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Assessment of Stormwater Harvesting Potential: The Case Study of South Korea

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Abstract: Stormwater harvesting (SWH) is emerging as a vital adaptive strategy for urban climate resilience. In South Korea, different types of storage facilities have been constructed under different regulations and laws. Each type of storage facility has its own original purpose of construction. Although these facilities have better outcomes, we aim to investigate the potential use of these facilities as additional water resources. In this study, we assess the stormwater harvesting (SWH) potential of different types of already-constructed storage facilities. Five different types of storage facilities and three different cases are considered in the present study. Case 1 excludes SWH volume during the flood and winter seasons, while in Case 2, only winter season SWH volume is excluded. In Case 3, the winter season and combined sewer overflows (CSOs) facilities are excluded. The Rainwater Utilization Facility is considered as a baseline for comparison in the present study. The results show that, in Case 2, the Sewage Storage Facility, Stormwater Runoff Reduction Facility, Nonpoint Pollution Reduction Facility, and Buffer Storage Facility has 53.5, 4, 2.4, and 1.2 times more stormwater average annual usage potential, respectively. The findings suggest that these facilities can be utilized as additional water resources. It should be mentioned that the primary objective for which each facility was constructed will remain unaffected. Nevertheless, forthcoming research should focus on a detailed exploration of the quality of the collected stormwater and the energy required to supply the stormwater for the end usage.

Keywords: rainwater harvesting; stormwater harvesting; storage tank; daily water inflow model; average annual usage potential; South Korea

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1. Introduction

Rapid urbanization has resulted in a rise in non-permeable surface areas, causing detrimental hydrological consequences, including risks of flooding and the degradation of water quality [1,2]. As the population increases, particularly in developing nations, the varied water needs for domestic, industrial, and agricultural uses exert increasing pressure on water resources [3]. Water stress and scarcity have emerged as urgent challenges for numerous countries globally, compounded by the risks posed by extreme climate events, intensified human activities, population growth, and rapid urbanization [4,5]. In response to the evolving challenges and in anticipation of impending water stress, numerous relevant authorities are embracing diverse sustainable technologies and methodologies [2].

The approach that has the potential for addressing increasing water demands is the proper implementation of a decentralized water supply system. Stormwater harvesting (SWH) is regarded as a highly effective solution, applicable during periods of peak discharge as well as peak demand [6,7]. The technique of stormwater harvesting, which entails capturing runoff from metropolitan regions to provide a non-potable water supply, is currently recognized as a valuable resource for urban development requiring a resilient array of water supply sources [8–10]. The primary elements of SWH is the process of collection, storage, treatment, and distribution [11–13]. Stormwater runoff, channeled directly into streams using drainage systems, constitutes a significant origin of various pollutants, thereby being recognized as a primary agent contributing to the degradation of receiving water bodies [14–16]. Therefore, of essential importance in urban water management is to mitigate stormwater pollution, aiming to transform cities and towns into the most resilient and livable environments globally [17].

Several research studies have investigated pollutants in urban stormwater, along with their origins and the processes associated with these pollutants [18–20]. The appropriate handling of stormwater is essential to enable its proper usage. The extent of treatment is predominantly influenced by the unique attributes of the catchment area and its eventual utilization [21,22]. Achieving the intended function of stormwater best management practices necessitates the suitable care of stormwater harvesting facilities [23]. The suitable site selection for the stormwater harvesting system is also important. Researchers have dedicated substantial effort to developing a robust methodology for effectively identifying suitable hotspots and ultimately determining the optimal location. This involved using various multi-criteria decision-making approaches, including fuzzy theory, the analytic hierarchy process (AHP), simple additive weighting, and the interval analytical hierarchy process, among others [24–30].

The regional variability in rainfall and its uneven distribution have profound implications for agriculture, ecosystems, climate, economies, water resources, and society as a whole. Comprehending these patterns is essential for promoting sustainable development, implementing effective resource management, and fostering resilience to the challenges posed by evolving climatic conditions [31–33]. The precipitation patterns in South Korea are significantly influenced by the region's topography, leading to recurrent instances of flooding attributed to extreme weather conditions. Seoul, the capital of South Korea, faces persistent urban flooding challenges due to heightened summer precipitation and a densely concentrated population, posing a threat to the city's long-term sustainability [34]. Numerous studies have investigated the efficiency, reliability, and investment feasibility of rainwater tanks in diverse geographical regions around the globe [35–40].

Stormwater harvesting in urban areas presents a potential solution to mitigate the floods and water shortages caused by population growth, climate change, and impermeable surfaces [41]. J Steffen et al. analyzed residential rainwater harvesting systems across 23 U.S. cities. They found that the efficacy of such systems in terms of water supply and stormwater reduction depends on the cistern size and climatic region [42]. Urban stormwater harvesting offers a promising solution to augment water supplies for water-scarce cities by capturing, treating, and recharging urban runoff. Despite successful demonstrations internationally, barriers such as regulatory frameworks and treatment uncertainties hinder widespread adoption, emphasizing the need for further research and technological advancements [8]. Although research on the SWH systems has been increasing globally, there remains a frontier to be fully explored in adapting these insights to the unique climatic, geographical, and urban context of South Korea [43,44].

The focus of the current study is to assess the stormwater harvesting potential for different types of storage facilities. A daily water inflow model was developed using MATLAB (R2015a) software. The foundational principle of the simulation model is the collection of daily rainfall from the capture area near to the storage facility, excluding initial rainfall of 5 mm. The volume of the collected daily rainfall is limited by the capacity of the storage tank since the water demand near each facility is unknown. Thus, different percentages (20%, 40%, 60%, 80%, and 100%) of daily inflow water volume usage potential were considered for each facility. The local rainfall data from Seoul rainfall station (station No. 108) for a period of ten years (from January 2012 to December 2021) were used as input in the calculations. Three different cases and five various types of storage facilities were considered in the present study. Case 1 excludes SWH volume during the flood and winter seasons, while in Case 2, only winter season SWH volume was excluded. In Case 3, the winter season and combined sewer overflows (CSOs) facilities were excluded. The Rainwater Utilization Facility was considered as a baseline for comparison. The stored storm or rain (SR) water can be delivered to the region near to the storage facility for non-potable use. It is hoped that the daily water inflow developed in the current study will provide an academic contribution and help professionals to develop more efficient water resource management planning in South Korea.

2. Materials and Methods

2.1. Description of the Facilities

In South Korea, several types of water storage facilities have been constructed for urban flood control, water quality control, and rainwater use. These different types of storage facilities have been constructed under different regulations and laws. Five types of water storage facilities were chosen for the present study. The locations of the selected storage facilities are shown in Figure 1. Furthermore, detailed information such as the number of facilities in the country, installation purpose, total storage volume, monitoring ministry, location in watershed, potential use of SR water, treatment facility (existence), and water supply pumping system (existence) about each type of storage facility is provided in Table 1.

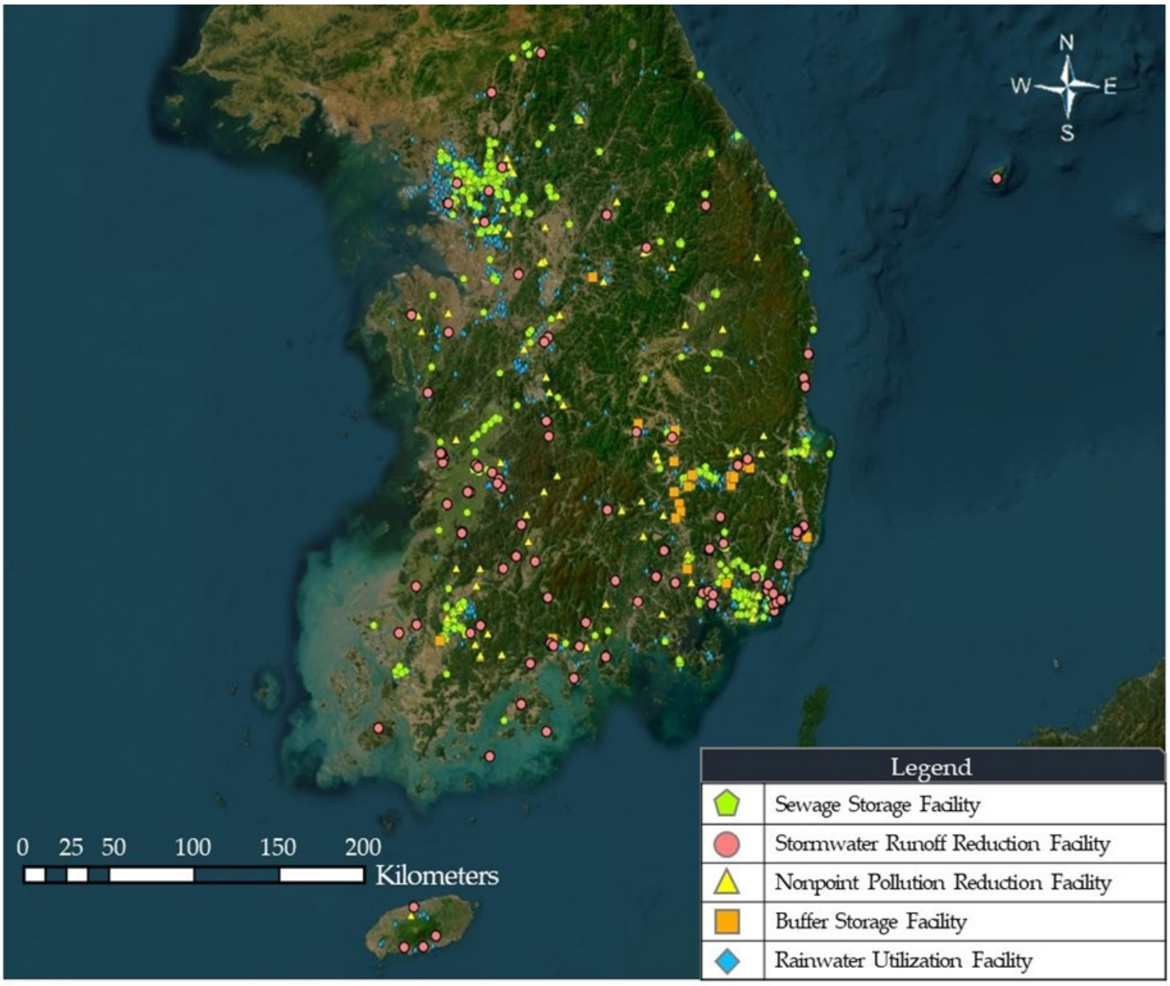

Figure 1. Regional location map showing five different types (a total of 1440 facilities) of storage facilities in South Korea [44].

Table 1. Installation purpose, number of facilities, total storage volume, monitoring ministry, location in watershed, potential use for storm or rain water, treatment facility for reuse, pump requirement, and energy usage of the studied storage facilities table upgraded from reference [44]).

Type of Facility	Sewage Storage Facility (SS Facility)	Stormwater Runoff Reduction Facility (SRR Facility)	Nonpoint Pollution Reduction Facility (NPR Facility)	Buffer Storage Facility (BS Facility)	Rainwater Utilization Facility (RU Facility)
Installation purpose	• Urban flood control • Water quality control • Water reuse	Urban flood control	Water quality control	Water quality control	Water use
Number of facilities	536 [a]	110 [b]	73 [c]	24 [d]	697 [a]
Total storage volume (1000 m^3)	31,861	1828	644	330	1804
Monitoring ministry	Ministry of Environment	Ministry of the Interior and Safety	Ministry of Environment	Ministry of Environment	Ministry of Environment
Location in watershed	Watershed middle and end	Watershed middle and end	Dispersion	Watershed end	Roof and small basin
Potential use for storm or rain water	Available after treatment	Available after treatment	Available after treatment	• Impossible • Water collected from industries	• Direct use • Water collected mostly from rooftop
Treatment facility for reuse	Required	Required	Required	Required	Pre-installed
Water supply	Pump required	Pump required	Pump required	Pump required	Pre-installed
Energy for reuse	High	Medium	High	High	Low

[a] 2020 Sewer Statistics report, Ministry of Environment. [b] Ministry of the Interior and Safety. [c] Korea Environment Corporation. [d] Water Quality and Aquatic Ecosystem Division, Ministry of Environment.

2.2. Overview of the Studied Cases

In the present study, the SWH potential was calculated considering three different cases. Figure 2 shows the summarized details regarding each case. Based on the geographical location and the overall meteorological conditions in South Korea, December to February was considered winter season and from June 21 to September 20 was considered flood season in this study. As shown in Figure 2, in the calculation of SWH potential in Case 1, the flood and winter seasons were excluded, while in Case 2, only the winter season was excluded. Additionally, for Case 3, the winter season and the combined sewer overflows (CSOs) facilities were excluded for the calculation of SWH potential.

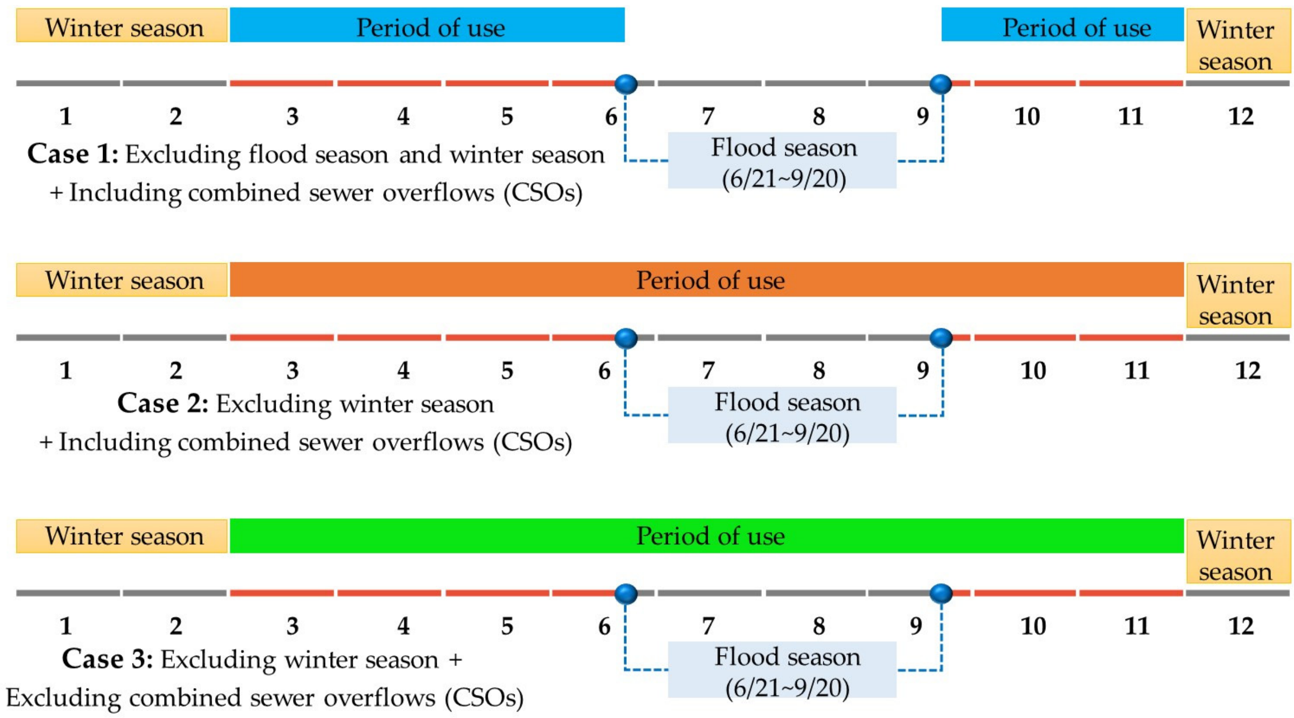

Figure 2. Overview of the cases considered in the present study. Case 1 excludes flood and winter seasons, while in Case 2, only the winter season is excluded. In Case 3, the winter season and combined sewer overflows (CSOs) facilities are excluded.

A comprehensive reason for this categorization of different cases was that in the winter season, there is less monthly rainfall and it is usually the dry season. Thus, operating SWH in the winter season would not be suitable for water demand supply. Similarly, in the flood season, monthly rainfall is high due to monsoons for this reason, the SWH will experience more inflow of rainwater than the water demand. Furthermore, in CSOs, many contaminants are present [45–48], so the water quality is low and the treatment of the water to the required quality standard requires special treatment systems.

2.3. Methodology of the Current Study

In the current study, we devised a daily water inflow model using MATLAB (R2015a) software. The model developed in the current study calculates the potential collected SR water quantity for five different types of existing SWH facilities in South Korea. In addition, the annual usage potential of the SWH facilities was calculated for three different cases. Rainfall data from Seoul rainfall station (Station No. 108) for a period of 10 years (January 2012 to December 2021) were gathered from the Korea Meteorological Administration (KMA) [49] and utilized as input for the computations. It should be mentioned that the local regional rainfall for each location should be used to assess the annual potential of SR water quantity. However, this will increase the complexity of the model, and throughout the country there is not much difference in the annual rainfall, so to keep the model simple, data from only one rainfall station (Station No. 108) were used as input. Figure 3 shows a summary of the schematic procedure used in the current study.

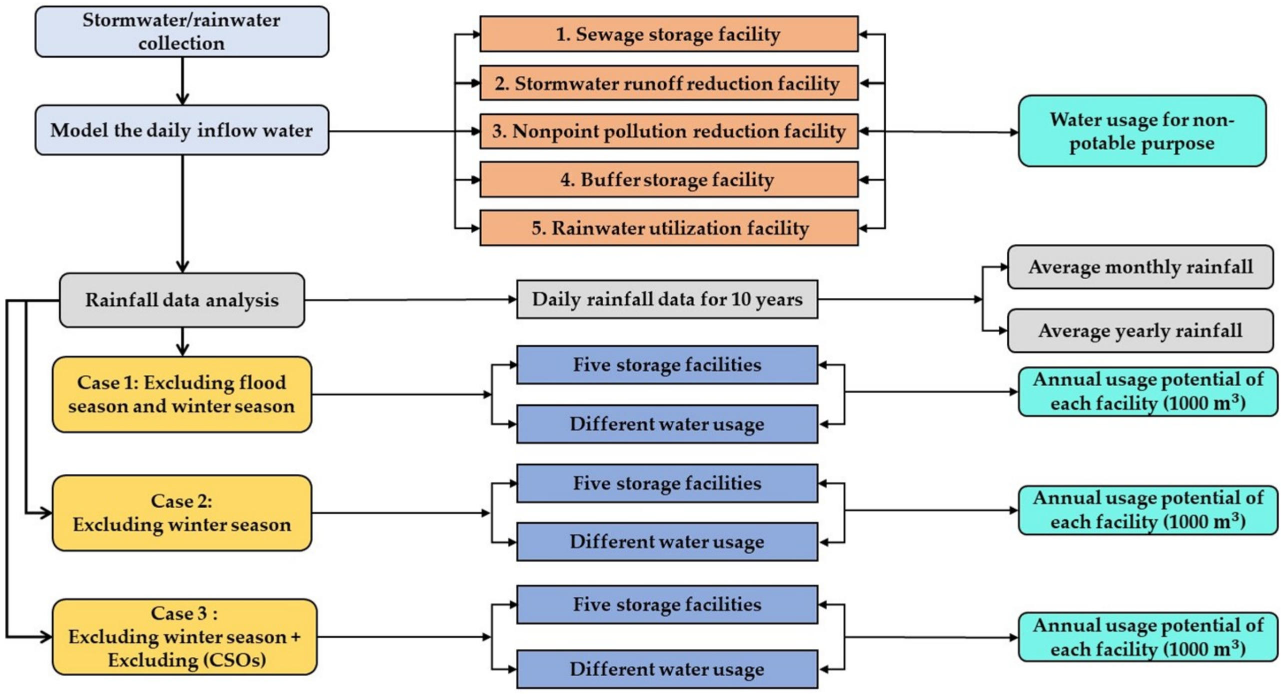

Figure 3. The schematic methodology for the current study.

2.4. Rainfall Data Analysis

A thorough examination of rainfall trends over a period of ten years (from January 2012 to December 2021) was conducted as a component of the current investigation. The collected rainfall data from the Korea Meteorological Administration (KMA) [49] offers important insights into the patterns of rainfall in South Korea. In the present study, the data from Seoul rainfall station No. 108 were utilized as input for the computations.

Figure 4a shows the monthly rainfall data from the Seoul rainfall station. There is a notable seasonal difference, and the rainfall during the summer months in the northern hemisphere accounts for 70% of the total rainfall. The monsoon season typically starts in mid-June, lasting for almost seven weeks. In the monsoon season, the water collection potential increases drastically.

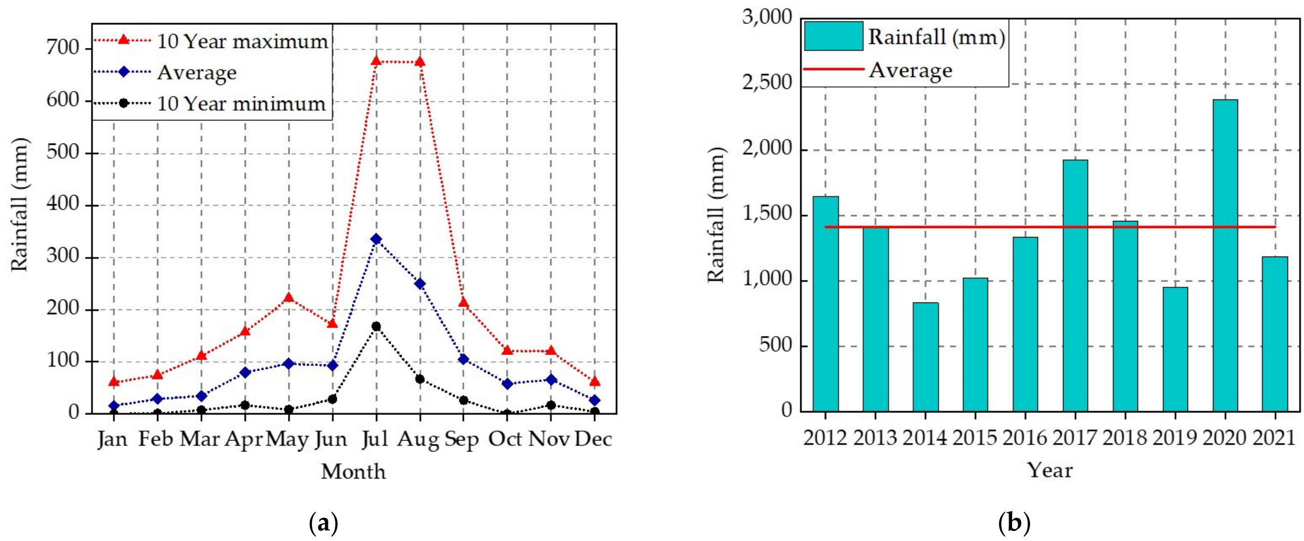

Figure 4. Rainfall from selected rain station (years 2012–2021): (**a**) monthly rainfall, (**b**) annual rainfall.

In contrast, Figure 4b illustrates the average annual precipitation recorded at the Seoul rainfall station over a span of ten years (January 2012 to December 2021). Upon closer examination of the graph, it is evident that Seoul experienced its highest annual rainfall of 2380 mm in the year 2020. Conversely, Seoul had a low annual rainfall of 832 mm in the year 2014. The average annual rainfall for the ten years was approximately 1412 mm, despite these variations.

2.5. Daily Water Inflow Simulation Model

In order to evaluate the viability of stormwater runoff (SR) harvesting for the existing storage facilities, we devised a daily water inflow model in our current investigation using MATLAB (R2015a) software. This simulation model integrates various input parameters, including the catchment area, daily rainfall, and runoff coefficient. Moreover, dynamic input data were incorporated to account for varying water usage percentages across different types of storage facilities over a ten-year period, from January 2012 to December 2021. The foundational principle of the simulation model revolves around the collection of rainwater from the catchment area: an initial rainfall of 5 mm was deducted from the total daily rainfall, with the remaining precipitation collected in the storage tank.

Figure 5 illustrates the flow chart depicting the daily water inflow simulation model used to estimate the stormwater runoff (SR) potential for current storage facilities. Additionally, a runoff coefficient of 0.65 was utilized in this investigation. Within the simulation model, an initial 5 mm of rainfall was subtracted from the total daily rainfall. The remaining daily rainfall amount was then multiplied by the runoff coefficient and the runoff capture area to calculate the volume of captured runoff. This methodology, outlined in Equation (1), concludes with the calculation of the harvested SR water volume. It should be mentioned that for the calculation of the harvested SR water, if the daily rainfall depth was less than 5 mm, the amount of harvested SR water was considered to be zero. However, on occasions where the SR water daily inflow volume is greater than the storage tank capacity, the excessive amount of inflowing rainfall is lost as overflow. The calculations were made daily for the existing storage facilities, considering three different cases and utilizing rainfall data spanning a decade (January 2012 to December 2021). Moreover, different percentages of SR water usage were considered in the present study to assess the potential of SR water harvesting for the existing storage facilities.

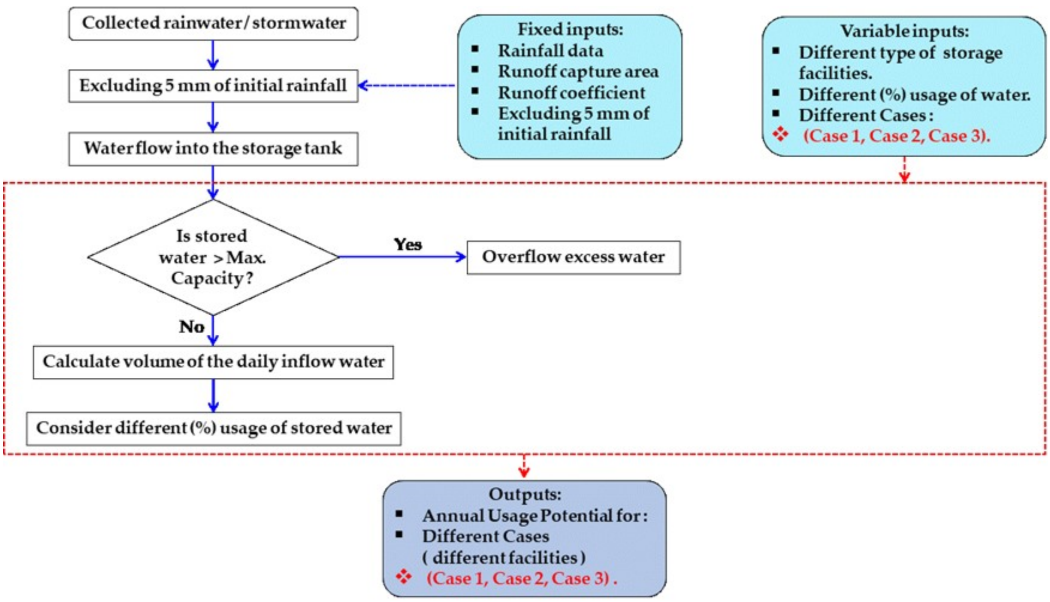

Figure 5. The schematic procedure of daily water inflow simulation model developed in the current study, considering the SWH facility's fixed inputs, variable inputs, and outputs.

The mathematical equation for the collected SR water from the catchment area is:

$$V_i = (I_t - 5) \times A \times R_c \times 0.001, V_i = 0, \text{ for } (I_t - 5) < 0, \tag{1}$$

$$V_i = C, \text{ for } V_i > C, \tag{2}$$

where V_i is the daily inflow SR water (m^3) from the catchment area, I_t is the rainfall (mm) on the day t, 5 mm is the initial rainfall, A is the catchment area (m^2), C is the capacity of the storage tank (m^3), and R_c is the runoff coefficient (0.65).

The annual SR water volume is calculated using the following equation:

$$V_t = \sum_{t=1}^{365} V_{it} \tag{3}$$

where V_t is the annual volume (m^3) of SR water. In Equation (1), the number of days were excluded according to the specification of Case 1, Case 2, and Case 3. More explanation regarding each case is provided in Figure 2. The annual usage potential of SR water is obtained, adding the daily inflow SR water volume over the span of ten years (January 2012 to December 2021), considering different cases.

The AAU potential of the SR water volume is calculated using the equation below:

$$V_a = \frac{\sum_{n=1}^{10} V_{tn}}{10} \tag{4}$$

where V_a is the AAU potential volume (m^3) of SR water.

3. Results and Discussion

3.1. Assesment of SWH Potential for Case 1

Figure 6a–e show the calculated SR water AAU potential of five selected storage facilities for Case 1 considering different percentages (20%, 40%, 60%, 80%, and 100%) of inflow of SR water. In Case 1, for the calculation of SR water potential, the flood season and winter season were excluded. The method developed in the current study considers different percentages of SR water inflow as the water demand near to each storage facility is unknown. The Rainwater Utilization Facility (RU Facility) was considered as a baseline for comparison in the present study. We found that in Case 1, the SS Facility, SRR Facility, NPR Facility, and BS Facility had 22.4, 5.6, 3.4, and 1.7 times more stormwater AAU potential, respectively. Table 2 shows the details regarding the number of already-constructed storage facilities for Case 1, Case 2, and Case 3. A deeper look at the table shows that, among the five selected types of storage facilities, the Rainwater Utilization Facility (RU Facility) type was the highest in number (697), while the Buffer Storage Facility (BS Facility) type was the lowest in number (24).

Table 2. Summary of selected studied storage facilities' SWH AAU potential for **Case 1, Case 2,** and **Case 3**.

S. No.	Type of Facility	Number of Facilities Case 1	Number of Facilities Case 2	Number of Facilities Case 3
1	SS Facility [a]	536	536	66
2	SRR Facility [b]	110	110	29
3	NPR Facility [c]	73	73	17
4	BS Facility [d]	24	24	7
5	RU Facility [a]	697	697	697

[a] 2020 Sewer Statistics report, Ministry of Environment. [b] Ministry of the Interior and Safety. [c] Korea Environment Corporation. [d] Water Quality and Aquatic Ecosystem Division, Ministry of Environment.

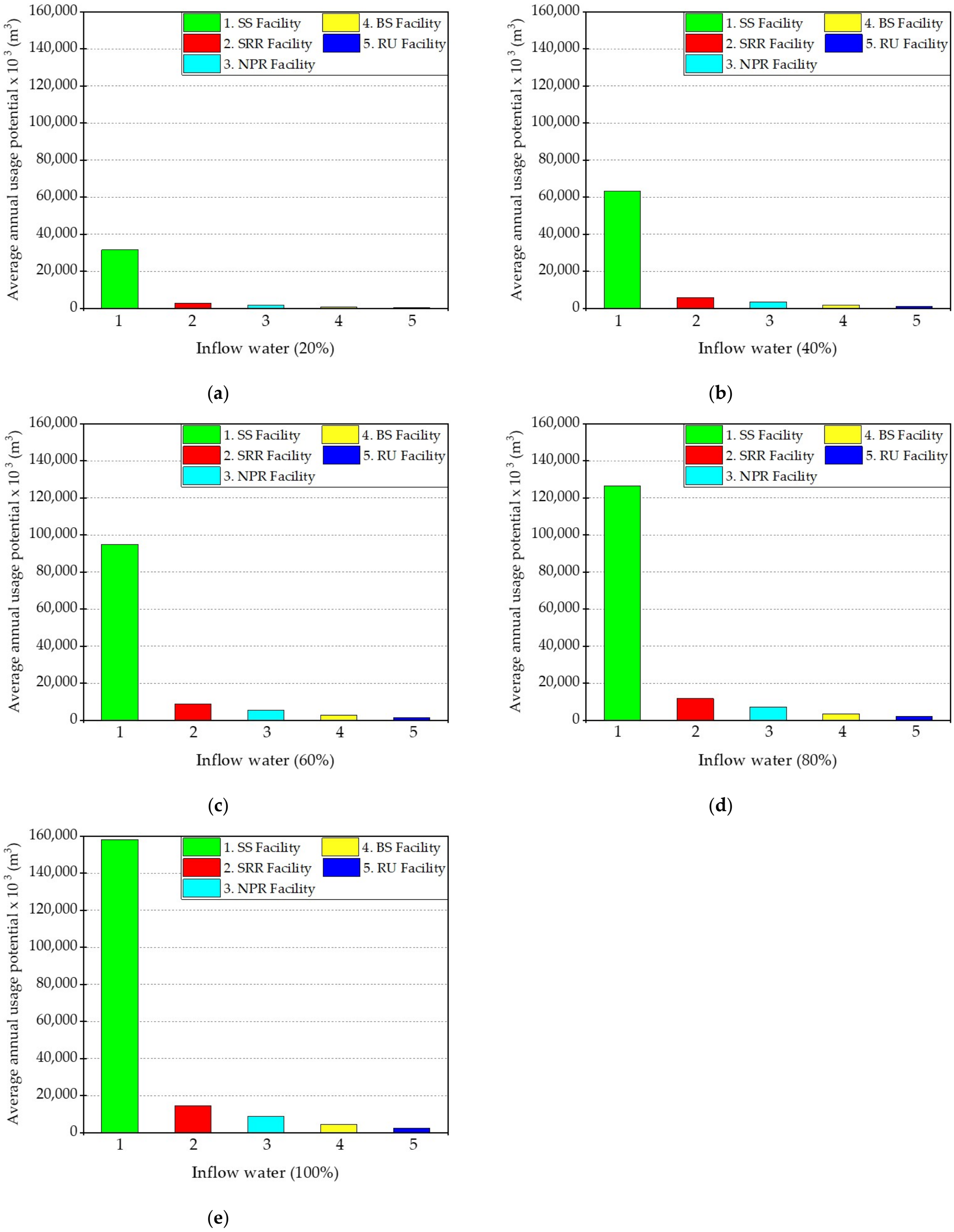

Figure 6. Studied storage facilities' SWH AAU potential for **Case 1** considering inflow water: (**a**) 20%; (**b**) 40%; (**c**) 60%; (**d**) 80%; (**e**) 100%.

3.2. Assesment of SWH Potential for Case 2

The SR water AAU potential of the five selected storage facilities considering different percentages (20%, 40%, 60%, 80%, and 100%) of inflow of SR water for Case 2 is shown in Figure 7a–e. In Case 2, for the calculation of SR water potential, only the winter season was excluded. The reason for excluding the winter season from Case 2 is that this is usually the dry season, with less monthly rainfall. Thus, operating an SWH facility in the winter season would not be suitable for the supply of water. Table 2 shows the details regarding the number of existing storage facilities for Case 2. We found that in Case 2, the SS Facility, SRR Facility, NPR Facility, and BS Facility had 53.5, 4.3, 2.4, and 1.2 times more stormwater AAU potential, respectively. Furthermore, we found that the stormwater AAU potential in Case 2 increased sevenfold for the SS Facility compared to Case 1.

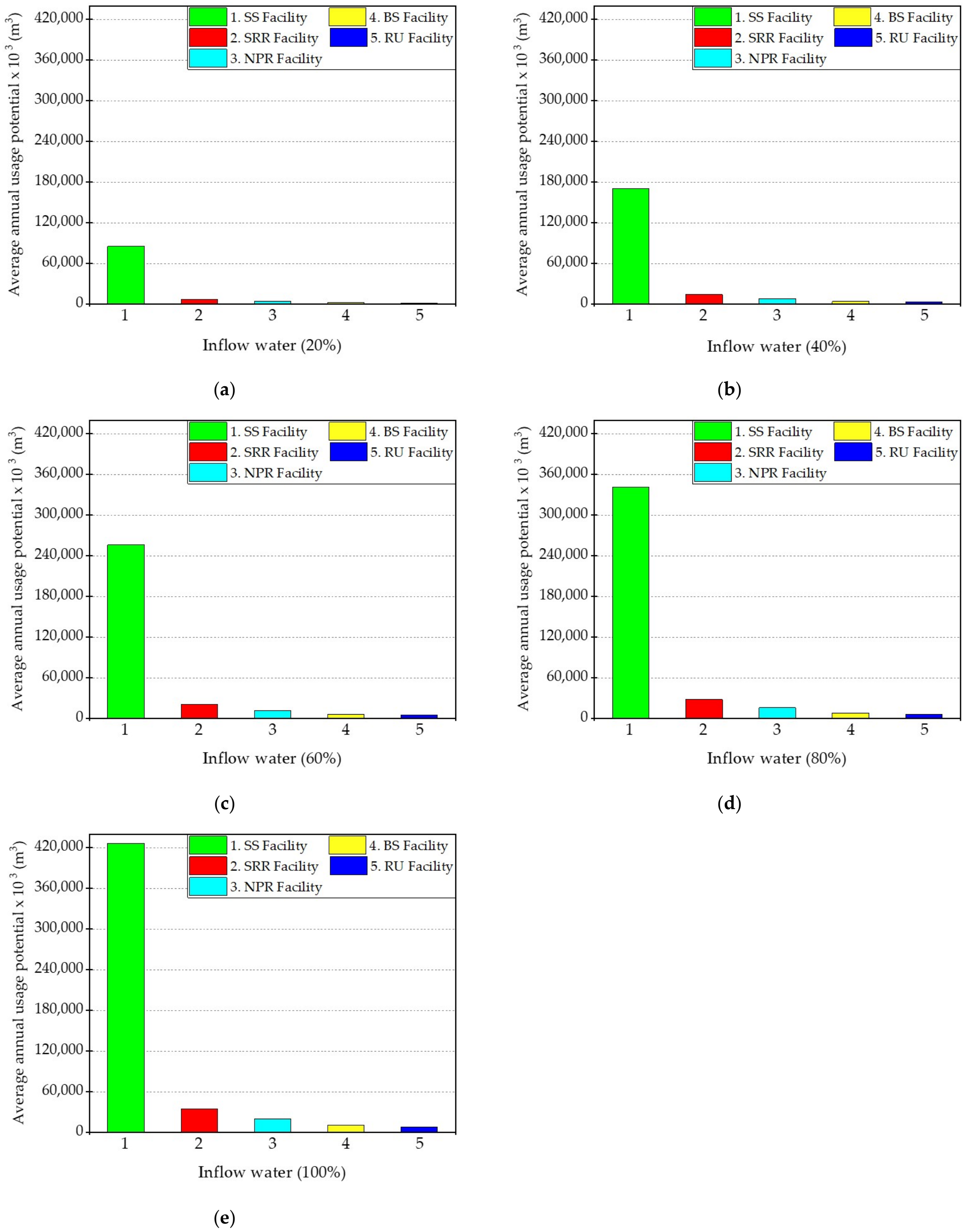

Figure 7. Studied storage facilities' SWH AAU potential for **Case 2** considering inflow water: (**a**) 20%; (**b**) 40%; (**c**) 60%; (**d**) 80%; (**e**) 100%.

3.3. Assesment of SWH Potential for Case 3

Figure 8a–e illustrate the SR water AAU potential of five selected storage facilities considering different percent (20%, 40%, 60%, 80%, and 100%) inflow of SR water for

Case 3. In Case 3, for calculation of SR water potential winter season and the combined sewer overflows (CSOs) facilities were excluded. The exclusion of combined sewer overflows (CSOs) in Case 3 is due to the high concentration of contaminants within these overflows [45,46,48]. The presence of numerous contaminants in the CSOs make stormwater unsuitable for direct usage, a specialized treatment system to achieve the required water quality standards is required. We found that in Case 3, SS Facility has 7.5 times more stormwater AAU potential. While, SRR Facility, NPR Facility, and BS Facility has 1.1, 3.3, and 2.05 times less stormwater AAU potential, respectively.

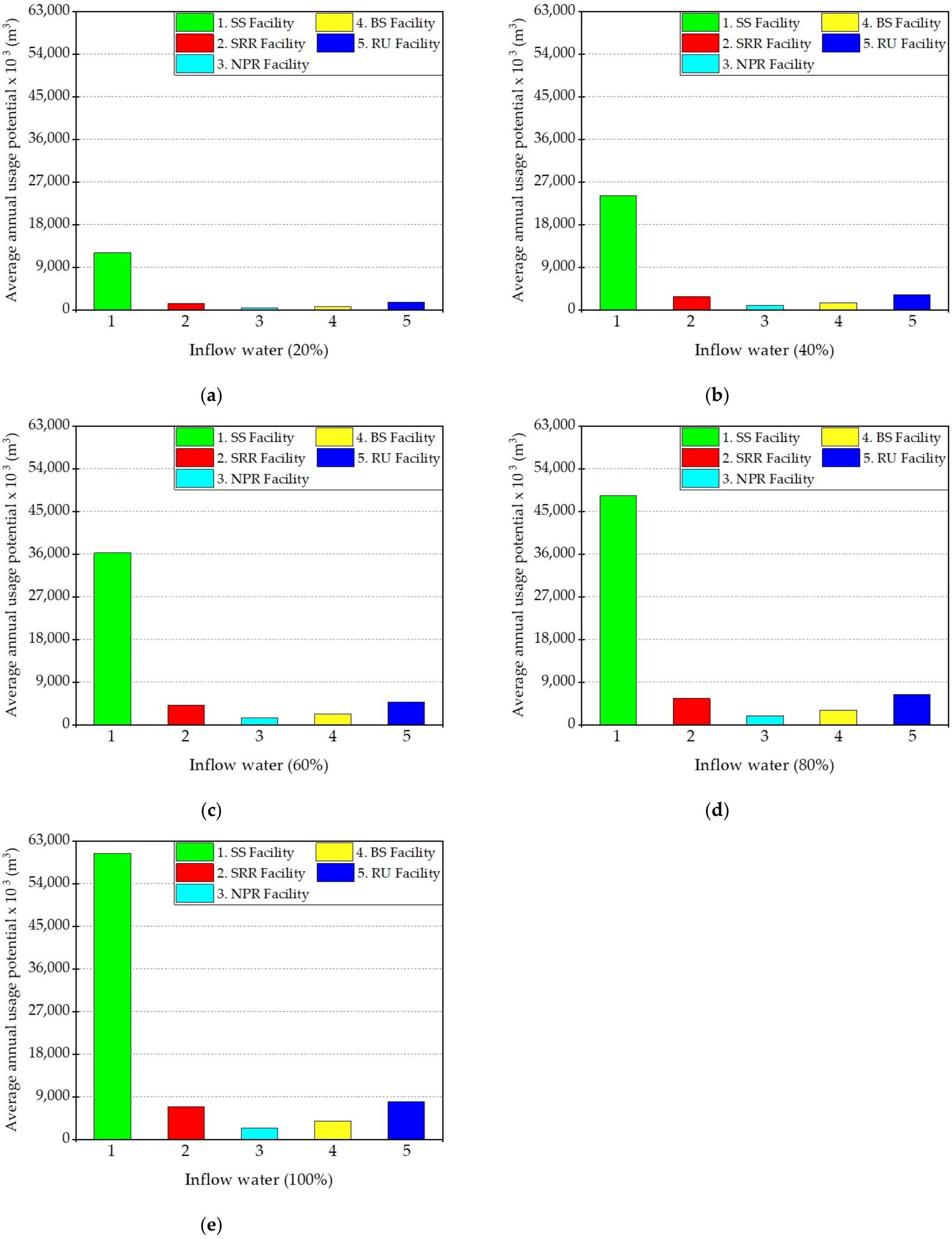

Figure 8. Selected studied storage facilities' SWH AAU potential for **Case 3** considering inflow water (**a**) 20%; (**b**) 40%; (**c**) 60%; (**d**) 80%; (**e**) 100%.

Table 2 provides the summary about the number of existing storage facilities for Case 3. A deeper look at Table 2 reveals that the number of storage facilities has been decreased significantly, as the storage facilities having CSOs has been excluded in Case 3. However, better quality water as compared to Case 1 and Case 2 can be collected. Furthermore, it was found that for Rainwater Utilization Facility (RU Facility), AAU potential is same in Case 3 and Case 2. In South Korea, for RU Facilities rainwater is mostly collected from rooftop. So, the number of facilities remain same (697) in Case 3 and Case 2.

3.4. Comparision of SWH Potential for Case 1, Case 2, and Case 3

The comparison of the SR water harvesting potential for the five different types of storage facilities considering three different cases is summarized in Figure 9. Furthermore, the primary installation purpose for each facility is shown in Figure 9. Among the studied facilities, the SS Facility has the highest stormwater AAU potential and is multifunctional (urban flood control, water quality control, water reuse). The RU Facility was considered as a baseline for comparison in the current study.

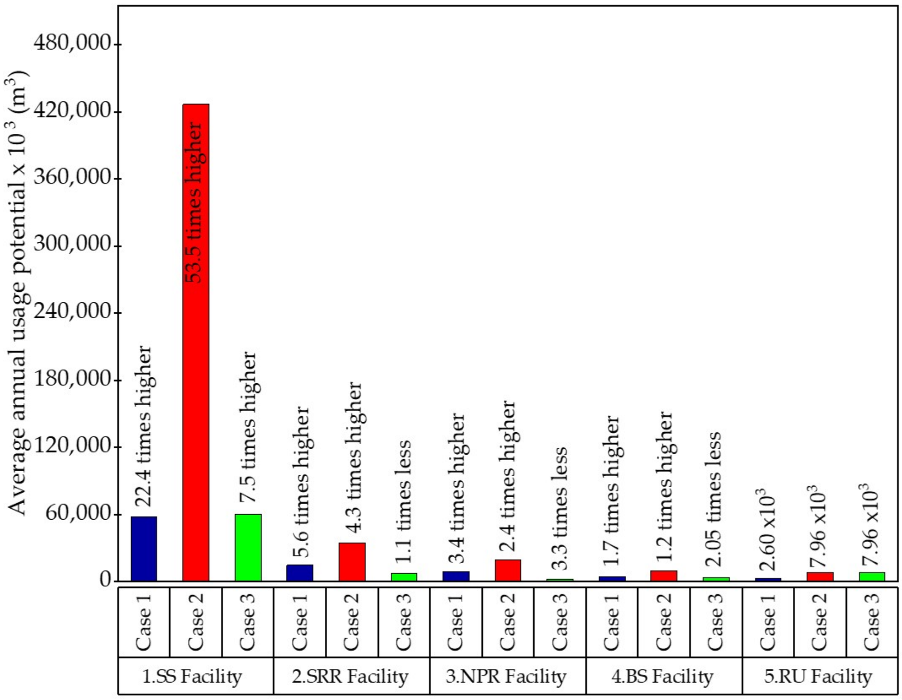

Figure 9. Comparison of selected studied storage facilities' SWH AAU potential for Case 1, Case 2, and Case 3.

4. Conclusions

Stormwater harvesting in urban areas presents a potential solution to mitigate urban floods and water shortages. This study assessed the stormwater harvesting potential for different types of existing storage facilities in South Korea. A daily water inflow model was developed using MATLAB (R2015a) software, considering three different cases. The study considered decade-long data (January 2011 to December 2020) of daily rainfall collected from the KMA. Five different types of storage facilities were considered. Among these five storage facilities, the RU Facility was used as a baseline for comparison in the present study. Based on an in-depth observation of the results, we can conclude the following:

- In Case 1, the SS Facility, SRR Facility, NPR Facility, and BS Facility had 22.4, 5.6, 3.4, and 1.7 times more stormwater AAU potential, respectively.
- In Case 2, the SS Facility, SRR Facility, NPR Facility, and BS Facility had 53.5, 4.3, 2.4, and 1.2 times more stormwater AAU potential, respectively.

- In Case 3, the SS Facility had 7.5 times more stormwater AAU potential, while the SRR Facility, NPR Facility, and BS Facility had 1.1, 3.3, and 2.05 times less stormwater AAU potential, respectively.
- As the CSOs were excluded from Case 3, the SR water collected in Case 3 will have better water quality than Case 1 and Case 2.

The approach we developed for calculating the stormwater harvesting potential for the existing storage facilities is noteworthy for policymakers involved in urban rainwater management. The findings support the utilization of these facilities as additional water resources. It should be mentioned that the primary purpose for which each facility was constructed, as summarized, will remain unaffected. Moreover, as the storage facilities have already been constructed in South Korea, the cost of the initial construction is eliminated.

Nevertheless, forthcoming research should concentrate on a detailed analysis of the quality of the collected stormwater. Furthermore, the development of treatment systems to treat the stormwater according to the end usage standards needs further attention.

Author Contributions: The paper was supervised by R.K., A.K. and Y.P. monitored the data and analyzed the results. J.P. and I.S. developed the daily water-inflow model. The whole manuscript was composed and written by A.K. All authors have read and agreed to the published version of the manuscript.

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

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