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Development of a Multi-Objective Optimal Design Approach for Combined Water Systems

Mun Jin Ko and Young Hwan Choi *

Department of Civil and Infrastructure Engineering, Gyeongsang National University,
Jinju 52725, Republic of Korea
* Correspondence: yh.choi@gnu.ac.kr; Tel.: +82-55-772-3292

Abstract: Recently, due to extreme climate change, damage from flooding has been increasing; however, water shortages are being announced simultaneously. Moreover, the water distribution system's ability to supply consumers is being overwhelmed because of urbanization, population concentration, and increases in water consumption. For this reason, to solve the water shortage problem, water reuse technologies are developing and improving that perform simple chemical treatment processes to reuse water for flushing toilets, washing, gardening, etc. but not as drinking water. However, most water reuse systems are designed and operated as independent systems, such as reusing water used in individual buildings or using rainwater. Therefore, this study develops an optimal design for the combined water systems, which is modeling and designing water distribution systems, urban drainage systems, and water reuse systems simultaneously to solve the water shortage and reduce flooding damage. To consider the combined water systems design, the existing water distribution system (WDS) demand is divided into drinking water and other uses, and the resource of other water is assumed by the rainwater storage tank for covering the amount of exceeding precipitation. To derive optimal design solutions for the combined three water systems, single- and multi-objective optimization techniques are applied considering various design criteria (i.e., construction cost, system resilience, and flooding volume on the exceeding design rainfall intensity). The developed combining water system design techniques could be used to create designs that solve the problems of medium and long-term water shortages and sustainable water systems development.

Keywords: multi-objective optimal design; combined water system; water distribution system; drainage systems; water reuse systems; harmony search

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1. Introduction

A combined water system is an operations and modeling system that analyzes and combines a water distribution system (WDS), an urban drainage system (UDS), and a water reuse system (WRS). A water distribution system aims to supply a sufficient quantity of water from water sources to consumers at an adequate water pressure and safe water quality so that water is supplied even in abnormal circumstances in the same way as that used under normal circumstances. A stormwater drainage system aims to prevent inundation damage caused by flooding and improve public health and sustainable development to allow for coexistence with the local environment.

Although the frequency and intensity of floods are increasing in Republic of Korea due to an increase in precipitation due to climate change, it is expected that usable water will continue to be insufficient [1,2]. In addition, it declares water shortage due to the increase in water consumption per capita and urban development. Accordingly, it is necessary to establish a stormwater drainage system, efficient operation of a water supply system, and a WRS. Previous studies have focused on using rainwater to minimize the impact of drought and water shortage. The hydrological operation method and optimal capacity of the rainwater storage tank in the building were determined through the analysis of the capacity, usage rate, and reliability of the rainwater storage tank, and the effectiveness and applicability were judged [3–6]. In addition, Sample and Liu [7] performed an optimal design by introducing a hydraulic-hydrological optimization formula using the trade-off between the capacity of a rainwater storage tank for rainwater collection and the capacity of use time. Furthermore, the feasibility of water reuse in large-scale areas, rather than existing buildings or small-scale greywater use, was evaluated from a hydraulic point of view, and a positive evaluation was made in areas with water shortages [8].

Moreover, in a study using gray water to solve water shortage, a collaborative hydraulic analysis approach was presented with EPANET, a WDS hydraulic analysis solver, for hydraulic analysis. Sally and Mohammad [9] presented a simulation methodology for small-scale WRSs, and the efficiency and feasibility analysis results of WRSs emphasized the need for WRSs in the future in terms of sustainability [10,11]. Momeni et al. [12] demonstrated the economic effect of water demand reduction and water supply when using WRSs through various simulations. In addition, some studies have improved the hydraulic stability of WDSs by predicting the demand and supply of WDSs to prepare for water shortages [13,14]. However, although the above studies improved the hydraulic stability of WDSs through rainwater reuse or water reuse, UDSs lacked preparation for future uncertainties such as water shortage prevention, urban population concentration, and water shortage. In this way, combined hydraulic simulation is needed to solve the problems of WDSs and UDSs at the same time. To solve this problem, Chung and Ohk [15] and Chung et al. [16] developed a model that integrates EPANET, a WDS hydraulic solver, and EPASWMM, an urban flood analysis program. However, although the above studies predicted demand through an integrated model, reused water in the WRS does not undergo chemical disinfection and sterilization, unlike normal tap water for WDSs; therefore, WRSs and WDSs should be designed separately.

Therefore, this study proposed an optimal design technique for combining WDSs, UDSs, and WRSs to overcome water shortage and reduce excessive flooding damage due to extreme climate change. The proposed design approach combines EPANET and EPASWMM, which are the hydraulic solvers for WDS and UDS analysis. In addition, since the hydraulic analysis for WRSs has not been developed, EPANET was configured to supply water to consumers using water from rainwater storage tanks as a limited reservoir to simulate a WRS. The basic design criteria used are the total construction cost, the system resilience, and the flooding volume. Moreover, the applied constraints use the standard of nodal pressure and flooding on the design rainfall intensity. According to those objective functions and constraints, the combined water system designs through single- and multi-objective harmony search. If the design is carried out by dividing supply water according to usage characteristics, the resilience of the WDS will be improved due to the diversification of water sources and the economic aspects such as the production cost of WDS water, and the prevention of the flooding, inundation, and overflow of UDSs will be effective in public health.

2. Optimal Design of Combined Water Systems

2.1. Concept and Modeling for the Combined Water System

To design the combined water system, this study designed the WRS and WDS separately according to the use of water. Figure 1 shows the process of differentiating between water for use in water distribution systems and water for use in reused-water systems. Water that is treated at a water purification plant can be used in WRSs and water distribution networks; however, reused water, which is rainwater or wastewater that has gone through a sewage treatment facility, cannot be used as drinking water in a water distribution system despite chemical treatment. Therefore, modeling was performed so that the water for the existing water distribution system and water for the reused water system were not mixed.

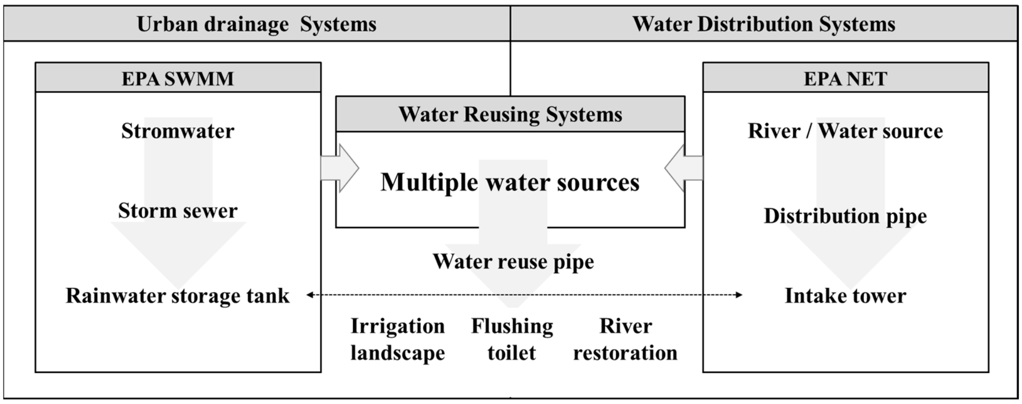
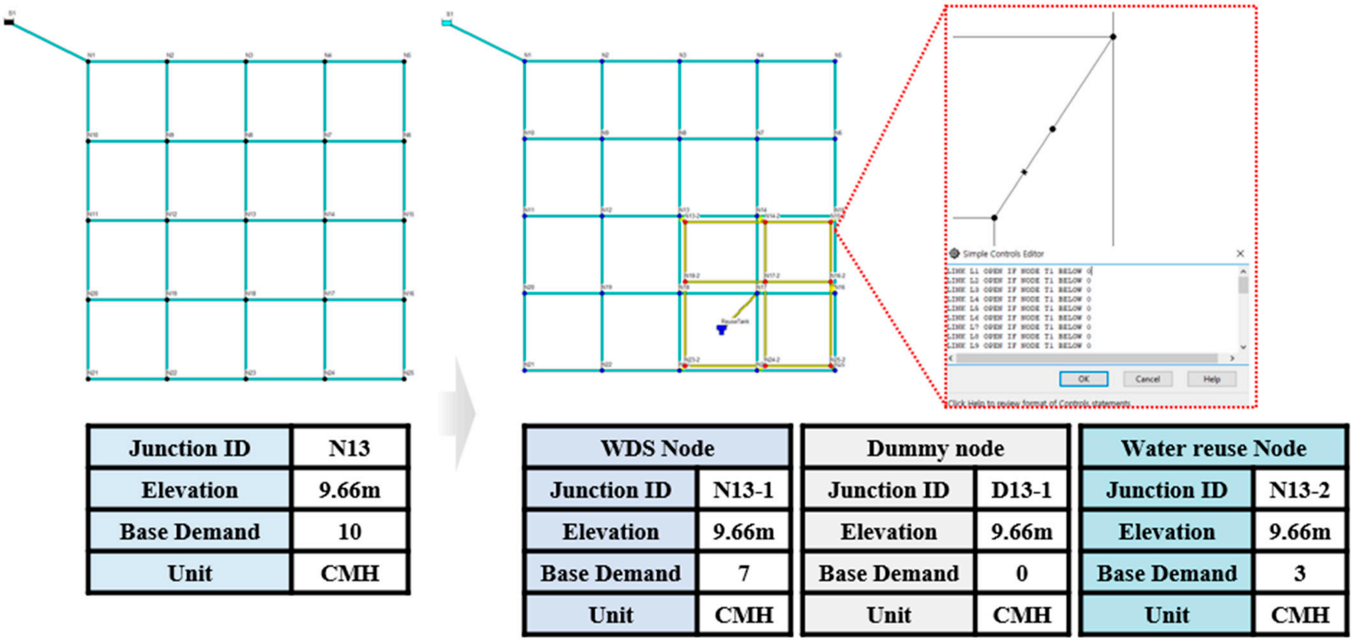


Figure 1. Flowchart of combined water systems and urban drainage systems.

Furthermore, in this study, a plan was developed for restricting reused-water systems to rainwater only and using this as toilet water, landscaping water, and firefighting water to reduce the water used by existing water distribution systems. Therefore, EPASWMM, which is an urban runoff analysis program provided for free by developers at the EPA, was used to calculate the capacity of rainwater storage tanks that can be used in the reused-water system. The capacity of the rainwater storage tanks was set to that of multiple water sources in the water distribution system analysis program EPANET. The analysis was performed by differentiating between nodes in the water distribution system and nodes in the reused-water system, as shown in Figure 2.



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LINK L1 OPEN IF NODE T1 BELOW 0
LINK L2 OPEN IF NODE T1 BELOW 0
LINK L3 OPEN IF NODE T1 BELOW 0
LINK L4 OPEN IF NODE T1 BELOW 0
LINK L5 OPEN IF NODE T1 BELOW 0
LINK L6 OPEN IF NODE T1 BELOW 0
LINK L7 OPEN IF NODE T1 BELOW 0
LINK L8 OPEN IF NODE T1 BELOW 0
LINK L9 OPEN IF NODE T1 BELOW 0
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Junction ID	N13
Elevation	9.66m
Base Demand	10
Unit	CMH

WDS Node	
Junction ID	N13-1
Elevation	9.66m
Base Demand	7
Unit	CMH

Dummy node	
Junction ID	D13-1
Elevation	9.66m
Base Demand	0
Unit	CMH

Water reuse Node	
Junction ID	N13-2
Elevation	9.66m
Base Demand	3
Unit	CMH

Figure 2. Schematic view of water reuse systems modeling using EAPNET 2.2.

According to the data published by the Korea National Sewer Information System (https://www.hasudoinfo.or.kr/, accessed on 2 January 2023), the water reuse rate is approximately 30%. Therefore, in this study, 70% of the existing WDS demand is set as the demand of the WDS for drinking water, and the remaining 30% is set as the demand of the WRS, mainly used for nonpotable uses such as flushing toilets, cooling of industrial units, watering gardens, etc.

Furthermore, to allow water for the water distribution system to be used when the water for the reused water system is exhausted, EPANET's control tool was used to install nodes that have the same properties as conventional nodes but no demand (dummy nodes) and flow control valves (check valves) so that water for the water distribution system can be used when the water in the rainwater storage tanks is exhausted. The capacity of the rainwater storage tanks was set as the amount of stormwater that cannot be accommodated by the stormwater drainage system, and the pipes that combined the water distribution system and the reused-water system were set to the same length, assuming that the nodes were the same as the existing nodes.

2.2. Design Optimization

In this study, we propose an optimal design method for a water system that combines a WDS, a UDS, and a WRS. To perform the optimal design of the combined water system, the Harmony search (HS) algorithm, a well-known metaheuristic optimization algorithm, was used [17]. Since WDSs and WRSs are based on pressure water supply, EPANET was used, and the UDS used EPASWMM. For the design of the combined water system, these two hydraulic solvers were linked with HS through MATLAB, and two design approaches based on single-objective and multi-objective optimization were proposed according to the decision variables and objective functions.

2.2.1. Combined Water System Single-Objective Optimization

In this study, a single-objective optimal design was created for a combined water system. The objective function was set as minimizing the sum of the stormwater drainage system design cost, water distribution system design cost, and the WRS design cost. For the constraints, the stormwater drainage system constraints, water distribution system constraints, and the WRS constraints were all considered when the design was created. Figure 3 shows a flow chart of the optimal single-objective design process for the combined water system.

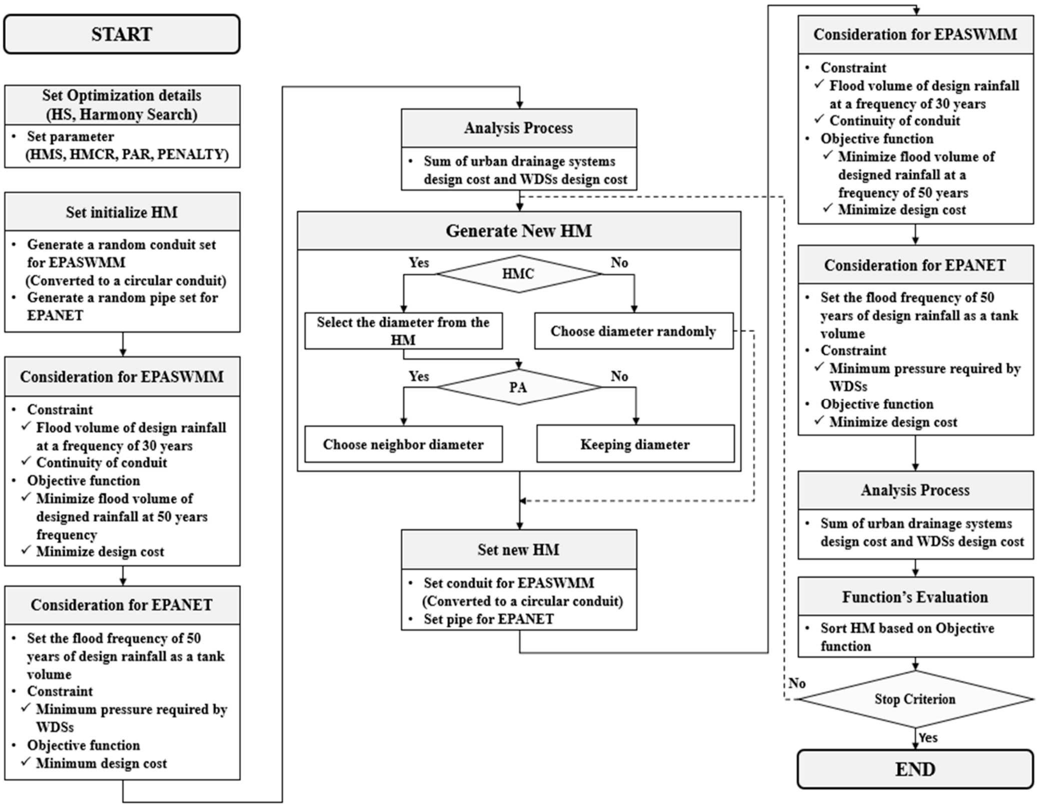

Figure 3. Optimal design of combined water system based on the single-objective harmony search.

First of all, the piping of the stormwater drainage system was converted to circular pipes, and the pipe diameters of the pipes of the water distribution system, the WRS, and the stormwater drainage system were selected randomly. Then, the urban inundation analysis program EPASWMM was set so that inundation does not occur at a 30-year frequency design precipitation intensity, and the rainwater storage tank capacity in the water distribution system analysis program EPANET was set as the flood volume of a 50-year frequency design precipitation intensity. In addition, the water pressure at all nodes in the water distribution system and the WRS was set to meet the minimum pressure required by the water distribution network to improve hydraulic stability. The harmony search optimization algorithm was used to perform iterative calculations and derive the result values.

2.2.2. Combined Water System Multi-Objective Optimization

Figure 4 is a flowchart of the optimal multi-objective design process for the water distribution system and the WRS, which was performed after the optimal multi-objective design process for the stormwater drainage system.

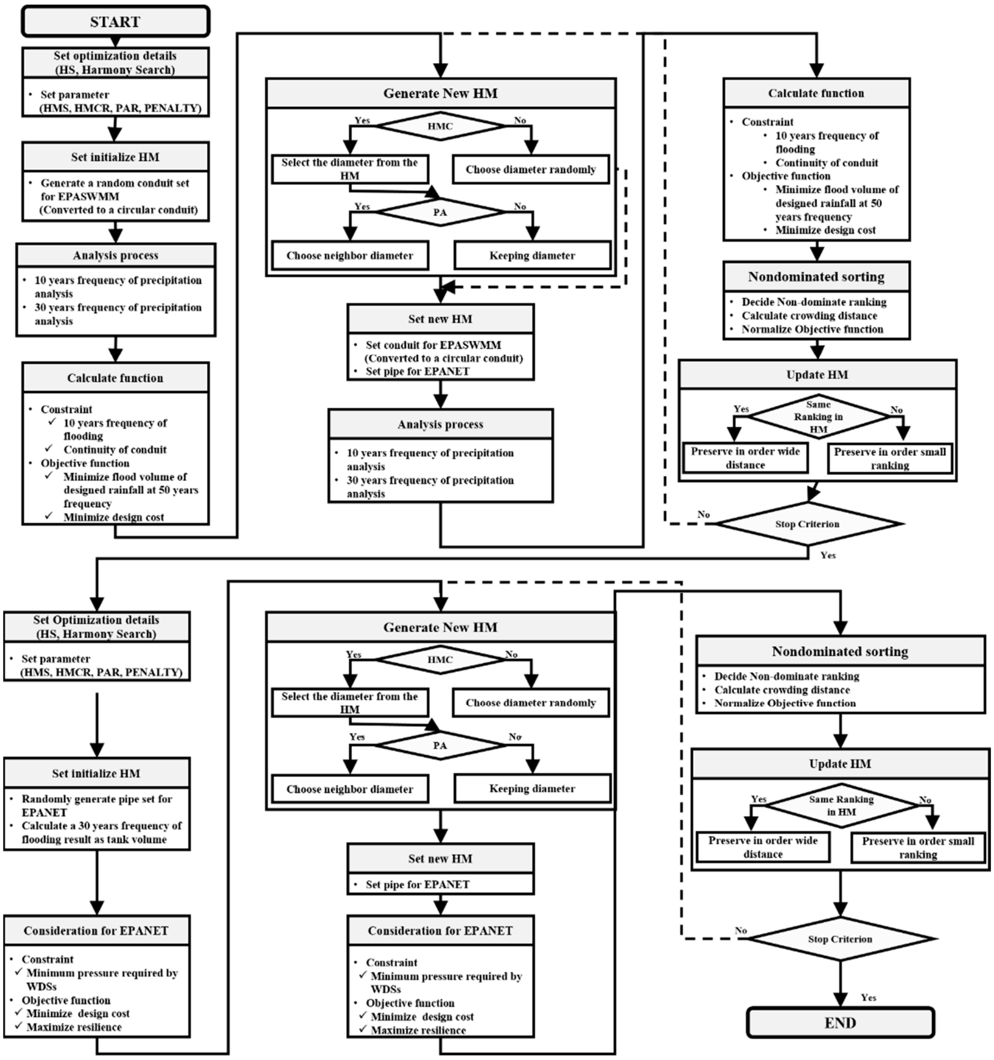

Figure 4. Optimal design of combined water system based on the multi-objective harmony search.

The optimal multi-objective design process for the WRS was performed based on the results of the Pareto-optimal solutions of the stormwater drainage system. The stormwater drainage system design was created for a 30-year frequency design precipitation intensity so that there was no flood volume at a 30-year frequency. Minimization of flood volume at a 50-year frequency design precipitation intensity and minimization of design cost were set as the objective functions.

The reason why the 50-year frequency design precipitation intensity is applied in this study, if the 50-year frequency design precipitation intensity is exceeded, flooding occurs at all nodes by already exceeding the capacity of the system. Although an optimal design was performed to minimize it, there was almost no difference between the optimal solutions, so this study used a 50-year frequency design precipitation intensity as an exceeded rainfall intensity. The rainwater storage tank capacity in EPANET was set as the flood volume of the 50-year frequency design precipitation intensity, and the design cost of the WRS was minimized while resiliency was maximized to determine the Pareto-optimal solutions.

Figure 5 shows the results of the design process illustrated in Figure 4. The multi-objective optimal design for the combined water system was performed in two stages, the first step is the multi-objective optimal design of the UDS, and the second is a multi-objective WDS design based on the Pareto-optimal solutions for the UDS.

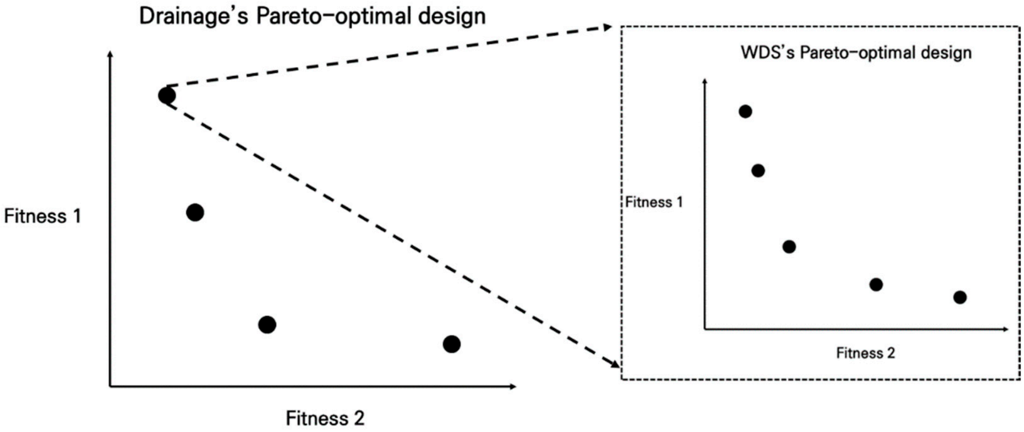

Figure 5. Schematic diagram of multi-objective optimization for the optimal design of a combined water system and the black circle is each Pareto-optimal solution considering the objective function 1 and 2.

2.3. Objective Function and Constraints

The existing UDS was designed with a design rainfall of 10-year frequency. However, because flood damage occurs due to rainfall exceeding the design frequency due to climate change, the optimal design of the UDS was performed by applying the design rainfall with a 30-year frequency. In addition, in order to minimize flooding damage for rainfall exceeding the design rainfall, flooding does not occur in the 30-year design rainfall, and flooding was minimized in the design rainfall with a frequency of 50 years, and the optimal design was performed. The design cost, which is the objective function of UDSs and WDSs, was conducted under the assumption that the design cost increases as the pipe diameter increases [18].

Minimizing the design cost assumed a linear increase in the design cost as the diameter increased. In addition, the design cost can be expressed as Equation (1) by multiplying the cost according to the diameter of the pipe by the length.

$$Minimum\ design\ cost = \sum_{p=1}^{P} Cost\left(D_p\right) L_p \quad (1)$$

where P represents the total number of pipes, $Cost(D_p)$ means the design cost according to the diameter of the pipe, and L_p means the length of the pipe. Therefore, the design cost means the sum of the design cost according to the diameter per unit length of the pipe multiplied by the length of the pipe.

For the objective function of the stormwater drainage system, an analysis was performed by increasing the design precipitation intensity to improve the resilience of the existing design for the drainage system. Minimization of flood volume at the increased design precipitation intensity was considered, as shown in Equation (2). The greater the design cost minimization, the greater the pipes overloading and flood vulnerability. Therefore, the objective function was configured using the tradeoff between design costs in which there was a high vulnerability to flooding and overflow at the increased design precipitation intensity.

$$Minimize\ Flooding = \sum\nolimits_{n=1}^{N} Flooding_n \tag{2}$$

where, N represents all the nodes in the stormwater drainage network, and n indicates a particular node. Flooding is the sum of the flooding volume at all times at a particular node.

Another objective function was the resilience of the WDS. The resilience of the WDS refers to the ability to recover from various abnormal situations to the pressure of normal situations. Therefore, it means the amount of extra energy excluding the minimum pressure required by the system out of the total energy supplied by the entire WDS, and maximization of the resilience of the WDS was considered to increase the extra energy [19]. The resilience of the WDS is shown in Equation (3).

$$Maximize\ Resilience = \frac{\sum_{n=1}^{N} q_n \left(h_n - h_{req}\right)}{\sum_{n=1}^{NR} \left(Q_r \times H_r\right) - \sum_{n=1}^{N} \left(q_n \times h_{req}\right)} \tag{3}$$

where N is the number of nodes, q_n is the demand at the corresponding node, h_n is the pressure at the corresponding node, h_{req} is the minimum pressure required by the WDS, NR is the number of water sources, r is the corresponding water source, Q_r is the flow rate supplied from the corresponding water source, H_r is the head of the corresponding water source. Therefore, the restoring force is the value obtained by dividing the surplus energy supplied to the nodes of the water distribution networks, which is given a value between 0 and 1.

In this study, three constraints (i.e., no flooding under design rainfall, pipes continuity, and required nodal pressure) were considered. If the constraints are not satisfied, the penalty function is considered according to the degree of unsatisfaction, and it is configured to be eliminated during the iterative calculation [20].

The first constraint of the stormwater drainage system was configured to prevent flooding from occurring under the existing design rainfall intensity. Thus Equation (4) can be expressed as

$$Penalty_{Flooding} = \begin{cases} if\ Flooding_n > 0\ then\ Flooding_n \times a \\ if\ Flooding_n \le 0\ then\ 0 \end{cases} \tag{4}$$

where $Flooding_n$ is the flood volume in the stochastic rainfall of 30-year frequency, which is the existing design rainfall intensity, and a is the penalty constant. Therefore, it was set so that floods and inundation did not occur based on the probability of rainfall over 30 years.

The continuity of the pipe was considered a constraint of the second stormwater drainage system, as in the actual design. The continuity of the pipe was compared with the pipe before and after in the flow path of flow, and the optimal design was carried out to increase according to the flow direction. Therefore, constraints were set so that the pipe closer to the outlet was larger than the pipe in the upstream part. The pipe continuity constraint is described in Equation (5).

$$Penalty_{continuity} = \begin{cases} if\ D_i > D_j\ then \sum_{p=1}^{P}\ No.\ D_j \times a \\ if\ D_i \le D_j\ then\ 0 \end{cases} \tag{5}$$

where D_i means the upstream pipe, and D_j represents the pipe close to the outlet according to the flow rate. Therefore, the value of D_j represents the number of pipes in which the outlet pipe is smaller than the upstream pipes.

One constraint of the WDS is that it was set to satisfy the minimum pressure required by the system (Equation (6)). During the simulation times, both the nodes of the WDS and the nodes of the WRS were set to satisfy the minimum pressure of the system.

$$Penalty_{Pressure} = \begin{cases} if\ h_i < h_{req}\ then\ \sum_{p=1}^{P}\left(\left|h_n - h_{req}\right|\right) \times a \\ if\ h_i \geq h_{req}\ then\ 0 \end{cases} \tag{6}$$

where N is the total number of nodes in the water supply network, n is the corresponding node, h_{req} is the minimum pressure required by the water supply network, and a is the penalty point constant.

3. Application and Results

The water distribution system and stormwater drainage system that were used in this study to create the optimal design for the combined water systems were the systems in G-city, Republic of Korea. The number of subareas, nodes, and pipes in the stormwater drainage system was 32, and the existing stormwater drainage network was designed for a 10-year frequency design precipitation intensity. The water distribution network consisted of 118 consumers and 130 pipes. Figure 6 shows the sewer pipe piping diagram and the water distribution network diagram of the target region.

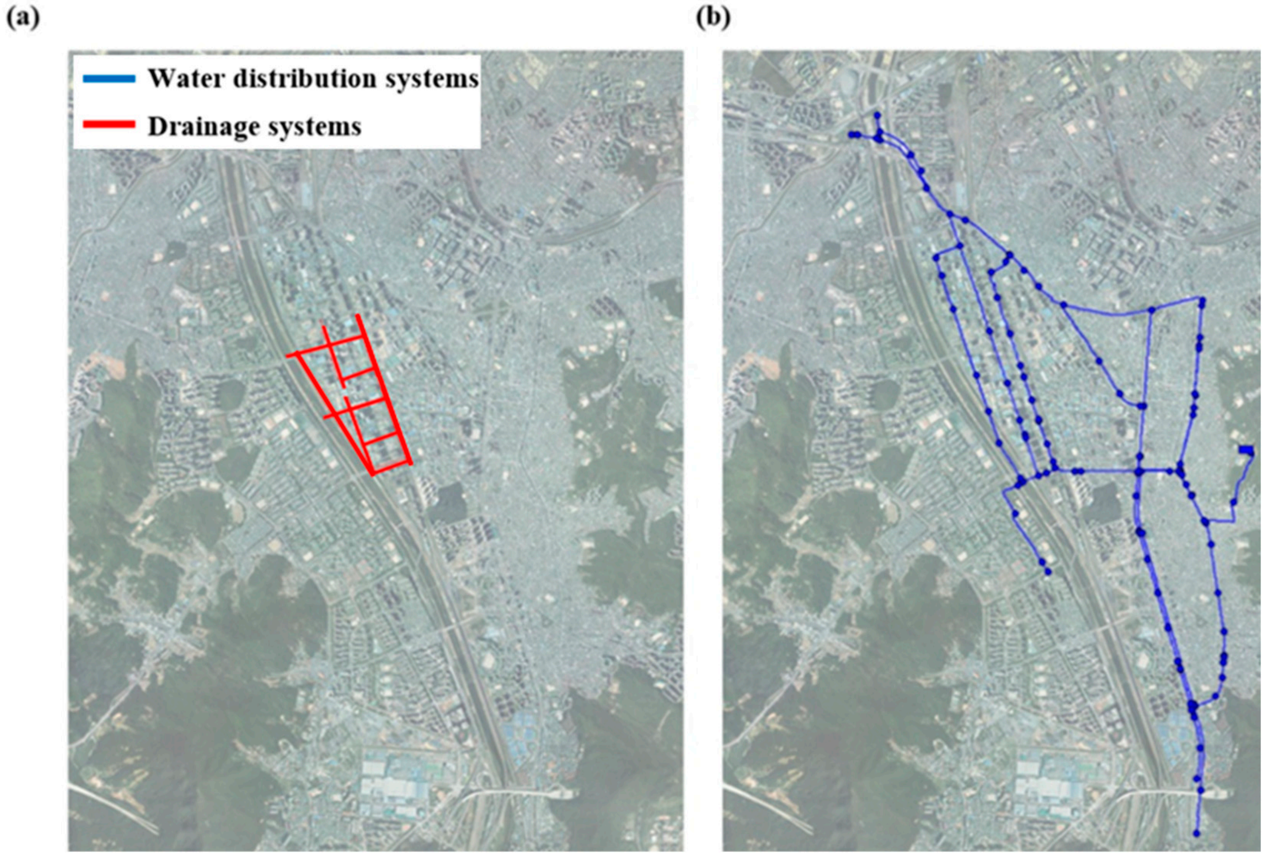

Figure 6. Layout of G-city (**a**) Layout of urban drainage system; (**b**) Layout of the water distribution system.

Based on this, the stormwater drainage and water distribution networks were used to derive the water reuse network, and modeling was performed by dividing the demand of the water distribution system nodes into a 7:3 ratio based on the water reuse rate in Republic of Korea. For Figure 7, the stormwater drainage system network diagram, the water distribution system, and the WRS were derived simultaneously. The WRS area was partitioned based on the stormwater drainage system network. The area indicated by the dotted line is the water reuse area, the number of nodes in the combined water system was 192, and the number of pipes was 227.

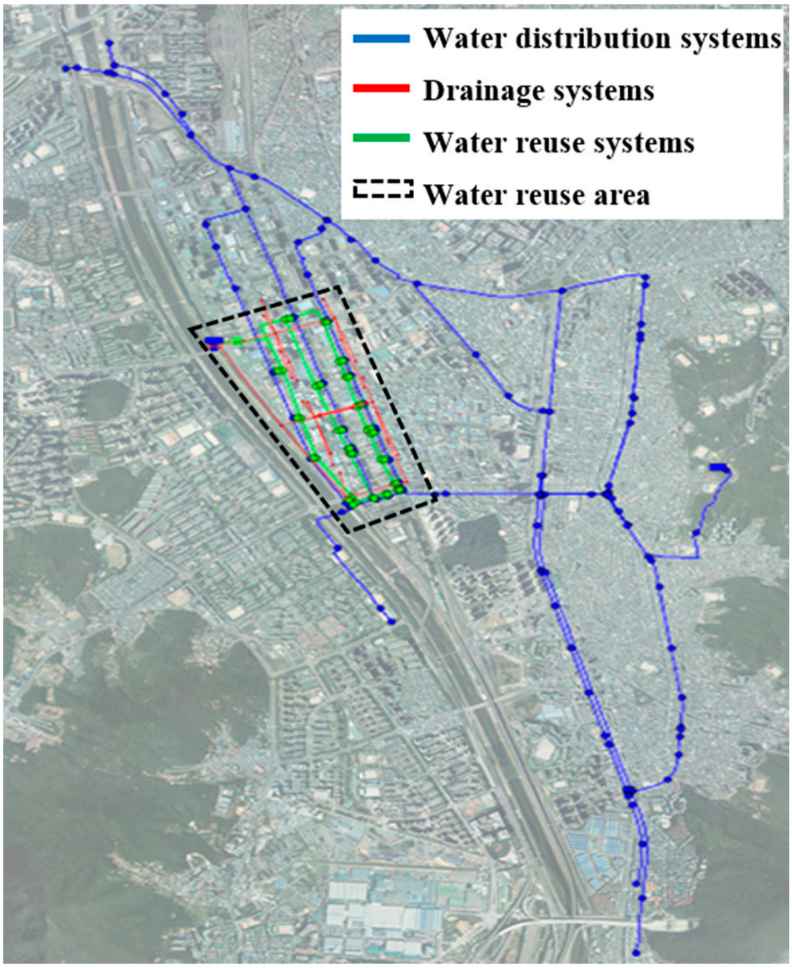

Figure 7. Layout of water reclamation and reuse systems.

3.1. Comparison with Existing Systems

To judge the suitability of the optimal designs for the stormwater drainage system and the water distribution system, the optimal designs were first compared with the existing designs. The Pareto-optimal solutions for the existing design and the optimal design of the stormwater drainage network were derived, as shown in Figures 8 and 9 and Tables 1 and 2.

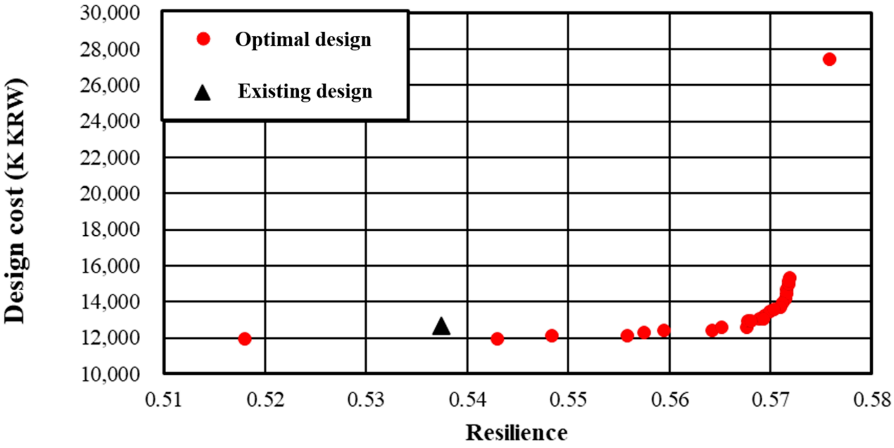

Figure 8. Pareto-optimal solutions for the optimal design of water distribution systems.

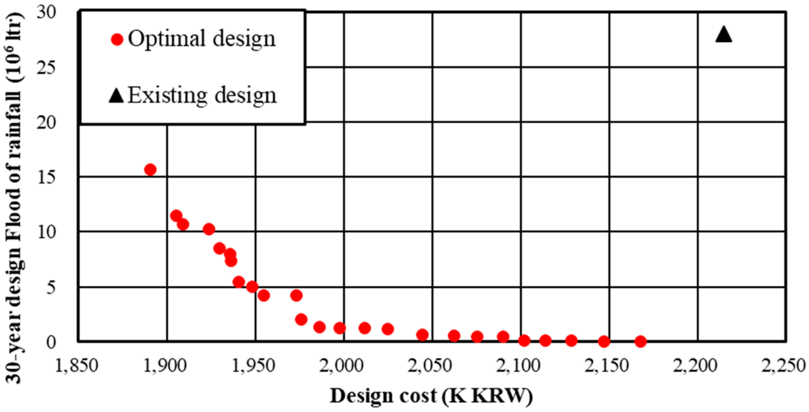

Figure 9. Pareto-optimal solutions for the optimal design of urban drainage systems.

Table 1. Comparison results between optimal design and existing design for the WDS.

Solution	Cost (K KRW)	Resilience
Existing design	12,667,965.6	0.537
Optimal design	11,922,710.0	0.543
Difference	745,255.6	0.006

Table 2. Comparison results between the optimal design and existing design for UDSs.

Solutions	Cost (K KRW)	Volume of Flood Water (10^6 ltr)
Existing design	2,514,715	28.056
Optimal design	2,167,664	0
Difference	347,051	28.056

The comparison between the optimal and the existing designs was performed based on the closest designs. The difference in resiliency in Figure 8 and Table 1, which show a comparison of the water distribution system, was 0.006, which means that the difference between the existing and the optimal designs was not drastic, but the design with 1.2% (0.006) better resiliency led to better result values in terms of construction cost.

The existing stormwater drainage network was designed based on the 10-year frequency design precipitation intensity, and the optimization was performed using 30-year frequency flood volume minimization as the objective function. The difference between the existing and the optimal designs was drastic. In particular, it was found that there was a 28.056×10^6 L difference in flood volume at a 30-year frequency design precipitation intensity.

3.2. Combined Water System Single-Objective Optimization

The stormwater drainage system was designed for a 30-year frequency design precipitation intensity to accommodate increased precipitation volume, and the capacity of the WRS rainwater storage tanks was calculated based on the flood volume of the stormwater drainage system at a 50-years frequency design precipitation intensity. In addition, flow control valves and dummy nodes were used to differentiate demand volumes. In the model, EPANET control rules were applied so that the water in the rainwater storage tanks could be used first, and potable water was used when the water level in the rainwater storage tanks fell to 0 m or below. In addition, the installation locations for the rainwater storage tanks were set so that they could be used primarily after chemical treatment, considering the surrounding local environment. Furthermore, the maximum height of the rainwater storage tanks was fixed at 3 m, and the diameter of the rainwater storage tanks was set according to the flood volume resulting from a 50-year frequency design precipitation intensity.

Single-objective optimization was performed on the combined water system, which combines a water distribution system, a stormwater drainage system, and a WRS. A constraint condition was set so that flood volumes did not exist at a 30-year frequency design precipitation intensity, and the continuity of the stormwater drainage system pipe was considered. The water distribution nodes and water reuse nodes were set up so that they met the Korean water distribution system standard for the minimum pressure required by a pipe network, which is 15 m. Figure 10 shows the convergence of the single-objective optimization as it minimizes the total design cost of the combined water systems.

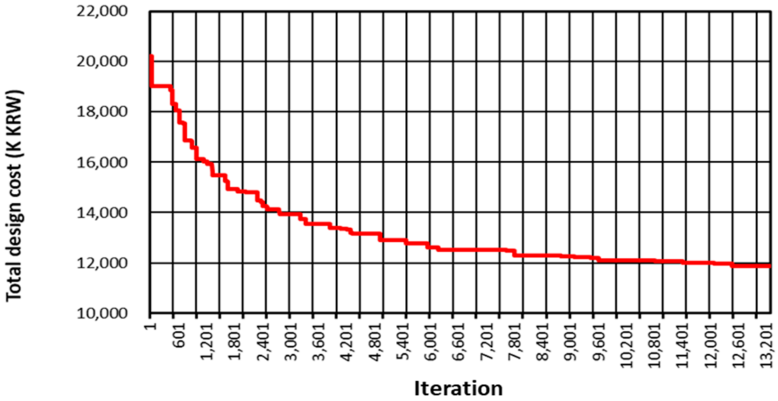

Figure 10. Convergence of single-objective harmony search for the optimal design of the combined water system.

Figure 10 shows the convergence of the design cost starting when the penalty function was not in effect because of the constraints, and the total construction cost was calculated as 11,880,705.78 (K KRW). This design cost is 787,259.82 (K KRW) higher than that of the existing water distribution system. A relatively high design cost was calculated because the design costs of the stormwater drainage network and water reuse network were added to it. However, it was possible to derive a design that satisfied the requirements of the stormwater drainage system regarding pipe diameter continuity and flood volume at a 30-year frequency design precipitation intensity while satisfying the hydraulic constraints for the water distribution system and the stormwater drainage system. Thus, it was possible to devise a design approach that combines a stormwater drainage system and a water distribution system.

3.3. Combined Water System Multi-Objective Optimization

The stormwater drainage system multi-objective optimization was used to perform the multi-objective optimization of the combined water systems. The minimization of design costs and flood volumes at a 50-year frequency design precipitation intensity were set as the objective functions to perform the optimization. Figure 11 shows the Pareto-optimal solutions of the optimal multi-objective design of the stormwater drainage network.

The existing stormwater drainage network was designed for a 10-year frequency design precipitation intensity, but the optimal design was created for a 30-year frequency design precipitation intensity to handle the precipitation caused by increasing weather abnormalities. To minimize design costs and allow for resilient operation, minimization of flood volumes at a 50-year frequency design precipitation intensity was set as an objective function. A multi-objective optimization was performed based on 18 optimal designs for the stormwater drainage system to minimize the design cost and maximize the resiliency of the water distribution system. To compare and analyze the plans quantitatively, the largest pipe diameter was selected to be the initial memory from among the pipe diameter candidates.

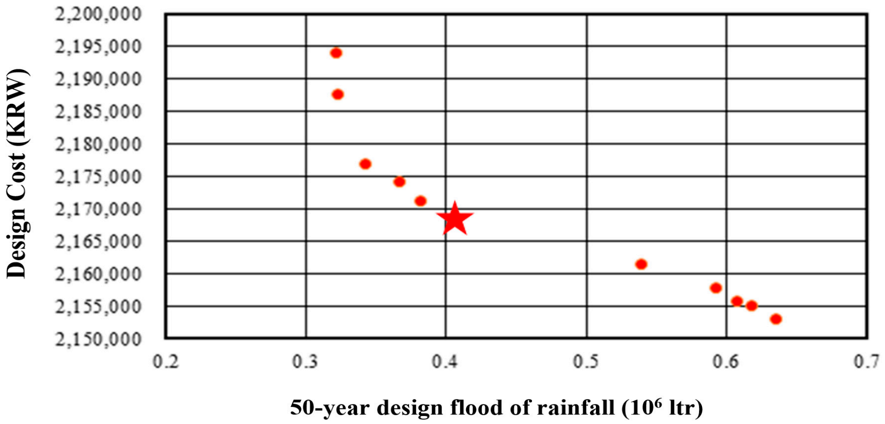

Figure 11. Pareto-optimal solutions of urban drainage systems and the red circle is each Pareto-optimal solution considering the minimum design cost and minimum flood volume as the objective functions.

Figure 12 shows the existing WDS design, the multi-objective optimal design of the WDS, and the combined water systems. In the case of the optimal design for the combined water systems, the optimal design was derived based on a flood volume at a 50-year frequency design precipitation in-tensity of 0.413 × 10^6 L, which is the median value excluding extreme values (solution ★ in Figure 11).

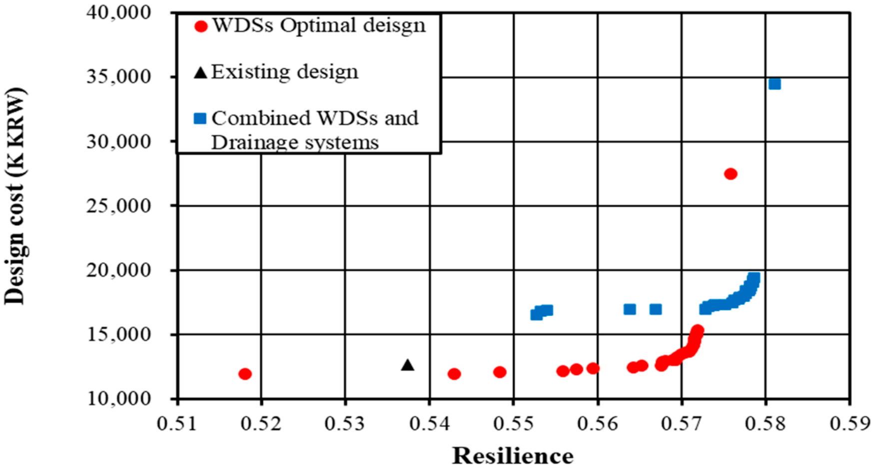

Figure 12. Pareto optimal solutions for combined water systems and WDSs.

The design cost increased by the amount of the design cost of the WRS and that of the UDS. However, the difference between the Pareto-optimal solutions for the WDS and the combined water systems was not as much as the difference. This result can describe that the existing UDS is overdesigned, and the design cost was reduced, and as for the WDS's resiliency, according to the WRS's demand increment, it makes be improved the system water supply performance under abnormal conditions.

4. Conclusions

This study developed a multi-objective optimal design approach for a combined water system comprising a WDS, a UDS, and a WRS as one system. To consider the combined water systems design, the existing WDS demand was divided into drinking water and other uses (e.g., flushing toilets, cooling of industrial units, gardening water, etc.). Water for other uses is supplied by the WRS, and the resources of the WRS were assumed by the capacity of the rainwater storage tank for covering the amount of exceeding precipitation. To design the three combined water systems (i.e., WDS, UDS, and WRS), the objective functions were applied to the minimum construction cost of these systems, the maximum system resilience of the WDS and WRS, and the minimum flooding volume exceeding the designed rainfall intensity of the UDS. For the constraints, the minimum nodal pressures for the WDS and WRS and zero flooding in the designed rainfall intensity of the UDS were applied. The diameter of pipes and conduit was used as the decision variables, and to derive the reasonable optimal solution for three highly correlated systems, single- and multi-objective optimizations were performed and compared.

First, the existing and optimal designs for the stormwater drainage system and the water distribution system were compared and analyzed. Doing so confirmed that, in the case of the water distribution system, the optimal design produces better resiliency than the existing one despite its low design cost. In the case of the stormwater drainage system, all the optimal designs were superior to the existing designs despite considering the continuity of the pipe. This confirmed that the existing designs are vulnerable to flooding and inundation despite being overdesigned.

Second, an optimal single-objective design was created for the combined water system. A water distribution system analysis program and an urban runoff analysis program were combined to perform the optimization. The flood volumes produced as a result of the urban inundation analysis program were used as input data in the water distribution system analysis program to derive an optimal design that is superior in terms of both hydraulic stability and design cost.

Third, an optimal design was derived for the combined water systems based on the multi-objective optimal design of the stormwater drainage system. The increase in the plan resiliency factor was slight compared with the increase in cost, but the results were superior to those of the existing design and the optimal design for the water distribution system in terms of resiliency and pressure. The stormwater reuse water was modeled as multiple sources to ensure resiliency against urban population concentration and rapidly increasing water usage. The increase in the resiliency factor was slight compared with the increase in design cost, but it was possible to develop an effective pipe network design method when considering future water resource usage costs and water reuse costs. Currently, water in WDSs is used for various uses such as drinking, irrigation landscapes, flushing toilets, river restoration water, and dividing water demand for reused water is expected to reduce the water treatment costs for generating drinking water.

In future studies, the multi-objective optimization of WDSs, UDSs, and WRSs can be performed by examining the tradeoffs between the water treatment costs and design cost, system resilience, and CO_2 emission in the combined water systems. Furthermore, studies that consider not only hydraulic stability but also water quality safety should be able to assist managers and designers in their decision-making by providing various Pareto-optimal solutions.

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References

1. Park, J.H.; Kim, K.B.; Chang, H.Y. Statistical properties of effective drought index (EDI) for Seoul, Busan, Daegu, Mokpo in South Korea. *Asia-Pac. J. Atmos. Sci.* **2014**, *50*, 453–458. [CrossRef]
2. Byun, H.R.; Wilhite, D.A. Objective quantification of drought severity and duration. *J. Clim.* **1999**, *12*, 2747–2756. [CrossRef]
3. Guo, Y.; Baetz, B.W. Sizing of rainwater storage units for green building applications. *J. Hydrol. Eng.* **2007**, *12*, 197–205. [CrossRef]
4. Kahinda, J.M.M.; Taigbenu, A.E.; Boroto, J.R. Domestic rainwater harvesting to improve water supply in rural South Africa. *Phys. Chem. Earth Parts A/B/C* **2007**, *32*, 1050–1057. [CrossRef]
5. Han, M.Y.; Park, S.; Kim, S.; Kim, S.R. Analysis of rainwater quality in rainwater harvesting systems at dormitories in Seoul National University, Seoul, Korea. *IWA World Water Congr.* **2006**, *7*, 2013.
6. Basinger, M.; Montalto, F.; Lall, U. A rainwater harvesting system reliability model based on nonparametric stochastic rainfall generator. *J. Hydrol.* **2010**, *392*, 105–118. [CrossRef]
7. Sample, D.J.; Liu, J. Optimizing rainwater harvesting systems for the dual purposes of water supply and runoff capture. *J. Clean. Prod.* **2014**, *75*, 174–194. [CrossRef]
8. Zhang, D.; Gersberg, R.M.; Wilhelm, C.; Voigt, M. Decentralized water management: Rainwater harvesting and greywater reuse in an urban area of Beijing, China. *Urban Water J.* **2009**, *6*, 375–385. [CrossRef]
9. Ramezanianpour, M.; Kung, S. Simulation study of water reuse system for a regenerative houseboat by epanet. *Proc. Int. Struct. Eng. Constr.* **2020**, *7*, 2. [CrossRef]
10. Momeni, A.; Yerri, S.; Piratla, K.R.; Madathil, K.C. Evaluation of water supply reliability improvement enabled by on-site greywater reuse systems. *Resour. Conserv. Recycl.* **2022**, *182*, 106326. [CrossRef]
11. Jeong, H.; Broesicke, O.A.; Drew, B.; Crittenden, J.C. Life cycle assessment of small-scale greywater reclamation systems combined with conventional centralized water systems for the City of Atlanta, Georgia. *J. Clean. Prod.* **2018**, *174*, 333–342. [CrossRef]
12. Koo, J.Y.; Yu, M.J.; Kim, S.G.; Shim, M.H.; Akira, K. Estimation of long-term water demand by principal component and cluster analysis and practical application. *J. Korean Soc. Environ. Eng.* **2005**, *27*, 870–876.
13. Lee, D.; Kim, J.; Kim, H. Statistical analysis on non-household unit water use for business categories. *KSCE J. Civ. Environ. Eng. Res.* **2009**, *29*, 385–396.
14. Chung, G.; Ohk, W.S. Development of the urban water balance model by linking water distribution and sewer networks. *J. Korean Soc. Hazard Mitig.* **2020**, *20*, 369–377. [CrossRef]
15. Chung, G.; Ohk, W.S.; Yoo, D.G.; Kim, G.T.; Jun, H.D. Development and Application of An Integrated Urban Water Cycle System by Combining Water Cycle Elements. *J. Korean Soc. Hazard Mitig.* **2022**, *22*, 311–319. [CrossRef]
16. Geem, Z.W.; Kim, J.H.; Loganathan, G.V. A new heuristic optimization algorithm: Harmony search. *Simulation* **2001**, *76*, 60–68. [CrossRef]
17. Fonseca, C.M.; Fleming, P.J. Genetic algorithms for multiobjective optimization: Formulationdiscussion and generalization. *Icga* **1993**, *93*, 416–423.
18. Alperovits, E.; Shamir, U. Design of optimal water distribution systems. *Water Resour. Res.* **1977**, *13*, 885–900. [CrossRef]
19. Todini, E. Looped water distribution networks design using a resilience index based heuristic approach. *Urban Water* **2000**, *2*, 115–122. [CrossRef]
20. Yazdi, J.; Choi, Y.H.; Kim, J.H. Non-dominated sorting harmony search differential evolution (NS-HS-DE): A hybrid algorithm for multi-objectives design of water distribution networks. *Water* **2017**, *9*, 587. [CrossRef]