CHAPTER 11

Groundwater Environment in Bangkok and the Surrounding Vicinity, Thailand

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11.1 INTRODUCTION

Bangkok is one of the megacities of Southeast Asia. It occupies the southern part of the Lower Central Plain (LCP) in Thailand (Figure 11.1), covering an area of about 10,300 km^2, with a total population of 11 million. Due to its fast-growing economy, rapid urbanization, poor planning, and failure of its authorities to prevent land development for various uses (e.g., residential, industrial, and commercial), the metropolitan area and its vicinity are susceptible to serious problems in water supply, sewerage, transportation, waste disposal, and other related problems.

Bangkok and its vicinity (seven provinces including Bangkok) receive water supplies from three authorities namely, the Metropolitan Waterworks Authority (MWA), Provincial Waterworks Authority (PWA), and the municipal/local authority. The MWA draws solely from surface water to supply water within its service area, which is the inner city (Bangkok, Samut Prakan, and Nonthaburi provinces). However, water supplied in the area outside the inner city (four provinces), which is the service area of the PWA and municipal/local authority, comes from both surface and groundwater.

Traditionally, water supplies for this area relied heavily on groundwater. The MWA gradually switched the source from groundwater to surface water and stopped using groundwater as a source of water in 2001. Even though water for domestic use is supplied by the MWA, groundwater is still an important source of water used to support the fast-growing economy in business and industry because of its lower cost and better quality. Groundwater abstraction in the area gradually increased and reached 2.4 million cubic metres per day (MCM/d) in 2000, which far exceeded the safe yield of 1.25 MCM/d for the area.

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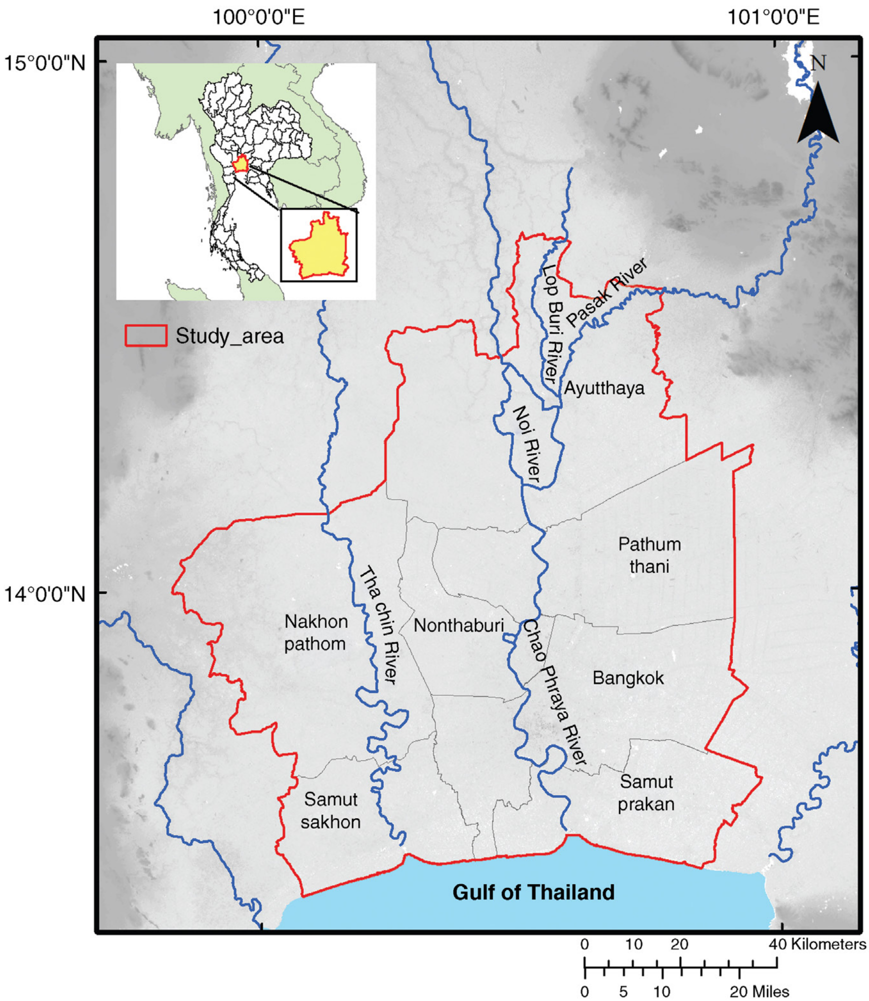

Figure 11.1 ***Morphology of Bangkok and its Vicinity, Thailand.***

The overexploitation of groundwater has prominently induced land subsidence in the area. Throughout the history of groundwater management, government authorities in Thailand have put a lot of effort into the introduction of regulatory measures to control groundwater pumpage in this area, aiming to reduce the rate of land subsidence. Some of the efficient tools introduced to achieve that goal were the declaration of critical zones, introducing the conjunctive use of groundwater and surface water to business and industry, and pricing groundwater competitively for the supply of piped water to the public.

This chapter aims to compile all the available data, information, and knowledge to assess the status of the groundwater environment in Bangkok and its vicinity by analyzing: driver (D), pressure (P), state (S), impact (I), and response (R) (DPSIR), as well as their extent and interrelationships. The results will be useful for all stakeholders and policy makers, improving their understanding of the situation and serving as a basis for decision-making processes regarding the sustainable utilization of groundwater in the long term.

11.2 ABOUT THE STUDY AREA

Bangkok is located on an extremely flat, fertile, and low-lying elevation in the southern part of the LCP in Thailand. The city has been developed on the banks of the Chao Phraya River; the main river of the country, flowing through Bangkok from the northern highlands and discharging into the Gulf of Thailand 25 km south of the city (Figure 11.1). The LCP consists of the fluvial and marine deposits of the Chao Phraya Delta. It is bounded by a mountain range on the west, upper plain on the north, and the Khorat Plateau on the east. Fans and terraces occupy the west and east marginal zones of the plain. The delta that hosts Bangkok is formed by deposits of seaward tidal flat and brackish clays, marine clays, and a tidal zone. Although largely an alluvial plain, inliers of older rock occur around margins of the plain, concealed beneath a fault-bounded basin of Cenozoic nonmarine sediments (Ridd et al., 2011). Bangkok's climate is monsoon with three seasons a year: wet season from May to July with the arrival of the southwest monsoon in early May; cool season from November to February with the start of the northeast monsoon around November; and summer season from March to May. The temperature in Bangkok is high at around 30°C for most of the year but often reaching in excess of 40°C.

The total population of the study area in 2013 was about 11.3 million. With a total land area of about 10,300 km2, the average population density ranges from 300 to 3600 persons/km2 with an overall average of 1100. The population in Bangkok accounts for more than half of the total population in the study area. The total gross provincial product (GPP) of the study area in 2013 was BHT5180 billion (baht), representing approximately 44% of the country's GDP, 64% of which was generated in Bangkok (NESDB, 2013).

The study area covers the groundwater control areas of Bangkok and its six surrounding provinces, consisting of underlying unconsolidated sediment with a multiaquifer system. The top soil consists of soft to stiff, dark gray to black clay, also known as "Bangkok clay," ranging in thickness from 20 m to 30 m. Beneath the Bangkok clay layer are unconsolidated and semiconsolidated sediments intercalated by clay layers and containing large volumes of voids for water storage, forming several confined aquifers, distinguished into eight layers as follows: (i) Bangkok aquifer (BK, 50 m zone), (ii) Phra Pradaeng aquifer (PD, 100 m zone), (iii) Nakhon Luang aquifer (NL, 150 m zone), (iv) Nonthaburi aquifer (NB, 200 m zone), (v) Sam Kok aquifer (300 m zone), (vi) Phaya Thai aquifer (350 m zone), (vii) Thonburi aquifer (450 m zone), and (viii) Pak Nam aquifer (550 m zone) (JICA, 1995; Ramnarong, Buapeng, 1992) (Figure 11.2). The aquifers are highly productive, consisting of well-sorted sand and gravel. The wells tapped to these aquifers can yield over 1000 m^3/d.

11.3 DRIVERS

Population growth, urbanization, tourism, and industrialization are the main drivers of the groundwater environment in Bangkok and its vicinity. The status of indicators for drivers and other components of the DPSIR framework are tabulated in Table 11.1.

11.3.1 Population Growth

Bangkok witnessed a slow increase in population until 1975. Subsequently, in the last 40 years, the city has changed a lot due to the flow of tourists and international activities. The population of the city was only 1.5 million before Bangkok became a destination for American servicemen during the Vietnam War. The rural poor were attracted by US dollars and development began. The city grew to more than 8.5 million in 25 years. This represents nearly 15% of the country's population and is 40 times the size of any other city in Thailand (Haapala, 2002).

Trends in annual population and growth rate are shown in Table 11.2. The growth rate in Bangkok Metropolis from 1960 to 1970 was 4.8%, which increased to 5.2% between 1970 and 1980 and started to decrease over subsequent decades. While the annual growth rate in Bangkok decreased from 1980, the growth rate in its vicinity increased substantially from 1.7% in 1960 to 4.7% in 2000. The total population in both Bangkok Metropolis and its vicinity increased continuously from 3.3 million in 1960 to 11.1 million in 2010. This shows that the Bangkok suburbs are growing faster than the city center. The population densities in Bangkok Metropolis and its vicinity areas in 2010 were 3600 and 300–1800 persons/km^2, respectively.

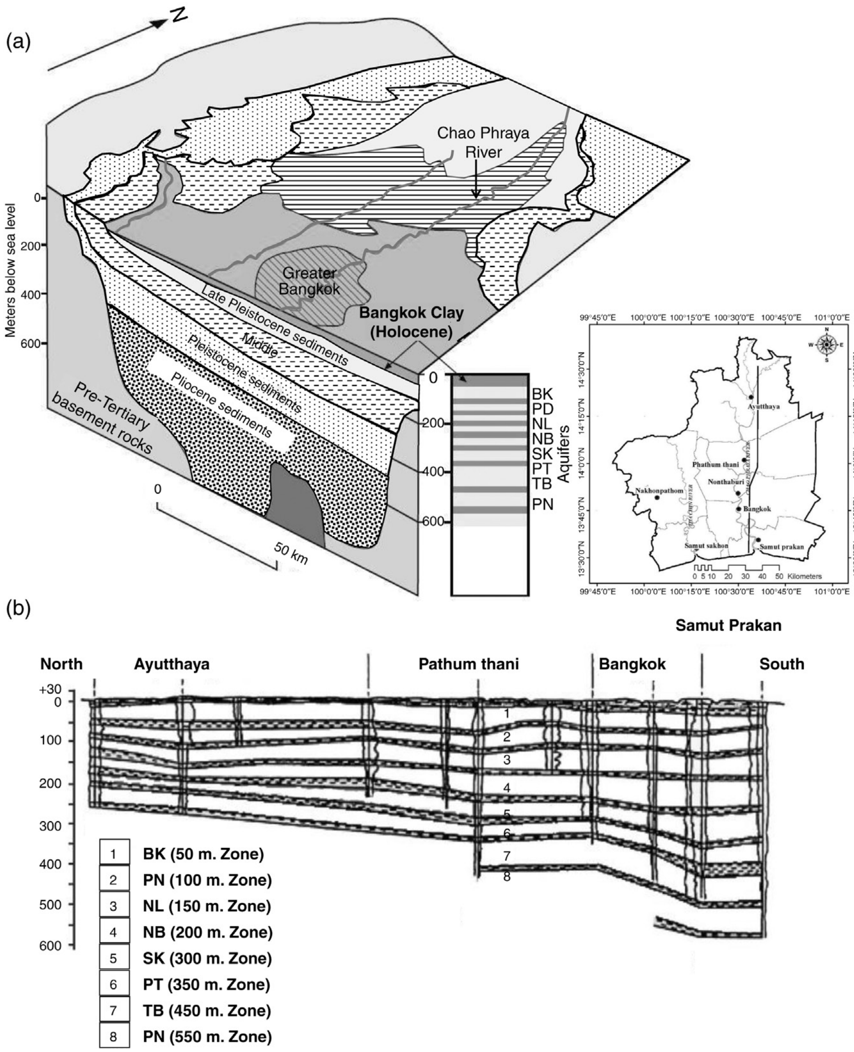

Figure 11.2 (a) Hydrogeological block diagram to show the Lower Central Plain and alluvial aquifer system (Jica, 1995); (b) Hydrogeological cross section in North-South direction to show depths of aquifer system.

11.3.2 Urbanization

Urbanization in Bangkok started in the 1960s. The rapid expansion of Bangkok and its vicinity is depicted in Figure 11.3. This is obviously attributed to the development of infrastructures such as road networks, real estate, land values, as well as an advancing economy, which has resulted in urban

Table 11.1 Status of DPSIR indicators in Bangkok and its vicinity, Thailand

	Indicators	Year 1	Year 2
Drivers	Population growth (see Table 11.2 for details)	Population: 6.6×10^6 (in 1980) Population density (persons/km^2): 782 (in 1980)	11.1×10^6 (in 2010) 3600 in the city core and 300–1800 in its vicinity (in 2010)
	Urbanization (see Table 11.3 for details)	Urban area: 1119 km^2 (in 1988)	3031 km^2 (in 2011)
	Tourism: number of tourists arriving (millions)	7.76 (in 1998)	26.74 (in 2013)
	Industrialization	Share of industry in Thailand's GDP is continuously increasing (Figure 11.6); Thai manufacturing output grew at an average annual rate of 9.7% during 1961–1985 to 13% during 1986–1996; the groundwater development pattern and depression cone in Bangkok and its vicinity also followed the pattern of industrial development in Thailand.	
Pressures	Inadequate surface water resources	Dependence on surface water has increased as indicated by increasing numbers of customers of the MWA from 1.44 to 1.75 million during 2001–2006. The MWA has increased production of surface water resources from 1482 to 1700 MCM/y. Reduced quantity of surface water in per capita terms, inadequate quality, and uneven distribution over the area has encouraged groundwater use and hence put pressure on the groundwater environment of Bangkok's aquifers.	
	Groundwater overexploitation	Groundwater abstraction: 2.3 MCM/d (in 1997)	0.836 MCM/d (in 2015)
		Recharge: 0.6 MCM/d (DGR, 2004) to 0.7 MCM/d (DGR, 2008)	
	Land cover changes	Agricultural area: 8326 km^2 (in 1995)	4996 km^2 (in 2002)

State	Well statistics	Number of production wells: 9077 (in 2001) Well density: 0.89 wells/km^2	7200 (in 2010) 0.70 wells/km^2
	Groundwater abstraction	0.008 MCM/d in 1954, 0.45 MCM/d in 1982, 2.3 MCM/d in 1997, with a drop in abstraction from 1998 onward after control measures were put in place.	
	Groundwater level	2 to −77 m (in 2001)	2 to −67 m (in 2010)
	Groundwater quality	Cl^{-1}: 2.4–4400 mg/l (in 2001)	3.4–9200 mg/l (in 2010)
	Recharge	0.6 MCM/d (DGR, 2004) to 0.7 MCM/d (DGR, 2008)	
Impacts	Land subsidence	0.9–9 cm/y during 1978–1982	1.5–2.4 cm/y (2003–2005); 1.0 cm/y (2006–2012)
	Depletion and recovery of groundwater level	Groundwater level: 50–60 mbgl (in 1977)	20–40 mbgl (in 2013)
	Degradation in groundwater quality	Large areas of high chloride concentration in 1993 were reduced during the period of low pumpage in 2009 (Figure 11.13)	
Responses	Aquifer monitoring	Networks of 150 groundwater level–monitoring wells (Figure 11.14) and land-subsidence–monitoring wells (Figure 11.15) were established in 1978, monitoring frequency being at least twice a year for groundwater level and once for land subsidence	
	Environmental standards and guidelines	Drinking standard for groundwater established by DGR consisting of 27 parameters under the domains of physical quality, chemical quality, toxic elements, and microbiological concentrations (Table 11.6)	
	Groundwater management instruments	Management instruments in the form of regulatory measures, economic measures, and supporting measures adopted since the Groundwater Act 1977. The instruments helped to recover groundwater table and land subsidence in recent years (Section 11.7.3)	

DGR, department of groundwater resources; DPSIR, driver–pressure–state–impact–response framework; mbgl, meters below ground level; MCM, million cubic meters; MWA, metropolitan waterworks authority.

Table 11.2 Population growth of Bangkok and its vicinity, Thailand

	Total population (millions)						Annual growth rate (%)				
	1960	1970	1980	1990	2000	2010	1960 – 1970	1970 – 1980	1980 – 1990	1990 – 2000	2001 – 2010
(a) Bangkok metropolis	2.1	3.1	4.7	5.9	6.3	5.7	4.8	5.2	2.6	0.7	-1
(b) Vicinity (6 provinces)	1.2	1.4	1.9	2.7	3.8	5.4	1.7	3.6	4.2	4.7	4.2
(a) + (b)	3.3	4.8	6.6	8.6	10.1	11.1	4.5	3.7	3	1.7	1.09

Sources: National Statistical Office (NSO), 2010; Ministry of Interior, 2011

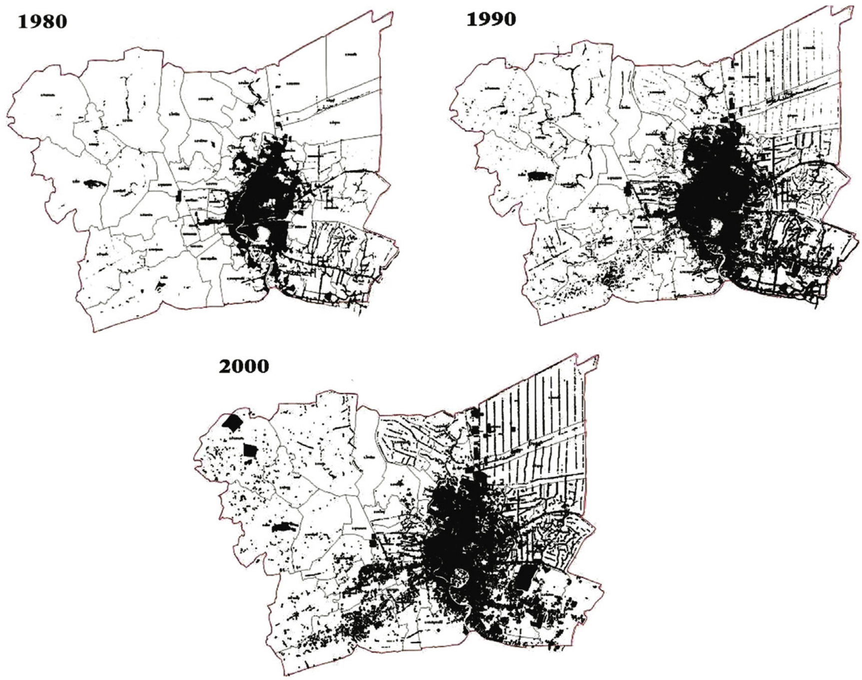

Figure 11.3 ***Expansion of Bangkok and its Vicinity in 1980, 1990, and 2000.*** *Source: Department of Public Works and Town & Country Planning (2008).*

agglomeration into surrounding areas. The urban area of Bangkok Metropolis and its vicinity increased drastically from 39% and 5% in 1988 to 63% and 23% in 2011 (Table 11.3). The Bangkok Comprehensive Plan (BMA, 2006)

Table 11.3 Urban areas of Bangkok and its vicinity

Region	Total area (km^2)	Urban area (km^2)				
		1988	2002	2007	2009	2011
Thailand	513,115		18,246 (3.56%)	23,729 (4.62%)	24,179 (4.71%)	
(a) Bangkok metropolis	1565	610 (39.15%)	842 (53.54%)	897 (57.33%)	993 (63.46%)	1001 (63.93%)
(b) Vicinity (6 provinces)	8750	509 (5.82%)	1110 (12.69%)	1568 (17.92%)	1605 (18.34%)	2030 (23.20%)
(a) + (b)	10,315	1119 (10.85%)	1952 (18.92%)	2465 (23.90%)	2598 (25.19%)	3031 (29.38%)

Source: Land Development Department (2014).

set targets to accommodate a population of 9.3 million in 2002, 10.2 million in 2017, and 11 million in 2022. Approximately 54.5% growth was expected between 1995 and 2015 with urban areas estimated on the basis of agglomeration instead of administrative boundaries (Figure 11.4).

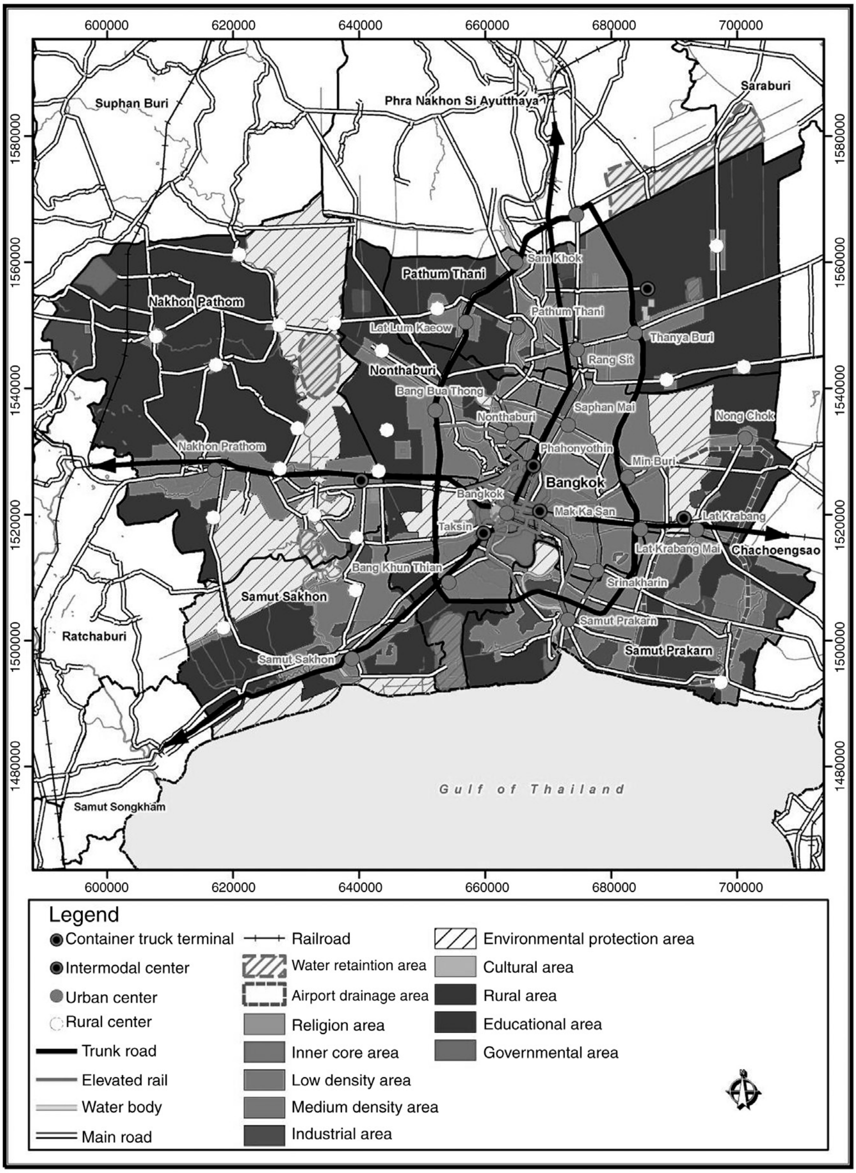

Figure 11.4 ***Land Use of Bangkok, Its Vicinity, and Provinces in 2007.*** *Source: World Bank, 2009 (modified from Department of Public Works and Town & Country Planning, 2008.)*

Bangkok and its vicinity play a fundamental role in the administration and governing of the country. Regional development in the past has enabled the area to attract various developmental activities, including infrastructures, social services, and particularly those relating to economics. The subsequent development resulted in the rapid growth of all activities, with the region being the center for settlement, industry, commerce, and services, including social services. These are key factors attracting labor, industry, and individuals from other regions (MLIT, 2013).

The urban sprawl of the area has led to inappropriate land use, causing various urban problems. There has been rapid growth within the area joining the inner city and urban fringe, creating economic, commercial, industrial, and residential centers in both vertical and horizontal directions. These types of development have problems due to insufficient services and facilities, as well as growth of urban communities along transportation routes in both the urban fringe and suburban areas. Most of these areas are developed into residential quarters, with huge department stores and industrial clusters along the main transportation routes and intersections between main roads.

11.3.3 Tourism

Thailand considers tourism to be a fast track to economic growth. Tourism requires less investment than other industries and is an effective means of creating job opportunities, and increasing local income. This sector contributed an estimated 7.3% to Thailand's GDP in 2012. If indirect benefits are also included, it accounts for 16.7% of Thailand's GDP (WTTC, 2014)

Thailand has devised a tourism-marketing approach, which encourages low, medium, and high-cost mass tourism to nearly all regions of the country. It has become one of the best known, and most sought after, international tourist destinations. On June 1, 2013, *Time* magazine reported that Bangkok was identified as the most visited city in the world by the 2013 Global Destination Cities Index (Pfotenhauer, 1994). Figure 11.5 depicts the trend in the arrival of tourists in Thailand.

Critics claim that tourism promotion in Thailand aims at quantity rather than quality. The explosion of tourism has brought an uneven distribution of financial benefits in favor of large enterprises, while costs are shouldered by local people who have no direct gain from tourist promotion. Worse still are the environmental effects of unbridled tourism development. However, most large hotels are located in the city, which already uses piped water supplies from the MWA or PWA. Therefore, pressure from the tourism industry on water usage, and groundwater in particular, may not be that large in comparison with other cities in Asia.

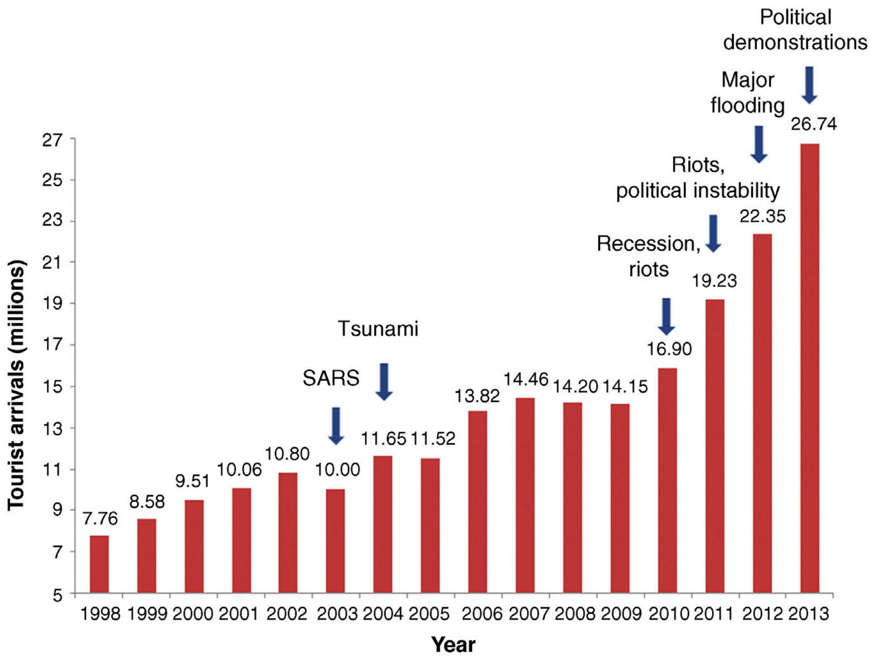

Figure 11.5 ***Yearly Tourist Arrivals and Major Critical Events in Thailand from 1998 to 2013.*** *Source: Department of Tourism (2014).*

11.3.4 Industrialization

Industrial development in Thailand has been successful for a newly industrialized country. However, industrial geographical dispersion has failed as indicated by a very high concentration of industrialization in the Bangkok Metropolis Region (BMR). The Thai government attempted to persuade business sectors to locate to the periphery or rural areas, including moving their industries from central Bangkok using several types of tax incentives, secondary city or growth pole, and supporting subregional development. However, this has not been successful and rural Thailand has yet to be industrialized (Pansuwan, 2010).

During the postwar era, manufacturing grew much faster than other sectors, resulting in its increased importance, most noticeably between 1986 and 1996. As a matter of fact, Thai manufacturing output grew at an average annual rate of 9.7% during the period 1961–1985, while from 1986 to 1996 the sector attained an annual average growth rate of around 13%. However, with the onset of the financial crisis, growth in the manufacturing sector slowed down, dropping to as low as 4.4%/y. Considering the past four decades, growth patterns of the Thai manufacturing sector can be separated into two subperiods: 1960–1985 and 1986–present day (Kohpaiboon, 2003). The purpose of such segregation is to illustrate the growth performance of different industrialization strategies between import substitution (IS) and export promotion (EP) regimes (Figure 11.6).

It is worth noting that during an IS industrialization period, the country's development started with a rapid expansion of manufacturing of textiles and clothing as well as that of transport equipment. Such trends led to the dramatic increase in the share of manufacturing from 1.7% in 1950 to 13.1% between 1976 and 1980. In order to gradually lessen successive deficits in the balance of payments between the late 1970s and early 1980s, the government shifted its industrialization strategy toward EP. In the early 1980s, the government implemented the Board of Investment (BOI) promotion scheme to partly mitigate the adverse impact of input tariffs on the international competitiveness of export-oriented industries. Under such a scheme, the BOI imposed tariff exemptions on imports over and above the usual investment promotion privileges for export-oriented activities. In the mid-1980s many East Asian investors were seeking an export base to maintain international competitiveness in their labor-intensive products, such as textiles, garments, and footwear. This was also the case with electronics and other durable consumer goods industries.

On the other hand, trade in exports of Thai-manufactured products also rapidly expanded between 1986 and 1995. Between 2001 and 2003,

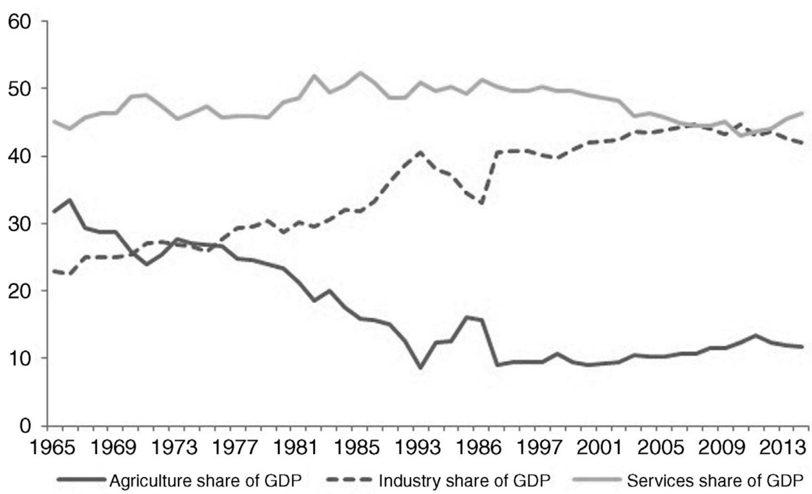

Figure 11.6 ***Sectorial Share of GDP during 1965 to 2006.*** *Source: World Bank (2014).*

manufactured products accounted for 75.2% of the country's total exports. This takes into consideration the fact that Thailand's development in manufacturing for export commenced in the late 1970s (Figure 11.6) with the production of several processed food products, especially canned pineapple, canned tuna, frozen chicken, as well as traditional labor-intensive manufactured goods (garments in particular). In 2006, the export of Thai manufactured products amounted to BHT4315 billion, which mainly constituted machinery and mechanical appliances; including computers and computer parts, vehicles and auto accessories, and electrical appliances – especially integrated circuit products.

The pattern of groundwater development in Bangkok and its vicinity also reflected industrial development. The early stage of groundwater development was concentrated in the inner zone and eastern part of Bangkok province. During the IS period, most textiles and related industries relocated in the eastern adjacent province of Samut Prakan. Subsequently, during the EP period, processed food products, canned fruit, canned tuna, frozen chicken, as well as traditional labor-intensive manufactured goods located to the western adjacent province (Samut Sakhon). The groundwater depression cone also followed this industrial development pattern.

11.4 PRESSURES

Pressures on Bangkok's groundwater environment come from inadequate surface water resources, overexploitation of groundwater resources, and land cover change.

11.4.1 Inadequate Surface Water Resources

The piped water supply in Bangkok and its vicinity is the responsibility of different agencies in each service area. The area receives its water supply from the MWA, PWA, and municipal or local authority. In addition, private water suppliers also serve some areas (World Bank, 2008). The MWA supplies water to Bangkok, Samut Prakan, and Nonthaburi provinces and the PWA to the remaining provinces. The MWA and PWA are responsible for the sourcing, production, and distribution of water. With population growth and subsequent rise in water demand, there is higher dependency on surface water as indicated by an increasing number of MWA customers (i.e., 1.44–1.75 million between 2001 and 2006). The MWA has increased production of surface water resources from 1482 to 1700 MCM/y. Increased production has reduced the availability of surface water in per capita terms.

In addition, inadequate quality of surface water has encouraged users to go for groundwater to supplement their supply. The uneven distribution of surface water is also an issue that is causing the use of groundwater to become a source of piped water for the vicinity of Bangkok. Villages without installed piped water systems, housing estates, and factories located outside the service of the MWA and PWA still depend on groundwater. Inadequate surface water is therefore putting pressure on groundwater resources.

11.4.2 Groundwater Overexploitation

Total water demand in this area for 2009 was estimated at 20.67 MCM/d and demand for groundwater was 1.5 MCM/d (Table 11.4). The total water produced by both the MWA and PWA was 6.9 MCM/d (MWA, 2014; PWA, 2013, 2014). The summation of water demand for domestic and industrial sectors, to be supplied through the piped system, was 7.04 MCM/d. Moreover, it is estimated that people outside the PWA and MWA service area still depend on groundwater over 0.5 MCM/d.

In the early stage of pumping, most of the water was drawn from the aquifer. This resulted in a lowering of the groundwater level in the aquifer, developing a hydraulic gradient between the aquifer and aquitard. This hydraulic gradient induced flow from the aquitard to the aquifer accompanied by a decrease in its hydraulic head. Such an aquifer and aquitard–dewatering process led to a concurrent reduction in pore pressure, pore volume, and land subsidence.

A groundwater modeling exercise suggested that recharge to Bangkok's aquifer system is approximately 0.6–0.7 MCM/d with the safe yield or permissible yield of this area being 1.25 m^3/d with the control groundwater level 30 meters below ground level (mbgl). Groundwater pumpage for the public water supply alone was 1.2 MCM/d in 1995 and 0.836 MCM/d in 2015. Statistics indicate the overexploitation of

Table 11.4 Water demand in Bangkok and its vicinity in 2009

Region	Total water demand/groundwater demand (MCM/d)			
	Domestic (DGR, 2009a)	Industrial (DGR, 2009a)	Agricultural (DGR, 2009b)	Total
Bangkok	1.55/0.01	0.98/0.06	0.81/–	3.34/0.07
Vicinity*	1.12/0.29	3.39/1.01	12.82/0.12	17.33/1.43
Total	2.67/0.30	4.37/1.08	13.63/0.12	20.67/1.50

*Vicinity (six surrounding provinces, currently declared as groundwater critical areas).

groundwater resources, which certainly exerts pressure on the groundwater environment.

11.4.3 Land Cover Changes

Bangkok and its vicinity is rapidly becoming urbanized as discussed in Section 11.3.2. Agricultural areas have decreased from 8326 km^2 to 4996 km^2 between 1995 and 2002, and have no doubt decreased further in recent years. Most of those areas have been converted into urban built-up sectors, creating a reduction in recharge to groundwater. Restricting inflow to groundwater imposes pressure on the groundwater environment.

11.5 STATE

The state of the groundwater environment in Bangkok and its vicinity is discussed from the perspective of well statistics, groundwater abstraction, groundwater level, groundwater quality, and recharge into the aquifers.

11.5.1 Well Statistics

Bangkok is a city with a relatively high water consumption per person per day. The MWA is responsible for supplying drinking water for domestic and industrial use. At present, the MWA and PWA use surface sources only to produce treated water. The major groundwater users apart from industrial users, are municipal and local authorities, which supply water outside the service area of the MWA and PWA. The total number of privately owned wells in Bangkok and its vicinity used by domestic, business, and agricultural sectors in 1997 and 2015 are shown in Table 11.5. This shows that the total number of working wells in Bangkok and its vicinity have decreased from 9771 in 1997 to 4240 in 2015.

Taking the statistics from 2001 and 2010, the number of production wells has decreased from 9077 to 7200 and well density from 0.89 wells/km^2 to 0.70 wells/km^2.

11.5.2 Groundwater Abstraction

Groundwater development for the public supply in Bangkok began in 1954 with an abstraction of 8360 m^3/d, increasing to 0.45 MCM/d in 1982. Including abstraction from private sectors, the figure in 1982 was 1.4 MCM/d. In 1983 the authorities designed and implemented control measures under the title "Mitigation of Groundwater Crisis and Land Subsidence in the Bangkok Metropolis." This led to a sharp drop in groundwater

Table 11.5 Well statistics (private wells) of the study area

Province	Domestic		Business		Agriculture		Total	
	Number of wells	Pumpage (m^3/d)	Number of wells	Pumpage (m^3/d)	Number of wells	Pumpage (m^3/d)	Number of wells	Pumpage (m^3/d)
	1997							
Bangkok metropolis	711	221,294	634	178,303	33	3395	1378	402,992
(a) Vicinity (6 provinces)	4033	624,364	4257	1,283,736	103	6686	8393	1,914,786
*(b)		436,954						436,954
(a) + (b)		1,061,318						2,351,740
Total	4744	1,282,612	4891	1,462,039	136	10,081	9771	2,754,732
	2015							
Bangkok Metropolis	51	1554	130	5324	9	273	190	7151
(a) Vicinity (6 provinces)	784	46,922	3179	172,861	87	40,697	4050	260,480
(b)		568,979						568,979
(a) + (b)	784	615,901	3179	172,861	87	40,697	4050	829,459
Total	835	617,455	3309	178,185	96	40,970	4240	836,610

The amount of groundwater supplied by municipal/local authorities was estimated from population.
* Population serviced by local authorities outside the MWA and PWA service area (2,844,895 persons) × rate of 200 liter/person/day is equal to 568,979 m^3/d.

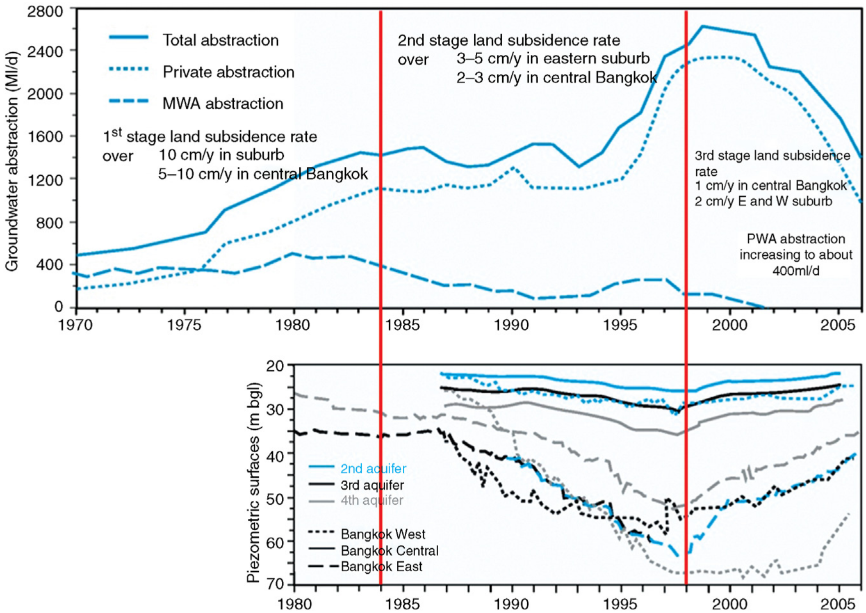

Figure 11.7 ***Groundwater Abstraction and Corresponding Groundwater Levels and Land Subsidence.*** *Source: Modified from Buapeng and Foster (2008).*

abstraction between 1985 and 1990. However, abstraction began to increase again from 1991 onward due to high economic growth. By 1997, total groundwater abstraction in the control area of the four provinces: Bangkok, Samut Prakan, Nonthaburi, and Pathumthani was 1.67 MCM/d. The total for seven provinces was 2.3 MCM/d. After the economic crisis and full implementation of economic instruments for groundwater usage, plus the groundwater conservation charge, groundwater use declined steeply (Figure 11.7).

11.5.3 Groundwater Levels

The initial groundwater levels in Bangkok were very close to the ground surface and some wells were said to be artesian. In those days, groundwater was believed to have been pumped from the shallowest good–water quality aquifer (PD aquifer) since the overlying Bangkok aquifer (BK aquifer) produced brackish to saline water.

A plot of west–east cross-sections during the period of groundwater decline and recovery is shown in Figure 11.8. In the early stages of groundwater development in around 1959, groundwater levels ranged from

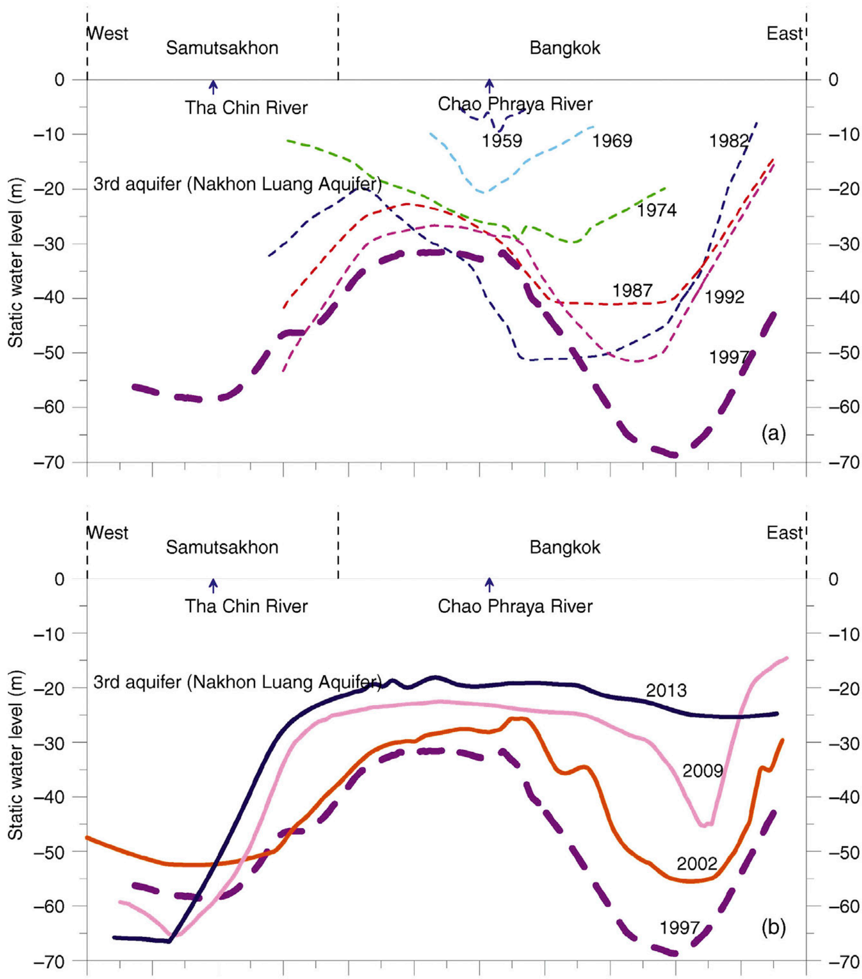

Figure 11.8 ***Groundwater Level Decline (a) and Recovery (b).***

4 mbgl to 5 mbgl in eastern Bangkok to 12 mbgl in central Bangkok. After 1967, a heavy use of groundwater was observed in the eastern part of the city. By 1967, the lowest water level in the NL aquifer in central Bangkok and the eastern suburbs was 30 mbgl. Annual rates of water level decline in the NL aquifer from 1969 to 1974 were 3.6 m (i.e., 0.7 m/y) in the eastern part and 1–2 m (0.2–0.4 m/y) in central Bangkok.

From 1959 to 1982, the water level in the NL aquifer declined by 38 m in central Bangkok and 60 m in the eastern suburbs. Since 1983, the control measures on groundwater pumping together with the introduction of a groundwater tariff in 1985 have had a marked effect on groundwater use in Bangkok; the consequent decrease in groundwater withdrawal produced a rapid recovery of water levels in three aquifers (PD, NL, and NB). In central Bangkok, the public water supply produced from surface water sources replaced much of the groundwater, resulting in a continuous rise in the groundwater level. Although the groundwater crisis in central Bangkok has been improved, depression cones have developed in new areas on the outskirts of Bangkok both in the eastern province (Samut Prakan) and the western province (Samut Sakhon), which are areas of extensive industry (Figures 11.9 and 11.10).

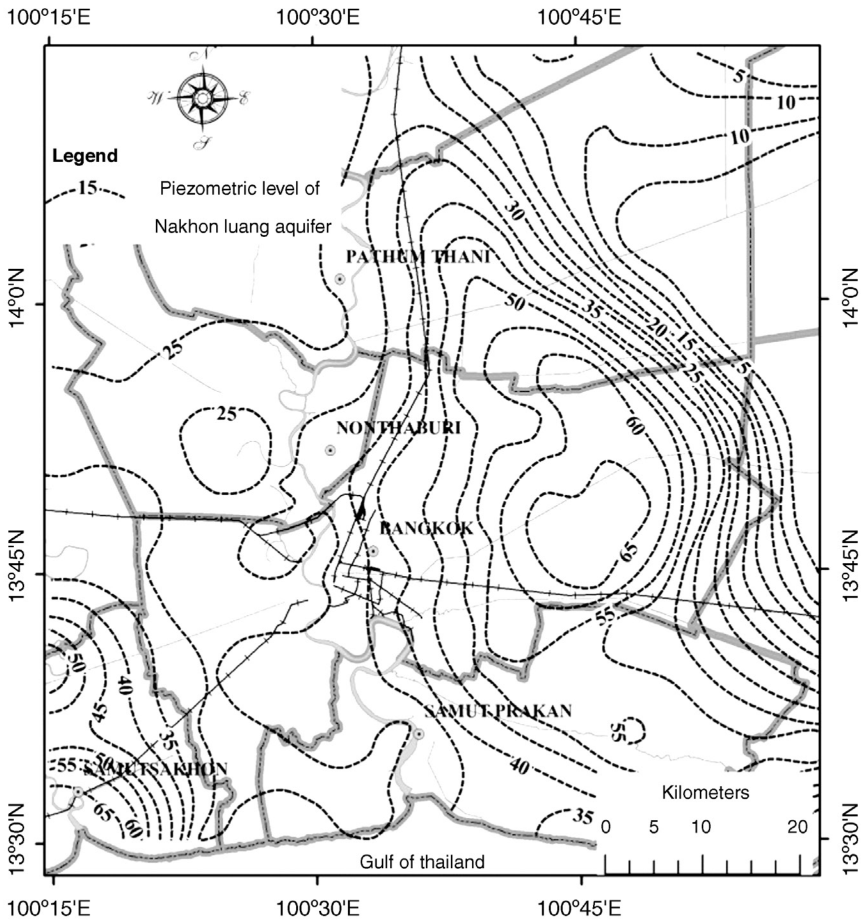

Figure 11.9 ***Water Level at the NL Aquifer in 1996.*** *Source: Lorphensri et al. (2011).*

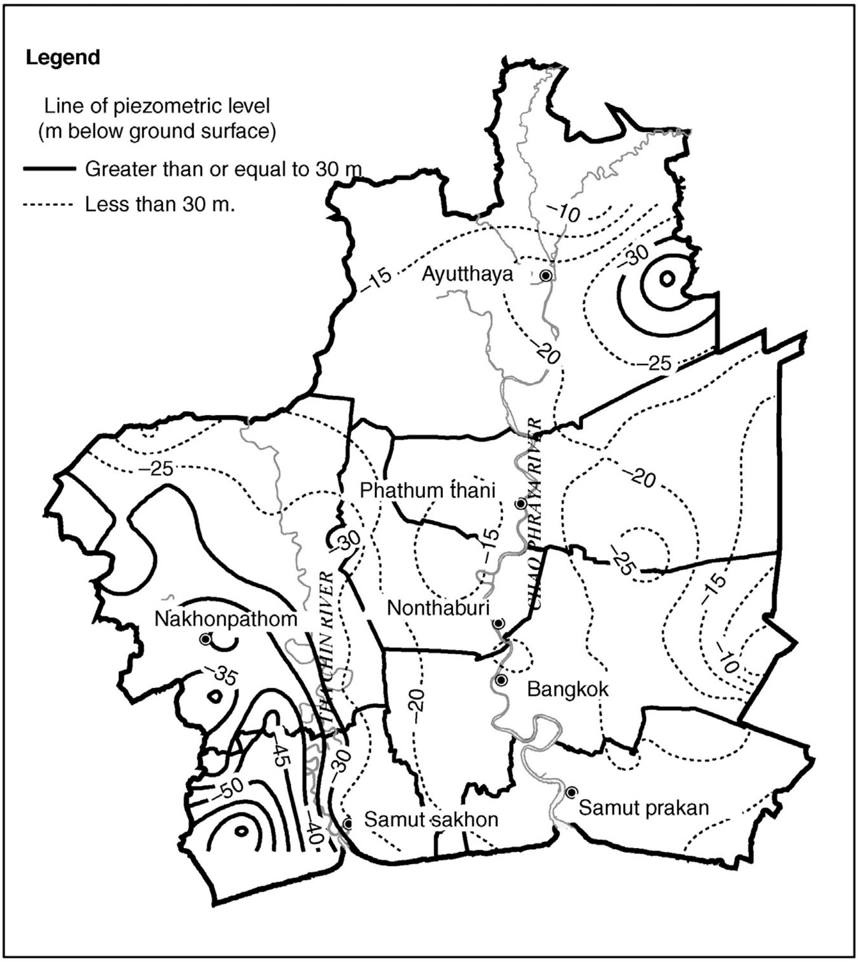

Figure 11.10 ***Groundwater Level at the NL Aquifer in 2014.***

11.5.4 Groundwater Quality

The status of groundwater quality is assessed using water samples collected from monitoring and production wells. Fundamental parameters (e.g., physical and chemical) are measured in the water samples. The parameters of concern in this area are total dissolved solids, iron, and hardness. Maps of chloride concentrations and the total dissolved solids are regularly produced to monitor the water quality status of the area. Most high chloride content in the three uppermost production aquifers (PD: 100 m, NL: 150 m, NB: 200 m) occurred in areas near the river mouth and shoreline. However, inland salt water in some areas also exists. The upper 50 m deep aquifer (i.e., BK aquifer) is the only aquifer that totally contains salt water. The source of high salinity is found to be diffusion of salt from the overlying marine clay layer.

11.5.5 Recharge

The study area is totally covered by a thick marine clay layer, hence direct recharge should be minimal. However, almost no percolation of surface water or precipitation occurs due to the presence of clay layers. AIT (1981) revealed that only 3% of total recharge is through direct percolation from soil layers and surface water. This implies that almost all recharge comes through the movement of groundwater from outside the discharge areas.

Groundwater in the Bangkok aquifers is basically recharged away from abstraction areas (Figure 11.11). However, such natural recharge is limited

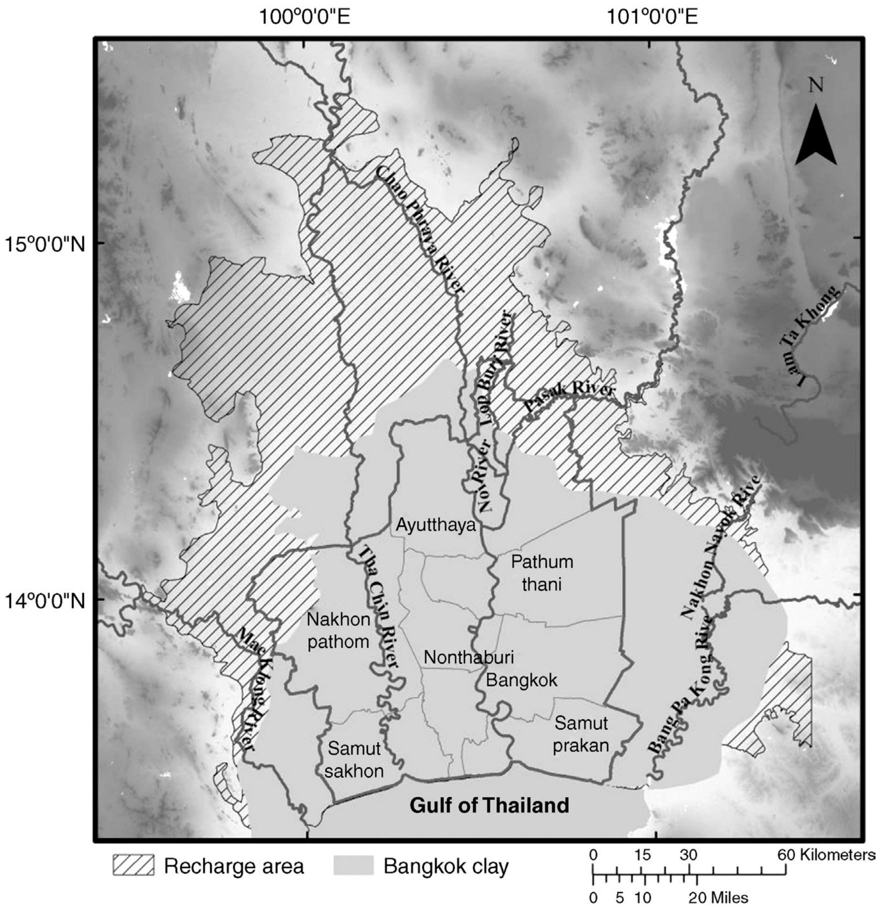

Figure 11.11 *Recharge Area in Bangkok and its Vicinity.*

because of the slow movement of groundwater. An estimated sustainable yield from all the aquifers in the Bangkok area is 0.6 MCM/d (DGR, 2004) to 0.7 MCM/d (DGR, 2008a). This means that this amount of groundwater is supposed to be recharged to maintain a balance against pumping. Estimated groundwater use in the study area is 0.836 MCM/d (Table 11.5). Comparing the amount of recharge and groundwater use shows that groundwater balance is still in deficit.

11.6 IMPACTS

Major adverse impacts of groundwater overexploitation in Bangkok's aquifers include land subsidence, depletion, and recovery of groundwater levels, together with degradation in groundwater quality.

11.6.1 Land Subsidence

Land subsidence in the area can be divided into three stages: early (1978–1981), mid (1984–2000), and recent (2000–2008) (Figure 11.12). The response of land subsidence to groundwater level changes is well described by long-term monitoring at Ramkhamhaeng University (Figure 11.12). The slope of land subsidence follows the slope of groundwater level

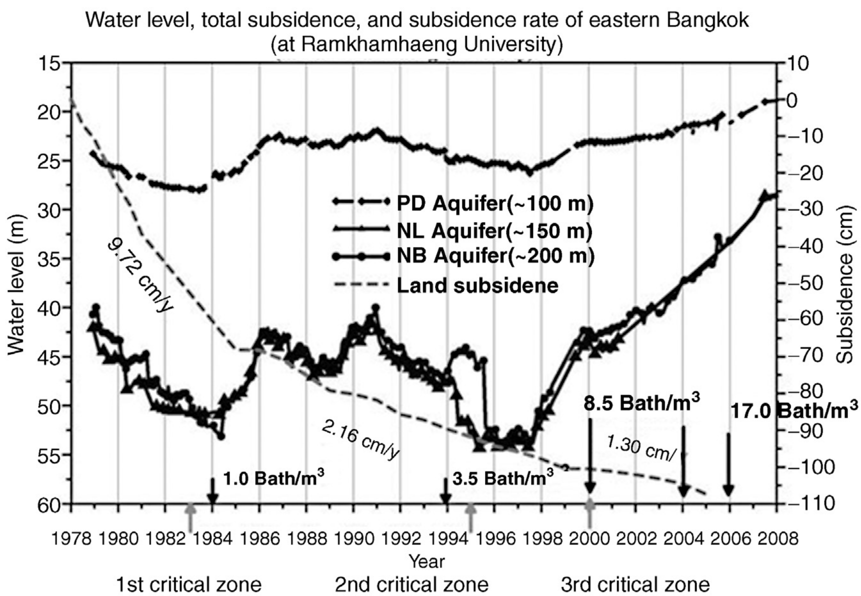

Figure 11.12 ***Trends in Groundwater Levels, Land Subsidence and Chronology of Mitigation Measures at a Monitoring Station in the Eastern Suburb of Bangkok.*** *Source: Lorphensri et al. (2011).*

(decline and recovery) (Lorphensri, 2011). In the early stage, land subsidence was over 10 cm/y in the eastern suburbs, and 5–10 cm/y in central Bangkok. Soil compression during this period in the top 50 m and in the deeper zone of 50–220 m in depth, contributed 40 and 60% to total surface subsidence, respectively (AIT, 1982). Leveling in 1982 by the Royal Thai Survey Department (RTSD) indicated that the lowest elevation in Bangkok was 4 cm below sea level at a land subsidence–monitoring station within Ramkhamhaeng University.

During the mid-stage, after introducing control measures against groundwater use in 1983, a short continuous recovery of the groundwater level was observed in central Bangkok and its eastern suburbs. This resulted in a decrease in the rate of land subsidence. The annual subsidence rate in 1989 reduced to 2–3 cm/y in central Bangkok and 3–5 cm/y in the eastern suburbs (Ramnarong and Buapeng, 1992).

From 2000 to 2014, the subsidence rate stabilized or recovered. The average subsidence rate for the entire area is 1 cm/y. The higher rate of 2 cm/y can still be found in the eastern province (Samut Prakan) and the western province (Samut Sakhon).

11.6.2 Depletion and Recovery of Groundwater Levels

The study area has experienced several stages of groundwater development. At the stage of overexploitation, the groundwater level declined to 50–60 mbgl (in 1997) at the rate of 2 m/y. After implementing control measures and expanding the services of the MWA and PWA, which use surface water, groundwater levels recovered to 20–40 mbgl in 2013 at the rate of around 3 m/y. The new concern for authorities is preparing for the possible consequences if the groundwater level continues to rise steadily.

11.6.3 Degradation in Groundwater Quality

It is noticeable that groundwater quality deteriorates during periods of high pumpage, and increasing chloride concentrations have been observed in several areas. A comparison of chloride concentrations during the years 1993 and 2009 is shown in Figure 11.13. Large areas of high chloride concentrations in 1993 have been reduced during periods of low pumpage (2009). Leakage of salt water from the uppermost layer and salt water pockets in some aquifers can be expected to diffuse or leak to the fresh water aquifer due to the past history of heavy pumpage.

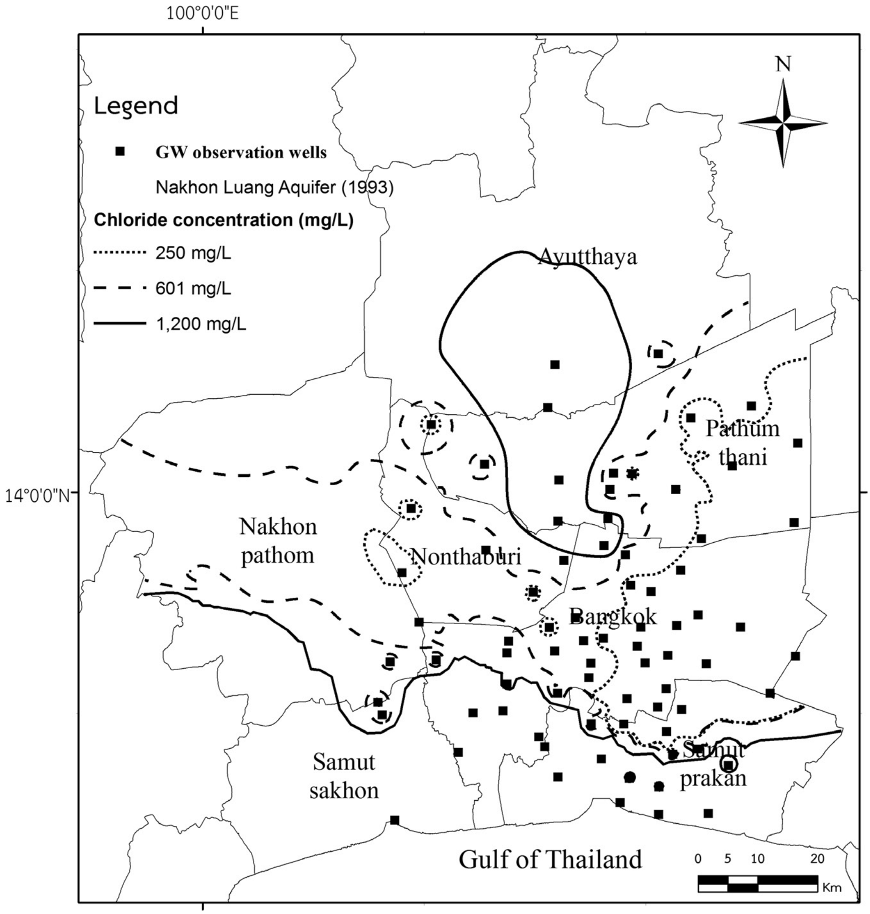

Figure 11.13 ***Chloride Concentrations in 1993 and 2009.***

11.7 RESPONSES

11.7.1 Aquifer Monitoring

This consists of monitoring groundwater levels and land subsidence. Networks for groundwater level–monitoring wells (Figure 11.14) and land subsidence (Figure 11.15) were established in 1978. Groundwater levels are monitored at 150 stations (Figure 11.14), each consisting of a set of wells tapping at least three top aquifers of interest. The distance between the aquifer generally ranges from 5 km to 10 km depending on gradients of water level. Monitoring frequency is at least twice a year. For land subsidence, a network (Figure 11.15) has been established of 1 m deep benchmarks,

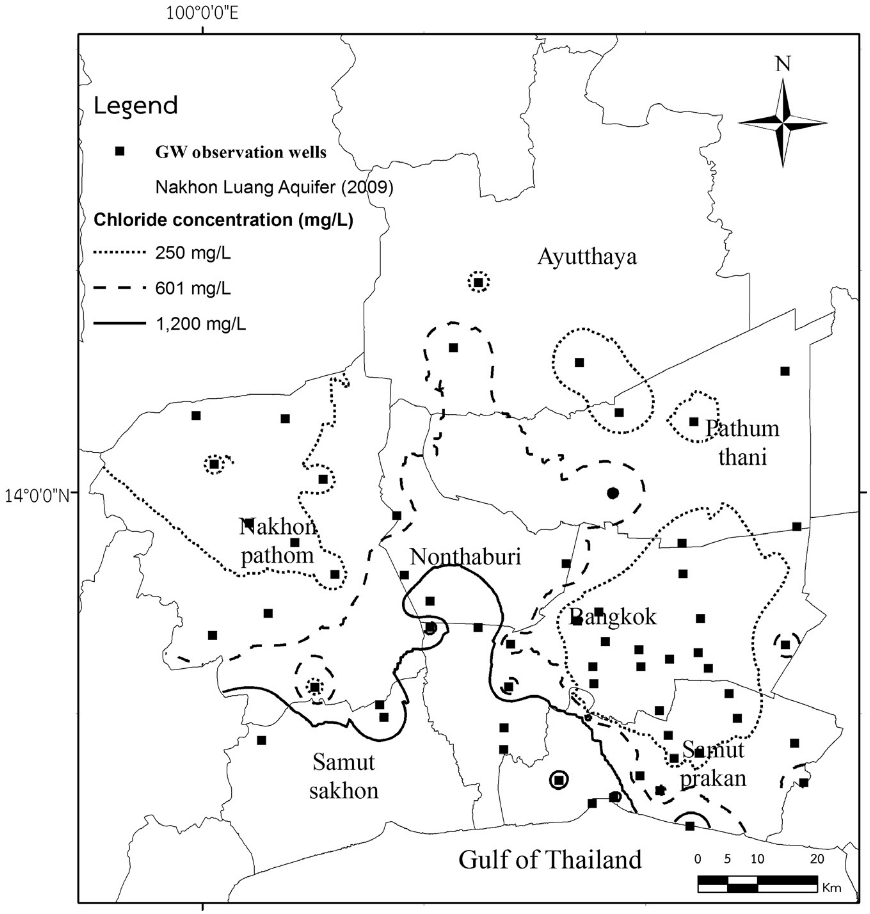

Figure 11.13 ***(cont.)***

distributed evenly throughout the area. Once a year, the RTSD carries out a survey on land leveling.

11.7.2 Environmental Standards and Guidelines

The Department of Groundwater Resources (DGR) has established drinking standards for groundwater (Table 11.6). The main concerns are physical, chemical, biological, and toxic, and 27 parameters are considered for quality characterization. The Ministry of Natural Resources and Environment, the agency responsible for determining environmental standards and guidelines, has set an additional standard in order to cope with recent problems in the groundwater environment. More stringent groundwater

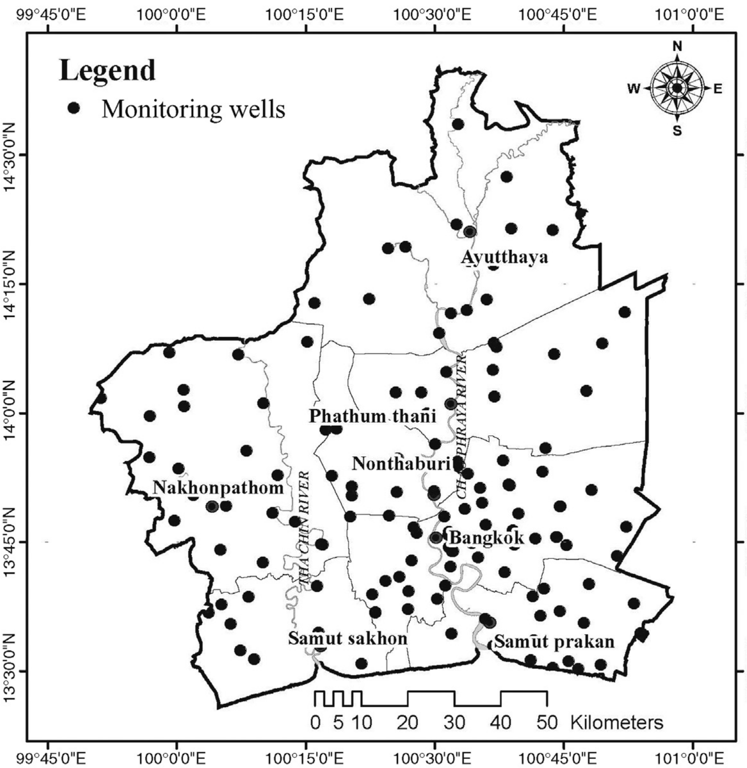

Figure 11.14 ***Groundwater-Monitoring Network.***

standards have been established with consideration given to several organic constituents.

11.7.3 Groundwater Management Instruments

The Groundwater Act (1977) prescribes technical measures to protect it from pollutants and introduces standards for groundwater to be used for drinking purposes. The PWA established the Provincial Waterworks Authority Act with the intention of improving and expanding waterworks and services in provincial areas, and is also authorized to provide water supply services to areas not catered for by the MWA.

The Groundwater Act is a basic law that provides definitive terms concerning groundwater exploitation activities, such as "groundwater," "drilling," "groundwater usage," "wells," and other related terms that need legal definition. The main concept of this law is that groundwater exploitation is a public

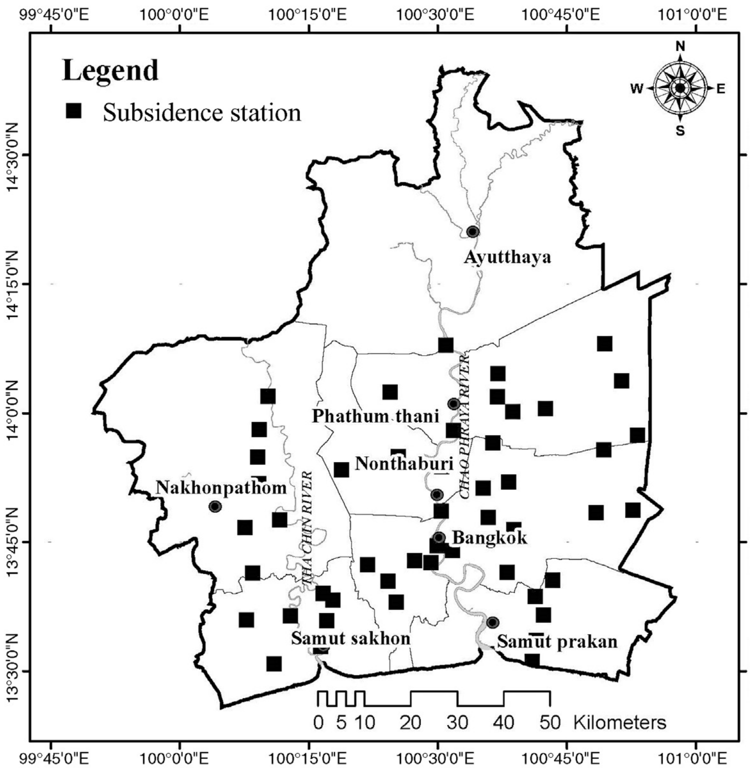

Figure 11.15 ***Land Subsidence–Monitoring Network.***

matter (DGR, 2008b). Therefore, a landowner who wants to drill and exploit groundwater lying under his own land must apply for the relevant permits from the DGR. This concept may be considered an exemption to the absolute right of property owners as recognized by the Civil and Commercial Code.

In addition, the Groundwater Act requires three kinds of permit for different purposes, namely, a 1-year permit for drilling, a 10-year permit for groundwater exploitation, and a 5-year permit for discharging water into a well. In this connection, the law sets out rules and conditions for extension of permits, administrative appeals, and grounds for refusing permits or extensions, including certain measures for overseeing and control.

A second revision to the act was made in 1992, in which no pumpage areas were designated. This was in order to control water quality, prevent endangerment or deterioration of aquifers, protect natural resources and the environment, protect public health or property, and to avoid land subsidence. In addition, there are criminal sanctions for pumping groundwater

Table 11.6 Drinking standard for groundwater quality in Thailand

Parameter	Allowable (not exceed)	Maximum allowable
Physical quality		
Color	5 TCU	50 TCU
Turbidity	5 NTU	20 NTU
pH	7.0–8.5	6.9–9.2
Chemical quality (mg/L)		
Fe	0.5	1.0
Mn	0.3	0.5
Cu	1.0	1.5
Zn	5.0	15.0
SO_4	200	250
Cl	200	600
F	1.0	1.5
NO_3	45	45
Total hardness	300	500
Noncarbonate hardness	200	250
Total dissolved solids	750	1500
Toxic elements (mg/L)		
As	0	0.05
Cn	0	0.2
Pb	0	0.05
Hg	0	0.001
Cd	0	0.01
Se	0	0.01
Microbiological water quality		
Standard plate count	500 CFU/m^3	0.05
MPN of coliform organism	<2.2/100 m^3	0.2
Escherichia coli	0	0.05

CFU, colony-forming unit; MPN, most probable number; NTU, nephelometric turbidity unit: TCU, true color unit.

into a no-pumpage area and for pumping without a permit, including a procedure for the court to order an offender to return the well back to its previous condition prior to occurrence of the violation.

The third revision to the act in 2003 involved the setting up of a "Groundwater Development Fund" within the DGR to fund studies and research on conservation of groundwater and the environment. The fund is managed by a board chaired by the Director General of the DGR.

The policy/action plan for the study area is still the same as in the past few years, namely, to limit groundwater abstraction to within a "safe yield." Cooperation from the MWA and PWA is necessary to implement the policy/action plan. Domestic licences will be declined for wells when the public water supply service is extended to the area. Moreover, a certain percentage of business and industry licences will need to be switched to the public piped water supply, depending on the type of industry. The ratio of the conjunctive use of surface water to groundwater is to be maintained at between 20 and 50%.

Until recently, the DGR has adopted the policy of modernizing the well-licencing information system by introducing a geographical information system to help the licencing process. Currently, the procedure to pay a groundwater use fee has been transferred from direct payment at a provincial office to the government bank. The DGR is now in the process of decentralizing groundwater licencing and fee collection to local administration offices throughout the country. The transfer process will operate in a gradual manner. Initially, three pilot provinces were chosen for the decentralization process, with the aim of completing decentralization for all the provinces within five years. The process started by training local officers in the necessary practices and law.

As a result of the implementation of the groundwater conservation charge and expansion of the MWA and PWA services, groundwater use has been reduced below the controlled safe yield, and the rate of subsidence has reduced to 1.0 cm/y. Due to these achievements, the groundwater conservation charge has been reduced accordingly.

A groundwater conservation strategy to curb water demand takes a multiprong approach through pricing and mandatory water conservation. Pricing of water is an important and effective mechanism to encourage users to conserve water. Groundwater should be treated as an economic benefit. The water is priced not only to recover the full cost of groundwater management, but also to reflect the scarcity of this precious resource. A water conservation tax was also implemented in 1991 to further encourage water conservation. The groundwater tariffs and groundwater conservation tax were restructured over a 4-year period, starting in 1997, to reflect its strategic importance and environmental impact.

A groundwater tariff was first implemented in 1985 in the six provinces of Bangkok and its vicinity, where 1.0 baht/m^3 was charged. By 1994, the charge had increased to 3.5 baht/m^3, and the government began to charge the whole country for groundwater use. Between 2000 and 2003, the groundwater tariff was gradually increased in the Critical Zone from 3.5 baht/m^3 to 8.5 baht/m^3.

In 2003, the Groundwater Act was amended to impose a Groundwater Preservation Charge for all groundwater users in the Critical Zone. Starting at 1.0 baht/m^3 in 2004, the charge was set to increase to 8.5 baht/m^3 in 2006. The total cost of groundwater use in the Critical Zone has therefore become relatively high, but has helped in limiting the abstraction of groundwater in the area. Total groundwater charges increased from 9.5 baht/m^3 in 2004, to 12.50 baht/m^3 in 2005, and to 17 baht/m^3 for 2006 and beyond, which is deterring groundwater users in the area, especially those using large amounts such as industries. A chronological summary of the adoption of groundwater management instruments (e.g., regulatory measures, economic measures, and supporting systems) is shown in Table 11.7 and a timeline of response to land subsidence is shown in Figure 11.16.

Table 11.7 Chronology of groundwater management instruments adopted in Bangkok, Thailand (regulatory and economic)

Regulatory measures	
1977	Groundwater law: the Groundwater Act was enacted in 1977 and has been amended twice (1992 and 2003). Provision for controlling of well drilling, groundwater use, discharging to well, and protection and conservation of groundwater resources in the country.
1978/1983	Designation of groundwater regions and critical zones: a groundwater region is the selected area that needs to apply for a license for groundwater use. To control groundwater use and mitigate environmental problems associated with it, areas most severely affected by groundwater-related problems such as land subsidence and groundwater depletion were designated as Groundwater Critical Zones and were subjected to more control over private and public groundwater uses.
1978	Licensing for groundwater well drilling and groundwater use: licenses were required to extract groundwater, and pumpage limits were controlled through these permits.
1985	Groundwater use metering: business and industry use of groundwater were subjected to installation of well meters. Groundwater use was charged according to meter readings.
1992/2000	Establishment of a groundwater quality standard: standards for groundwater for drinking purposes were established through the Groundwater Act. In 2000, groundwater quality standards for the conservation of environmental quality were issued.

(Continued)

Table 11.7 Chronology of groundwater management instruments adopted in Bangkok, Thailand (regulatory and economic) *(cont.)*

Economic measures	
1977	Penalizing violators of regulations: violation of regulations will result in a fine of not more than THB 20,000 or imprisonment for not more than 6 months (drilling machinery and equipment will also be confiscated).
1985	Implementation of groundwater use charge: the charge was first implemented in six provinces at 1.0 baht/m^3. In 1994, the charge increased to 3.5 baht/m^3 and applied to the whole country. During 2000–2003, only in the Critical Zone, the charge gradually increased to 8.5 baht/m^3.
2003	Implementation of conservation charge: during 2003–2006, the charge for conservation started at 1–8.5 baht/m^3. In 2006, the total groundwater charge was 17 baht/m^3. These brought up the cost of groundwater use close to the public water supply. Later in 2012, after evidence that groundwater levels had persistently recovered, the conservation charge reduced from 8.5 baht/m^3 to 4.5 baht/m^3 making the total cost of groundwater use 13 baht/m^3.
Supporting systems	
1978	Groundwater-monitoring system: monitoring networks were established under the study program of groundwater and land subsidence in 1978. The data collected were water level, water quality, and land subsidence in critical areas.
1982	Groundwater database: a Groundwater Database System was established electronically in 1982 and has been persistently improved through several study programs. The current status of the groundwater database is available to the public using a geographical information system and well information via web services.

11.8 SUMMARY

Groundwater development in the area has a long history, which follows the pattern of social and economic development. It is obvious that there are several impacts due to long-term groundwater development. After strict implementation of the Groundwater Act 1977 in the Bangkok area, groundwater depletion has now recovered. Land subsidence, a well-known issue for the area, is now systematically monitored. Although, land subsidence has recovered over time, there are still other impacts, which must be carefully examined, such as groundwater quality deterioration and groundwater level

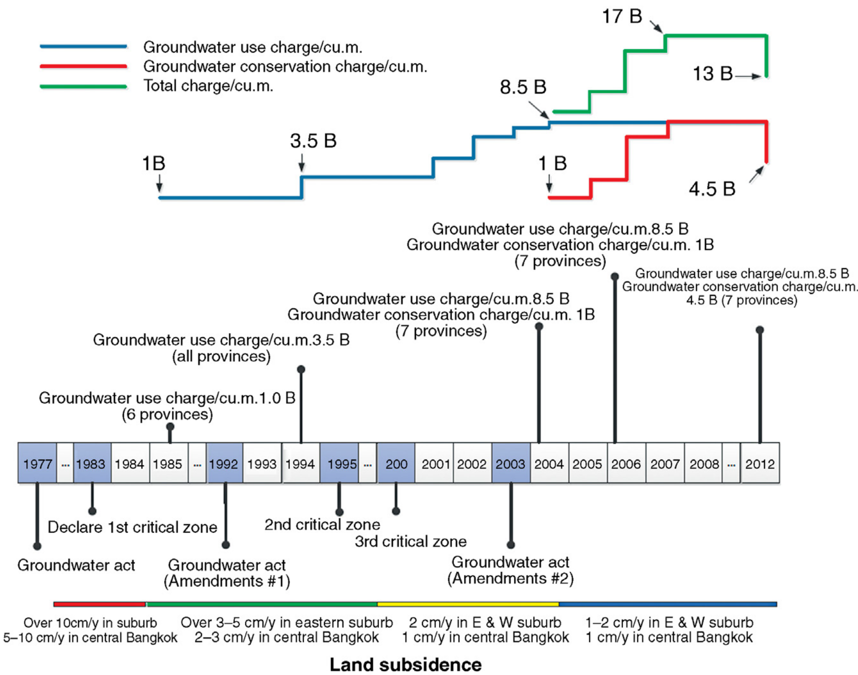

Figure 11.16 ***Timeline of Response to Land Subsidence in the Bangkok Aquifers.***

recovery. Groundwater resources in the area are available in large quantities, and should be used wisely in the economic development of Thailand. Overall the ultimate goal of groundwater management in the area is the sustainable utilization of groundwater resources to achieve the best possible economic growth. The results of this DPSIR analysis have produced a useful knowledge base for such a purpose.

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