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Urbanization and subsurface environmental issues: An attempt at DPSIR model application in Asian cities

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ABSTRACT

This paper synthesizes existing information and knowledge on subsurface environments to understand the major cause and effect relationships of subsurface environmental issues by using the DPSIR (Driving force–Pressure–Status–Impact–Response) approach as the framework of analysis. Description is given to the major subsurface environmental issues common among the selected Asian cities (Bangkok, Jakarta, Manila, Osaka, Seoul, Taipei and Tokyo), such as excessive groundwater abstraction, land subsidence and groundwater contamination. The DPSIR framework is used to analyze the issues and problems of subsurface in key stages and suggestions are made for additional indicators to improve our description of the stages of urban development for the future.

1. Introduction

Economic growth and industrialization have stimulated rapid urbanization and population growth in Asia. This rapid economic growth has been beneficial to the cities as they have become centers of production, commerce, education and governance, and other productive activities. However, it has also created environmental problems, manifested in the deterioration of air and water quality, decreasing water supply, insufficient housing and sanitation facilities, traffic congestion and increasing solid waste, among others.

In urban development, the subsurface also plays a very significant role especially in the development of infrastructures for water supply, sanitation and drainage and in the disposal of industrial effluent and solid waste (Foster, 2001). Groundwater is tapped as a supply for domestic and industrial needs because of its excellent natural quality, thus reducing the cost of treatment, and its reliability as a source of supply especially in extended dry periods. The subsurface is also important in urban wastewater disposal. When infiltration capacity is adequate, the ground is the most economical receptor for urban runoff, thereby avoiding the need for costly surface drainage measures (Foster et al., 1998). The subsurface also acts a major receiver of effluents from industries and leakage or spillage of fuels stored in tanks at industrial sites.

Although groundwater can provide for the needs of households and industries, especially in places where surface water supply is unstable, aquifers are replenished slowly and popula-

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tion and industrial demand can exceed the natural recharge and may cause drops in water tables. Declines in groundwater levels due to heavy pumping of underground aquifers can cause land subsidence which can create damage to buildings, streets, railways and sewage systems and worsen the impacts of flooding in low lying coastal areas.

Urban waste water, oil and sewer leakages, fertilizer and pesticide residues and effluents from mining activities deposited in the ground and reached the aquifers have the potential to generate subsurface contaminant loads such as chemical pollutants and microbial pathogens which pose risks to human health. Changes in redox condition in groundwater zones, changes of biological diversity, vegetation changes with modification of agricultural practices and impacts at the biosphere scale, such as the increase in concentration of nitrous oxides in the atmosphere, also impact groundwater ecosystems (Danielopol et al., 2003).

Declines in groundwater quantity and degradation of groundwater quality are the common problems of the subsurface environment, but these have been given little attention. The “hidden” or “invisible” character of the subsurface makes it difficult to measure or evaluate changes in its state as well as the conditions of living organisms in its environment. Moreover, there is a time lag between the period of occurrence and detection of the problem, making it more complicated to assess causality of factors and impacts to the surface environment and human life.

This research applies the Driving force–Pressure–Status–Impact–Response (DPSIR) framework to assess the factors that contribute to the degradation of the subsurface environment. Although the DPSIR framework has been widely used to analyze different environmental problems, only a few studies have focused on the problems of the subsurface environment. The DPSIR model is dynamic and here focus is given to important subsurface environmental issues such as groundwater quantity and quality. On a temporal scale, the framework is based on the occurrence of subsurface problems during the different stages of urban development in the last 50–100 years in Asian metropolitan areas of Bangkok, Jakarta, Manila, Osaka, Seoul, Taipei and Tokyo.

2. Driving forces–pressure–state–impact–response (DPSIR) framework

Different methods were developed and used to analyze environmental issues and impacts. The simple Pressure–Status–Response (PSR) framework was developed by the OECD (1993) as a common framework for environmental evaluation. Environmental problems and issues were taken as variables to show the cause and effect relationships between human activities that exert pressure (P) on the environment, the changes in the state of the environment (S), and the responses to the change in conditions of the environment (R). This PSR model was further enhanced by the European Environmental Agency (1999) to become the Driving force–Pressure–State–Impact–Response (DPSIR) framework, in order to provide a more comprehensive approach in analyzing environmental problems. This systems view of analysis states that economic and social development, which are common driving forces (D) exert pressure (P) on the environment, and as a result, the state (S) of the environment changes, such as depletion of natural resources, decrease in biodiversity and degradation of environmental quality. These changes then have impacts (I) on the ecosystems, human health and other materials. Due to these impacts, society responds (R) to the driving forces, or directly to the pressure, state or impacts through preventive, adaptive or curative solutions.

The application of the DPSIR model involves a great deal of information gathering to formulate indicators that can reflect the causal relationships between human activities, environmental consequences and responses to environmental changes. Common indicators for driving forces include economic, social and demographic changes in societies such as changes in production and consumption patterns and people’s lifestyles. Intensive production and consumption exert pressure as these processes entail alteration in the uses of land and resources and the release of substances or emissions. State indicators describe the changes in quantity and quality of the physical environment, biological components of the environment (organisms) and chemical concentration in a certain area. Impact indicators involve the effects on the social and economic functions of the environment, such as provision of adequate conditions for health, resources availability and biodiversity. Response indicators refer to responses by different groups in society, as well as government initiatives to prevent the negative consequences in the environment, improve the conditions of the environment or to adapt to changes in the state of the environment. These can be in the form of policy measures such as regulations, information or taxes (Borja et al., 2005). In some cases, responses are directed to the driving forces by changing the prevailing trends in consumption and production patterns. Responses vary depending on how the situation or the environmental problems are perceived, evaluated and understood. Initial responses are mostly directed to impacts because the consequences are easily perceived while it will take more time to understand pressures and root causes of the environmental problems. Different responses have also different temporal implications, whether they can achieve long-term goals or short-term benefits. The cost of implementation also varies and the prioritization of responses will depend on the capacity of governments and societies to address these problems. Response to pressures usually follows after deeper understanding of the issues. Responses directed to the driving forces such as changes in production and consumption patterns have long-term effects, however the cost of such responses is also high.

Some studies have used the DPSIR model in analyzing different water environment problems. Bowen and Riley (2003) applied this framework to understand the linkages and interdependencies of socio-economic and coastal environmental dynamics. In order to assess the feasibility of the European Water Framework Directive (WFD), Borja et al. (2005) used the model together with other methodologies to identify the relevant pressures and impacts of water quality changes in estuarine and coastal areas. Following this framework, Danielopol et al. (2003) reviewed the changes in the status of groundwater ecosystems and the important driving forces, resulting from the direct or indirect impacts of human activities. Their discussion divided the environmental pressures which are largely produced by human activities in two major classes, namely (1) groundwater quantity problems and the critical depletion of aquifers in many parts of the world and (2) groundwater quality problems, where the systems are overloaded with contaminants.

3. Selection of study areas

This research describes the changes in the subsurface environment of selected metropolitan areas in Asia: Bangkok, Jakarta, Manila, Osaka, Seoul, Taipei, and Tokyo. Unless otherwise indicated, Bangkok refers to Bangkok Metropolitan area, Jakarta is DKI Jakarta, Manila refers to Metropolitan Manila, Seoul is Seoul City, Taipei is Taipei City and Tokyo is Metropolitan Tokyo. Except for Osaka, these metropolitan areas are the seats of capital in their respective countries. These areas are mostly located along the coastal zones.

These areas were selected in order to describe the timing of occurrences of subsurface environmental problems according to the stages of urban development. Population increases as well as the rise of the economies in these seven areas began in different periods of time, and the scale and pace of growth also differed. Osaka and Tokyo have advanced economies, and experienced severe subsidence problems due to over extraction of groundwater during the period of high economic growth since the 1950s. But these cities were able to immediately develop measures that reduced groundwater abstraction and control land subsidence. Taipei also has encountered groundwater problems at the height of its economic development in the 1960s and as the Japanese cities, was able to establish groundwater regulatory measures in the late 70s. Several lessons can be drawn from the experiences of these cities, especially for other urban areas such as Bangkok, Jakarta and Manila, which are still struggling to cope with these problems. Bangkok, however, is considerably ahead of Jakarta and Manila in controlling groundwater mining, with the implementation of Groundwater Act since 1977. Groundwater development in South Korea where Seoul is located started in the 1960s was mostly promoted by the private sector and out of government control. However, problems such as groundwater level decline and contamination occurred in populated areas and industrial complexes, prompting the government to establish the Groundwater Law in 1994.

4. Methodology and materials used

Here, the DPSIR framework is applied in order to understand the issues on the subsurface and assess the factors that contribute to its degradation. Cause and effect relationships of subsurface environmental issues are analyzed using information from official environmental reports and statistics, and research results from previous studies in order to create links and indicators of the components of DPSIR. On a temporal scale, the application of DPSIR is based on the occurrence of subsurface problems during the different stages of urban development in the last 50–100 years. On a spatial scale, our analysis of the issues is limited to the experiences of metropolitan areas in Asia such as Bangkok, Jakarta, Manila, Osaka, Seoul, Taipei and Tokyo, where relatively rich data and information are available and where the experiences of the subsurface problems have also been documented.

Subsurface problems such as decreasing groundwater levels, declining groundwater quality and anomalies in subsurface temperature occurred during different stages of the development of urban areas. The issues of the subsurface are described for key stages using the DPSIR elements.

The basic information on groundwater consumption and groundwater levels are taken from the reports of different government agencies concerned in each urban area (Bureau of the Waterworks – Tokyo Metropolitan Government (TMG); Bureau of the Environment – TMG; Osaka Municipal and Prefecture Government; Water Resources Agency (WRA), Taiwan; Department of Mineral Resources (DMR) and Department of Groundwater Resources (DGR), Thailand; Ministry of Public Works and Mining Service, Jakarta Metropolitan Government, Indonesia; National Groundwater Information Management Service Center (GIMS), South Korea; Japan International Cooperation Agency (JICA) and Metropolitan Waterworks and Sewerage Systems (MWSS), Philippines). Groundwater issues and land subsidence records were also taken from results of previous researches in Tokyo (Yamamoto, 1984a; CEC, 2006); in Osaka (Osaka Prefecture, 1971; Yamamoto, 1984b); in Taipei (Wu, 1976, 1992); in Bangkok (DMR, 1992; DMR-JICA, 1995; Nutalaya et al., 1996; Ramnarong, 1999; Phien-wej et al., 2006); in Jakarta (Abidin et al., 2001) and in Manila (Rodolfo and Siringan, 2006).

The population data from the 1950s for all urban areas, except Taipei, were taken from the "World Urbanization Prospects: The 2005 Revision" of the United Nations (UN, 2006). Data before the 1950s were from various government statistical reports and previous researches. The population statistics of Taipei were taken from the "Statistical Abstract of Taipei City 2004 (DBAS, 2004). To compare the long-term GDP per capita of the different countries where these urban areas are located, the estimates from Maddison (2003) are used. A detailed listing of the sources is given in the reference list.

5. DPSIR framework and subsurface issues

Based on the review of different studies, researches, and environmental reports in the study areas, the cause and effect relationship between urban development and subsurface environment in a DPSIR framework are summarized in Fig. 1.

Most of the discussions in the literature were focused on two subsurface environmental problems such as changes in groundwater quantity and quality. Some of the common problems, impacts and responses are described to illustrate the relationship among the components of the DPSIR and the link between groundwater quantity and quality is illustrated. This reflects the situation wherein changes in groundwater quantity affect the quality of groundwater (i.e. saline intrusion, artificial recharge). The response (R) component in the center means that the responses to the subsurface environmental problems are varied and directed either to driving forces, pressure, state or impacts, or to a combination of these components.

6. Driving forces (D)

The unprecedented growth and intensive industrialization, especially during the early stages of development in the urban

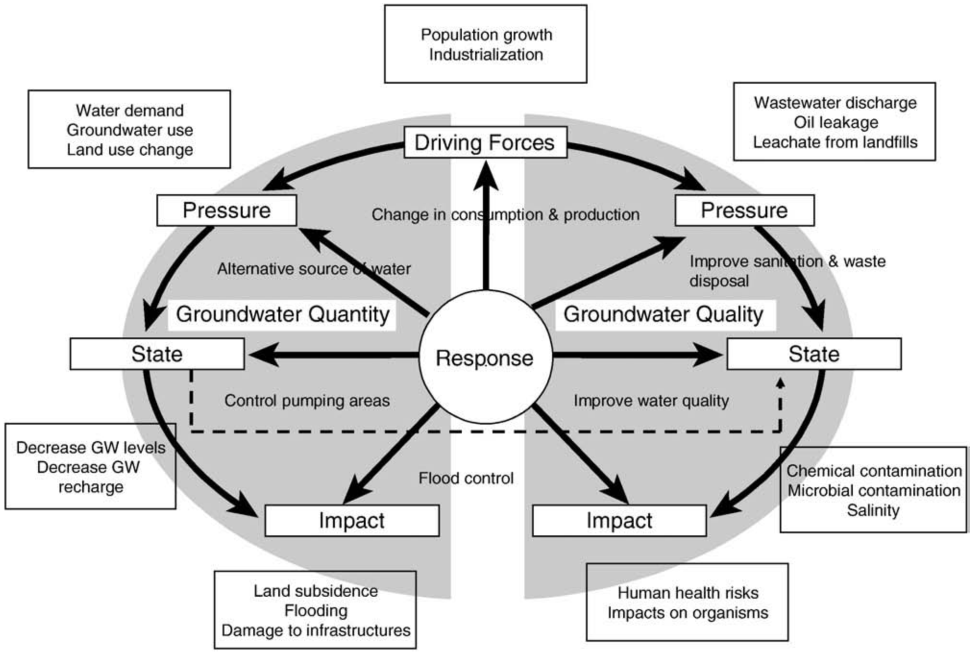

Fig. 1 – DPSIR framework and subsurface environmental problems.

areas are the common driving forces that exert pressure and cause changes in the subsurface environment. Growth in population size and density, economy, and space (built-up areas and administrative boundaries of urban areas) has increased the demand for water. The associated industrialization in metropolitan areas resulted in increasing demand for water in manufacturing of products, cooling and cleaning purposes. Industrialization has promoted changes in land uses to accommodate additional location for manufacturing industries and its related service sectors.

7. Pressures on groundwater quantity and quality (P)

Water usage increases with the increase in population and improvement in people's socio-economic condition. Likewise, the change in the industrial structure from agriculture to manufacturing also resulted in high demand for water in production, cooling and cleaning purposes. The increased demand for labor in manufacturing and service sectors encourages migration of people to urban areas. Increasing population size and density result in increased pressure on food, water supply and sanitation services. Groundwater is often preferred by households and industries because of its reliability, especially in places where surface water is unstable, and because of its lesser cost. Moreover, groundwater is also preferred because of its superior quality and the belief that it is pure and devoid of any harmful substances. Textile, food and beverage, and chemical industries prefer to use groundwater because piped water is often subjected to chlorination in the purification process before distribution by the waterworks system.

During this period of rapid population expansion and high economic productivity groundwater abstraction began to increase. Before the establishment of industrial waterworks which take water from rivers and lakes, industries in Osaka and Tokyo relied heavily on groundwater since the 1950s. In Taiwan, due to its unusual geographic condition (almost two thirds of the island consists of steep terrain) and hydrologic conditions, surface water resources are limited (Hsu, 1998). Thus, in the 1950s, a groundwater development agency was created to explore groundwater potential in the whole island, including Taipei Basin (Wu, 1992). Uncontrolled large scale abstraction of groundwater in Taipei Basin for industrial purposes, cooling of buildings and domestic supply started in 1957 (Wu, 1976). As Bangkok began to develop in the 1950s, surface water supply failed to cope with the increasing demand from the population and industries. Large scale development of groundwater resources for public water supply started in 1954, and increased over the years, with more wells commissioned in areas where public supply facility was not available (Das Gupta and Babel, 2005).

Another important pressure in groundwater quantity is the change in land cover and use. Industrialization promoted land use changes to accommodate additional location for factories and related service sector. Land uses were also altered for infrastructure development such as roads, railways, transportation networks and services, to enhance accessibility to production and distribution centers and promote mobility among the population. More and more lands were also needed for housing facilities to accommodate increases in the number of households. These changes in land cover and uses reduce the recharge capacity of aquifers by increasing impervious areas.

Households and manufacturing industries which consume large quantities of water because of its excellent quality can also produce large quantities of waste which contaminate the groundwater systems. Pathways of entry of contaminants into groundwater systems depend largely on patterns of waste disposal and human interaction with the environment. In urban areas, most of contaminants in groundwater can come from point sources such as septic systems, landfills, fuel storage tanks that may leak gasoline or other petrochemicals, or wastewater systems that may leak effluents from metals and other chlorinated solvents. Waste buried in landfills and other garbage dumps is subject to leaching by percolating groundwater. Some sources of aquifer recharge in urban areas also affect groundwater quality. On-site sanitation systems, leaking sewers which can contribute to groundwater recharge also contain potential contaminants such as nitrates, boron, chlorides, flourocarbons and sulfates (Eiswirth and Hotzl, 1997; Foster et al., 1998). A list of contaminants that are major threats to the groundwater is given by Sampat (2000) and Morris et al. (2003). Nitrogen oxides from the atmosphere can also be a potential groundwater contaminant. Overpumping also causes a particular type of pollution where the depletion of the aquifers fosters the intrusion of saltwater (Das Gupta and Sabanathan, 1998).

8. Changes in the state of groundwater quantity and quality

The increased in groundwater withdrawal can cause a massive decline of piezometric levels in aquifers. The extraction of groundwater may be balanced if groundwater recharge can offset the amount being taken. However, as has been mentioned, changes in land cover and uses in urban areas greatly affect the recharge capacity of aquifers. As building density rises and the ratio of built-up areas increases, the extent of impervious area also increases. These can modify the natural drainage system and the proportion of incident that appears as runoff becomes bigger, compared to when the area was not yet developed (Hall, 1984). Since the volume of runoff becomes larger with the onset of development, the amount of soil moisture recharge is reduced. Consequently, less water is likely to percolate into any aquifer underlying the urban area, thus affecting groundwater recharge rate. In a study of Kim et al. (2001) in Seoul, estimates of precipitation recharge rate in groundwater reveal that rural and mountainous areas have higher recharge rates of 5 and 16% respectively, while built-up areas (houses, industries, schools and rails) ranged from 2 to 3%. Roads have the lowest recharge rate of only 0.2%.

As mentioned earlier, groundwater is preferred by many because of the belief that it is clean. However, groundwater may not always be in its pure and clean state. According to Egboka et al. (1989), any groundwater system may be naturally polluted or contaminated to a certain degree at all times and the concern is whether the amount of measurable contaminants is within the acceptable limits of groundwater quality. Some groundwater also naturally contains chemicals, such as arsenic and fluoride, which can be detrimental to health. Foster (2001) classified groundwater quality problems into three: anthropogenic pollution, naturally occurring pollution and well-head contamination. Discharges from population and industrial activities contain pathogens, nitrogen compounds, chlorides, sulfates, boron, heavy metals, dissolved carbons and other contaminants (Morris et al., 2003). Although limited in urban areas, nitrates, chlorine and pesticides, are matters of concern in intensive agricultural practices. Contaminants in groundwater may also consist of pathogens and other microorganisms that are harmful to the health (Crane and Moore, 1984; Dillon, 1997). Declines in groundwater levels due to overpumping can result in the contamination of groundwater by saline water.

9. Impacts of decreasing groundwater levels and groundwater quality (I)

In the subsurface water occupies spaces between the soil and rock particles. When water is pumped from an aquifer, empty spaces are developed between the particles that then become more tightly packed. Continued pumping of groundwater without adequate recharge (replacement) causes the sediments to become increasingly compressed making the upper surface settle or subside (Ramos, 1998). This phenomenon of land subsidence has been observed in different urban areas in Asia such as Tokyo (Yamamoto, 1984a; CEC, 2006), Osaka (Osaka Prefecture, 1971;Yamamoto, 1984b), Taipei (Wu, 1976), Bangkok (DMR, 1992; DMR-JICA, 1995; Phien-wej et al., 2006; Ramnarong, 1999; UNESCAP, 2001), Jakarta (Abidin et al., 2001; Soetrisno, 1999) and Manila (Ramos, 1998; Rodolfo and Siringan, 2006).

Land subsidence can cause damage to infrastructure such as roads, sewers and pipelines because of the creation of subsidence bowls. One example is the Huay Kwang Waste Water Treatment Plant (WWTP) which was built in 1975 in the northern part of Bangkok (UNESCAP, 2001). Wastewater leaks to the ground caused by the breakage of wastewater sewers leading to the Huay Kwang WWTP can pollute groundwater and increase the risks of water-borne diseases. Subsidence causes cracks in the ground, roads, and buildings in Jakarta (Abidin et al., 2001). Land subsidence does not only affect flooding and tidal incursion, but in some cases it can trigger minor seismicity (Yerkes and Castle, 1976).

When an area is at almost sea level with natural ground elevation, the most serious impact of land subsidence is flooding. Land subsidence can increase the size of flooded areas and prolong the time an area is flooded. Since Bangkok is almost at sea level, with natural ground elevation ranging from 0.5 to 2.0 m, land subsidence worsens the impact of floods during the rainy season (Holzer, 1985). Notable floods occurred in 1983, 1995 and 1996, which cost billions of baht in infrastructure damages such as in the foundations of buildings, roads, bridges and buried pipelines (UNEP, 2001). When floods occur, the water brings in a lot of wastes, excrements and garbage that can cause water-borne diseases, such as cholera, typhoid, dysentery, hepatitis and diarrhea, among others. Flooded areas form a good breeding ground for mosquitoes, which are also carriers of diseases.

Another consequence of the lowering of the piezometric level of the aquifers is the intrusion of saline water in the aquifers. When saline water mixes with groundwater, groundwater becomes undrinkable and wells have to be abandoned. Saline water also causes other environmental changes that can harm vegetation.

Groundwater contaminants from domestic and industrial sources can cause severe degradation of groundwater quality, produce changes in the structure and functions of the ecosystems, and very importantly, threaten the health of humans. Diseases related directly to drinking water are most likely to result from consumption of poorly protected or unimproved groundwater sources, untreated or poorly treated surface water, contamination of distribution systems and recontamination of water during transport (Schmoll et al., 2006). However, diarrhea and other water-borne diseases can also be transmitted due to poor sanitation practices. Lee et al. (2002) found that twenty-nine (74.4%) of the 39 drinking water outbreaks in the US, including the outbreak associated with bottled water, were associated with groundwater sources (wells and springs). In developing countries the limited evidence of the role of groundwater in causing disease outbreaks reflects the often limited capacity of local health monitoring systems to identify factors or causes of the spread of diseases, especially when several factors may be implicated in the spread of diseases (Schmoll et al., 2006).

10. Responses to groundwater problems

Problems in the subsurface are often detected because of their impact on the environment above the ground and to the population as well. In most cases, the effects of excessive groundwater abstraction were not perceived and detected until land subsidence occurred which resulted to huge damages in infrastructures, buildings, and induce flooding in low areas. In the initial stage, when flooding was not recognized as an effect of land subsidence, most responses were devoted to repair of structures damaged by inundation of water, construction of flood control and prevention infrastructures, such as dikes and floodways. When the impact of the subsurface problems began to place a heavy toll on development, more efforts and studies were undertaken to understand the dynamics of the changes in the state of the subsurface and the responses were then directed to decreasing the pressures created by massive groundwater use. In the selected areas strategies on groundwater management include regulatory policies, economic instruments, provision of alternative supply of water, information gathering, monitoring and public awareness programs, and other supporting measures. These major laws and regulations related to groundwater management are given in Tables 2 and 3.

11. Stages of urban development

11.1. *Stage 1: D–P–S–I stage*

The early stage of urban development is described as the stage of intensive growth in the population, economy, urban boundaries, and the change in industrial structure. In relation to the

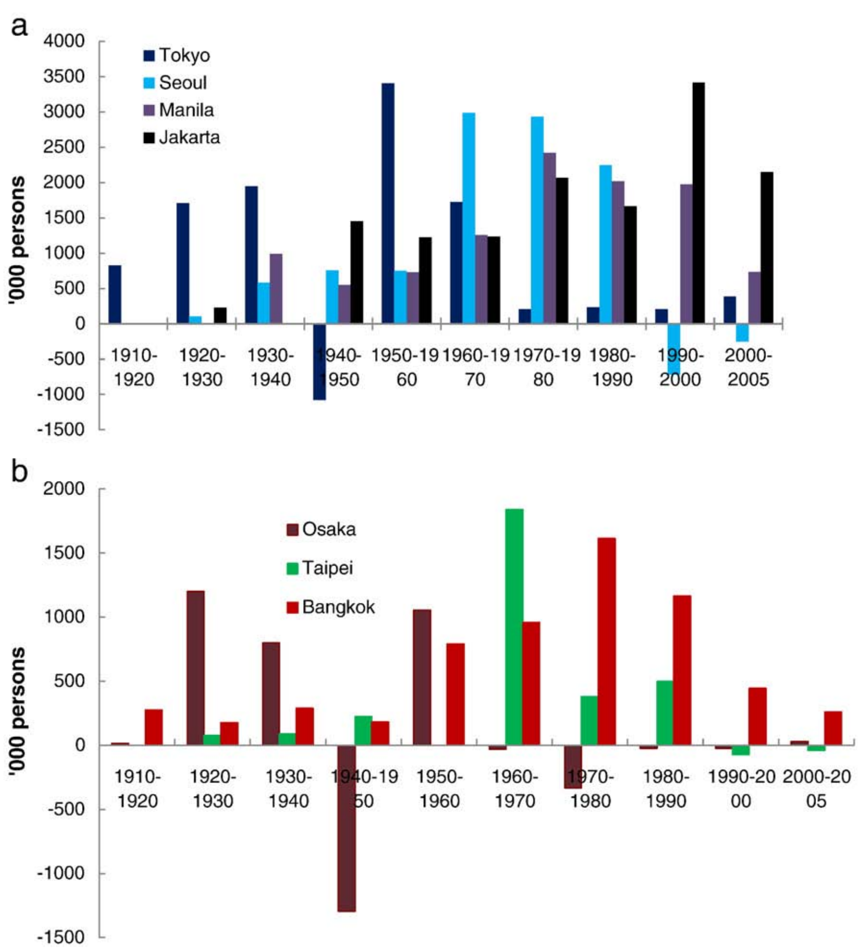

Fig. 2 – (a) Population increase (decrease) in Tokyo, Seoul, Manila and Jakarta (1910–2005). Source: compiled from Abeyasekere (1987), JICA (1992), Magno-Ballesteros (2000), NSO, (2004), UN (2006), SDI (2005). (b) Population increase (decrease) in Osaka, Taipei and Bangkok (1910–2005). Source: compiled from DBAS (2004), NSO (2006), UN (2006), Wilson (1983).

subsurface environment, the experiences in these urban areas during this stage revealed high consumption of groundwater, especially by industries. This is also the period of detection of subsurface problems such as declining groundwater levels and land subsidence.

The rapidly changing structural situation in Asia since the 1950s had an impact on the social and spatial organization of societies. The labor force shifted from agriculture to manufacturing and service sectors in urban areas. Population grew at unprecedented rate and speed. This is not only due to natural increase, but also of the increased migration of people from rural areas who were attracted to employment in the cities. Considerable improvements in transportation and communications have promoted greater accessibility of regions to the urban centers.

Fig. 2a,b shows the population increases or decreases by decade in the selected urban areas from early 20th century to 2005. Fig. 2a shows the urban areas with a current population of more than 10 million people, while Fig. 2b shows the urban areas with less than 10 million people. Tokyo's population was already 6 million in the 1950s, while Seoul, Jakarta and Manila had only around 1.5 million people. However, remarkable increases occurred after the 1950s, with as much as 2 to 3 million people were added in a span of a decade. This happened in Tokyo from 1950–1960; in Seoul from 1960–1980 and in Jakarta and Manila, from 1970–1990. Osaka's population in 1950 was 2 million and it only increased by a million from 1950–1960. From 1960 until 2000, the city experienced negative growth rates as people moved to the suburbs but in recent years it started to slowly increase its population. Taipei's highest increase in population was from 1960–1970, however after 1970s, the growth was slower and since the 1990s, it has been experiencing negative growth, as the population shifts to suburbs. In 2005 the population of Osaka and Taipei was about 2.6 million. Similar with Jakarta and Manila, Bangkok also had around 1 million people in the 1950s, however its growth rate was lower compared with the two urban areas. In 2005 Bangkok had 6 million people.

Most of these increases were the result of massive in-migration as plenty of jobs were available in these urban areas with the start of industrialization and modernization process. However, the pace of population increase began to slow down in the 1990s due to suburbanization with the

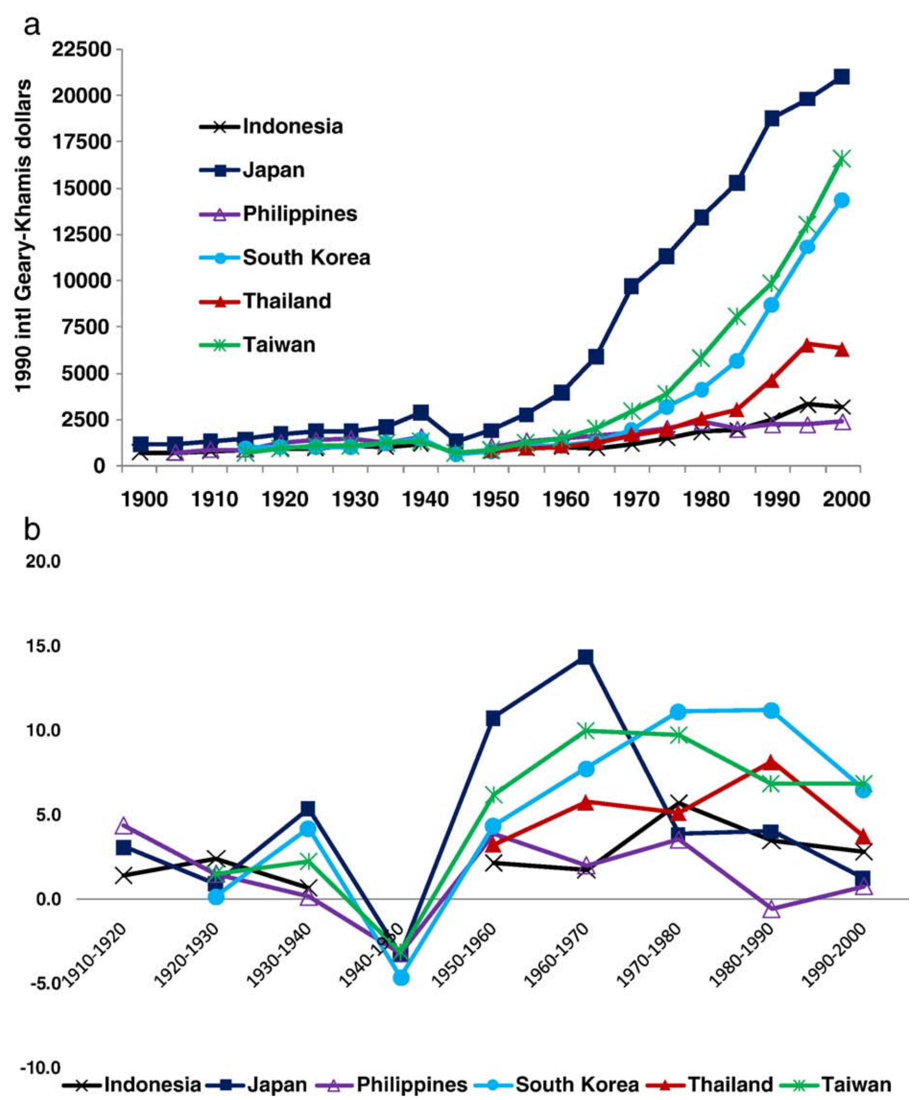

Fig. 3 – (a) GDP per capita from 1900–2000. (b) GDP per capita growth rate (%).

development of new residential towns and relocation of industries outside the urban centers. The increase in population was also brought by the extension of some administrative boundaries. Dramatic expansion of the Seoul area happened in 1963, from 268 km^2 in 1949 to 613 km^2, with the inclusion of the significant portion of surrounding Gyeonggi province into the city (SDI, 2005). When Taipei became a special municipality as an economic and political center of Taiwan in 1966, the land area increased from 85 km^2 in 1932 to 272 km^2. Six municipalities were added to the territory of Taipei (DBAS, 2004). Bangkok and Thonburee municipality combined in 1971 with a total land area of 290 km^2. Two years after, it expanded to include additional districts and formed the Bangkok Metropolis with a total area of 1558 km^2. Metro Manila is also an integration of 17 formerly distinct municipalities. The consolidation into a metropolitan region first started in the 1940s and the final political reconstitution of the metropolitan region took place in 1975 with an expanded area of 636 km^2 (Balisacan et al., 1994).

The period of growth and development of these urban areas have been well documented in several studies such as in Tokyo (Glickman, 1979; Osada, 2003; Takahashi and Sugiura, 1996), Osaka (Glickman, 1979; Edgington, 2000), Seoul (Hong, 1996; Kim, 2003; Mills and Song, 1979), Taipei (Speare et al., 1988; Tsai, 1996), Jakarta (Abeyasekere, 1987; Soegijoko, 1996; Herderson et al., 1996), Bangkok (Krongkaew, 1996; Murakami et al., 2005; Sternstein, 1982) and Manila (Balisacan et al., 1994; Caoili, 1988; Pernia et al., 1983).

In most of the urban areas, this period of high population growth rate is accompanied by rapid growth in the economy. Japan increased its industrial production after its rehabilitation from the war and most of the industries were established in the three metropolitan areas of Tokyo, Osaka and Nagoya (Glickman, 1979). Seoul's and Taiwan's industrial output also increased from the 1960s. Fig. 3a shows the trend in GDP per capita from 1900. Japan started to grow its economy from the 1930s but its income greatly increased with GDP per capita of 2000 dollars in 1950 to almost 10,000 dollars two decades after. The economies of Seoul and Taipei increased from the 1960–1990 with an average annual GDP per capita growth rate of 8 to 11%. All the countries with the exception of the Philippines experienced high annual growth of more than 5% from 1960–1990 (Fig. 3b).

Fig. 4 shows the trend in groundwater abstraction in the selected urban areas. There is a shortage of full information for the same period of time because some areas have either started monitoring later or have not done the monitoring of groundwater continuously. In the 23 ward areas of Tokyo (Tokyo Ku), the peak of groundwater usage was in 1964 with a daily abstraction of 1.162 million m^3. Tokyo's groundwater is utilized both for domestic and industrial use (Fig. 5a). However, this figure began to decrease in 1966 and it fell to 128,000 m^3 per day in 1975. Similarly in Osaka, trends in the rise and fall of groundwater use changed according to the stage of economic growth. After rehabilitation from war, groundwater use increased and peaked in the 1960s, with a volume of around 395,000 m^3 per day. Groundwater withdrawal in Osaka after the 1950s was mostly for industrial purposes (Fig. 5b).

In the case of Taipei, the data of Wu (1976) is used for the information on groundwater abstraction. Average daily groundwater use in Taipei in 1957 was only 25,000 m^3, but since then consumption rapidly increased and peaked in 1970 with a rate of 1.192 million m^3. The quantity of groundwater abstraction in Jakarta seems to be very low compared with other metropolitan areas. This may not reflect true values as the percentage of wells registered is lower than the actual number of industries using groundwater and there is the concomitant difficulty of monitoring industries' actual groundwater use (IWACO, 1994). The actual deep well abstraction is estimated to be at least 3 times higher than the registered deep groundwater abstraction. Groundwater use in Bangkok includes abstraction from adjacent provinces of Nonthaburi, Pathum Thani and Samut Prakan from 1954 to the

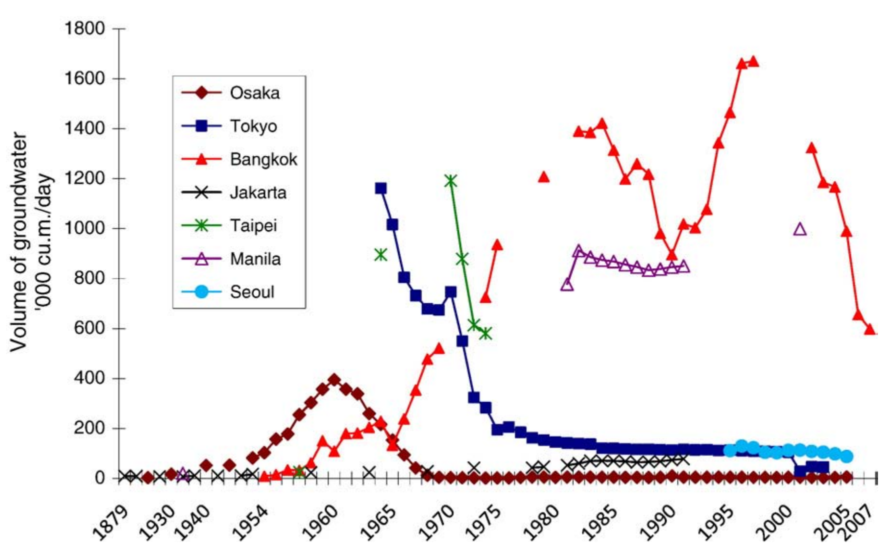

Fig. 4 – Groundwater abstraction in selected metropolitan areas in Asia. Sources of basic data for Osaka: Osaka Prefecture Government; Tokyo: Bureau of Waterworks and Bureau of the Environment — TMG; Bangkok: DMR, DGR; Seoul: GIMS, 2006. The data for Jakarta are compiled from IWACO (1994); for Manila, from JICA (1992), Rodolfo and Siringan (2006); and for Taipei from Wu 1976, 1992.

present. During the start of the large scale groundwater development for public supply, the rate of abstraction was around 840,000 m^3 per day. Total groundwater abstraction increased and first peaked in 1984 with a rate of 1.4 million m^3 per day, however it decreased from 1985–1990. A large proportion of the groundwater withdrawn is used for industrial purposes (Fig. 5e). From 1991–1997, private use of groundwater increased again, however from 2002, the rate of abstraction decreased until the present. The Metropolitan Waterworks Authority (MWA) limited the use of groundwater from 2001.

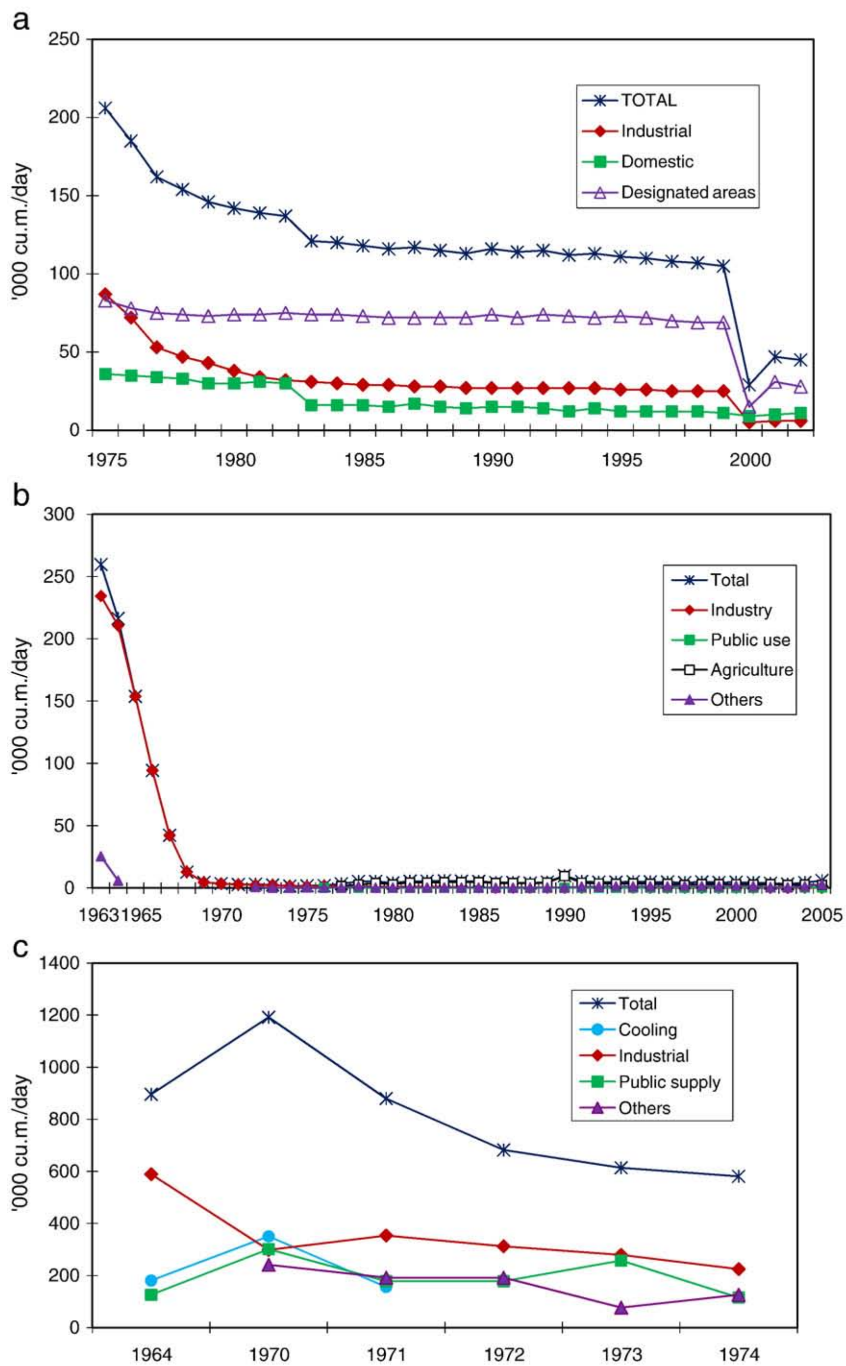

Fig. 5 – (a) Volume of groundwater abstraction by sector in the 23 Ward Areas of Tokyo. (Before 2000 the volume of groundwater from small wells (diameter of less than 21 cm^2) was estimated as 99,000 m^3/day, but after 2000 when regulations were changed and small industries were required to report their actual consumption, the reported volume of abstraction was found to be less than the previous estimates. This resulted in a sharp decrease in volume since 2000). (b) Volume of groundwater abstraction by sector in Osaka city. (c) Volume of groundwater abstraction by sector in Taipei Basin. (d) Volume of groundwater abstraction by sector in Seoul. (e) Volume of groundwater abstraction by sector in Bangkok. (f) Volume of groundwater abstraction by sector in Manila.

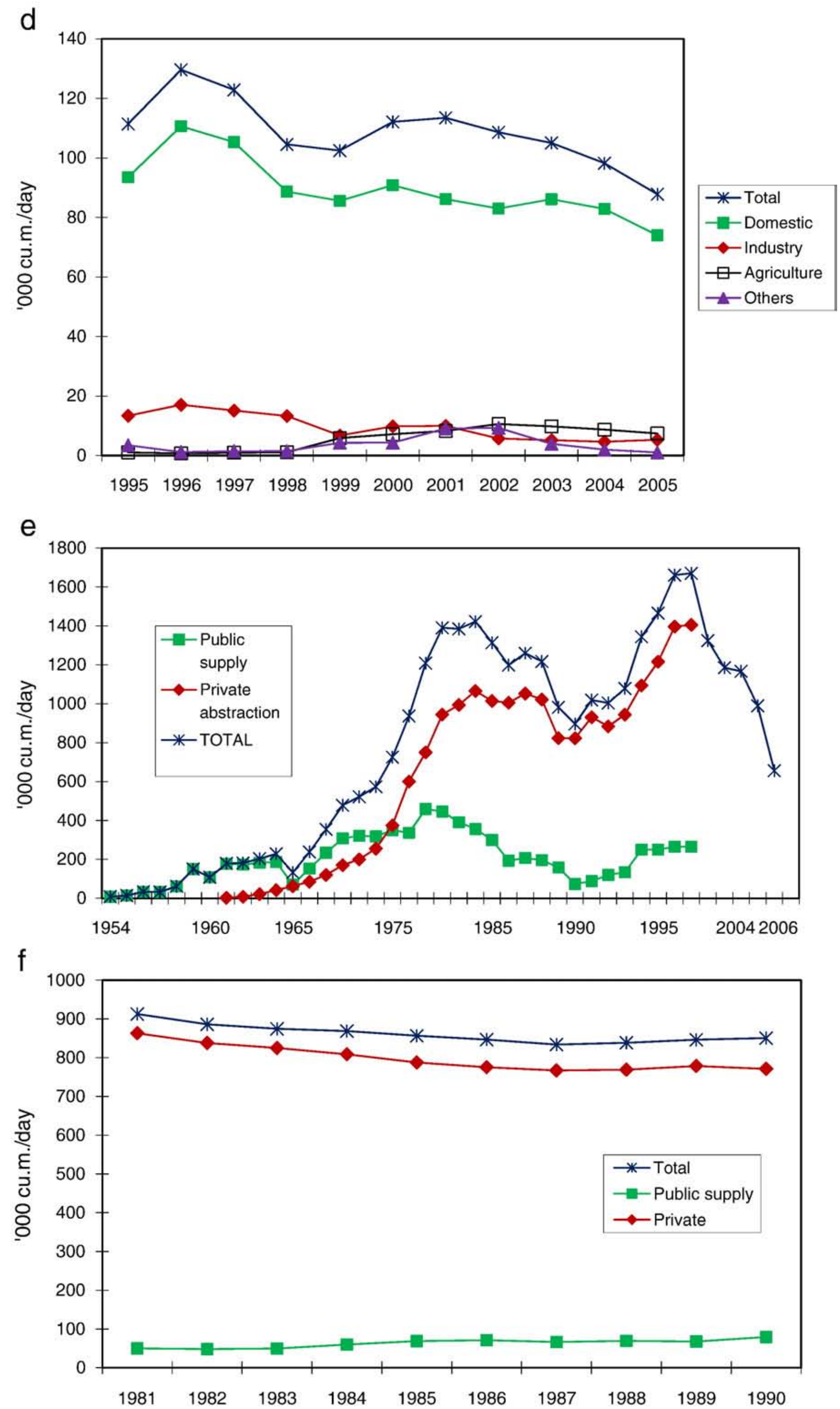

Fig. 5 (*continued*).

In Manila, groundwater abstraction in 1930 was only 20,000 m^3 per day and in 1970 the recorded daily abstraction was 250,000 m^3. A steep increase occurred a decade later when in 1981 the daily abstraction was recorded at 913,000 m^3. Although the trend seems to be decreasing years after, as in Jakarta, the inefficiency in monitoring of actual pumping rates and groundwater use by industries poses a great problem for accurate estimation of abstraction rates, and values recorded may not reveal the volume of actual consumption. In terms of groundwater use by sector, Fig. 5f only shows values from 1981 to 1990.

The massive abstraction of groundwater has lowered groundwater levels. Fig. 6 shows groundwater levels in selected monitoring points in Tokyo, Osaka, Taipei, Bangkok and Jakarta. The trend in Tokyo shows a lowering and rising of groundwater levels. This is concomitant to the period of massive groundwater abstraction and control. Data on Osaka and Taipei only show the rise in groundwater levels from 1965 and 1976, respectively, which was the beginning of groundwater control. The rise and fall of groundwater levels in Bangkok also reflect the pattern of increasing and decreasing groundwater abstraction in the area. There is barely a trend in Jakarta because of the short period of available monitoring data.

Because of uncontrolled groundwater abstraction, land subsidence posed great problems and some of these subsidence records are given in Table 1. From 1938–1975, the maximum subsidence in Tokyo was about 460 cm and the maximum rate was 2.7 cm/year (Yamamoto, 1984a). From 1934–1968, the subsidence rate in Osaka was 8.2 cm/year. Yamamoto (1984b) described four phases of land subsidence in Osaka, to show increases in massive groundwater abstraction and decreases in groundwater levels when regulations on groundwater were imposed. In Taipei City, rapid subsidence rates of 28 cm/year (east side) and 24 cm/year (west side) occurred from 1957–1974 and the total subsidence reached 117 cm and 90 cm, respectively (Wu, 1976). Nutalaya et al. (1996) reported that the largest subsidence in Bangkok city from 1933–1987 was 160 cm. The latest data from Phien-wej et al. (2006) showed that subsidence increased to 205 cm in 2002. In the Jakarta area although there has been limited subsidence data up to the present, results from the leveling surveys in Abidin et al. (2001), revealed that the maximum land subsidence for the period 1982–1991 was almost 80 cm while during the period of 1991–1997 it is about 154 cm. The rates of land subsidence during the period of 1991–1997 are generally larger than those from 1982–1991. From the period 1980–1999, subsidence was already 206 cm. In the northern part of Metro Manila, subsidence rate was around 5 cm/year from 1991–2003 and the subsidence area was more than 100 cm (Rodolfo and Siringan, 2006).

11.2. Stage 2: R — Quantity stage

During the initial stage of urban development, massive abstraction of groundwater has caused land subsidence problems. To solve these problems, various regulations on groundwater control and management were implemented as shown in Table 2. The second stage is focused on responding to groundwater quantity problems.

In Japan surface water is governed under the “River Law”, however there is no specifically defined law on groundwater. The regulations on groundwater utilization were implemented in pursuant to the Industrial Water Law in 1956 and the Law Concerning Regulation of Pumping-up Groundwater for Building Use (Building Water Law) in 1962, to prevent land subsidence (Osaka City Waterworks Bureau, 2004). The Industrial Water Law specifies restriction on groundwater pumping in designated areas. This regulation also promoted conservation of water and the establishment of waterworks for industrial use. The Building Water Law imposes restrictions of pumping of groundwater for building use, such as for air-conditioning, flush toilets, vehicle washing, etc. These two regulations were both implemented in Osaka and Tokyo. Supporting measures include projects for securing alternative water resources to shift the use from groundwater to surface water. Osaka City constructed industrial waterworks system in 1962 to provide surface water for industries. In 1970, the Osaka Prefectural government also established its industrial waterworks system, using water from the Yodo River, a tributary of Biwa Lake, the largest lake in Japan. Industrial water supply started in Tokyo in 1964.

Taipei began to decrease its groundwater abstraction after the imposition of groundwater control regulations in 1977. Importation of surface as an alternative supply began in 1985. The situation of land subsidence in Taipei Basin has improved after the importation of surface water since 1985 and a steady decrease of the subsidence rate has been successively recorded. Groundwater management in Bangkok consists of four major components: (1) Institutional arrangements; (2) Groundwater resources evaluation; (3) Groundwater Act of 1977; and (4) Mitigation of Groundwater Crisis and Land Subsidence program. The Groundwater Act of 1977, with amendments in 1992 and 2003, provides the framework for the management of groundwater resources in Thailand. The provisions include restrictions and control on drilling and pumpage, the introduction of groundwater charges in 1985, and the creation of the groundwater fund. In order to mitigate the worsening land subsidence problems, the government has established monitoring networks and

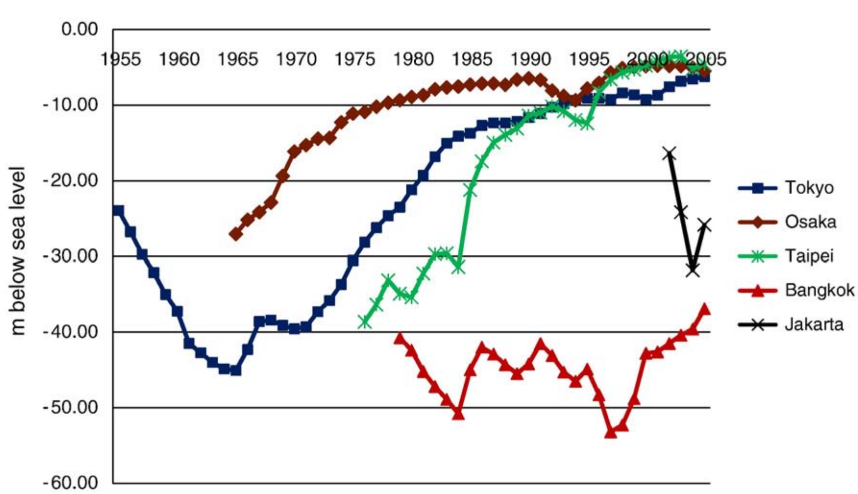

Fig. 6 – Trend in groundwater levels in selected areas in Tokyo, Osaka, Taipei, Bangkok and Jakarta.

Table 1 – Land subsidence due to groundwater withdrawal in selected metropolitan areas in Asia.

Subsidence (cm)				
Location	Period	Cumulative	Rate (cm/year)	Reference
Tokyo (Edogawa Ku)	1918–1975	238		CEC (2006)
(Koto Ku)	1938–1975	460	2.7	Yamamoto (1984a)
Osaka	1934–1968	280	8.2	Yamamoto (1984b)
Nishi Yodogawa	1936–1970	236		Osaka Prefecture (1971)
Taipei (East side)	1957–1974	117	28 (max)	Wu (1976)
(West side)	1957–1974	90	24 (max)	Wu (1976)
Taipei Basin	1955–1994	224		WRA (2008) (accessed May 4, 2008)
Bangkok	1933–1988	160		Nutalaya et al., 1996
SE part	1940–1980	114		Ramnarong (1999)
	1978–1982	54	>10	Ramnarong (1999)
	2002	205		Phien-wej et al. (2006)
Jakarta	1980–1999	260		Abidin et al. (2001)
	1982–1991		8.9	Abidin et al. (2001)
	1991–1997		26.7	Abidin et al. (2001)
	1997–1999		10	Abidin et al. (2001)
Manila	1991–2003	>100	5	Rodolfo and Siringan (2006)

designated critical areas/zones where groundwater pumpage is strictly controlled. The Metropolitan Waterworks Company has also expanded its capacity to supply water for industrial needs. Following the implementation of strict controls and economic measures, the rate of land subsidence in Bangkok decline and groundwater levels began to increase. Regulation on groundwater management in Indonesia was implemented in 1994 and it defines the framework for groundwater management which covers, inventory, supervision, and licensing of groundwater use.

Bangkok, Osaka, Taipei and Tokyo have restricted water use to control declines in water tables and land subsidence. In Manila regulations on groundwater use are subsumed under the Water Code of the Philippines which has been in placed since 1976 with amended rules and regulations in 2005. However, the policy lacks provision on land subsidence issues contrary to some other cities where such is integrally considered in groundwater policies. Most sectors of the government still ignore the fact that overuse of groundwater cause land subsidence in the plains around northern Manila Bay even though the government's Department of Public Works and Highways (DPWH) has verified this geodetically (Rodolfo and Siringan, 2006). Ameliorative measures can only begin after the problems caused by excessive use of groundwater have been recognized by the government and the public made aware of the scope and consequences of the problem.

11.3. *Stage 3: R— Quality stage*

During the second stage of urban development, groundwater management in most of the urban areas (Table 2) is primarily focused on quantity related issues and control of land subsidence. Even most of the studies on groundwater are related to groundwater quantity problems. When groundwater abstraction was controlled, land subsidence rate decreases, and the capacities of governments for groundwater monitoring increases, the concern shifted to groundwater quality issues and these become the focus in the next stage of urban development. Table 3 shows groundwater management measures from 1989 which are mostly focused on groundwater quality.

Table 2 – Relevant laws and regulations on groundwater management, 1956–1985.

Groundwater management	1956	1962	1964	1977	1983	1985
Tokyo	Industrial Water Law	Building Water Law	Establishment of industrial waterworks			
Osaka	Industrial Water Law	Building Water Law Establishment of industrial waterworks				
Taipei				Groundwater regulatory measures		Use of surface water
Bangkok				Groundwater Act	Mitigation of Groundwater Crisis and Land subsidence	Introduction of GW charges and groundwater fund

In previous years, groundwater quality was not given much attention because groundwater for domestic purposes is generally used after treatment in water purification plants. For example in Japan, seawater intrusion, pathogenic microbiological and nitrogen contamination from domestic wastewater or fertilizers were identified in the past but they were not considered serious threats assuming that pollution controls such as treatment at water purification plants would be effective (IGES, 2007). It was not until the 1980s that the Japanese government paid attention to contamination by volatile organic compounds (VOCs) and started investigation on groundwater quality in the cities of Japan, including Tokyo, which started in 1982. In order to address groundwater pollution control at the national level, the "Water Pollution Prevention Law" was amended in 1989 to set regulations on groundwater quality management and in 1997, the Environmental Standard for groundwater contamination was established (IGES, 2007).

In order to prevent and remediate soil and groundwater pollution, Taiwan promulgated the Remedying Soil and Groundwater Pollution law in 2000 (WRA, 2008). In Thailand groundwater quality standards were also established in 2000 (PCD, 2000).

The experience of Seoul is quite different from the rest of the study areas. In the previous two stages groundwater quantity issues are not discussed due to the limited monitoring data available. Groundwater monitoring data are only available from 1995 and the volume of use is quite low compared with other cities. Monitoring of water level changes indicated that groundwater recharge and discharge in the Seoul area have been approximately balanced over recent years and the resource is not endangered when it comes to quantity (Kim et al., 2001), but there are still concerns on the increase of groundwater pumping for domestic use. A more serious problem is quality degradation of shallow groundwater. It was reported in Kim et al. (2001) that numerous sections of sewers are broken or cracked and sewage interact with shallow groundwater systems by the intake of groundwater or loss of sewage. Landfills are also potential sources of contaminants in Seoul as revealed in the investigations by Lee et al. (1997). They pointed out that the leachate from the Nanjido landfill discharges into both the Han River and the groundwater system. Monitoring also revealed the effects of various discontinued landfills on groundwater quality. Park et al. (2005) investigated the contamination of Seoul groundwater by trace metals and VOCs, and its relationship with land uses. Results of the study revealed that concentrations and spatial distribution of some trace metals (especially Fe, Mn, As, Cr, Pb, Cd) and VOCs are significantly influenced by the land use in Seoul. Groundwater in the less developed areas are the least contaminated, as reflected by very low concentrations of trace metals and VOCs, while concentrations of most trace metals and some VOCs are significantly higher in the industrial, residential and traffic areas. Recognizing the problems associated with unregulated groundwater use and contamination, the government of South Korea established the "Groundwater Act" with the main objective of regulating all kinds of groundwater — development activities (Kim et al., 1995). This law also contains regulations on construction and management of groundwater monitoring networks. This law was largely revised in 1997 and again in 2001 when the concept of public water (not private water) for groundwater was adopted and obligation for remediation of contaminated water was established (Lee et al., 2007).

11.4. *Stage 4: R — Complex stage*

The first three stages describe groundwater level declines, the impacts of land subsidence, groundwater contamination, and the subsequent responses to these issues. The dynamic relations in the subsurface are not simple and there are still several uncertainties, given its "invisible" character, and the time lag between the occurrence of the problem and the realization of the impacts.

In the fourth stage of development, urban areas will be dealing with new and more complex concerns such as the impacts of recovery of groundwater potential. Fig. 7 shows 2 monitoring points (Nerima and Shinjuku) in Tokyo with groundwater levels that are above mean sea levels. The recovery

Table 3 – Relevant laws and regulations on groundwater management, 1989–2001.

Groundwater management	1989	1993	1994	1997	2000	2001
Tokyo	Amendments to the "Water Pollution Prevention Law"			Environmental Standard for Groundwater Contamination		
Osaka	Amendments to the "Water Pollution Prevention Law"			Environmental Standard for Groundwater Contamination		
Taipei					Remedying Soil and Groundwater Pollution Law	
Bangkok					Establishment of groundwater quality standards	Restricted use of groundwater in MWA
Seoul		Groundwater Act				
Jakarta			Regulation on Groundwater Management			

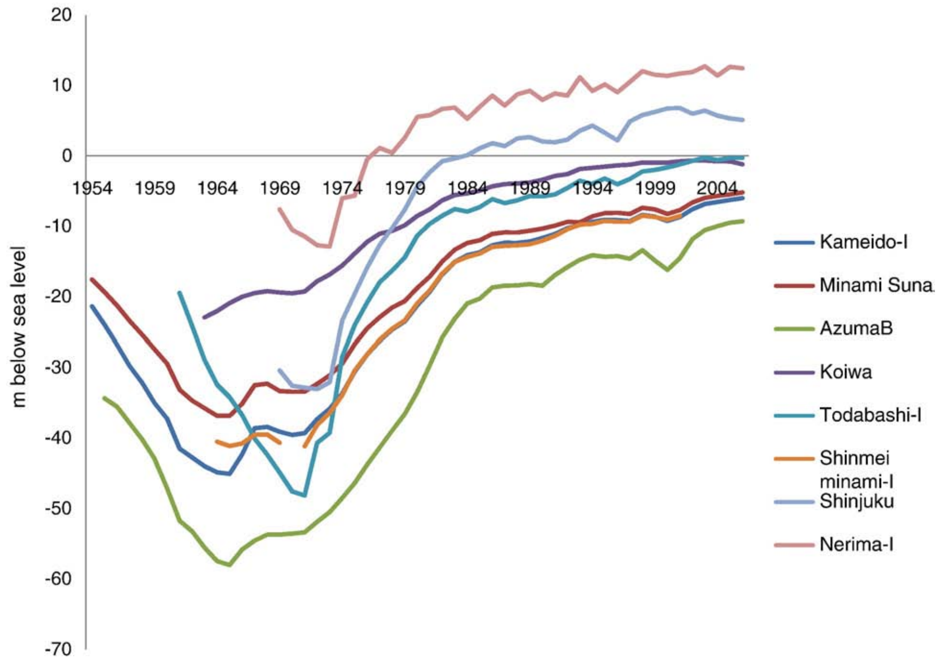

Fig. 7 – Trend in groundwater levels in the 23 Ward Areas of Tokyo, 1954–2005.

of groundwater potential can create new types of damages to the underground infrastructures which have been constructed during the drawdown period as happened in underground structures of Tokyo and Osaka (Tokunaga, 2005). Seoul pumps groundwater in order to dewater subway facilities and construction sites (Kim et al., 2001).

Another issue is the effect of urbanization on the changes in subsurface temperature. Subsurface temperatures in Tokyo, Osaka, Seoul and Bangkok have been evaluated to estimate the effects of surface warming due to urbanization and global warming (Taniguchi et al., 2007). The heat island effect due to urbanization on subsurface temperature is important as this may alter groundwater ecosystems.

12. Discussion

The DPSIR framework is effective in understanding the effects of rapid urbanization and industrialization on the subsurface environment. By reviewing subsurface environmental issues in seven metropolitan areas in Asia, the timing of occurrences of groundwater problems and impacts, and the focus of responses were identified in key stages of urban development. In the early stage attention was focus on declining groundwater levels and land subsidence problems. Responses to control groundwater abstraction were effective when adequate alternative surface water supply became available. The shift in industrial structure from heavy water intensive manufacturing industry to less water intensive service sector has also reduced the stress on groundwater resource. As the cities developed, they have taken preventive and remediation measures on groundwater contamination. But groundwater quality still remains a challenge in places with insufficient sewerage, wastewater treatment facilities, and unsanitary waste disposal systems.

The DPSIR components identified in this article can help anticipate effects of urban development on the subsurface environment which will be helpful in urban planning efforts. The experiences of these metropolitan areas will serve as lessons for other developing cities which have not yet established effective institutions on groundwater management. However, with complex subsurface environmental issues to confront in the future, there is a need to develop concrete indicators of urban development for DPSIR analysis in future researches, such as: (1) growth (population, economy and space); (2) change in industrial structure of society; (3) development of water resources (groundwater and surface water); (4) development of water related infrastructure and technology (water purification, wastewater treatment, sewerage, etc.); and (5) establishment of institutions (laws, regulations, responsible agencies, stakeholders participation, etc.) related to groundwater management.

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