CHAPTER IV

HYDROGEOLOGY OF THE NAKHON LUANG AQUIFER

4.1 Water Wells

The water wells that selected to reveal the condition of the study area are shown in Figure 4.1-4.3. In Figure 4.1 shows three types of water wells as follows: the first one is the 5 **primary reference wells** which including the Electric loggings and the cuttings data, the second one is the 7 **lithologic logging wells** which composing of the cuttings data only, and the last one is the 117 **groundwater monitoring stations (or the secondary wells)** which consisting of the electric logging and the lithologic loggings data. Each type of wells colors as green, red, and pink respectively. In Figure 4.2 shows the **94 observation wells** of the 117 DMR monitoring wells stations that penetrating into the NL aquifer. Figure 4.3 shows the 201 **pumping test wells**, which are the 17 pumping test wells for computing the transmissivity and the hydraulic conductivity and the 184 pumping test wells for calculating the specific capacity.

Figure 4.4 displays the hydrogeologic cross section lines. They are 8 lines in east-west direction and 4 lines in north-south direction.

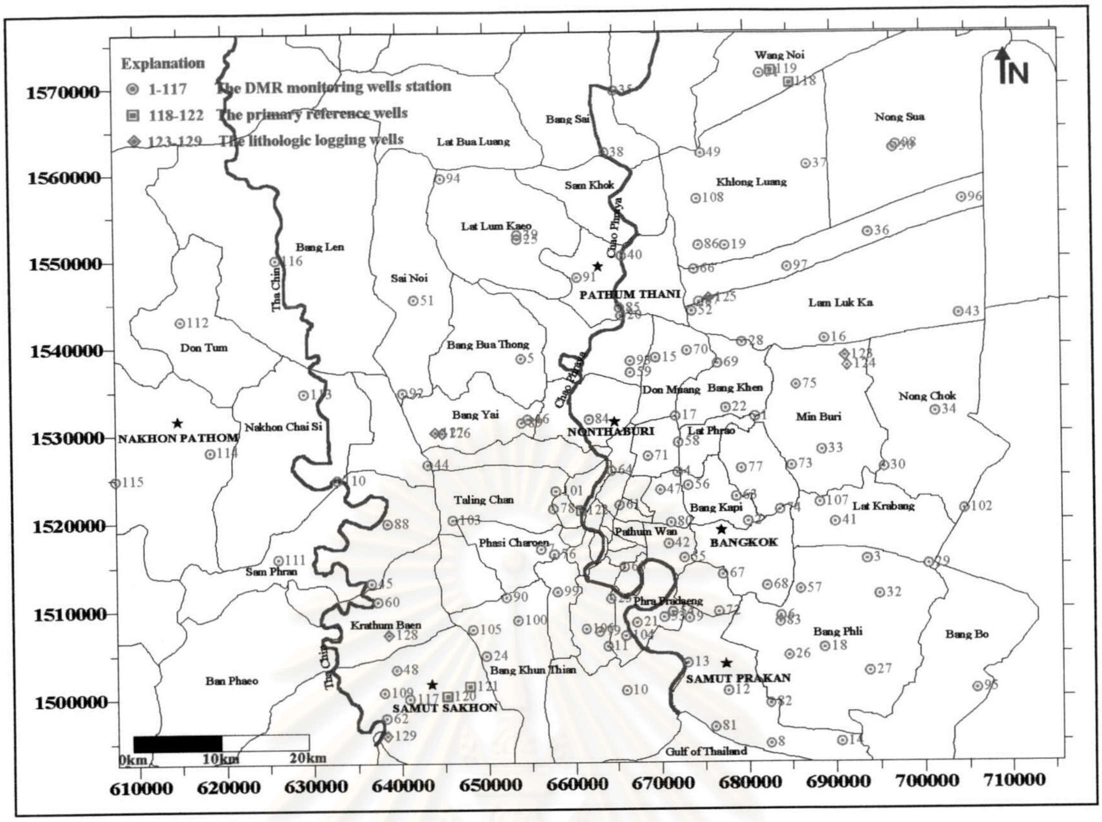


Figure 4.1 Location of the water wells in the study area

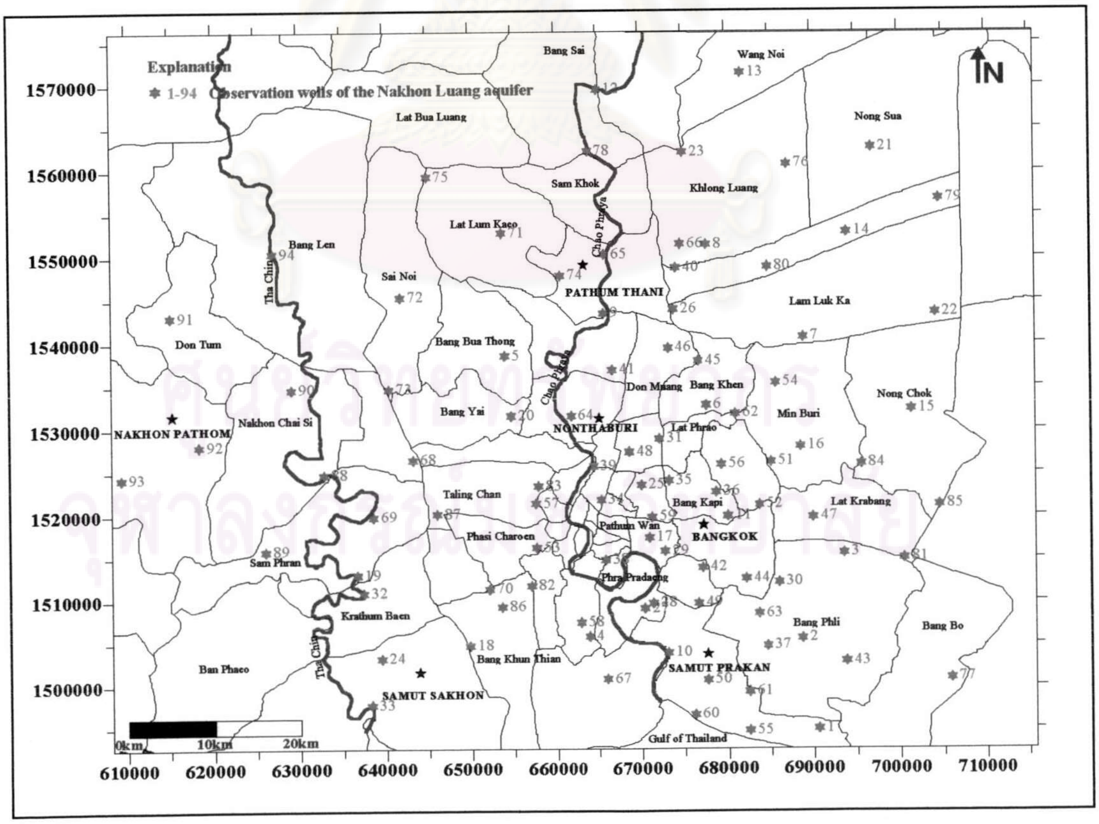


Figure 4.2 Location of the observation wells of the Nakhon Luang aquifer

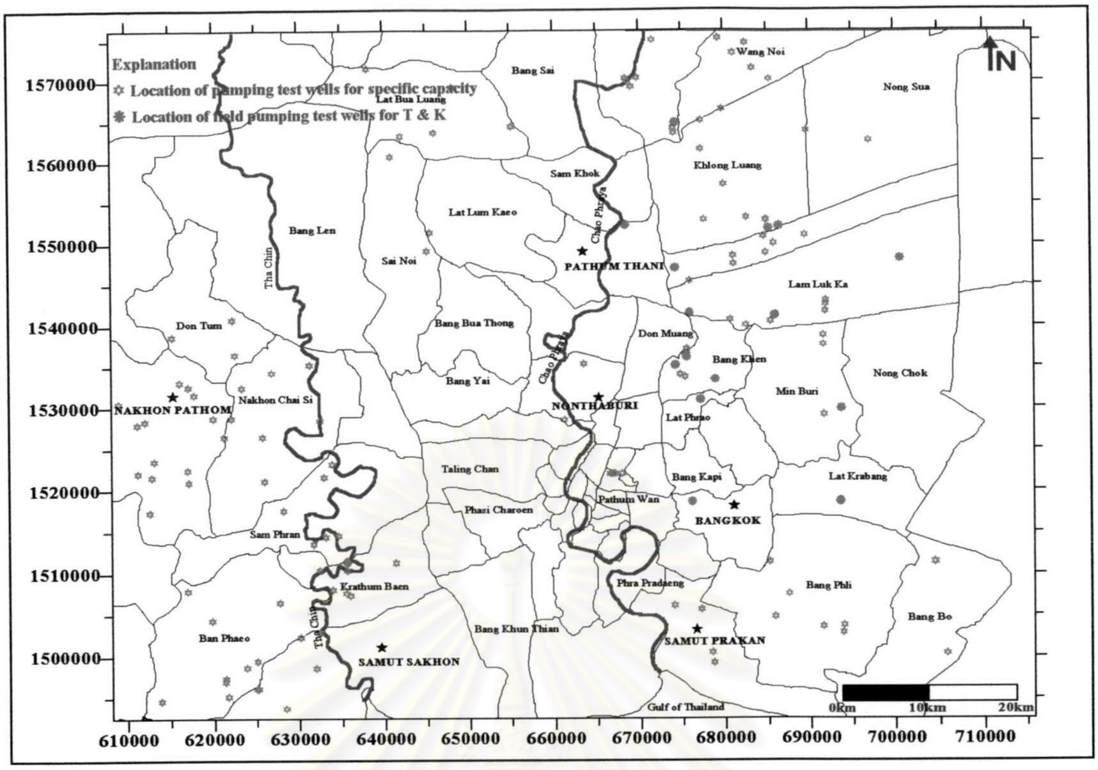


Figure 4.3 Location of the pumping test wells of the Nakhon Luang aquifer

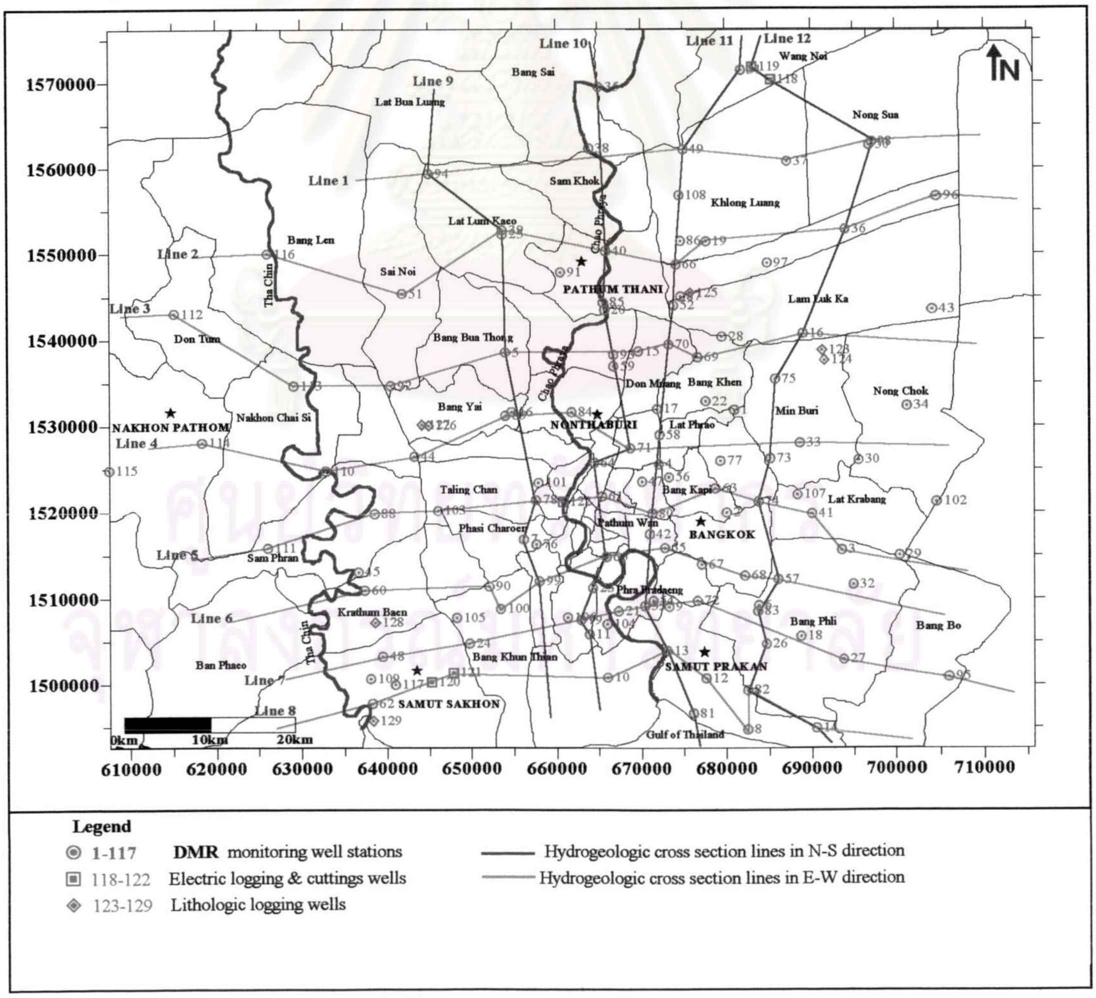


Figure 4.4 Hydrogeologic cross section lines in the study area

4.2 Hydrogeology of the Nakhon Luang Aquifer

The hydrogeologic cross sections, coverage the study area, are pursued from the geological data, namely lithological data as well as electrical logging data and well-rock cuttings. The 12 hydrogeologic cross section lines, Figure 4.5-4.16, are constructed from 117 DMR monitoring wells stations and 5 Primary reference wells. Line 1 to Line 8 are the sections of east-west direction while Line 9 to Line 12 are the sections of north-south direction. The aquifer boundaries (dash lines) are used to divide each aquifer unit by means of the extension of clay layer; water quality and compacted clay/silty clay to separate the NL aquifer form the PD aquifer and the NB aquifer. Whereas, the boundary sequence and the sedimentary facies are interpreted and correlated according to the lithology, obtained from mainly resistivity and SP logging. From the hydrogeologic cross section lines they depicts that the Nakhon Luang Aquifer; NL, can be differentiated among the Phra Pradaeng Aquifer; PD, and the Nonthaburi Aquifer; NB, by means of the pattern of the electric loggings, the thickness as well as compacted clay layers and water quality. The NL aquifer is located from 125-180 meters below ground surface. The thickness of the aquifer ranging from 15-75 meters and its averages are approximately 50 meters thick. It consists mainly of sand with some gravel and clay lens intercalated. In the eastern part, the clay layers subdivided the NL aquifer into three sub aquifers whereas in the western part subdivided into two sub aquifers (Fig. 4.6 cross section line 2). The thickness of the aquifer is thickening westward and northward directions (Fig. 4.17). The thickness of sand-gravel layers within the aquifer ranging from 10-25 meters intercalated with thin clay layers 2-10 m thick. The compacted clay and sandy clay, which capping the NL aquifer, are approximately 2-15 meters in thickness. These clay layers are the thinnest in the central part of the area (Fig. 4.9 cross section line 5).

Moreover, there are also more and more sandy in the layer, thus, it may lead to the interconnection between the PD aquifer and the NL aquifer in this southern part (Fig. 4.15 cross section line 11 and Fig 4.16 cross section line 12), central part (Fig. 4.9 cross section line 5) further to the northeast (Fig. 4.6 cross section line 2, Fig. 4.9 cross section line 5) of the area (Fig. 4.18).

The bottom layer, the compacted and sandy clay, of the NL aquifer is approximately 4-15 meters thick as well. It is quite thin in the southeastern (Fig. 4.9 cross section line 5 and Fig. 4.12 cross section line 8) and the southwestern parts (Fig. 4.11 cross section line 7). Thus, it might be connected between the NL aquifer and the NB aquifer in this zone. (Fig. 4.19)

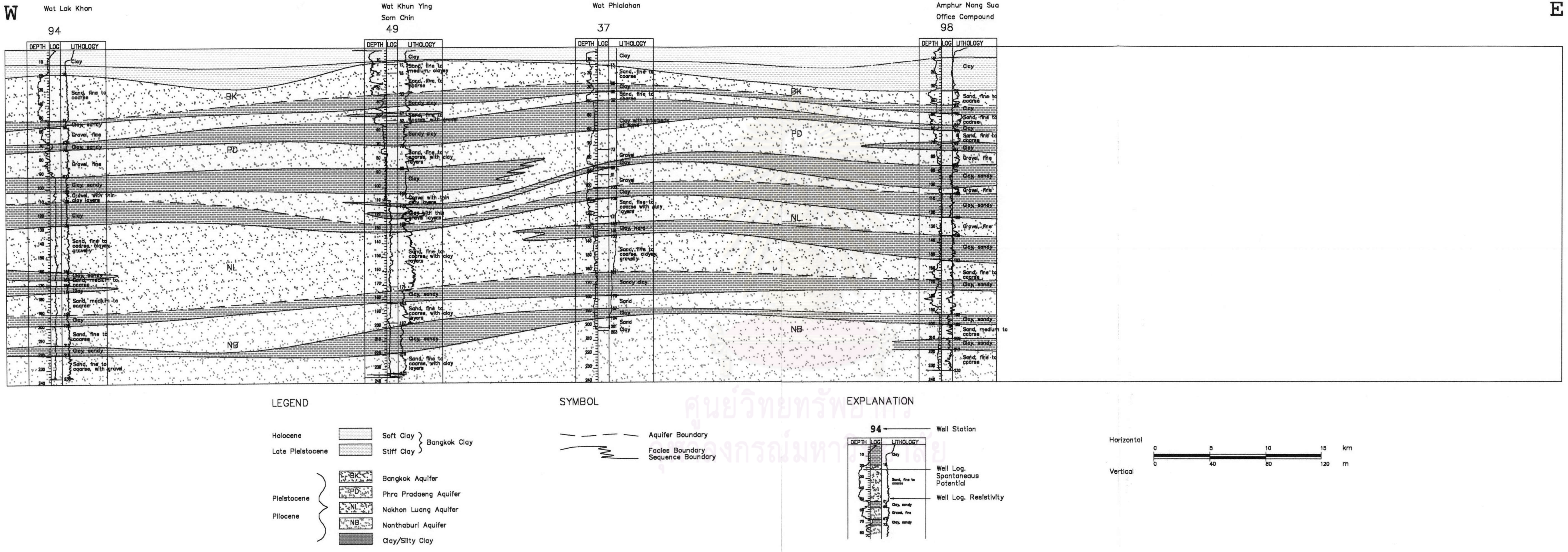


Figure 4.5 Hydrogeologic East-West Section Line1

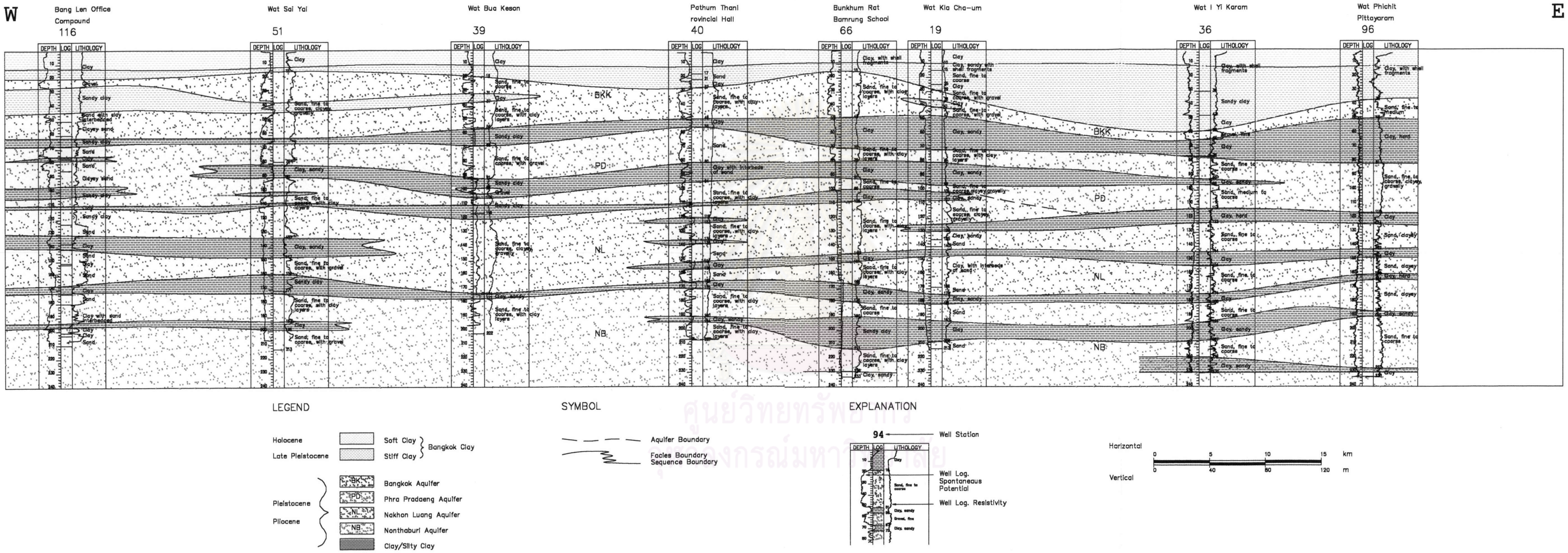


Figure 4.6 Hydrogeologic East-West Section Line2

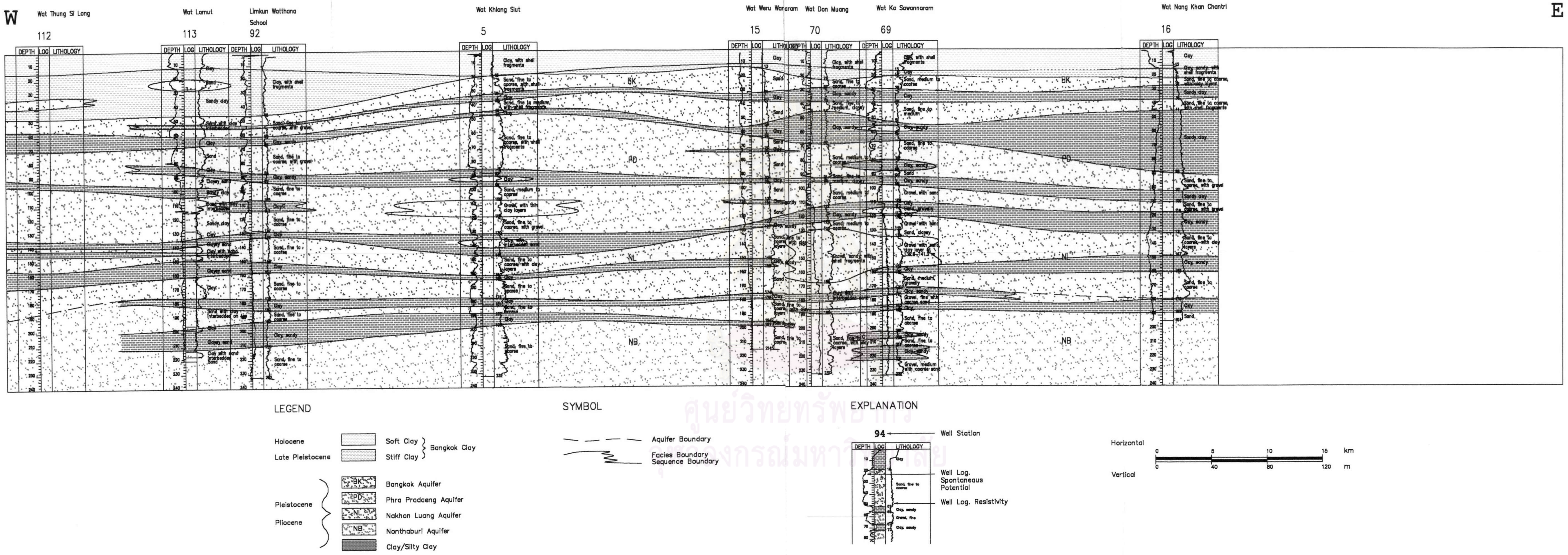


Figure 4.7 Hydrogeologic East-West Section Line3

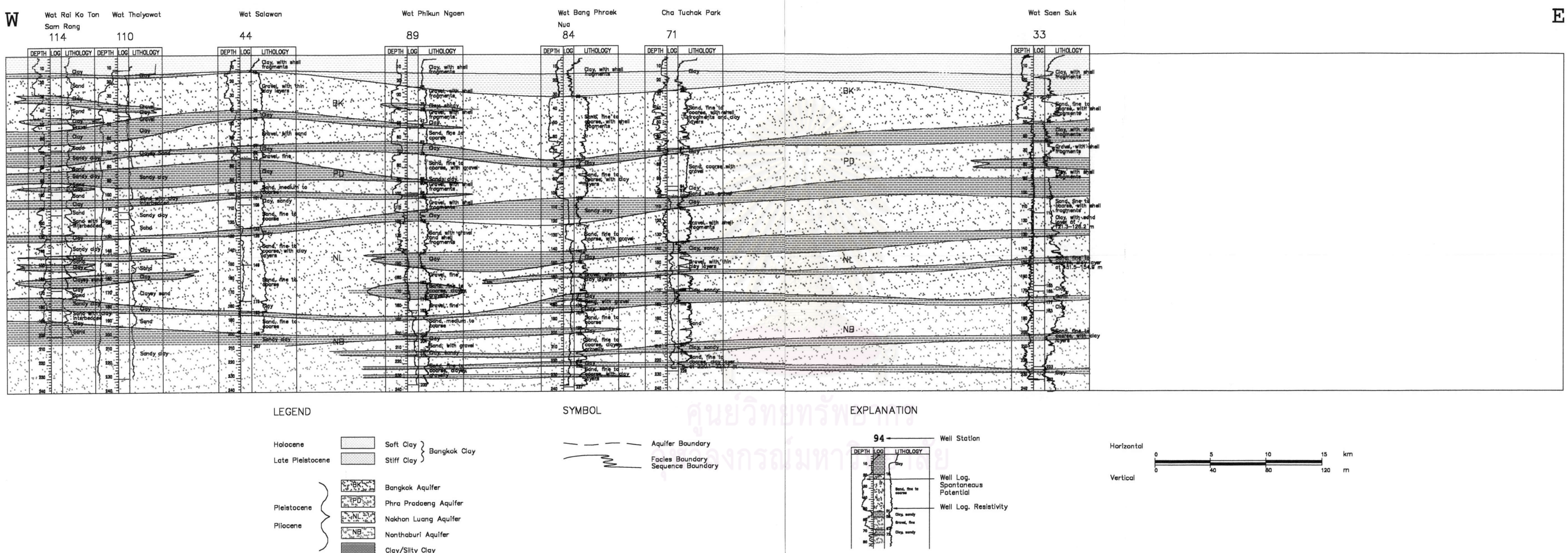


Figure 4.8 Hydrogeologic East-West Section Line4

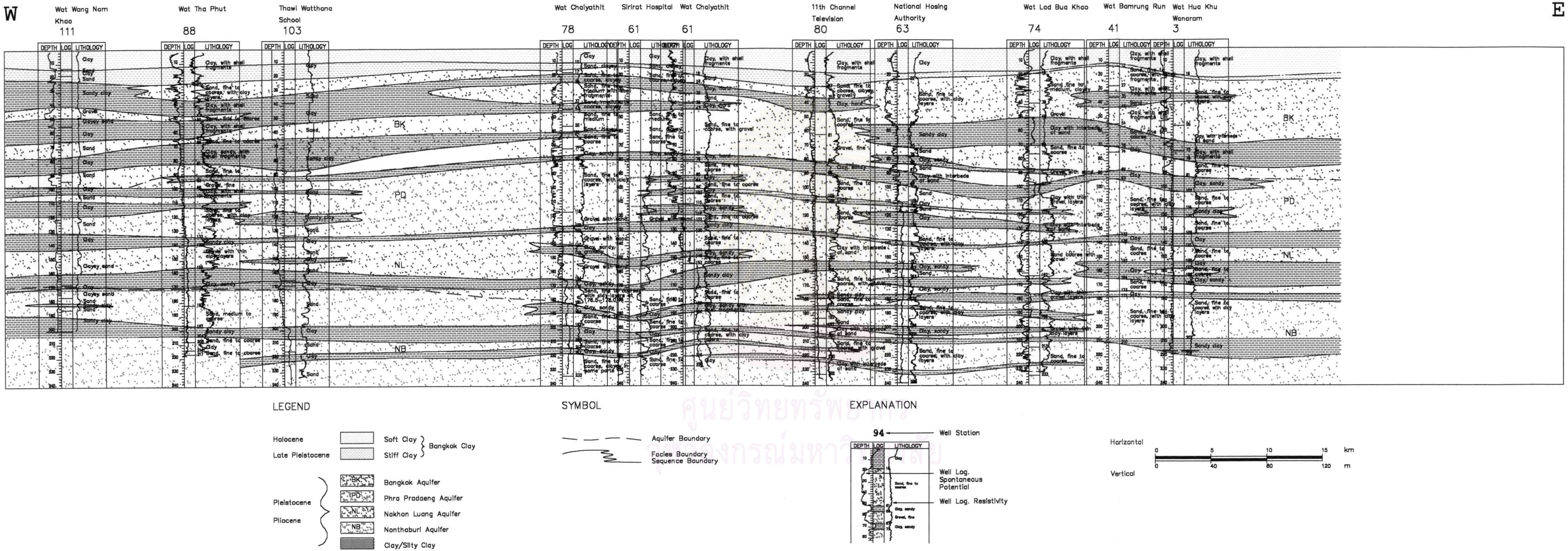


Figure 4.9 Hydrogeologic East-West Section Line5

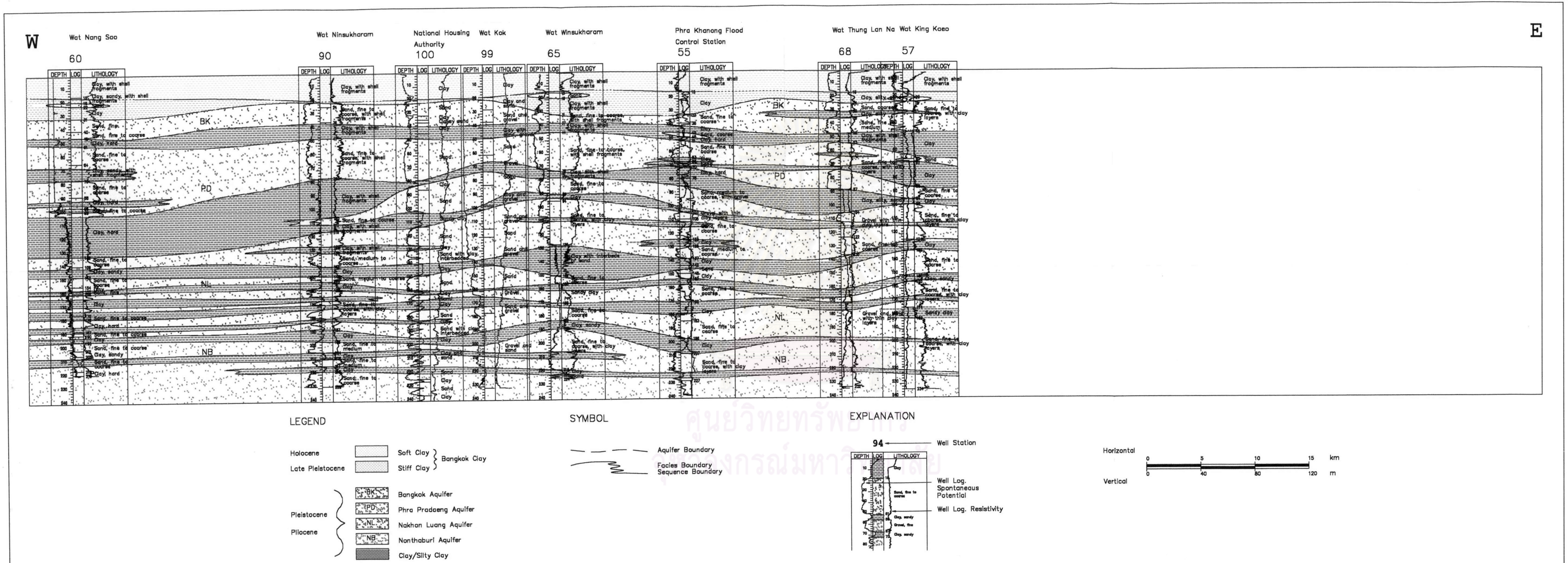


Figure 4.10 Hydrogeologic East-West Section Line6

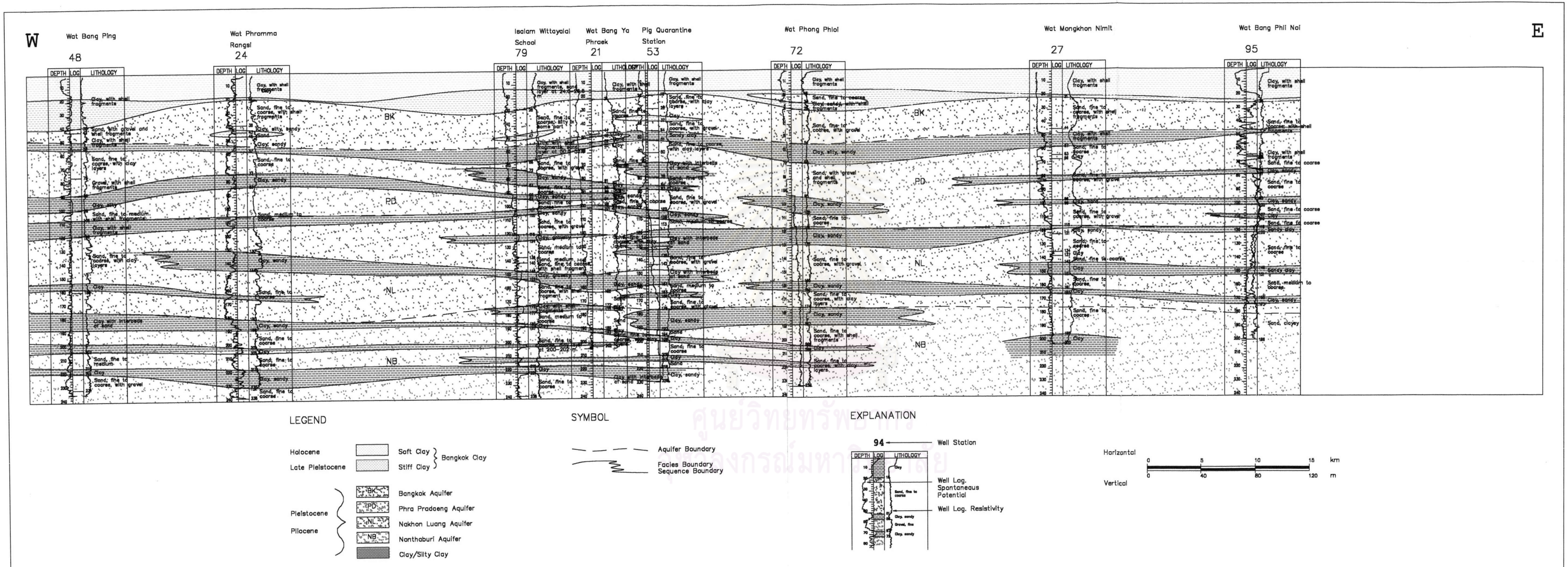


Figure 4.11 Hydrogeologic East-West Section Line7

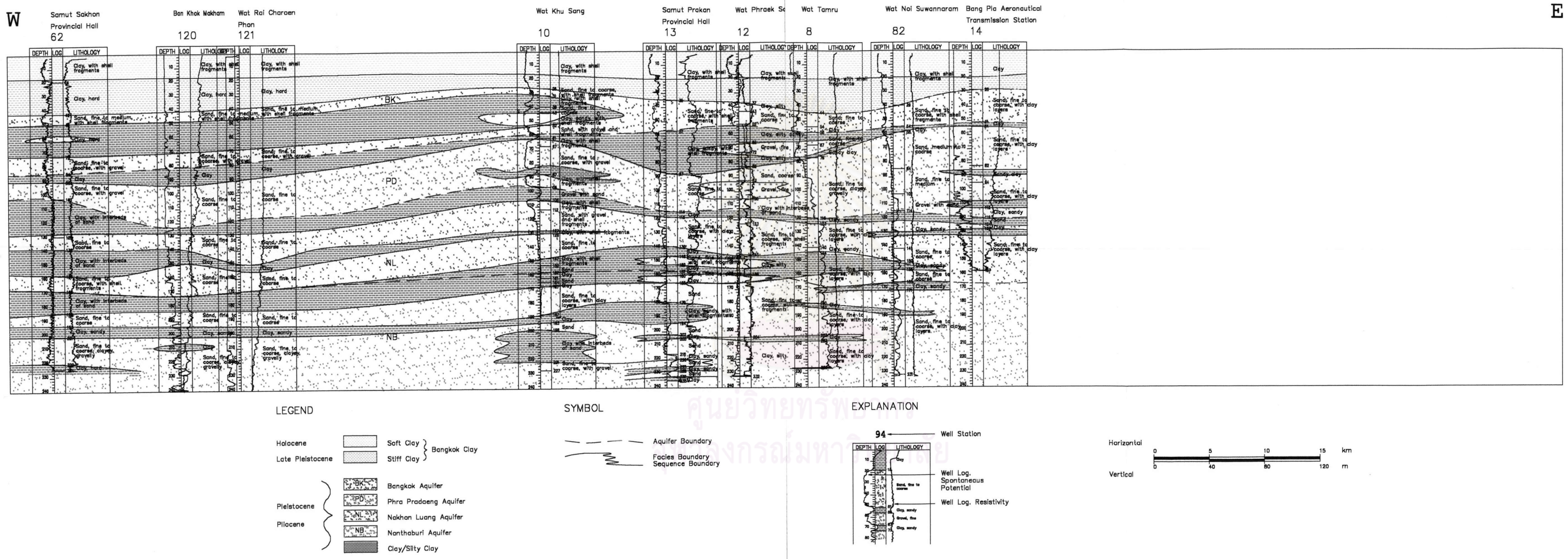


Figure 4.12 Hydrogeologic East-West Section Line8

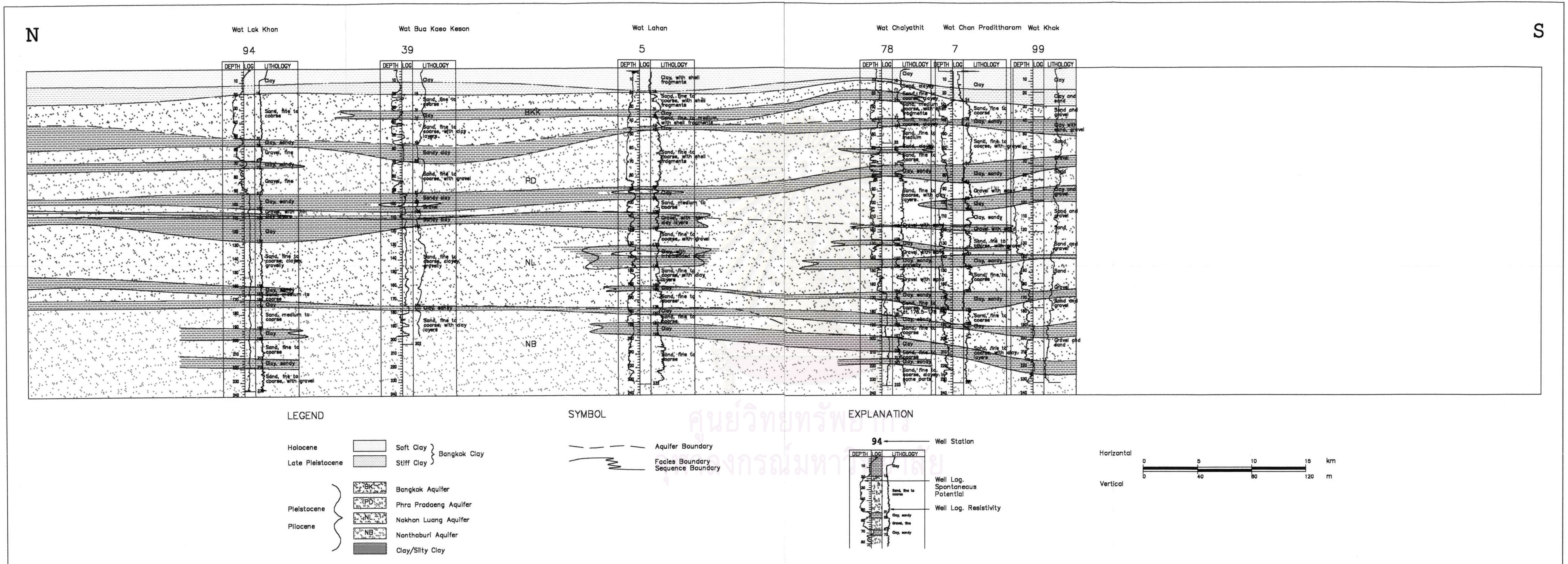


Figure 4.13 Hydrogeologic North-South Section Line9

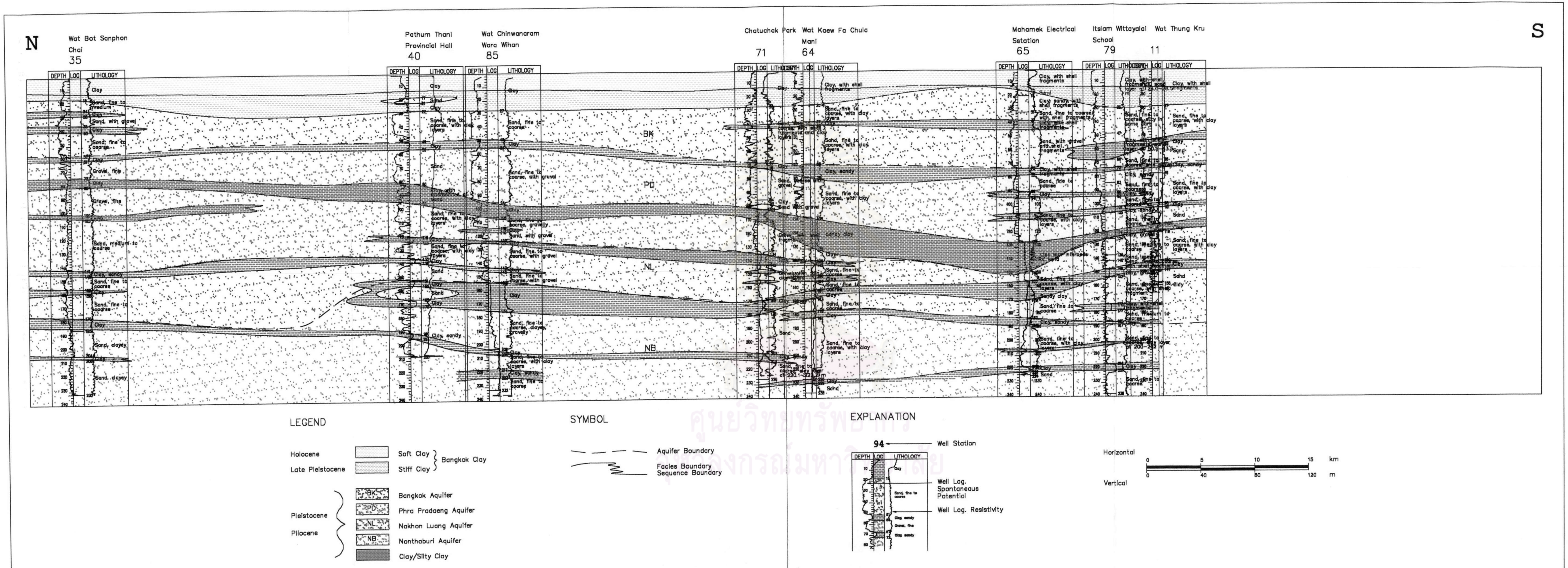


Figure 4.14 Hydrogeologic North-South Section Line10

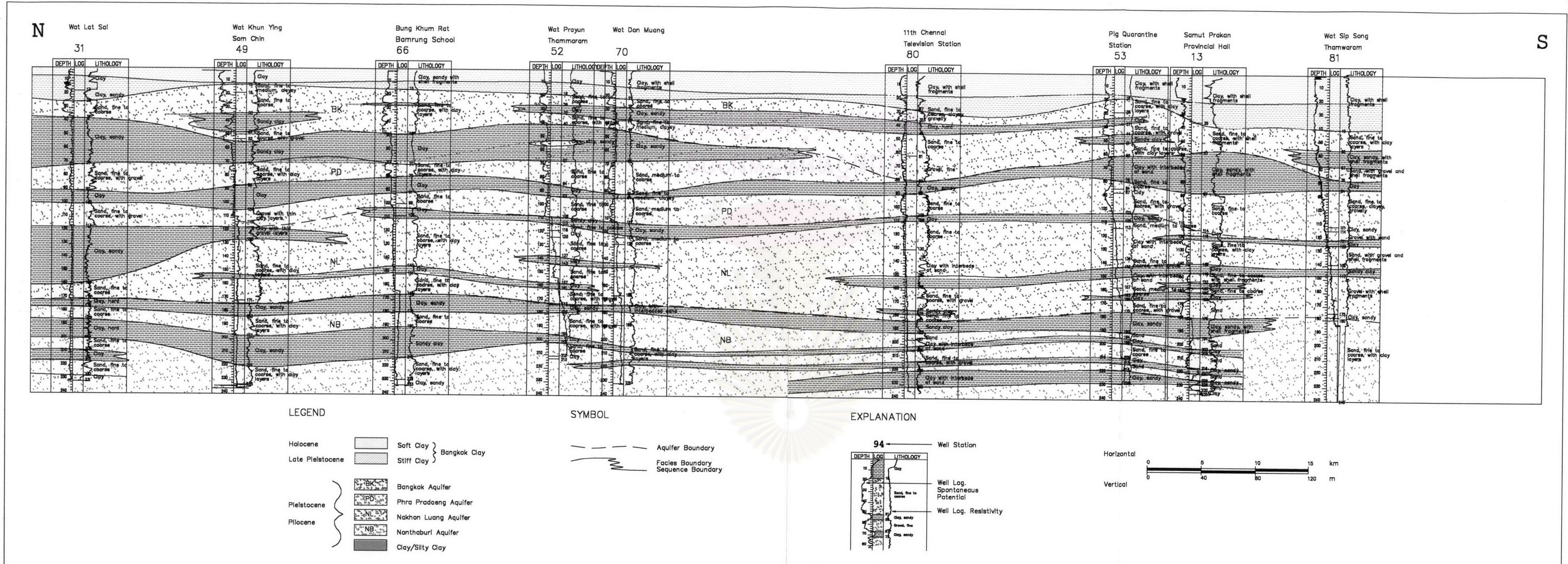


Figure 4.15 Hydrogeologic North-South Section Line11

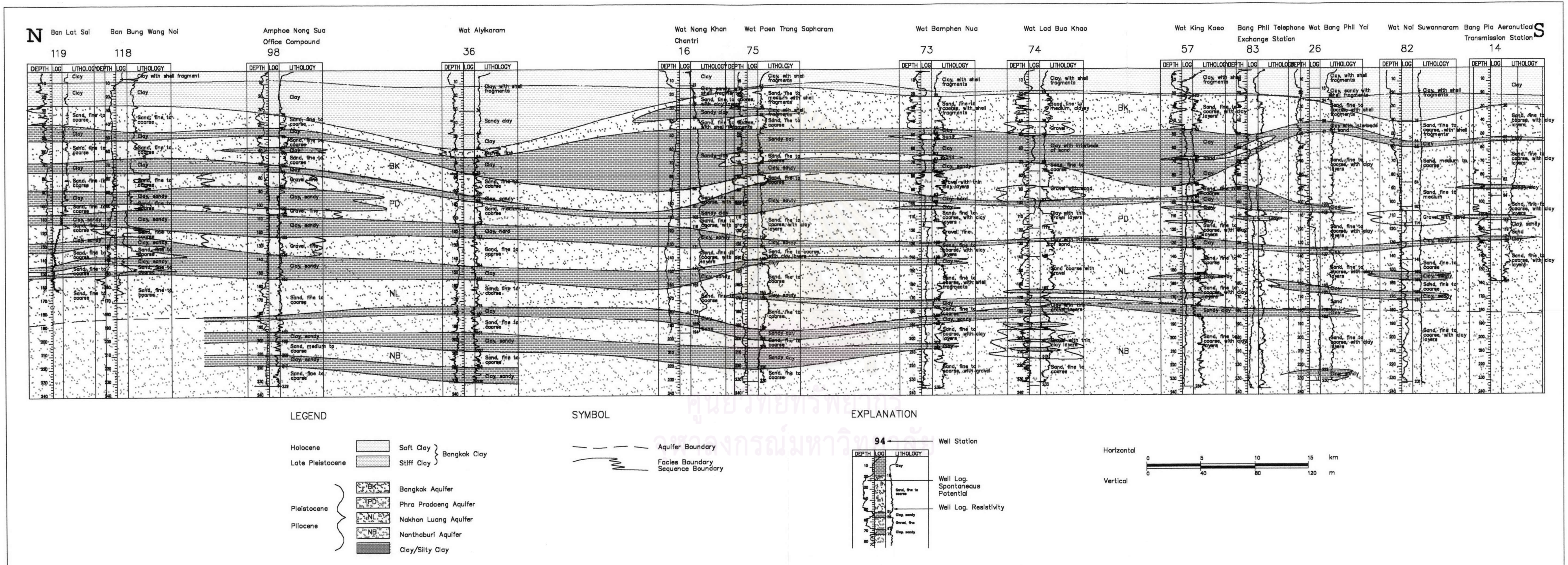


Figure 4.16 Hydrogeologic North-South Section Line12

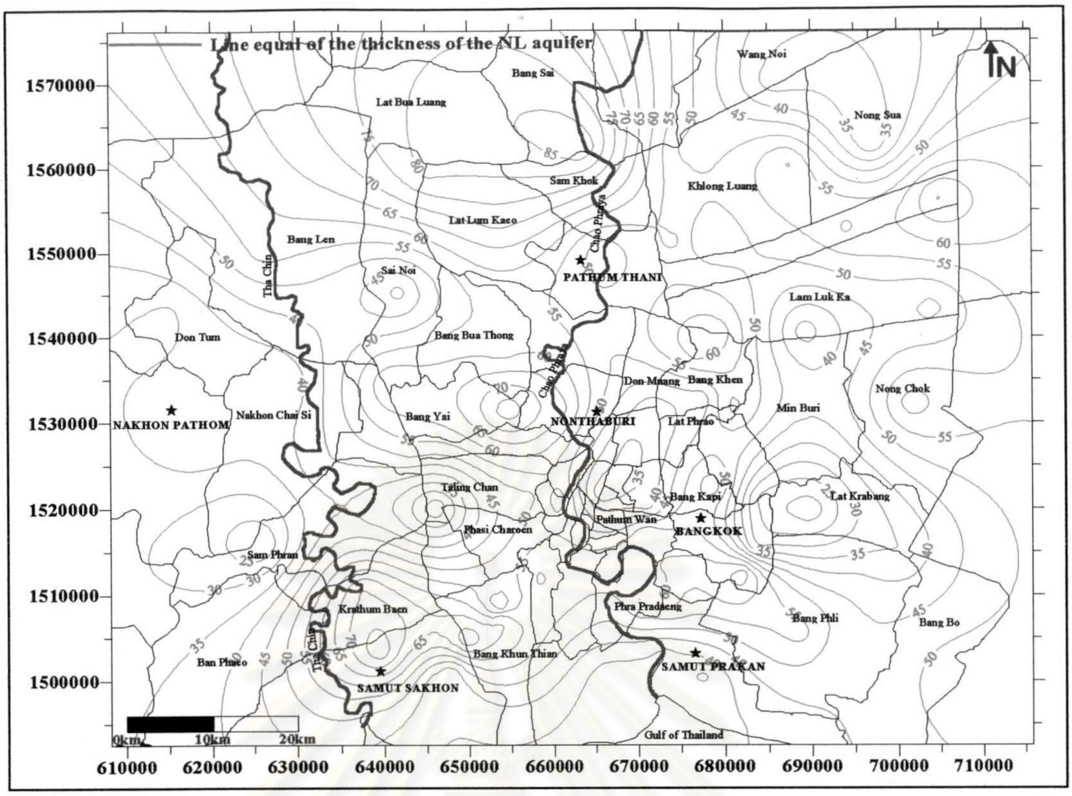


Figure 4.17 Thickness of the Nakhon Luang aquifer

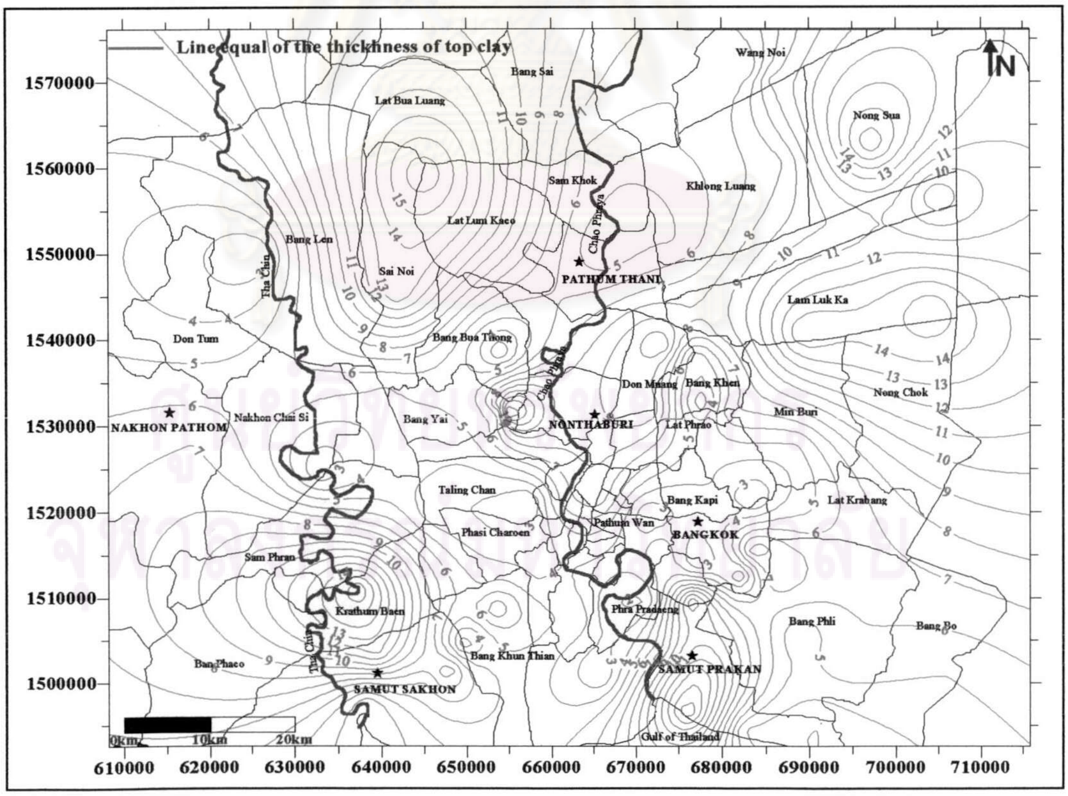


Figure 4.18 Thickness of the top clay of the Nakhon Luang aquifer

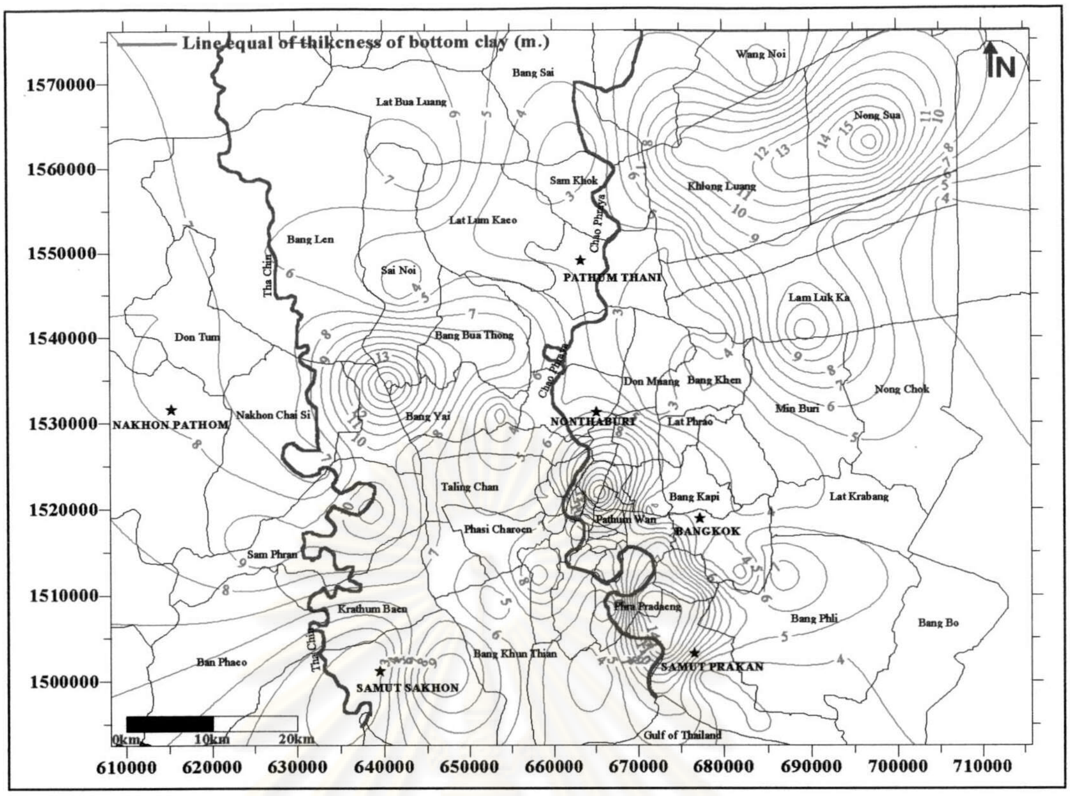


Figure 4.19 Thickness of the bottom clay of the Nakhon Luang aquifer

4.3 Sedimentary Facies Analysis of the Nakhon Luang Aquifer

4.3.1 Grain Size Identification

From the total 12 hydrogeologic cross section lines, the NL aquifer are located at the depth of 125 m to 180 m below ground surface. The average thickness is 50 m. The cuttings, 12 boreholes (Table 4.1 and Appendix I) being used, are selected only within the NL aquifer interval to correlating with the adjacent well. The cutting identification depicts that the NL aquifer is generally composed of fine to coarse-grained sand. In the southwestern part of the NL aquifer; Amphoe Muang, Samut Sakhon Province, the sediment is fine to coarse-grained with a lot of gravel, whitish gray and yellowish brown in color. The mineral composition is composed mainly of quartz more than 95 % and the rest are weathered feldspar, chert, flint, jasper and rock fragments (Fig. 4.20-4.23). Sand layer ranging from 8-20 meters with clay layer, 4-8 meters thick, intercalated. The sediment is poorly sorted, subangular to subrounded. In the central part of the area; Sirirat Hospital and Amphoe Bang Yai, Nonthaburi Province (Fig.4.24-4.28) the sediments of the NL aquifer is whitish gray and yellowish brown. The sediment is poorly to moderately sorted (Amphoe Bang Yai, Nonthaburi), subangular to subrounded. Grain size is varies from fine to coarse-grained sand with some gravel. The mineral composition consists mostly of quartz and the rest are weathered feldspar, chert, flint, jasper and rock fragments. The thickness of sand layers ranging from 10-20 meters with clay layer, 3-6 meters thick, intercalated. The western part in the upper corner of the eastern part of the study area; Amphoe Wang Noi, Phra Nakhon Si Ayutthaya and Amphoe Lam Luk Ka, Pathum Thani Province (Fig. 4.29-4.31), the sediment is whitish gray and yellowish brown. They are composed of fine to coarse sand with some gravel (Fig. 4.29-4.31), poor to moderately sorted, subangular to subrounded. The thickness of sand layers ranging from 10-20 meters with clay layer, 3-10 meters thick, intercalated. The main constituents are similar to the western and central parts.

In general, the sediment is poorly to moderately sorted, subangular to subrounded. The mineral composition consists mainly of quartz, weathered feldspar, flint, jasper, chert, a few rock fragments such as quartzite, sandstone, limestone and shale. Figure 4.32 displays the availability of the rock fragments in the cuttings. In comparison with the central and the eastern part, the finer grain is appeared a lot more in the western part of the area.

Table 4.1 The description of the primary reference wells and the primary wells

Well station	UTM E	UTM N	Well Code	Location	Depth Drilled (m.)
118	685400	1570300	G1362PSA119	Ban Bung Wang Noi, A.Wang Noi,	172.5
				Phra Nakhon Si Ayutthaya	
119	683200	1571750	G1364PSA121	Tombon Wang Noi, Ayutthaya	165
120	645300	1500300	DN37SSN14	Tombon Khok Makham, A. Muang,	390
				Samut Sakhon	
121	647900	1501400	DN40SSN15	Wat Rai Charoen Phon, A. Muang,	480
				Samut Sakhon	
122	660800	1521200	DS33BKK1	Sirirat hospital, Bangkok	642
123	691350	1538750	DN58BKK5	Musayid Darussalama, Bangkok	186
124	691600	1537600	DN59BKK6	Musayid MarussaahDa, Bangkok	174
125	675900	1545400	DR51PT1	A. Lam LukKa, Pathum Thani	264
126	645000	1530075	DR43NB5	Wat ton Chuak, A.Bang Yai, Nonthaburi	276
127	644200	1530175	DR60NB6	Ban Ton Chuak, A.Bang Yai, Nonthaburi	339
128	638650	1507250	DN35SSN13	Tombon Khlong Madue, A. Muang,	474
				Samut Sakhon	
129	638375	1495800	DN44SSN3	Wat Khrok Khrak, A.Muang, Samut Sakhon	465

Note: Wells station numbers 118-122 are the primary reference wells and wells numbers 123-129 are the lithologic logging wells (primary wells)

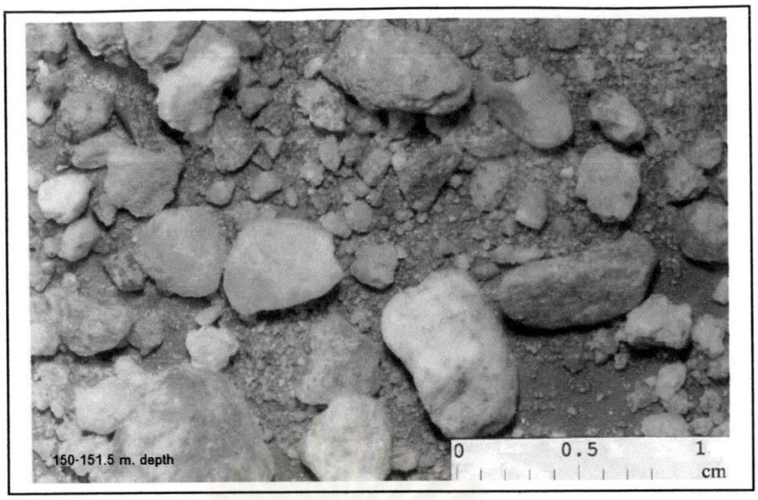


Figure 4.20 Cuttings from DN37SSN14, Samut Sakhon Province

Figure 4.21 Cuttings from DN40SSN15, Samut Sakhon Province

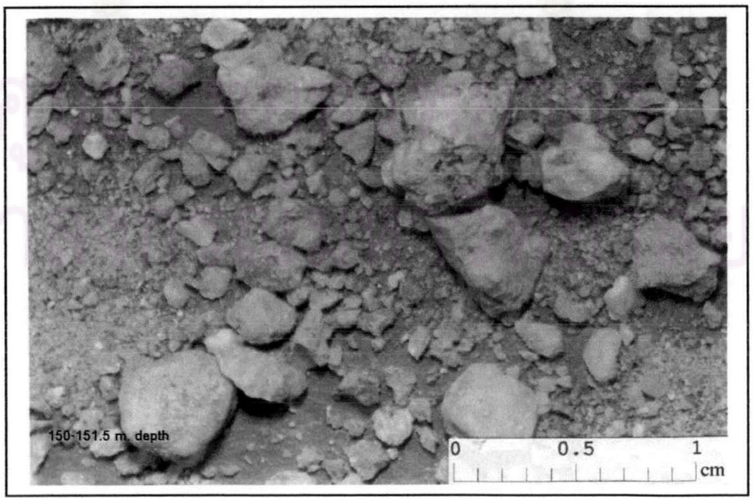


Figure 4.22 Cuttings from DN35SSN13, Samut Sakhon Province

Figure 4.23 Cuttings from DN44SSN3, Samut Sakhon Province

Figure 4.24 Cuttings from DR43NB5, Nonthaburi Province

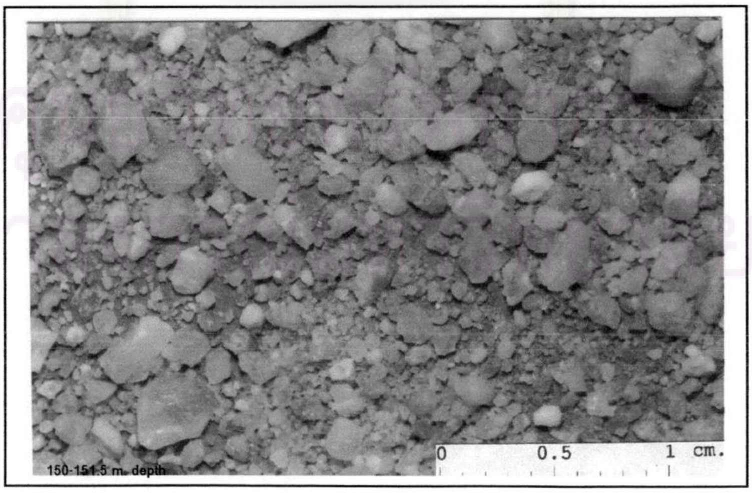


Figure 4.25 Cuttings from DR60NB6, Nonthaburi Province

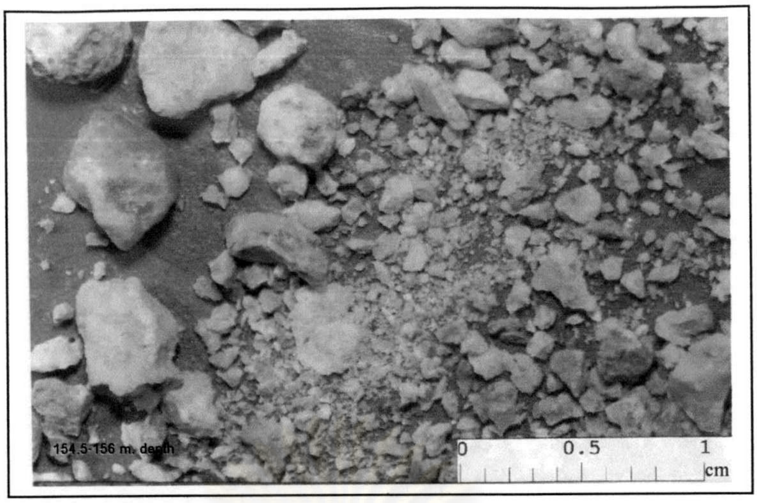


Figure 4.26 Cuttings from DS3BKK1, Bangkok Metropolis

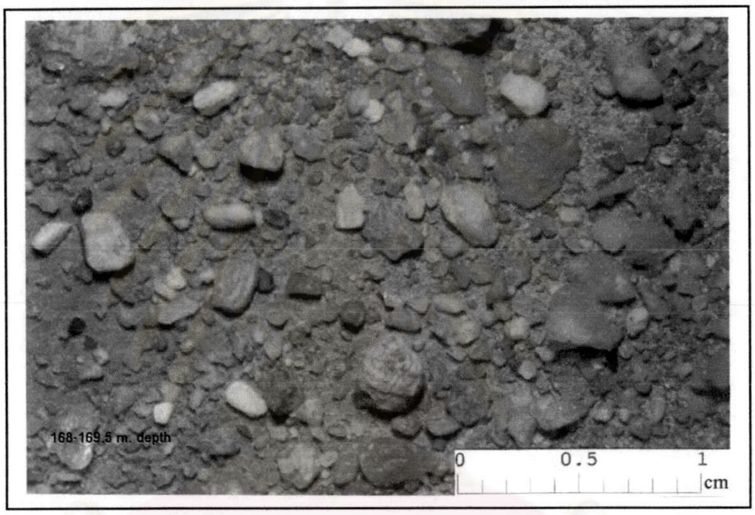


Figure 4.27 Cuttings from DN58BKK5, Bangkok Metropolis

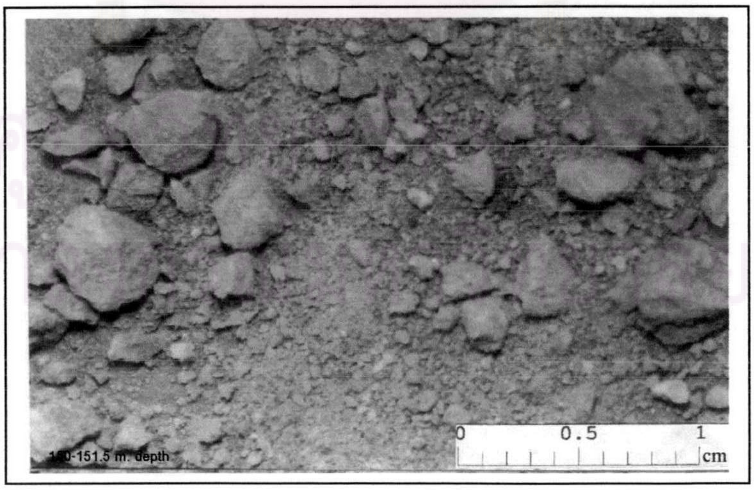


Figure 4.28 Cuttings from DN59BKK6, Bangkok Metropolis

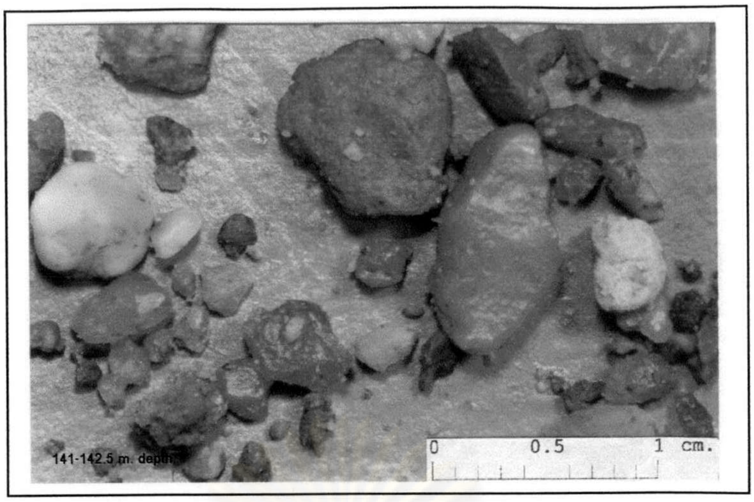


Figure 4.29 Cuttings from DR51PT1, Pathum Thani Province

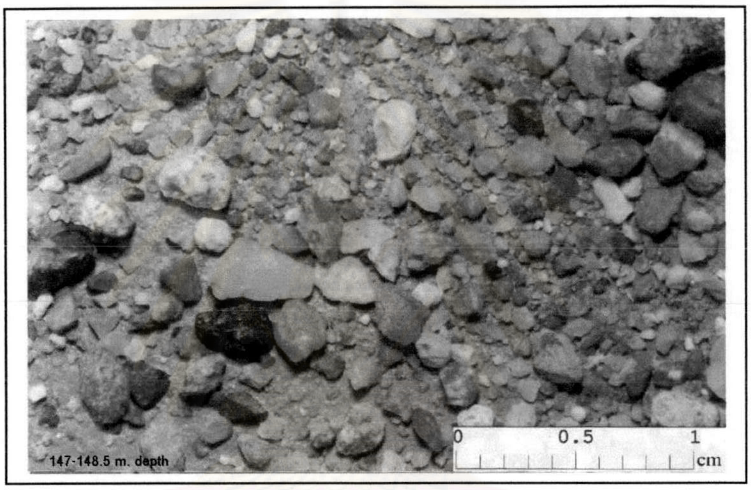


Figure 4.30 Cuttings from G1362PSA119, Phra Nakhon Si Ayutthaya

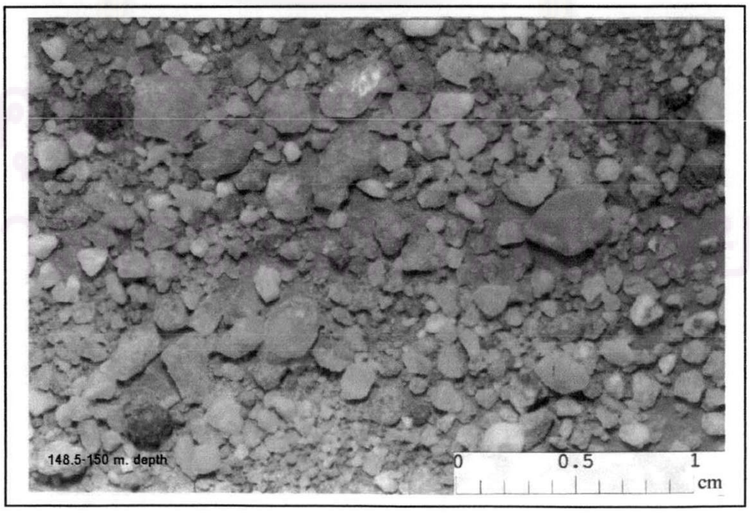
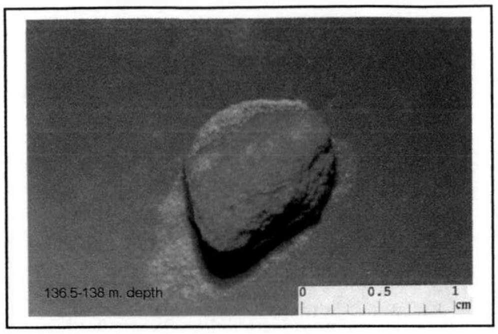
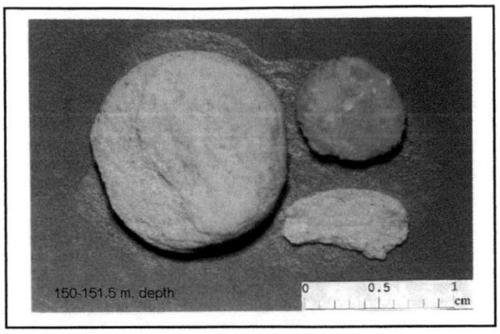


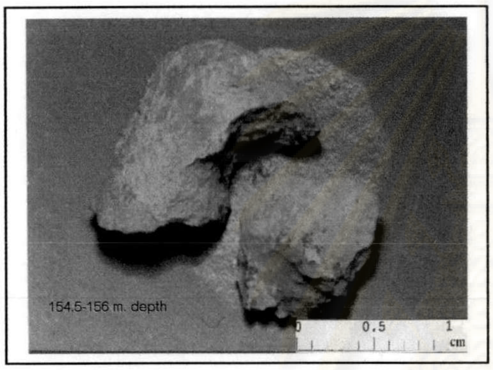
Figure 4.31 Cuttings from G1364PSA121, Phra Nakhon Si Ayutthaya



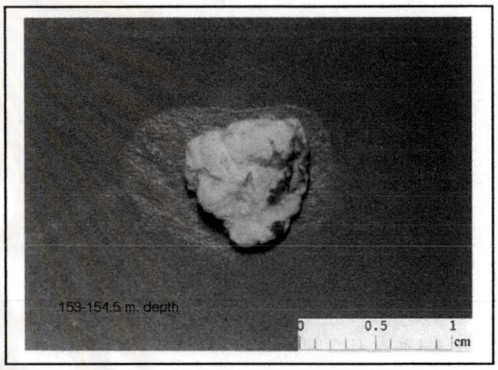
Sandstone from DN37SSN14



Quartzite from DN35SSN13

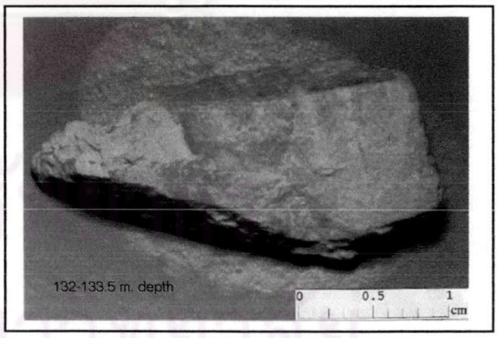


Shale bit from DR60NB5



Quartzite from DS33BKK1

Limestone from DN59BKK6



Shale from G1362PSA119

Figure 4.32 Rock fragments in the study area

4.3.2 Depositional Environment

Within the 99 SP curves, they are indicated that the sediment is coarsening upward sequence in the southern part and western part, further to the north of the area (Fig. 4.6 station 39 and Fig. 4.12 station 14) whereas in the eastern, western and central parts, the sediment is fining upward sequence (Fig. 4.8 station 44 and 33). From the sequences of sediment, it can be interpreted that in the southern part of the NL, the deltaic environment is dominant while in the east, west and central parts, the fluvial process especially point bar and channel environments is dominant.

With the combination of the 12 cuttings and the 99 SP curves, it can be classified the environment of deposition of sediment in this area into 3 types as follow:

- Alluvial Fan. As the gravel is mainly found in the western part of the area, and the gravel is mainly subangular in roundness, which indicated that, the sediment was transported rather short distance and supplied from the west.

- Floodplain, point bar and channel deposits. The geomorphological deposition is interpreted from the cuttings that are fine to coarse-grained sand with some gravel; poorly to moderately sorted; fining upward sequence, and the Christmas Tree-SP curves. They are mostly found in the central, northward and eastward of the area.

- Delta. It is found from the SP curves as the coarsening upward sequence, which is found in the southern part of the area and the western part, further to the north.

From the interpretation of cuttings and SP curves, it can be concluded that, from the hydrogeologic cross sections indicated that the rate of subsidence of the north is higher than the south, so the thickness increasing to the north, while the rate of subsidence of the sediment in the west is rather higher than the east, thus, the thickness is decreasing to the east. The sedimentary facies of the NL aquifer are varied probably due to the paleomorphology and paleoenergy within the basin. In the eastern part, the Sp curves show the fining upward sequences and the evidence from the cuttings, containing fine to coarse grained sand with some gravels, subangular to subrounded which may be indicated the short distance supplied from the east and part of the channel lag deposit of the point bar sequences. In the central part and west bank of the Chao Phraya River, the SP curves show the fining upward sequence (Christmas tree and block of sand indicated the distributary environment) and the cuttings is fine to coarse grained sand with a few gravel, moderately sorted which indicating the flood plain, point bar and channel deposit. In the western part of the area, the evidence from the cuttings shows a lot of gravel, which is more content and bigger than the central and the eastern parts, it may be indicated that the sediment is supplied by the alluvial fan in the west with short distance. In the south and some part of the west further to the north of the Chao Phraya River are found the relicts of coarsening upward sequences developed which indicating the deltaic environment. Thus, from this evidence, the NL aquifer, some area is deposited in the fluviatile environment while some is in the deltaic environment, so it is appropriated to call as "the Fluvio-Deltaic environment". According to the study of Piancharoen and Chauamthaisong in 1976, it revealed that the whole sediment at the depth 100-400 meters that deposits under the subaerated fluviatile environments during the Lower-Middle Pleistocene periods. Hence, the NL aquifer might be the Middle Pleistocene in age.

4.4 Groundwater Potential Analysis

4.4.1 Water Quality

4.4.1.1 Formal Analysis: Hydrochemical Facies

The water quality analysis was conducted, by Groundwater Division: DMR, from water samples that collected from 1991-2000 (Appendix II-a – II-b). The analytical data were plotted in the Piper trilinear diagram (Fig.4.33- 4.37). From the diagram, the **hydrochemical facies** can be divided into two major types and one minor type. The **first major** type is Na-K-Cl-SO_4 type (Type IV), which is indicating the chemical properties of groundwater is dominated by alkali and strong acids, that means the sodium and potassium contents as well as the chloride and sulfate contents are more than 50 percent. Thus, its water quality is brackish and salty water. Whereas the Na-K-HCO_3-CO_3 type (Type II) is the **second major** type which is depicting the chemical properties of groundwater is dominated by the alkali and weak acid, that means the sodium and potassium contents as well as the bicarbonate and carbonate contents are more than 50 percent. Hence, it is soft water. While, the **minor type** is mixing water (Type V) that means the chemical properties are neither cation nor anion dominant. Its properties are mixing of fresh and saline water. However, if processing the analytical data by means of computer via Aquachem, the **water sub facies** of 4 types are obtained (Fig.4.38-4.42) to support the distribution of the quality of groundwater that mentioned above in the study area as follow:

Type A : Sodium Chloride component Na-Cl. Water sub facies type I is characterized by Na^+ and Cl^- as the dominant ions which indicated the saline water (Yong and Nutalaya, 1987). It is distributed along the Chao Phraya River as well as in the southeastern and southwestern parts of the area.

Type B : Sodium Sulphate component Na-SO_4. There is a significant enrichment in Na^+ and SO_4^{2-} concentration when considering with Cl^- concentration and the high total dissolved solids content, it is pointed out that the result of the mixing of saline ocean water or brackish water condition (Yong and Nutalaya, 1987). It is concentrated only in the central part of the area.

Type C : Sodium Bicarbonate component Na-HCO_3. Type III water sub facies has been enrich in Na^+ and HCO_3^-, which is explained by the combined effects of carbonate mineral dissolution and cation exchange of clay mineral with exchangeable Na^+ (Yong and Nutalaya, 1987). This type is distributed in the central part further to the eastern part of the area.

Type D : Calcium Chloride component Ca-Cl. This type is Ca^+ and Cl^- content are dominant. This type may be associated with series of water formed by mixing with saline water and modified by some hydrochemical process to remove Na^+ and to enrich Ca^{2+} (Yong and Nutalaya, 1987). It is distributed in the central and further to the southern part of the area.

From four types of water sub facies, it can be concluded that the Na-Cl type (Type A) which is indicated the brackish to saline water and concentrated in the along the Chao Phraya River as well as in the southeastern and southwestern parts of the area and the Na-HCO_3 type (Type C) which is depicted the softer water that distributed in the central part further to the eastern part of the area are dominated component. While, the Na-SO_4 type and the Ca-Cl type are observed less abundant in the central and further to the southern part of the area. In 1994-1995 the Na-Cl type is increasing while the Na-HCO_3 type decreasing, the direction of Na-Cl type moved toward to replace the zone of type C distribution in the eastern part further to the north of the area. The areas that the Na-Cl type and the Na-HCO_3 type dominate are associated to denote the zone of hydrochemical facies dominance.

Generally, the type of hydrochemical facies in groundwater is mainly controlled by the lithology, mineralogy of aquifer material and the groundwater flow pattern. The hydrochemical facies in evolution paths are primarily grouped based on dominant anion constituents because anions tend to remain in solution rather than to enter an ion exchange process. With an increasing of flow path or age, HCO_3^--rich groundwater that are usually observed in shallow zones of recharge areas evolve to Cl^--rich waters close to the composition of seawater via the stage where SO_4^{2-} is the dominant anion.

The hydrochemical facies from the study of Fuangswasdi in 1991 is HCO_3-CO_3-Cl-Na-K and Jayakrishnan in 1993 is Cl-Na-K type and HCO_3-CO_3-Na-K type. It is considered that during the period 1986-1995 (the last update data for formal analysis), the water types of the NL aquifer are not significantly different. If comparing to the prior study by Jitapunkul in 1980, he depicted that the Type II is the major hydrochemical facies developed in the study. Moreover, it should be pointed that the water quality in this area is changed due to the anion (such as Cl^- and HCO_3^-) concentrations are high. It can be notified here that the water quality of the Nakhon Luang will be changed due to the overpumping of groundwater.

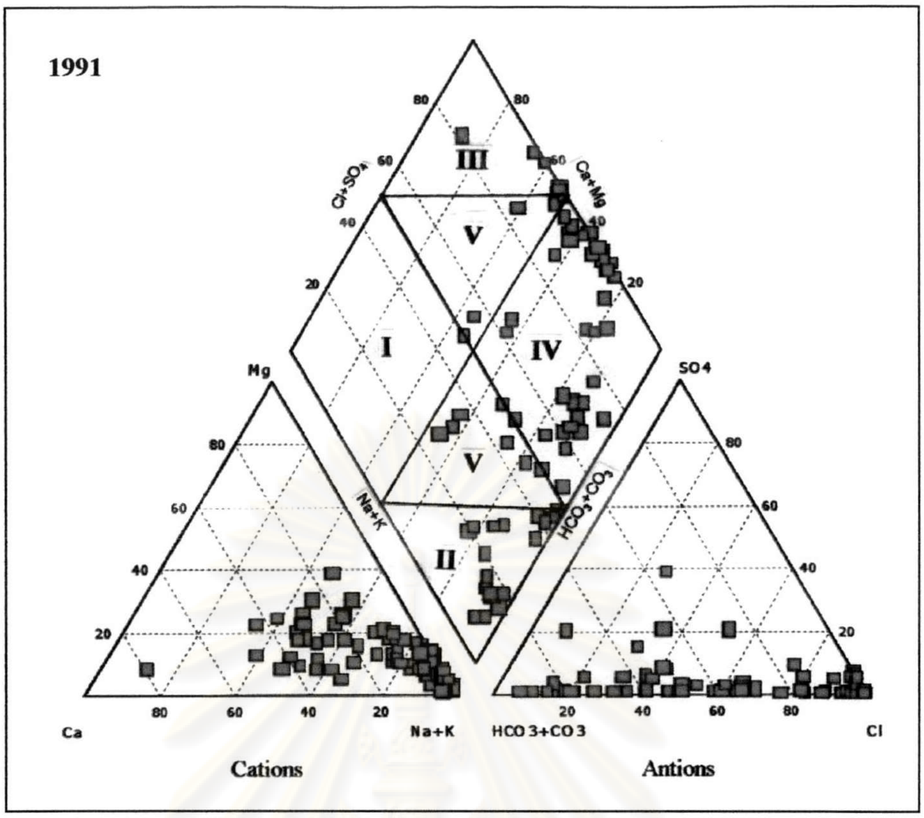


Figure 4.33 Trilinear diagram of water quality from the observation wells in 1991

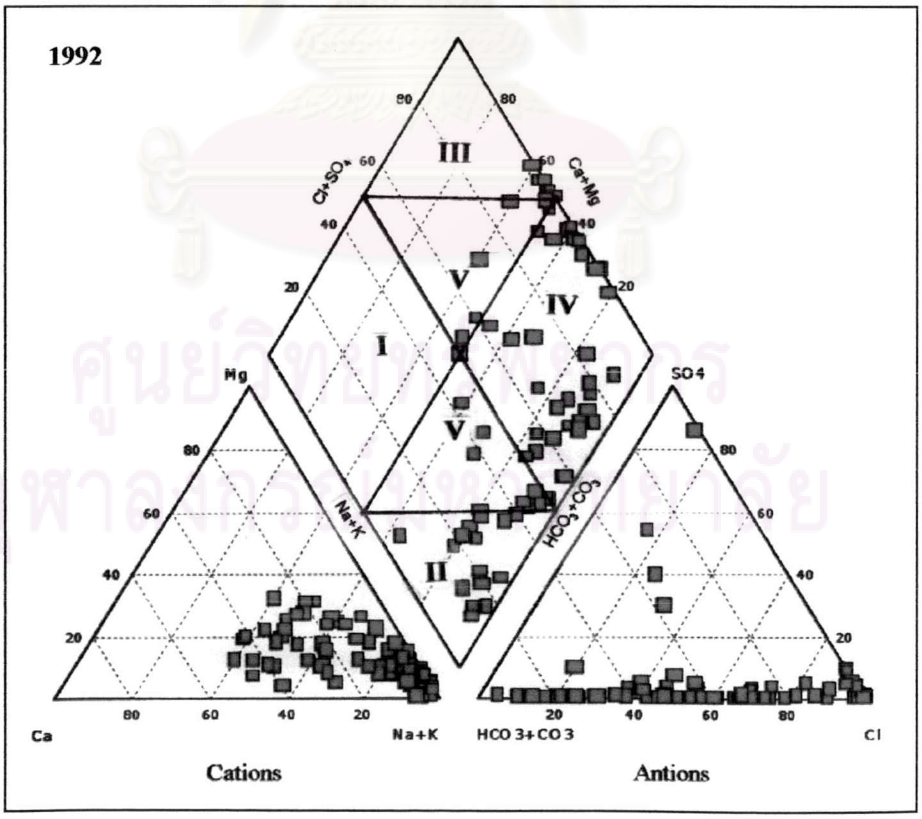


Figure 4.34 Trilinear diagram of water quality from the observation wells in 1992

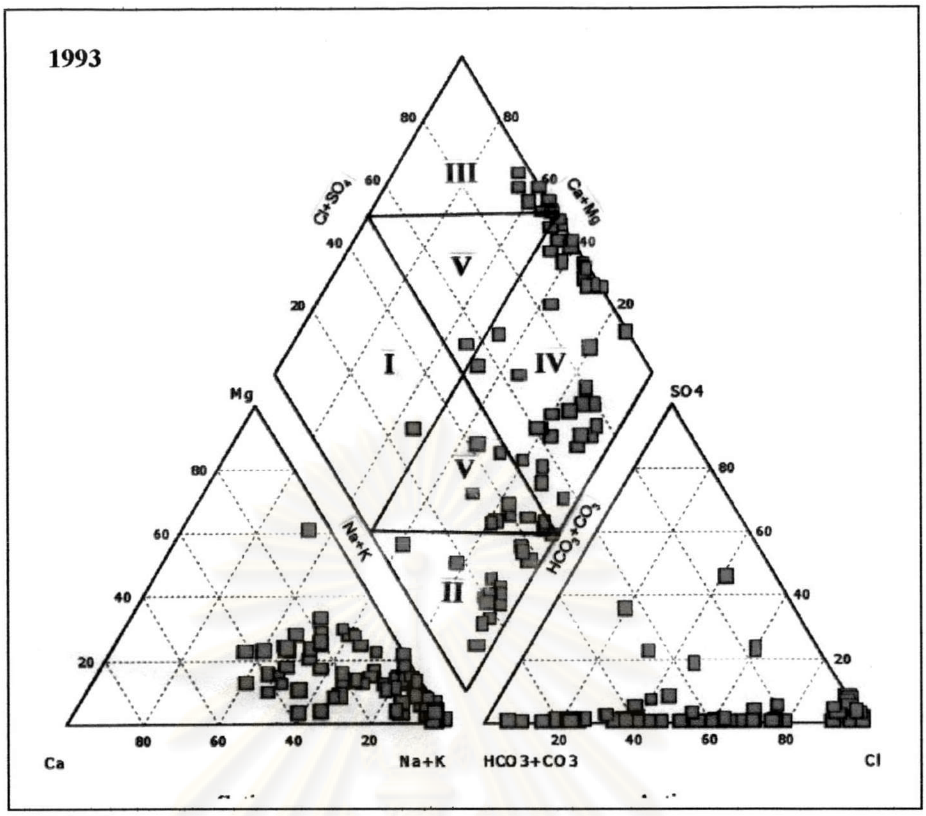


Figure 4.35 Trilinear diagram of water quality from the observation wells in 1993

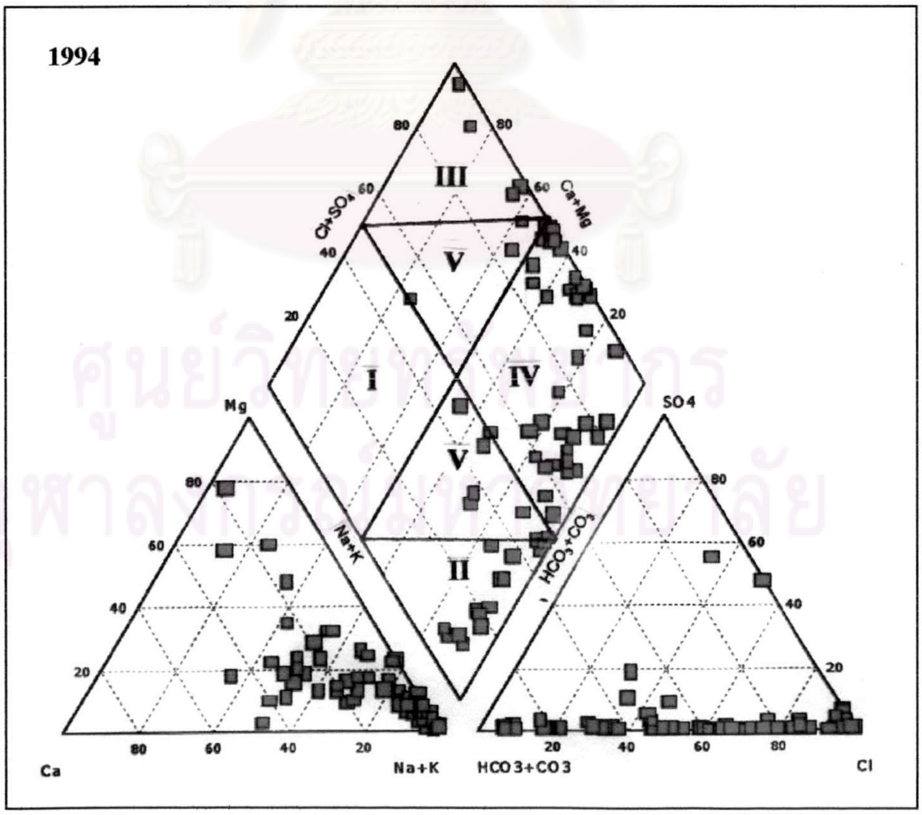


Figure 4.36 Trilinear diagram of water quality from the observation wells in 1994

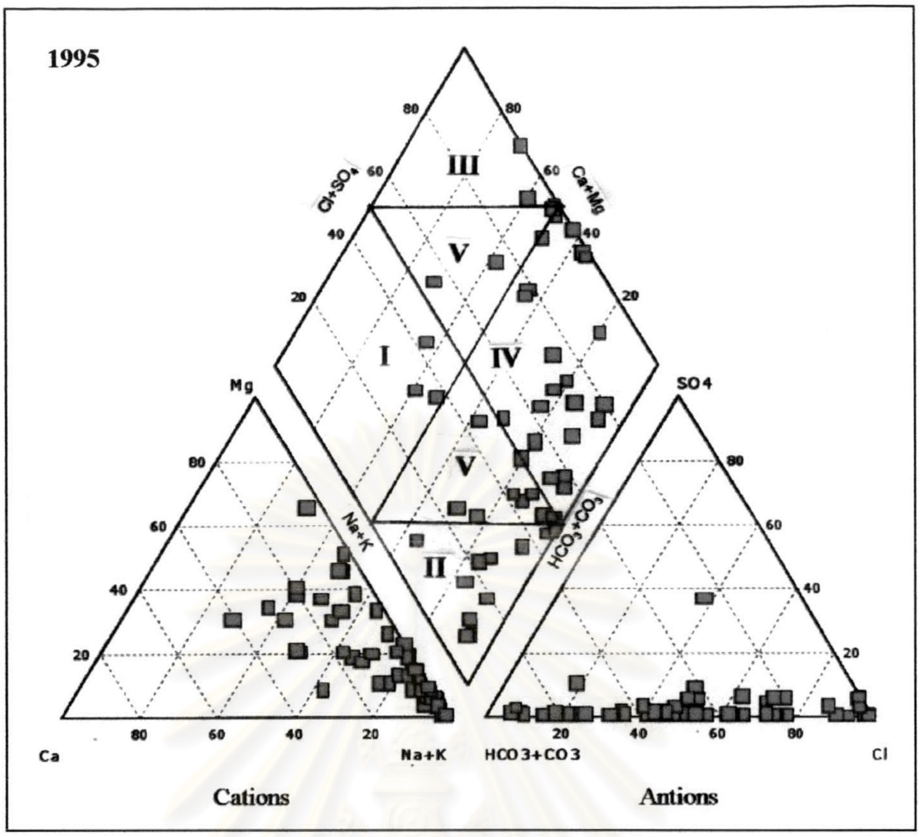


Figure 4.37 Trilinear diagram of water quality from the observation wells in 1995

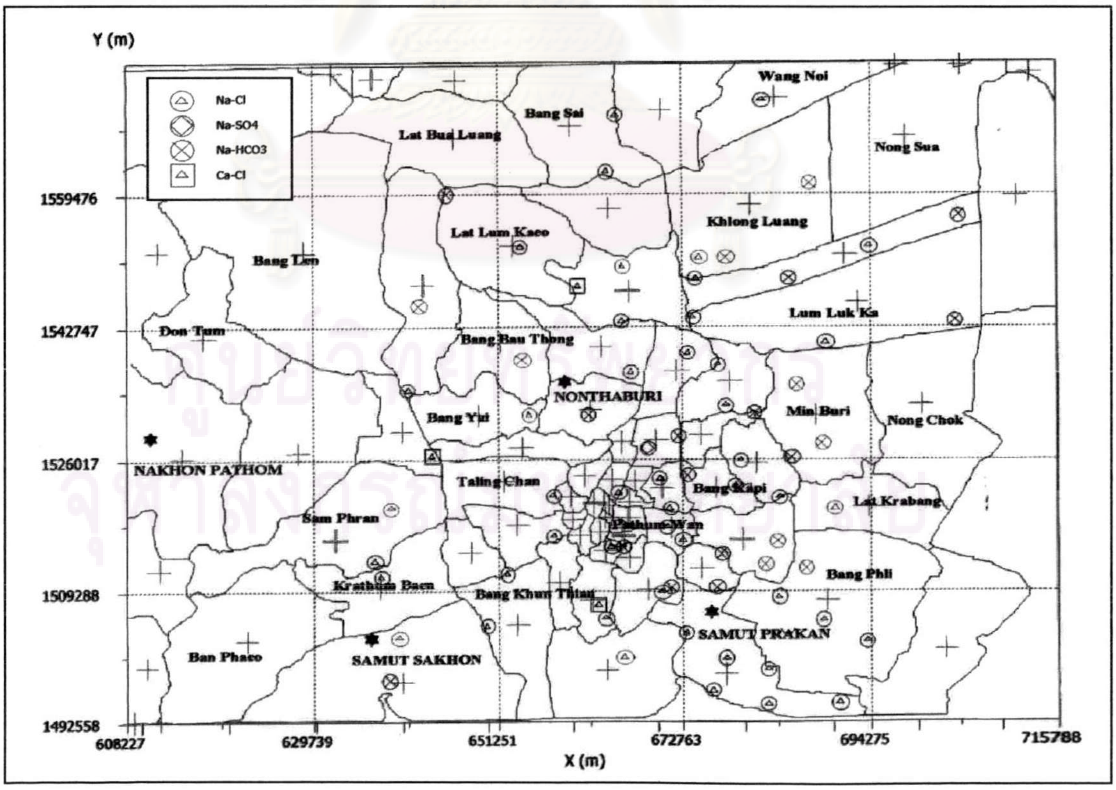


Figure 4.38 Water sub facies of water quality from the observation wells in 1991

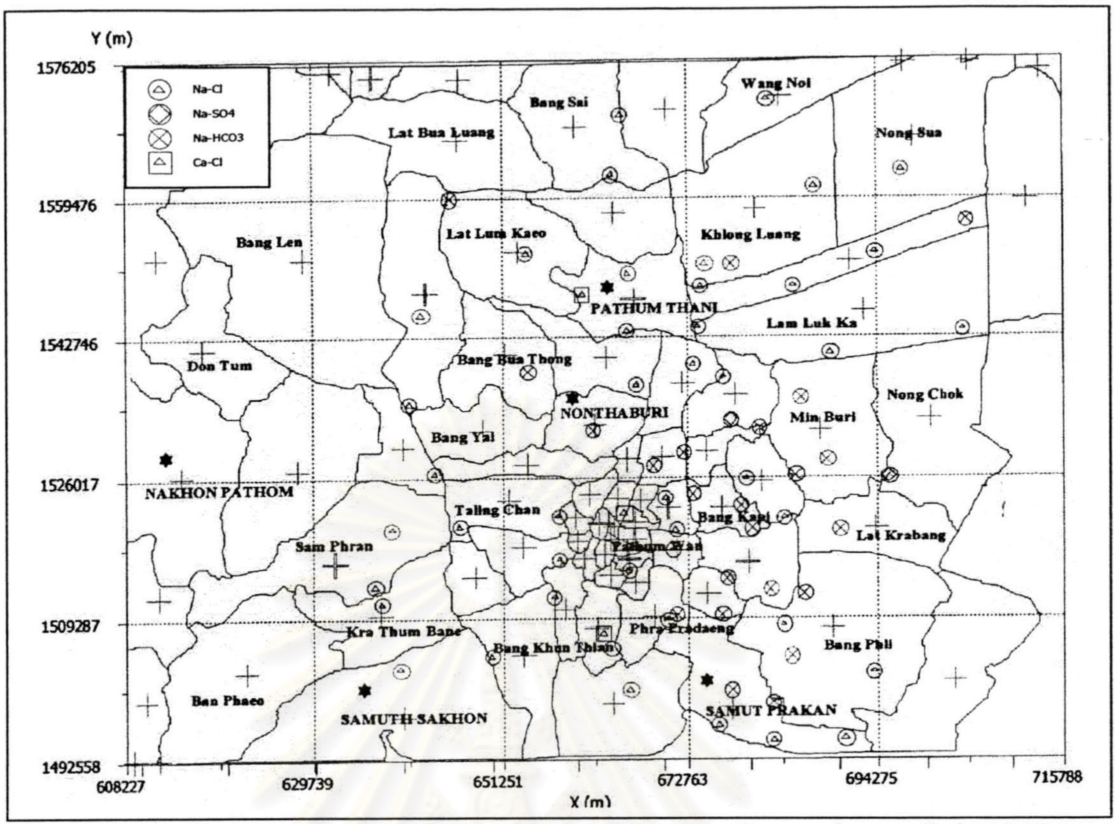


Figure 4.39 Water sub facies of water quality from the observation wells in 1992

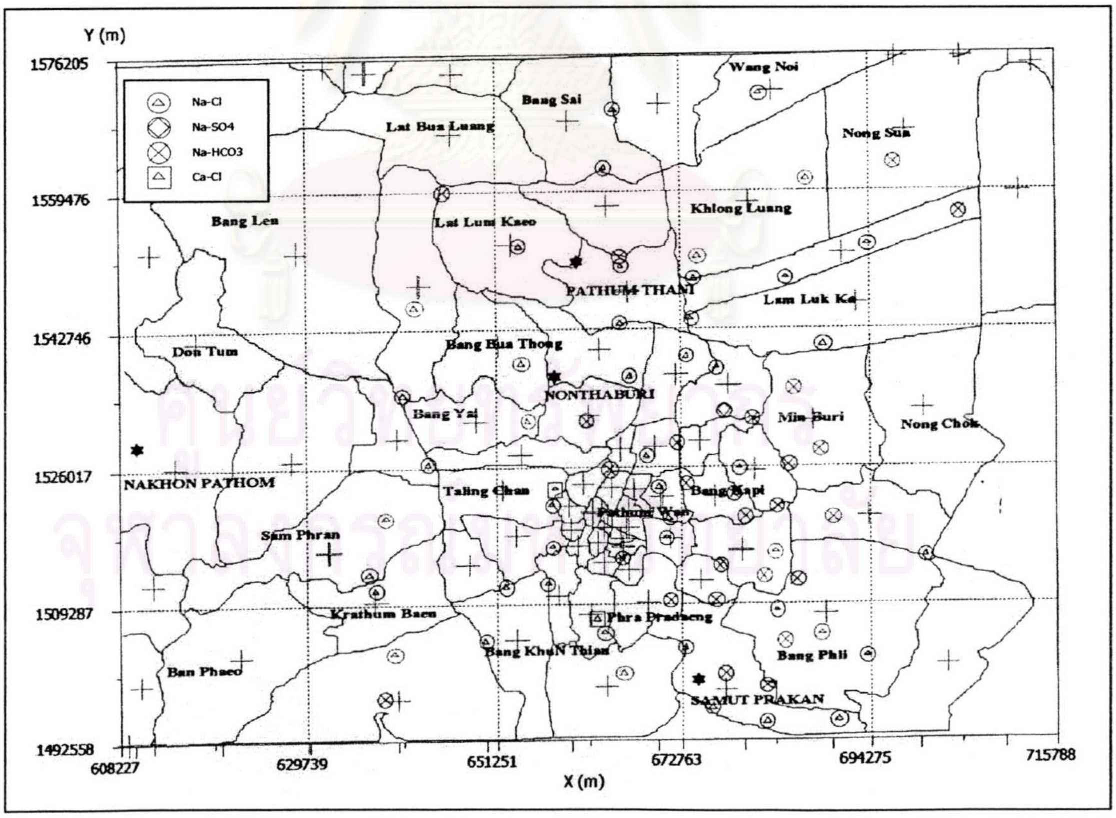


Figure 4.40 Water sub facies of water quality from the observation wells in 1993

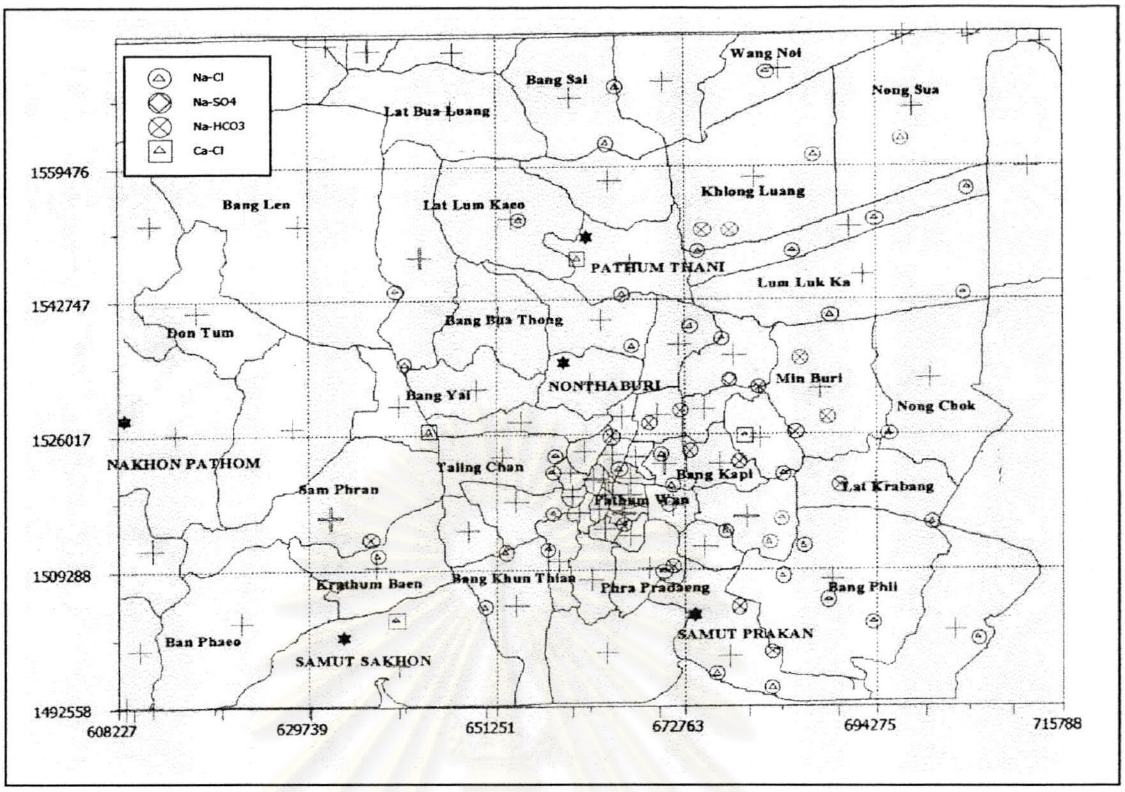


Figure 4.41 Water sub facies of water quality from the observation wells in 1994

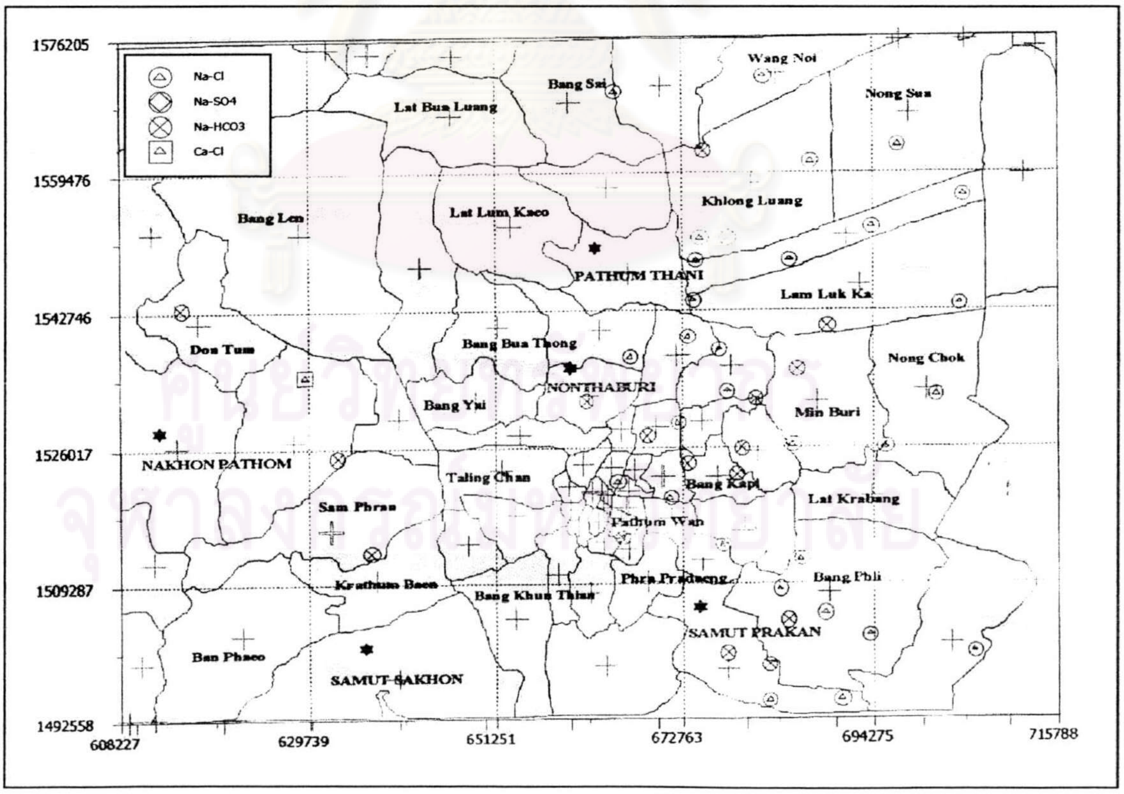


Figure 4.42 Water sub facies of water quality from the observation wells in 1995

4.4.1.2 Informal Analysis: Critical Parameters

These parameters consist of Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^{+}), Potassium (K^{+}), Total Iron (Fe), Sulfate (SO_4^{2-}), Chloride (Cl^{-}), Bicarbonate (HCO_3^{-}), Nitrate (NO_3^{-}), Fluoride (F^{-}), Total Dissolved Solids, Total Hardness as CaCO3, Manganese (Mn), the Power of Hydrogen ions (pH), and Specific Electrical Conductivity (EC). They are extensively studied concerning with the determination of acceptable limits for potable water using the standards of Drinking Water, GROUNDWATER ACTS B.E. 2520 (Table 2.1). However, if the content is extremely higher than the Standard, the new classification will be established. The data concerning these parameters are gathered from 1991-2000.

a) The Power of Hydrogen Ion (pH). Groundwater quality map of pH is shown in Fig. 4.43-4.45. The map shows that value of pH is within the suitable limit of drinking water standard (pH: 6.5-9.2, the green color) in major portion of the study area. The groundwater of the eastern part of the area shows high alkalinity (> pH 9.2, the pink color) and small portion of the western part of the area whereas the high acidity (< pH 6.5, the red color) is concentrated in the southern part of the area.

b) Specific Electrical Conductance (EC). Figures 4.46-4.48 display the electrical conductivity values of the studied area. The electrical conductivity values vary within the range of 200-34,000 micromhos. In rainwater will usually has a conductance range from 5.0 to 30 micromhos, while subsurface water has a conductance range from 30 to 2,000 micromhos. The area where electrical conductivity values are over 2,000 micromhos is located along the Chao Phraya River, the southwestern and the southeastern parts and the middle of eastern part further to the north.

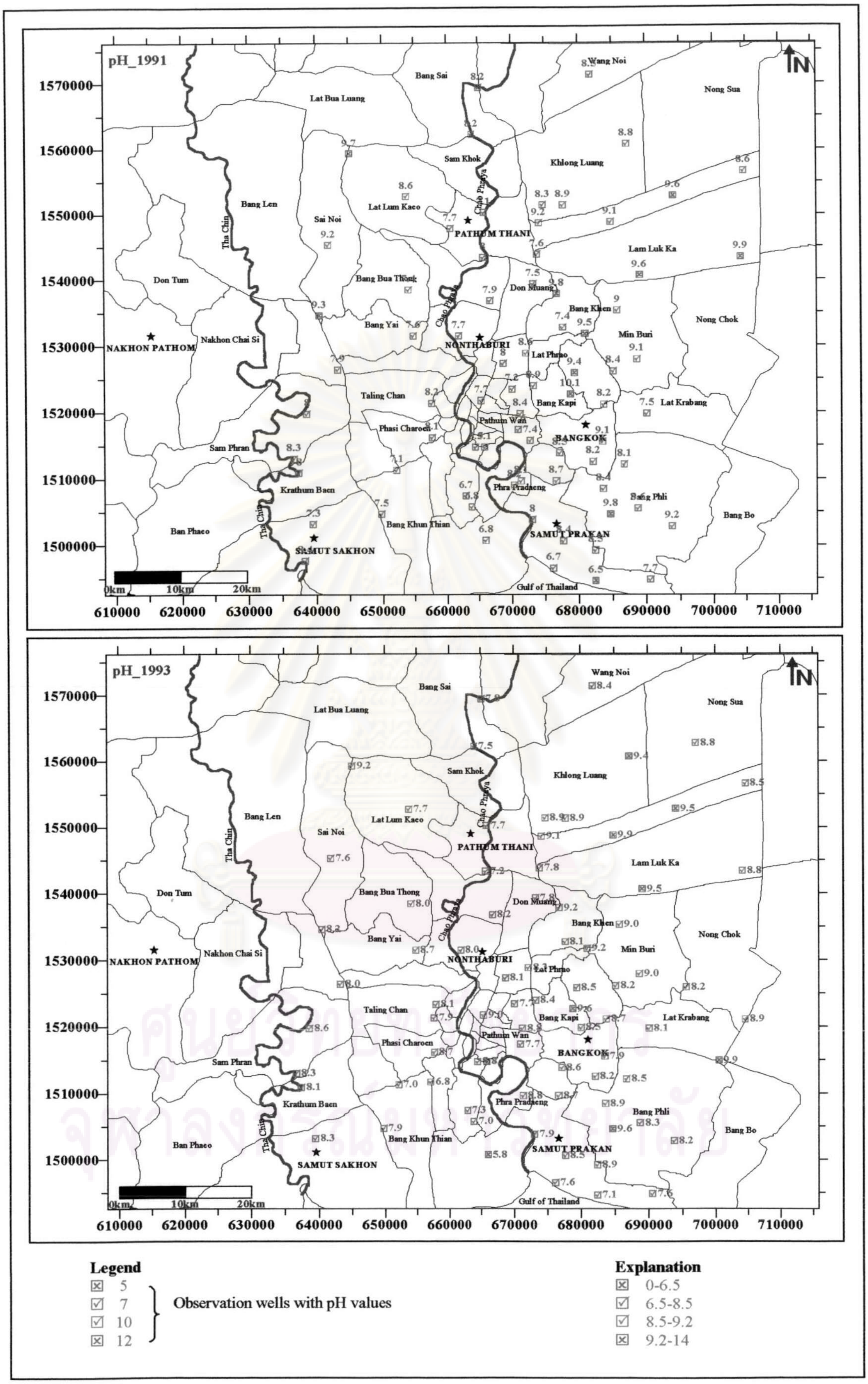


Figure 4.43 pH values in 1991 and 1993

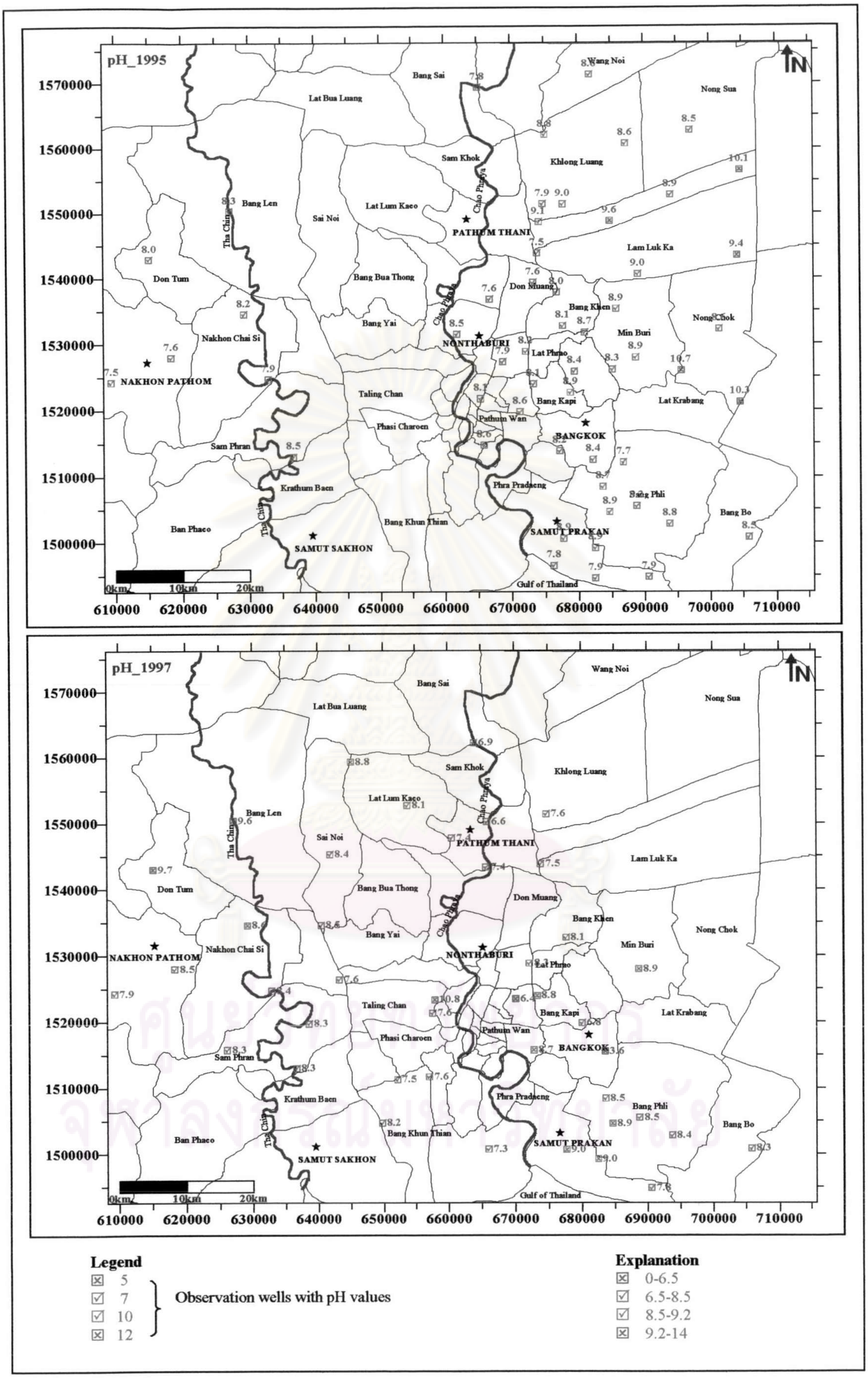


Figure 4.44 pH values in 1995 and 1997

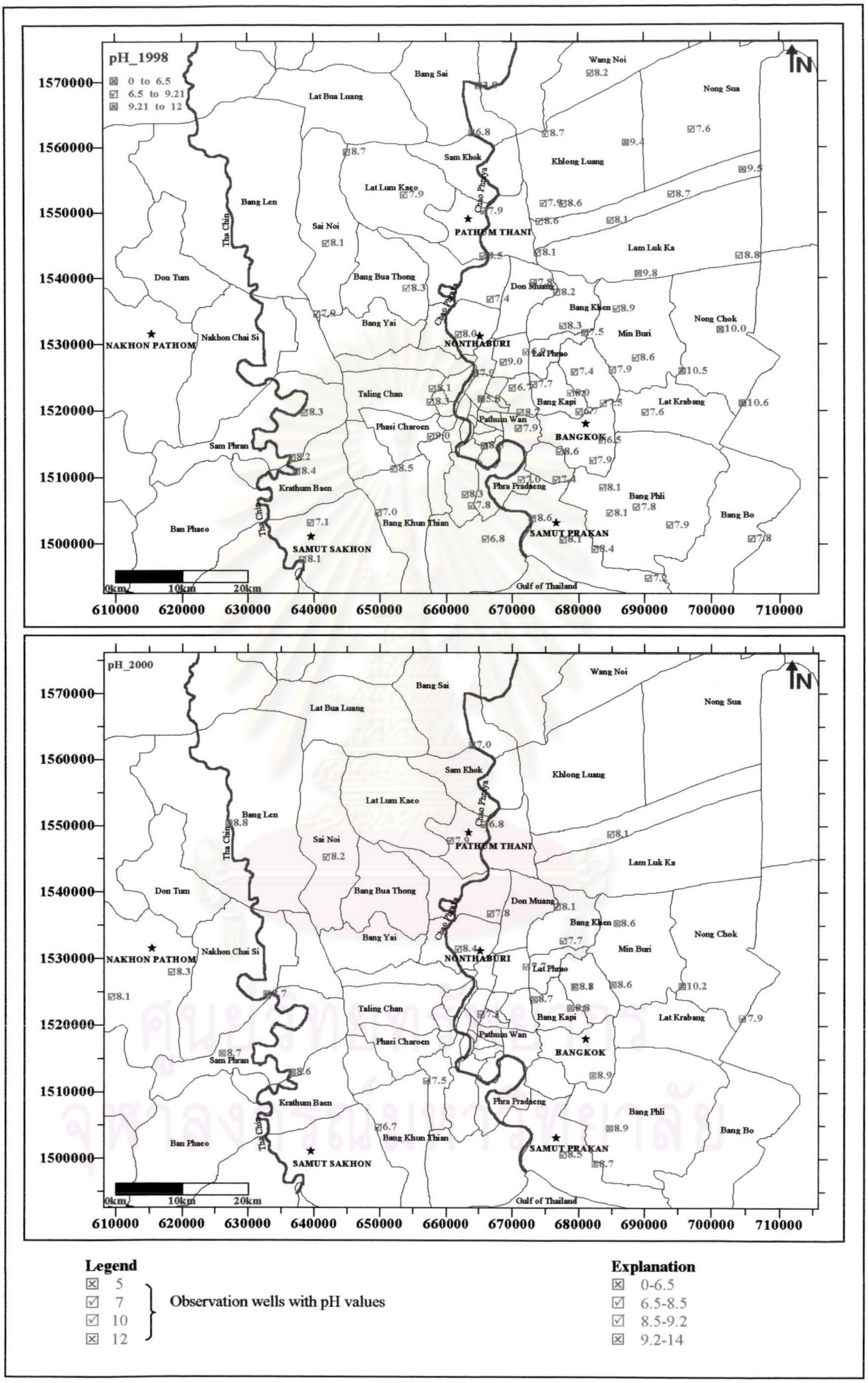


Figure 4.45 pH values in 1998 and 2000

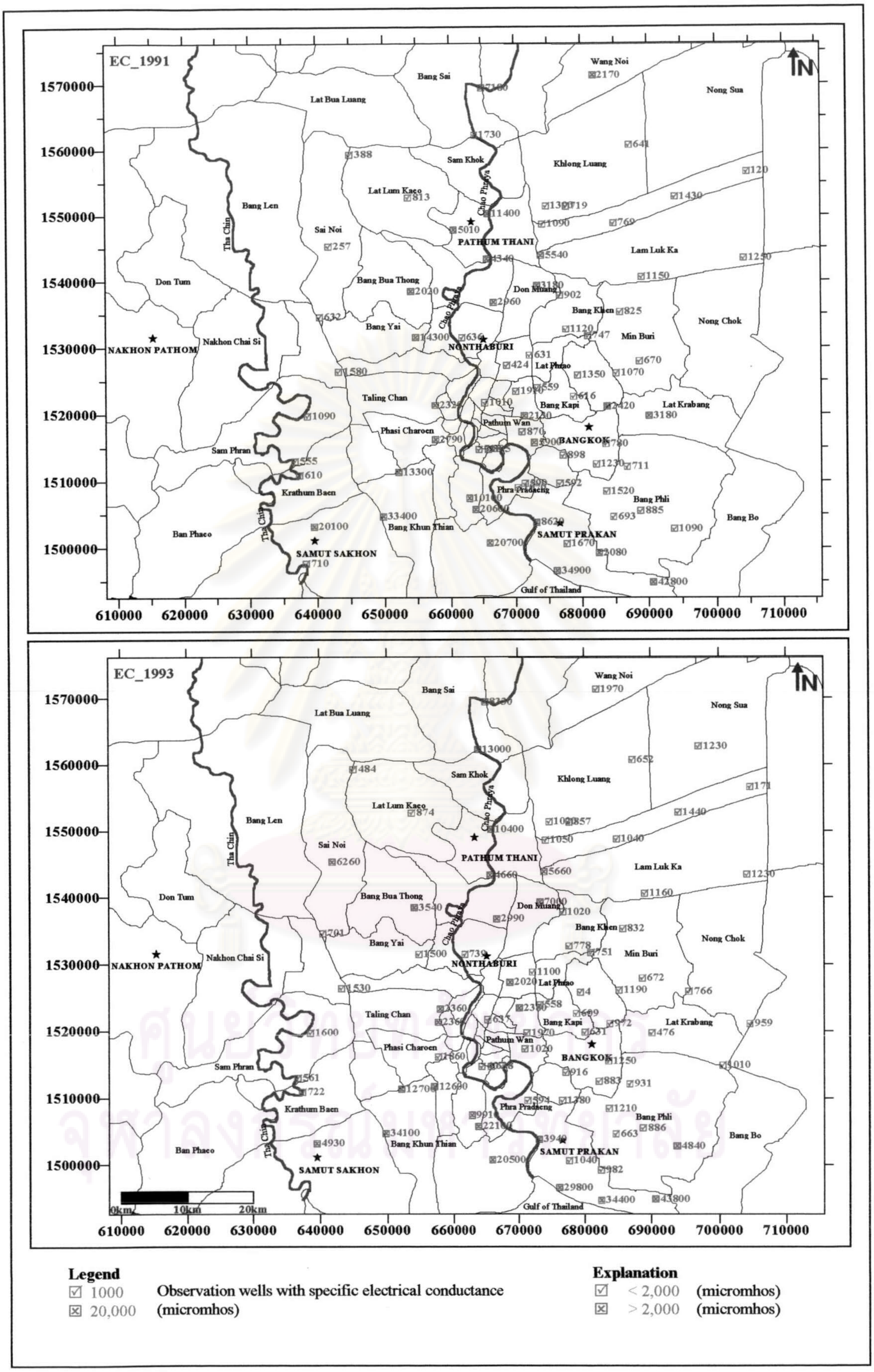


Figure 4.46 Specific Electrical Conductance in 1991 and 1993

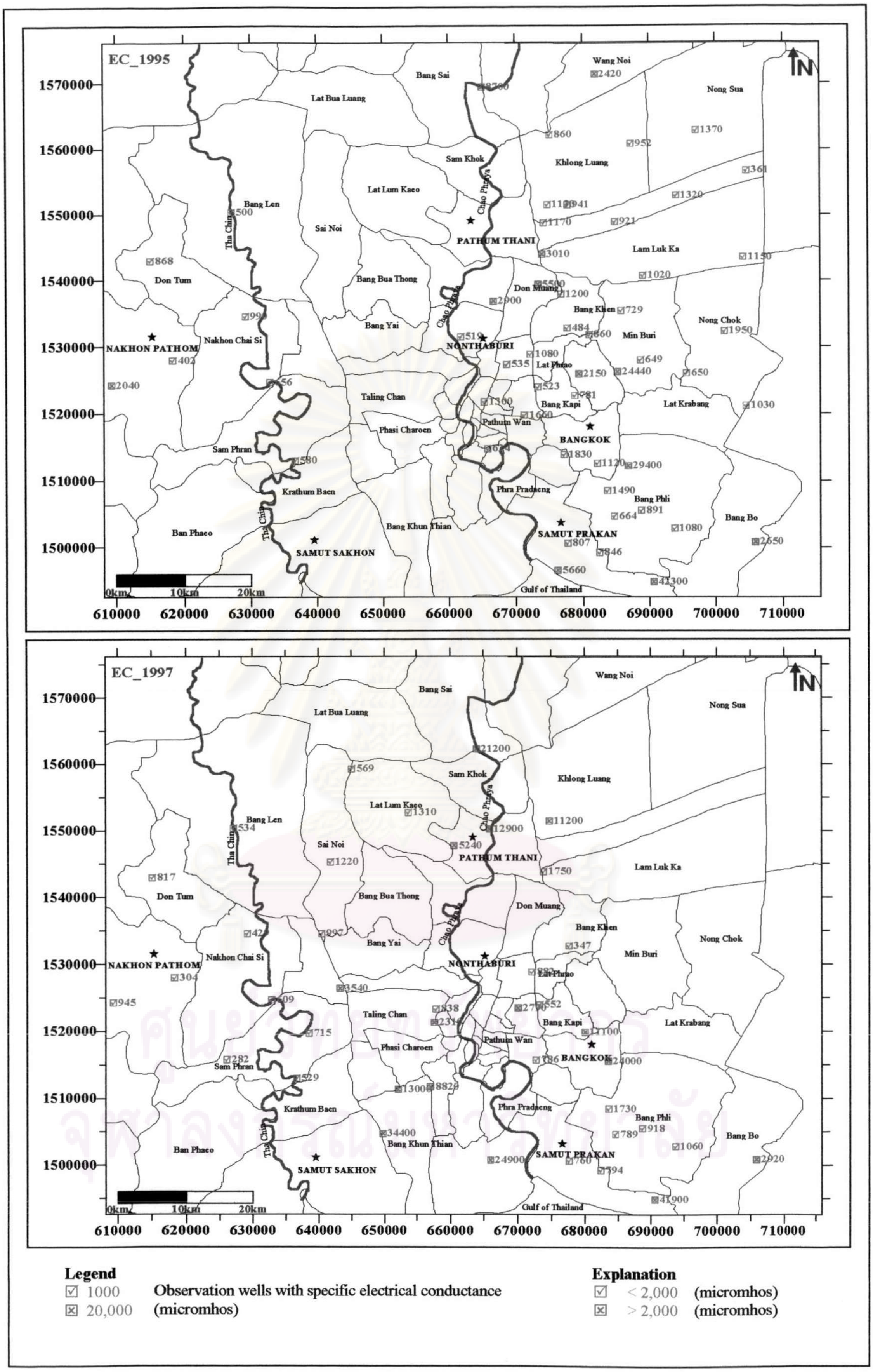


Figure 4.47 Specific Electrical Conductance in 1995 and 1997

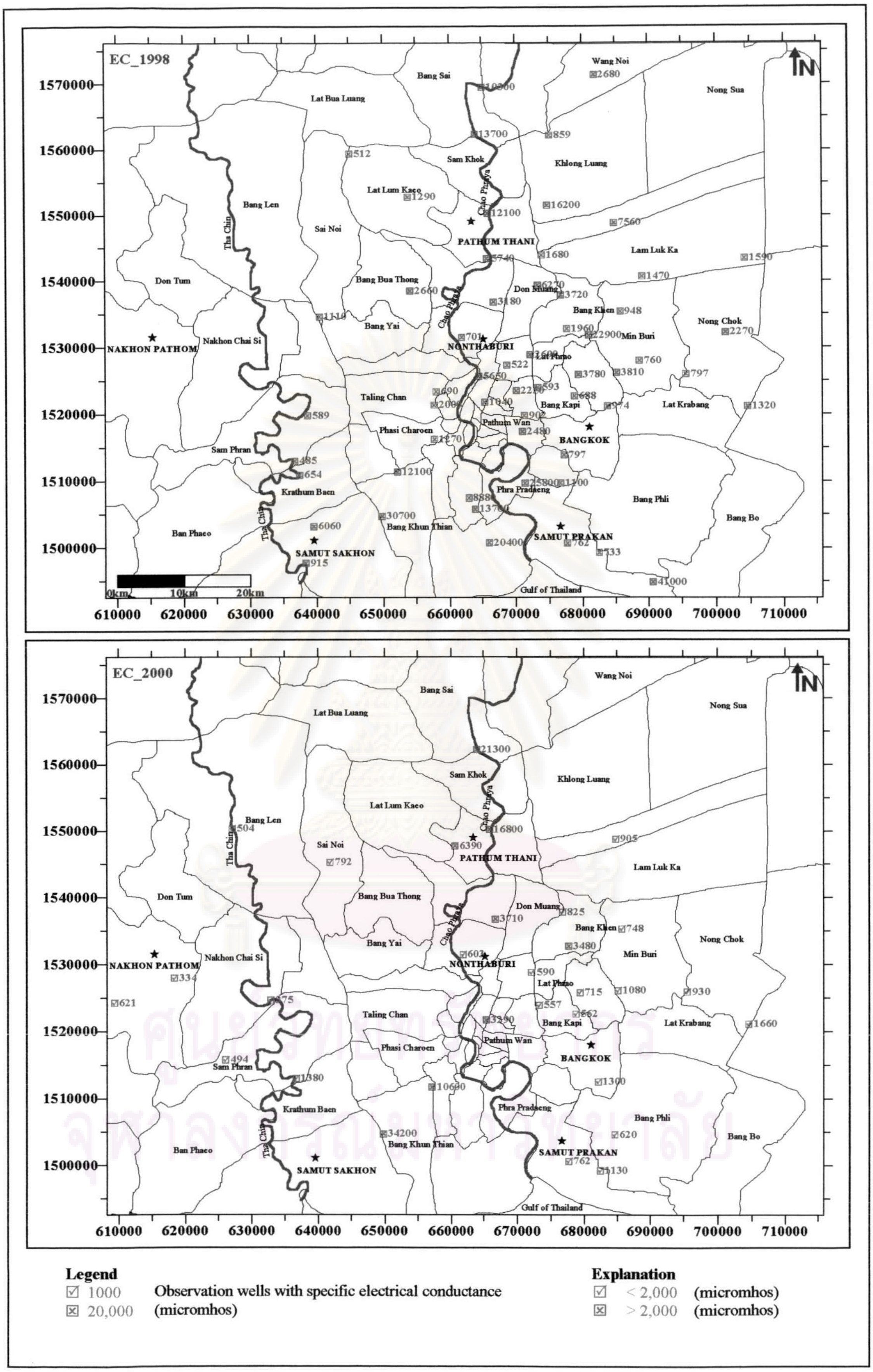


Figure 4.48 Specific Electrical Conductance in 1998 and 2000

c) Sodium (Na$^+$). The groundwater quality maps of sodium are shown in Figure 4.49-4.51. Generally, all natural water content measures amount of sodium concentrations range from 0.2 ppm in rainwater to more than 100,000 ppm in brines that contact with salt beds. Water with total dissolved solids is ranging from 1,000 to 5,000 ppm generally have more than 100 ppm of sodium. The sodium concentration in the studied area varies within the range of 40 ppm to 8,000 ppm. The area where the sodium content more than 100 ppm to 1,000 ppm is located mainly in the eastern part further to the north of the area whereas sodium concentration is more than 1,000 ppm is concentrated along the Chao Phraya River and the southern part of the area (Amphoe Bang Khun Thian, Bangkok Metropolis, Amphoe Muang, Samut SaKhon Province, Amphoe Muang and Amphoe Phra Pradaeng, Samut Prakan Province). Source of sodium content in this area may be derived from the seawater in the southern part and connate water along the Chao Phraya River.

d) Potassium (K$^+$). Figures 4.52-4.54 display the potassium concentration in the area. The range of potassium concentration is from 2.0-120 ppm. In general, most potable groundwater contains less than 10 ppm and commonly ranges between 1.0 ppm to 5.0 ppm. The high potassium content (red colors) is concentrated in the southern part (Amphoe Muang, Samut Sakhon Province, Amphoe Bang Khun Thian, Bangkok Metropolis, Amphoe Muang, Amphoe Phra Pradaeng, Samut Prakan Province) and along the Chao Phraya River further to the north (Amphoe Muang, Pathum Thani , Amphoe Bang Bua Thong, Amphoe Bang Sai, Phra Nakhon Si Ayutthaya Provinces) while, very high potassium constitute is concentrateed especially in the southern part of the area. Normally, the common sources of potassium are the products formed by the weathering of orthoclase, microcline, biotite, leucite, and nepheline in igneous and metamorphic rocks.

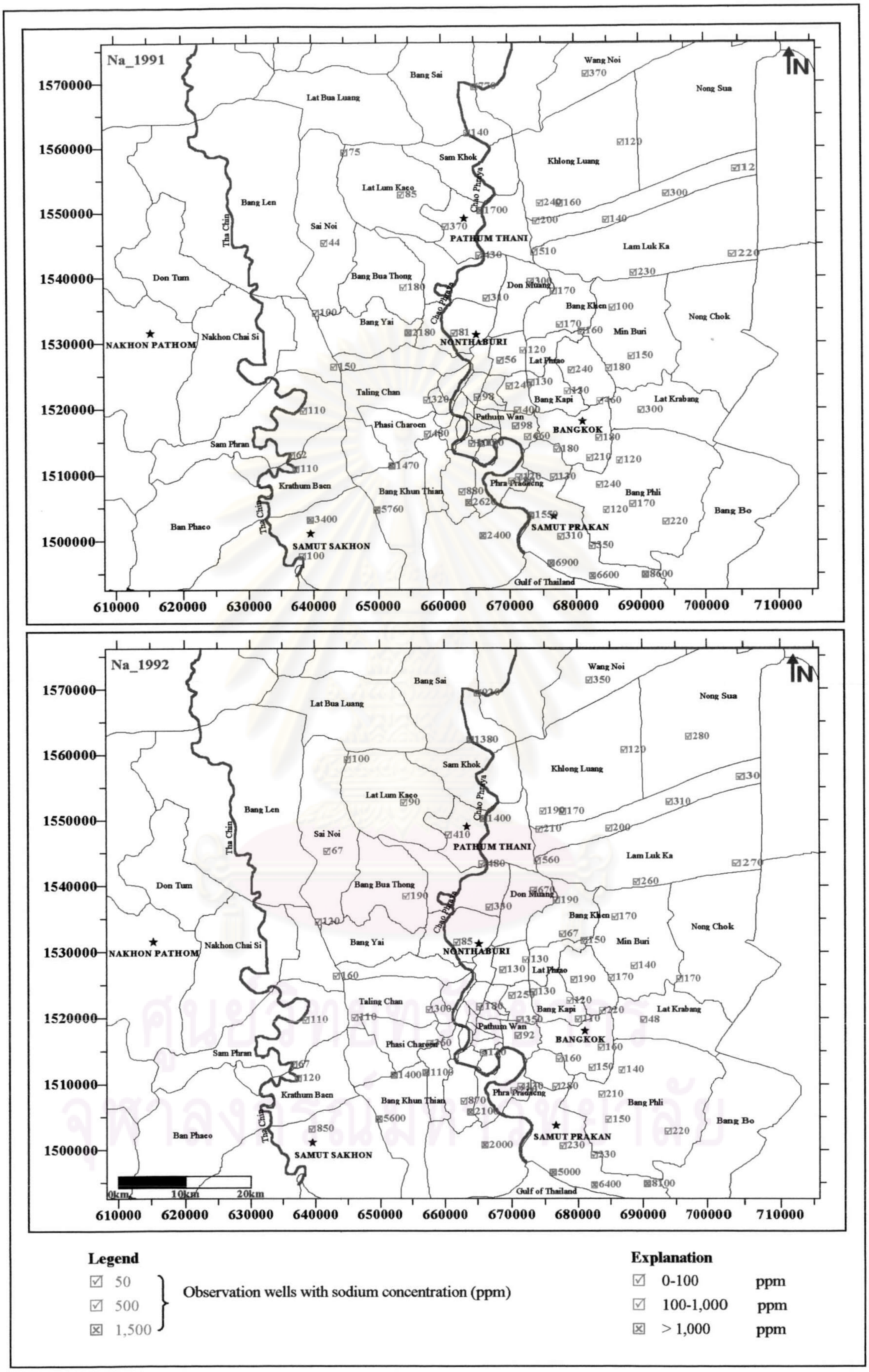


Figure 4.49 Sodium concentration in 1991-1992

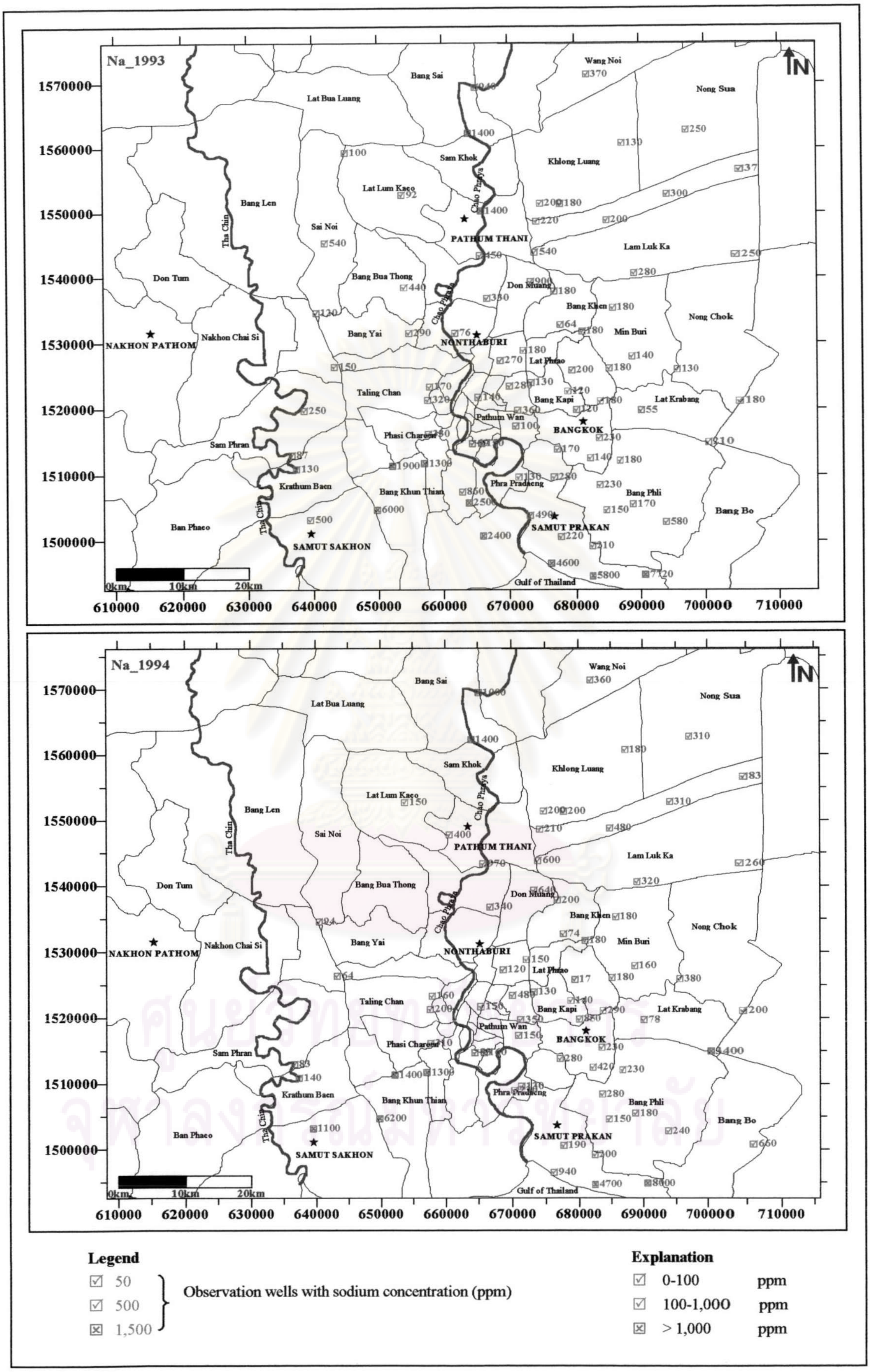


Figure 4.50 Sodium concentration in 1993-1994

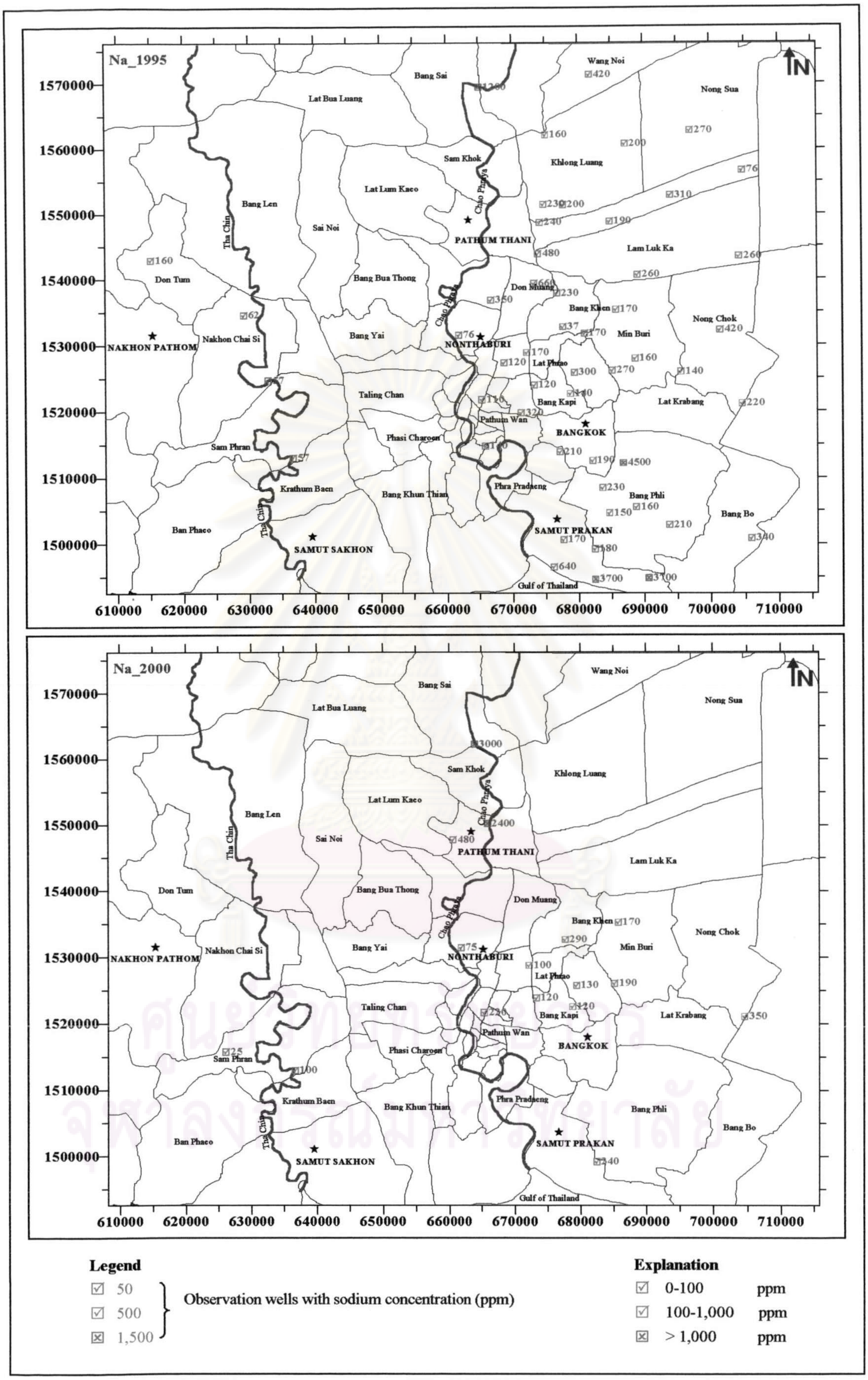


Figure 4.51 Sodium concentration in 1995 and 2000

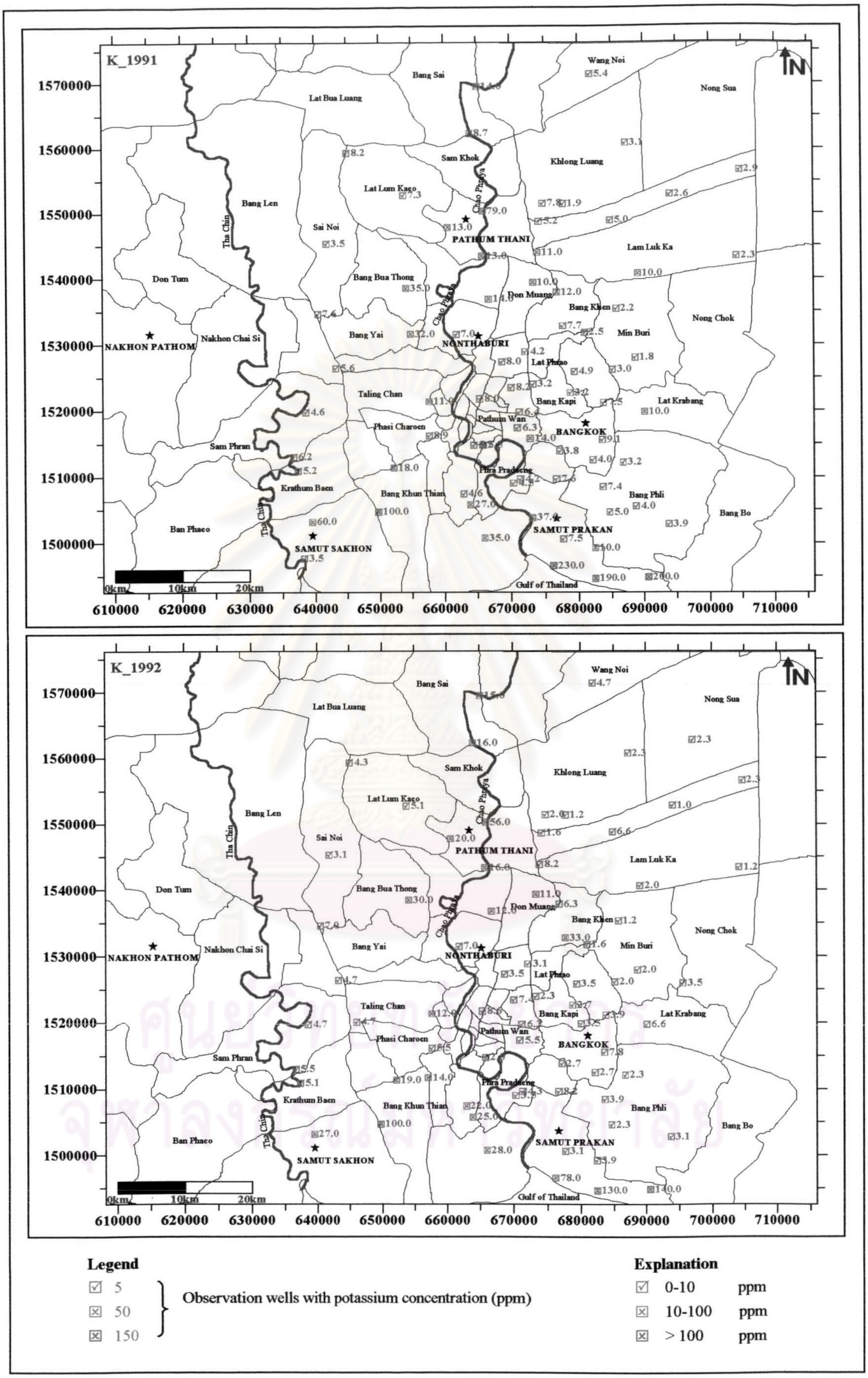


Figure 4.52 Potassium concentration in 1991-1992

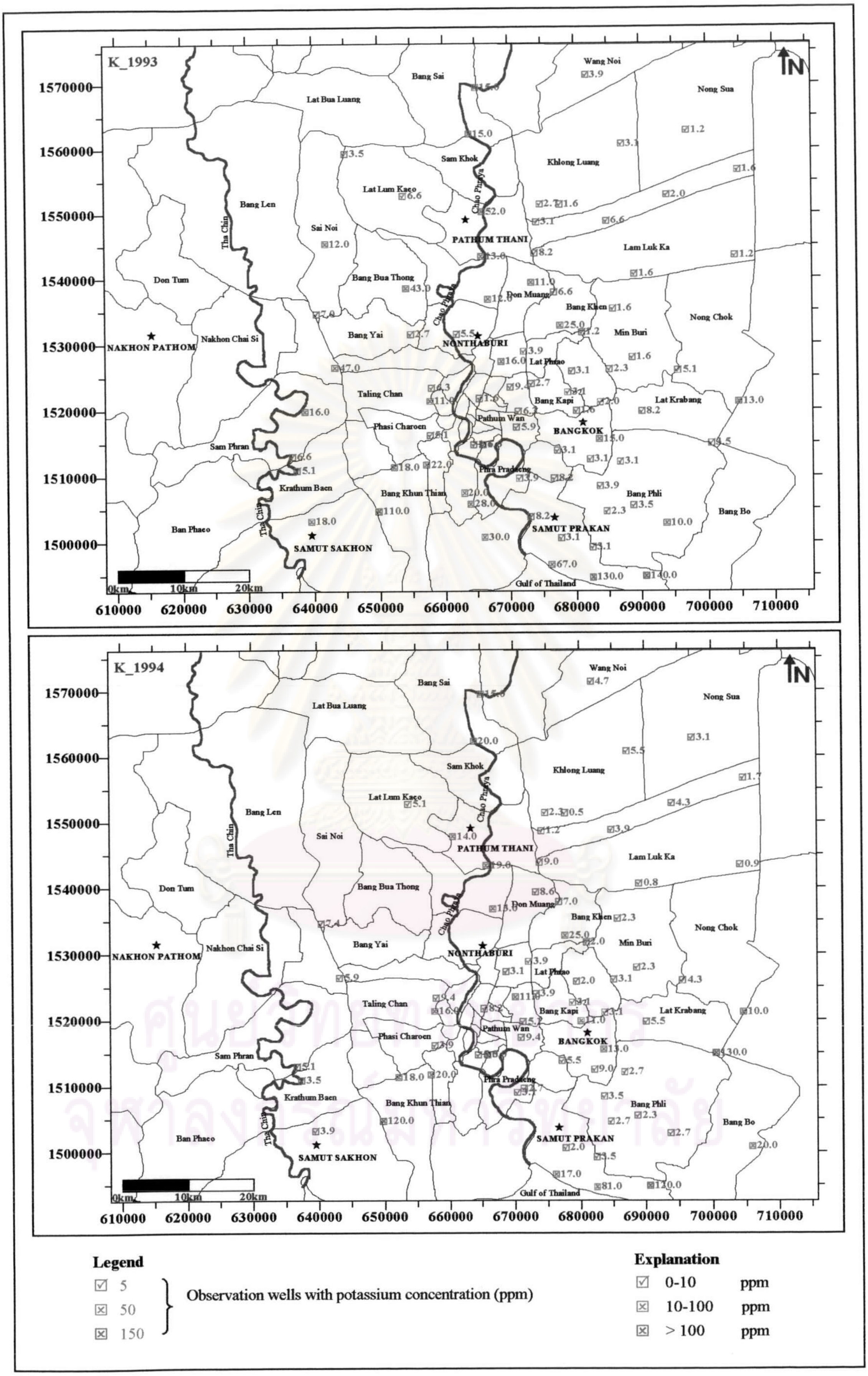


Figure 4.53 Potassium concentration in 1993-1994

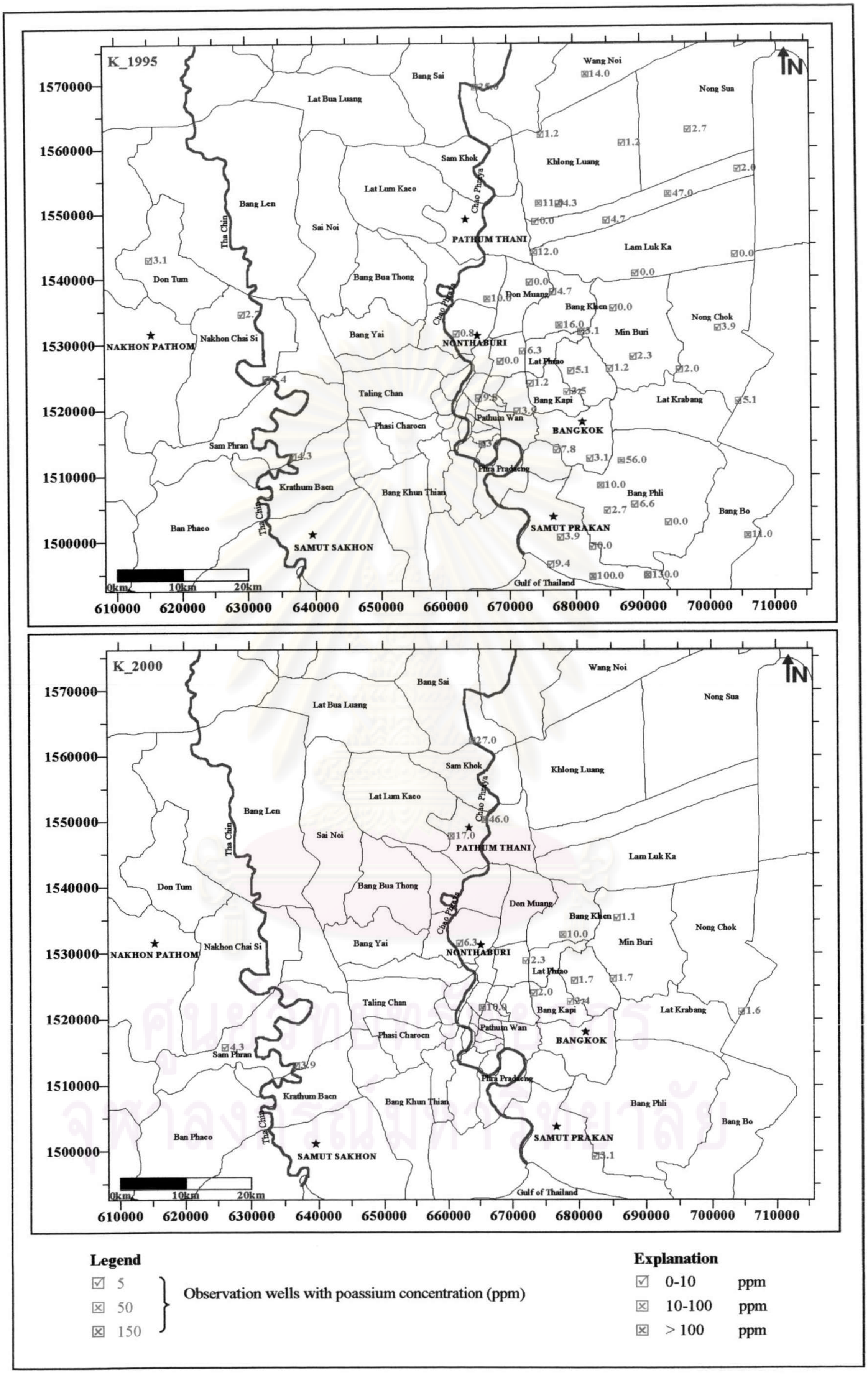


Figure 4.54 Potassium concentration in 1995 and 2000

e) Calcium (Ca^{2+}). Figures 4.55-4.57 shows the calcium concentration in the study area. Concentrations of calcium in normal potable groundwater generally range between 10 ppm to 100 ppm which these content is unknown the effect on the health of humans or animals but more than 1,000 ppm of calcium may be harmless (Davis and De Wiest, 1966). The range of calcium concentration in this area falls within 1 ppm to more than 1,000 ppm. The calcium concentrations that more than 100 ppm are observed in the southern and southwestern parts of the area and along the Chao Phraya River. Subsurface water in contact with sedimentary rocks of marine origin derives most of their calcium from the solution of calcite, aragonite, dolomite, anhydrite, and gypsum.

f) Magnesium (Mg^{2+}). The groundwater quality maps of magnesium are displayed in Figure 4.58-4.60. The magnesium concentration in the area is varies from 2 ppm to 1,000 ppm. In general, magnesium concentrations in groundwater are ranging from 1 to 40 ppm. Water from rock rich in magnesium may have as much as 100 ppm, while concentrations of magnesium that more than 100 ppm are rarely encountered except in sea water and brines (Davis and De Wiest, 1966). The zone of high to very high magnesium (more than 100 ppm) is located along the Chao Phraya River, the southwestern, and the southern parts of the area. Sources of magnesium in the hydrosphere are dolomite in sedimentary rocks; olivine, biotite, hornblende, and augite in igneous rocks; and serpentine, talc, diopside, and tremolite in metamorphic rocks

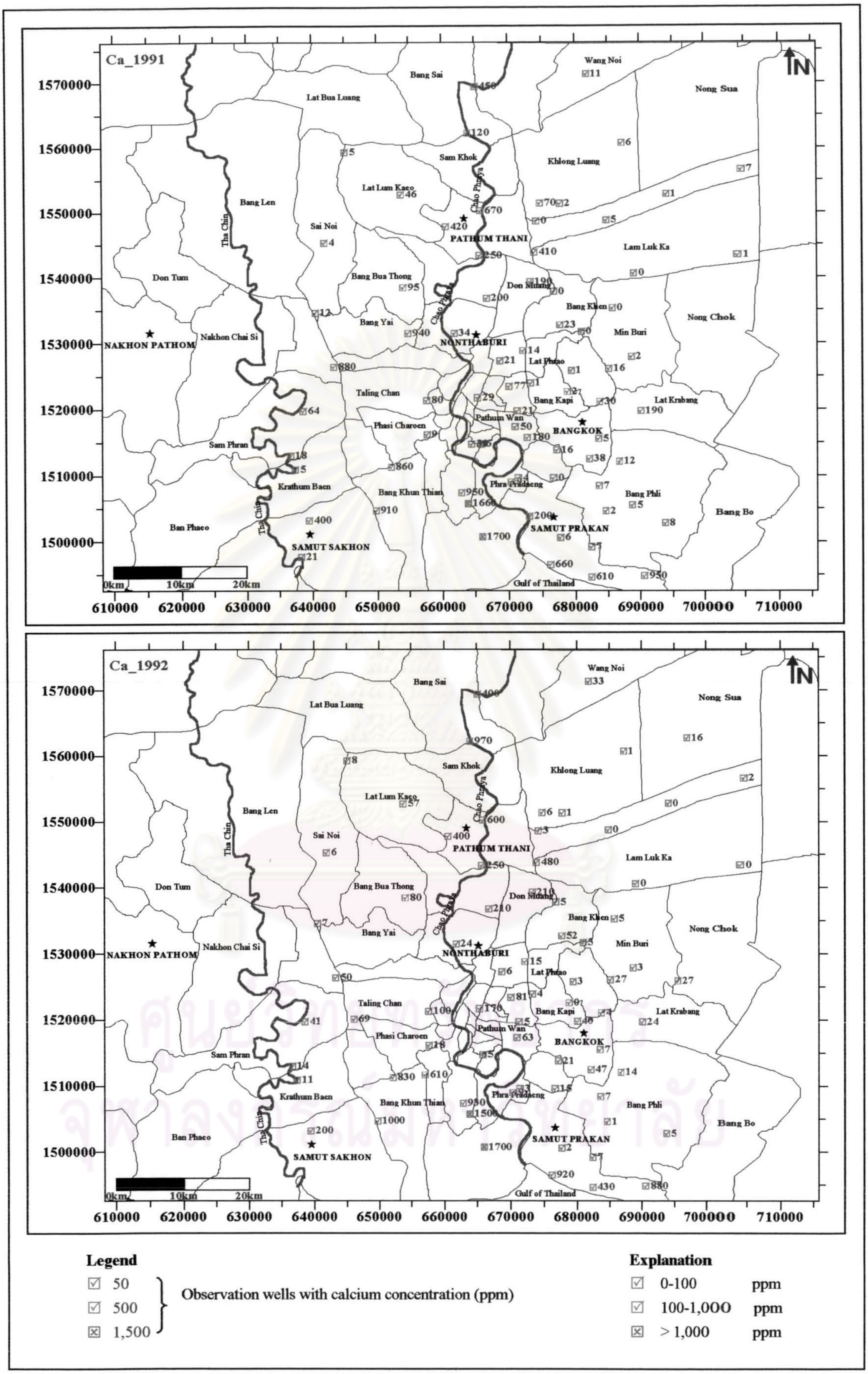


Figure 4.55 Calcium concentration in 1991-1992

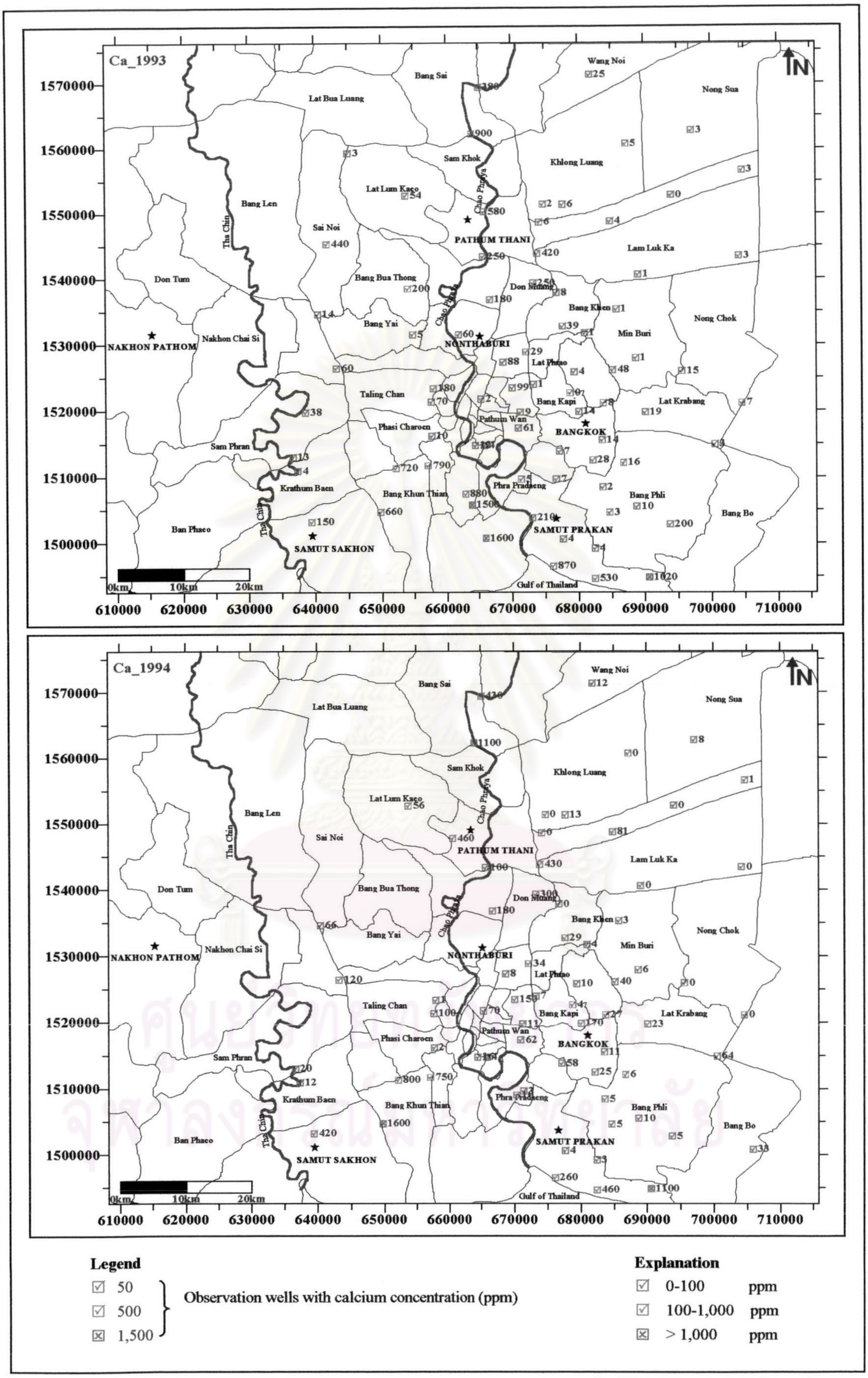


Figure 4.56 Calcium concentration in 1993-1994

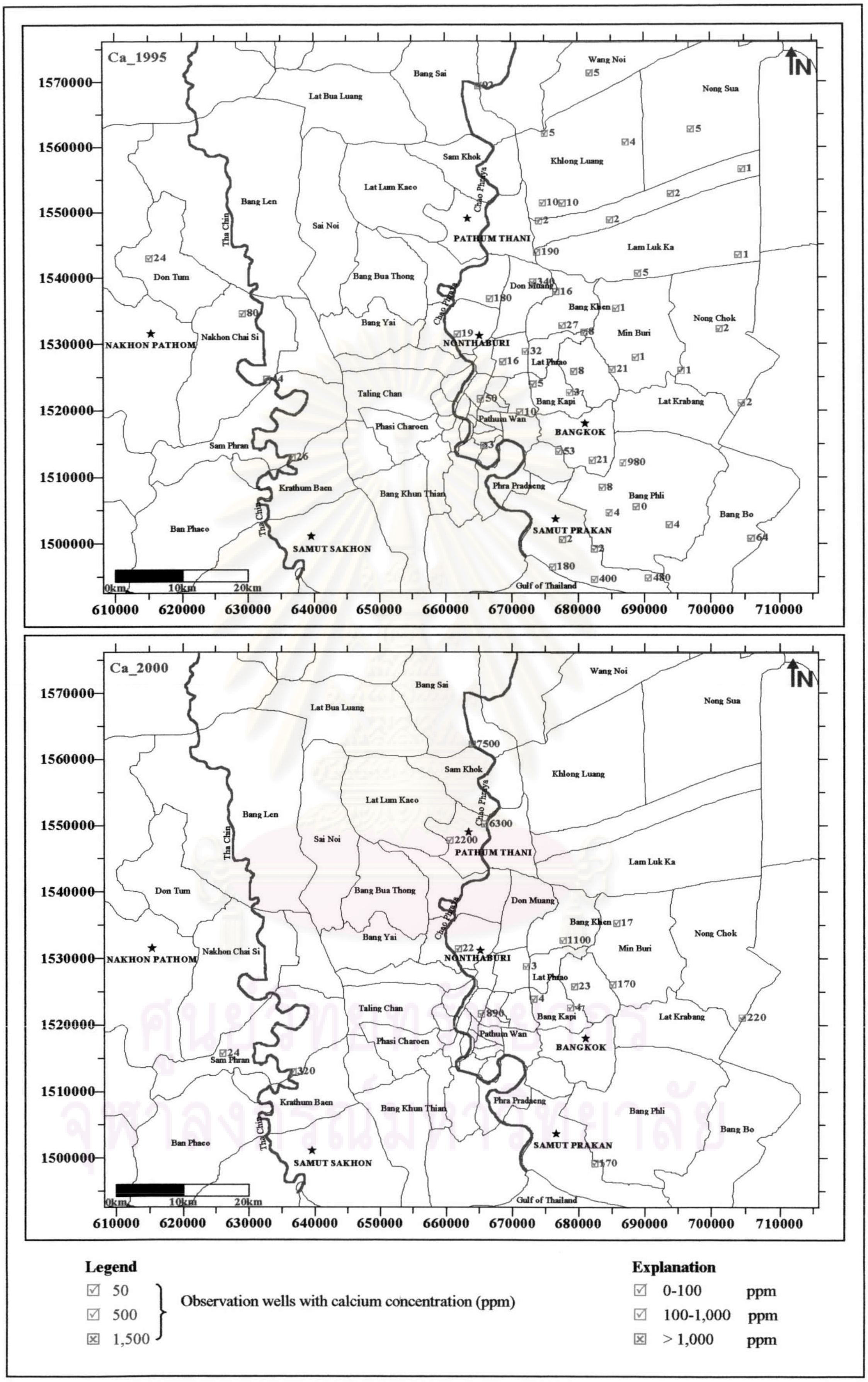


Figure 4.57 Calcium concentration in 1995 and 2000

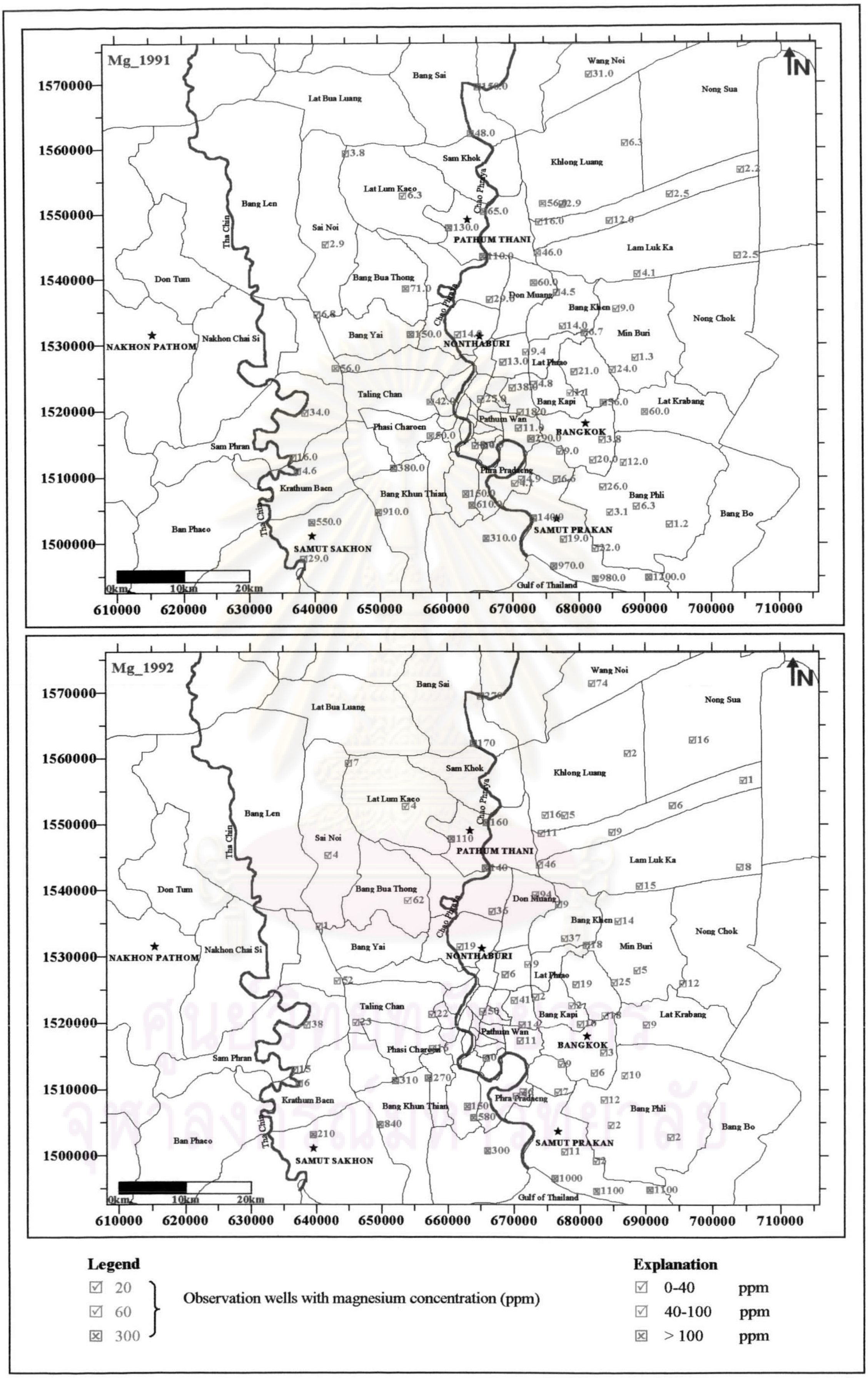


Figure 4.58 Magnesium concentration in 1991-1992

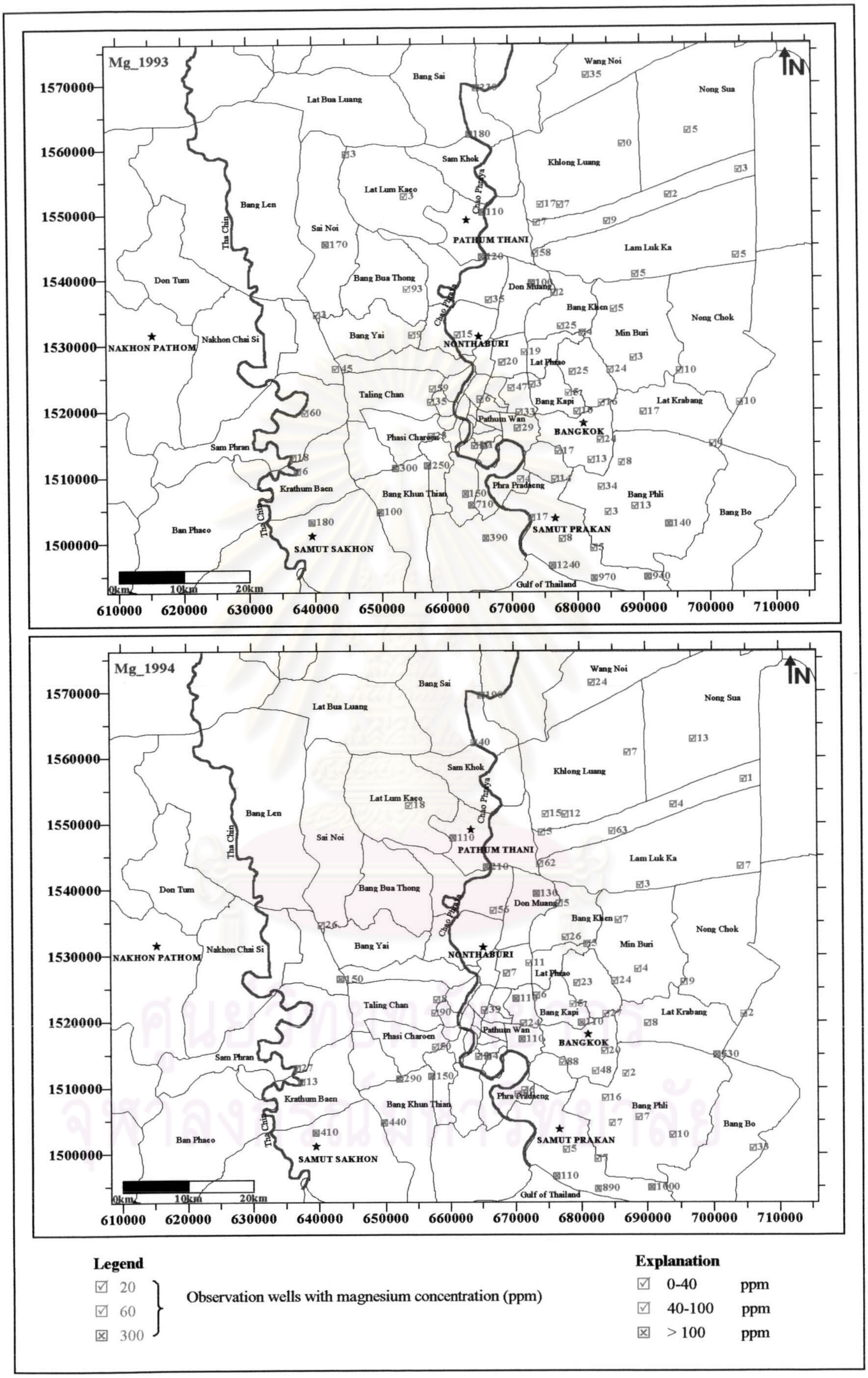


Figure 4.59 Magnesium concentration in 1993-1994

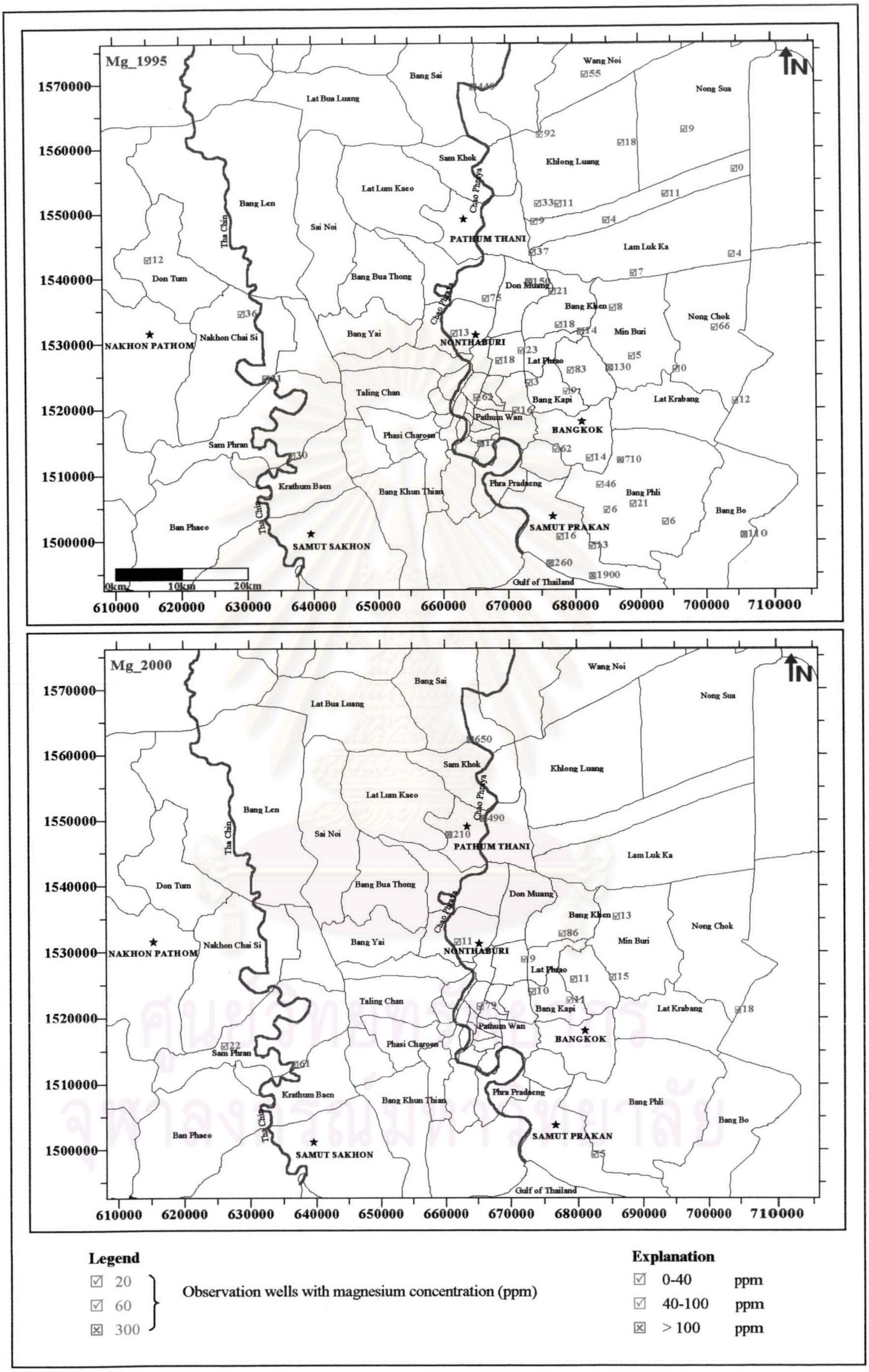


Figure 4.60 Magnesium concentration in 1995 and 2000

g) Manganese. The new classification for Manganese content is done. It can be classified into three levels as follow:

Level I	0-0.3	ppm.	Low Manganese Content
Level II	0.3-0.5	ppm.	Moderate Manganese Content
Level III	0.5-5.0	ppm.	High Manganese Content

Figs.4.61-4.65 displays the Manganese concentration of the study area. The range of manganese concentration is from 0.0-4.8 ppm. In general, the manganese concentration is under suitable standard drinking water limits less than 0.3 ppm. and not exceeds the maximum allowable limit 0.5 ppm. High Manganese content is concentrated in the southern part (Amphoe Muang, Samut Sakhon Province, Amphoe Bang Khun Thian, Bangkok Metropolis, Amphoe Muang, Amphoe Phra Pradaeng, Samut Prakan Province) and a bit in the central part toward the north (Amphoe Muang, Pathum Thani , Amphoe Bang Bua Thong, Amphoe Bang Sai, Phra Nakhon Si Ayutthaya Provinces) and the eastern part (Amphoe Lat Krabang, Bangkok Metropolis) of the area.

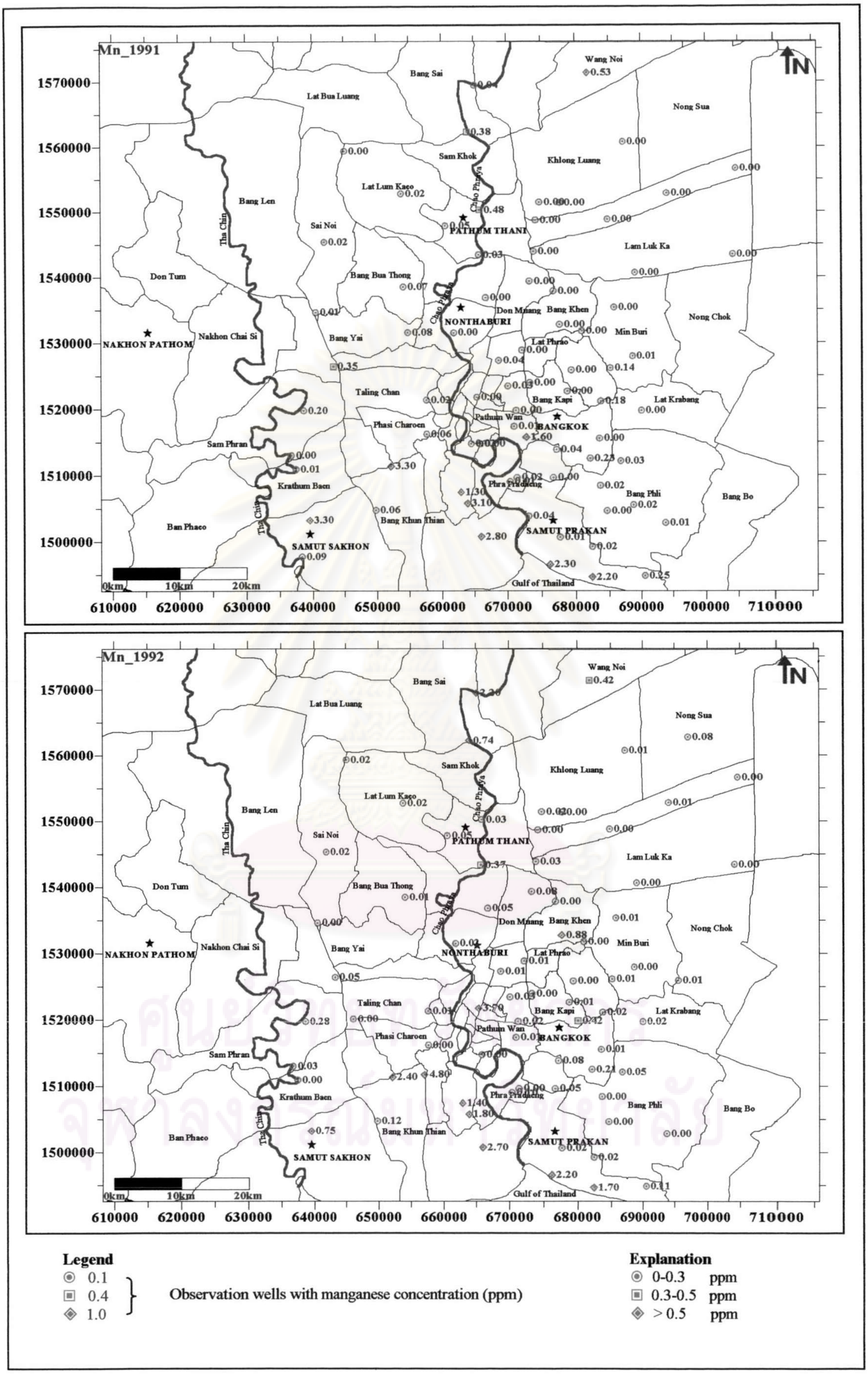


Figure 4.61 Manganese concentration in 1991-1992

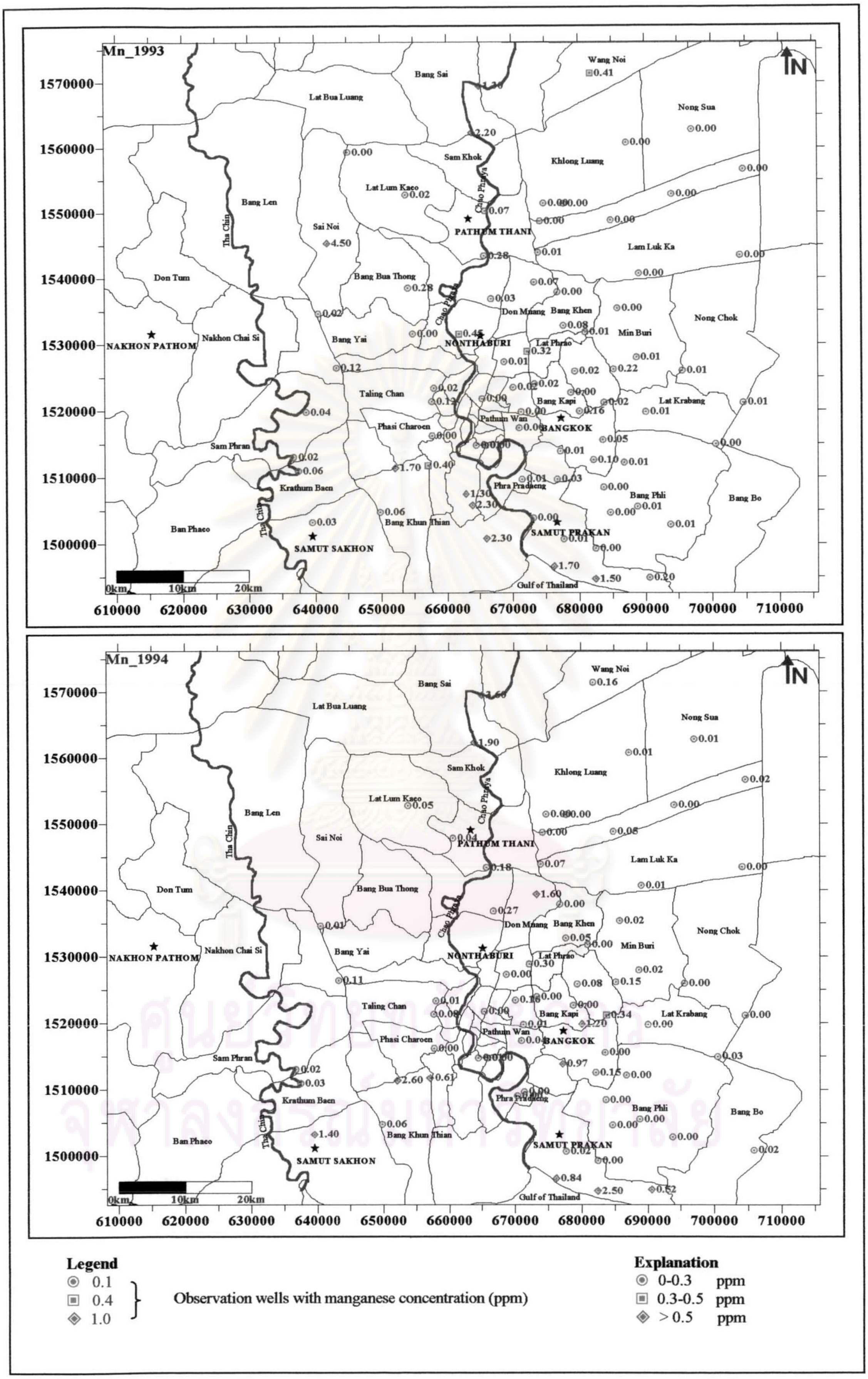


Figure 4.62 Manganese concentration in 1993-1994

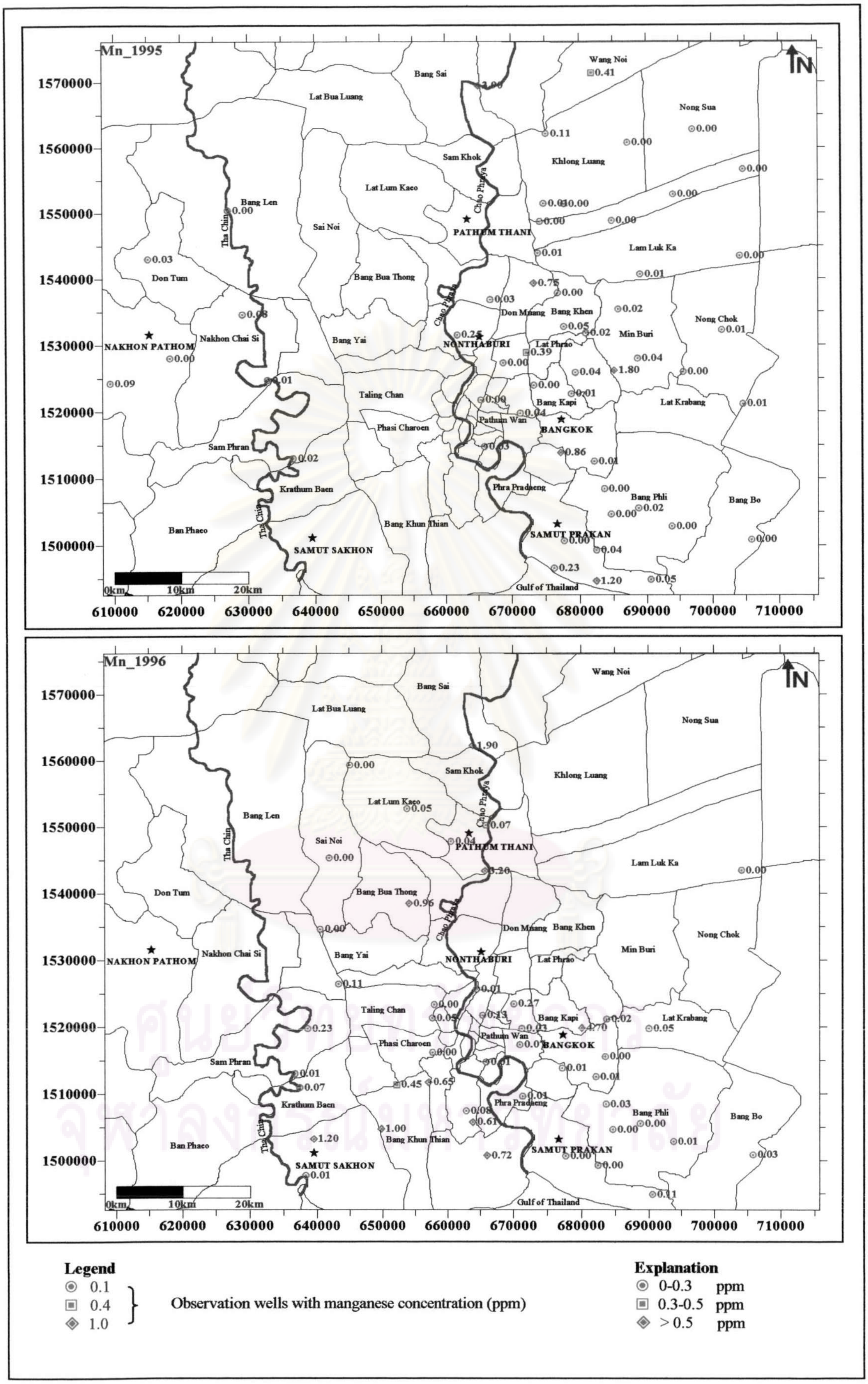


Figure 4.63 Manganese concentration in 1995-1996

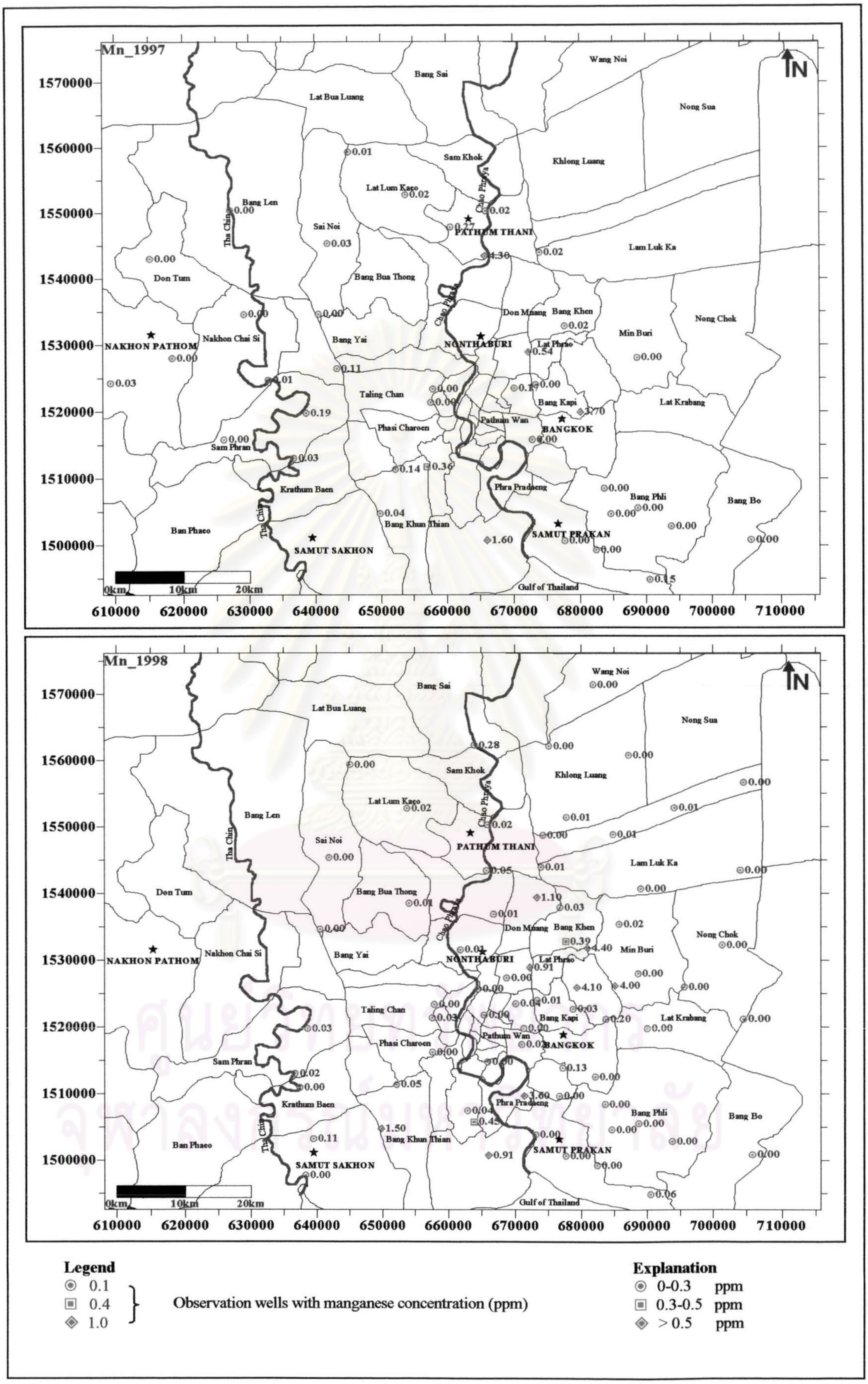


Figure 4.64 Manganese concentration in 1997-1998

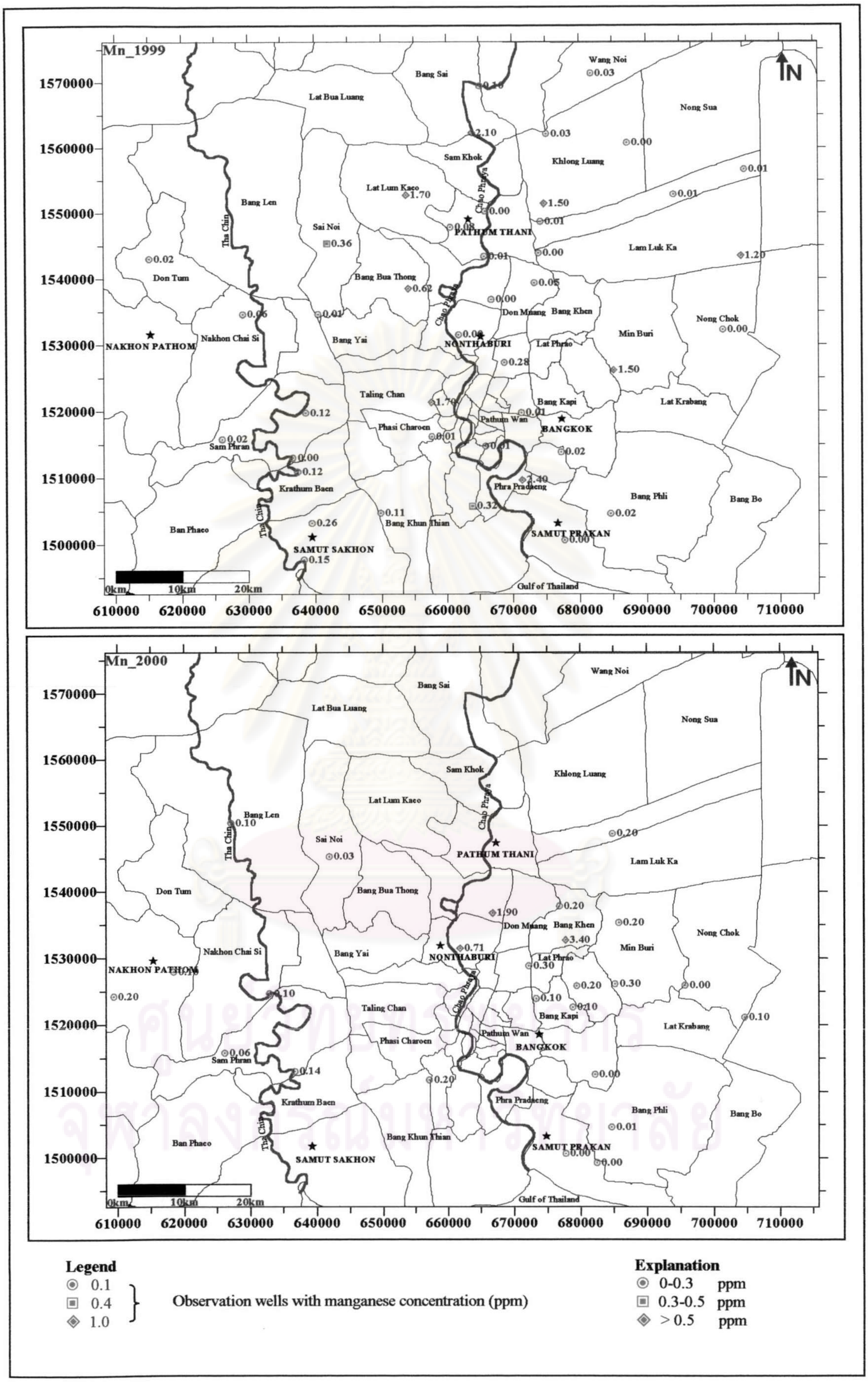


Figure 4.65 Manganese concentration in 1999-2000

h) Chloride. Since the Chloride content in the studied area is very high, comparing to the standard, thus, the Chloride analysis in this study is classified into 4 levels upon the Chloride content according to the standard of Drinking Water, Groundwater Acts B.E. 2520.

Level I	0-200	ppm.	Low Chloride Content
Level II	200-600	ppm.	Moderate Chloride Content
Level III	600-1,000	ppm.	High Chloride Content
Level IV	1,000-20,000	ppm.	Very High Chloride Content

Figs 4.66-4.70 display the Chloride concentration of the study area. The chloride concentration varies within the range of 10-16,000 ppm. The area where the chloride content under the suitable quality (less than 200 ppm.) and not exceeds the maximum quality allowed (600 ppm.) is located in the middle of western part, central part and middle of eastern part further to the north. High and Very High Chloride content are concentrated along the Chao Phraya River and the southern part of the area (Amphoe Bang Khun Thian, Bangkok Metropolis, Amphoe Muang, Samut SaKhon Province, Amphoe Muang and Amphoe Phra Pradaeng, Samut Prakan Province).

The tendency of chloride concentration increasing is westwardly and southwestwardly and along the Chao Phraya River. From study of Gupta and Arbhabhirama in 1979 indicated that the saltwater encroachment of the NL aquifer does not occur only from the sea. Connate water trapped in less permeable sediments subsequent to their time of deposition under marine conditions is the predominant source contaminating the freshwater supply. This connate water body lies on the western side of the Chao Phraya River extending north of the Gulf of Thailand of

Amphoe Bang Bua Thong, Nonthaburi Province and beyond. However, data available at this stage is not adequate to delineate the distributation of the saline water bodies. Saltwater contamination is not only due to the lateral movement from the source but also appears to be due to the vertical leakage of brackish water from other aquifers and confining layers.

The term connate water can be explained as follows: the openings of pore spaces of materials that have been built up on ocean floors by sedimentation were originally filled with seawater. Some of these sediments were uplifted above sea level by later geologic processed of some magnitude. Salt water entrapped in the pores of the sediments was, of course, raised above sea level along with the containing formation. Groundwater of this origin is called connate water. As uplift of the land continued, the salt water began to drain out under the influence of the hydraulic gradient created by the uplift. Fresh water from precipitation, percolating of downward, followed and replaced the slowly departing salt water. Continued addition of fresh-water recharge flushed out more and more of the salt water. In many cases, displacement of all the original water was partially fulfilled some connate water remains. Therefore we still can find some connate water in some formation within the zone of saturation.

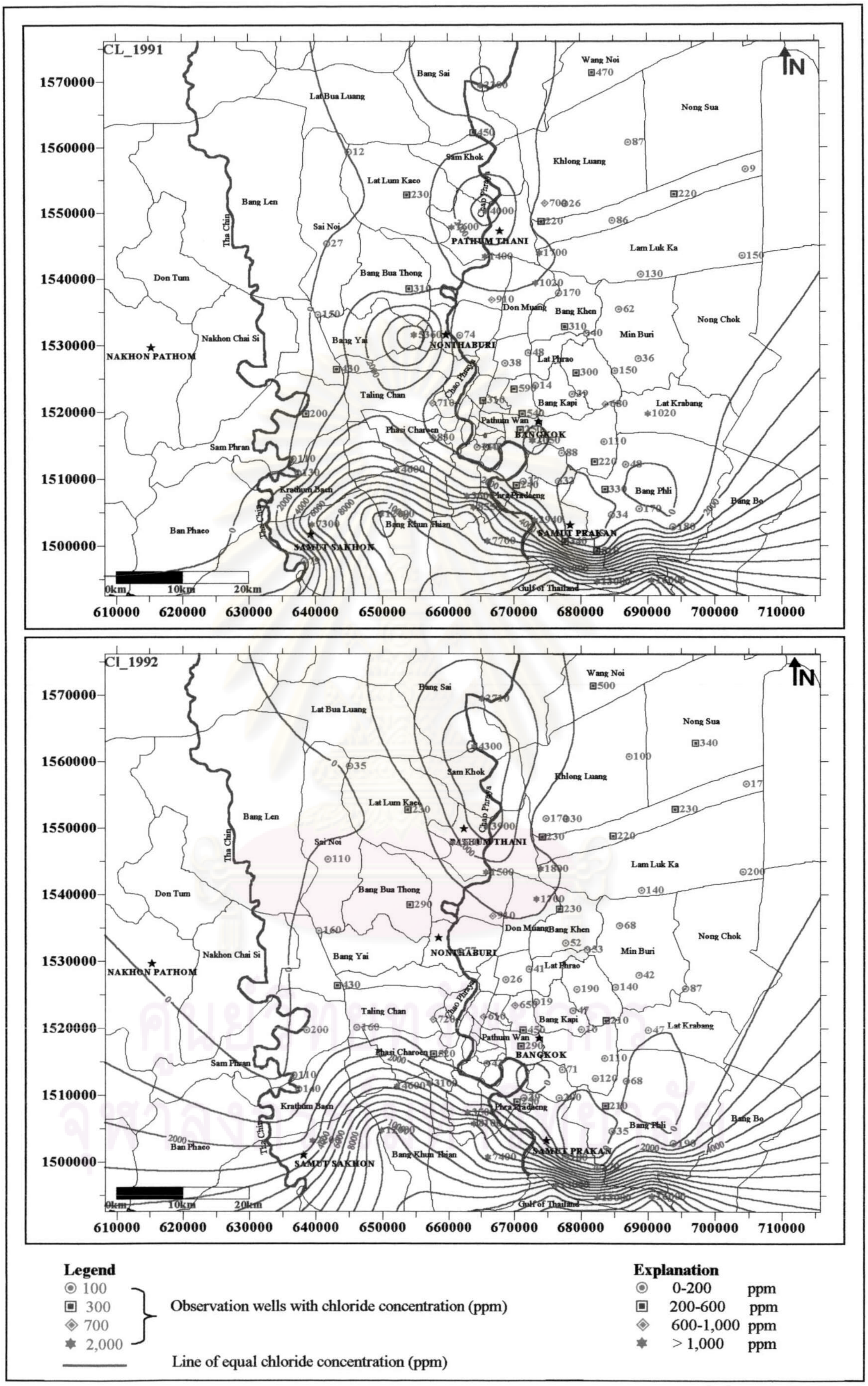


Figure 4.66 Chloride concentration in 1991-1992

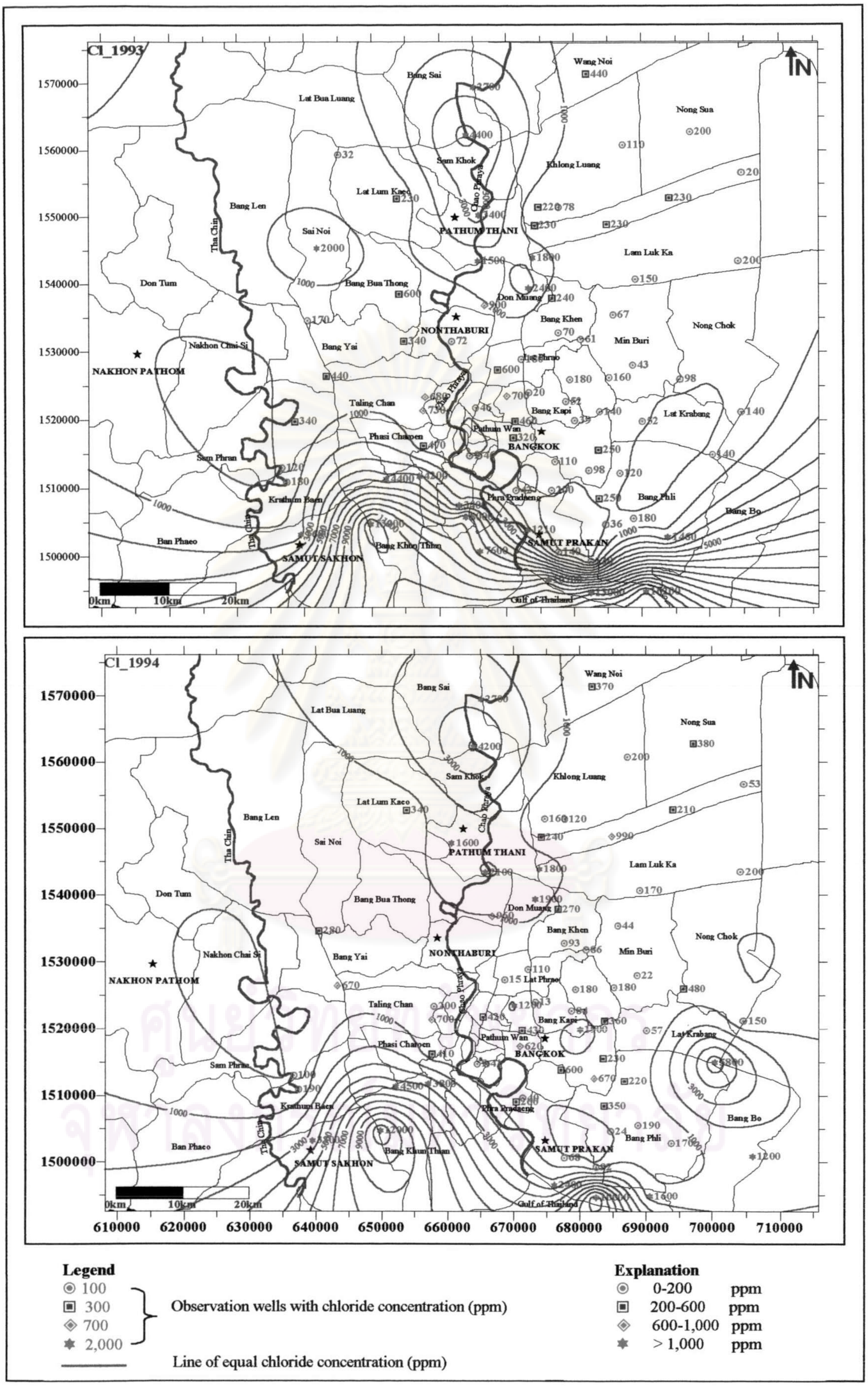


Figure 4.67 Chloride concentration in 1993-1994

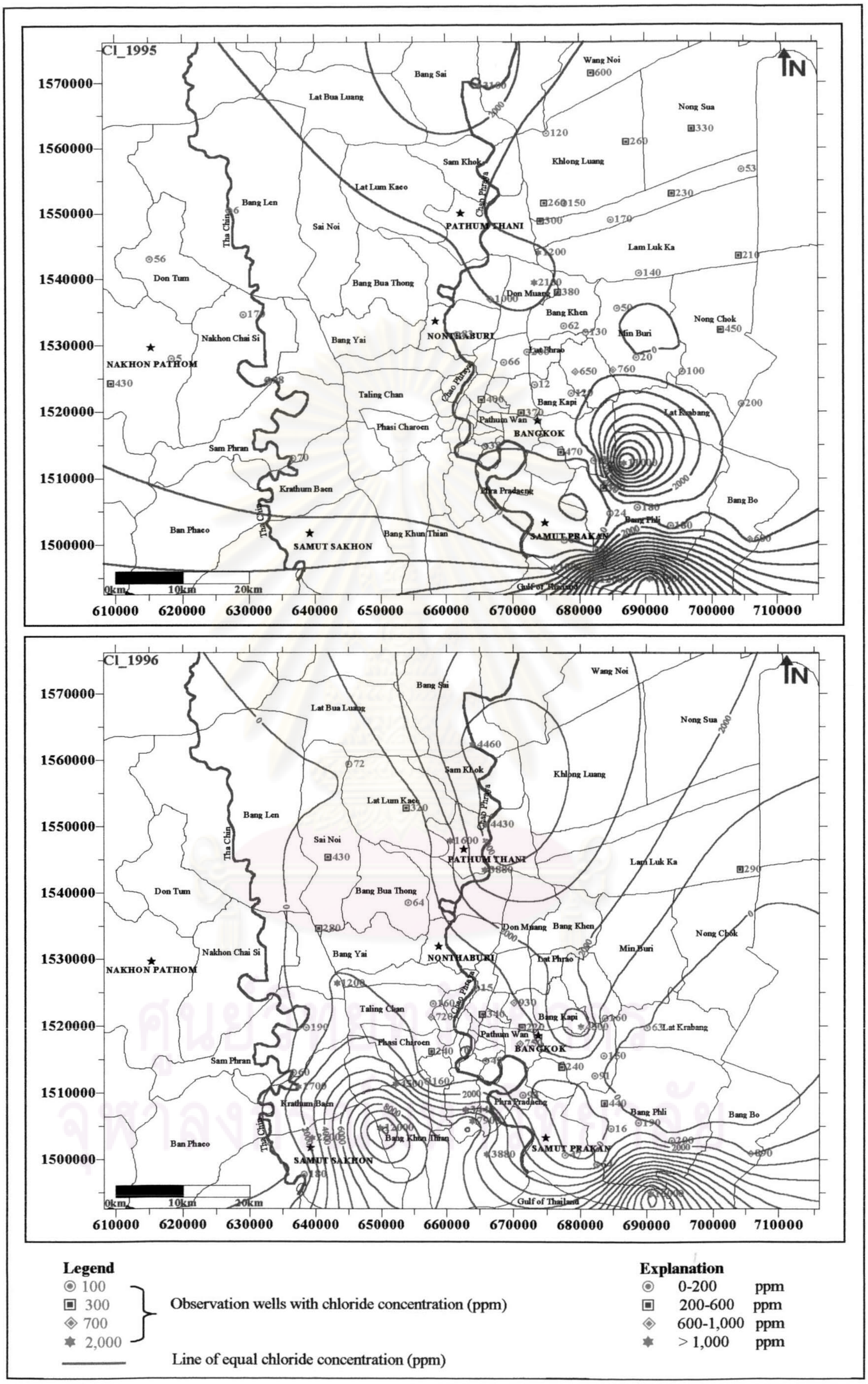


Figure 4.68 Chloride concentration in 1995-1996

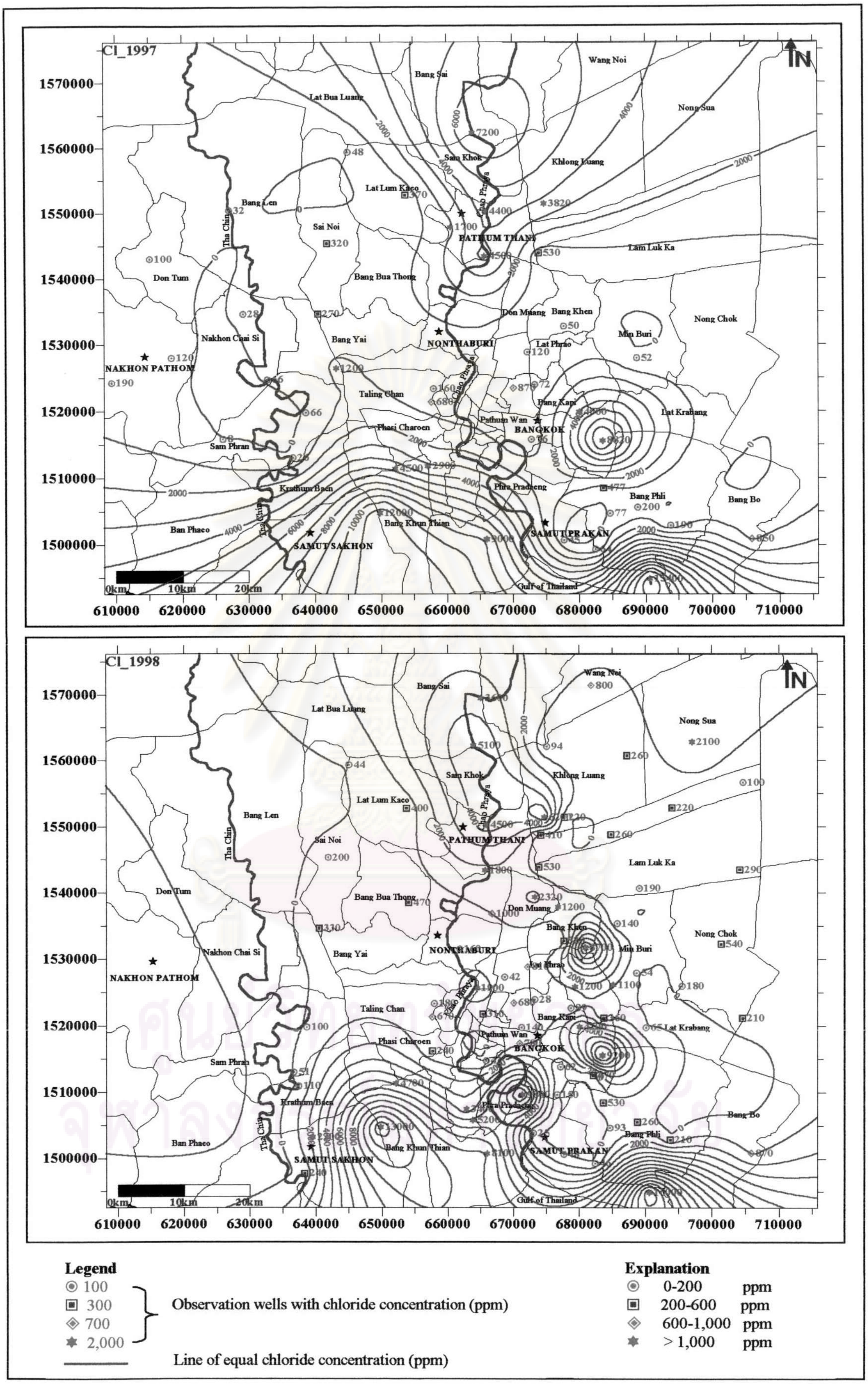


Figure 4.69 Chloride concentration in 1997-1998

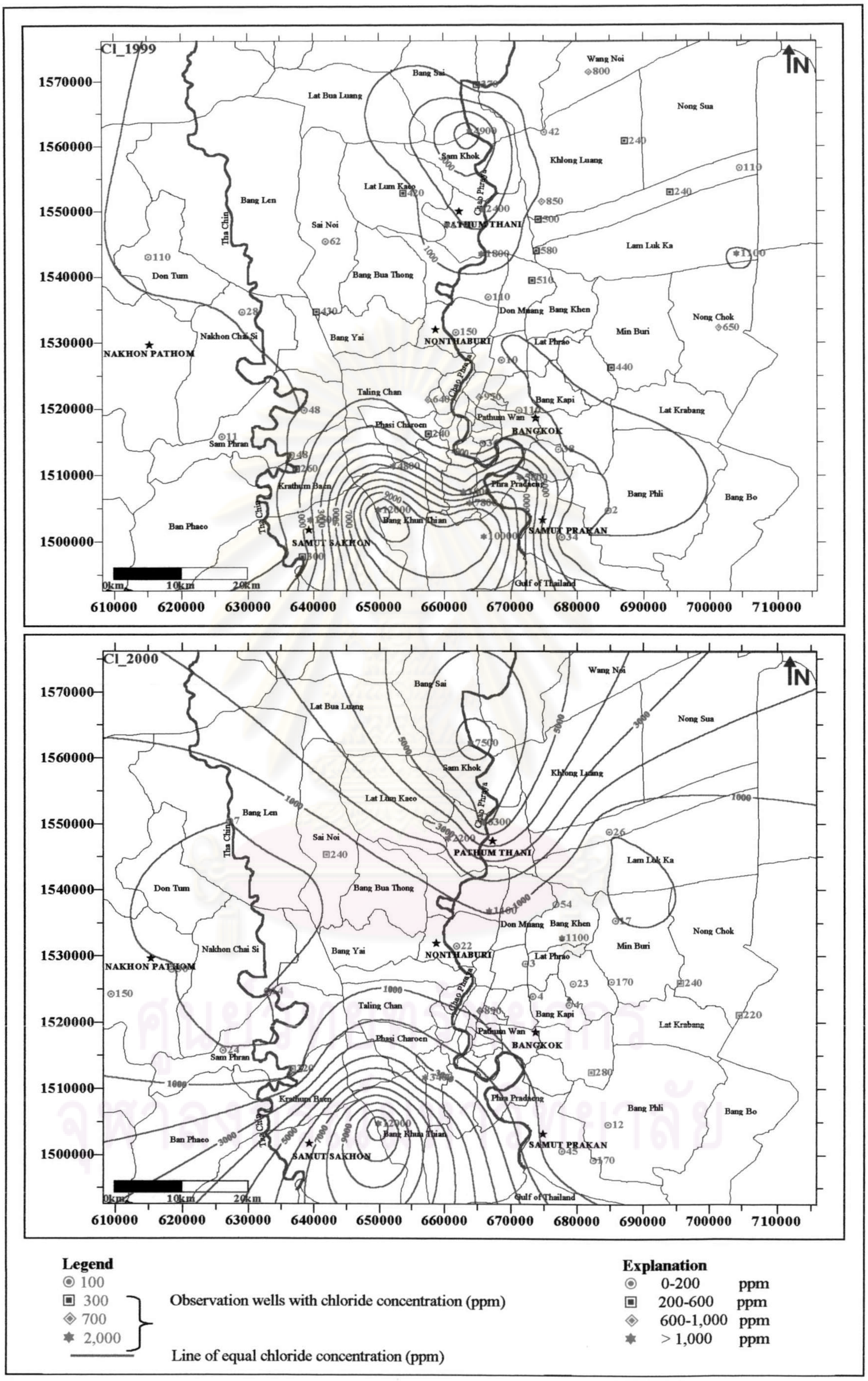


Figure 4.70 Chloride concentration in 1999-2000

i) Bicarbonate ($HCO3^-$). Figures 4.71-4.73 show the bicarbonate concentration in the area. The bicarbonate concentration in this area is ranging from 20 to 500 ppm. Groundwater generally contains more than 10 ppm but less than 800 ppm bicarbonate. Concentrations between 50 to 400 ppm are most common (Davis and De Wiest, 1966). The zone that bicarbonate contents more than 400 ppm is observed a little bit in the southern part (Amphoe Muang , Samut Prakan Province) and the central part (Amaphoe Bang Bua Thong, Nonthaburi Province). Most bicarbonate ions in groundwater is derived from the carbon dioxide in the atmosphere, carbon dioxide in the soil, and solution of carbonate rocks.

j) Sulfate ($SO4^{2-}$). Figures 4.74-4.76 show the sulfate concentration in the area. The sulfate concentration in this area is ranging from 2 to 1,600 ppm. The zone which under the suitable quality (less than 200 ppm.) and not exceeds the maximum allowable limt (250 ppm.) is located most part of the study area. The location that shows the high sulfate is concentrated mainly in the southern part of the area (Amphoe Bang Khun Thian, Bangkok Metropolis, Amphoe Muang , Amphoe Phra Pradaeng, Samut Prakan Provine). Generally, concentrations of sulfate from less than 0.2 ppm to more than 100,000 ppm are found in nature. The lowest concentrations of sulfate are in rainwater, snow, and subsurface waters subject to sulfate reduction. The highest concentrations are in magnesium sulfate brines. Sources of sulfate are derived from igneous, metamorphic, sedimentarty rocks and seawater.

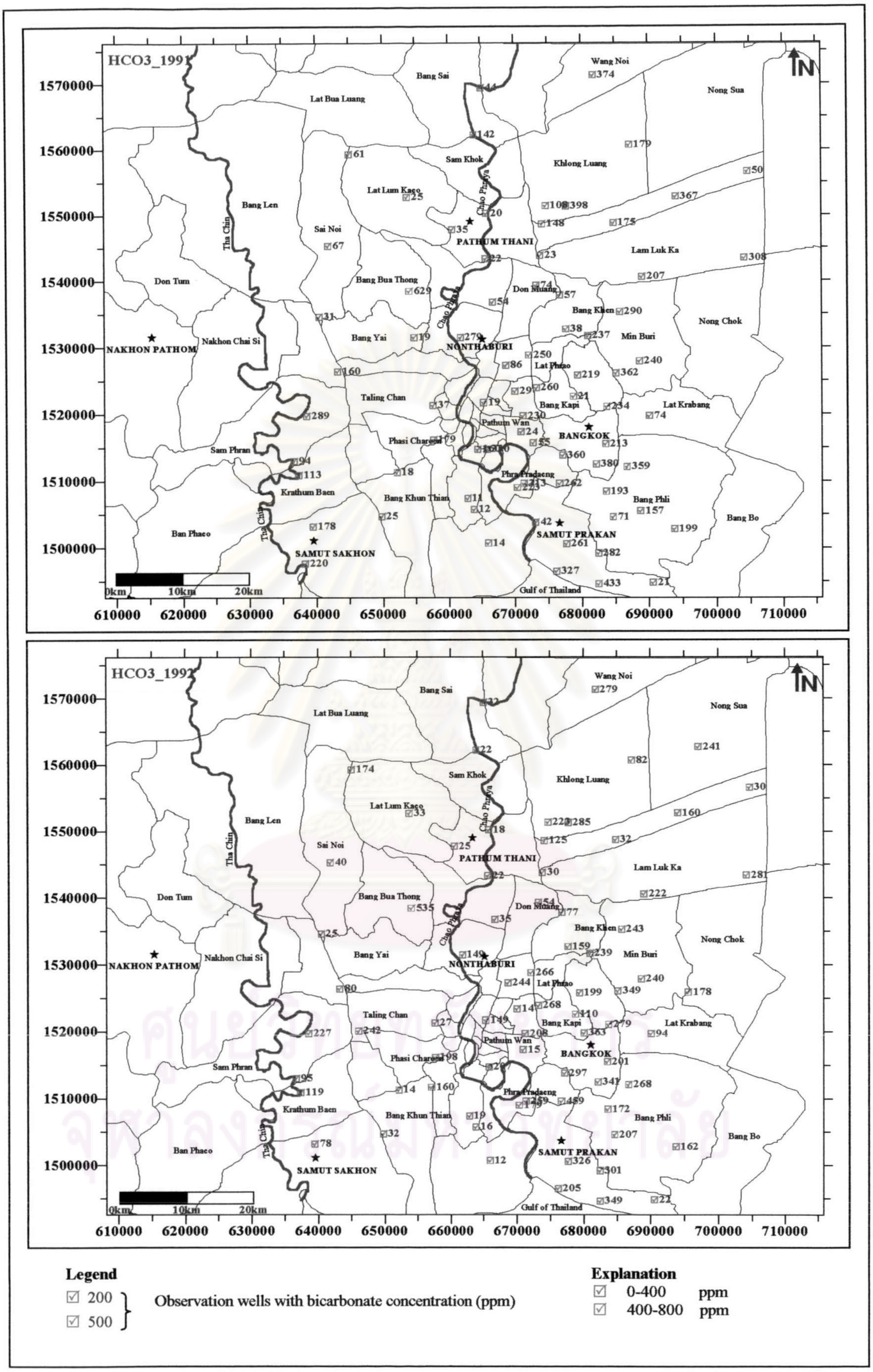


Figure 4.71 Bicarbonate concentration in 1991-1992

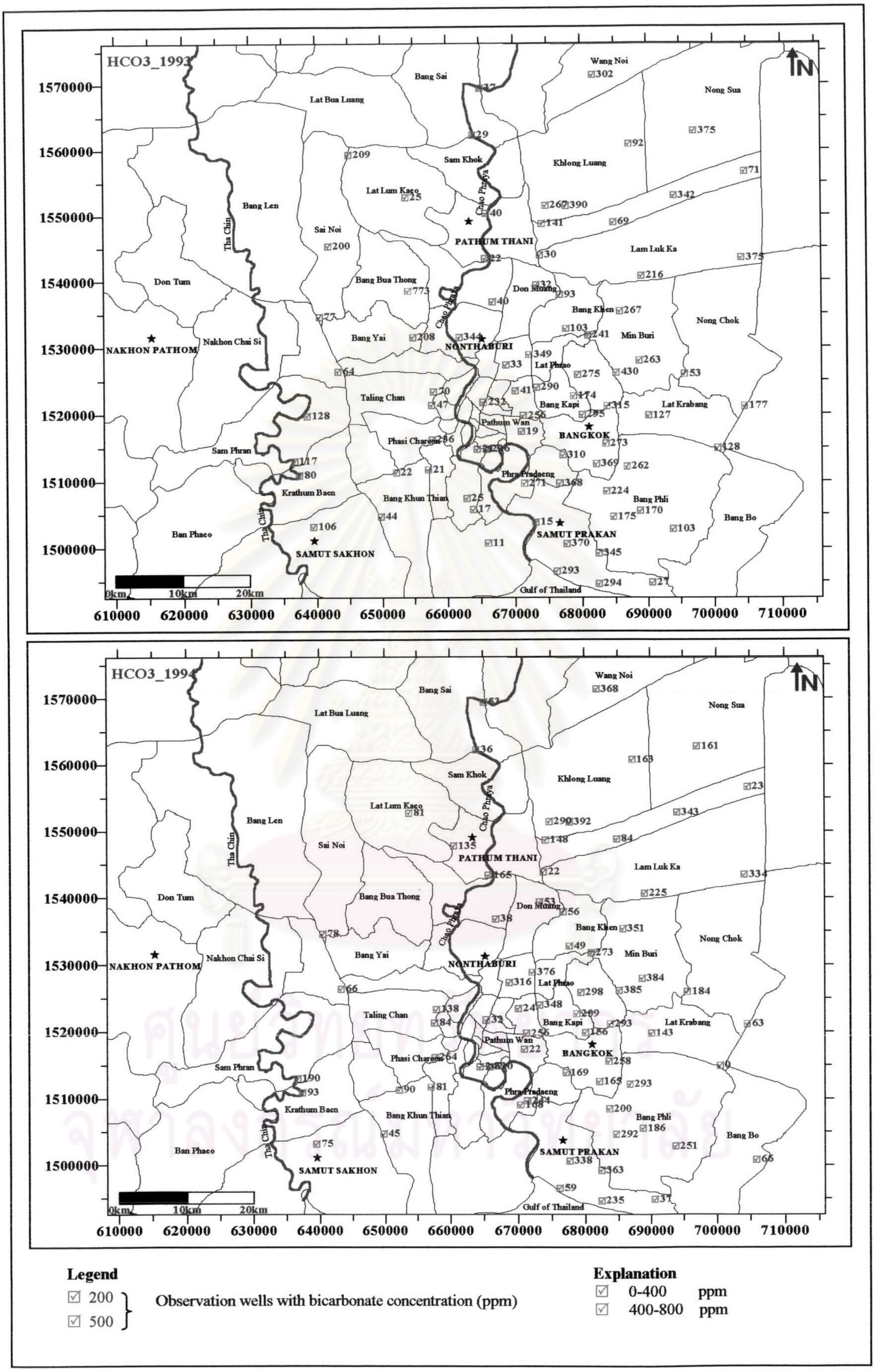


Figure 4.72 Bicarbonate concentration in 1993-1994

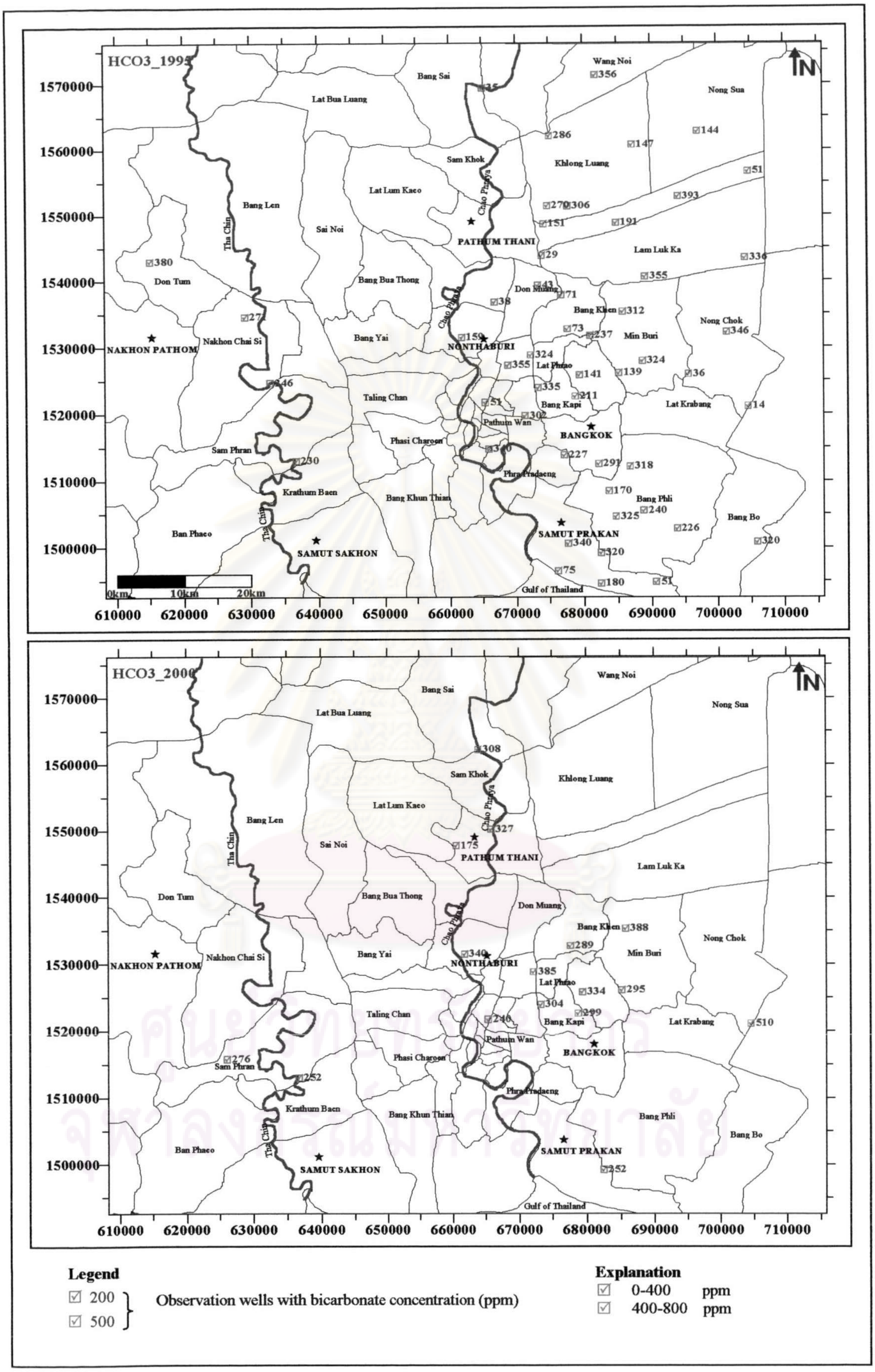


Figure 4.73 Bicarbonate concentration in 1995 and 2000

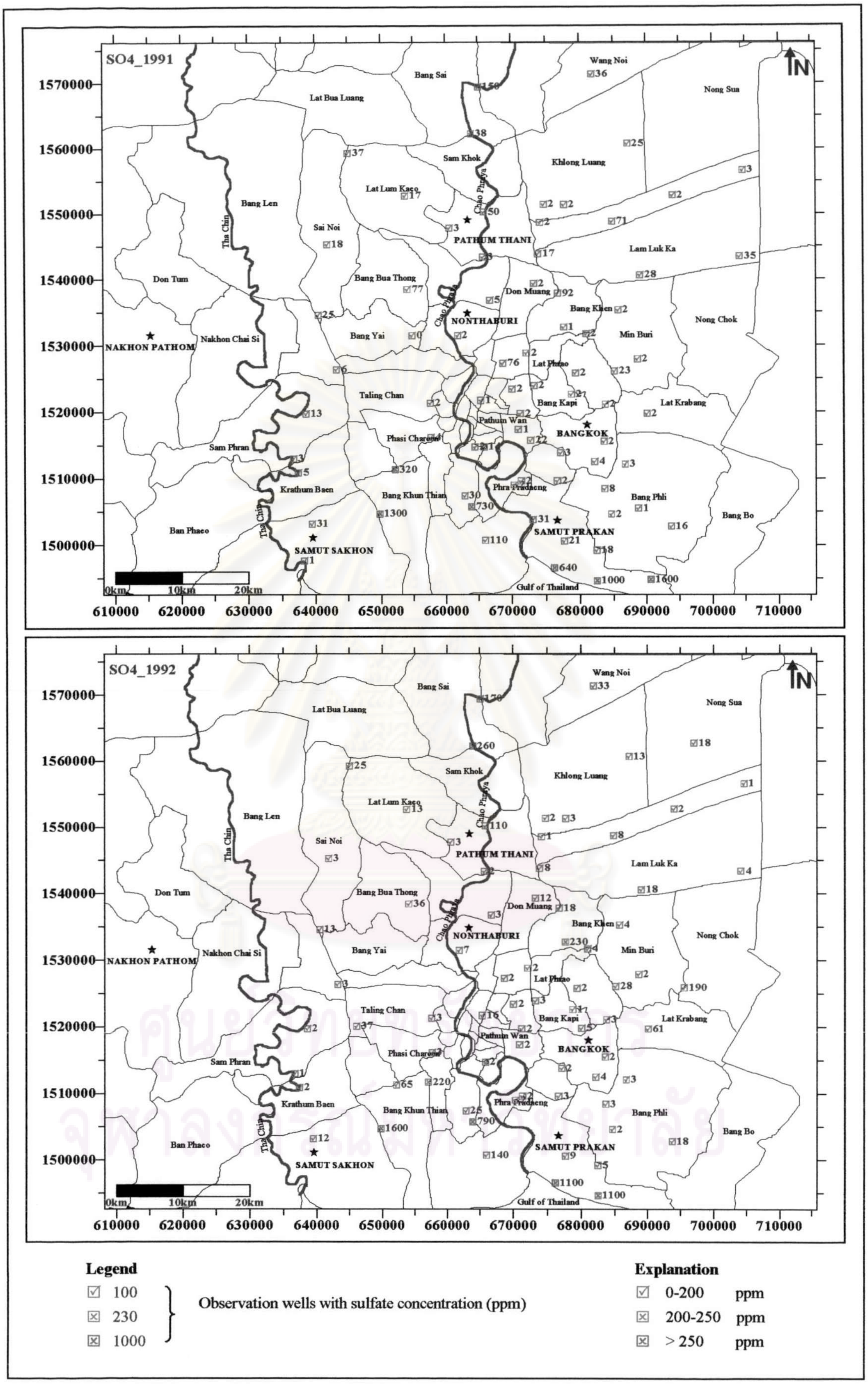


Figure 4.74 Sulfate concentration in 1991-1992

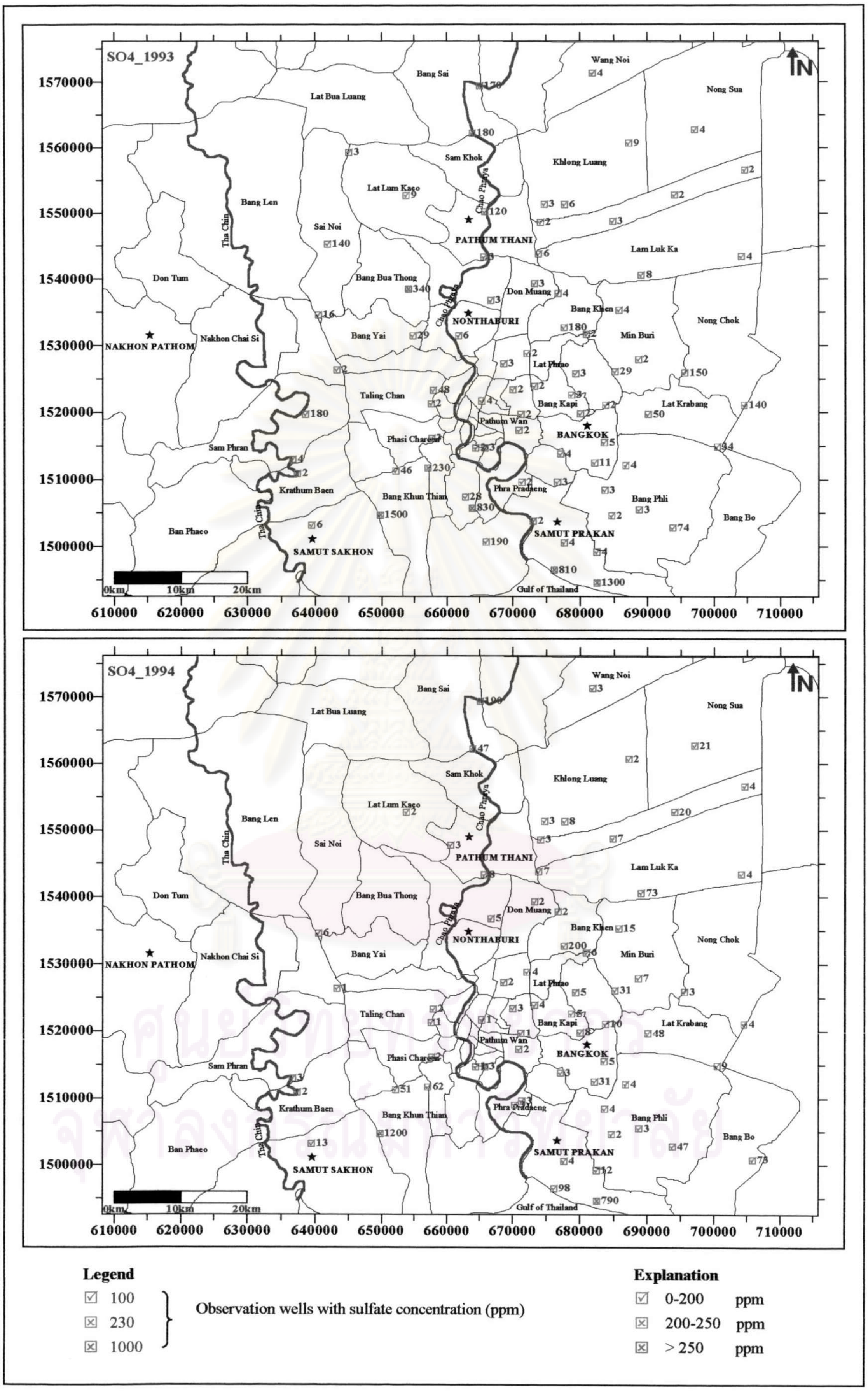


Figure 4.75 Sulfate concentration in 1993-1994

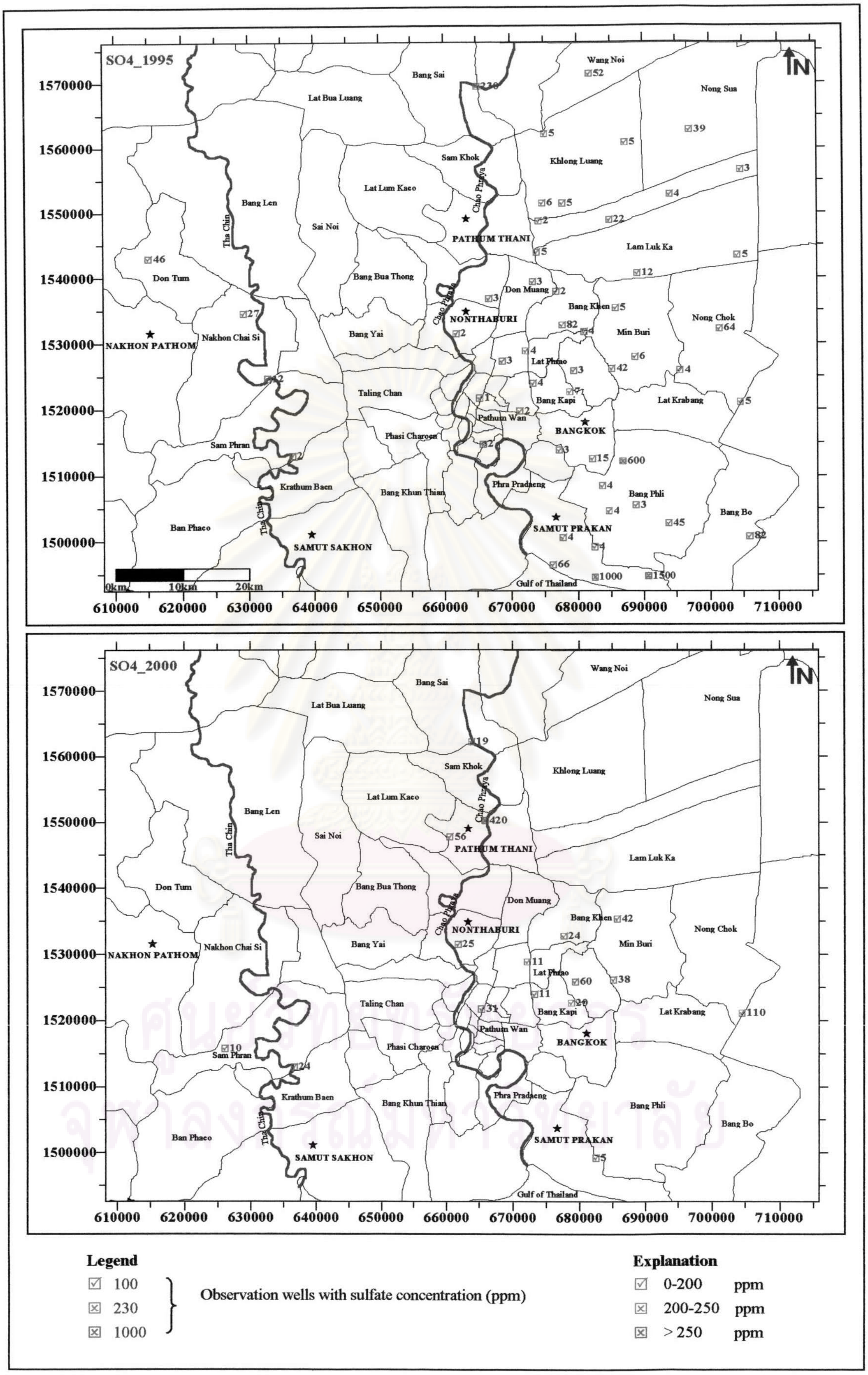


Figure 4.76 Sulfate concentration in 1995 and 2000

k) Nitrate ($NO3^-$). The nitrate concentration maps are shown in Fig. 4.77-4.79. The concentration of nitrate is varies from 0 to 35 ppm. The whole study area shows the low concentrations of nitrate under the standard drinking water that is allowed not exceed 45 ppm. Most nitrates in natural water come from organic sources or from industrial and agricultural chemicals. Common nitrate concentrations in water range from 0.1 to 0.3 in rainwater to as much as 600 ppm in groundwater from areas influenced by excessive applications of nitrate fertilizer or runoff from barnyards. Normal groundwater contains only from 0.1 to 10.0 ppm (Davis and De Wiest, 1966).

l) Fluoride (F^-). Figures 4.80-4.82 shows the fluoride concentration in this area. The fluoride concentration is ranging from 0 to 2 ppm. Most of them are within the standard drinking water limit that is allowed (less than 1.0 ppm.) and not exceeds the maximum allowable limit (1.5 ppm.). Especially, in Amphoe Minburi, Bangkok Metropolis is found the fluoride concentration 2 ppm. In natural concentrations of fluoride commonly range from about 0.01 to 10.0 ppm (Davis and De Wiest, 1966). The natural concentration of fluoride appears to be limited by the solubility of fluorite (CaF_2).

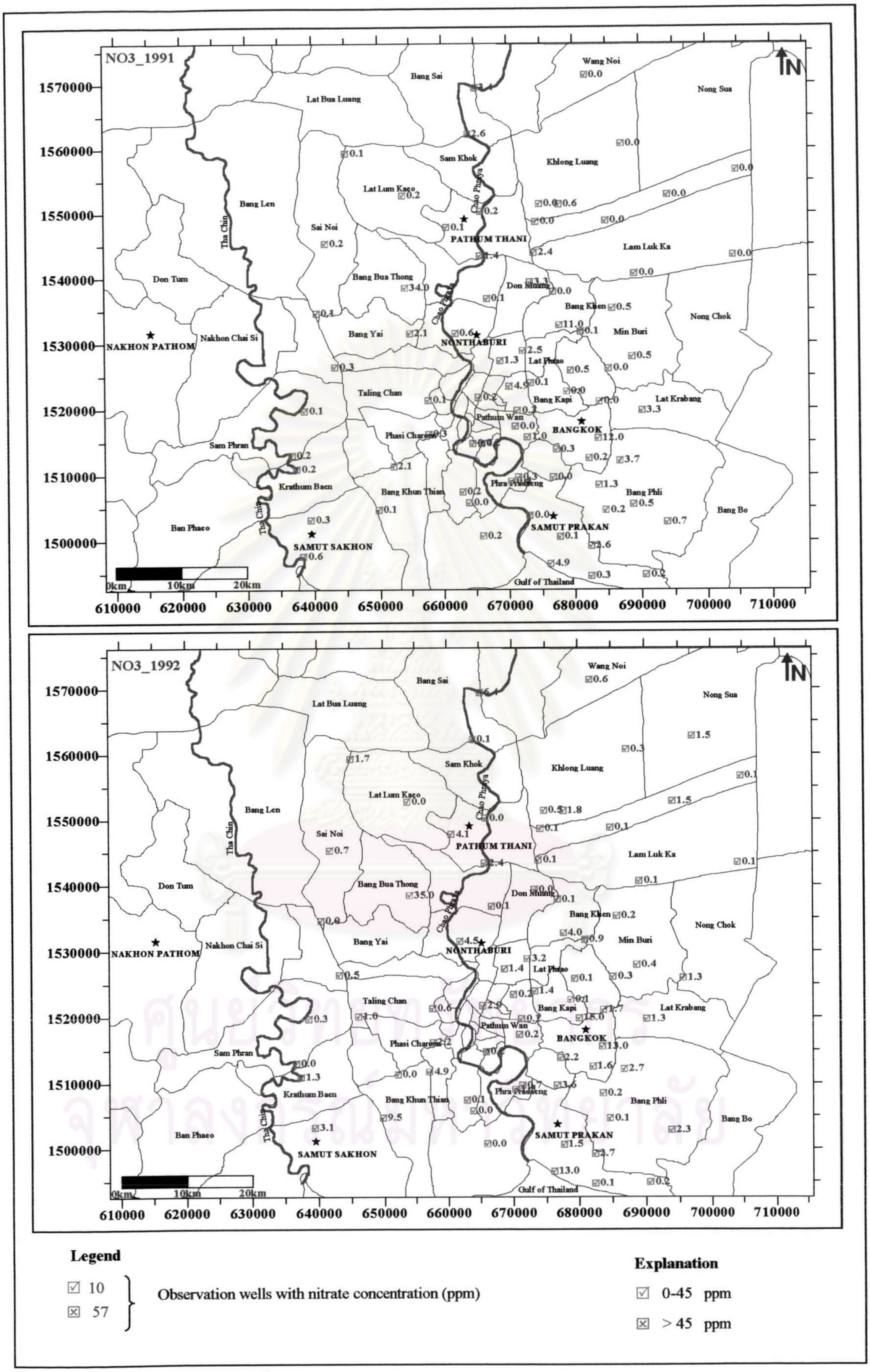


Figure 4.77 Nitrate concentration in 1991-1992

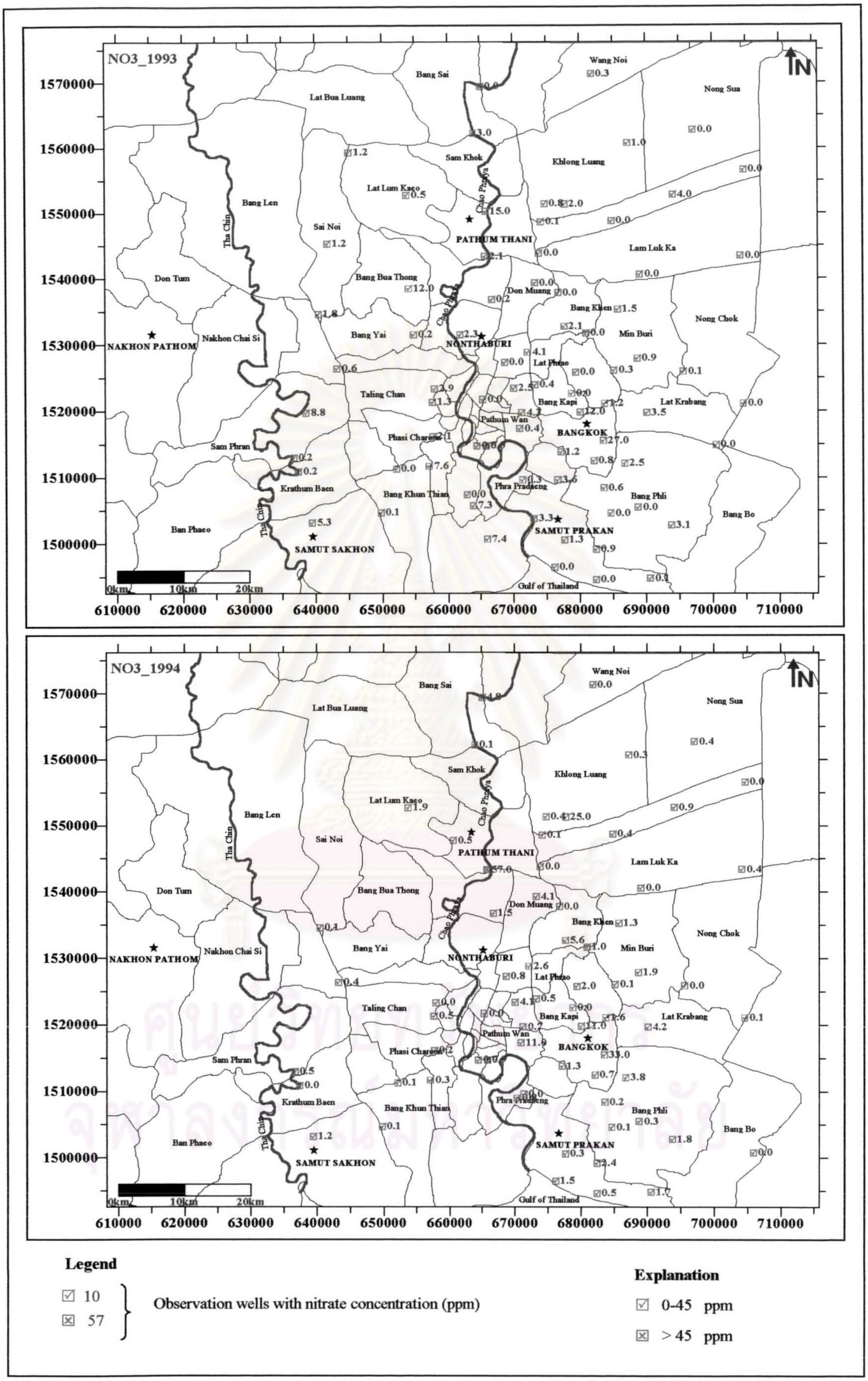


Figure 4.78 Nitrate concentration in 1993-1994

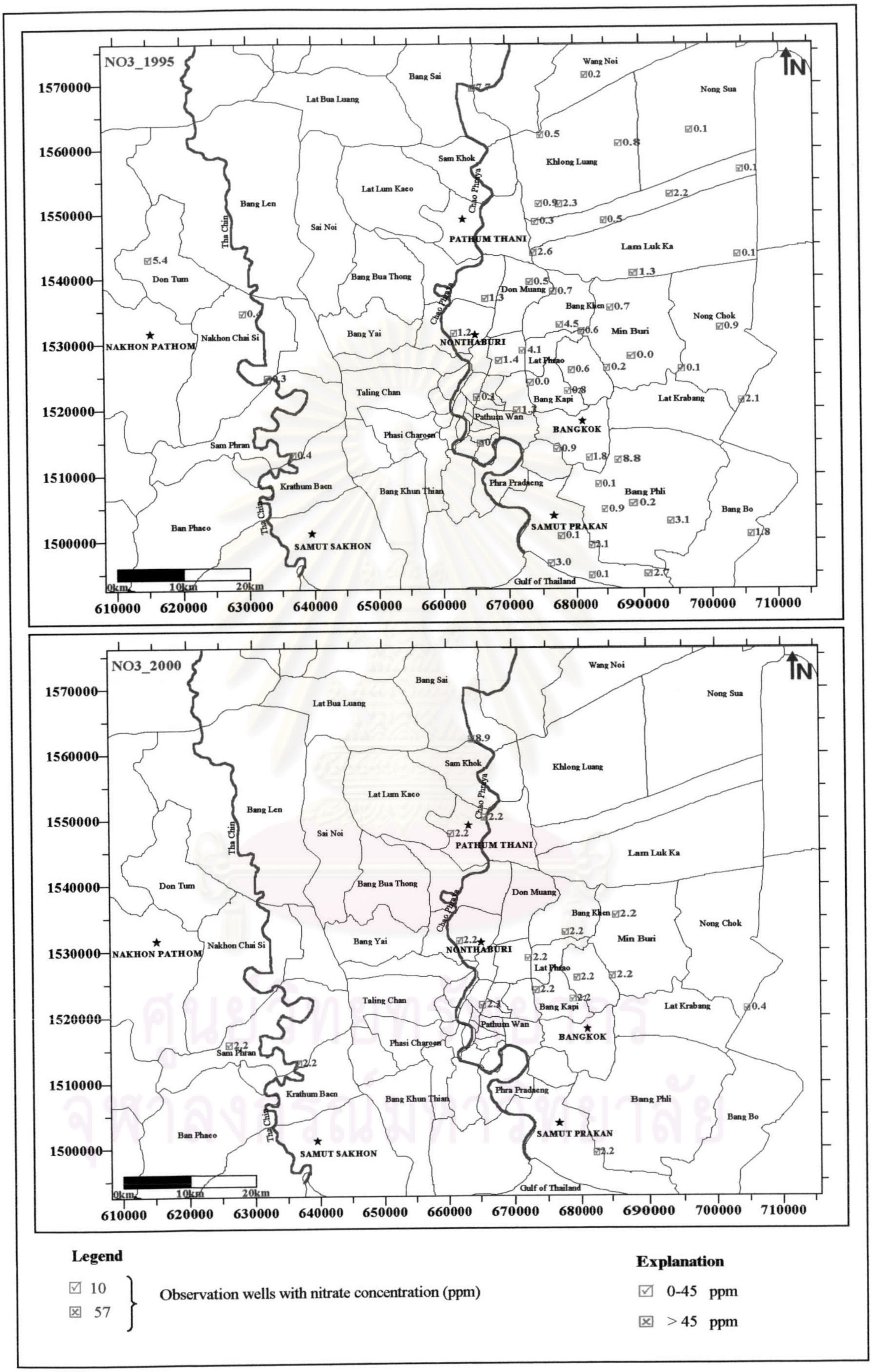


Figure 4.79 Nitrate concentration in 1995 and 2000

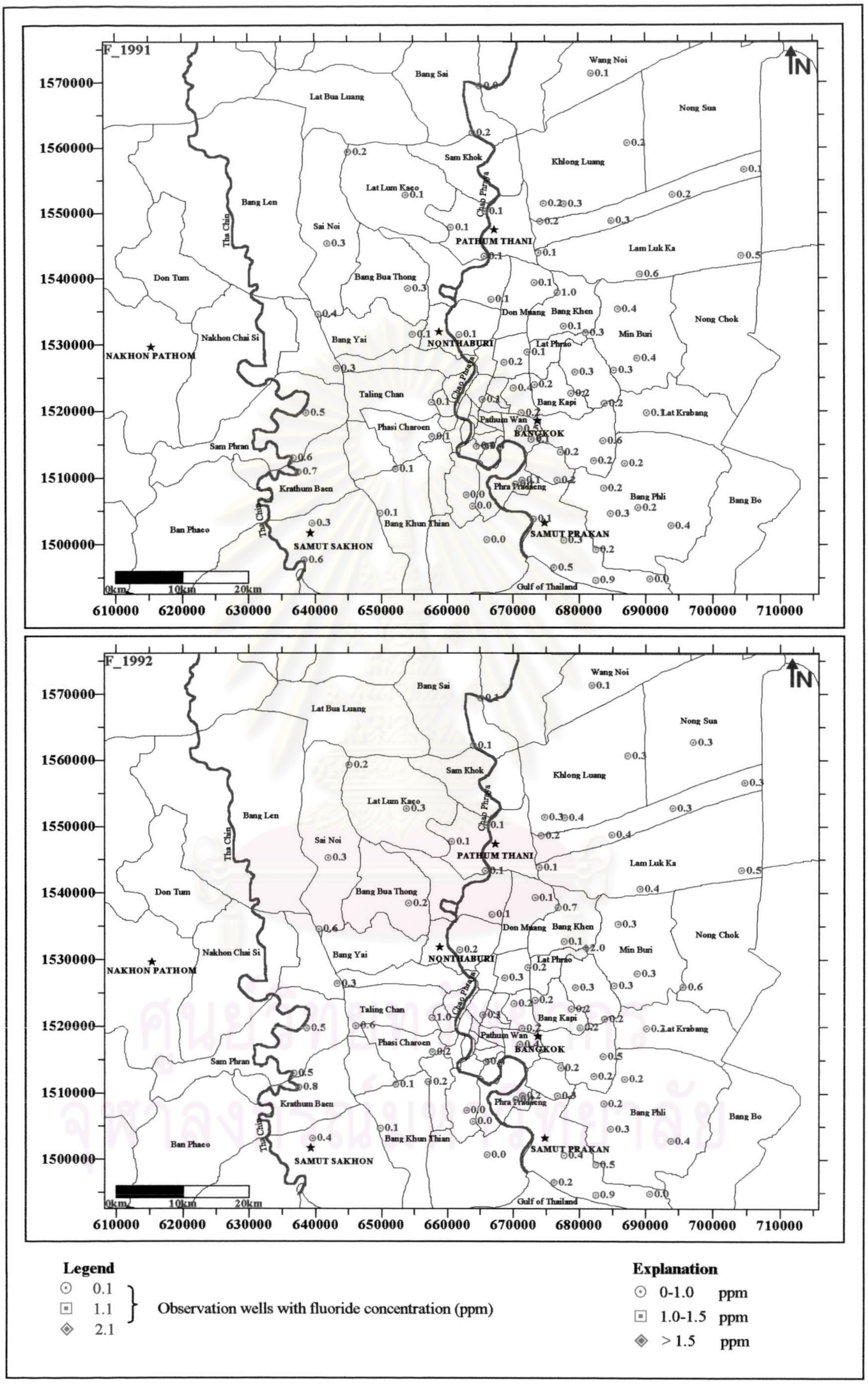


Figure 4.80 Fluoride concentration in 1991-1992

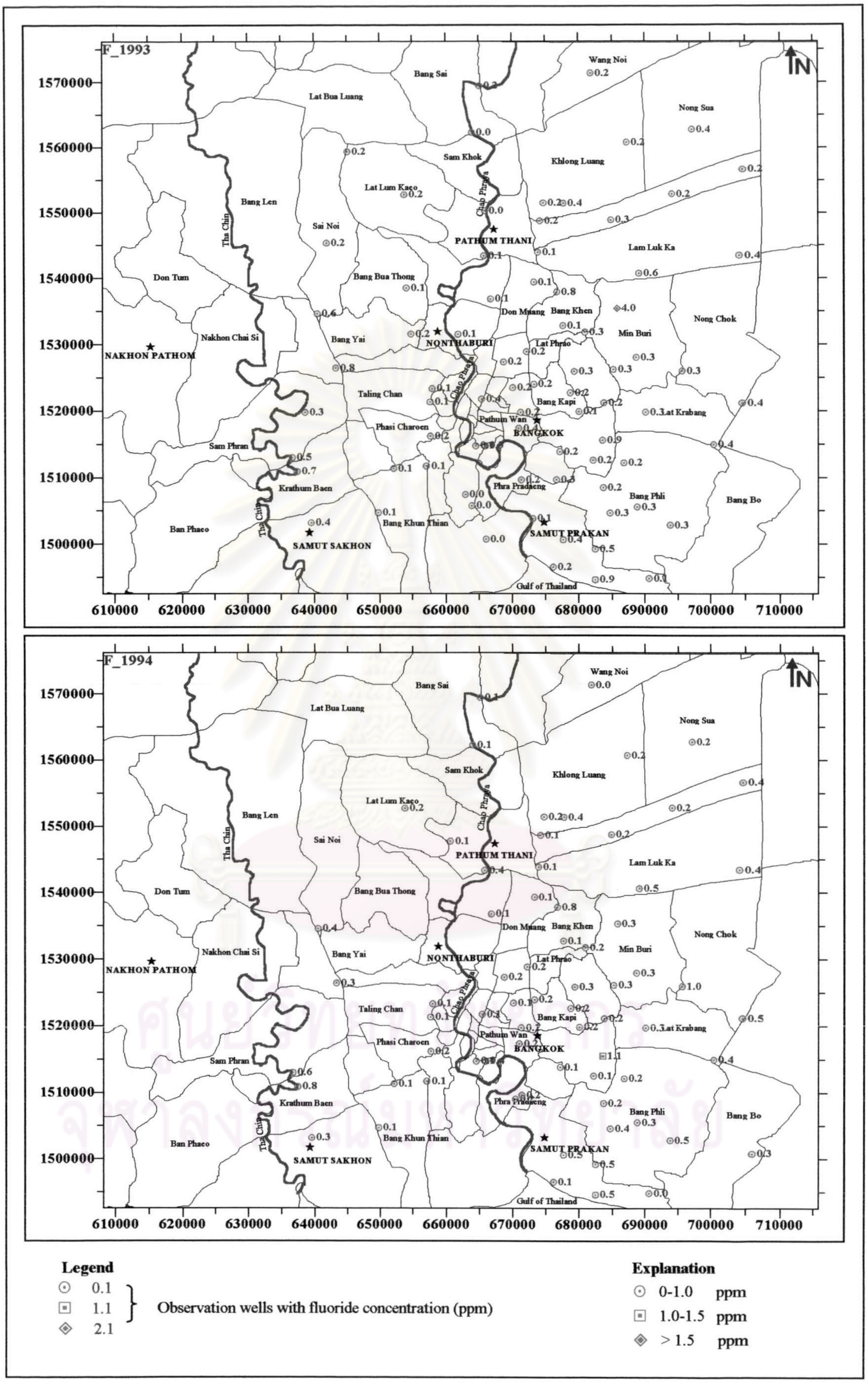


Figure 4.81 Fluoride concentration in 1993-1994

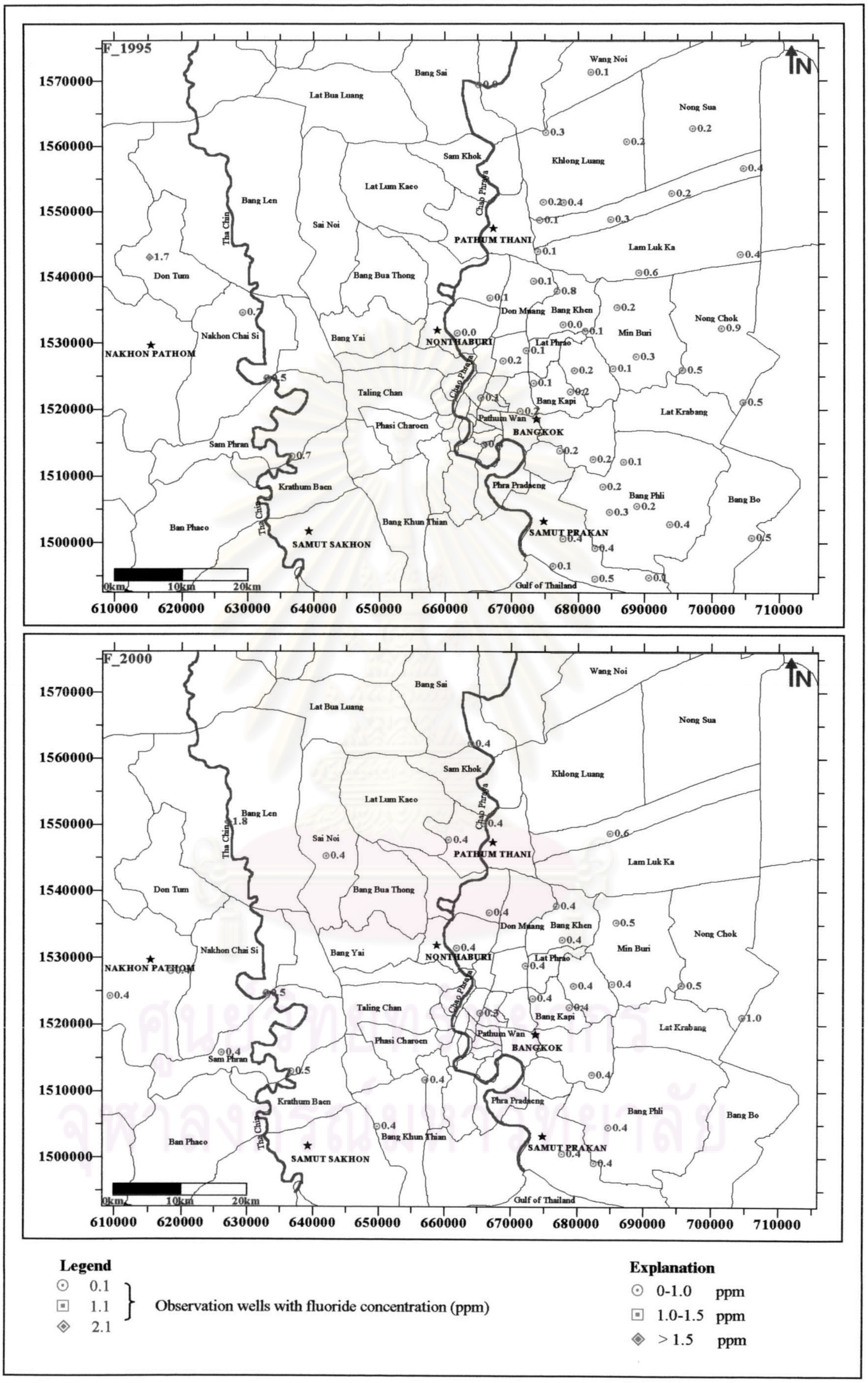


Figure 4.82 Fluoride concentration in 1995 and 2000

m) Total Dissolved Solids, TDS. The new classification of the TDS is also established. There are four levels as follow:

Level I	0-750	ppm.	Low TDS Content
Level II	750-1,500	ppm.	Moderate TDS Content
Level III	1,500-5,000	ppm.	High TDS Content
Level IV	5,000-30,000	ppm.	Very High TDS Content

Figs 4.83-4.87 display the TDS concentration of the studied area. The TDS is varies with in the range of 300 to 25,000 ppm. Under the standard drinking water for the suitable quality, the TDS concentration is allowed less than 750 ppm. and not exceeds 1,500 ppm. for the maximum allowable limit. The acceptable limit for potable (< 1,500 ppm.) is located in the middle of western part, central part and middle of eastern part further to the north. High and Very High TDS content are concentrated along the Chao Phraya River and the southern part of the area (Amphoe Bang Khun Thian, Bangkok Metropolis, Amphoe Muang, Samut SaKhon Province, Amphoe Muang and Amphoe Phra Pradaeng, Samut Prakan Province). It is interesting to note that the zone of high to very high TDS content is conformed to the areas of the excessive quantities of chloride.

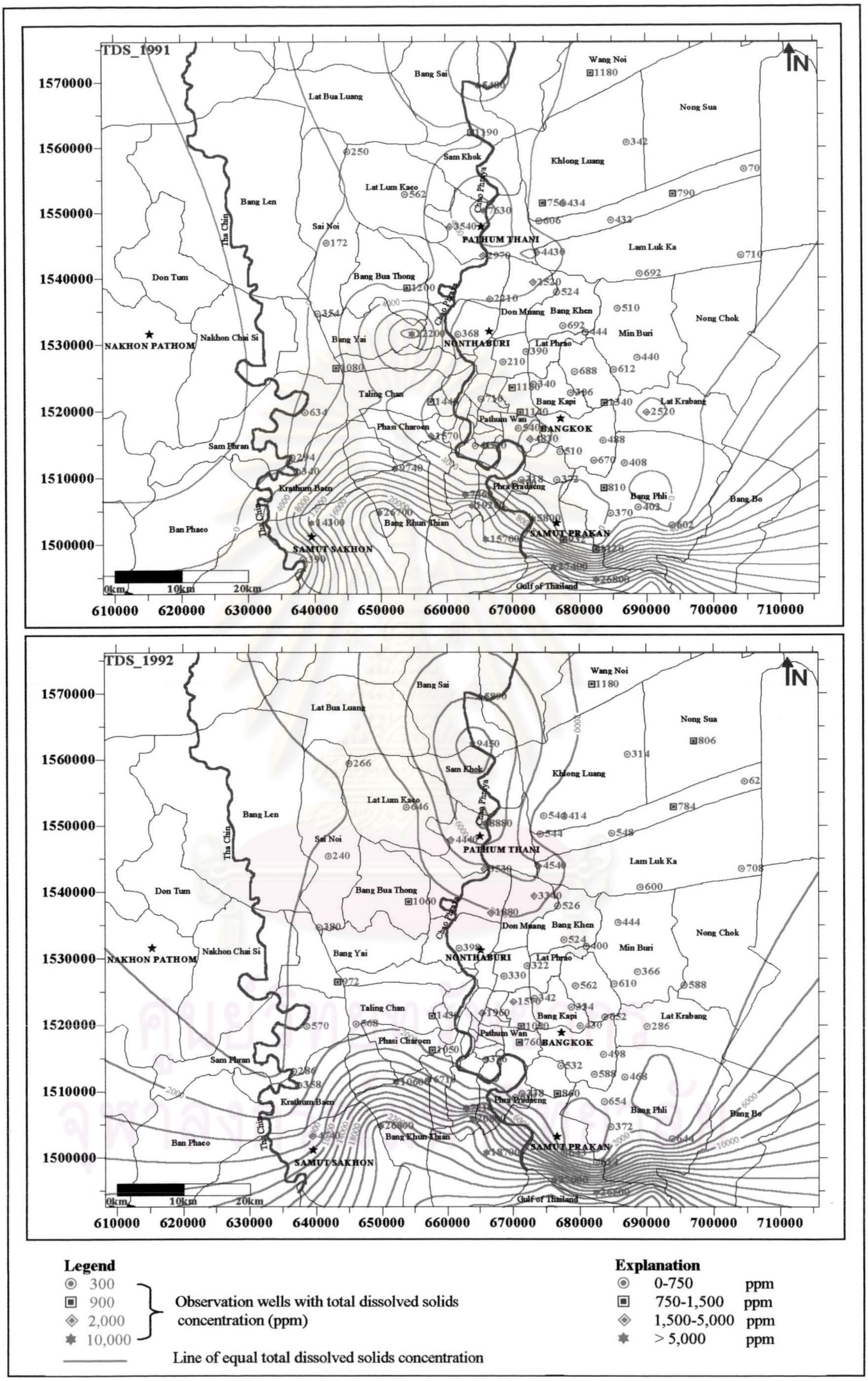


Figure 4.83 Total dissolved solids concentration in 1991-1992

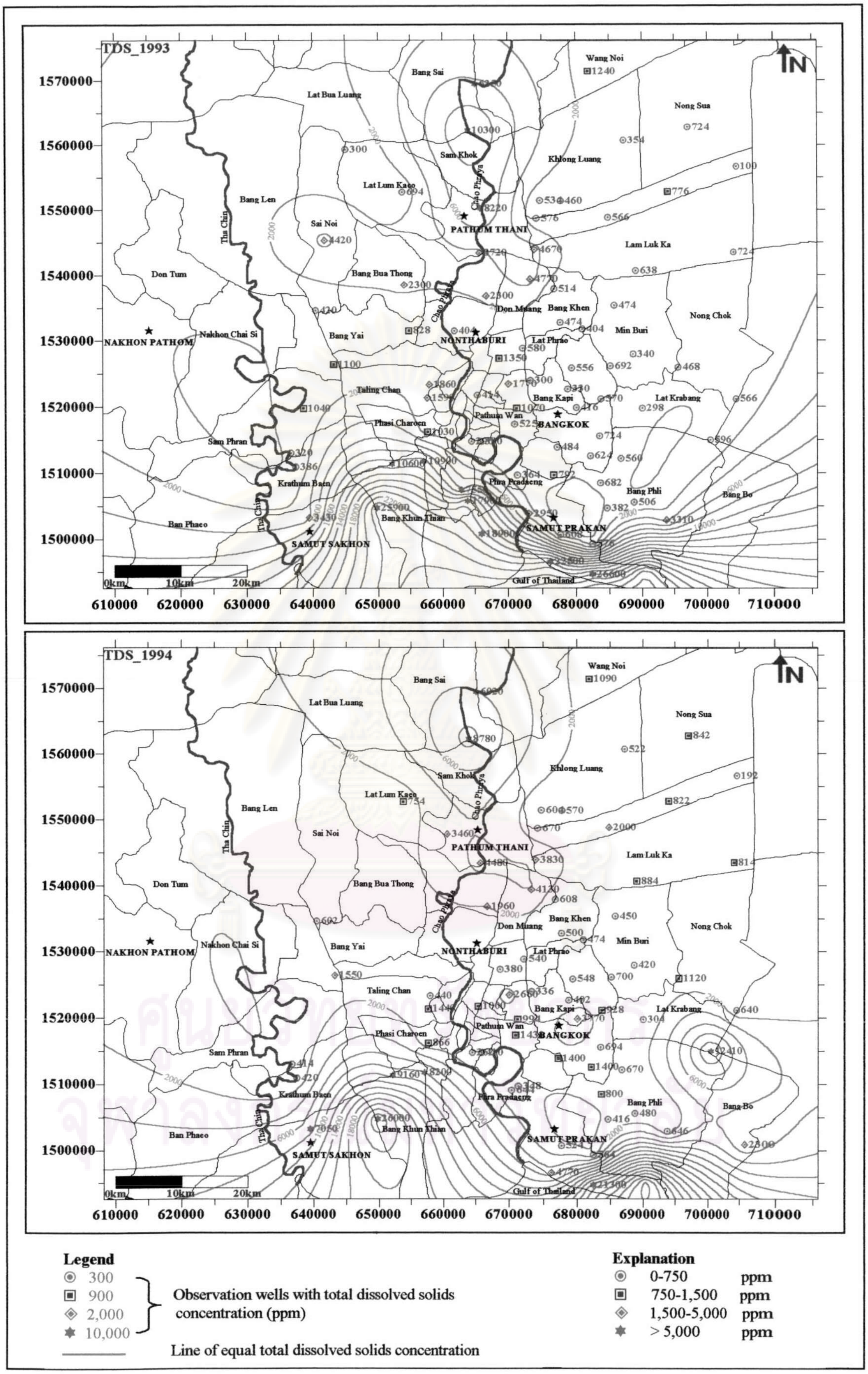


Figure 4.84 Total dissolved solids concentration in 1993-1994

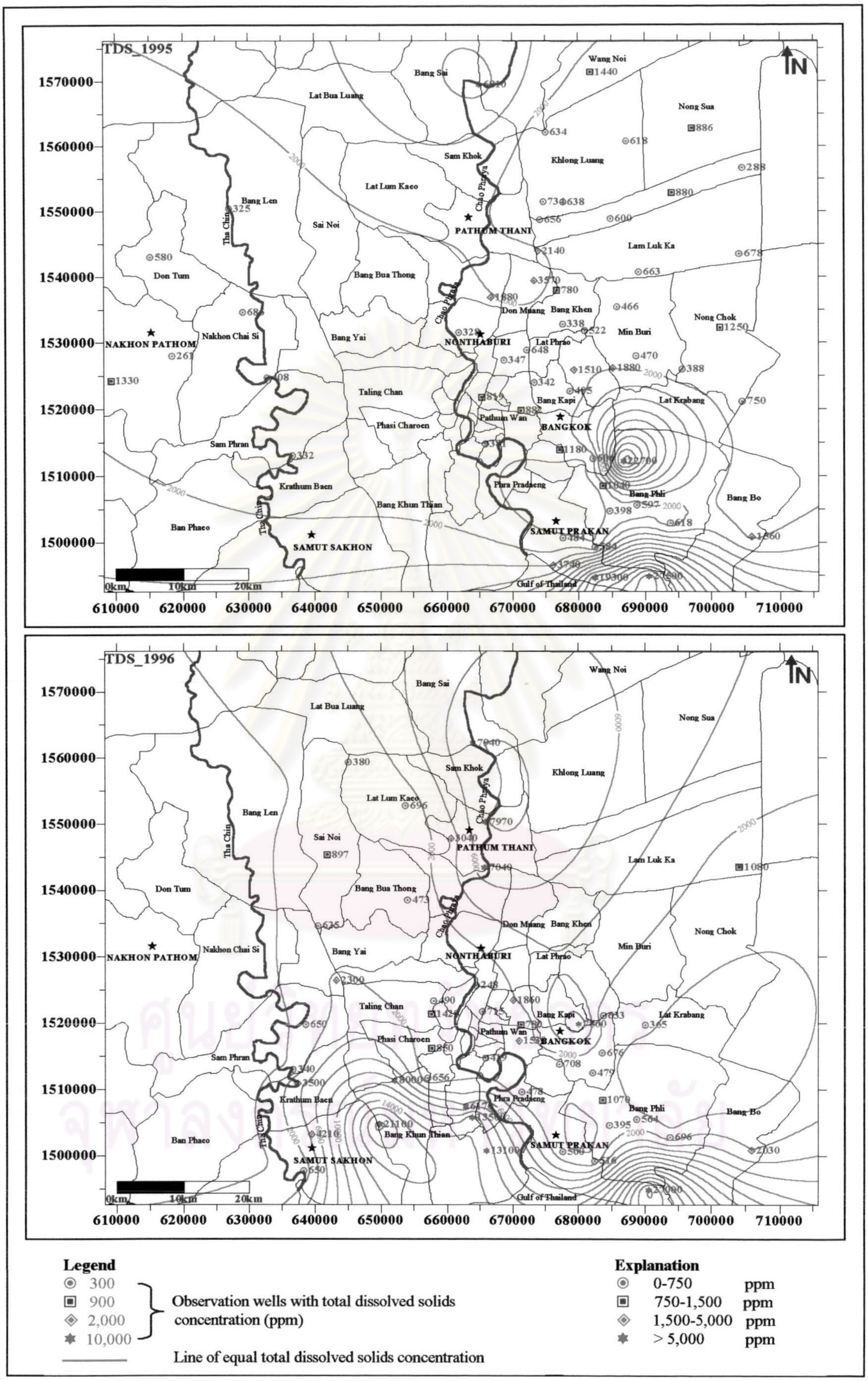


Figure 4.85 Total dissolved solids concentration in 1995-1996

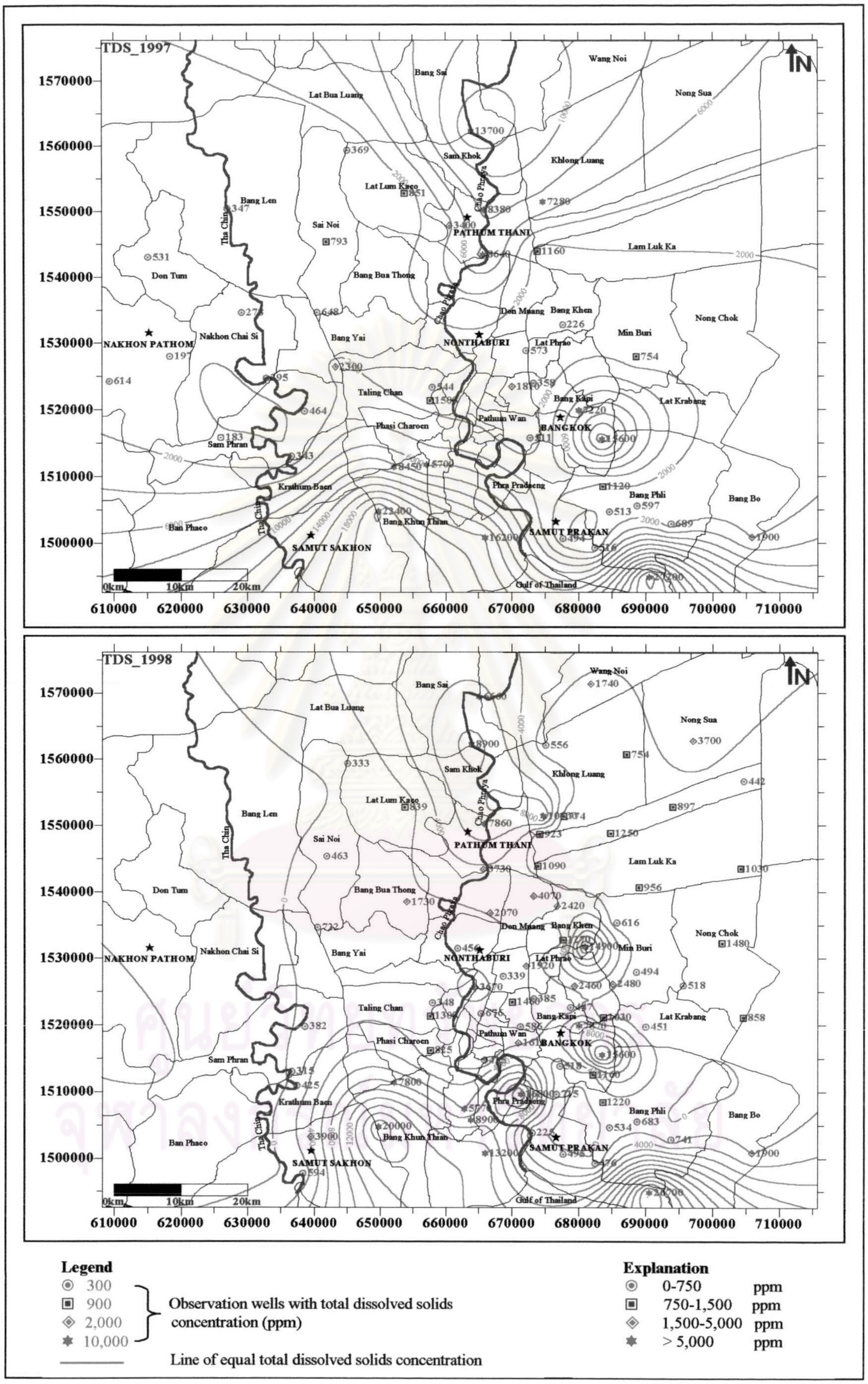


Figure 4.86 Total dissolved solids concentration in 1997-1998

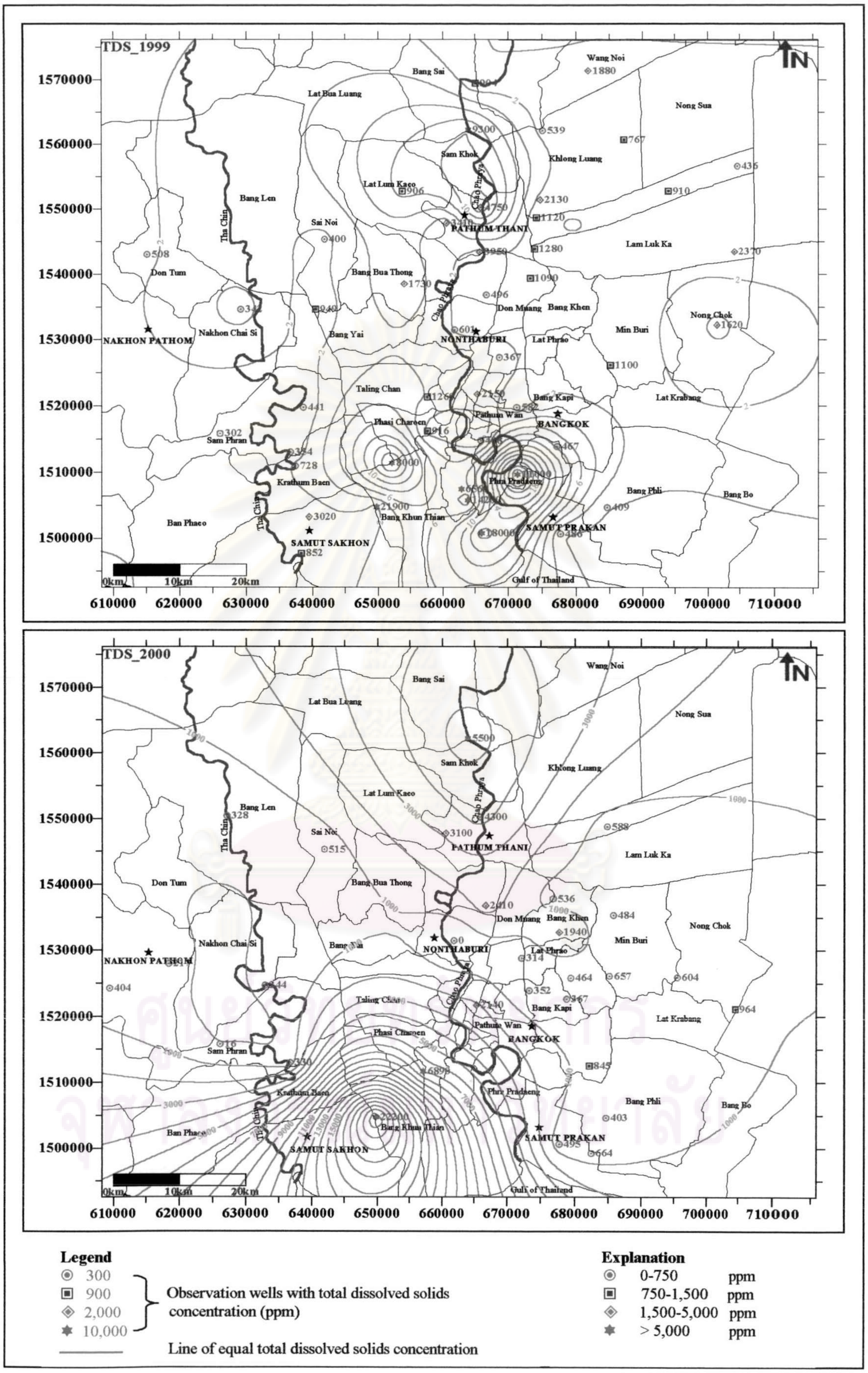


Figure 4.87 Total dissolved solids concentration in 1999-2000

n) Total Hardness. The new classification of the Total Hardness is also established. There are four levels as follow:

Level I	0-300	ppm.	Low Total Hardness Content
Level II	300-500	ppm.	Moderate Total Hardness Content
Level III	500-1,000	ppm.	High Total Hardness Content
Level IV	1,000-30,000	ppm.	Very High Total Hardness Content

Figs 4.88-4.92 display the Total Hardness concentration of the study area. The total hardness concentration falls within the range of 30 to 13,000 ppm. The concentration of total hardness under the standard drinking water is permitted less than 300 ppm. for suitable quality and not exceeds 500 ppm. for the maximum amount allowed. In the western, central and eastern parts of the study area the total hardness concentration appears to be low and is under the acceptable limits. The zone of over acceptable limits for drinking water are concentrated along the Chao Phraya River and the southern part of the area (Amphoe Bang Khun Thian, Bangkok Metropolis, Amphoe Muang, Samut SaKhon Province, Amphoe Muang and Amphoe Phra Pradaeng, Samut Prakan Province). However, the degree of hardness (Table 2.3) is considered to be soft to moderately hard water is located in the central part and eastern part further to the north of the area, while the zone of hard and very hard water developed in the central, the southern parts of the area and along the Chao Phraya River. It is interesting to note that the zone of high to very high of the total hardness content is also conformed to the areas excessive quantities of the TDS and chloride concentrations.

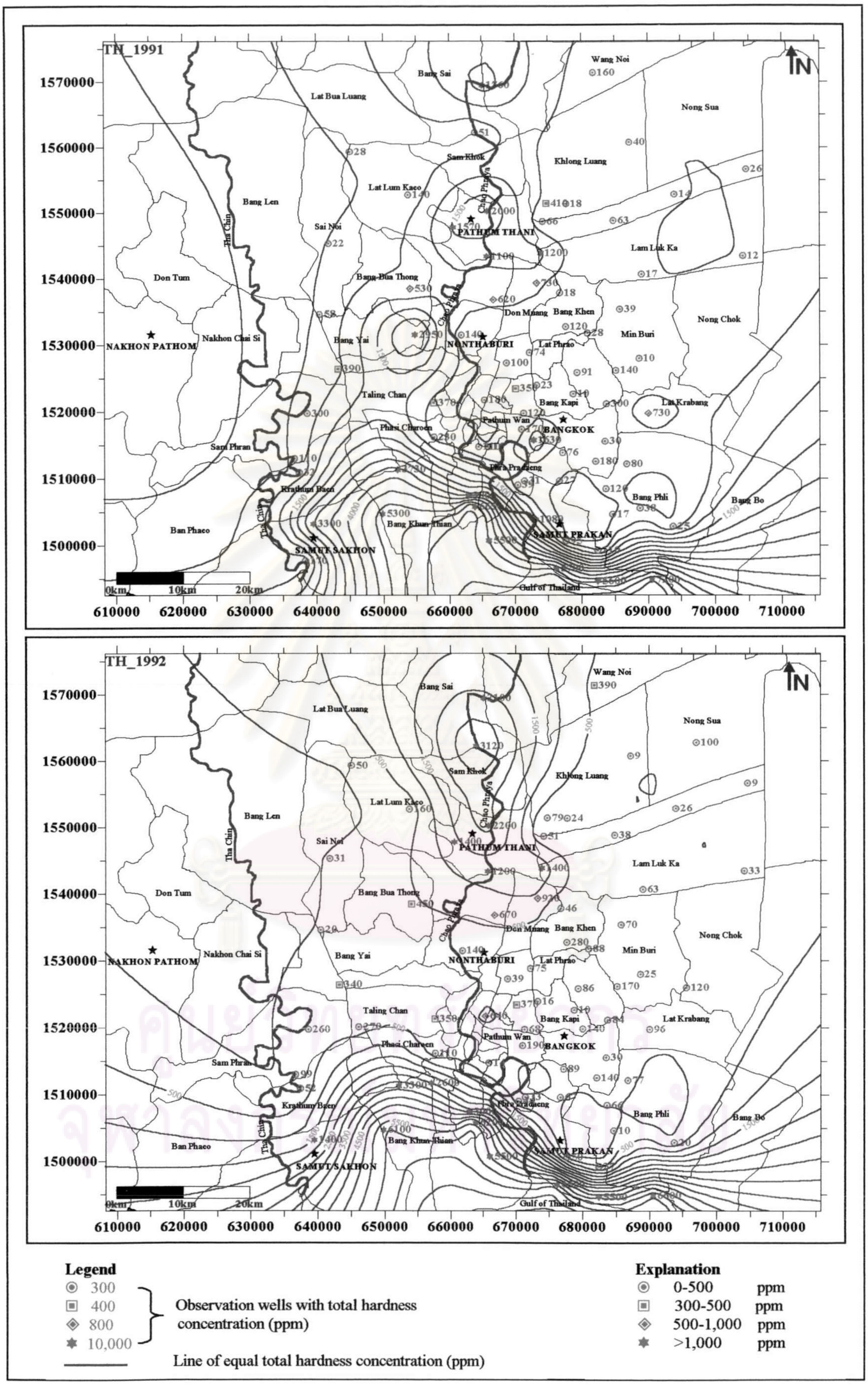


Figure 4.88 Total hardness concentration in 1991-1992

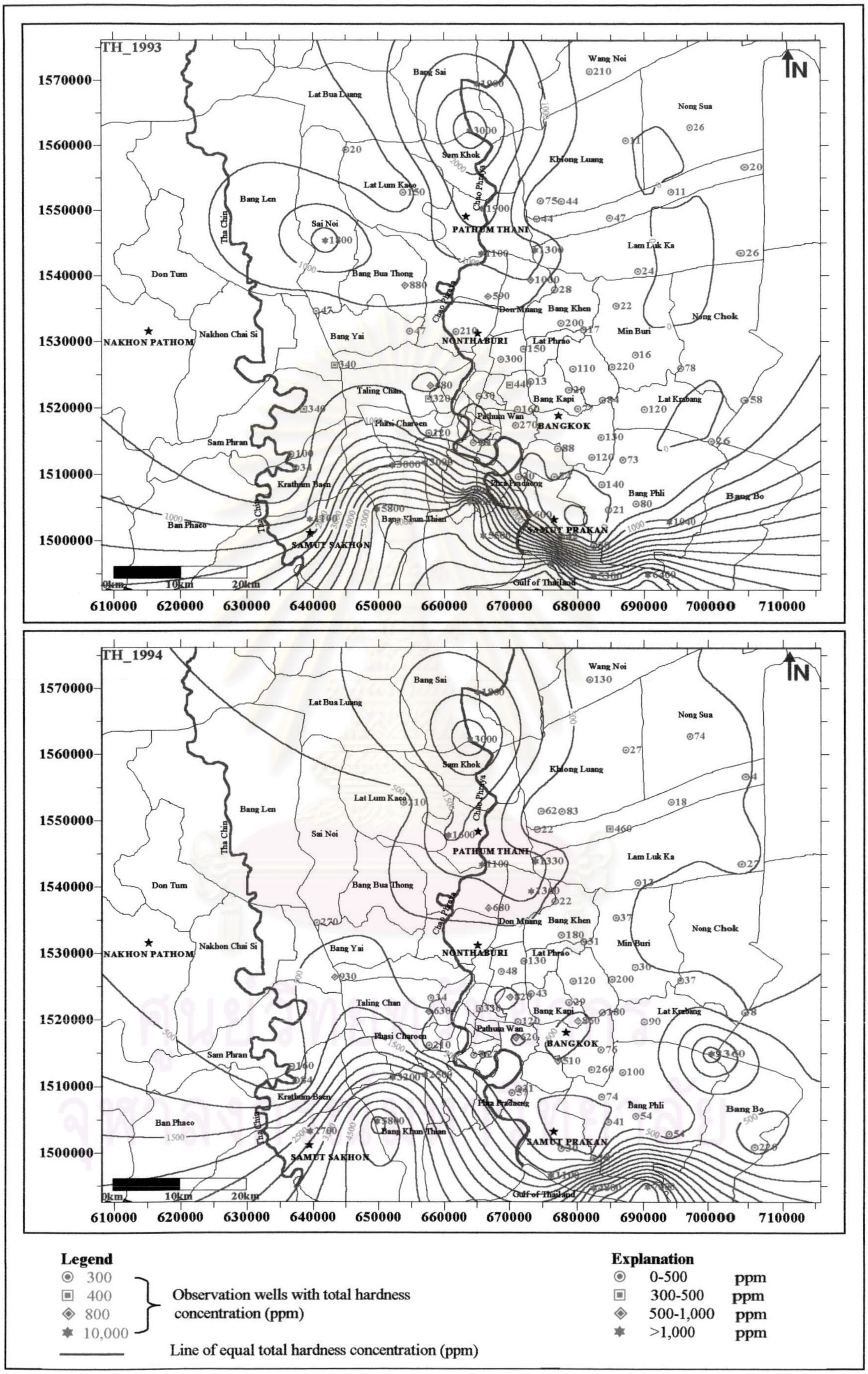


Figure 4.89 Total hardness concentration in 1993-1994

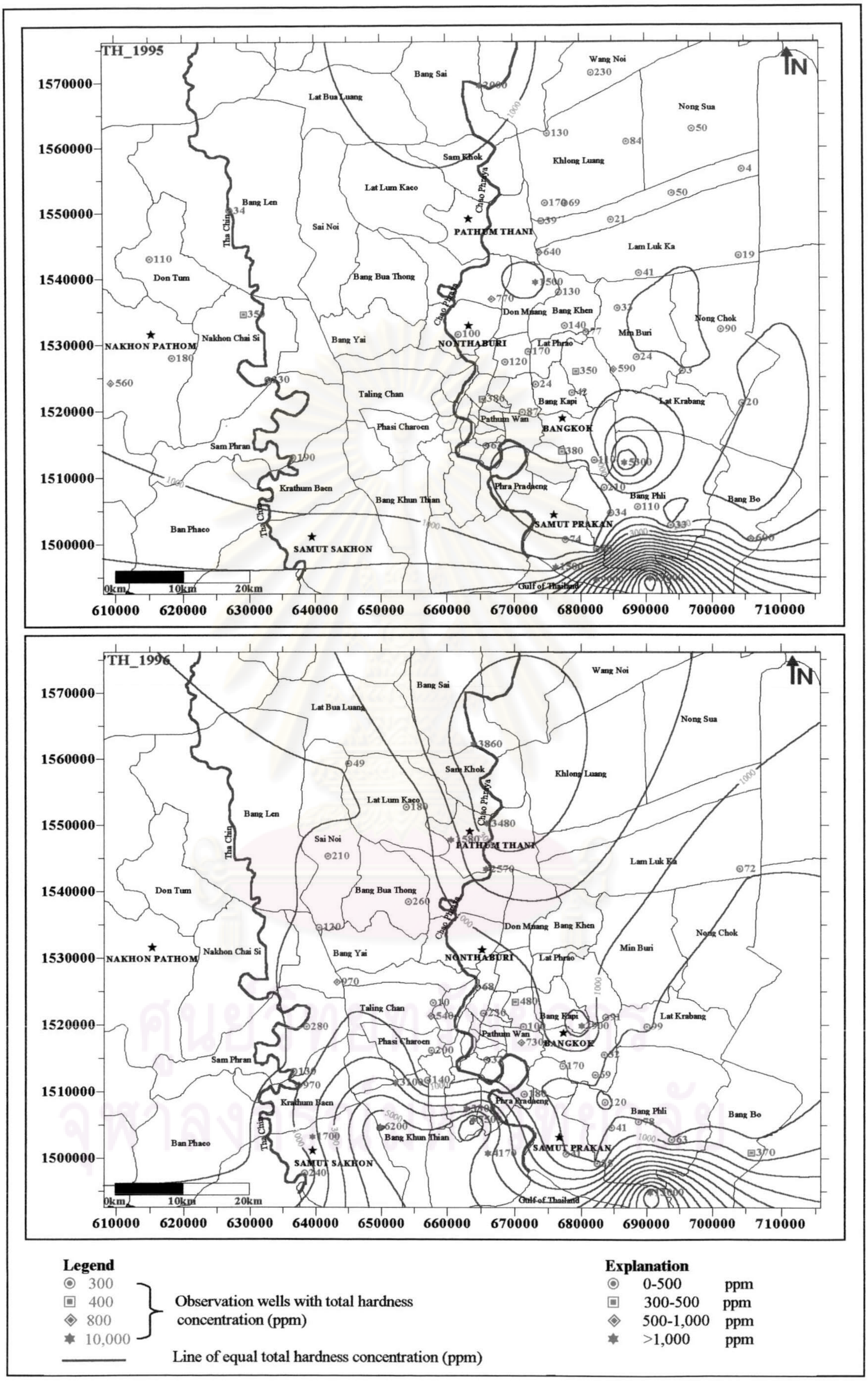


Figure 4.90 Total hardness concentration in 1995-1996

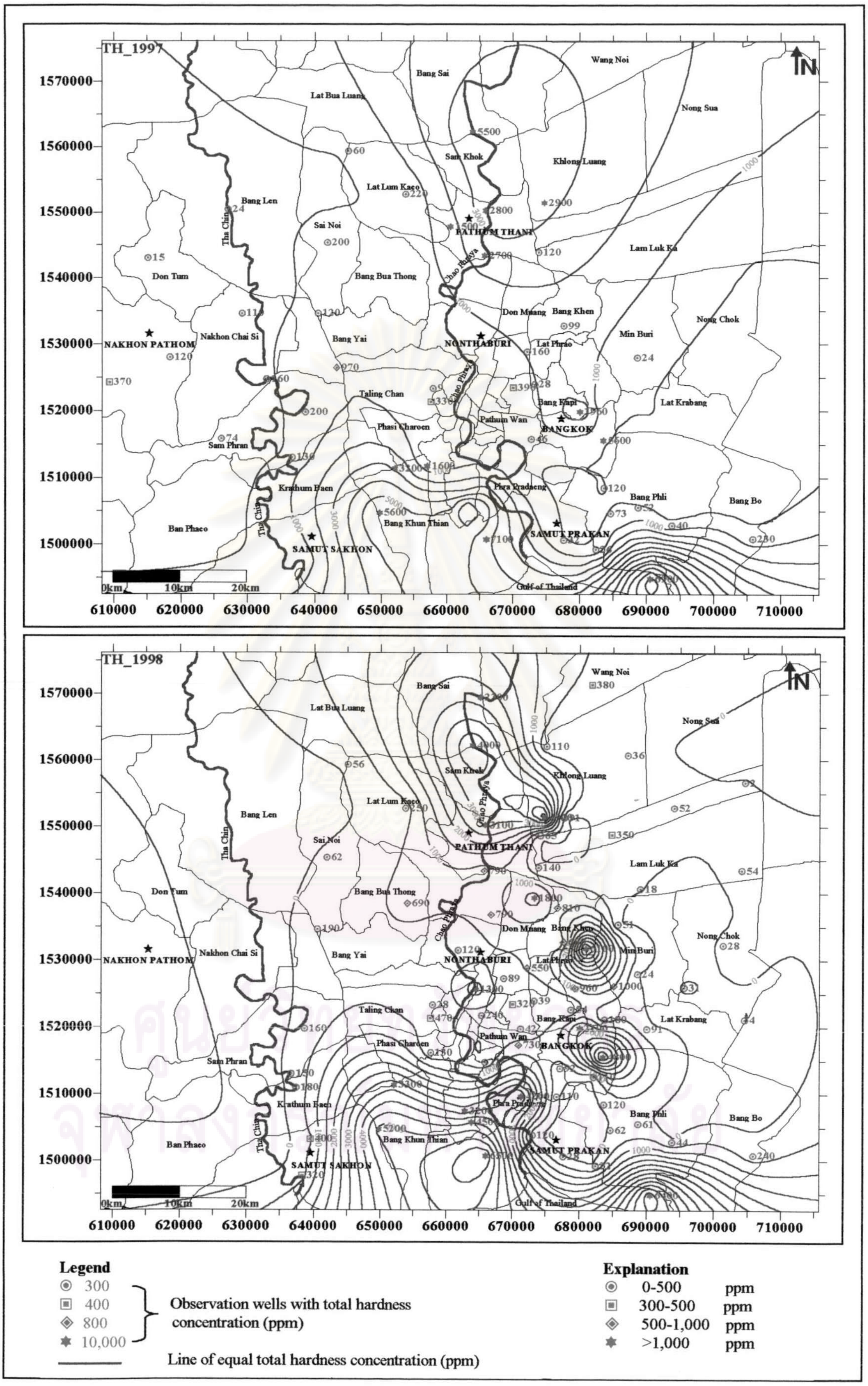


Figure 4.91 Total hardness concentration in 1997-1998

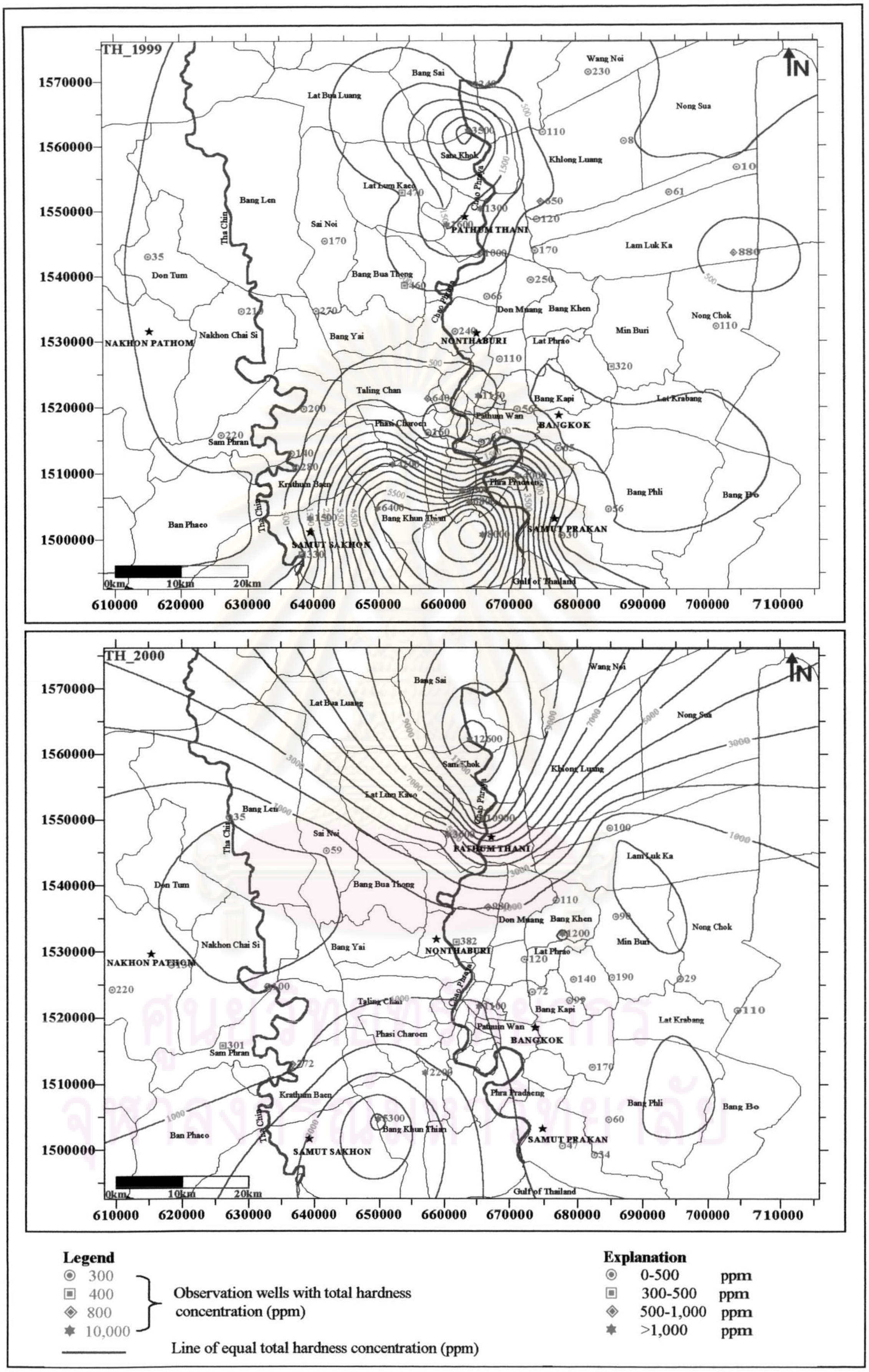


Figure 4.92 Total hardness concentration in 1999-2000

o) Total Iron (Fe). The new classification for Iron content is carried out as follow:

Level I	0.0-0.5	ppm.	Low Total Iron Content
Level II	0.5-1.0	ppm.	Moderate Total Iron Content
Level III	1.0-10.0	ppm.	High Total Iron Content
Level IV	10.0-100.0	ppm.	Very High Total Iron Content

Figs.4.93-4.97 displays the Total Iron concentration of the study area. Generally, the total iron concentration is ranging 0-30 ppm. The zone which under the suitable quality (less than 0.5 ppm.) and not exceeds the maximum allowable limit (1.0 ppm.) is located in the middle of western part, central part and middle of eastern part further to the north. High and Very High Total Iron content are concentrated in the central, a bit further to the northern part (Amphoe Sam Kok, Pathum Thani Province) and in the southern part (Amphoe Phra Pradaeng, Samut Prakan). It is interesting to note that the presence of total iron concentration appears to be related to the chloride content in the groundwater. Therefore, the zone that high chloride concentration must be found the total iron high as well (Jitapunkul, 1980).

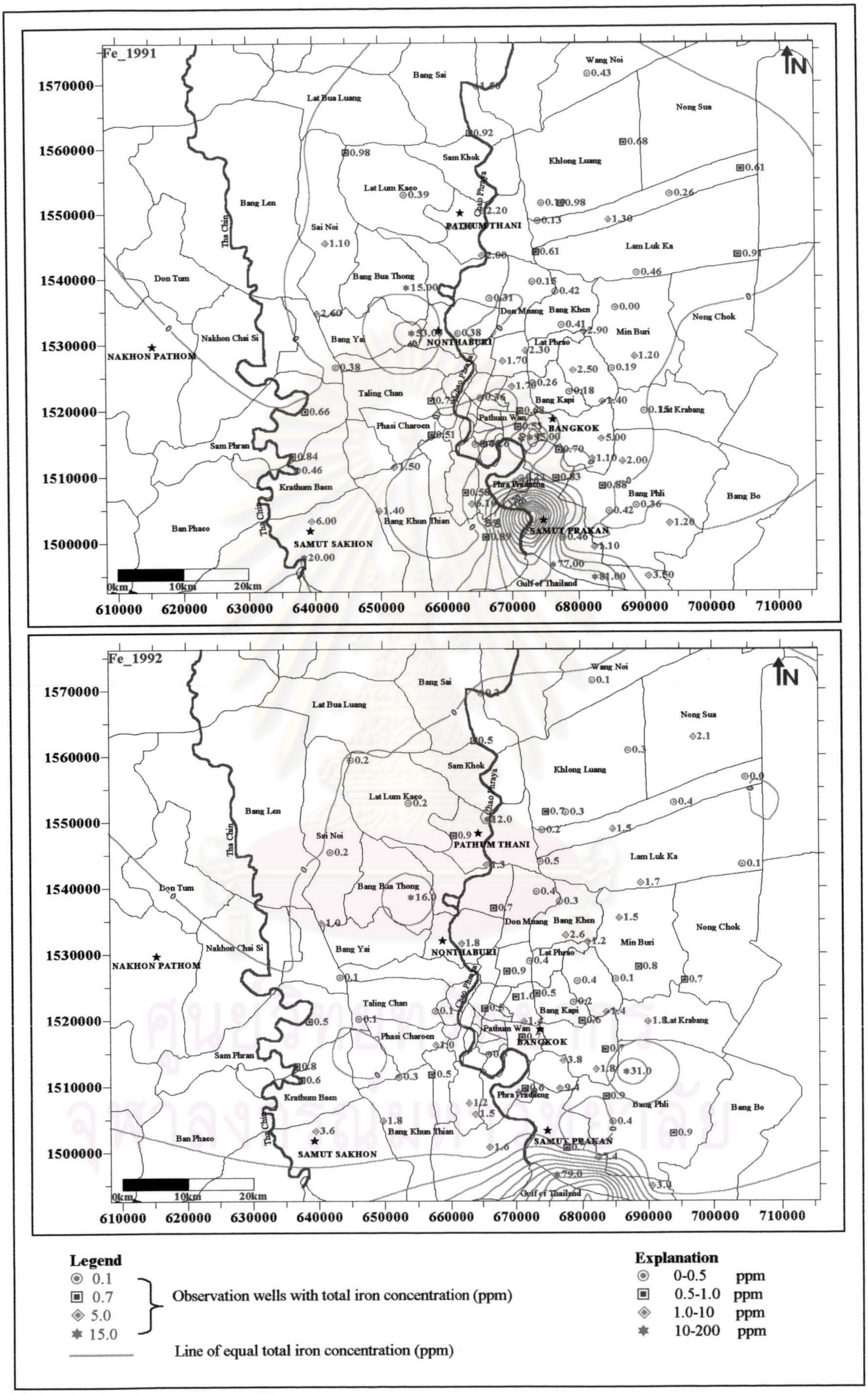


Figure 4.93 Total iron concentration in 1991-1992

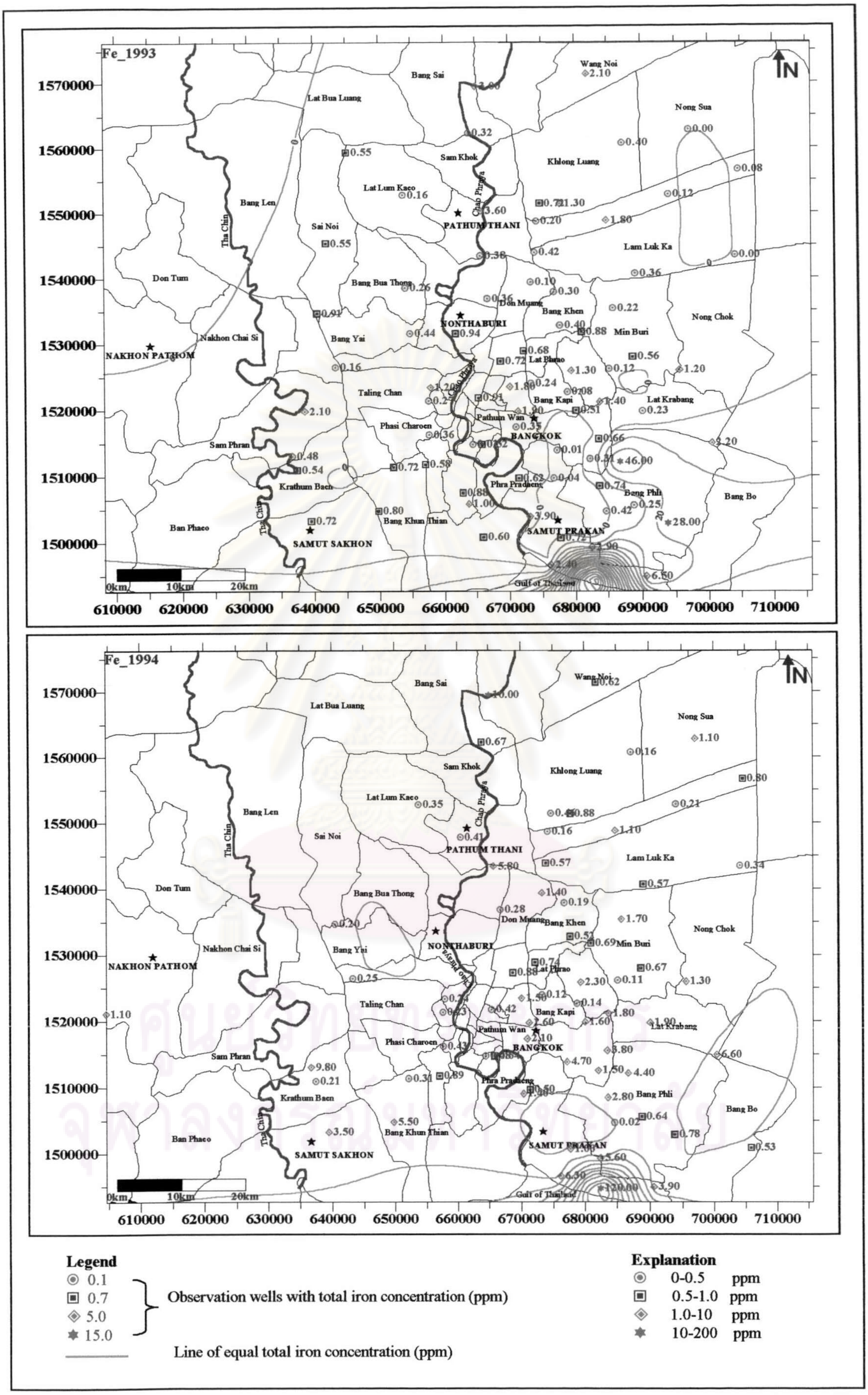


Figure 4.94 Total iron concentration in 1993-1994

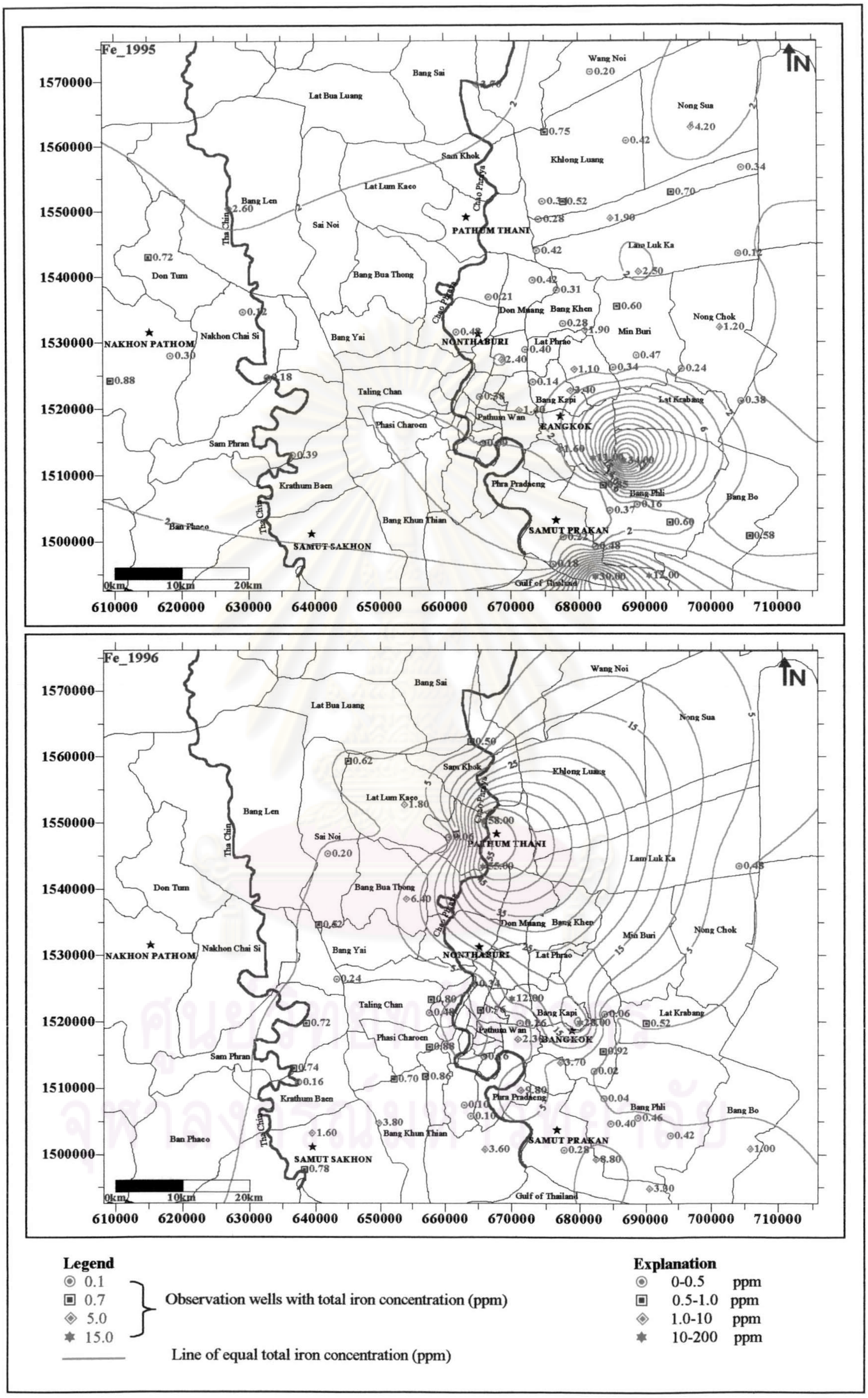


Figure 4.95 Iron concentration in 1995-1996

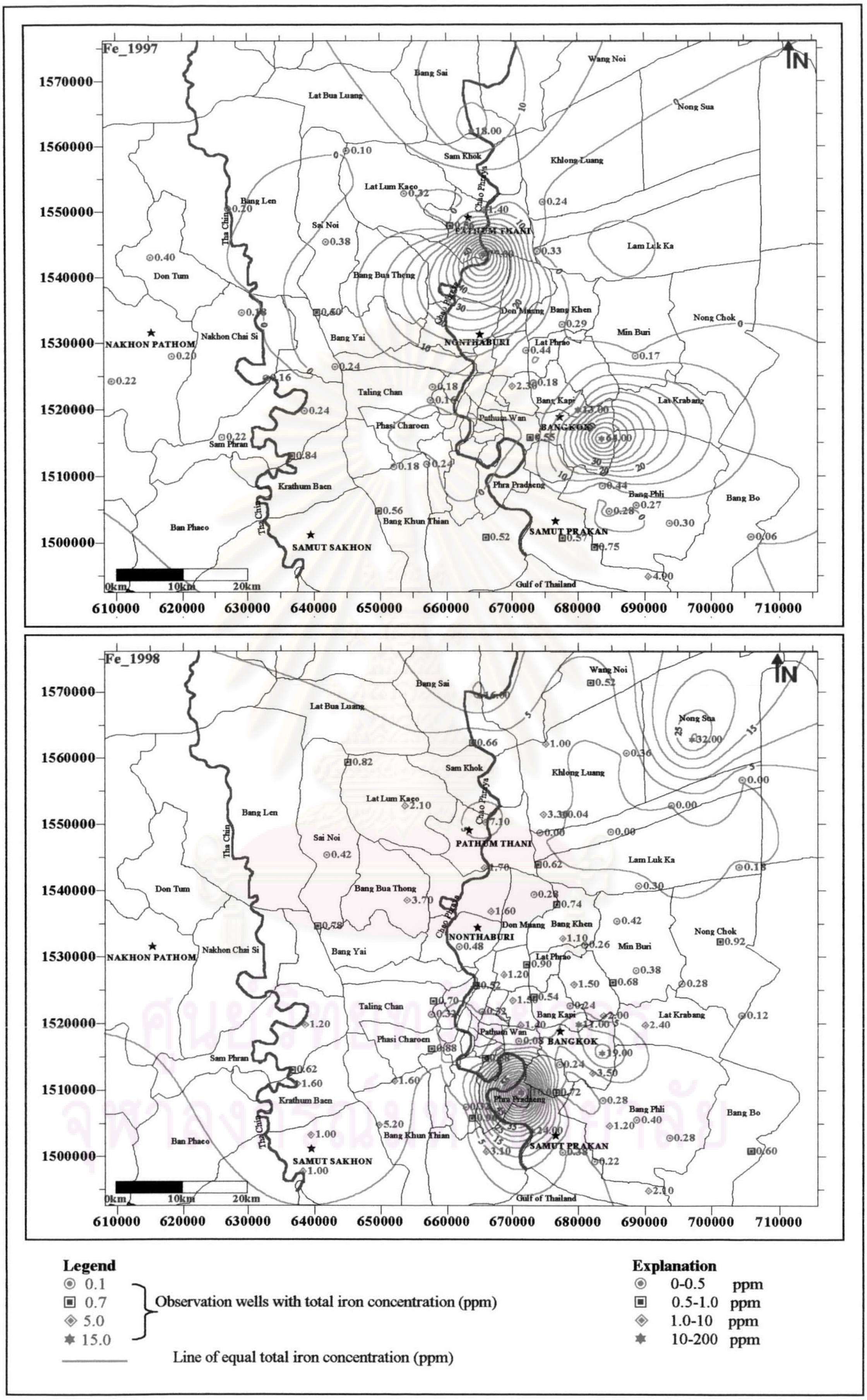


Figure 4.96 Total iron concentration in 1997-1998

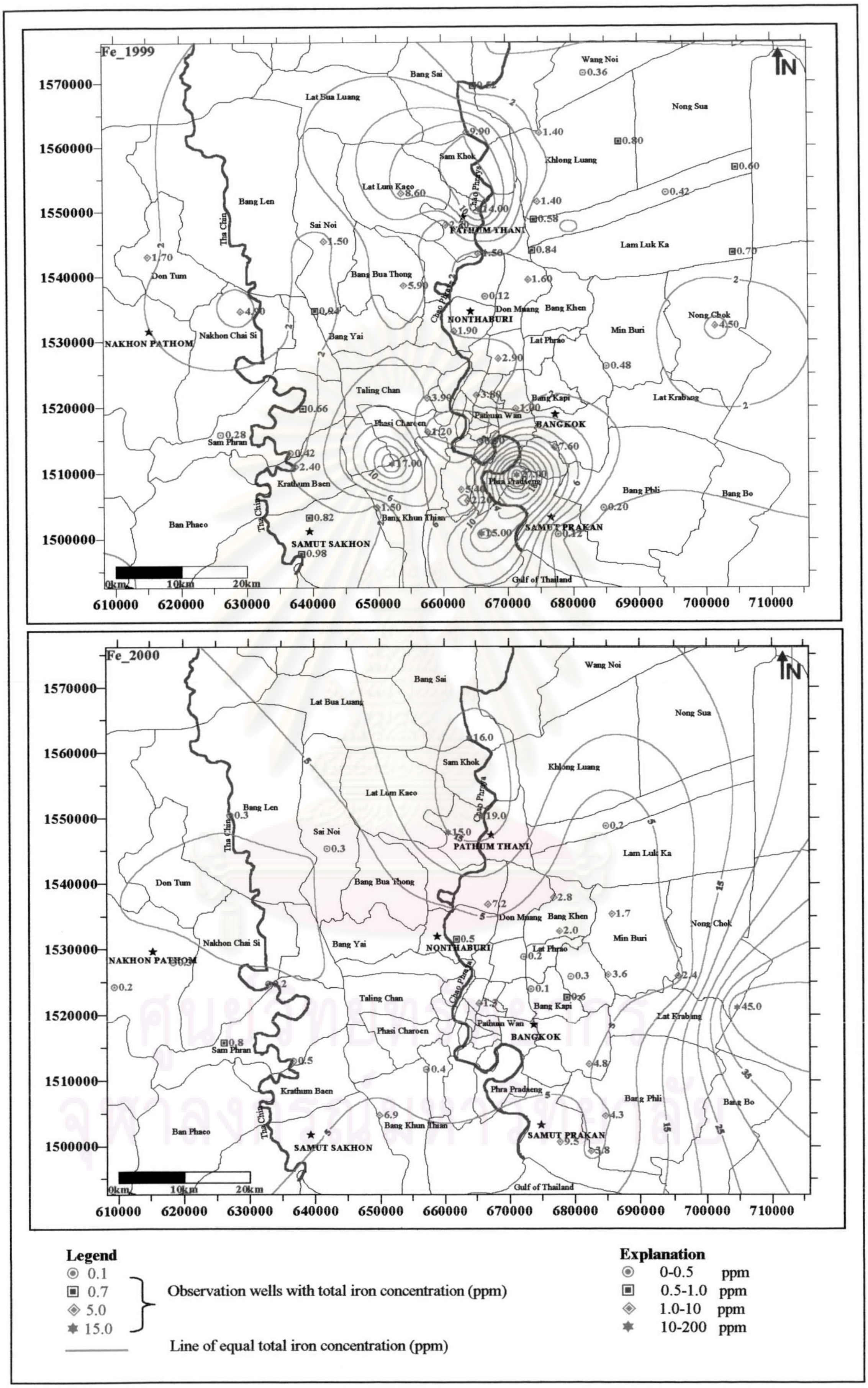


Figure 4.97 Total iron concentration in 1999-2000

4.4.2 Hydraulic Properties

The hydraulic properties of the NL, the transmissivity, the hydraulic conductivity and the specific capacity, are calculated via pumping tests. These aquifer parameters are computed under partial penetration from equation 2.8 and plotted time–corrected drawdown curve to calculate the transmissivity and hydraulic conductivity (Appendix III-a). Table 4.2-4.3 depicts the transmissivity and the hydraulic conductivity of the 17 pumping test wells.

4.4.2.1 Transmissivity

The transmissivity can be calculated from the constant rate-pumping test as well as from the recovery test (Driscoll, 1986). The transmissivity, obtained from the constant rate-pumping test, varies from 26 to 1,300 m^2/day (Fig. 4.98). Whereas the transmissivity, obtained from the recovery test, varies from 40 to 2,200 m^2/day. From Table 4.2 the transmissivity cannot be calculated from the well number 3, 4, 5, 7, 8, and 9 due to the flow rate is obtained from the step-drawdown test. The same is true for the well number 6,11 and 15, the transmissivity cannot be calculated neither, even though the flow rate is obtained from constant rate pumping test, due to the fluctuation of water level during the test period. However, it is known that the time-recovery plot for the pumped well is more accurate than its time-drawdown plot because during the recovery period, water-level measurements can be made without being affected by pumping vibration and momentary variation in the pumping rate (Driscoll, 1986). In 1979, Freeze and Cherry reported that transmissivity greater than 0.015 m^2/s (or 1,926 m^2/day) represent good aquifers for water well exploitation and Driscoll (1986) also stated that if an aquifer has a transmissivity of less than 1,000 gpd/ft (or 12.4 m^2/day), it can supply only enough water for domestic wells or other low-yield uses. When the transmissivity is 10,000 gpd/ft (124 m^2/day) or more, well yield can be adequate for industrial, municipal, or irrigation purposes. Hence, the calculated transmissivity, from Table 4.2, indicates that the NL aquifer is adequate for industrial, municipal, or irrigation purposes.

Table 4.2 The transmissivity from pumping tests

Well No.	UTM Grid		Transmissivity (m^2/day)	
	Easting	Northing	Constant Rate	Recovery
1	635625	1511550	237	-
2	674300	1564972	1235	2080
3	685200	1551825	-	166
4	693550	1518700	-	1114
5	693650	1529900	-	672
6	675949	1541535	-	2282
7	686465	1552088	-	154
8	668400	1552300	-	878
9	685925	1541175	-	117
10	700685	1548175	26	41
11	674256	1547045	-	1255
12	674200	1535200	1358	1991
13	675500	1536550	75	-
14	675600	1536175	517	-
15	677250	1531000	-	52
16	676200	1518650	32	-
17	678975	1533450	702	481

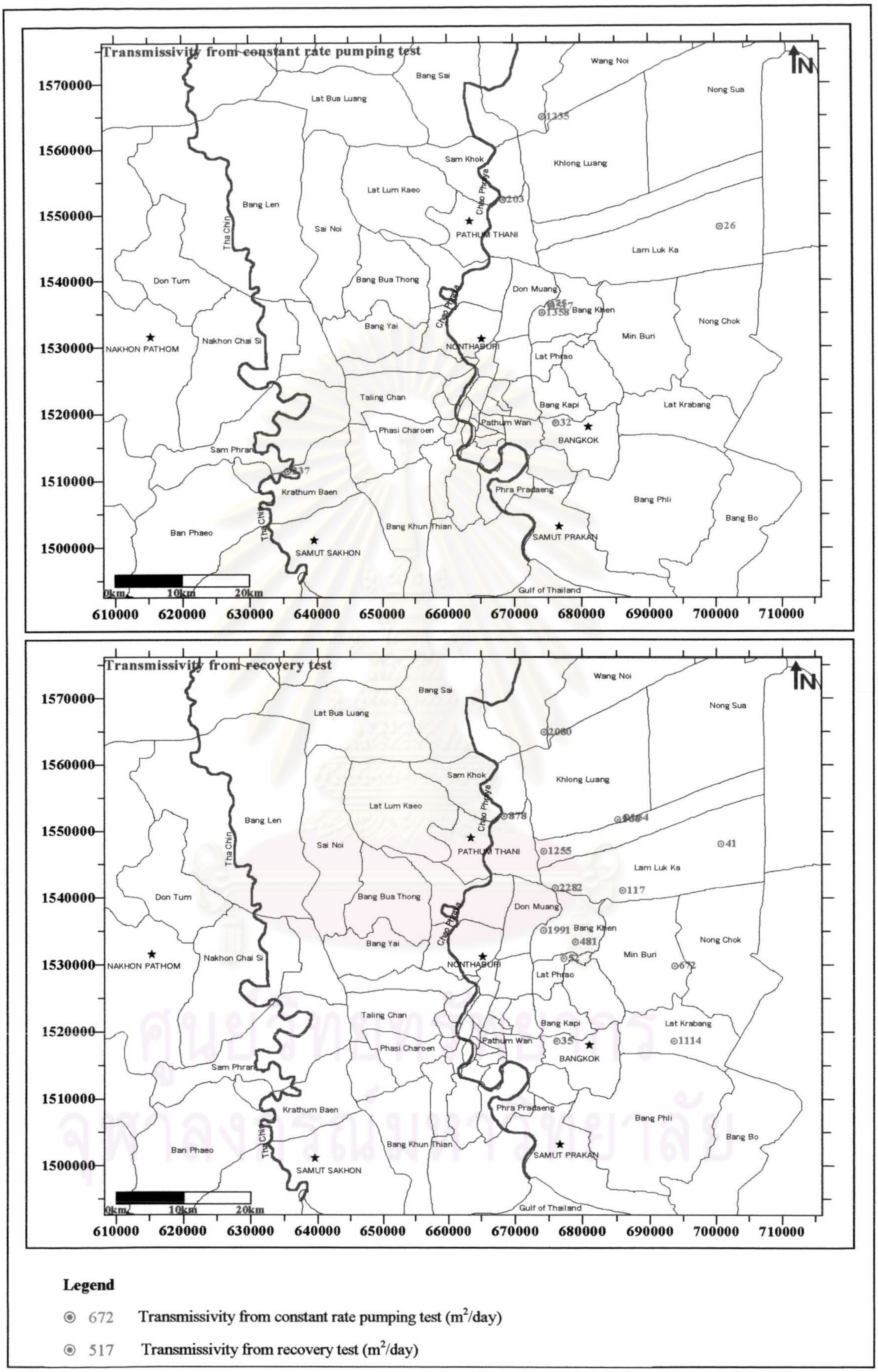


Figure 4.98 Transmissivity from field pumping test

4.4.2.2 Hydraulic Conductivity

The hydraulic conductivity can be calculated by using the formula as follow:

$$T = Kb$$

Where

T = Transmissivity (m^2/day)

K = Hydraulic conductivity (m/day)

b = Saturated thickness, in m. (at the pumping well)

Therefore;

$$K = T/b$$

Table 4.3 The hydraulic conductivity from pumping tests

Well No.	UTM Grid		Thickness of aquifer at a pumping well m.)	Hydraulic Conductivity (m/day)	
	Easting	Northing		Constant Rate	Recovery
1	635625	1511550	18	13	-
2	674300	1564972	24	51	87
3	685200	1551825	15	-	11
4	693550	1518700	10	-	111
5	693650	1529900	9.9	-	67
6	675949	1541535	16	-	143
7	686465	1552088	12	-	13
8	668400	1552300	17	-	52
9	685925	1541175	14	-	8
10	700685	1548175	14	2	3
11	674256	1547045	6.4	-	196
12	674200	1535200	32	42	62
13	675500	1536550	30	3	-
14	675600	1536175	42	12	-
15	677250	1531000	21	-	2
16	676200	1518650	19.1	2	-
17	678975	1533450	25	28	19

The hydraulic conductivity, obtained from the constant rate-pumping test, varies from 2 to 51 m/day. Whereas the hydraulic conductivity, obtained from the recovery test, varies from 3 to 195 m/day (Fig. 4.99). Table 4.3 depicts the variation of the hydraulic conductivity of the NL aquifer. As the hydraulic conductivity is rather low and not corresponding to the transmissivity which is due to the variation of the thickness of the NL aquifer.

4.4.2.3 Storativity; S

The storativity is defined as the ability of aquifer to release water from storage. In unconfined aquifer, S is the same as the specific yield of the aquifer. In confined aquifer, S is the result of compression of the aquifer and expansion of the confined water when the head (pressure) is reduced during pumping (Driscoll, 1986). From this study cannot be calculated the storativity because the field pumping test is the production well which cannot be specified the area to calculate the storage per unit of aquifer and pumping test obtained from single well test so storativity value cannot be defined. Therefore, the storativity of the Nakhon Luang aquifer is complied from the previous study which demonstrated in Table 4.4.

The hydraulic properties of the NL aquifer from this study is rather different from the previous study of others organizations (Table 4.4), compiled by AIT and DMR, in 1982 but if comparing the hydraulic properties of the aquifer to the data from pumping test in the observation well (Table 4.5 and Fig. 4.100) which is conducted by the AIT and DMR, 1982, it is appeared that the values of the hydraulic properties from this study are corresponding to the figures of the AIT and DMR.

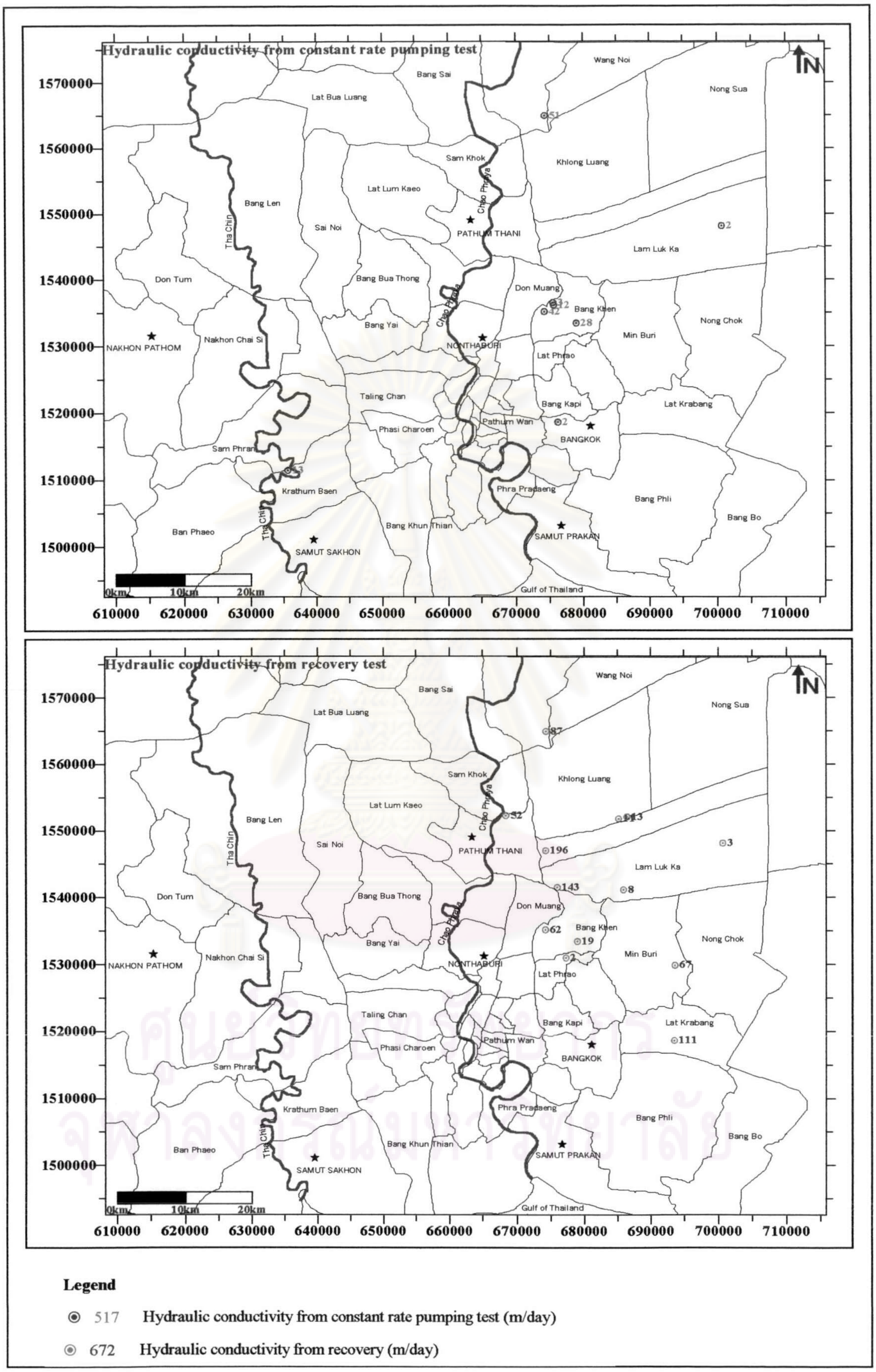


Figure 4.99 Hydraulic conductivity from field pumping test

Table 4.4 Hydraulic properties of the Nakhon Luang aquifer complied by AIT and DMR, 1982

Location	Transmissivity ; T (m^2/hr)	Permeability (m/hr)	Storativity ; S
Bangkok Area	67-115	2.2-3.4	1×10^{-4} to 2×10^{-4}
Wat Phai Ngoen	65	2.21	1×10^{-4}
Lumphini Park	100	3.4	2×10^{-4}
Pak Kret	110	2.55	-
The DMR	50	2.65	2.6×10^{-4}
Bang Bua	130-155	3.45	2.03×10^{-4} to 3.4×10^{-3}
Well 89/1	67	-	-

Table 4.5 Transmissivity of the Nakhon Luang aquifer conducted by AIT and DMR, 1982)

Well No.	Easting	Northing	Transmissivity (m^2/day)	
			From recovery data	From residual drawdown data
NL004	663884	1505820	112	68
NL005	654109	1538551	120	111
NL007	677700	1532800	875	-
NL006	689100	1540700	13	12
NL009	665764	1543431	423	380
NL010	673100	1503900	100	34
NL011	680100	1519900	458	337
NL012	665126	1569478	1737	1447
NL018	649800	1504800	748	641
NL019	636700	1513100	9	6
NL020	654800	1531600	223	446
NL024	639500	1503300	1093	984

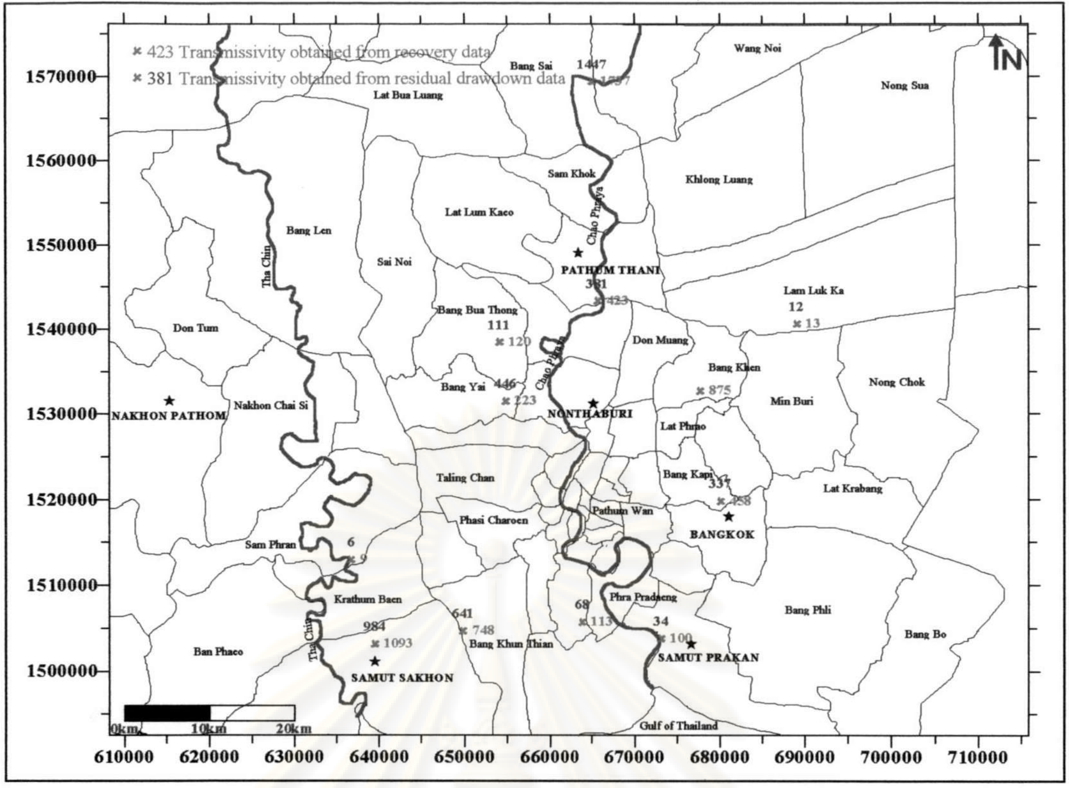


Figure 4.100 The transmissivity from the pumping test of the AIT and DMR, 1982

4.4.2.4 Specific Capacity

The specific capacity varies from 0.27 to 40 m^3/hr/m (Appendix III-b). Specific capacity varies with the time of the pumping period, longer pumping time, and the smaller of specific capacity. That means the drawdown increases while the discharge rate decreases. Moreover, the maximum specific capacity attained varies directly with the percent of aquifer screened (Ramnarong, 1976)

As the results of data analysis are shown a lot of variation, thus, the specific capacity can be classified into 2 levels:

Level	Specific Capacity (m^3/hr/m)
I	0-5
II	5-50

The level I represents the area of adequate water for domestic wells or other low-yield uses whereas the level II represent the area of adequate for industrial, municipal, or irrigation purposes (assume the level as the transmissivity level from Driscoll, 1986). The **level I** is concentrated in the central part of west bank of the Tha Chin River and the northeastern part of the Chao Phraya River while the **level II** is distributed in the southwest bank of the Tha Chin River as well as along the east bank of the Chao Phraya River. However, it would be remarked here that the area between the Tha Chin River and the Chao Phraya River is lack of data, thus, the specific capacity of this area can only be an intellect guess as the level II (Fig. 4.101) because the hydrogeologic cross sections indicated that the thickness of the aquifer in the central part of the area is quite consistence.

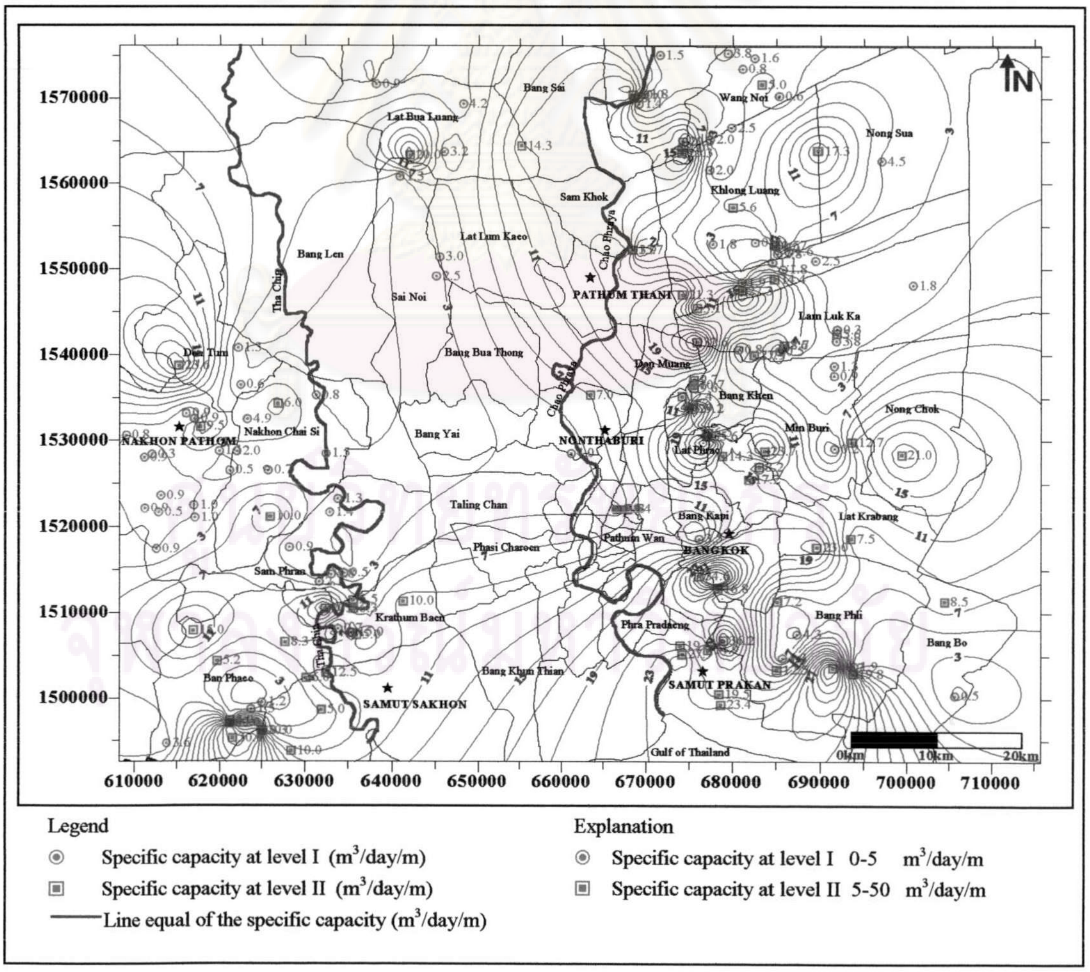


Figure 4.101 The specific capacity from the pumping test

However, the hydraulic properties obtained in this study might be too high or too low from the actual hydraulic properties because of two parameters. The first is the drawdown should be obtained from at least one observation well as it is no effects from the pumping of water. The second is the effects of the recharge and boundary of aquifer.

a. Recharge Effects

The time-drawdown curves in well no. 9, 12, 13, 14, 15, 16 are quite horizontal due to recharge effects. This condition can be explained, as the drawdown will be stabilized when recharge within the zone of influence of the pumping well equals the rate of discharge of the well. That means no further lowering of the water levels will occur as pumping continues at a constant rate. The time-drawdown curve then becomes horizontal (Fig. 4.102). Whereas the same recharge effects can be applied to the condition of well no. 6 and 11 as the recharge rate within the cone of depression is lower than the pumping rate of the well which affecting to the slope of the time-drawdown curve, at the second part of log cycle, is not horizontal but flatter than the initial slope (Fig. 4.103). It indicates that the cone of depression is enlarging more slowly than during the first part of log cycle of the pumping period.

b. Impervious Boundary Effects

The time-drawdown curves in well no. 10 is quite steep (Fig. 4.104) due to boundary effects. Normally, an impervious boundary will effect directly to the drawdown as it will control the flow paths of recharge i.e. the flow paths will not uniform or flow equally from all direction toward a well. When the expanding cone of depression encounters an impervious boundary on one side of a pumped well, it can expand no further in that direction and no additional water can be supplied from that locality. Thus the cone must expand and deepen more rapidly in all other directions to maintain the yield of the well (Driscoll, 1986). It is quite contrasts to the recharge effects.

In this study, the transmissivity and the hydraulic conductivity, are calculated from Δs based on the first part of log cycle of the time-drawdown curve. Thus, the transmissivity calculated from the flatter slope will be higher than the actual value. In contrast, the transmissivity calculated from the steeper slope will be lower than the actual value.

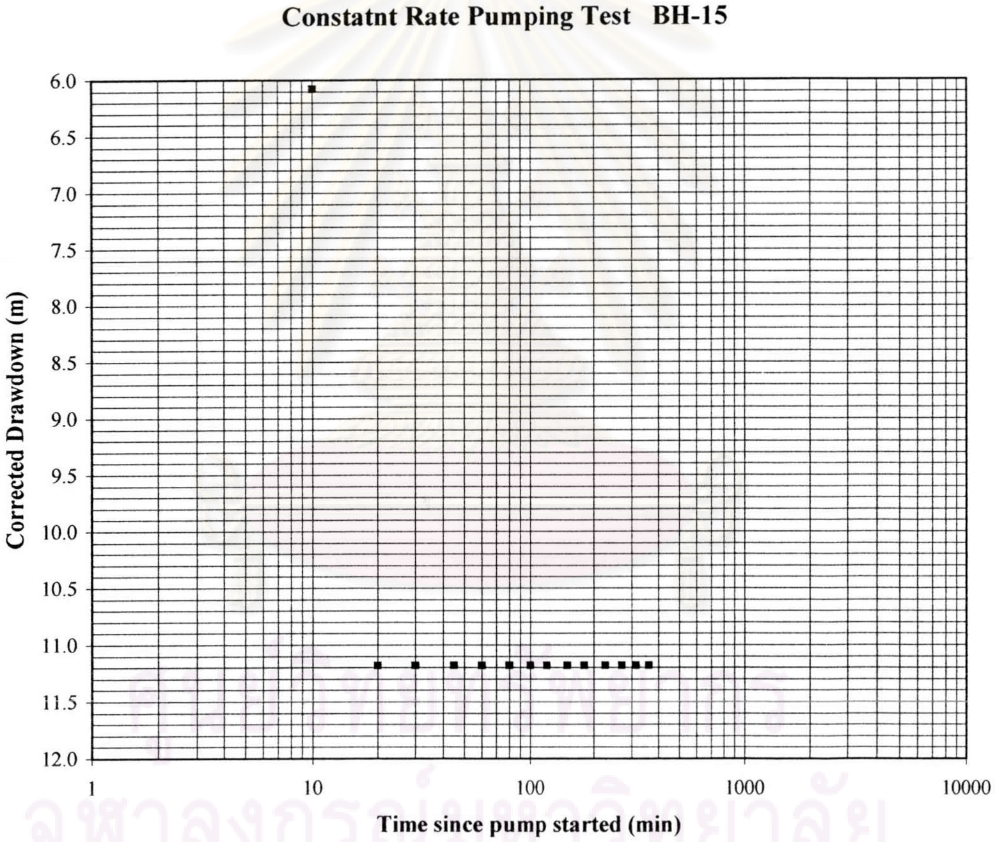


Figure 4.102 The recharge effects to the time-drawdown curve becomes horizontal

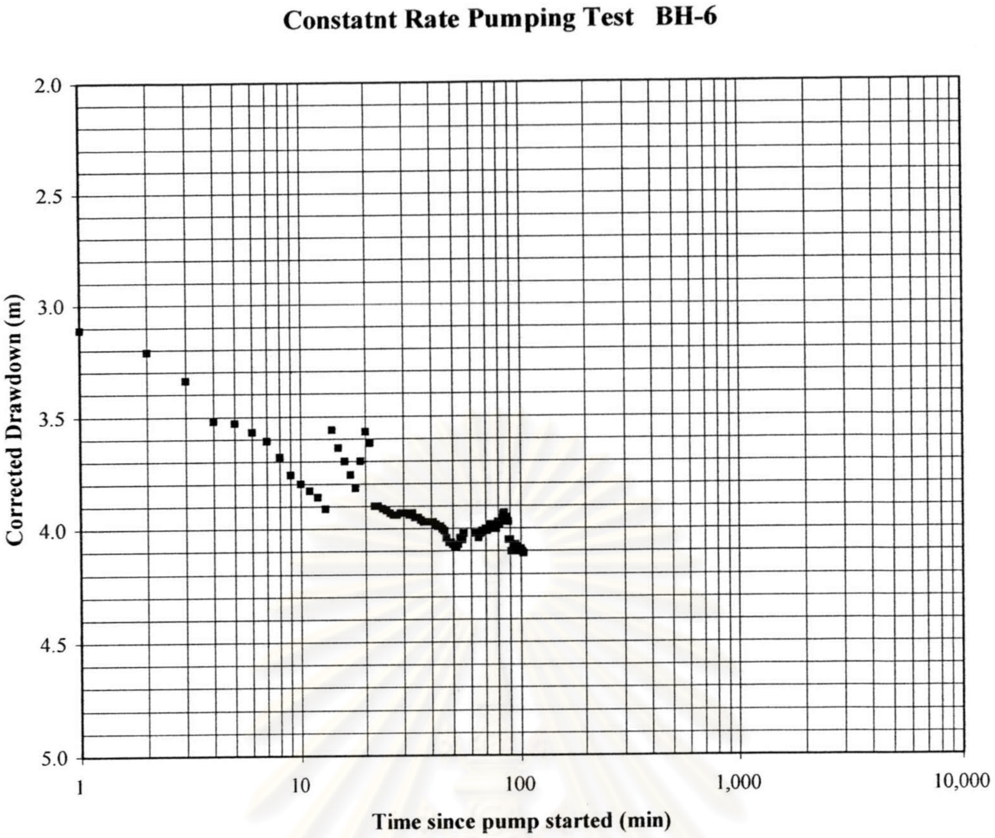


Figure 4.103 The recharge effects to the time-drawdown curve becomes flatten

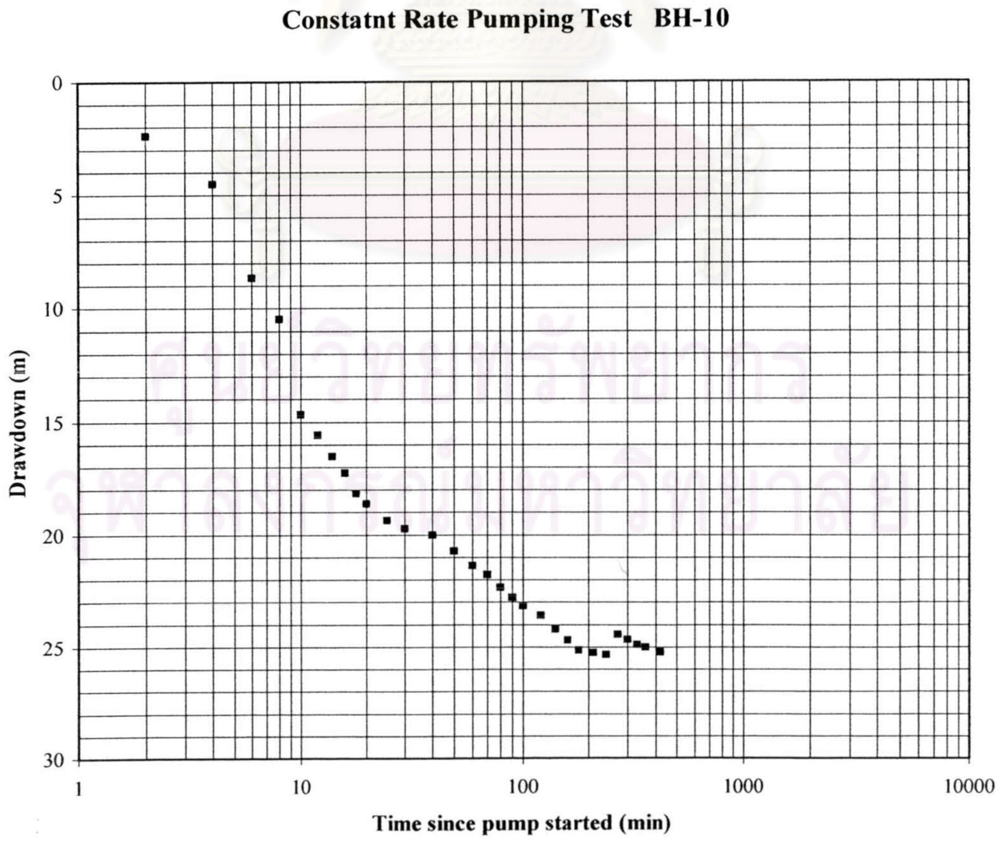


Figure 4.104 The boundary effects to the time-drawdown curve becomes steep

4.4.3 Potentiometric Surface Situation

The potentiometric surface of the NL aquifer in 1997-2000 is shown in Figure 4.105-4.106. A large potentiometric surface depression lower than 70 m below ground surface is at southwestern part of the study area, namely: Amphoe Muang, Samut Sakhon Province and Amphoe Lat Krabang, Amphoe Minburi, Bangkok Metropolis. The potentiometric surface below 50 m. is at the southeastern part: Amphoe Muang, Bang Phli, Samut Prakan Province and the northeastern of Pathum Thani Province: Amphoe Lum Luk Ka, Amphoe Khlong Luang. At present, the potentiometric surface that is drastically decreasing at the Samut Sakhon, Bang Poo, Lat Krabang, and Bang Kradi Industrial Estates. If comparing to the potentiometric surface of the PD aquifer (Fig. 4.107-4.108) and the NB aquifer (Fig. 4.109-110) from 1997-2000, it is shown that the zone of the potentiometric surface lowering of the PD aquifer is concentrated in the east bank side the Chao Phraya River (Amphoe Muang, Amphoe Phra Pradaeng, Samut Prakan Province, Amphoe Pravet, Bangkok Metropolis, Amphoe Lamluk Ka, Pathum Thani Province) and the western part of the area (Amphoe Dontum, Nakhon Pathom Province). While, the lowering zone of the potentiometric surface of the NB aquifer is located in the southwestern part of the area (Amphoe Krathum Baen, Samut Sakhon Province) and the eastern part of the area (Amphoe Lat Krabang, Amphoe Minburi, Bangkok Metropolis and Amphoe Lam Luk Ka, Pathum Thani Province). From this study, the lowering potentiometric zone of the PD aquifer is similar to the NL aquifer while the potentiometric surface depression zone in the NL aquifer and the NB aquifer are resembled. It might be stated that these aquifers are interconnected in those zone, which is corresponding to the hydrogeologic cross sections. They indicated that the interconnection between the PD aquifer and the NL aquifer in this central part further to the northeast of the study area

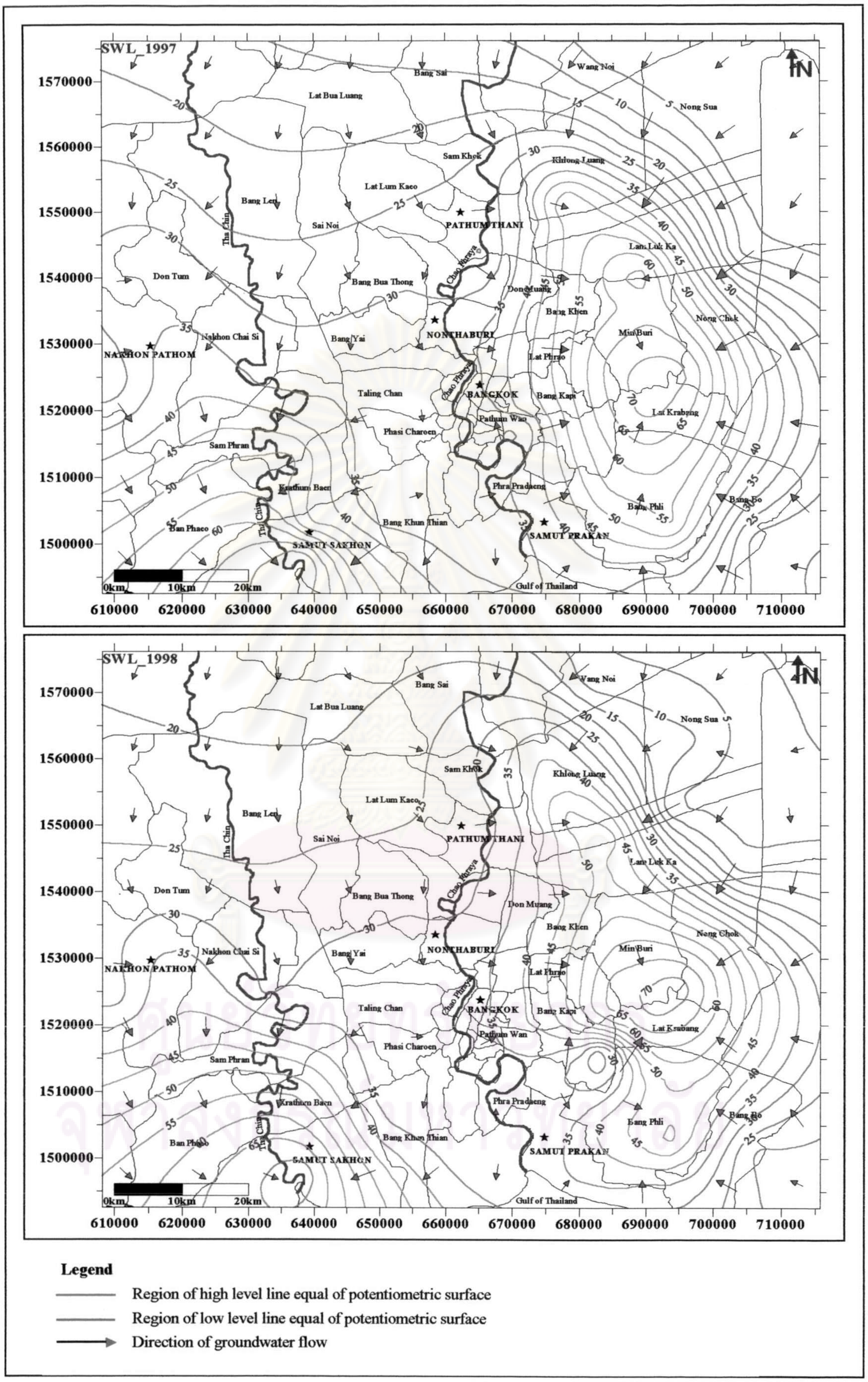


Figure 4.105 Potentiometric surface map of the Nakhon Luang aquifer in 1997-1998

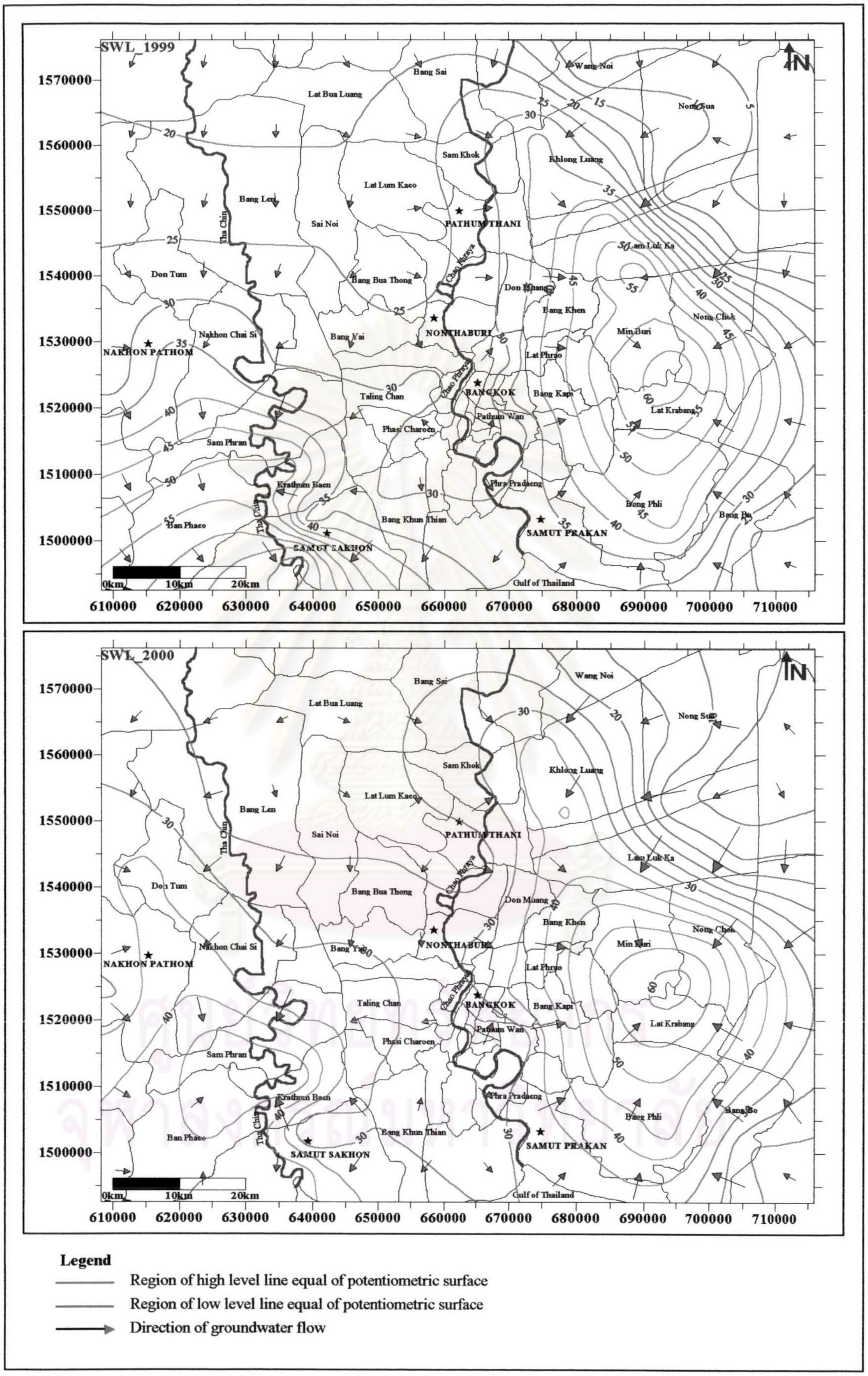


Figure 4.106 Potentiometric surface map of the Nakhon Luang aquifer in 1999-2000

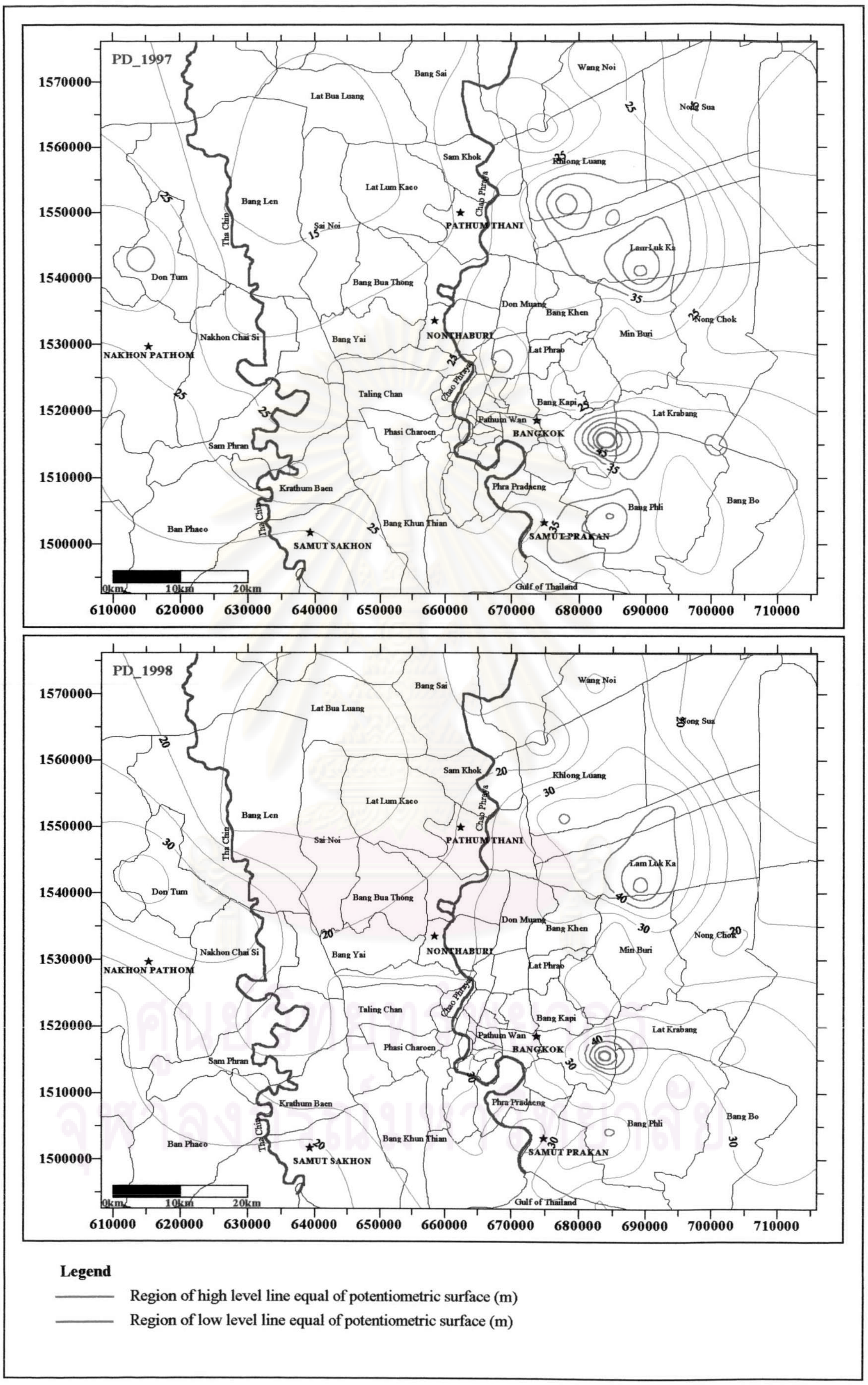


Figure 4.107 Potentiometric surface map of the Phra Pradaeng aquifer in 1997-1998

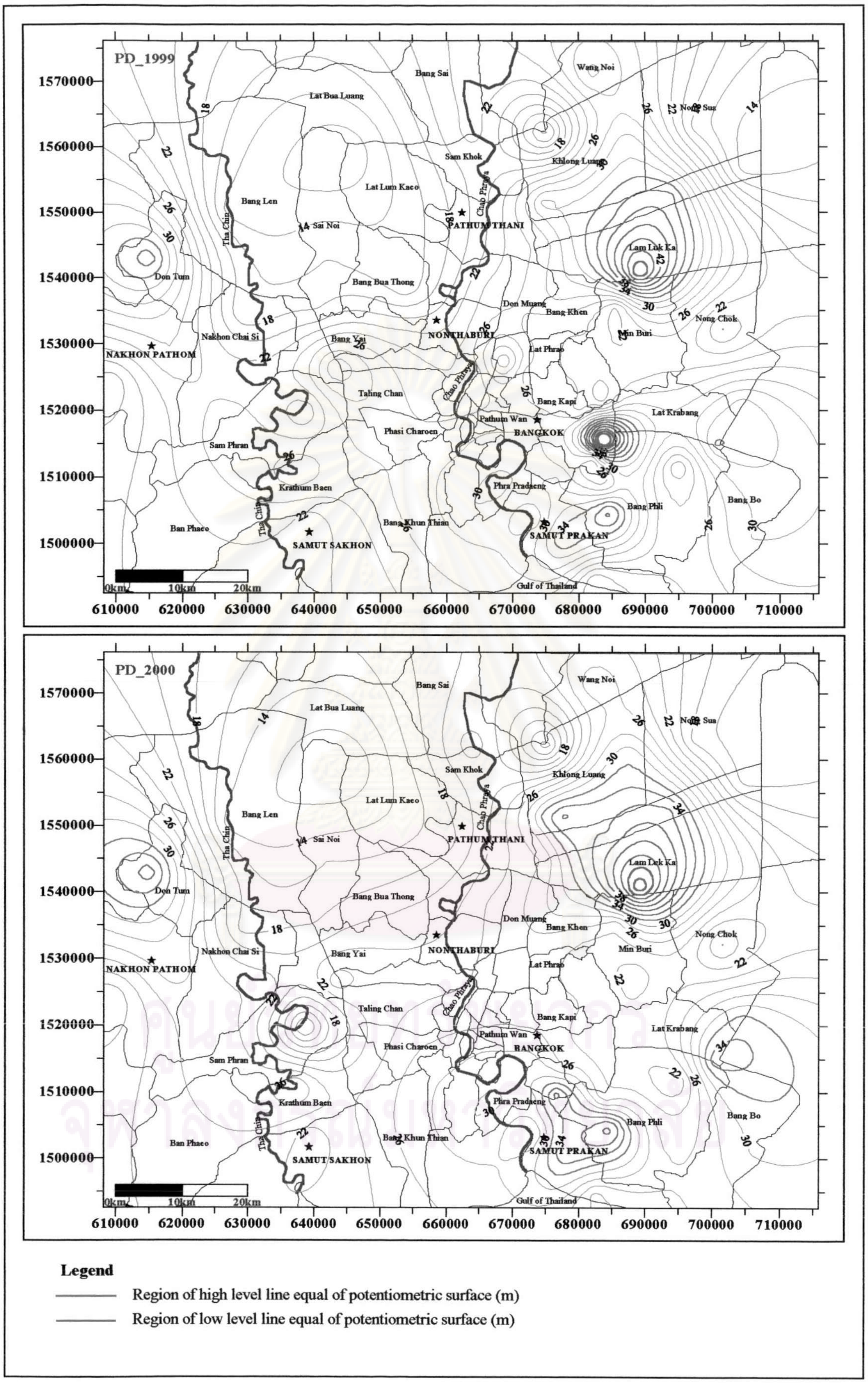


Figure 4.108 Potentiometric surface map of the Phra Pradaeng aquifer in 1999-2000

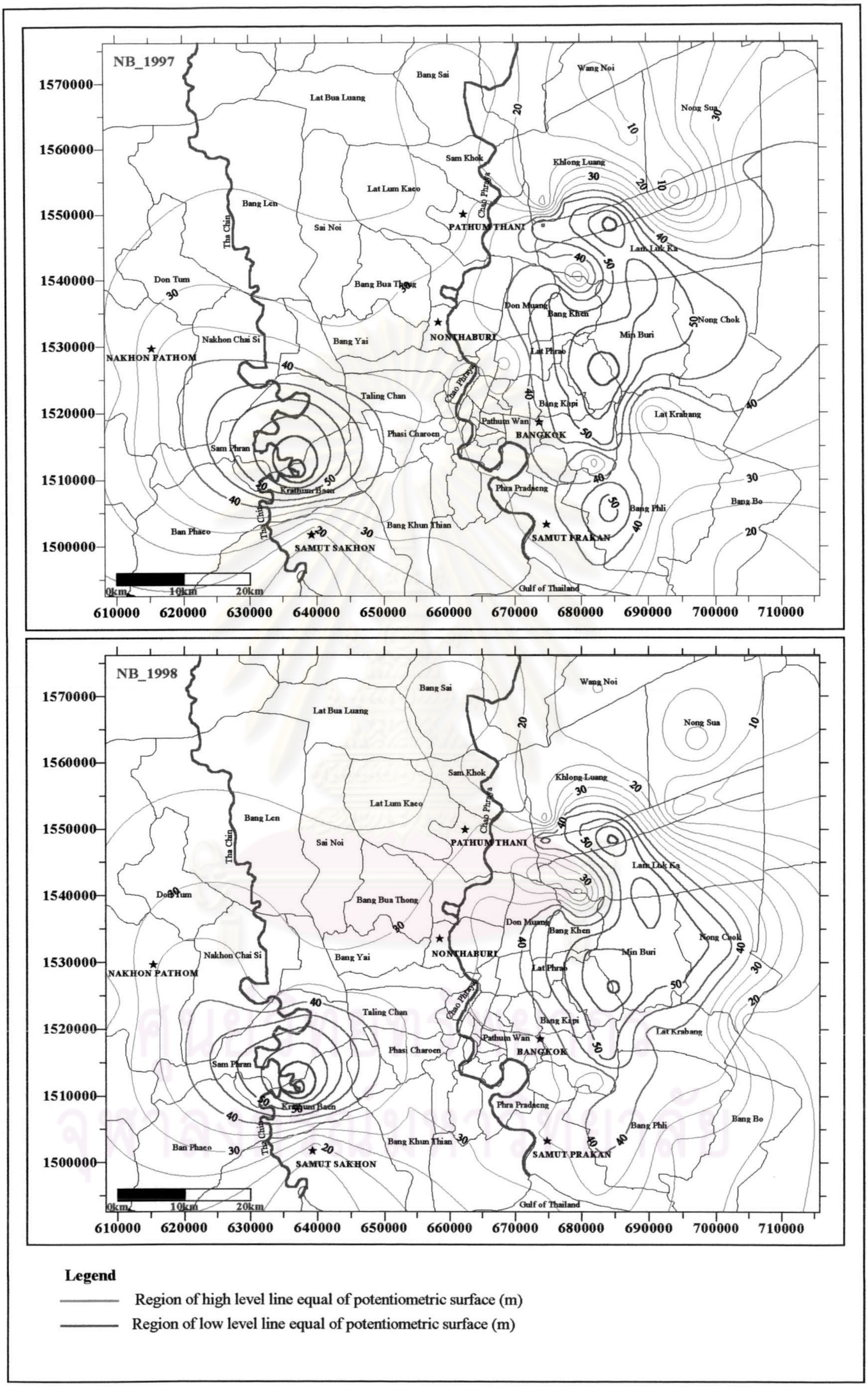


Figure 4.109 Potentiometric surface map of the Nonthaburi aquifer in 1997-1998

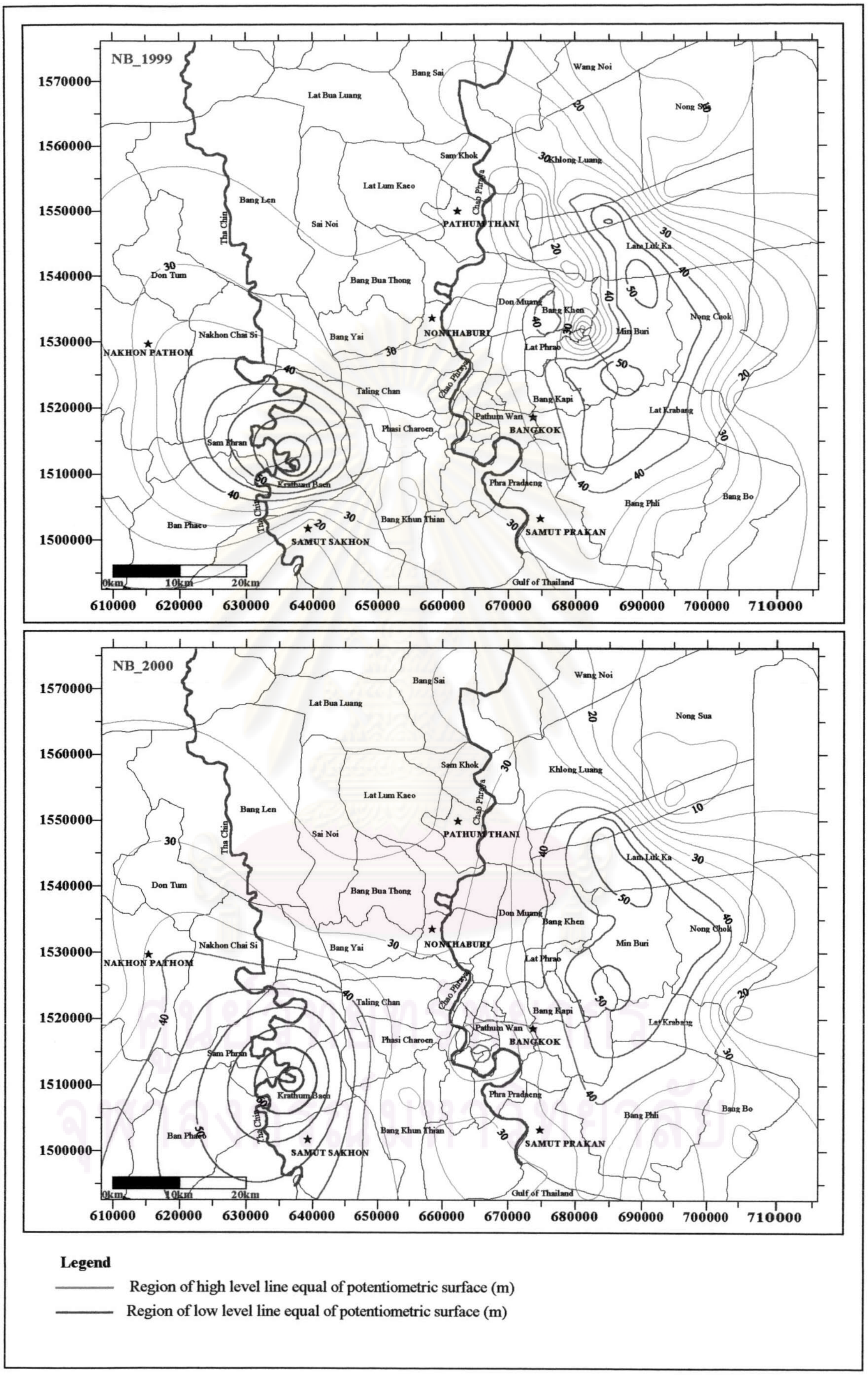


Figure 4.110 Potentiometric surface map of the Nonthaburi aquifer in 1999-2000

(Fig. 4.6 cross section line 2, Fig. 4.9 cross section line 5). Whereas the bottom layers, the compacted and sandy clay, of the NL aquifer is quite thin in the southeastern and southwestern part. Thus, it might be connected between the NL aquifer and the NB aquifer in these zones (Fig. 4.11 cross section line 7).

4.4.4 Land Subsidence

Land subsidence is the lowering of the land surface elevation from changes that take place underground. Common causes of land subsidence from human activity are pumping water, oil, and gas from underground reservoirs; dissolution of limestone aquifers (sinkhole); collapse of underground mines; drainage of organic soils; and initial wetting of dry soils (hydrocompaction). Water in an aquifer is under tremendous pressure from the weight of soil and water above it. When an aquifer is over-pumped, the water that was supporting the soil above it is removed, and the structural integrity of the aquifer is reduced. Without water pressure to support it, the land surface begins to settle and compress in a process. When an aquifer collapses, the pore spaces that once held water are eliminated, meaning that the storage capacity of that aquifer is lost forever. Subsidence can appear as a small local collapse or as broad regional lowering of the land surface height.

According to the previous study up to now, it is indicated that the study area has been subjected to land subsidence, in the past as well as nowadays. This occurrence is very often experienced in areas which heavily dewater occurs in the groundwater reservoir and also occurs within the soft clay and the definite evidence of the land subsidence which is caused by overpumping that was found in subsidence areas over the globe is the protrusion of the well. It is however worth noting that in the area this subsidence has reached severe proportions. For example: at

Ramkhamhaeng University, the subsidence is approximately one meter as observing over the last 24 years since started in 1978 up to the present.

Causes of Land Subsidence. In Bangkok and its surroundings there are two main causes of the problem:

1. Overpumping of groundwater. The water level or piezometric pressure of the various water bearing sand layers (or aquifers) is drawn down due to the overpumping of groundwater. As a result, the *pore water pressure* in the sand layers, and also in the surrounding clay layers, decrease. This lowering of the pore water pressure results in compression of those sand and clay layers. Since the clay layers are more susceptible to compression than sand layers, they are largely responsible for the rate and magnitude of this cause of land subsidence.

2. Loading and settlement of the upper clay layer. The upper clay layer (better known as the "Bangkok Clay") is a very soft and weak type of clay. Due to construction of roads, buildings and bridges the pressure on the surface increases. This process is known as *surcharge loading*. The other process involved, *settlement*, is the process of loading of the clay due to its own weight. Both loading and settlement are the causes of the compaction of the clay layer. On the coarse grained clastic compaction mechanism, while the local piezometric pressure is lowered to couple with horizontal flowing fluid that created the differential pressure upon grains. The differential pressure occurs might be able to create loose grains to rotate and bring about the compaction.

It is very difficult to determine the rate and magnitude of these two causes. It can be stated that loading is a more local process, while the process of land subsidence due to overpumping affects a much larger area. Moreover, it should be remarked here that after a certain period of time the process of loading stops, while the land subsidence due to overpumping of groundwater continues for a much longer time span.

The consequences of such severe land subsidence which are observed in the study are as follow:

1. Damage to and destruction of the infrastructure such as the foundations of buildings, buried pipelines, wastewater sewers, roads and bridges, sinking of the reference benchmarks, and rupture of the water wells casing.

2. Disturbance of the local natural water system, for instance extended and more intense flooding by river or seawater, intrusion of salt water to the aquifers, disturbance and deterioration of the existing rainwater drainage system.

3. Reduction of the hydraulic properties due to the layers of aquifer and aquitard compaction.

Most of effects of subsidence are irreversible. Loss of elevation due to subsidence is permanent. Even if when water levels in an aquifer are restored to their original levels, the clay layers will not regain their previous thickness.

The data used in land subsidence analysis were the data that was collected by the DMR from 1992 to 2000. The data collected can be subdivided into 2 types. The first one is the 72 reference points at the depth of the NL aquifer that are used to support the interpretation of subsidence of the NL aquifer. However, it would be remarked here that the obtained data can be used or referred within a certain limit due to a lot of fluctuation in terms of quantity and quality. Whereas, the second one is 169

Benchmarks at the depth of one meter. Figures 4.111-4.114 show the intensity of land subsidence in 1992-2000 and Figure 4.115 shows the rate of land subsidence (1998-2000) at 1-meter depth of Benchmarks. From the analysis it reveals that the severe subsidence is concentrated in Amphoe Muang , Samut Sakhon Province, Amphoe Muang and Amphoe Bang Phli, Samut Prakan Province, Amphoe Lat Krabang and Amphoe Minburi, Bangkok Metropolis, Amphoe Lam Luk Ka, Pathum Thani, Amphoe Phutha Monthon and Amphoe Nakhon Chai Si, Nakhon Pathom Province. However, the Groundwater Acts and the Sufficient Water Supply were launched by the DMR since 1983. This remedy affects the land subsidence rates of the central and eastern parts is decreasing whereas the area affected by land subsidence expanded to the southwest, the southeast and the west of the Chao Phraya River.

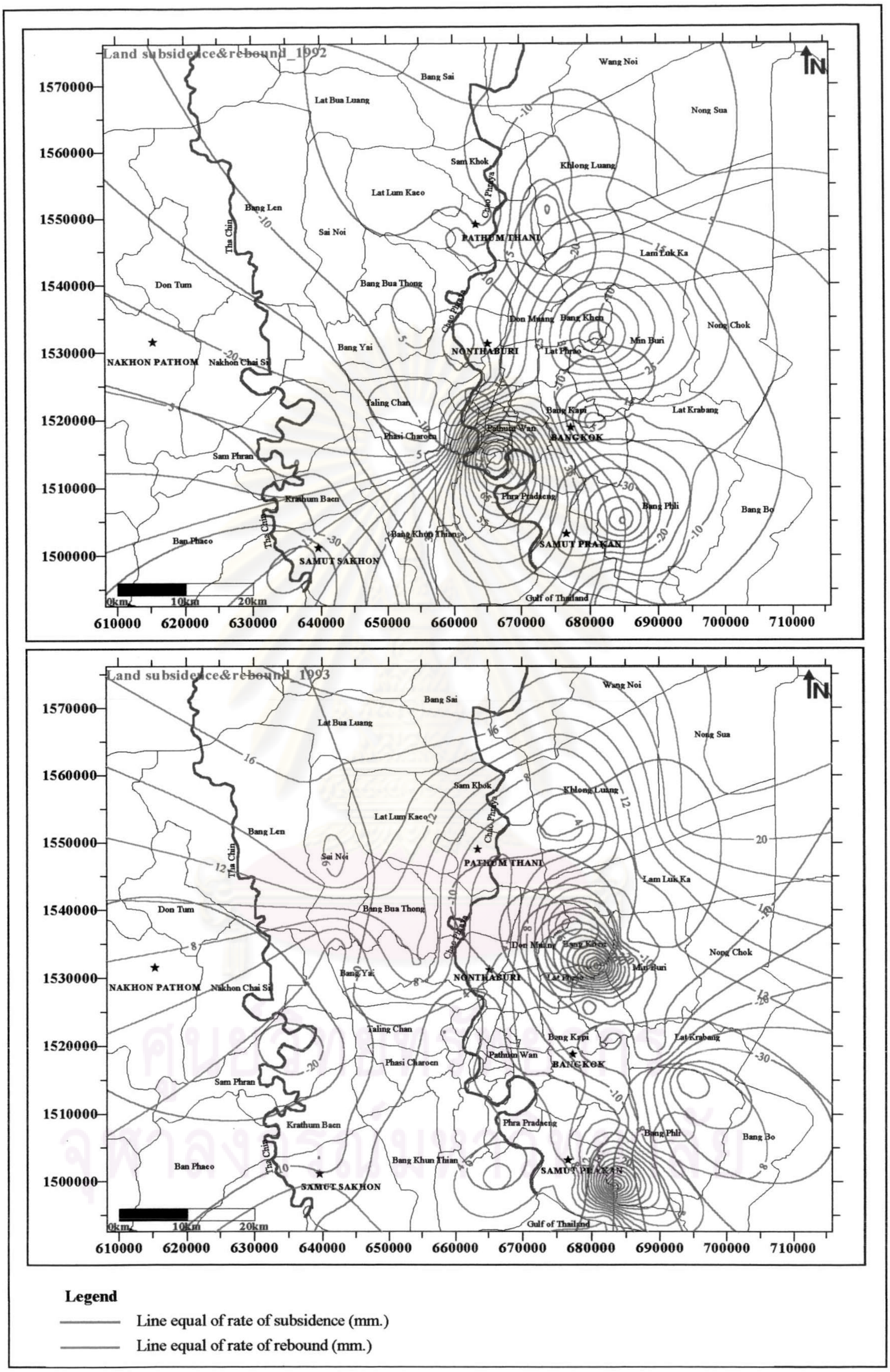


Figure 4.111 Rate of land subsidence and rebound map of the reference points at the depth of the Nakhon Luang aquifer in 1992-1993

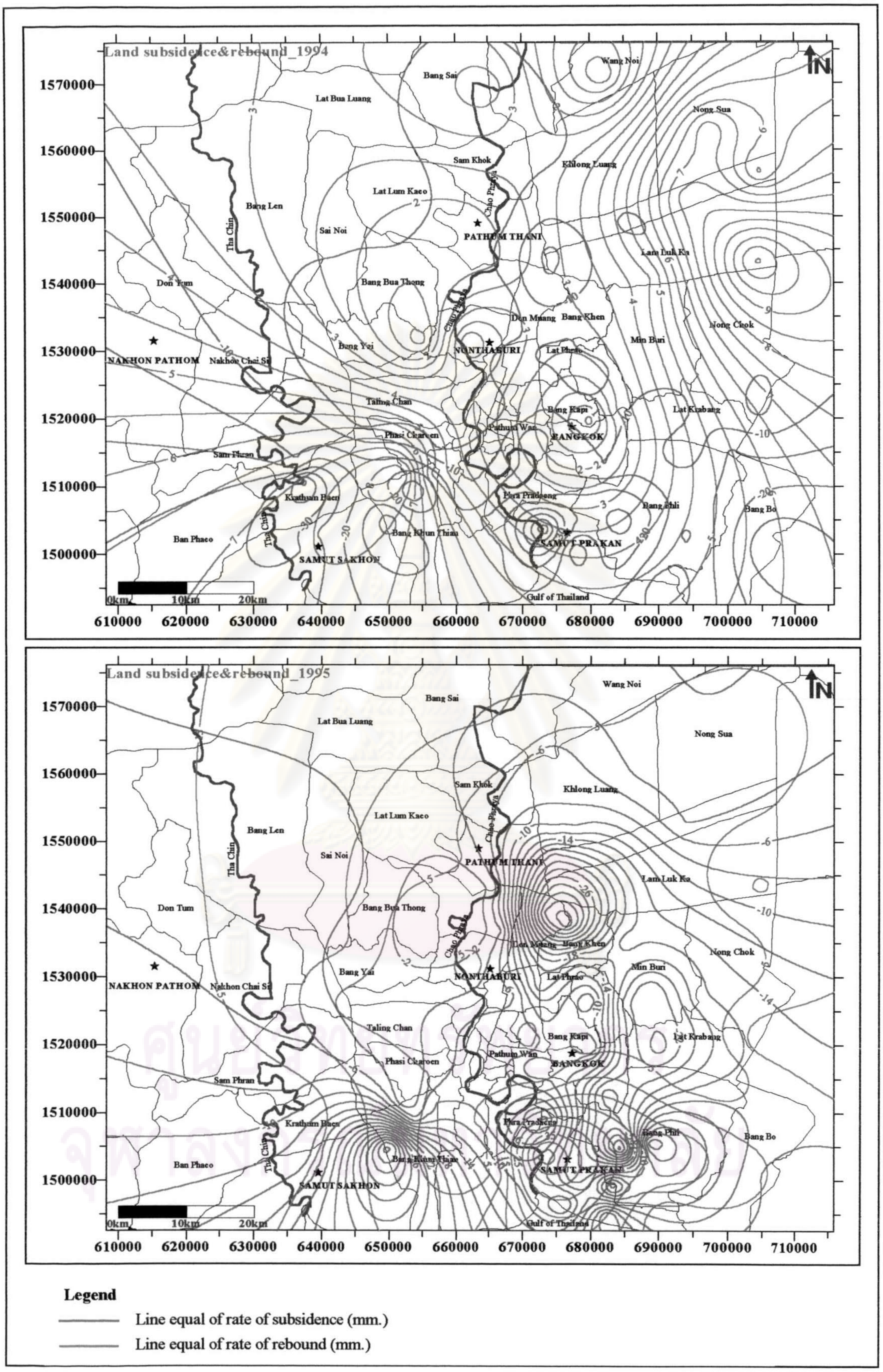


Figure 4.112 Rate of land subsidence and rebound map of the reference points at the depth of the Nakhon Luang aquifer in 1994-1995

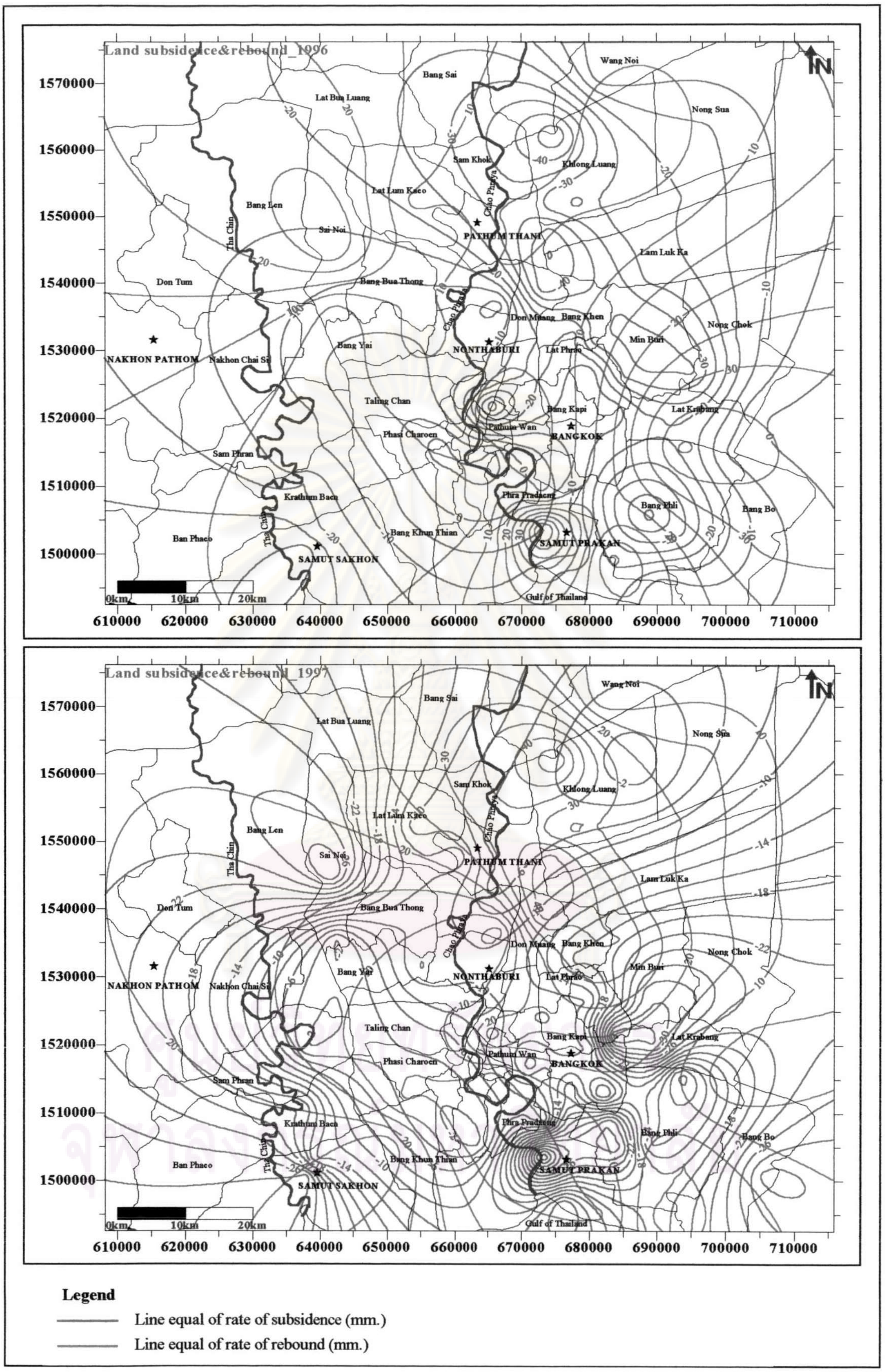


Figure 4.113 Rate of land subsidence and rebound map of the reference points at the depth of the Nakhon Luang aquifer in 1996-1997

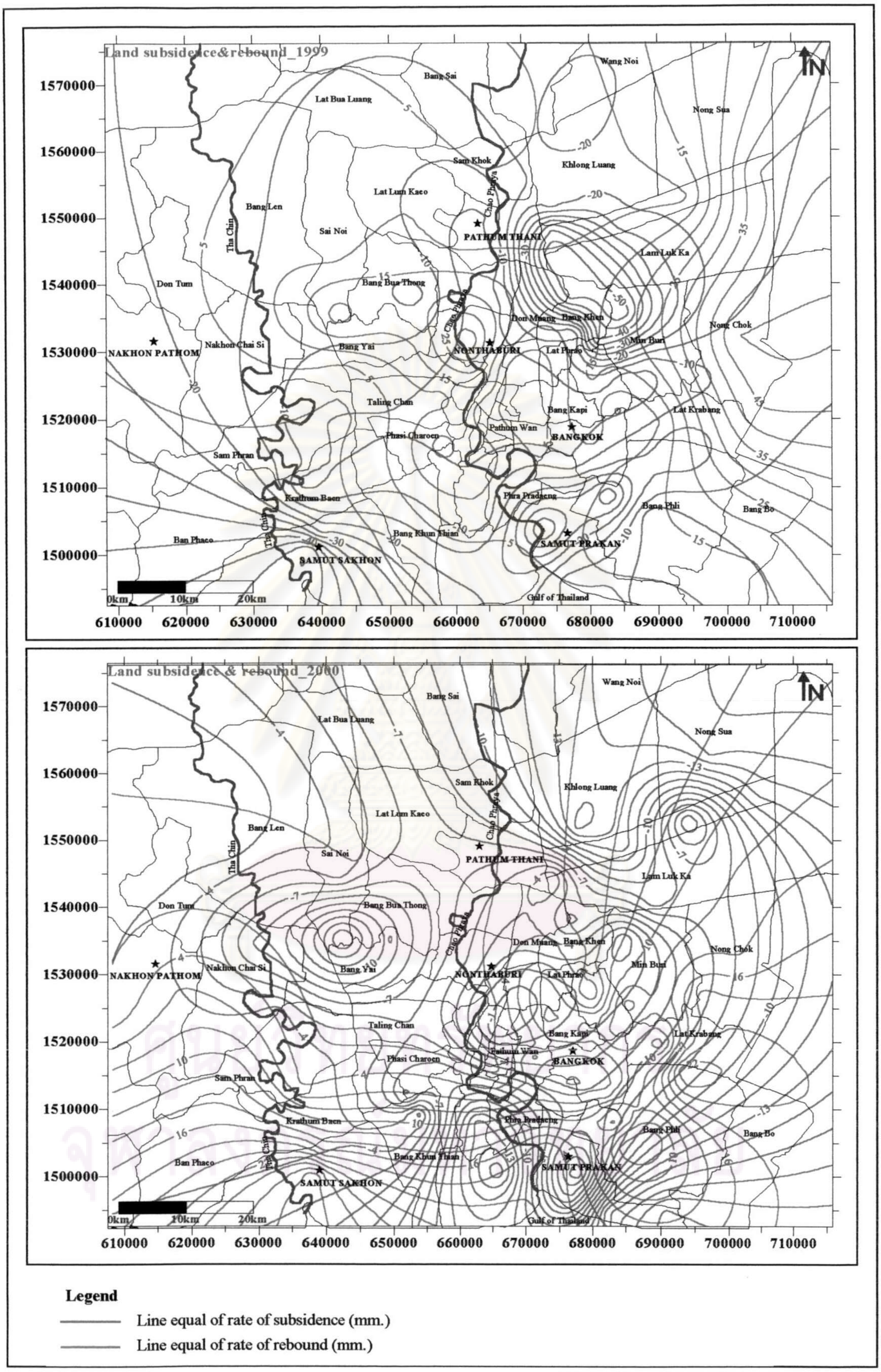


Figure 4.114 Rate of land subsidence and rebound map of the reference points at the depth of the Nakhon Luang aquifer in 1999-2000

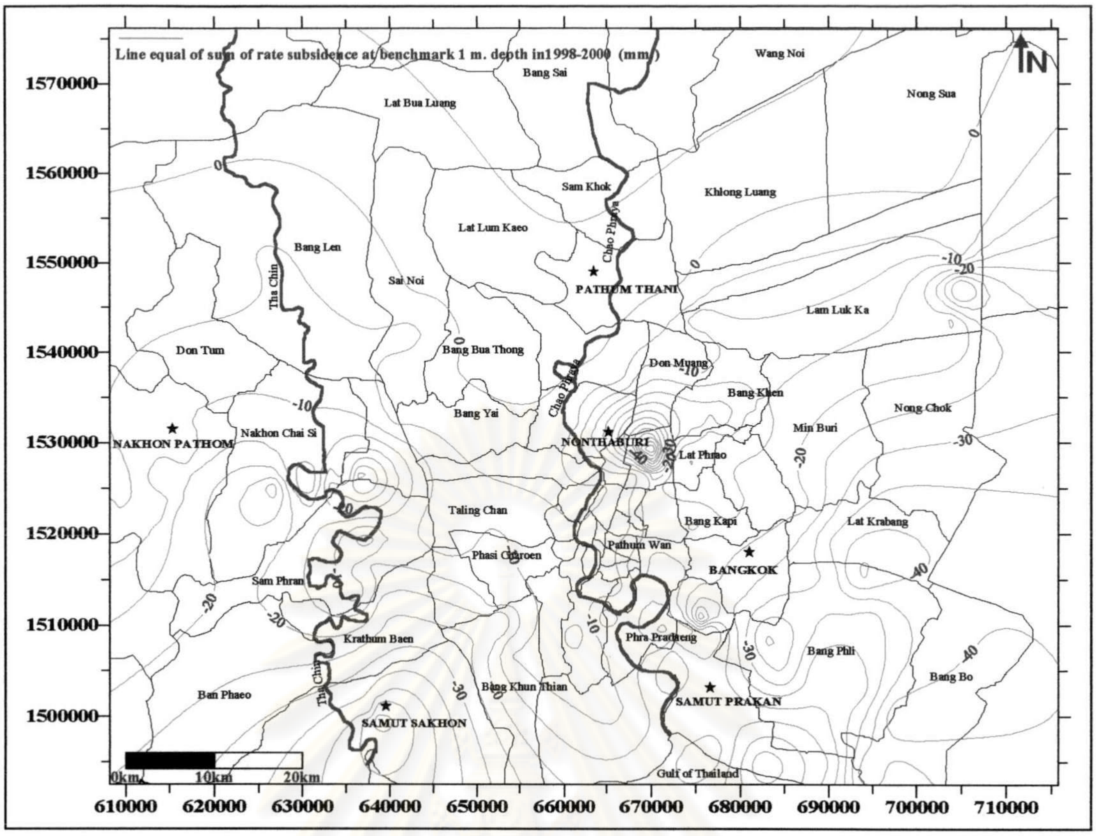


Figure 4.115 Rate of land subsidence of benchmarks at 1 m. depth of ground surface in 1998-2000

4.4.5 Groundwater Recharge

From the results of the Cabon-14 analysis (Buapeng, 1992), it is concluded that the age of groundwater from the Nakhon Luang aquifer ranges from 11,000 ± 3,100 to 16,900 ± 2,700 years. It is found that the oldest groundwater is in the eastern area of Bangkok with an approximately 40,000 years. Factually, the groundwater recharges from the north to the south, hence, the groundwater in the south is older than in the north. Generally, the regional groundwater flows from the periphery of the basin toward the Gulf of Thailand. The flow velocity of groundwater in the Nakhon Luang aquifer is approximately 4 cm/day (Chuamthaisong and others, 1982).

4.5 Flow Nets Analysis

The flow rate Q is expressed as the volumetric flow rate per unit time per unit thickness of the flow field, the total flow or total Q (Fig. 4.116) can be expressed as equation 2.19.

$$Q = \frac{K\, nf\, h}{ne}$$

Due to the variation of the hydraulic conductivity in the area, it causes the flow nets analysis encountered the problem. Thus, the solution from those mentioned is tried to make an experiment to study the variability of hydraulic conductivity from each flow tube in order to get the approximate general hydraulic conductivity of the area. These results came out 87 m/day which quite satisfy with the AIT and DMR , 1982 estimate the figures.

The total Q that received from this study is 5,220 m^3/day (see in Appendix IV) which covering an approximately area 1,612 square kilometers.

Since the average thickness of the NL aquifer is 50 m.

Thus Q total = 5,220 x 50

= 261,000 m^3/day

From hydrogeologic cross sections, it is found that there are the variations of thickness and sedimentary facies through out the area and so the hydraulic properties, which are used in flow nets analysis. Factually, that, the data on the hydraulic properties of the western part of the area are quite a few. Hence, it is not solid enough to be used in flow net analysis. Thus, the Q total will be assumed to be the representative of the whole area.

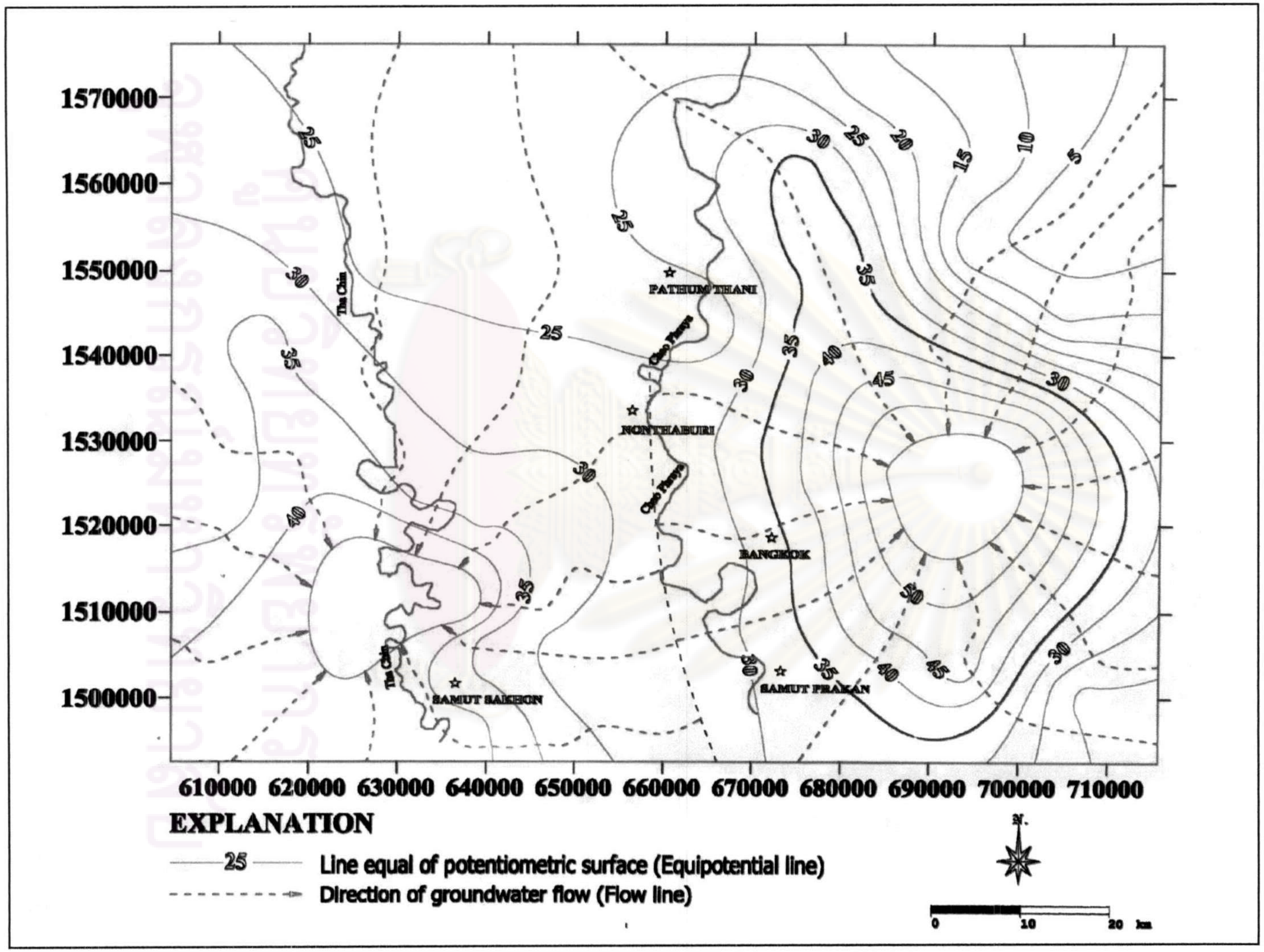


Figure 4.116 The flow nets of the Nakhon Luang aquifer in 2000

As the flow nets analysis is one in 4.96 of the total area, hence, the Q total can be computed as:

$$= \quad 4.96 \ \times 261{,}000 \ m^3/day$$

$$= \quad 1{,}294{,}560 \ m^3/day \ \sim 1{,}295{,}000 \ m^3/day$$

The possible total Q is equal **1,295,000 m^3/day** that are obtained from the Nakhon Luang aquifer covering an area **8,000 square kilometers.** In comparison with the data of the Q total quantity of groundwater, collected by the DMR in 2000, from the Bangkok Metropolitan area and its vicinity is 2,265,435 m^3/day (excluding Phra Nakhon Si Ayutthaya Province), the possible total Q obtained from flow nets analysis on the NL aquifer when compare with the total groundwater extracted is **57 %.**

The total Q that mentioned above is presented as the **maximum production**, which exploited from the NL aquifer. From the another idea for the possible **minimum production**, the low side angle the flow nets mentioned represent the amount of 261,000 m^3/day for the East flow nets, which collected groundwater from half of the study area. For another half area on the west that present with incomplete flow nets due to lesser data available. The incomplete flow nets could be designed to account for 2/3 the amount of 261,000 m^3/day which withdrawal from the east nets, which will be closed to 174,000 m^3/day. So the daily withdrawal from the whole study area can be abstracted from the flow nets as **435,000 m^3/day** from the minimal amount produced from the NL aquifer.