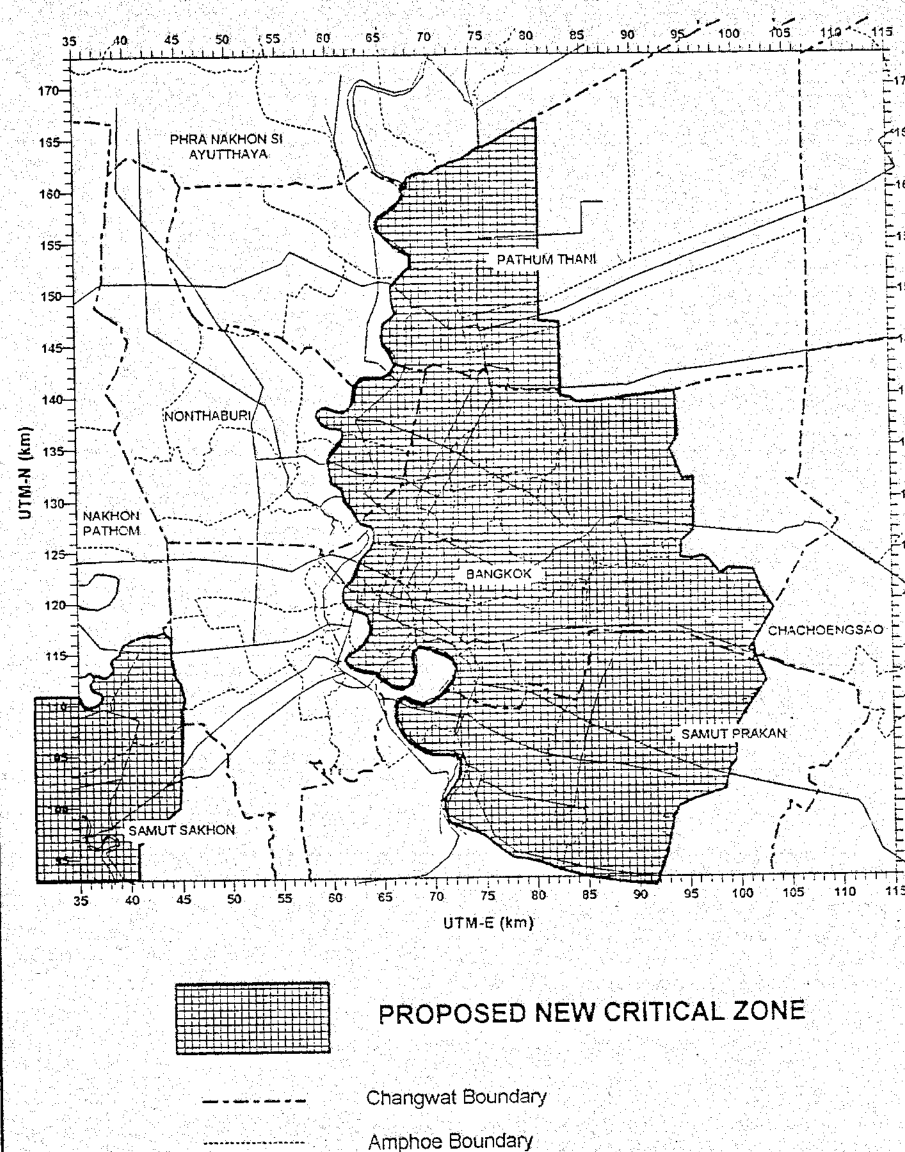

Figure 8.10.2	PROPOSED NEW CRITICAL ZONE
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CHAPTER 9 ASSESSMENT OF PERMISSIBLE YIELD

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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

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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

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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.