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Assessing Urban Water Management Sustainability of a Megacity: Case Study of Seoul, South Korea

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Received: 17 April 2018; Accepted: 22 May 2018; Published: 24 May 2018

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Abstract: Many cities are facing various water-related challenges caused by rapid urbanization and climate change. Moreover, a megacity may pose a greater risk due to its scale and complexity for coping with impending challenges. Infrastructure and governance also differ by the level of development of a city which indicates that the analysis of Integrated Water Resources Management (IWRM) and water governance are site-specific. We examined the status of IWRM of Seoul by using the City Blueprint®Approach which consists of three different frameworks: (1) Trends and Pressures Framework (TPF), (2) City Blueprint Framework (CBF) and (3) the water Governance Capacity Framework (GCF). The TPF summarizes the main social, environmental and financial pressures that may impede water management. The CBF assesses IWRM of the urban water cycle. Finally, the GCF identifies key barriers and opportunities to develop governance capacity. The results indicate that nutrient recovery from wastewater, stormwater separation, and operation cost recovery of water and sanitation services are priority areas for Seoul. Furthermore, the local sense of urgency, behavioral internalization, consumer willingness to pay, and financial continuation are identified as barriers limiting Seoul's governance capacity. We also examined and compared the results with other mega-cities, to learn from their experiences and plans to cope with the challenges in large cities.

Keywords: Integrated Water Resources Management; water management sustainability; urban resilience; urban water cycle; water governance

1. Introduction

Globally, more than half of the world's population resides in urban areas, and this figure is projected to increase to 66% by 2050 [1]. Cities are important engines of innovation and wealth creation, as well as sources of improved efficiencies for the use of materials and energy [2]. On the other hand, primarily due to the concentration of people in a relatively small area, cities also act as centres of intense resource consumption and pollution [3,4]. Rapid urbanization along with the effects of climate change creates multiple challenges regarding water quality, water scarcity, and flooding resulting in high vulnerability and, sometimes, unforeseen consequences [5]. Actually, these risks are amplified in cities that lack the necessary infrastructure and/or institutional arrangements with the adaptive capacity to cope with these challenges [6,7]. A sustainable city thus requires appropriate and efficient management and control of a large variety of issues, notably the availability of sufficient clean freshwater and the protection against flooding as a prerequisite for health, economic development and social well-being of their inhabitants [7].

Water management and water governance challenges are often more prominent in larger cities [6]. Twenty-five million people—50% of the population of the Republic of Korea—reside in the metropolitan area of Seoul, which is amongst the largest urban regions in the world [8]. The city of Seoul has undergone extensive growth over the past half-century and has grown into a prosperous metropolis. The city's growth has been accompanied by the development and adoption of advanced water technologies and water policies. However, continuous efforts are necessary to improve Seoul's water management to cope with pressures that constantly change and may aggravate due to climate change, aging infrastructures, and evolving social demands. Moreover, due to its complex geomorphology [9] and a high spatiotemporal variability in hydro-climatic conditions, water management in Korea has always been challenging [10].

The City Blueprint®Approach (CBA) has been developed to assess the sustainability of Integrated Water Resources Management (IWRM) in a municipality [11,12]. The CBA consists of three assessment frameworks: (1) the Trends and Pressures Framework (TPF), which summarizes the principal social, environmental and financial pressures that impedes water management, (2) the City Blueprint Framework (CBF), which provides an overview of the performances of IWRM, and, (3) the water Governance Capacity Framework (GCF), which identifies key barriers and opportunities in urban water governance (Figure 1). The CBF has been used extensively since its development for rapid baseline assessments in about 70 cities around the globe. This allows for a comparison with other cities and facilitates city-to-city learning on strategic planning, exchange of knowledge, experiences, and best practices [13]. Results for 45 municipalities and regions in 27 different countries have been published [14], and, a recent update with references to publications and presentations for 70 municipalities and regions in 37 countries is available as an E-Brochure (European Commission: Brussels, Belgium) on the EIP (European Innovation Partnerships) Water website [15].

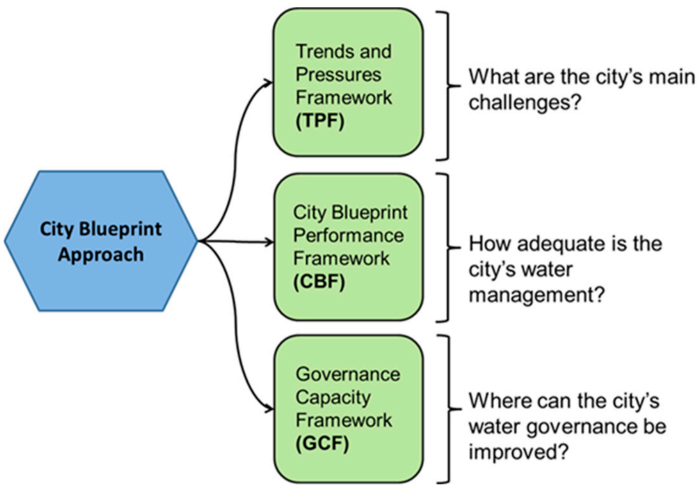


Figure 1. Overview of the City Blueprint Approach which consists of three complementary diagnostic frameworks to assess the urban water cycle management and governance [12–14].

The aim of this study is to identify barriers, enablers, and city-to-city learning opportunities to improve Seoul's water management and resilience. Also, regarding the scale of Seoul, and given that scale matters for tackling water management challenges, we compare CBF results with other megacities that were examined in earlier studies [14,15]. This comparative study will allow Seoul to learn from other well-managed cities and improve on weaknesses that were identified through this assessment.

2. Materials and Methods

2.1. Study Area

Korea is located in the northeastern part of the Asian continent, and Seoul, the capital of Korea, is in the northwestern part of the country. Seoul has been the capital of the country for more than 600 years since the foundation of the Joseon Dynasty in 1394. The geographical area of Seoul has expanded throughout history with the increasing population, and has shown explosive growth since the end of the Korean War in the early 1950s [16]. The total area of Seoul is 605.2 km^2 with a population of 10,112,070 as of 2017 [17]. The population of Seoul increased from 1.7 million in 1950 to 10 million in 1992, with an average growth rate of 278,583/year. Since then, the population has stabilized at around 10 million due to elevated housing prices and the government policy of controlling urban sprawl by constructing satellite cities and towns around Seoul [16]. Currently, the population density is around 17,200/km^2, which has been sustained for a decade. However, this number is still 70% greater than the average population density of the 34 other megacities worldwide (10,100/km^2). Although the population density within the administrative boundary of Seoul has stabilized since the early 1990s, the population of the Seoul metropolitan area, which includes several large satellite cities, keeps increasing and is expected to grow further in coming decades.

Seoul has four distinct seasons with the average temperature varying from −1 °C during the winter season (from December to February) to 25 °C during the summer season (from June to August). About 65% of the annual rainfall is concentrated in summer due to the monsoon. While the highly variable hydro-climatic conditions have already posed many water-related challenges in Seoul, climate change effects are also apparent in precipitation and air temperature records [18]. While the mean annual rainfall before the 1950s was around 1230 mm, it has now increased to around 1400 mm. The frequency and intensity of torrential rainfall in summer also increased, resulting in a greater intra-annual rainfall variability [18]. The mean air temperature increased from 10.4 °C in 1909 to 13.4 °C in 2014 by an overall rate of 0.0238 °C/year, which is higher than global trends of 0.0066 ~0.0189 °C/year [16,19]. This trend has become more significant since the 1950s due to rapid urbanization and, correspondingly, the urban heat island (UHI) effect [16,20]. Since the UHI effect increases energy consumption, health problems (e.g., heat strokes), and surface water quality deterioration, a rapid increase in air temperature poses a serious IWRM challenge [21].

2.2. City Blueprint Approach

In order to assess the trends and pressures, IWRM and the governance capacities of Seoul, we applied the CBA (Figure 1). Detailed information about the data sources, the calculations and examples are provided in three questionnaires available on the EIP Water website [15].

2.2.1. Trends and Pressure Framework (TPF)

Each city has its own unique social, financial and environmental background. As such, cities' performance regarding urban water management should be carefully assessed based on the context that has shaped the current state of infrastructure and governance for urban water management. The TPF aims to provide a concise understanding of these contextual trends and pressures that affect water management of a city [13]. It is evaluated with 12 indicators, which are divided over social, environmental, and financial categories (Table 1). Each indicator is scaled from 0 to 4 points, where a higher score indicates stronger pressure or concern. Note that many of these indicators are evaluated based on the ranking of the city among all countries, thus a specific score does not necessarily imply its absolute pressure state [13,15]. After each indicator is scored, these scores are classified into five categories: no concern (0–0.5), little concern (0.5–1.5), medium concern (1.5–2.5), concern (2.5–3.5), and great concern (3.5–4). More detailed descriptions of the indicators, data requirements and sample calculations as well as a critical discussion on its limitations, can be found elsewhere [13,14].

Table 1. Basic method and features of the Trends and Pressures Framework and City Blueprint Framework [13,15,22].

Trends and Pressures Framework (TPF)		
Goal	Baseline assessment of social, environmental, and financial pressures	Indicators
Framework	Social pressures	1. Urbanization rate 2. Burden of disease 3. Education rate 4. Political instability
	Environmental pressures	5. Flooding 6. Water scarcity 7. Water quality 8. Heat risk
	Financial pressures	9. Economic pressure 10. Unemployment rate 11. Poverty rate 12. Inflation rate
Data	Public data or data provided by Seoul Metropolitan Government	
Scores	0: no concern, 1: little concern, 2: medium concern, 3: concern and 4: great concern	
Overall score	Trends and Pressure Index (TPI), the arithmetic mean of 12 indicators. Indicators scoring a concern or great concern (3 or 4 points) are communicated as a priority	
City Blueprint Framework (CBF)		
Goal	Baseline performance assessment of the state of IWRM	
Framework	Twenty-five indicators divided over seven broad categories: 1. Water quality 2. Solid waste 3. Basic water services 4. Wastewater treatment 5. Infrastructure 6. Climate robustness 7. Governance	
Data	Public data or data provided by the water and wastewater utilities and cities based on a questionnaire [15]	
Scores	0 (low performance) to 10 (high performance)	
Overall score	Blue City Index (BCI), the geometric mean of 25 indicators	
Governance Capacity Framework (GCF)		
Goal	Baseline assessment of the governance capacity of a city	
Framework	Five challenges: (1) water scarcity, (2) flood risk, (3) wastewater treatment, (4) solid waste treatment, and (5) UHI. In each water challenge, 27 indicators are divided over nine broad categories: 1. Awareness 2. Useful knowledge 3. Continuous learning 4. Stakeholder engagement process 5. Management ambition 6. Agents of change 7. Multi-level network potential 8. Financial viability 9. Implementing capacity	
Data	Policy documents, scientific literature, and interviews Total interviewees: 10 (academia: 5, practitioners or civil servants: 5) 2~3 interviewees for each challenge	
Scores	'very encouraging (++)' to 'very limiting (−−)'	

2.2.2. City Blueprint Framework (CBF)

The CBF comprises 25 indicators divided over seven broad categories: (I) water quality, (II) solid waste, (III) basic water services, (IV) wastewater treatment, (V) infrastructure, (VI) climate robustness and (VII) governance (Table 1) [5,6]. The indicators are scored on a scale between 0 (very poor) to 10 (excellent). The geometric average of these 25 indicators is the Blue City Index (BCI) [6,7]. As the CBF was developed as the first framework of the CBA [11], the applications of this methodology in many municipalities and regions have been published [14,15]. Details regarding data, calculation of each index, and scaling methods are described in Koop and Van Leeuwen [13] and on the EIP Water website [15]. For the assessment of Seoul, most of the data were collected from public sources. For indicators that require self-assessment, the relevant materials and data were collected by interviewing experts in the Seoul Water Institute and the Seoul Metropolitan Government.

2.2.3. Governance Capacity Framework (GCF)

The sustainability of any resource management regime depends on the institutional capacity that enables adaptive management that can cope with external shocks and pressures [23,24]. The GCF was developed as the third framework of the CBA to assess the governance capacity of a city that allows or limits its sustainable management of water [12,23]. The GCF aims to identify the key enabling or limiting of governance conditions regarding five main urban water challenges that are relevant to urbanization and climate change. These challenges include (1) water scarcity, (2) flood risk, (3) wastewater treatment, (4) solid waste treatment, and (5) UHI [23]. For each challenge, the GCF assesses nine governance conditions, each of which includes three indicators. Each indicator is evaluated by a Likert-scale scoring method which ranges from 'very encouraging' (++) to 'very limiting' (−−) (Table 1). Since its development, the GCF has been successfully operationalized in several cities including Amsterdam, Quito, Ahmedabad, and New York City [22,25–27]. More details on the methodology are reported in Koop et al. [23].

The GCF indicator scoring was done through two steps: (1) preliminary scoring based on an analysis of policy documents and scientific literature, and (2) confirmatory scoring based on qualitative semi-structured interviews and surveys with experts to obtain additional details on the governance for each water challenge. The respondents were categorized as government personnel and academic scholars. Ten respondents were carefully selected based on their relevance to each of the five water challenges. Several respondents from the government sector had professional experience in multiple categories (e.g., flood risk and wastewater treatment). In those cases the interviewees were allowed to respond to multiple water challenges, resulting in at least two to three responses for each water challenge (Table 1).

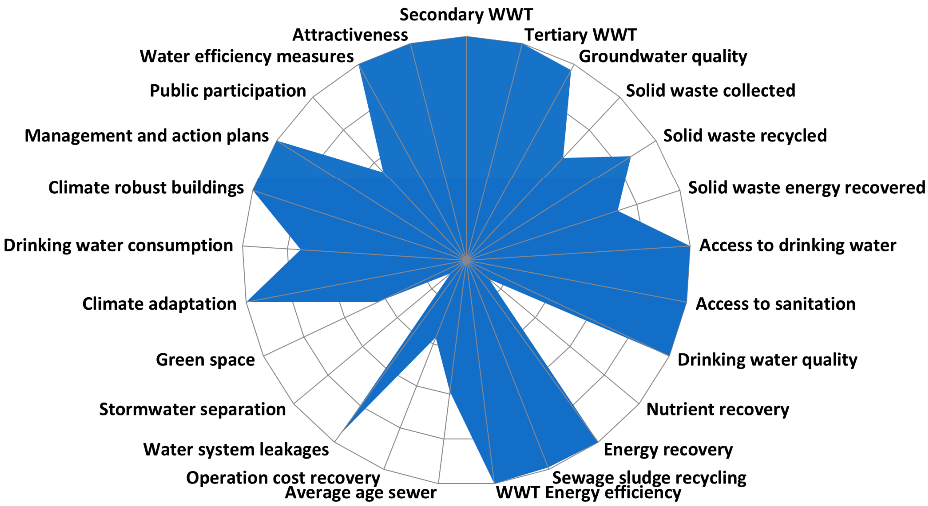
3. Results

3.1. Trends and Pressures of Seoul

All TPF indicators of Seoul ranged from no concern (0–0.5) to medium concern (1.5–2.5), except heat risk, for which the indicator score was 2.72 (concern). The indicators categorized as medium concern included education rate, political instability, water scarcity, and economic pressure, with respective scores of 1.70, 1.92, 1.67 and 2.12. The arithmetic mean of all indicators, i.e., the Trends and Pressures Index (TPI) was 0.90, which is rather low and comparable to cities in the Netherlands and Sweden [15]. Among the 11 Asian cities analyzed with CBF, Singapore, with a TPI of 1.0, and Taipei, with a TPI of 1.4, were most comparable to Seoul. However, the other eight Asian cities (with TPIs of 1.9~2.6) face greater concerns, generally due to social pressure from high urbanization rates, environmental pressure from water scarcity, flooding, and heat risk, and financial pressure from low GDPs [28]. A full overview of TPI scores for 70 municipalities and regions, including 11 Asian cities, is provided in the most recent version of the E-Brochure [15].

3.2. City Blueprint of Seoul

The CBF presents a snapshot, i.e. the current performance of a city regarding IWRM. The geometric mean of all 25 CBF indicators, i.e. the Blue City Index, for Seoul is 7.3 (Figure 2). Based on a hierarchical clustering analysis of CBF indicator scores of 45 municipalities, Koop and Van Leeuwen [14] identified five different levels of sustainability of IWRM in cities worldwide: (1) cities lacking basic water services (BCI 0–2), (2) wasteful cities (BCI 2–4), water efficient cities (BCI 4–6), resource efficient and adaptive cities (BCI 6–8), and (5) water-wise cities (BCI 8–10). According to this categorization, Seoul is classified as a 'resource efficient and adaptive city.' Moreover, among the 70 cities assessed so far, Seoul has one of the highest BCI scores. However, our analysis reveals that there are also opportunities for improvement. The specific areas where improvement can be made are represented by relatively low indicator scores. Since many of the indicators obtained a full score of 10, we arbitrarily regarded any score less than six as the criterion for selecting areas for further improvement. Indicators that scored lower than six included nutrient recovery, average age of the sewer network, operation cost recovery, and stormwater separation (Figure 2a).



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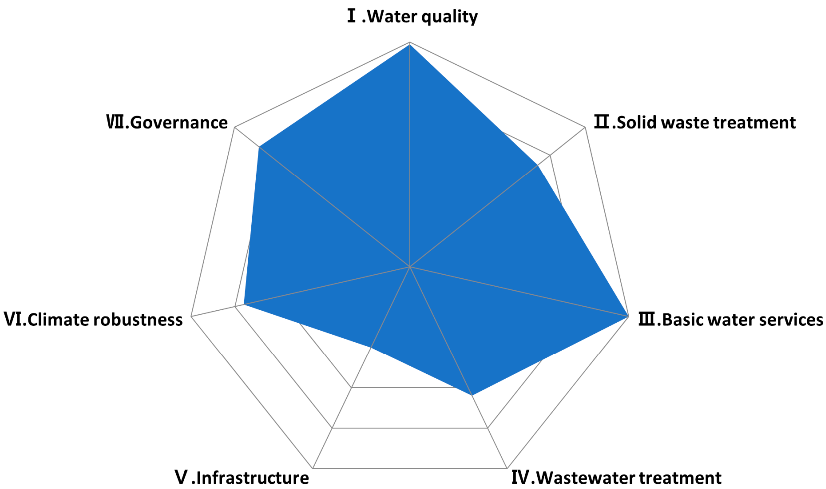

(**b**)

Figure 2. The City Blueprint of Seoul (**a**) based on 25 indicator scores and (**b**) the average scores of the seven categories. The Blue City Index, the geometric mean of all 25 indicators, is 7.3.

Among the seven broad categories, wastewater treatment (IV) and infrastructure (V) have average scores of 6.4 and 4.0, respectively (Figure 2b). In particular, infrastructure includes three indicators, i.e. stormwater separation, average age of sewer, and operating cost recovery, where improvements can be made. In other words, infrastructure improvement is thought to be an effective measure to enhance IWRM in Seoul.

3.3. The Water Governance Capacity of Seoul

Table 2 shows the results of GCF analysis for five urban water challenges in Seoul, whereas Figure 3 summarizes the average of each indicator score for all five challenges. According to our analysis, four indicators, i.e., indicator 1.2 local sense of urgency, indicator 1.3 behavioral internalization, indicator 8.2 consumer willingness to pay, and indicator 8.3 financial continuation, were found to be limiting (Table 3). Furthermore, the governance capacity for water scarcity and UHI was relatively low with a few indicators that limited the governance capacity. Specifically, the indicators 1.2 and 1.3 were found to limit the capacity to govern the challenges of water scarcity, wastewater treatment, and UHI. In addition, the indicators 8.2 and 8.3 limited the capacity to govern flood risk and solid waste treatment. Water scarcity was the only challenge with five limiting governance indicator, i.e., indicators 1.2, 1.3, 6.3, 7.1, and 7.3.

Table 2. Results of the water governance capacity analysis of Seoul.

Dimension	Conditions	Indicators	Water Scarcity	Flood Risk	Waste Water Treatment	Solid Waste Treatment	Urban Heat Islands
Knowing	1. Awareness	1.1 Community Knowledge	0	+	0	++	0
		1.2 Local sense of urgency	−	+	−	0	−
		1.3 Behavioral internalization	−	+	−	+	−
	2. Useful knowledge	2.1 Information availability	+	+	0	0	0
		2.2 Information transparency	+	+	0	+	+
		2.3 Knowledge cohesion	+	+	+	+	+
	3. Continuous learning	3.1 Smart monitoring	+	+	+	+	0
		3.2 Evaluation	+	0	0	+	0
		3.3 Cross-stakeholder learning	0	0	+	+	0
Wanting	4. Stakeholder engagement process	4.1 Stakeholder inclusiveness	+	+	+	+	+
		4.2 Protection of core values	0	+	+	+	+
		4.3 Progress and variety of options	+	0	0	+	+
	5. Management ambition	5.1 Ambitious realistic management	0	0	0	+	0
		5.2 Discourse embedding	0	+	0	+	+
		5.3 Management cohesion	0	+	0	+	0
	6. Agents of change	6.1 Entrepreneurial agents	0	+	+	+	0
		6.2 Collaborative agents	0	+	+	0	0
		6.3 Visionary agents	−	++	+	+	0
Enabling	7. Multi-level network potential	7.1 Room to maneuver	−	+	+	0	0
		7.2 Clear division of responsibilities	0	0	+	+	0
		7.3 Authority	-	+	+	+	0
	8. Financial viability	8.1 Affordability	++	0	++	+	+
		8.2 Consumer willingness to pay	0	-	0	0	-
		8.3 Financial continuation	0	-	0	0	-
	9. Implementing capacity	9.1 Policy instruments	0	+	+	+	+
		9.2 Statutory compliance	0	+	+	+	+
		9.3 Preparedness	+	+	+	+	+

Yellow: limiting (−); light green: encouraging (+); dark green: very encouraging (++).

Table 3. Overview of the four most limiting governance indicators.

1.2 Local sense of urgency.
To what extent do actors have a sense of urgency, resulting in widely supported awareness, actions, and policies that address the water challenge? The perception regarding this indicator varied considerably between the stakeholders. Few experts and NGOs have recognized the uncertain threats from climate change and urbanization, and express their increasing concerns for the future. However, most of the general public does not feel this urgency about these water-related challenges.
1.3 Behavioral internalization
To what extent do local communities and stakeholders try to understand, react, anticipate and change their behavior in order to contribute to solutions regarding the water challenge? Although actions to improve urban water-related resilience (e.g. separate collection, green roofs, green space) exist, measures are only taken under external pressure, including restraints and economic incentives.
8.2 Consumer willingness to pay
How is expenditure regarding the water challenge perceived by all relevant stakeholders (i.e., is there trust that the money is well-spent)? Differences in awareness of the urgency of water challenges in communities determine the willingness to pay for measures. In general, rates of cost recovery in each neighborhood of the city are lower than the actual costs, even when funds are provided by the national or local governments, leading the neighborhood to maintain the status quo.
8.3 Financial continuation
To what extent do financial arrangements secure long-term, robust policy implementation, continuation, and risk reduction? To deal with future water challenges, long-term strategies have been planned in a ten-year cycle. However, since financial resource allocation support and maintain the status quo, there is a lack of resources to deal with prevention of unpredictable future risks. Furthermore, some water challenges that seem relatively minor issues for the communities do not receive sufficient financial resources for research and improvement.

3.4. Comparison with Other Cities

A full overview of BCI scores for 70 municipalities and regions, including 11 Asian cities, is provided in Figure 4. Cities with BCIs higher than Seoul are Singapore, and some cities in the Netherlands (e.g., Amsterdam and Groningen) and Sweden (e.g., Helsingborg, Malmo, Kristianstad, and Stockholm). As the major purpose of the CBA is city-to-city learning, i.e., improving implementation capacities of cities and regions by sharing best practices [15], these cities can be prime candidates for benchmarking. However, except for Singapore (with a population of 5.7 million in 2018), the scales of the other cities are much smaller than Seoul. The city with the largest population among these cities is Amsterdam with a population of 850,000, which is less than 10% of that of Seoul (or than 4% of the metropolitan area of Seoul). Also, all cities with BCIs lower than Seoul but higher than 6.0 are still not comparable to Seoul by scale. As many urban water management policies and plans are constrained by the scale of a city, e.g. large-scale replacement of sewer networks, we chose to limit the comparative analysis to megacities of a comparable size, i.e., Istanbul, London, and New York City (NYC). These are megacities with approximately 8–15 million inhabitants.

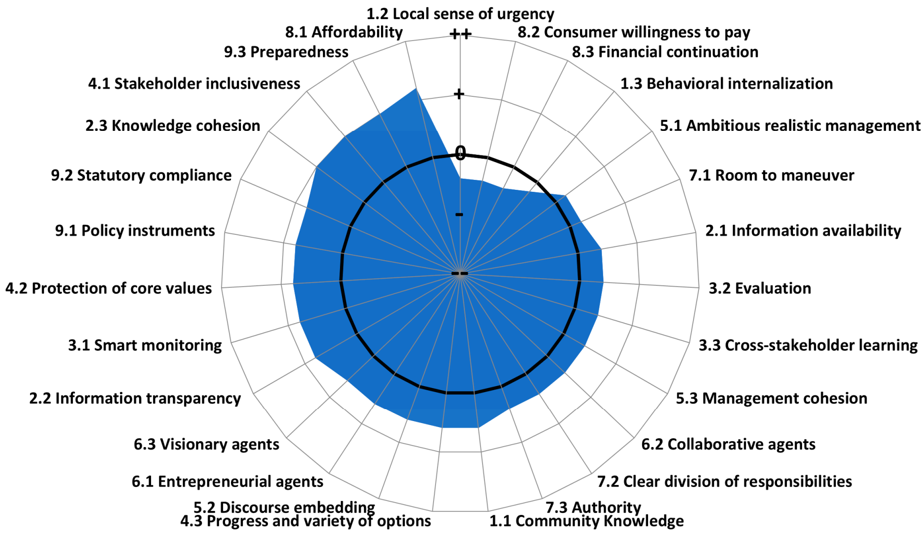

Figure 3. Result of the Governance Capacity Framework (GCF) of Seoul. The 27 indicators are organized clockwise around the spider web by most limiting (−−) to most encouraging (++) for the overall governance capacity.

The comparison of the 4 megacities is shown in Figure 5. The BCIs are highest for Seoul (7.3), then London (5.3), New York City (NYC) (4.8), and Istanbul (3.5). The common category with a high score is basic water services (Figure 5; indicators 7–9). On the contrary, wastewater treatment (indicators 10–13) and infrastructure (indicators 14–17) showed high variability among these cities. More specifically, in the wastewater treatment category, London and NYC showed better performance for the nutrient recovery (indicator 10) compared to Seoul.

In the category of infrastructure, NYC showed a higher indicator score than Seoul for stormwater separation. The type of sewer system depends upon the history of infrastructure installment of a city, and typically younger drainage systems are better separated in stormwater and sewage systems. Thus, Istanbul shows high indicator scores for both the average age of the sewer and stormwater separation. However, in NYC, the score for stormwater separation is relatively higher than the average age of the sewer system, which is exactly opposite to Seoul. This implies that there are opportunities to learn from NYC if Seoul is to improve its sewer system by expanding the portion of separate stormwater systems. Operation cost recovery is an indicator for which Seoul scores lower than London.

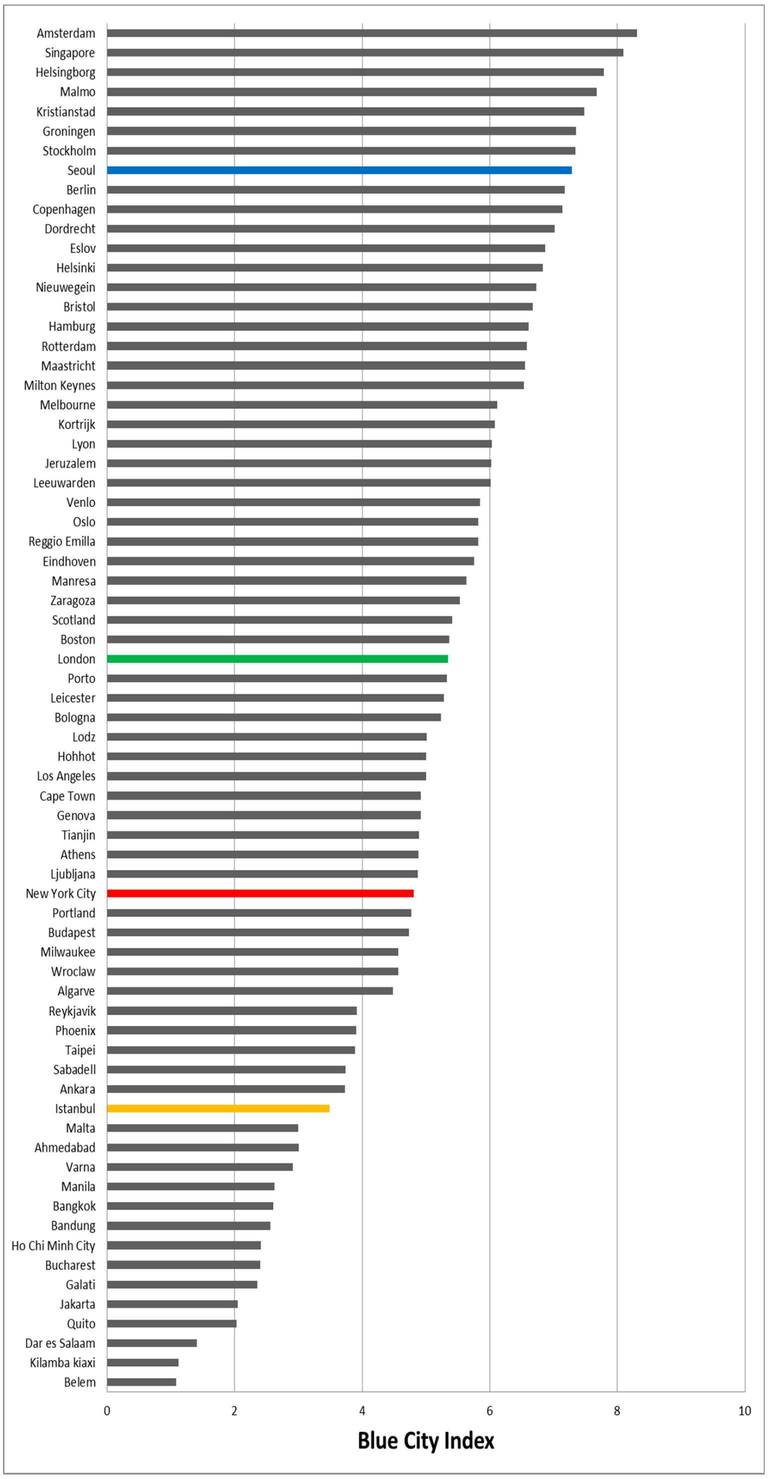

Figure 4. Results of the City Blueprint analysis of 70 municipalities and regions in 37 different countries. The Blue City Index, the geometric mean of 25 indicators of the City Blueprint, has been calculated according to Koop and Van Leeuwen [13–15]. The BCIs of Seoul, New York City, London, and Istanbul are highlighted.

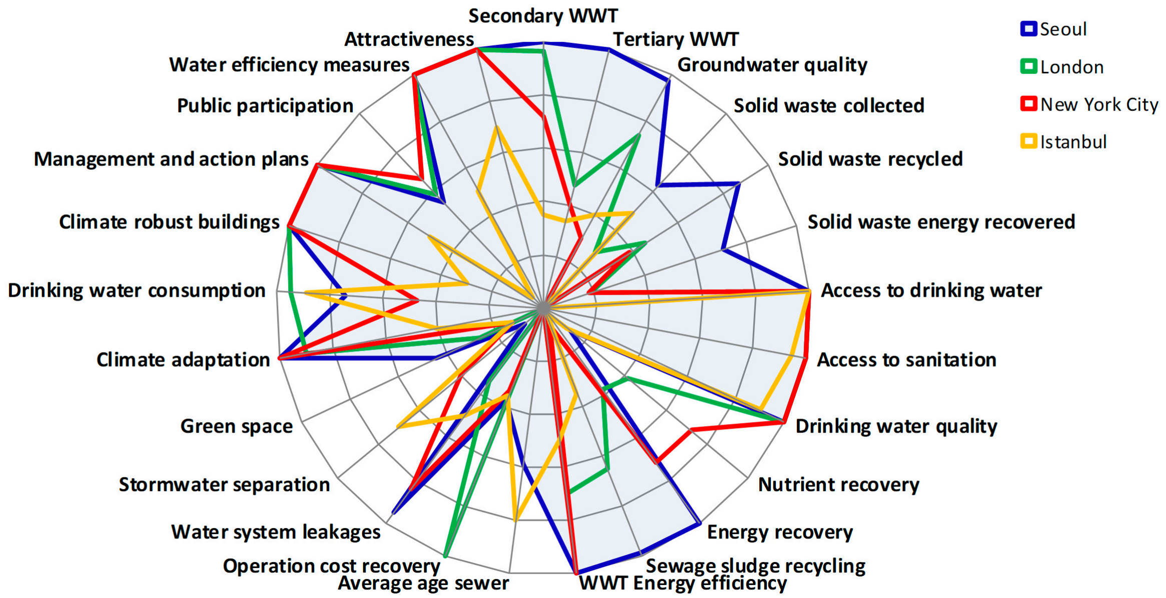

Figure 5. Comparison of 25 indicator scores between Seoul, New York City, London, and Istanbul.

4. Discussion

4.1. The Challenges for Seoul

Analyzing water management and water governance of a megacity, especially when its infrastructure has been developed over several decades, provides unique insights that may not be identified in smaller and younger cities. Due to its large scale and past propensity to build centralized infrastructures driven by economic efficiency, a full-scale replacement or renovation of these infrastructures to cope with changing conditions may not be economically nor technically feasible in the short-term. Thus, finding an innovative way to increase resilience in cities may be required and offers learning opportunities to other megacities, especially those on rapid development trajectories.

South Korea is recognized for its fast, intense economic development and industrialization. This has been accompanied by rapid urbanization along with an extensive installation of urban infrastructure in Seoul [29,30]. Due to the urgent need to provide essential water services for the rapidly growing population in the city, however, past water policies have focused on the expansion of water infrastructure in a quantitative manner without deliberation for long-term sustainable water management in the urban environment. This urban development process has been successful as reflected by the CBA analysis, which categorized Seoul as a 'resource efficient and adaptive city' with a BCI score of 7.3. However, climate change and aging water infrastructure act as drivers for further change and new emerging challenges, which call for further and continuous adaptation and improvement in infrastructure, policies, and practices of urban water management and governance [7,12]. Improving resilience is the big challenge. Based on our analysis, we provide some suggestions for priorities to improve IWRM in Seoul, which could potentially transform Seoul from a 'resource efficient and adaptive city' to a 'water-wise city' in the near future.

4.2. Nutrient Recovery

Nutrient recovery is one of the indicators which offers clear opportunities for improving Seoul's IWRM as it was shown as the only weakness in the category of wastewater treatment (Figure 1). Nutrient recovery is necessary in Korea for several reasons: (1) phosphorus is nonrenewable and a limited resource [31]; (2) Korea entirely depends on the imports of phosphorus; (3) phosphorus removal from wastewater will significantly contribute to the reduction of eutrophication of surface waters. Thus, the introduction of technology for recovering nutrients from wastewater is an effective option for coping with diminishing resources, while simultaneously reducing eutrophication and improving surface water quality. However, nutrient recovery from wastewater treatment is a rather recent technology which still needs further improvement to become economically feasible and to meet regulations for the quality of recovered materials in many countries. London and NYC recover phosphorus by producing biosolids. In the UK, 3–4 million tons of biosolids, which is about 75% of sewage sludge production, are applied annually to agricultural land [32]. Also, NYC produces approximately 1200 tons of biosolids every day. In 1988, US Federal government banned the ocean disposal of biosolids, and NYC needed to find alternative uses for this material. The NYC Department of Environmental Protection implemented a program to beneficially use most of the biosolids to fertilize crops and improve soil conditions for plant growth [33].

However, biosolids also contain chemical contaminants such as heavy metals and persistent organic chemicals, which limit the use of biosolids is many countries. This is one of the reasons that biosolids are not yet actively used in Seoul. Similar problems were observed in Amsterdam, and the produced struvite ($MgNH_4PO_4{\cdot}6H_2O$) can now be applied as fertilizer in parks and sports fields, preventing contaminants from entering the food chain [34,35]. Currently, in Korea, nutrient recovery from wastewater treatment plants (WWTPs) is done only by recycling through earthworm rearing and composting. The national legislation allows the use of these composts for landscaping of gardens, parks, etc., and not for edible and feed production purposes, as is the case in Amsterdam [34,35]. In 2014, the Seoul Metropolitan Waterworks Research Institute succeeded in developing a device for recovering phosphorus from sewage, but it has not yet been applied on a commercial scale mainly due to the economic feasibility.

The recovery of nutrients is still not common for WWTPs, even though recovery technologies are available. Countries like the Netherlands, Denmark, and Germany upgraded their plants recently. Although there are many economic, technical, and legislative issues to overcome for recovering nutrients from WWTPs, the limited availability of phosphorous, which is essential for food production, imposes a potential future geo-political risk. Currently, the economic viability and safety issues for using the recovered materials are the major barriers that hinder the active introduction of nutrient recovery facilities in Seoul. However, given that several cities, including Amsterdam, already installed the technology successfully [34,35], a stronger willingness of the government to achieve a long-term IWRM will be the most critical decision factor for enabling the new technology to become economically viable.

4.3. Operation Cost Recovery

Water infrastructure is the most expensive infrastructure in cities [12], which means securing an adequate long-term financial condition is necessary for effective maintenance and improvement thereof [36]. However, as the indicator of the operation cost recovery in Seoul shows, it may be a major obstacle hindering large-scale improvement of the sewer systems [37].

Among the other megacities, London is the only city with a higher score than Seoul. The primary reason for London's higher operation cost recovery is privatization in water sectors since 1989. Although London's water and sewerage charges are set by the regulator 'Ofwat', a non-ministerial government department that protects the interests of consumers, the charges should ensure the profitability of water companies. Total annual charges for drinking water and sewerage in London were 3.98 USD/m^3 in 2013 [38].

On the contrary, the total annual charge of water services in Seoul is extremely low with 0.53 USD/m^3 in 2013 [39,40] which makes the realization rate of drinking water and sewerage 89% and 67%, respectively. According to an OECD (Organisation for Economic Co-operation and Development) survey, the average water price of 114 cities in OECD countries was 3.84 USD/m^3 and the water price of Korea is the lowest among the OECD countries [38]. The low water pricing in Korea hinders secure reinvestment of resources for introducing new water infrastructure and improving old water facilities, such as those seen in other indicators. This may pose a serious threat to the long-term water security and supply stability in Seoul, which may result in a decline in service levels. Given that climate change tends to increase the vulnerability of water infrastructure in various ways, securing enough recovery from operation costs will be an essential option to provide water services sustainably to Seoul citizens. A political discussion and decision on a sufficient water price is one of the key components for improving urban resilience to unexpected future risks [37].

4.4. Sewer Systems

During the 1970s and 80s, the majority of the sewer system in Seoul was installed with combined sewers. Since 2000, the installment of separate sewer systems has been given priority. However, as the sewer maintenance project is limited to only small redeveloping areas, it is unlikely to increase the portion of the separated sewer system in the short term unless there is a substantial change in local water policy. Also, adverse effects, such as land subsidence, from the aging of pipe systems are escalating [16]. Thus, along with expanding separate sewer systems, giving higher priority to the replacement of old pipes may reduce the water-related risks significantly. The relevance of infrastructure maintenance is high as observed by both the OECD [7] and UN-Habitat [6].

Combined sewer systems are common in many cities, such as Seoul, London, and NYC. However, due to a continued increase in the impermeable surface area that increases stormwater runoff and higher peak precipitation due to climate change, there is a high likelihood of combined sewer overflow (CSO) [41]. NYC is also concerned about CSOs as 60~70% are combined sewer systems. Since it is a daunting task to change the existing infrastructure in such large cities, London and NYC have tried to implement various alternative ways to deal with CSOs. These include the construction of sewer tunnels or CSO retention tanks, upgrades in key WWTPs, and the development of green infrastructure [42].

Seoul and NYC are trying to increase the portion of separate sewer systems, but it will take a long time due to the scale of construction. Also, only a partial retrofitting of the whole system may result in misconnections between the different drainage types, which can cause undesired effects on sewer management and water quality. In this situation, implementing an alternative way to deal with combined sewers may serve as a solution for large cities.

4.5. Implications from the Governance Capacity Analysis

Even if weaknesses of specific sectors for the water management of a city can be identified (e.g., by CBF), if there is a barrier in the governance for disseminating core information and promoting future actions for fixing existing weaknesses, a city may not be able to cope with the challenges that threaten the sustainable provision of water services. Our analysis of the governance capacity indicated that awareness and financial viability are the weakest governance conditions in Seoul. Specifically, there is a low local sense of urgency and behavioral internalization for the challenges of water scarcity, wastewater treatment, and urban heat islands (UHI). Furthermore, there is a low consumer willingness to pay and financial continuation for the challenges of flood risk and UHI.

There are various efforts in education, promoting the engagement of local stakeholders, and using media for dispersing the information on water challenges that the citizens may face in the near future. In spite of these efforts, however, raising the local sense of urgency and behavioral internalization is a difficult task. Ironically, the most effective boost in awareness can be achieved if the local communities are frequently exposed to water threats and have experiences encountering inconveniencies within water services. As one of the cities with well-equipped water infrastructures, Seoul has overcome various urban water problems that have been the norm in the past. As unprecedented changes are expected, as indicated by our CBF analysis, it is important to disseminate existing and newly obtained information to the public as a governance condition for adequately managing urban resilience. Resilience is not a static property of a system but requires constant adaptation and transformation [43]. Keeping the status quo will not ensure the sustainability of IWRM of Seoul in the coming decades, as pressures are likely to aggravate. This will require strong governance for raising consumer willingness to pay and financial continuation. Without such a sense of urgency as water infrastructures currently perform well, efforts for enhancing financial capacity and continuity may raise political objection. Therefore, local stakeholders must perceive that resilience of the current water infrastructure in Seoul may be adequate to respond to pressures of the past, but not to pressures of the future. Therefore, in addition to mitigation, it is essential to develop adequate adaptive responses as a means of moderating damages or realizing opportunities associated with climate change [12,44].

5. Conclusions

We examined the current status of IWRM of Seoul by using the City Blueprint Approach in order to explore the options for improvement of water management and water governance in Seoul. This study also sets a good example to the challenges faced in IWRM in megacities, especially those with well-established water infrastructure. Our analysis revealed that there are several options to achieve better IWRM in Seoul. These include nutrient recovery, stormwater separation, and operation cost recovery, for which vigorous investments with high priority may provide strong opportunities for improvement.

When compared to other megacities, stormwater separation is a common weakness. Because of the large scale of these cities, their urban environment is complicated by the intertwined structure of multiple infrastructures, reducing the ability to manage infrastructure adaptively. While it is imperative to increase the portion of separated drainage systems in a city, especially to reduce the risk from combined sewer overflows, the experiences in other cities show that there are also other sustainable options such as expanding green infrastructure. When implemented with a long-term view on the sustainability of IWRM in cities, these options can also enhance other sectors, such as increasing the green area ratio and reducing impervious surface areas, thereby improving e.g. recreation, attractiveness and the livability of the city.

Resource recovery is another indicator that can improve Seoul's IWRM, especially regarding the depletion of phosphorous reserves in the near future [14]. Due to the early stage of establishment, nutrient recovery technologies are still not common in use. Low recovery rates, economic feasibility, and limited applicability of end-products by regulations are barriers that making cities reluctant to deploy the technology on a commercial scale. Nonetheless, megacities, where large-scale WWTPs are typically in operation, are the right places since the large flow rate of wastewater can improve the phosphorous recovery rate with high economic efficiency and profitability and, at the same time, improve surface water quality. Regarding its necessity in the coming decades, the benefits that a city gains include securing the depleting resources and relative advantages of a mega-scale for improving the efficiency, Seoul can benefit from embarking on a path to promote the development and installation of nutrient recovery technologies.

Several potential barriers—the local sense of urgency, behavioral internalization, consumer willingness to pay, and financial continuation—that may retard the efforts for improving urban water management sustainability were also identified through the water GCF. This finding is especially important for cities that rely heavily upon the current system with a false sense of security. A resilient city requires an adequate preparedness for the occurrence of future threats, as well as an adaptive capacity to cope with continuously changing pressures [14,44,45].

Many cities are facing similar water-related challenges. Although Seoul gained a high overall BCI score, it does not necessarily ensure the sustainability of IWRM in the future. Water-related risks constantly evolve due to non-stationary conditions resulting from urban dynamics and climate change, and it requires timely adaptation as well as the transformation of a city to respond to the changing environment [14,44,45]. The challenges of megacities may be proportional to their scale, but large cities are also known as centers of innovation. Finding sustainable and prompt solutions can be stimulated by sharing the experiences and knowledge of multiple cities that are trying to cope with these challenges [15].

Author Contributions: H.K. and J.S. acquired and analyzed data; J.P., K.v.L., and H.K. wrote the paper; K.v.L. and S.K. conceived and designed the analysis; S.L. and Y.J.C. and contributed to conception of the paper and interpretation of data.

Acknowledgments: This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (NRF-2016R1C1B1011770). The City Blueprint Action Group is part of Watershare (https://www.watershare.eu/) and the European Innovation Partnership on Water of the European Commission (http://www.eip-water.eu/City_Blueprints). Part of this research was carried out in the context of the POWER project. The European Commission is acknowledged for funding POWER in H2020-Water Under Grant Agreement No. 687809.

Conflicts of Interest: The authors declare no conflict of interest.

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