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ORIGINAL ARTICLE

Current water uses, related risks, and management options for Seoul megacity, Korea

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Abstract
Megacities worldwide face various challenging tasks associated with expanding populations and land exploitations; these include securing water supplies, appropriate operating of wastewater treatment/disposal, and the mitigation of natural hazards triggered by anthropogenic activities. Seoul megacity, Korea, where over ten million people populate, is not an exception to the issues. In this study, we examine water resources, their uses, and issues associated with them, specifically climate change, urban flooding, underground water seepage, and land subsidence in Seoul. The changing climate of this city manifests itself in a sharp escalation in air temperature. Increased torrential rainfall causes repeated human casualties from urban floodings, which are exacerbated by expanding impervious surface. The increasingly large interannual variability in precipitation makes it more difficult to take proper actions to secure water supplies. Despite a large annual budget being devoted to producing tap water from the Han River, only about 5% of the population drinks the tap water. Underground transport routes (subway lines) and high storied buildings with deep foundations produce high volumes of underground water seepage, and most of the valuable water resources are dumped without being reused. Underground water seepage also triggers a decline in groundwater levels and elevates the possibility of land subsidence. Recent increases in land subsidence and road sinks in the city are mostly related to old sewer lines and heavy underground work. In this study, we discuss options toward supporting sustainable urban water management in Seoul.

Keywords Urban sprawl · Water supply · Climate change · Groundwater · Land subsidence · Seoul · Water management

Introduction

Metropolitan regions which typically comprise over ten million residents face critical challenges in water management (Chan and Yao 2008; Kumar et al. 2015; Baklanov et al. 2016). The growing population and land exploitation lead to an increased water demand, resulting in degradation of water quality (Varis et al. 2006; Li et al. 2015; Sun et al. 2015; Kim et al. 2016). Overdraft of groundwater and construction of heavy buildings often cause land subsidence in urban areas (Gambolati and Teatini 2015; Qin and Perissin 2015; Kim et al. 2016; Ye et al. 2016). Urban floodings also frequently occur and have devastating environmental and social impacts (Haddad and Teixeira 2015; Mark et al. 2015; Costa et al. 2016; Yin et al. 2016). Thus, highly urbanized megacities are hot spots susceptible to both natural and anthropogenic stresses. Changing climate aggravates anthropogenic disasters and complicates the water management system in megacities (Alam and Rabbani 2007; Hunt and Watkiss 2011; Folberth et al. 2015). Concepts, plans, and programs to improve urban sustainability, however, are hampered by intensified land use and polarized societal perceptions toward climate change (Weber 2010).

Securing water supply is crucial to continued urban development. Because available water resources are limited and meteorological extremes (drought and floods) are more common, it has become increasingly difficult over the years to secure adequate water resources (Lohani et al. 2015). For megacities, river (surface) water and groundwater are the major water resources (Tortajada 2003; Lundqvist et al. 2005; Howard 2013). The extensive area covered by impermeable pavement prevents rainfall infiltration into the subsurface, which then reduces groundwater recharge

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rates and dramatically increases surface runoff; these factors consequently cause urban floods (Lee and Han 2013; Kim et al. 2016). Myriad subway lines, skyscrapers with deep underground spaces, and widespread construction sites also displace substantial amounts of groundwater, which are directly discharged into ditches; consequently, the stability of buildings and available water resources are greatly affected (Lee 2016).

Leaks in the municipal waterworks and sewer lines beneath the ground surface are other difficult problems to tackle (Kim et al. 2001; Lee et al. 2005). Replacement of the old mains would improve water arrival rates (accounted water rates) from water intake stations to individual houses. However, underground networks are complicated and possess varying ages of installation; the leakage problem is a formidable task to solve. All the municipal components mentioned above collectively influence the urban water budget, and all the cycles are interconnected; a holistic water management plan is thus required to sustain a megacity. The management must include efforts from both the government and the citizens, and sufficient financial investments must be made to devise mitigation measures (Kim et al. 2016; Lee 2016).

There were 28 cities declared as megacities home to 12% of the world's urban population, according to UN in 2014 (UN 2014). Among those, 16 megacities including Seoul are located in the Asia. There is an estimation of 13 new megacities in the less developed regions by the end of 2030 (UNESCO 2016). Each megacity has specific regional conditions like geographical location, climate, hydrogeology, population, and economic situations. Nevertheless, they all are facing similar water management challenges. To overcome water-related challenges has become a key role in the achievement of the Sustainable Development Goals (SDGs), specifically Goal 6 of the Agenda 2030, to achieve universal access to water and sanitation. A critical review of water-related problems and the options for their solution in a megacity would provide the water management opportunities to other megacities, facing the similar situation.

This paper examines the water resources, their uses, problems associated with them and their possible solutions in Seoul megacity. About 20% of Korea's total population lives in the only megacity of Korea, which constitutes only 0.61% of the area of whole country. This overcrowded city has been suffering from critical issues related to water management. In this study, we share our water-related experiences of Seoul megacity, and the objectives were to (1) analyze the reasons for and drivers standing behind the water use and its change over time; (2) critically insight into the potential interventions as climate change, urban flooding, underground water seepage, and road sinks/land subsidence, causing hindrances in the water management; and (3) develop the management options to cope with future water challenges in Seoul.

Methods and data resources

Study area

Korea is located in the northeastern part of the Asian continent, between the latitudes 33°N and 43°N and the longitudes 124°E and 132°E (Fig. 1a). It constitutes half of the Korean peninsula and is surrounded by the East, South, and West (Yellow) Seas (Fig. 1b). The city of Seoul is in the northwestern part of the country. The Han River, the second longest river in the country, flows through the center of the city from east to west, draining into the West Sea (Fig. 1c). The city measures 30.3 km from north to south and 36.8 km from east to west and has a total area of 605.21 km^2 with a population of 10,297,138 as of 2015 (Seoul Metropolitan Government (SMG) 2016). The metropolitan city consists of 25 self-governed districts (called "Gu" in Korean), each with an area ranging between 9.96 and 47 km^2 (mean = 24.21 km^2).

Seoul has been the capital of Korea for more than 600 years, since 1394, when the Joseon Dynasty (1392–1910) was founded. During the reign of the Joseon Dynasty, the central city consisted of inner and outer areas mainly located to the north of the Han River (Fig. 2a). The area measured about 16.5–25 km^2 and had a resident population of around 200,000 people (SMG 2016). Through the historical periods, Seoul extended into the area that lays to the south of the Han River, thus increasing its area and population over time. A modern administrative system was established with the further subdivision of districts in 1973. There have been 25 districts in Seoul since 1995.

The growth of the city area and population has led to the steady development of transportation roads (Fig. 2b). Until 1966, only a limited number of roads were present, mainly in residential and commercial areas. In 1972, the total road length was 5992 km and 53.6% of it was paved (SMG 2016). The road network was extended to 7999 km in 2000 and 89.5% of it was paved, and it accounted for about 13% of the total city area. In 2014, the road network had a total length of 8214 km, a 100% of which was paved, and it presently accounts for 13.9% of the urban area. Satellite images (Fig. 2c) show the progression of urbanization in the city. In the 1950s, the area to the north of the Han River was mostly urbanized (colored yellow in the figure). After the 1980s, urbanity exploded all over the city. Since 2000, many satellite cities and towns have appeared around Seoul (not shown in Fig. 2) by the government's plan, in an effort to control urban sprawl.

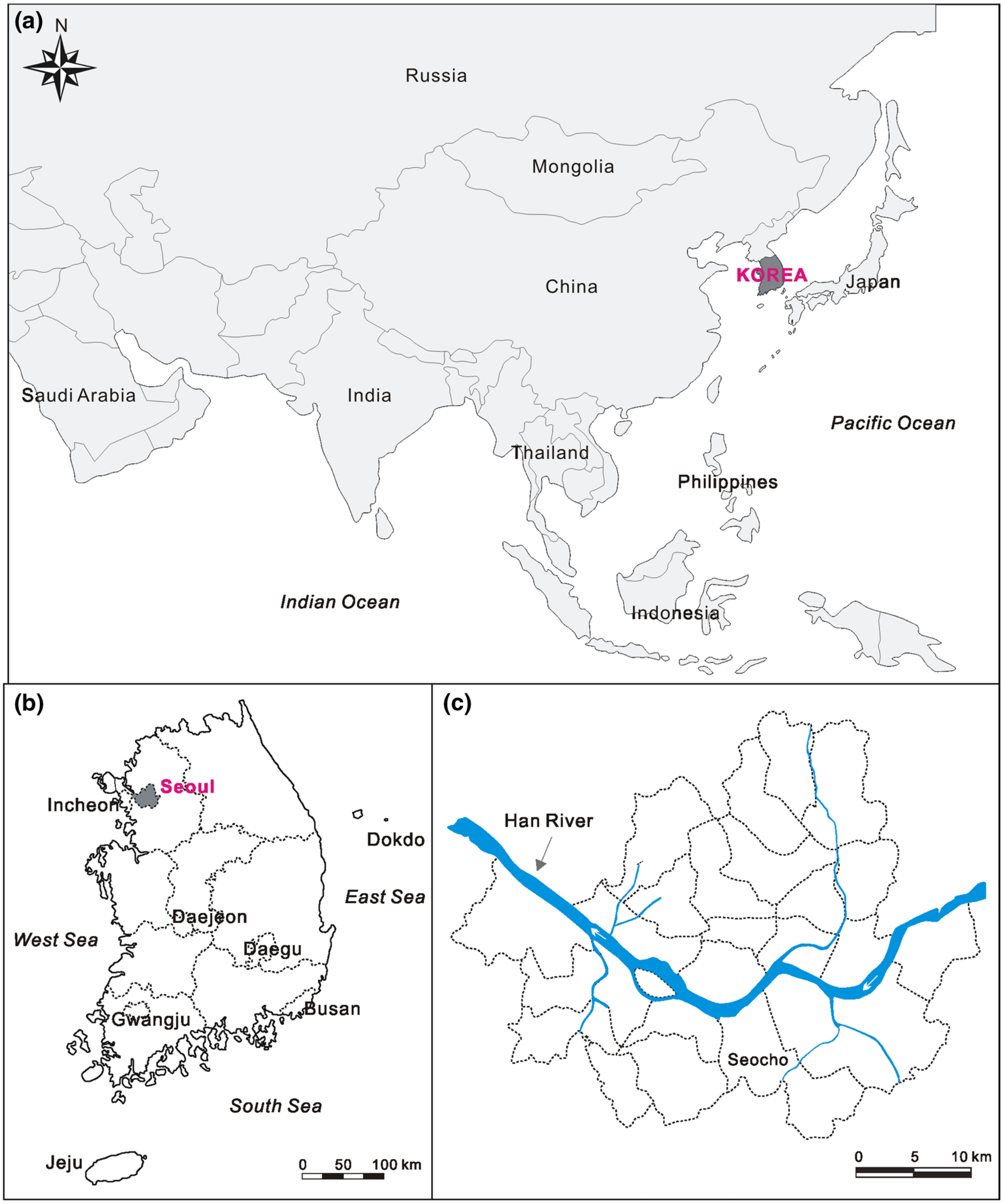

Fig. 1 Locations of **a** Republic of Korea, **b** Seoul (studied city), and **c** the Han River that flows through the center of the city

Figure 3 shows the details of the population, area, and population density of Seoul for the last 100 years (1915–2014). The population gradually increased starting at 241,085 in 1915, although a marked decrease was seen during the Korean War (June 1950 to July 1953). The city's population was 1,693,224 in 1950 and explosively increased to 10 million in 1992, which corresponds to a mean increase rate of 278,583/year. After 1992, the population in Seoul did not increase and rather decreased slightly. The decreasing trend can be explained by the highly elevated housing prices and the continuous construction of satellite cities and towns around Seoul (Son 2003, 2015).

The city's area increased in a stepwise fashion which reflects dramatic changes in the administrative system through history. The area was 36.18 km^2 in 1918 (Joseon Dynasty), 133.94 km^2 in 1936 (Japanese Colonial Rule),

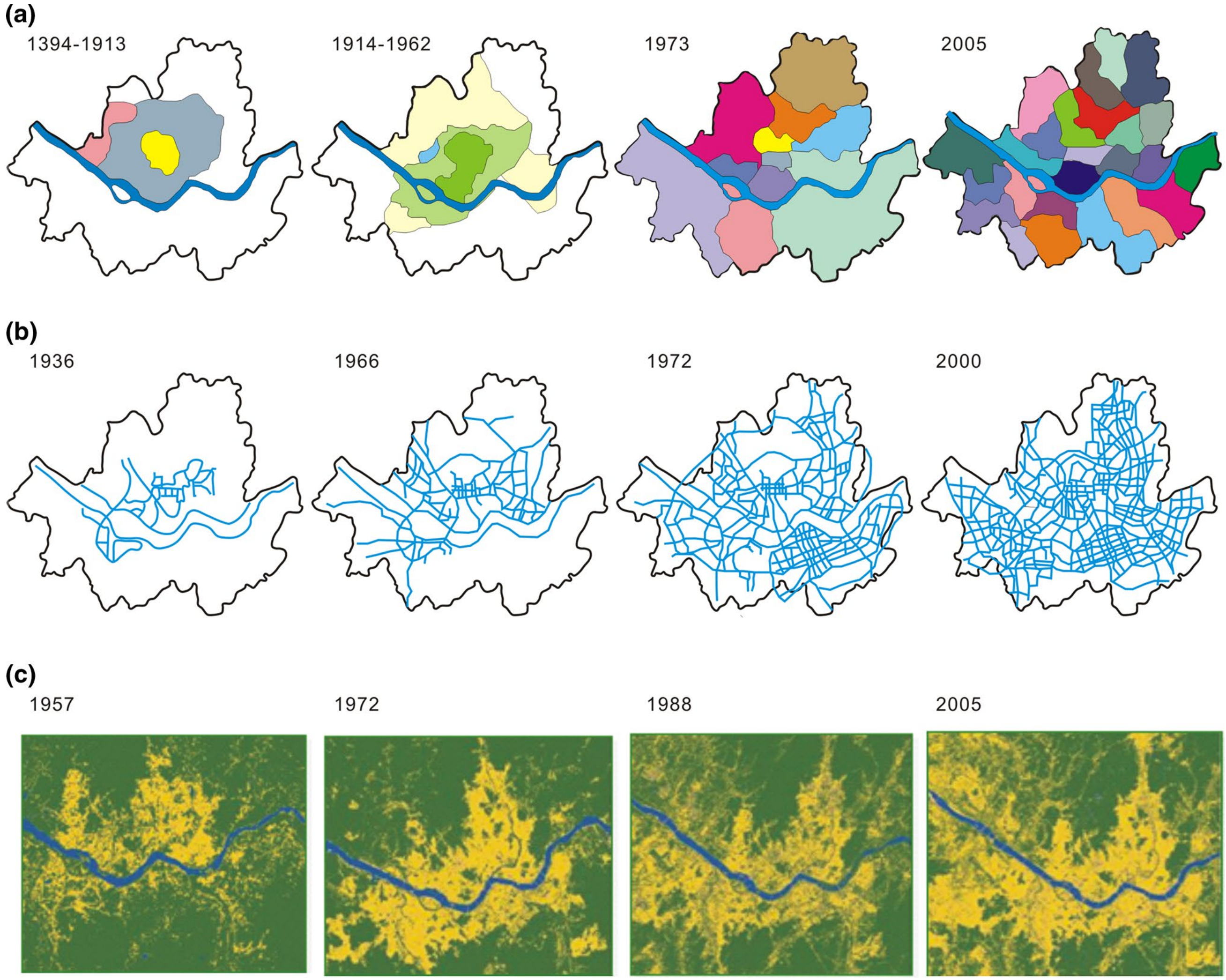

Fig. 2 Changes in **a** administrative districts, **b** transportation roads, and **c** satellite images of Seoul. (Reproduced with permission from SMG 2016)

268.35 km^2 in 1949 (National Independence), 613.04 km^2 in 1963 (the largest expansion), and 627.06 km^2 in 1973. The small decrease after that was due to the adoption of more accurate land survey methods, and not because of any actual area reduction. The population density shows somewhat irregular variations, which is mainly due to the area change during urban development. Since 1962, it has steadily increased and was 18,121/km^2 in 1992. A slight decrease followed, and the population density has been sustained at around 17,200/km^2 for the last 10 years. The current population density is strikingly high when compared to the average population density of 34 megacities worldwide (population > 10 million), around 10,100/km^2 (Demographia 2015). Seoul currently has the fifth highest population density among all the megacities worldwide.

Changing climate

Seoul has been experiencing gradual climatic changes, although the city is often defined as having a continental climate. In general, there are four distinct seasons. The temperature during the winter season (December–February) is around − 1 °C and that during the summer season (June–August) is around 25 °C. About 65% of the annual precipitation is from rainfall in the summer from the East Asian monsoon (Lee et al. 2005; Kim et al. 2016). Gradual climatic changes have been observed, particularly in the air temperature and precipitation (Kim et al. 2015a).

Figure 4a shows the annual mean air temperature of the city for the period 1909–2014, based on observation from Seoul weather station (Korea Meteorological Administration

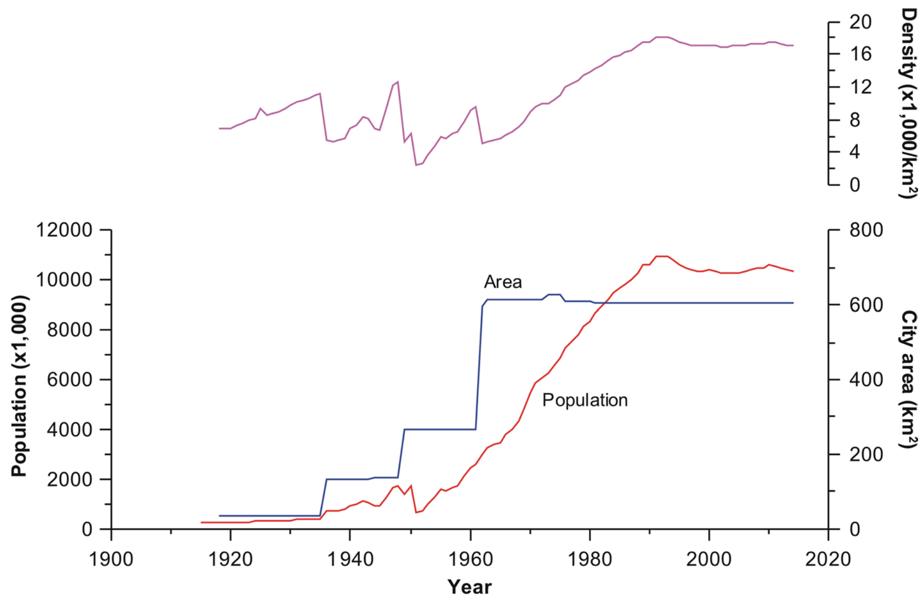

Fig. 3 Details on the population, city area, and population density of Seoul for the past 100 years (1915–2014)

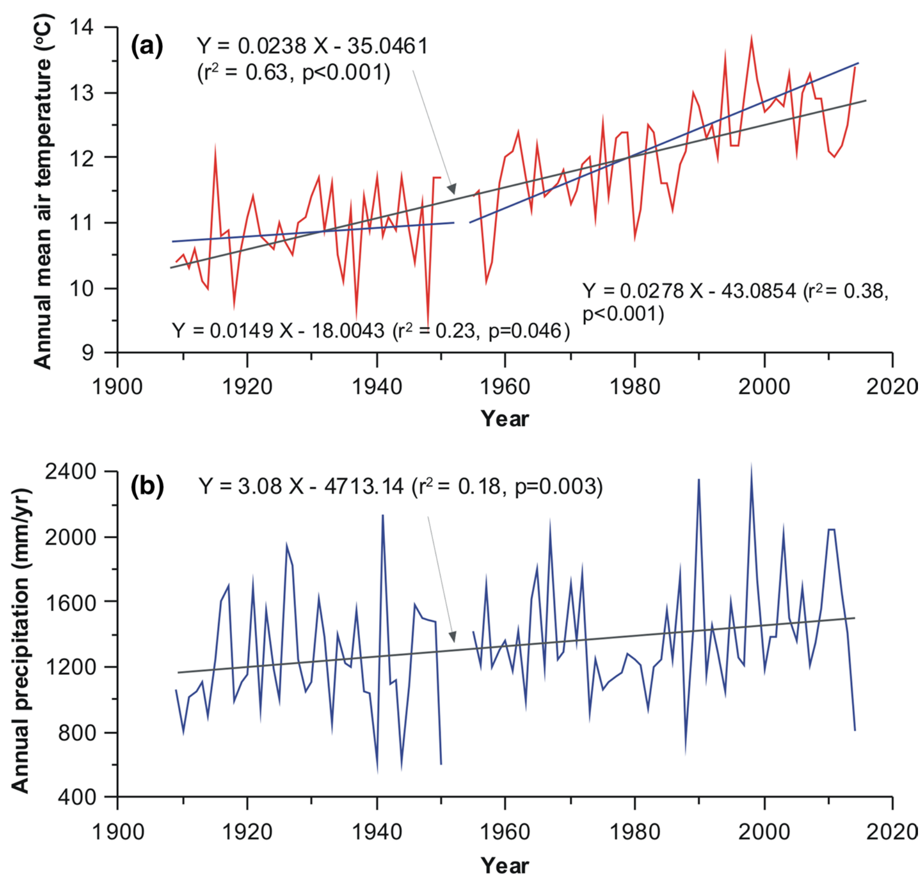

Fig. 4 Changes in **a** the annual mean air temperature and **b** the annual precipitation of Seoul for the period 1909–2014

2016). The mean air temperature increased from 10.4 °C in 1909 to 13.4 °C in 2014, and the overall rate of increase is 0.0238 °C/year for the total period. The global air temperature increase trends were 0.0066 °C (1901–2000) and 0.0189 °C/year (1975–2004) for similar periods (Rebetez and Reinhard 2008). Thus, the increasing temperature trend in Seoul is very high, like other megacities (e.g., Thundiyil 2003). The annual mean air temperature can be grouped into two periods: before the Korean War, 1909–1950, and after the Korean War, 1955–2014. The early period showed a relatively slight increase rate of 0.0149 °C/year; the later period showed a trend of greater increase of 0.0278 °C/year.

This trend in temperature increase corresponds to steep population growth and urban area expansion, which began in the 1950s (see Fig. 3). Furthermore, the rate of temperature increase in Seoul is far greater than that of the rest of Korea (0.017 °C/year for the period of 1912–2008; Lee and Kwon 2015), especially the less urbanized areas and forested areas of the country. This is referred to as the urban heat-island effect (Cheon et al. 2014). The increasing air temperature is causing more energy consumption for building and space cooling, increasing heat stroke patients, and deteriorating river (stream) water quality in the city (Kim et al. 2016; Son et al. 2016; Kim and Yun 2017). Besides air temperature, the temperatures of soil and groundwater are also increasing in Seoul (Park et al. 2011; Cheon et al. 2014) and pose additional threats to sustainable development in the long run.

The annual precipitation is apparently increasing, albeit not as sharply as the increase in air temperature (Fig. 4b). The mean annual precipitation was 1237 mm in the period of 1909–1950, while the precipitation was 1407 mm in the period of 1955–2014. Most of the increased precipitation is attributed to the increased frequency of torrential rainfall in the summer (Lee et al. 2012; Kim et al. 2015a). The torrential rainfall increases surface runoff and decreases groundwater recharge rates. On the other hand, Seoul records unprecedentedly large variations in annual precipitation every year. For example, while the total precipitation in 2013 was 1404 mm, in 2014, it was only 809 mm (only 57.6% of the previous year); this poses a challenge for water management efforts that deal with flood damages and water supply shortages.

Geology, hydrogeology, and land use

The geology of Seoul mainly comprises of Precambrian gneiss, Jurassic granite, and Quaternary alluvium (Kim et al. 2016; Fig. 5). The Precambrian banded gneiss (48.6% in area) lies mainly in the central and southwestern parts of the city across the Han River, and the Jurassic biotitic

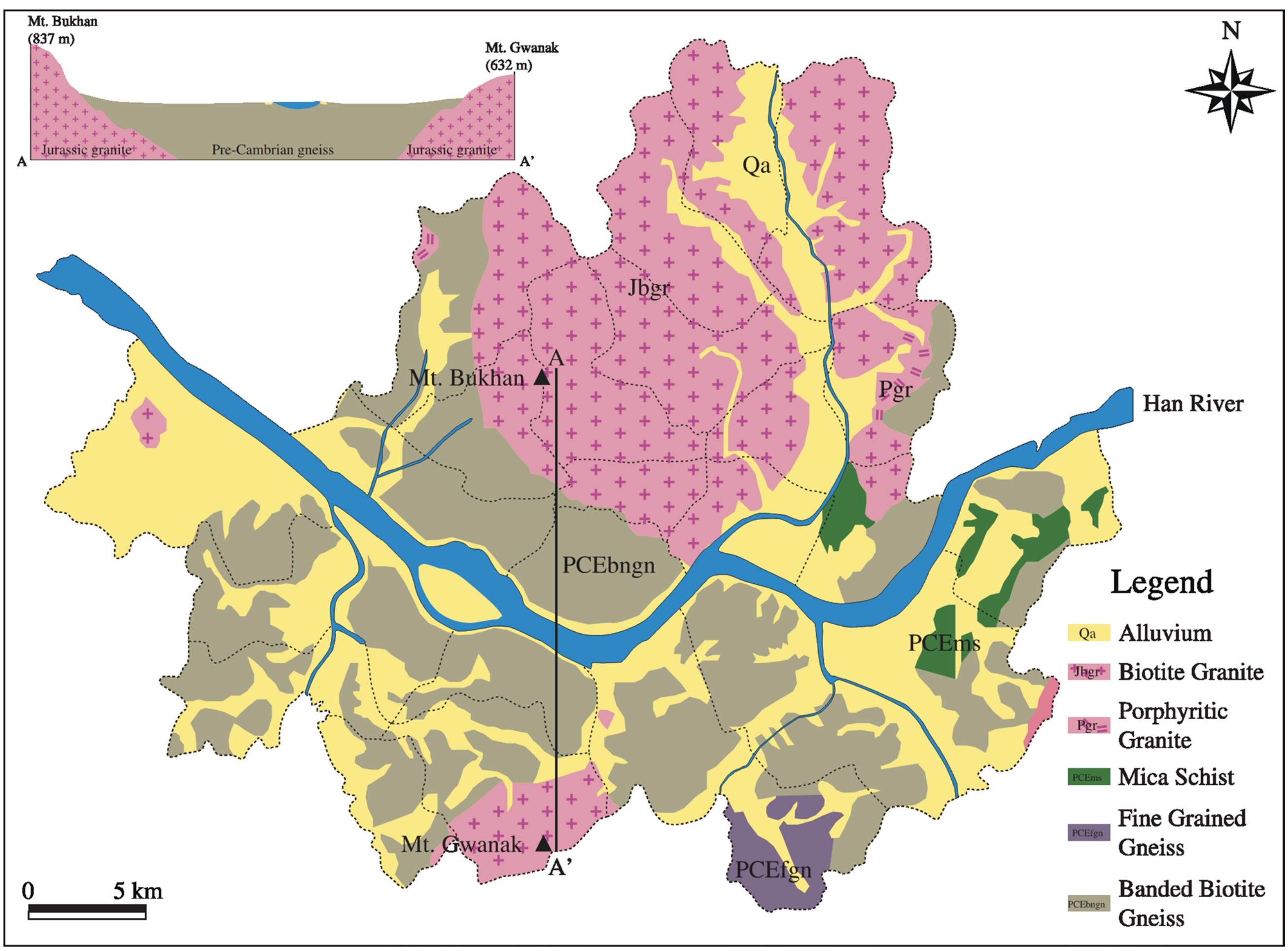

Fig. 5 Simplified geological map of Seoul. Modified from Kim et al. (2016)

granite (24%), which is present as an intrusion in the basement gneiss, outcrops extensively in the northern half of the city (Kwon et al. 1994; Yun et al. 2007). The two highest mountains in the city [Mts. Gwanak (632 m) and Bukhan (837 m)] are located in the granite region. The alluvium also covers a substantial area of the city (22.9%) along the Han River and its tributaries. The thickness of the alluvium ranges between 20 and 30 m within a radius of 2 km from the river and 5–10 m outside the radius (Lee 2016).

There are two main types of aquifers in the city, shallow alluvial aquifers and fractured bedrock aquifers (Kim et al. 2001; Lee et al. 2005). The alluvial aquifers are mainly composed of slit and fine to coarse sands and are mainly developed along the river and its tributaries. They possess a hydraulic conductivity of the order 10^{-3} cm/s (Kim and Lee 2003; Chae et al. 2008; SMG 2015). The bedrock aquifers are mostly composed of fractured gneiss in the low-lying part of the city, and their hydraulic conductivity ranges between 10^{-4} and 10^{-6} cm/s (Kim and Lee 2003; Lee et al. 2005; SMG 2015). Groundwater generally flows from the outlying mountainous areas to the riverine areas and mostly found at depths of 3–15 m but 40–70 m at subway construction areas (Lee 2016). Groundwater often seeps into subway tunnels, and surface subsidence occurs along the subway lines (Shin et al. 2015).

The current land utilization of the city is presented in Fig. 6. Residential areas are scattered all over the city interspersed by main and feeder roads, whereas commercial areas are rather confined to the northern central part of the city. Few industrial factories remain in the southwestern border of the city because land prices are high. The land covered by impermeable surfaces increased dramatically from 7.8% in 1962 to 48.6% in 2014 (77% in commercial areas) and thus greatly impacted the natural water cycle of Seoul (Kim 2012; Kim et al. 2015b). Table 1 shows the details of land utilization for the years 1970, 1990, 2010, and 2015. Over the last 45 years (note that the city area has practically remained unchanged since 1963; see Fig. 3), the forest, paddy, and field areas continuously decreased due to urbanization. It is notable that the area of green parks has increased but with

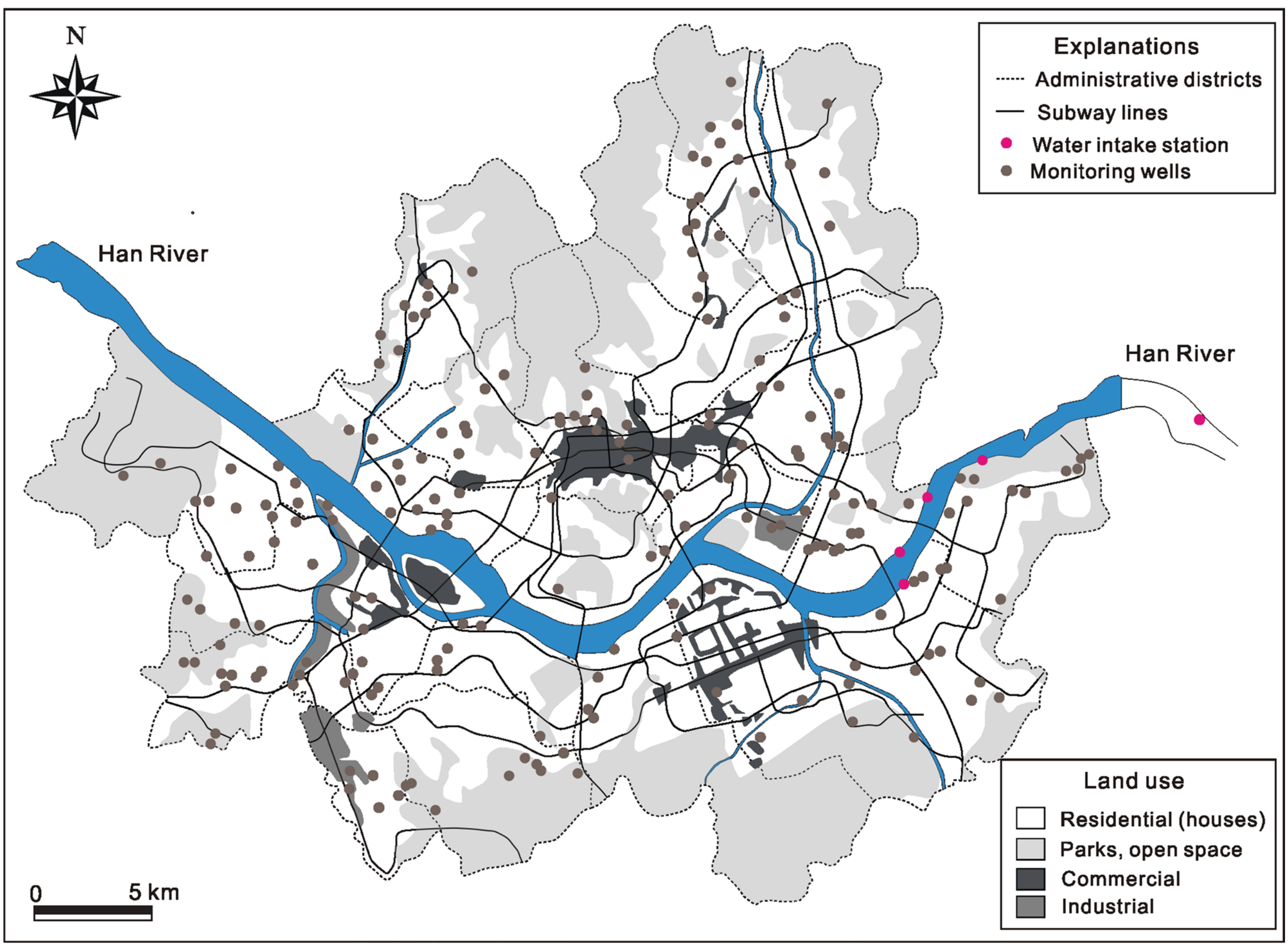

Fig. 6 Land use of Seoul in 2014 also showing the groundwater monitoring wells and 5 intake stations from the Han River for tap water. Modified from Kim et al. (2016)

Table 1 Land use of Seoul in 1970, 1990, 2010, and 2015. (Reproduced with permission from Kim et al. 2016; SMG 2016)

Land use	1970	1990	2010	2015
Forests (%)	31.7	27.1	24.5	23.3
Buildings (%)	25.7	33.8	35.7	36.0
Paddies and fields (%)	18.5	9.0	4.7	4.0
Roads (%)	6.3	10.3	12.6	14.2
River and streams (%)	8.2	8.5	8.6	8.6
Parks (%)	0.2	0.9	2.0	3.4
Factories (%)	0.6	0.7	0.5	0.5
Schools (%)	1.5	2.8	3.9	4.0
Others (%)	7.3	6.9	7.5	6.0

the use of artificial irrigation (tap water from the Han River; see five water intake stations in Fig. 6), which causes another distortion in the urban water cycle (Lawrence et al. 1998; Lee and Koo 2007).

Data sources and analyses

Most of the statistics related to the population, land, water use, and the status of the waterworks and sewer lines of Seoul were obtained from the Seoul Statistics Web site (http://stat.seoul.go.kr/jsp3/index.jsp), managed by the metropolitan government. Detailed waterworks data were obtained from annual reports of waterworks statistics of the period 1975–2013 in the digital library (http://library.me.go.kr/index.ax) managed by the Ministry of Environment (ME). Subsurface and geological data were obtained from the Integrated Management System of Subsurface Information (http://surveycp.seoul.go.kr/) of the city. Groundwater data of Seoul were obtained from the National Groundwater Information Center (https://www.gims.go.kr/ or http://203.237.1.25/En/) and My Water (http://www.water.or.kr/), a water information portal, managed by the K-Water (formerly Korea Water Resources Corporation) and the Ministry of Land, Infrastructure, and Transport and the Soil and Groundwater Information System (http://noon.nier.go.kr/), managed by the National Institute of Environmental Research and ME. The other data not described in the above were obtained from Korean Statistical Information Service (http://kosis.kr/eng/). Statistical decision in this study was made at $p = 0.05$ otherwise noted.

The obtained data were used to analyze area and population trend over time to evaluate the growth of Seoul. Annual air temperature and precipitation data were used to examine the effect of climate change regarding water level and use, over years. Land use in Seoul was categorized for convenient consideration of water use in different sectors, i.e., residential, commercial, and industrial. The trend of water use by municipal water supply was studied along with the ratio of economic loss/benefit. The dependency on groundwater (bottled water) as source of drinking water was reconnoitered to see the domestic sale benefits. Total number of wells and their use was presented by using coordinates values and obtained data in geographical information system (GIS). The precipitation rate and increase in number of urban floods were used to find the economic damage over years. The groundwater level data were used to see the change in water level over time. All the mentioned analyses helped to find water use and its change over time, potential interventions in water management, and to develop water management options for Seoul regarding present problems.

Results and discussion

Water sources and uses

Water supply

The city of Seoul depends heavily on the municipal waterworks water collected from the Han River, except for drinking and agricultural purposes (ME 2016). Currently, five intake stations (see Fig. 6) collect, treat, and distribute the river water to households and workplaces through the municipal waterworks pipes. In 2013, the total annual water usage of the city was 1.32 billion m^3, which was supplied mostly by the municipal waterworks (73.8%) and partly from groundwater (6.2%) and remaining (20%) from other sources, i.e., springs (Kim et al. 2015b). The proportions of domestic, industrial, agricultural, other (power generation, etc.) usages were 82.82, 0.54, 0.18, and 16.46% respectively. When compared with other major Asian megacities, Seoul did not utilize groundwater as much as Delhi (India), Beijing (China), Bangkok (Thailand), Tehran (Iran), and Dhaka (Bangladesh), but its usage was comparable to that of Tokyo (Table 2). This lack of dependence on groundwater is due to the strict governmental control over groundwater developed in the city, factory relocation plans, and highly equipped waterworks services (Lee and Koo 2007). It is observed that while Japan has similar controls in place, China and India do not.

Figure 7a shows the water supply-to-population ratio, a ratio between the population serviced by the municipal waterworks and the total population of the city, for the period 1975–2013. In 1975, 89.2% of the citizens were serviced by the municipal waterworks. The ratio increased to 99.6% in 1990 and reached 100% in 1997. On the other hand, the daily water supply and per capita water supply did vary monotonically (Fig. 7b). The water supply increased from 1975 to 1994, but after 1995, the water supply gradually decreased. Figure 7b shows that the maximum water supply was in 1994, where the daily water supply was

Table 2 Water sources and supply quantities in various Asian megacities

City	Population (million)	Total water supply (million L/day)	Water supply per capita (L/day)	River water (%)	Groundwater (%)	References
Seoul	10.39	3191[a]	301[a]	73.8	6.2	This study
Delhi	16.75	3047	182	85.7	14.3	Sarkar et al. (2016)
Beijing	21.15	7849	371	16.2	83.7	Shao et al. (2016)
Bangkok[b]	11.3	5493	486	84.8	15.2	Lorphensri et al. (2016)
Tokyo	13.3	6800	511	93.5	6.5	Shivakoti and Pandey (2016)
Shanghai	24.15	8466[a]	350[a]	99.9	< 0.1	Yao et al. (2015)
Tehran	13.12	3200	320	71.7	28.3	Ravanshadnia et al. (2015)
Dhaka	15.71	2400	153	19.1	80.9	ADB (2015)

[a]Amount supplied only by the waterworks from river water

[b]Includes its vicinity

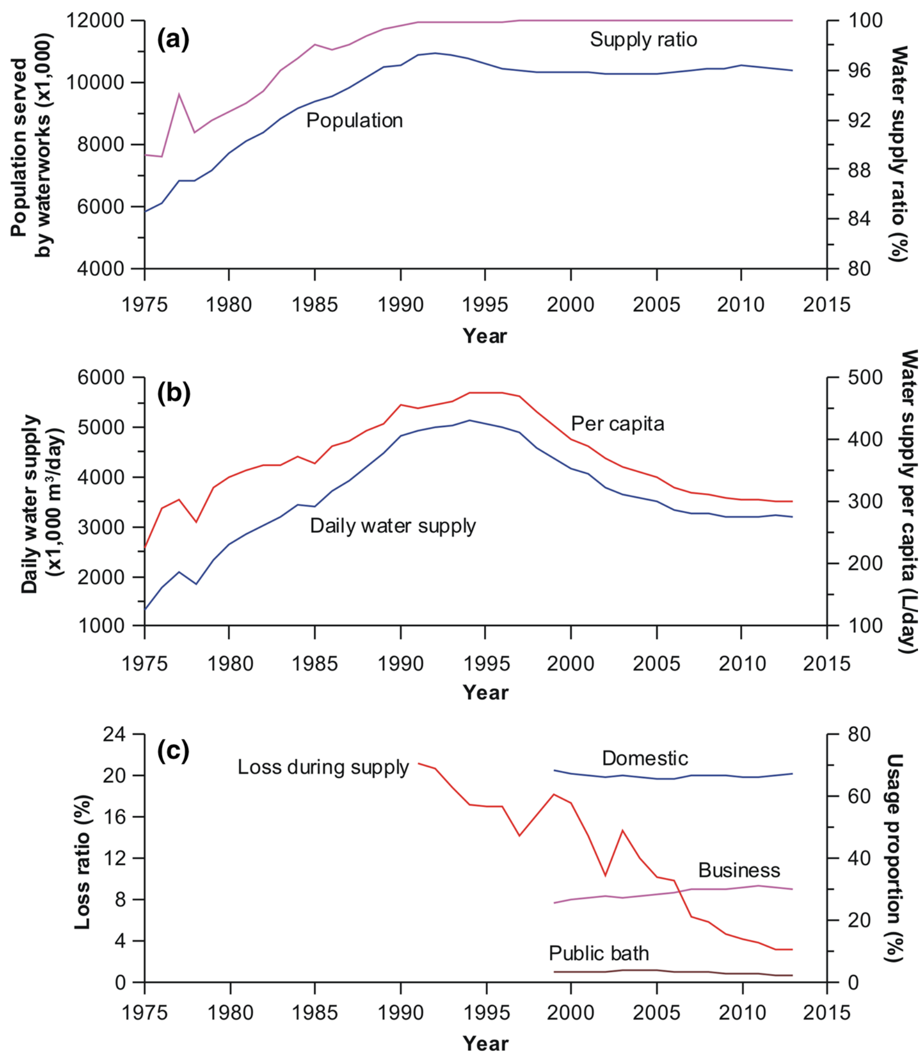

Fig. 7 Statistics of **a** water supply population and water supply ratio, **b** total water supply and per capita water supply, and **c** loss (leakage) ratio during the water distribution and usage of the supplied water for the period 1975–2013

5.14 million m^3 (MCM)/day and the per capita water supply was 476 L/day. The post-1995 decrease in the water supply may be attributed to the deterioration of water quality in water basin due to heavy use of river as a resource for economic growth in industrial sector (Choi et al. 2017). The entire water supply being supplied by the municipal waterworks in the 1990s (100% supply ratio in Fig. 7a) and the replacement of the old mains in order to reduce the amount of leaked water (Fig. 7c) was also considered as a reason for the negative trend.

Considering the reduced water leakage from the water supply pipes and the highly elevated ratio of revenue water (94.7% in 2013, comparable to New York (94.0%) and Tokyo (96.7%), the net water use per capita of the city has not decreased much and has been sustained at around 285–295 L/day in spite of the reduced water supply. The domestic water usage (around 70%) consumes most of the supplied water, while the consumption by businesses is much less (Fig. 7c).

Drinking water

Drinking water sources include filtered water from home water purifiers, boiled tap water, bottled water, groundwater (community drinking water facilities), and direct tap water (Lee et al. 2013). Because of frequent river water contamination episodes in the past, the quality of tap water sourced from rivers (tap water is only sourced from rivers in Seoul) has been questioned by the public (Ko et al. 2007; Sim et al. 2010). The metropolitan and central governments make continuous efforts to improve the reliability of tap water. The Han River Management Committee (under the supervision of ME) has spent around 500 million USD every year since 1999 to maintain and manage the quality of river water. However, the issues of the taste and odor of tap water remain to be addressed before total reliability can be achieved (e.g., Rosario-Ortiz et al. 2016). The portion of direct tap water use from the water sources has not exceeded 5% (Fig. 8a). This value is strikingly low when compared to the cases of France (70%), the USA (56%), and Japan (33%) (Kim et al. 2015b). Moreover, households incur additional costs for tap water purification; tap water is boiled or filtered before consumption as a personal safety measure, and this consumes extra energy.

The most notable changes have occurred in the commercial bottled water industry (Fig. 8b). In Korea, according to the Drinking Water Management Act, only groundwater is allowed as a bottled water source for commercial purposes (Lee and Kwon 2016). Due to safety concerns, bottled water sales (actually groundwater) have dramatically increased, with a mean annual increase rate of 11%. Thus, its proportion among drinking water sources has also increased. While tap water costs 0.29–0.65 USD/m^3, the most popular bottled water (domestic share 45% as of 2015) costs 625 USD/m^3,

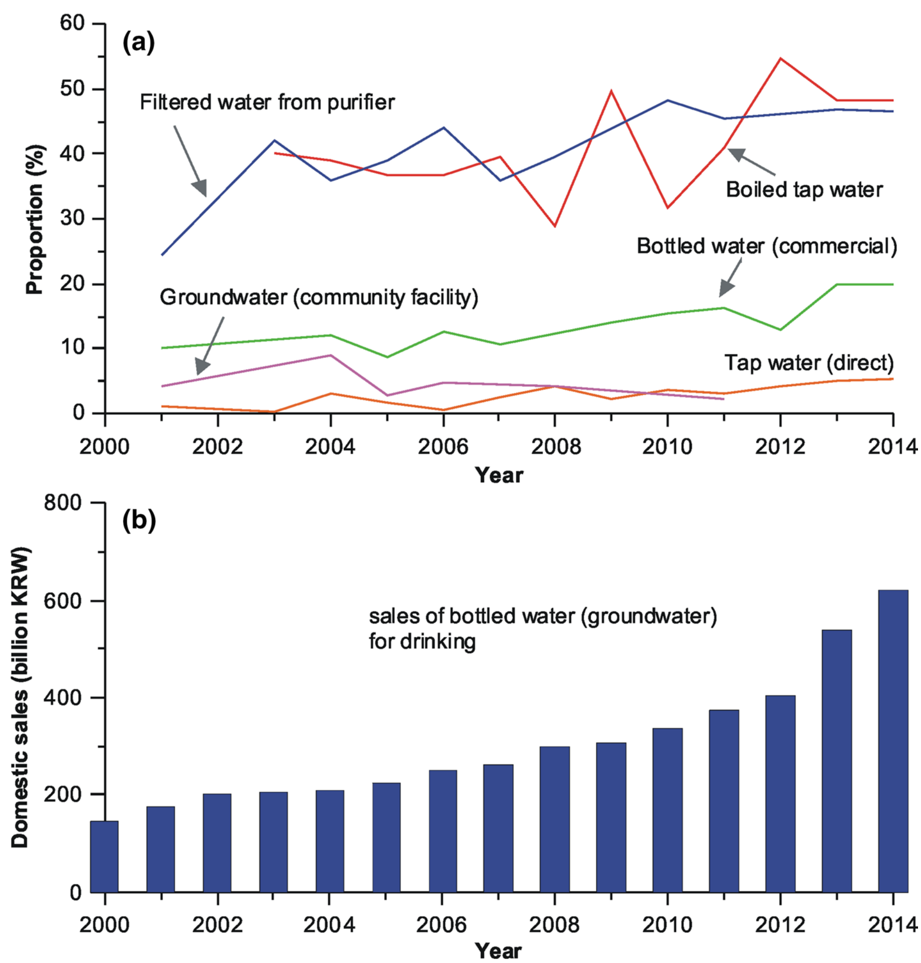

Fig. 8 Changes in **a** the sources of drinking water of Seoul and **b** domestic (for whole country) bottled water sales for the period 2000–2014. Sum of the proportions can be over 100% due to duplicate answers. The sales include bottled water and home purifiers. The data are from the Korea Natural Mineral Water Association (http://www.nmwater.or.kr/main/main.asp)

which is 961–2155 times more expensive than tap water. The bottled water market has also raised feelings of inequality in low-income communities (Lee et al. 2012).

Groundwater

In general, the use of groundwater as a resource in Seoul decreased as the number of groundwater wells decreased (Fig. 9a). The groundwater share of total water consumption is relatively low (6.2% as of 2013; see Table 2). The decrease was due to industrial relocation; industries are used to extract groundwater to suburban areas under environmental regulations and areas with high real estate prices (Kim et al. 2016) and the establishment of the municipal waterworks throughout the city. Among all the uses of groundwater, domestic use accounts for the

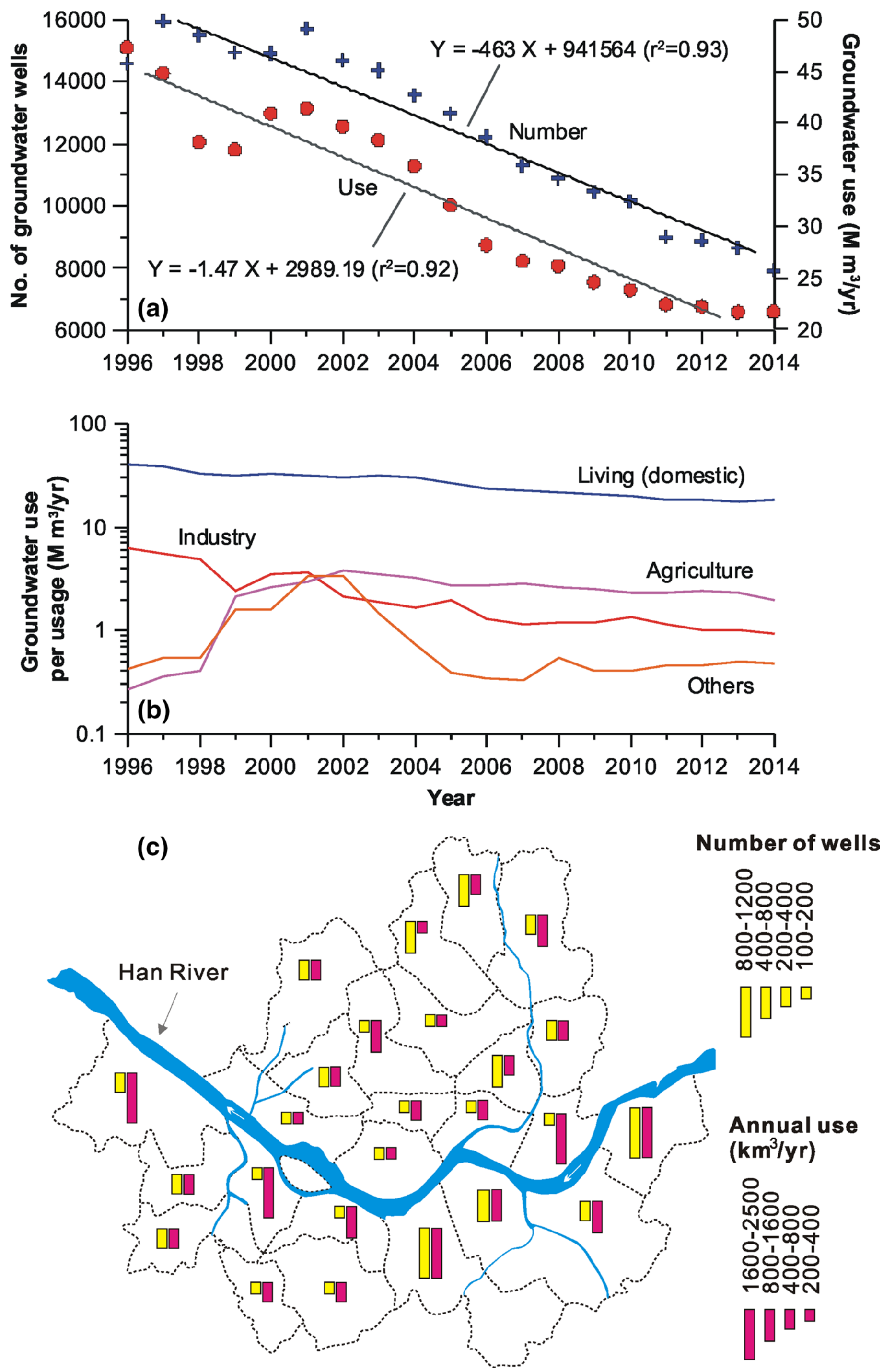

Fig. 9 Groundwater statistics of Seoul: **a** number of wells and annual groundwater use, **b** groundwater use with purposes, and **c** the number and areal distribution of groundwater wells

majority (76–86%), but this amount has steadily decreased (Fig. 9b).

Groundwater usage in agriculture (mainly growing flowers and vegetables) shows a different trend (Fig. 9b). The agricultural use gradually increased until 2003, and since then, it has not decreased because groundwater is the only water source for agriculture (Lee et al. 2005; Kim et al. 2016). Figure 9c shows the distribution of groundwater wells and the annual use in 2014. In the central urbanized areas (old town), there are a very small number of groundwater wells with a limited volume of groundwater use for domestic usage but with no agricultural or industrial uses. A relatively higher groundwater use and more groundwater wells are found along the river side in the lower half of the city, where greenhouse facilities for flowers and vegetables are abundant (see the left and rightmost areas in Fig. 6) (SMG 2015). Large groundwater consumption is observed in the central part of the lower half of the city, along the river, which is a new office building zone (see urbanization progress in Fig. 2a). Here groundwater is pumped for cleaning and washing due to its economic advantage (0.07 USD/m^3) over tap water (0.29–0.65 USD/m^3).

Groundwater amount in Seoul, up to 100 m below from the surface, is estimated at 1480 MCM. Because the annual groundwater recharge rate is 82.3 MCM/year, the groundwater capacity for sustainable development is reported to be 59.7 MCM/year (Shin et al. 2015). In 2014, the annual groundwater use was 22 MCM, and only 37.7 MCM was left for further use. The current, continuously decreasing groundwater use (see Fig. 9a) eliminates the possibility of a groundwater quantity problem. However, high groundwater use areas (mostly agricultural areas) need to be controlled (Shin et al. 2015; SMG 2015).

Water-related issues

The changing climate and water supply

The annual and seasonal precipitation data for the period 1960–2015 indicate that the annual precipitation of Seoul gradually increases but with a greater seasonal variation (Fig. 10). [Note that the monthly precipitation data are available for after 1960, while annual precipitation data are available for before the 1960s (Fig. 4b)]. For the period examined, the annual precipitation increased with a slope of + 23.3 mm/decade. Specifically, the rainfall in the June–August (JJA) season increased with a greater slope (+ 35.7 mm/decade) (e.g., Jeong et al. 2015), whereas snowfall in the December–February (DJF) season showed a negligible increase rate (+ 1.0 mm/decade). Overall, the proportion of the JJA season among total annual precipitation has gradually increased (+ 1.2%/decade) from 55 to 75% (Fig. 10b), but that of the DJF season is nearly constant.

The gradual decrease in the annual precipitation days (− 3.2 days/decade) and the JJA season precipitation days (− 0.41 days/decade) for the last 56 years (Fig. 10c) is interesting. These opposite trends between the summer precipitation and its precipitation days indicate increasingly frequent torrential rainfall episodes and extreme precipitation events in the last six decades (Jung et al. 2002). Accordingly, there are frequent reports of runoff over impermeable surfaces and a reduction in groundwater recharge rates in the city (Kim 2012). Most importantly, torrential rainfall induces turbidity in the water of the Han River, and these contain soil, dirt, and wastes (see Fig. 6); thus, the tap water supply then incurs extra treatment costs and it is often interrupted (Lee 2008).

Seoul began experiencing a significantly large variation in interannual precipitation post-1987 (Fig. 10a). For example, the annual precipitation in 2013 was 1404 mm, but was 809 mm the next year in 2014 (only 57% of the previous year). Because the river flow also varies greatly each year, water management plans centered on river and hydrologic drought and flood extremes are challenging to make (Piao et al. 2010). Consecutive very low precipitation years, as in 2014 and 2015 (792.1 mm), lead to the unprecedented spread of green algal blooms in the Han River (Kim et al. 2015c). As water management plans to secure water supply under highly variable precipitation conditions are underway, alternative water sources are considered such as bank filtration, rain harvesting, and increased groundwater use. The current strategy of depending upon a single source of water (i.e., river water) leaves the city vulnerable in the face of the changing climate and emergency situations (Vrba 2016).

Urbanization and urban flooding

The increasing urbanization has a positive relation with temperature. Figure 4 presents the same increasing trends for both annual temperature and precipitation in Seoul over years. Urbanization can have effect on precipitation due to surface heating (effect of heat island). This heating of atmospheric lower layer causes the temperature in urban area higher than the temperature in surrounding regions (Kug and Ahn 2013). The heat-island effect may cause thunderstorms and resulting in increased precipitation rate causing the risks of floods in urban areas. On the other hand, urbanization with more paved structures can lead to a clear reduction in rainwater infiltration to groundwater and a considerable rise in surface runoff (urban flood risk).

Highly developed cities cannot avoid natural disaster like flood, which cause many casualties and high damage levels. Figure 11 shows the number of flood victims and the amount of economic damage caused by urban floods in Seoul for the period 1971–2014. The disasters have recurred over the last 44 years, but the damage levels have not been reduced

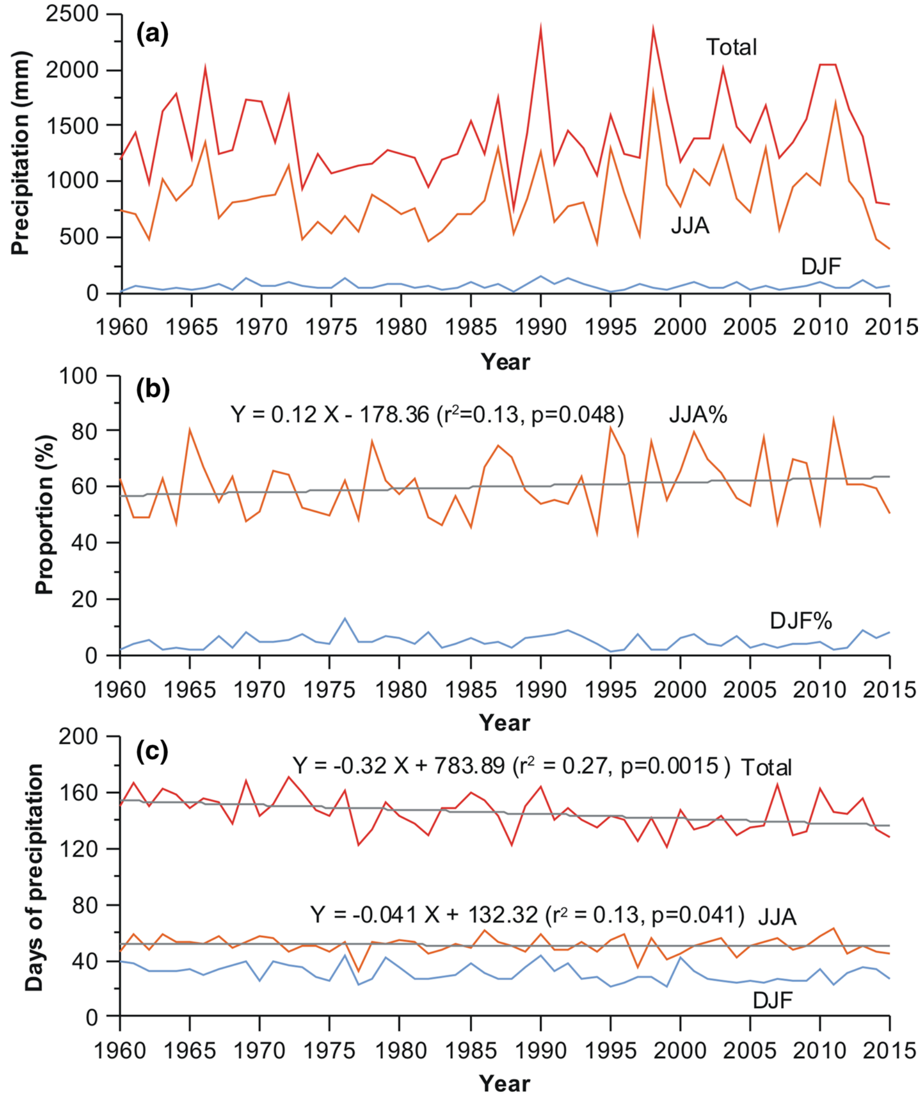

Fig. 10 **a** Total annual precipitation and the precipitations for the JJA and DJF seasons for the period 1960–2015, **b** proportions of the JJA and DJF seasons' precipitations among the annual precipitation rates, and **c** days of precipitation

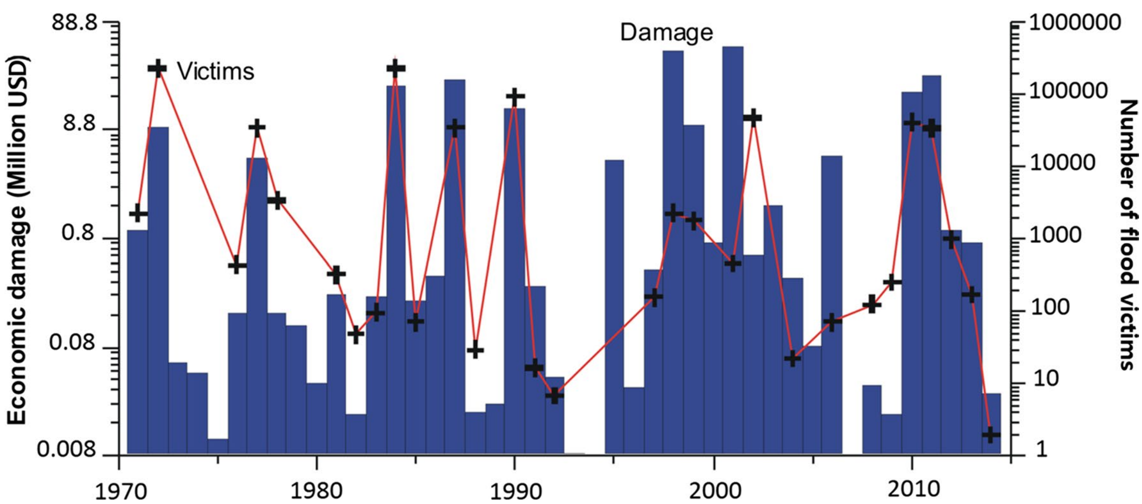

Fig. 11 The number of flood victims and the amount economic damage caused by urban floods in Seoul for the period 1971–2014. The data were obtained from the National Disaster Information Center (https://www.safekorea.go.kr/idsiSFK/index_web.jsp)

despite rapid economic and technological development. The increasing impervious surface area reduces the infiltration of rainfall into the subsurface and increases surface runoff, which consequently results in frequent urban flooding (Shuster et al. 2005; Shi et al. 2007). In addition, the frequent torrential rainfall, mainly occurring in the summer, is closely related to the economic damage caused by the floods ($r = 0.53$ at $p = 0.0002$); they also display a meaningful correlation with the number of victims ($r = 0.28$ at $p = 0.05$).

Archetypal city flood damages occurred in July 2011 in the Seocho-gu district, one of the three wealthiest neighborhoods in Seoul (see its location in Fig. 1c). A total of 301.5 mm of rainfall (14.8% of the annual precipitation) occurred in a single day and much of the rain flooded the district, causing inundations of 10–60 cm and heavy traffic congestion (Fig. 12a, b). Due to the torrential rain, a total of 147 catastrophic landslides, which swept away vast quantities of soil, rocks, and wood, occurred that day near residential areas of the district (Park et al. 2013; Fig. 12c, d). The debris flow hit residential houses and apartments, and left 16 dead, 30 houses buried, and 116 houses damaged (Yune et al. 2013).

Torrential rainfall due to urbanization and the changing climate is becoming more frequent (Wang et al. 2007; Jung et al. 2015), and thus, the possibility of flooding is on the rise in this city. When the West Sea is at high tide, the flow direction of the Han River is reversed at some submerged weirs, and this greatly exacerbates the floods (Kim et al. 2005). The implementation of permeable surface materials, rainwater harvest, and large underground discharge channels can be effective in mitigating the damage caused by urban floods (McGrane 2016; Su 2016). Propositions to restore the cement-lined streams and tributaries in the city to natural streams to mitigate urban flood damage have been made (Hasenmueller and Robinson 2016).

Underground water seepage

There are nine subway lines in the city (totally 332 km), which have a collective 268-km-long underground route as of 2015 (SMG 2015) (see the lines in Fig. 6). The underground routes are mostly located at a 20–30 m (up to 55 m) depth below the ground surface. Because the subway lines are several meters lower than the groundwater levels of the surrounding areas (SMG 2015), large quantities of groundwater seepage into the subway tunnels have occurred. The overall seepage water has slightly decreased over the years. This is due to reduced hydraulic gradients associated with lowering groundwater levels (Table 3; Chung 2010; Shin et al. 2015). The seepage amount was 47 MCM in 1997, 54 MCM in 2005, 35 MCM in 2008 (Chae et al. 2008), and 41 MCM (averagely 355 m^3/day per station) in 2014. However, the groundwater seepage volume is far greater than the groundwater pumped from wells in the city (22 MCM in 2014).

Fig. 12 A devastating flood (**a** and **b**) occurred recently in July 2011 in Seoul; it was followed by landslides (**c** and **d**). The photographs were obtained from the Yonhapnews Web site (http://www.yonhapnews.co.kr/) and the Ministry of National Defense (http://mnd-nara.tistory.com/)

Table 3 Groundwater seepage (discharge) from subway stations (as of 2008) in Seoul. (Reproduced with permission from Chung 2010)

Line	No. of stations	Total length (km)	Underground route (km)	Annual groundwater seepage/discharge (m^3/year)
Line #1	33	38.3	7.5	210,970
Line #2	54	60.2	44	2,547,335
Line #3	40	35.2	34.6	5,660,055
Line #4	26	31.1	28.8	2,588,580
Line #5	51	52.3	50	11,148,925
Line #6	38	35.1	23.8	4,785,515
Line #7	42	46.9	37.8	7,834,725
Line #8	17	17.7	14.5	741,315
Line #9	25	27.0	NA[a]	NA
Total	326	343.8	241	35,517,420

[a]Not available

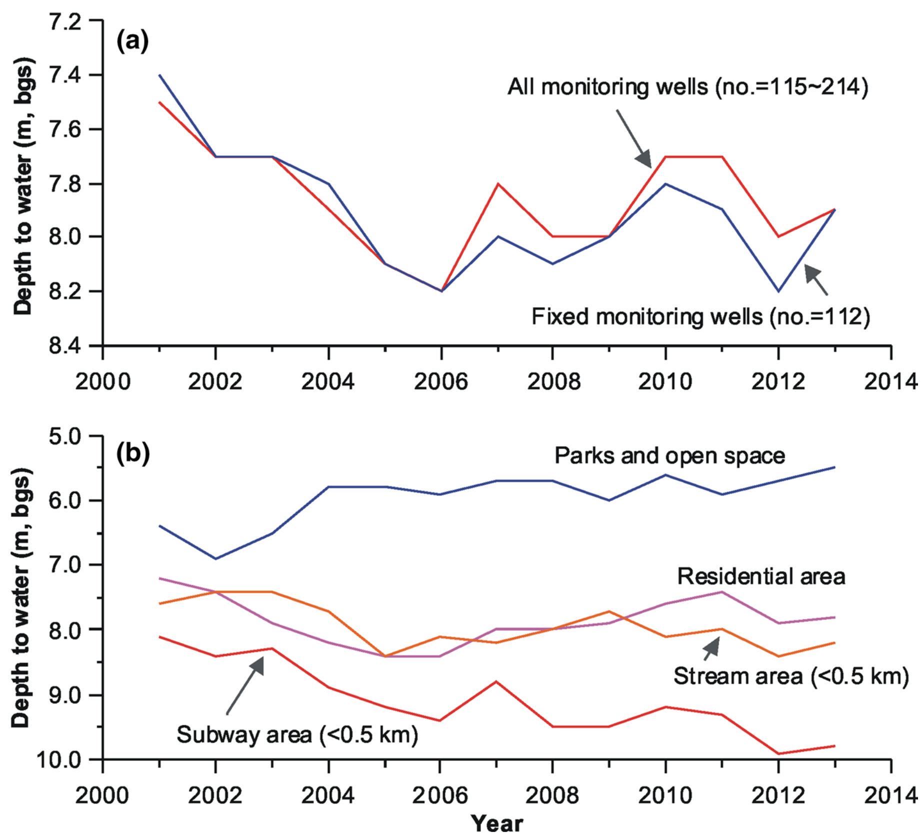

Fig. 13 Mean groundwater levels (depth to water below ground surface, m) obtained from the metropolitan groundwater monitoring wells for the period 2001–2013. The number of monitoring wells varies from 115 to 214

Figure 13a shows the mean groundwater levels of monitored wells (see Fig. 6) for the period 2001–2013. There were 112 wells that monitored annually for 12 years are termed as fixed monitoring wells and 115–214 varying monitoring wells (including 112 fixed monitoring wells) that monitored in different years from 2001 to 2013. The term varying monitoring well is used for wells whose monitoring was not annually constant over the specific time period. In spite of a continual decline in groundwater use (see Fig. 9a), distinctive decreasing trends in the overall groundwater level were observed in the city. However, the water level fluctuation in few monitoring wells present in alluvial aquifer (within 120 m from the river bank) was similar to the water level in Han River, but giving a negative trend in groundwater level of the city (Kim 2008). The groundwater levels differed depending on land uses (Fig. 13b). Urbanization resulted in the construction of paved areas and buildings. Such impermeable surfaces cause a reduction in groundwater recharge and the generation of surface runoff. The groundwater levels in the parks and open spaces showed an increasing trend (slope = + 7.8 cm/year, $r^2 = 0.86$), which can be mainly attributed to the artificial irrigation for flower trees and shrubs using piped water and leaked water from the municipal waterworks (Kim et al. 2001; Lee and Koo 2007). All the other land uses resulted in decreasing water levels, and the surrounding areas of the subways showed the most marked decreasing trends (− 12.8 cm/year, $r^2 = 0.77$). The distinctive water level declines were attributed to underground water seepage along the subway lines (Shin et al. 2015; SMG 2015).

The seeped groundwater is collected at a sump located at the midpoint between two stations and is then regularly pumped above ground. Out of the total 62 MCM/year of underground water seepage, 18% is directly discharged into sewer lines, 80% to nearby streams, and only 2% is reused in road cleaning, irrigation, toilets, and buildings (SMG 2015). Its supply from 11 subway stations as maintenance water for the Cheonggye-cheon (5.84-km-long artificial, cement-lined stream that runs through the center of the city, restored in 2005) is the most prominent reuse case, but the amount of water reused is very small compared to the total seepage (Shin et al. 2011). According to the Groundwater Act (article 9-2), owners or authorities responsible for subways, tunnels, and buildings producing a large quantity of groundwater seepage (300, 300, and 30 m^3/day, respectively) should establish appropriate reuse plans; however, most of the seeped groundwater is not properly reused. In addition, the subway tunnels (66%), tunnels for electrical (9%) and communication (7%) cables, and large buildings (18%) are also chief producers of seeped groundwater, with a total amount of 21 MCM/year (SMG 2015). These seepages largely affect groundwater levels and the stability of nearby roads and buildings (Lee 2016).

Land subsidence and road sinks

Land subsidence in megacities is becoming an increasingly common occurrence mainly due to lowered groundwater levels and the presence of heavy buildings (Chai et al. 2004; Phien-wej et al. 2006; Kearns et al. 2015). The recently frequent road sinks and the land subsidence in Seoul aroused relatively new concern for the disaster (Kim et al. 2016; Lee 2017). Table 4 shows the statistics of land subsidence and road sinks that occurred for the period 2010–2014 in the city. With the increasing number of total subsidence occurrences, the number of land subsidence occurrences with a large area of affect (> 2 m × 2 m) is also increasing. In August 2014, an abrupt land subsidence with dimensions of 2.5 m (width) × 8 m (length) × 10 m (depth) occurred in the middle of a main road in southeastern Seoul (Lee 2017). Four other occurrences of land subsidence that followed consecutively were within 500 m of the first one. Coincidently, large declines in the water level were perceived at two neighboring artificial lakes.

According to the metropolitan city's investigation (SMG 2016), sewer pipe leakage is the most frequent cause (84.2%) of land subsidence and road sinks of various sizes. When the sewer pipe gets old, it begins to deteriorate and leak. The sewage then erodes and extracts fine particles of surrounding soil (Davies et al. 2001). This finally causes sewer pipes to fail and land surfaces to collapse. Out of the total sewer line length (10,392.2 km) of the city, 48.2% are over 30 years old and 30.5% are over 50 years old (Table 5). Therefore, the potential of sewer line leakage is high, leading to soil erosion and groundwater contamination (Kim 2004). The other major causes of land subsidence are underground works (see Table 4), like subway construction and high storied building construction. Vast quantities of groundwater seepage and dewatering accompany groundwater level declines. They subsequently weaken the surrounding land mass. The 2014 land subsidence is attributed to both subway tunnel construction and underground excavation work for a 123-story skyscraper (Lee 2017).

Table 5 Sewer lines in Seoul with their installation years. (Reproduced with permission from SMG 2016)

Installation year (ages)	Line length (km)	Proportion (%)
After 1994 (< 20 years old)	2771.5	26.7
1984–1993 (20–30 years old)	2597.5	25.0
1974–1983 (30–40 years old)	1376.7	13.2
1964–1973 (40–50 years old)	472.7	4.5
Before 1963 (> 50 years old)	3173.8	30.5
Total	10,392.2	100

Table 4 Number of cases of road sinks and land subsidence (dimension > 0.1 m × 0.1 m) that occurred in Seoul for the period 2010–2014. (Reproduced with permission from SMG 2016)

Causes	2010	2011	2012	2013	2014	Total	Proportion (%)
Sewer pipes damage	409	413	611	754	616	2803	84.2
Waterworks pipe damage	5	11	13	8	20	57	1.7
Underground works	21	149	65	92	143	470	14.1
Total	435	573	689	854	779	3330	100
Dimension > 2 m × 2 m	2	4	1	2	12	21	0.6

Alluvial deposits adjacent to the Han River are vulnerable to land subsidence. The alluvial deposits of 20–30 m thickness are not enough to accommodate heavy urban buildings. Proper measures must be implemented to mitigate groundwater seepage damage during underground work. The replacement of old pipe lines may reduce occurrences of unpredicted land subsidence and road sinks.

Conclusions and management options

We have examined the status of water sources, water use, and its related problems in Seoul metropolitan city, home to over 10 million people, in Korea. The examination resulted in some important conclusions and suggestions for management as follows:

1. Due to the changing climate, the interannual variability of precipitation in the city is largely increasing even though the precipitation amount is generally increasing, ultimately cause of flood. The increasing torrential rains mostly in the summer and fewer in winters hinder the management of water. Thus, flood and metropolitan water supply could be managed by:
   - More tree plantation in the central area of city to reduce heat-island effect, in order to cease the increasing trend of temperature, precipitation, and flood risk.
   - Storing floodwater in aquifers upstream of flood risk areas, and using groundwater in the dry season is technical approach.
   - Depending on various water sources rather than the single source (the Han River water), strategy is viable.
   - Rainwater drainage systems in these cities are designed to manage sizeable volumes and aim (not always successfully) to reduce the risk of floods.
2. Presently, a very small number of citizens in Seoul, less than 5%, consume tap water directly even though a huge amount of money is spent on making it fit for consumption every year. Regarding the decreasing groundwater level and expensive bottled water (groundwater), the rate of citizen's tap water consumption can be increased by:
   - The development of proper treatment facilities, and monitoring stations with surety of treated water in accordance with Korean Drinking Water Standards.
   - Proper costing of water supply service in order to maintain the treatment and quality of supplied water.
   - Increasing 'no health risk by chlorinated water' awareness campaigns, in order to eradicate the fear of odor in tap water.
   - Monitoring of renewed water supply mains and their joints, with complete surety of no leakage and rusting of pipelines.
3. There has been large-scale underground water seepage that originates from many subway lines, tunnels for electrical and communication cables, and large deep rooted buildings in the city, amounting to 62 MCM/year. Most of them are discharged without being reused. The underground water seepage causes groundwater level declines, and consequently, occurrences of land subsidence threaten the stability of the surrounding buildings. Therefore, underground water seepage and its effects can be reduced by:
   - Proper geotechnical survey to find out the chances of water seepage, before the initiation of any project.
   - Grouting of the ground surface to minimize water seepage and consequently no effect on groundwater level.
   - Developing temporary storage system for seeped water and reuse it as irrigation water for plants.
4. There have been increasing amounts of road sinks and land subsidence occurrences of various sizes in the city. The leakage of sewer pipes accounts for most of the causes of land subsidence. The decrease in groundwater level with increasing dependency on groundwater also counted as the reason for land subsidence. Underground works in Korea like subway lines and high storied buildings also contributed to land subsidence. This problem of land/road sinks can be overwhelmed by:
   - The replacement of old pipes to reduce leakage accidents as soon as possible by megacity's government.
   - Underground work like the construction of the subway tunnels and large deep rooted buildings are also contributing causes, and thus, appropriate measures (reliable geotechnical surveys) should be implemented to mitigate seepage and consequently control land subsidence.
5. Presently, water quantity and its quality are controlled separately by different administrative authorities even though they are closely interconnected. Thus, we need integrated governing regulations or laws and combined controlling entities for sustainable water development and appropriate management for the city.

Similarly, other megacities in developed world could better manage their water-related issues by one major administrative authority with different divisions (groundwater, surface water, water quality) to control the relevant issues. Many developed megacities are facing the water-related issue, i.e., urban flooding, water quality deterioration in old pipelines, water seepage, and land subsidence. The water management options for Seoul could be helpful for such cities (with same water issues), by more tree plantation in centers of the cities, changing of old pipelines, grouting the land surface and proper geotechnical surveys. The megacities in developing world might have more water-related problems due to poorly planned infrastructure and dramatic increase in population. The solution to common heat-island problem would be applicable to such cities.

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References

Alam M, Rabbani MDG (2007) Vulnerabilities and responses to climate change for Dhaka. Environ Urban 19:81–97
Asian Development Bank (ADB) (2015) Bangladesh: Dhaka environmentally sustainable water supply project. ADB, Metro Manila
Baklanov A, Molina LT, Gauss M (2016) Megacities, air quality and climate. Atmos Environ 126:235–249
Chae GT, Yun ST, Choi BY, Yu SY, Jo HY, Mayer B, Kim YJ, Lee JY (2008) Hydrochemistry of urban groundwater, Seoul, Korea: the impact of subway tunnels on groundwater quality. J Contam Hydrol 101:42–52
Chai J-C, Shen S-L, Zhu H-H, Zhang X-L (2004) Land subsidence due to groundwater drawdown in Shanghai. Geotechnique 54:143–147
Chan CK, Yao X (2008) Air pollution in mega cities in China. Atmos Environ 42:1–42
Cheon JY, Ham BS, Lee JY, Park Y, Lee KK (2014) Soil temperatures in four metropolitan cities of Korea for 1960–2010: implications for climate change and urban heat. Environ Earth Sci 71:5215–5230
Choi IC, Shin HJ, Nguyen TT, Tenhunen J (2017) Water policy reforms in South Korea: a historical review and ongoing challenges for sustainable water governance and management. Water 9:717. https://doi.org/10.3390/w9090717
Chung SY (2010) Groundwater obstructions and countermeasures for groundwater discharge from subway in Seoul, Korea. J Geol Soc Korea 46:61–72
Costa D, Burlando P, Priadi C (2016) The importance of integrated solutions to flooding and water quality problems in the tropical megacity of Jakarta. Sustain Cities Soc 20:199–209
Davies JP, Clarke BA, Whiter JT, Cunningham RJ (2001) Factors influencing the structural deterioration and collapse of rigid sewer pipes. Urban Water 3:73–89
Demographia (2015) Demographia world urban areas (built up urban areas or world agglomerations). Demographia, Belleville
Folberth GA, Butler TM, Collins WJ, Rumbold ST (2015) Megacities and climate change: a brief overview. Environ Pollut 203:235–242
Gambolati G, Teatini P (2015) Geomechanics of subsurface water withdrawal and injection. Water Resour Res 51:3922–3955
Haddad EA, Teixeira E (2015) Economic impacts of natural disasters in megacities: the case of floods in São Paulo, Brazil. Habitat Int 45:106–113
Hasenmueller E, Robinson HK (2016) Hyporheic zone flow disruption from channel linings: implications for the hydrology and geochemistry of an urban stream, St. Louis, Missouri, USA. J Earth Sci 27:98–109
Howard KWF (2013) Sustainable cities and the groundwater governance challenge. Environ Earth Sci 73:2543–2554
Hunt A, Watkiss P (2011) Climate change impacts and adaptation in cities: a review of the literature. Clim Change 104:13–49
Jeong MS, Kim JS, Oh SM, Moon YI (2015) Sensitivity of summer precipitation over the Korean Peninsula to temperature gradients. Int J Climatol 35:836–845
Jung HS, Choi Y, Oh JH, Lim GH (2002) Recent trends in temperature and precipitation over South Korea. Int J Climatol 22:1327–1337
Jung M, Kim H, Mallari JB, Pak G, Yoon J (2015) Analysis of effects of climate change on runoff in an urban drainage system: a case study of Seoul, Korea. Water Sci Technol 71:653–660
Kearns T, Wang G, Bao Y, Jiang J, Lee D (2015) Current land subsidence and groundwater level changes in the Houston metropolitan area (2005–2012). J Surv Eng. 141(4):05015002
Kim YY (2004) Analysis of hydrochemical processes controlling the urban groundwater system in Seoul area, Korea. Geosci J 8:313–318
Kim SJ (2008) A study on the variation of groundwater level in the Han River estuary (the effect of the removing of a weir). J Korean Soc Coast Ocean Eng 20:589–601
Kim YR (2012) Impact of urbanization on water cycle and status of Seoul. 2012 urban water cycle forum. Seoul Metropolitan Government, Seoul, pp 1–26
Kim YY, Lee KK (2003) Disturbance of groundwater table by subway construction in the Seoul area, Korea. Geosci J 7:37–46
Kim S, Yun J (2017) Study on urban temperature prediction method using Lagrangian particle dispersion model. J Korean Soc Atmos Environ 33:45–53
Kim YY, Lee KK, Sung I (2001) Urbanization and the groundwater budget, metropolitan Seoul area, Korea. Hydrogeol J 9:401–412
Kim SH, Kim W, Lee ER, Choi KH (2005) Analysis of hydraulic effects of Singok submerged weir in the lower Han River. J Korea Water Resour Assoc 38:401–413
Kim HS, Chung YS, Tans PP, Yoon MB (2015a) Climatological variability of air temperature and precipitation observed in South Korea for the last 50 years. Air Qual Atmos Health 9:645–651
Kim MK, Moon B, Kim TK, Zoh KD (2015b) A study on production and removal of microcystin, taste and odor compounds from algal bloom in the water treatment processes. Korean J Public Health 52:33–42
Kim YR, Lee SO, Hwang SH (2015c) 2020 comprehensive management plan of water environment for Seoul special city. SMG, Seoul
Kim H, Lee JY, Jeon WH, Lee KK (2016) Groundwater environment in Seoul, Republic of Korea. Groundwater environment in Asian cities. Elsevier, Woburn, pp 411–447
Ko EJ, Kim KW, Kang SY, Kim SD, Bang SB, Hamm SY, Kim DW (2007) Monitoring of environmental phenolic endocrine disrupting compounds in treatment effluents and river waters, Korea. Talanta 73:674–683
Korea Meteorological Administration (KMA) (2016) Annual climatological report. http://www.kma.go.kr. Accessed 25 July 2017
Kug JS, Ahn MS (2013) Impact of urbanization on recent temperature and precipitation trends in the Korean peninsula. Asia Pac J Atmos Sci 49:151–159
Kumar P, Khare M, Harrison RM, Bloss WJ, Lewis AC, Coe H, Morawska L (2015) New directions: air pollution challenges for developing megacities like Delhi. Atmos Environ 122:657–661
Kwon ST, Cho DL, Lan CY, Shin KB, Lee T, Mertzman SA (1994) Petrology and geochemistry of the Seoul granitic batholith. J Petrol Soc Korea 3:109–127
Lawrence AR, Morris BL, Foster SSD (1998) Hazards induced by groundwater under rapid urbanization. Geohazards in engineering geology. Engineering Geology Special Publication, Geological Society, London, pp 319–328

Lee JY (2008) A hydrological analysis of current status of turbid water in Soyang River and its mitigation. J Soil Groundwater Environ 13:85–92
Lee JY (2016) Status of groundwater monitoring in Songpa, Seoul and suggestions. J Geol Soc Korea 52:57–66
Lee JY (2017) Lessons from three groundwater disputes in Korea: lack of comprehensive and integrated investigation. Int J Water 11:59–72
Lee JY, Han J (2013) Evaluation of groundwater monitoring data in four megacities of Korea: implication for sustainable use. Nat Resour Res 22:103–121
Lee JY, Koo MH (2007) A review of effects of land development and urbanization on groundwater environment. J Geol Soc Korea 43:517–528
Lee JY, Kwon K (2015) Groundwater resources in Gangwon Provinces: tasks and perspectives responding to droughts. J Geol Soc Korea 51:585–595
Lee JY, Kwon K (2016) Current status of groundwater monitoring networks in Korea. Water 168. https://doi.org/10.3390/w8040168
Lee JY, Choi MJ, Kim YY, Lee KK (2005) Evaluation of hydrologic data obtained from a local groundwater monitoring network in a metropolitan city, Korea. Hydrol Process 19:2525–2537
Lee JY, Jeon WH, Park Y, Lim HG (2012) Status and prospect of groundwater resources in Pyeongchang, Gangwon-do. J Geol Soc Korea 48:435–444
Lee JY, Park Y, Kim NJ, Jeon WH (2013) Status of community drinking water in Korea and implications for appropriate management. J Soil Groundwater Environ 18:56–68
Li E, Endter-Wada J, Li S (2015) Characterizing and contextualizing the water challenges of megacities. J Am Water Resour Assoc 51:589–613
Lohani B, Siddiqi Y, Kilroy G (2015) Economic growth and climate proofing Asia through sustainable water resources management. Water security, climate change and sustainable development. Springer, Singapore, pp 83–105
Lorphensri O, Nettasana T, Ladawadee A (2016) Groundwater environment in Bangkok and the surrounding vicinity, Thailand. Groundwater environment in Asian cities. Elsevier, Woburn, pp 229–262
Lundqvist J, Tortajada C, Varis O, Biswas A (2005) Water management in megacities. Ambio 34:269–270
Mark O, Jorgensen C, Hammond M, Khan D, Tjener R, Erichsen A, Helwigh B (2015) A new methodology for modeling of health risk from urban flooding exemplified by cholera-case Dhaka, Bangladesh. J Flood Risk Manag. https://doi.org/10.1111/jfr3.12182
McGrane SJ (2016) Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. Hydrol Sci J 61:2295–2311
Ministry of Environment (ME) (2016) Waterworks statistics. http://library.me.go.kr. Accessed 20 July 2017
Park YC, Jo YJ, Lee JY (2011) Trends of groundwater data from the Korean National Groundwater Monitoring Stations: indication of any change? Geosci J 15:105–114
Park DW, Nikhil NV, Lee SR (2013) Landslide and debris flow susceptibility zonation using TRIGRS for the 2011 Seoul landslide event. Nat Hazards Earth Syst Sci 13:2833–2849
Phien-wej N, Giao PH, Nutalaya P (2006) Land subsidence in Bangkok, Thailand. Eng Geol 82:187–201
Piao S, Ciais P, Huang Y, Shen Z, Peng S, Li J, Zhou L, Liu H, Ma Y, Ding Y, Friedlingstein P, Liu C, Tan K, Yu Y, Zhang T, Fang J (2010) The impacts of climate change on water resources and agriculture in China. Nature 467:43–51
Qin Y, Perissin D (2015) Monitoring ground subsidence in Hong Kong via spaceborne radar: experiments and validation. Remote Sens 7:10715–10736
Ravanshadnia M, Ghanbari M, Fardani MH (2015) Planning crisis management of water resources in Tehran in the next 25 years. J Appl Environ Biol Sci 5:50–59
Rebetez M, Reinhard M (2008) Monthly air temperature trends in Switzerland 1901–2000 and 1975–2004. Theor Appl Climatol 91:27–34
Rosario-Ortiz F, Rose J, Speight V, von Gunten U, Schnoor J (2016) How do you like your tap water? Science 351:912–914
Sarkar A, Ali S, Kumar S, Shekhar S, Rao S (2016) Groundwater environment in Delhi, India. Groundwater environment in Asian cities. Elsevier, Woburn, pp 77–108
Seoul Metropolitan Government (SMG) (2015) Groundwater management plan of Seoul special city (2015–2024). SMG, Seoul
Seoul Metropolitan Government (SMG) (2016) Seoul statistics. http://stat.seoul.go.kr. Accessed 9 Jun 2017
Shao J, Liu J, Zhang Q, Wang R, Li Z, Wang L, Yang Q (2016) Groundwater environment in Beijing, China. Groundwater environment in Asian cities. Elsevier, Woburn, pp 345–381
Shi PJ, Yuan Y, Zheng J, Wang JA, Ge Y, Qiu GU (2007) The effect of land use/cover change on surface runoff in Shenzhen region, China. Catena 69:31–35
Shin IK, Yi HB, Bae YJ (2011) Colonization and community changes in benthic macroinvertebrates in Cheonggye Stream, a restored downtown stream in Seoul, Korea. J Ecol Environ 34:175–191
Shin E, Kim HS, Ha K, Yoon H, Lee E (2015) Regional groundwater flow characteristics due to the subway system in Seoul, Korea. J Soil Groundwater Environ 20:41–50
Shivakoti BR, Pandey VP (2016) Groundwater environment in Tokyo, Japan. Groundwater environment in Asian cities. Elsevier, Woburn, pp 451–468
Shuster WD, Bonta J, Thurston H, Warnemuende E, Smith DR (2005) Impacts of impervious surface on watershed hydrology: a review. Urban Water J 2:263–275
Sim WJ, Lee JW, Oh JE (2010) Occurrence and fate of pharmaceuticals in wastewater treatment plants and rivers in Korea. Environ Pollut 158:1938–1947
Son SH (2003) Commuting trips and changing regional structures in the greater Seoul metropolitan area. J Korean Urban Geogr Soc 6:69–83
Son SH (2015) The change of commuting trips and spatial separation of job-housing in Seoul metropolitan area. J Kor Urban Geograph Soc 18:97–110
Son JY, Lane KJ, Lee JT, Bell ML (2016) Urban vegetation and heat-related mortality in Seoul, Korea. Environ Res 151:728–733
Su YS (2016) Urban flood resilience in New York city, London, Randstad, Tokyo, Shanghai, and Taipei. J Manag Sustain 6:92–108
Sun G, Michelsen AM, Sheng Z, Fang AF, Shang Y, Zhang H (2015) Featured collection introduction: water for megacities—Challenges and solutions. J Am Water Resour Assoc 51:585–588
Thundiyil KA (2003) Rising temperatures and expanding megacities: improving air quality in Mexico City through Urban Heat Island mitigation. MS Thesis, Department of Urban Studies and Planning, MIT, Cambridge
Tortajada C (2003) Water management for a megacity: Mexico city metropolitan area. AMBIO 32:124–129
UN (2014) A world of cities. United Nations Department of Social and Economic Affairs Population Division, POPFACTS, No. 2014/2
UNESCO (2016) Water, megacities and global change. United Nations Educational Scientific and Cultural Organization, 7, place de Fontenoy, 75352 Paris 07 SP, France
Varis O, Biswas AK, Tortajada C, Lundqvist J (2006) Megacities and water management. Water Resour Dev 22:377–394
Vrba J (2016) The role of groundwater governance in emergencies during different phases of natural disasters. Hydrogeol J 24:287–302

Wang B, Jhun JG, Moon BK (2007) Variability and singularity of Seoul, South Korea, rainy season (1778–2004). J Clim 20:2572–2580

Weber EU (2010) What shapes perceptions of climate change? WIREs Clim Change 1:332–342

Yao D, Zhang K, Wang C, Zhu L (2015) The analysis on the evaluation of Shanghai tap water quality in terms of inorganic anion concentration. In: International conference on circuits and systems 2015. CAS 2015, Paris, France, pp 109–111

Ye S, Xue Y, Wu J, Yan X, Yu J (2016) Progression and mitigation of land subsidence in China. Hydrogeol J 24:685–693

Yin J, Yu D, Wilby R (2016) Modeling the impact of land subsidence on urban pluvial flooding: a case study of downtown Shanghai, China. Sci Total Environ 544:744–753

Yun HS, Lee JY, Yang DY, Hong SS (2007) Areal distribution ratio of rock types with geologic ages in the Gyeonggi-Seoul-Incheon areas. J Petrol Soc Korea 16:208–216

Yune CY, Chae YK, Paik J, Kim G, Lee SW, Seo HS (2013) Debris flow in metropolitan area—2011 Seoul debris flow. J Mt Sci 10:199–206