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An integrated AHP-PROMETHEE II ranking method to evaluate the resilience of sewer networks considering urban flood and ground collapse risks

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ABSTRACT

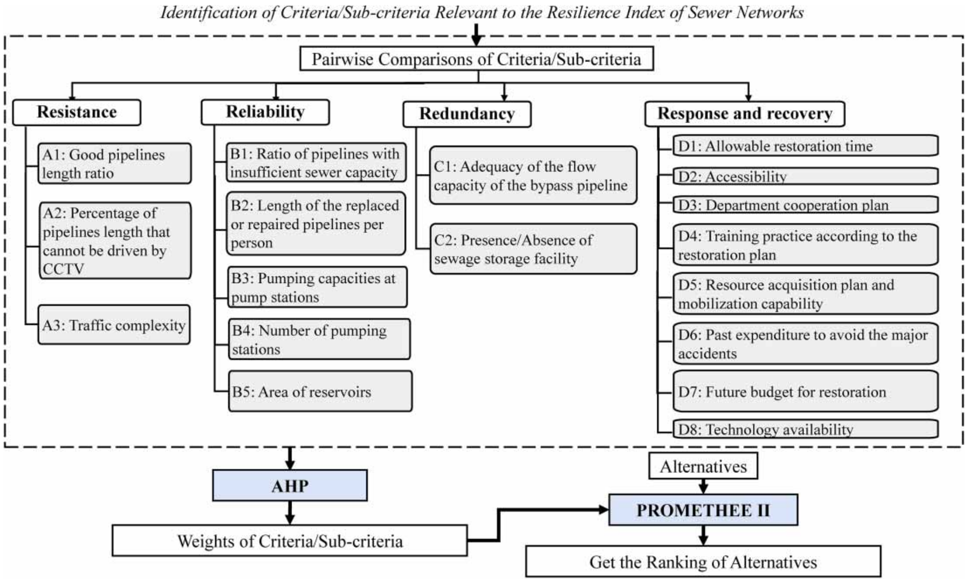
The aim of this study is to present criteria to evaluate the resilience of sewer networks related to ground collapse and urban flooding likely to occur in a specific region and then to determine the ranks of the sewer networks resilience of the selected regions to show the applicability of the analytic hierarchy process (AHP) and the Preference Ranking Organization Method for Enriching Evaluations (PROMETHEE II) method. Fourteen evaluation criteria representing resistance, reliability, redundancy, and response and recovery are presented and their weights are estimated by the AHP by asking questionnaires to 10 sewer experts, leading to the result that the sub-criteria of reliability showed the highest importance, followed by the length ratio of good pipelines (under resistance) and adequacy of the flow capacity of the bypass pipelines (under redundancy). Four separate small blocks of drainage areas (total area of 3.57 km^2; sewer length of 50.6 km) in Seoul are chosen for the case study. Using appropriate preference functions and thresholds for each evaluation criterion for PROMETHEE II application yields the resilience rankings of four blocks as Block III > Block IV > Block I > Block II. A sensitivity analysis was also carried out by changing the weights.

Key words: analytic hierarchy process, ground collapse, PROMETHEE, resilience index, sewer networks, urban flood

HIGHLIGHTS

- The factors that affect the sewer network resilience were identified and evaluated.
- 4Rs (Resistance, Reliability, Redundancy, Response and recovery) were considered.
- The AHP was used to determine the weights of the criteria.
- PROMETHEE II was used to obtain the final ranking of the sewer network resilience.
- Sensitivity analysis was carried out by changing the weights.

GRAPHICAL ABSTRACT



INTRODUCTION

In the underground space, various underground facilities are buried like spider webs, such as water supply, electricity, communications, gas, district heating, and sewage pipes. Among them, the problem of urban ground collapse caused by damaged sewer pipes has frequently occurred recently. Ground collapse can bring hidden dangers to traffic safety, pedestrian safety, and damage to street lights, gas pipes, and other municipal facilities. The destruction of sewer pipes will cause sewage to be unable to be discharged, collected, and treated normally. If the sewer pipes are damaged, it is difficult to check immediately. Since an abnormal situation can only be known when a direct accident such as a ground collapse occurs, it is very important to manage in advance to avoid large-scale accidents. As a metropolis in South Korea, Seoul often receives reports of ground collapse, of which a relatively large proportion is caused by damaged sewer pipes (Kwak *et al.* 2019).

Climate change has led to heavy rains, storms, and other full-scale damage in many countries. Seoul is a city with an intense concentration of political, economic, and other urban functions. It is densely populated with a complex network of buildings and underground infrastructure. Flooding in such a city would cause considerable damage, as well as prohibitive costs and restoration time. In recent years, major floods occurred in Seoul in 2010, 2011, 2018 (Kim *et al.* 2021), and 2022 (CBBC Newsround 2022). The short-term heavy rain caused floods and landslides in buildings and public facilities in Seoul, causing huge property losses and personal casualties. According to the analysis, the causes of floods are not only heavy rainfall exceeding the design capacity of drainage facilities but also surface runoff going to low-lying areas, insufficient flow capacity of sewage pipes, reduced conveyance due to sediment runoff, and backwater, failure to take account of impact of climate change in road design, vulnerable aspects in using land (e.g. underground arcades and housings), inadequate warning/alarm systems, ineffective traffic controls, poor management of vulnerable areas/facilities, and poor restoration systems and disaster follow-up. Therefore, in order to cope with climate change, major cities around the world are working hard to introduce new disaster prevention systems. In order to better cope with extreme weather conditions, Seoul has been directing its focus on the improvement of the system to become better prepared for potential flooding in the city. The officials in Seoul are making efforts to upgrade the design standards for newly installed sewers and pumping station, to implement sewer rehabilitation projects according to the revised master plan on sewer rehabilitation, to replace old pumps into new ones with expanded capacity, and to apply low impact development technologies to reduce the stormwater runoff (Kim 2017; Song *et al.* 2022). Several investigators (Butler *et al.* 2014; Casal-Campos *et al.* 2018; Binesh *et al.* 2019; Bakhshipour *et al.* 2021) introduced the concept of reliability, resilience, sustainability in considering water resource management method, improving the capacity issues of an existing integrated urban wastewater system, or examining the effectiveness of implementing BMPs to reduce urban flooding. Butler *et al.* (2014) illustrated a pyramid structure that is connected between reliability, resilience, and sustainability, in which resilience should be based on reliability and sustainability should be based on resilience. They also insisted, therefore, that disaster-risk reduction should not only focus on reducing the possibility of disasters but also on improving the resilience of the system to disasters such as ground collapse or urban flooding.

Resilience is a hot topic in urbanism today. Critical infrastructure networks such as electric power, water supply, and drainage, natural gas, telecommunications, and transportation provide the services necessary for the continuous operation of society and are the backbone of modern societies. Sun *et al.* (2020) focused on the resilience analysis of the transportation infrastructure to support planning and design, and to optimize emergency management and restoration schedules. Feofilovs & Romagnoli (2017) applied the probabilistic method to the district heating pipeline network to generate statistical data for the calculation of the resilience of the district heating pipeline network and clarified the resilience of the district heating pipeline network to specific hazards, as well as the possible impact of specific investment schemes to enhance the resilience. In addition, researches on the resilience of other infrastructures such as telecommunications (Bertelli *et al.* 2018) and electric power systems (Chen *et al.* 2020) are also under continuous exploration. However, the implementation of resilience concepts in urban drainage and flood management systems has been limited by the lack of guidelines, standards, and suitable quantitative evaluation methods (Mugume & Butler 2017). Juan-García *et al.* (2017), in their review of the incorporation of resilience theory into urban wastewater system management, pointed out that four key elements of system stressors, resilience properties, resilience metrics, and interventions were identified in resilience assessment. At the same time, it is pointed out that since the concept of resilience was introduced, only a small subset of the work in wastewater research has directly addressed resilience, and the implementation of resilience in wastewater management has been hindered by the lack of consensus in the definition of resilience and the elements of a resilience assessment. In the resilience research of urban stormwater management system, it is based on the background of responding to urban flood events caused by climate change (van Duin *et al.* 2021; Rentachintala *et al.* 2022). Valizadeh *et al.* (2016) considered the three technical aspects of urban hydrological characteristics, hydraulic factors, and network structure characteristics to quantify the technical resilience of stormwater systems to flooding.

Zhang *et al.* (2022)'s prior study used the four properties of resilience (robustness, rapidity, resourcefulness, and redundancy, 4Rs) presented by Bruneau *et al.* (2003) to identify 13 resilience indices of sewer networks in response to the urban ground collapse. In order to measure the robustness of the sewer networks in evaluating ground collapse resilience (GCR), the subfactors of the good pipeline length ratio, the percentage of pipelines length that cannot be driven by CCTV, and traffic complexity were considered. Two subfactors were included to measure the redundancy of the sewer network: adequacy of the flow capacity of the bypass pipeline and the treatment capacity of sewage storage facility. To measure rapidity of sewer network restoration, the four subfactors, such as the allowable restoration time, accessibility, department cooperation plan, and training practice according to the restoration plan, were used. Additional four subfactors to measure the resourcefulness affecting the resilience of the sewer network were the resource acquisition plan and mobilization capability, the past expenditure to avoid major accidents, the future budget for restoration, and the technology availability. Then, they used the analytic hierarchy process (AHP) to obtain the weight of sub-criterion through a questionnaire survey of 10 sewer experts. Finally, the quantification result of the resilience index is calculated by the weighted sum method. In this process, the actual values of some indicators of each selected case need to be normalized, such as converting some qualitative indicators into quantitative indicators and then performing weighted sum calculation to obtain quantitative results. The weighted sum model (WSM) is probably the most commonly used approach, especially in single-dimensional problems, but is not suitable for problems that often involve very different types of criteria and variables (Kabir *et al.* 2014).

Nowadays, multicriteria decision analysis (MCDA) is increasingly used in environmental policy evaluation (Turcksin *et al.* 2011). MCDA is a valuable tool that can be applied to many complex decisions. It is the most applicable to solving problems that are characterized as a choice of alternatives. It has all the characteristics of a useful decision support tool: it helps us focus on what is important, is logical and consistent, and is easy to use. There are a variety of MCDA methods, including multi-attribute value/utility theory (MAVT/MAUT), simple multi-attribute rating technique (SMART), AHP, Preference Ranking Organization Method for Enriching Evaluations (PROMETHEE), and Elimination and Choice Translating Relation (ELECTRE). Results of PROMETHEE II are known to be consistent, easy to understand, and require less information from decision-makers compared to the AHP (Balali *et al.* 2014). The PROMETHEE method is a pairwise comparison of decision points based on assessment factors. However, unlike other multicriteria decision-making methods, it defines a preference function consisting of different assessment factors and assigns a relative weight indicating the level of importance of each factor and the internal relations among them (Sharma *et al.* 2017). Karamouz *et al.* (2016) used the PROMETHEE method in the evaluation of flood resiliency for wastewater treatment plants in coastal areas, and this general concept for more than one alternative provided a way to better combine subjective and objective data by utilizing the geometric analysis to compare the values of each sub-criteria with the corresponding values of the other alternatives. Carone *et al.* (2019) evaluated the disaster resilience of local communities by simulating flood experience and processing anonymous survey data collected before and after flooding practice with PROMETHEE. Kessili & Benmamar (2015) used the AHP-PROMETHEE II ranking method to prioritize sewer rehabilitation projects, envisioning helping sewer managers evaluate and prioritize sewer rehabilitation. Yu *et al.* (2019) used PROMETHEE and Geometric Analysis for Interactive Aid (GAIA) methods to determine the conditional ranking of ageing sewer pipes. Ahn *et al.* (2020) applied PROMETHEE using the weights determined by the AHP for the selected sewer evaluation items to calculate the rehabilitation priorities. Some researchers tried to combine the AHP and PROMETHEE to further enhance the capabilities of both techniques (Balali *et al.* 2014). In these combined methods, the AHP has been used to analyse the structure of the decision problem and determine the weights of the criteria, whereas PROMETHEE has been used to obtain a final ranking of the proposed alternatives and to perform sensitivity analyses by changing the weights. The application of the hybrid model of AHP–PROMETHEE is an important tool for multicriteria decision-making (MCDM). So, in this study, an integrated approach combining AHP and PROMETHEE is applied with the following descriptions. Once criteria and sub-criteria of sewer network resilience are defined, weights of them will be obtained by the computation procedure of the AHP via pairwise comparisons. Subsequently, PROMETHEE II is used to evaluate and rank alternatives to the resilience evaluation of four small blocks of selected drainage areas in Seoul. Eventually, the rank of them regarding resilience from the best to worst one has appeared. Sensitivity analysis was conducted by computing 'stability intervals' values to assess the general robustness of the ranking.

Furthermore, in particular, in order to more fully consider the influencing factors of sewer network resilience, this paper applies infrastructure resilience as defined by the UK Cabinet Office: the ability of assets, networks, and systems to anticipate, absorb, adapt to, and/or rapidly recover from a disruptive event. In building resilience, the contribution of each of the four components of resistance, reliability, redundancy, response, and recovery (4Rs) needs to be considered. The resistance element of resilience is focused on providing protection. The objective is to prevent damage or disruption by providing the strength or protection to resist the hazard or its primary impact. This element is similar to the concept of robustness in the 4Rs (rapidity, robustness, resourcefulness, and redundancy) of resilience proposed by Bruneau *et al.* (2003). The reliability component is concerned with ensuring that the infrastructure components are inherently designed to operate under a range of conditions and hence mitigate damage or loss from an event. This element is not included in the 4Rs of resilience proposed by Bruneau *et al.* (2003). In the study of the reliability measure of a sewer network by Ermolin & Alexeev (2018), it is pointed out that compared with the research dedicated to the reliability problems of water supply systems, the reliability problems of the sewage disposal systems are still uninvestigated. They therefore quantify reliability by using a functional efficiency estimation of tree-like hierarchical structures, which will quantify the relative volume of raw sewage potentially discharged from the sewer network to the environment over some time period resulting from network component failures. However, data on failure rates are difficult to obtain. Moreover, the results obtained through the new questionnaire show that the importance of reliability is relatively large, so it is considered necessary to conduct further research on the quantification of the reliability index of the sewer pipe network to improve the resilience evaluation framework of the sewer network. Conventional hydraulic reliability-based urban drainage design and rehabilitation approaches focus on minimizing the probability of occurrence of hydraulic failures resulting from a given design rainstorm as a basis for determining the flood protection level of a given system. However, in view of emerging threats, it is now recognized that urban drainage systems should be designed not only to be reliable during normal (standard) conditions but also resilient to unexpected (exceptional) loading conditions (Mugume & Butler 2017). Even though Diao (2020) reported that quantitative studies on the resilience of urban drainage systems tend to focus on investigating hydraulic reliability, considering only functional failures such as the occurrence of extreme rainfall or increasing dry weather flows, the reliability problems of the sewage disposal systems are little investigated especially based on the actual operating data of sewer pipe networks, and there is no universally acceptable definition and measure of reliability of sewer network (Ermolin 2001; Jin & Mukherjee 2010; Haghighi & Bakhshipour 2016; Miszta-Kruk 2016; Ermolin & Alexeev 2018). Therefore, this study will supplement the analysis of reliability indicators based on the previous research. When the reliability of the sewer network is considered, the flooding issue cannot be neglected. As for the reliability of flooding (river flooding as well as sewer flooding) in Seoul in this study, we use five evaluation items evaluated by the River Management Division (RMD), such as the ratio of pipelines with insufficient sewer capacity, the length of the replaced or repaired pipelines per person, the pumping capacities at pump stations, the number of pumping stations, and the area of reservoirs. The redundancy element is concerned with the design and capacity of the network or system, which is consistent with the concept of redundancy in the 4Rs of resilience proposed by Bruneau *et al.* (2003). The response and recovery element aims to enable a fast and effective response to and recovery from disruptive events, which incorporate both the rapidity and resourcefulness elements of the 4Rs of resilience proposed by Bruneau *et al.* (2003).

METHODS

In general, the method is presented as a conceptual framework for evaluating the resilience of sewer networks illustrated in Figure 1 along with the following details of criteria/sub-criteria and alternatives as well as the integrated AHP-PROMETHEE II ranking method.

Criteria/sub-criteria and alternatives

First of all, these criteria and sub-criteria proposed in this study were finalized after brainstorming by the authors of this study based on existing references combined with considerations about the resilience of the sewer network system in the context of ground collapse and urban flood. This study uses the four components of resilience (resistance, reliability, redundancy, response, and recovery) presented by the Cabinet Office (2011) different from the 4Rs (rapidity, robustness, resourcefulness, and redundancy) of resilience proposed by Bruneau *et al.* (2003) previously used in the previous study by Zhang *et al.* (2022). However, the resistance, redundancy, response, and recovery indicators are conceptually consistent with the 4Rs (rapidity, robustness, resourcefulness, and redundancy) proposed by Bruneau *et al.* (2003). Therefore, the process that was undertaken to determine the sub-criteria of resistance, redundancy, response, and recovery indicators can refer to the previous research of Zhang *et al.* (2022). In this study, based on the original 13 factors identified by Zhang *et al.* (2022), a new factor to characterize reliability is added, as demonstrated in Table 1.

The flooding in Seoul should be considered from two perspectives: external (river) flooding and internal (sewer) flooding. Recently, this coastal city with a big River Han experienced only urban floodings, but it has ever faced the risk of external flooding since ancient times. South Korea used to suffer damage from floods caused by typhoons and heavy stormwater almost every monsoon season. Seoul metropolis, the capital and largest coastal city in Korea, is threatened by river flooding as well as inland flooding in the rainy season. In order to prevent flooding, 15 dams were installed upstream of the Han River and 23 rainwater reservoirs, and 120 drainage pump stations downstream in the city of Seoul. The burial depth of drainage pump stations and reservoirs deepens as the sewage including rain flows down through a long sewer pipeline. During very

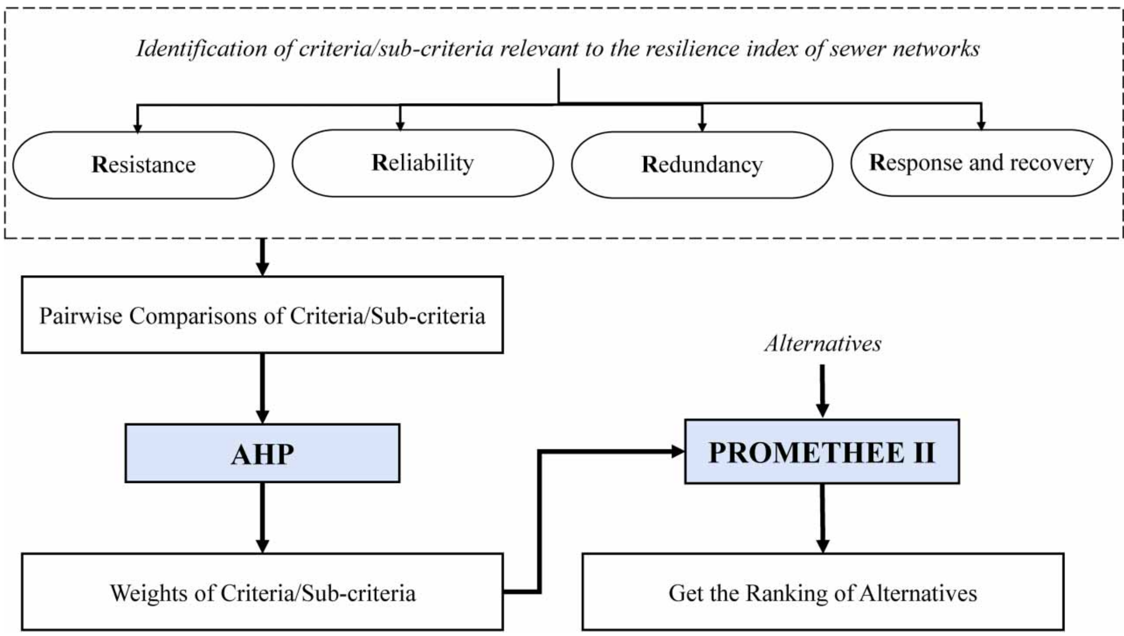


Figure 1 | The conceptual framework of the AHP-PROMETHEE II ranking method.

Table 1 | Criteria and sub-criteria of the evaluation project

Evaluation criteria			
Criteria	**Sub-criteria**	**Unit(s)**	**Indicator attributes**
Resistance	A1: Good pipelines length ratio	%	Quantitative
	A2: Percentage of pipelines length that cannot be driven by CCTV	%	Quantitative
	A3: Traffic complexity	10-Point scale	Qualitative
Reliability	B1: Ratio of pipelines with insufficient sewer capacity	%	Quantitative
	B2: Length of the replaced or repaired pipelines per person		
	B3: Pumping capacities at pump stations		
	B4: Number of pumping stations		
	B5: Area of reservoirs		
Redundancy	C1: Adequacy of the flow capacity of the bypass pipeline	%	Quantitative
	C2: Presence/absence of sewage storage facility	(Y/N)	Qualitative
Response and recovery	D1: Allowable restoration time	10-Point scale	Qualitative
	D2: Accessibility	10-Point scale	Qualitative
	D3: Department cooperation plan	(Y/N)	Qualitative
	D4: Training practice according to the restoration plan	(Y/N)	Qualitative
	D5: Resource acquisition plan and mobilization capability	(Y/N)	Qualitative
	D6: Past expenditure to avoid the major accidents	10-Point scale	Qualitative
	D7: Future budget for restoration	10-Point scale	Qualitative
	D8: Technology availability	10-Point scale	Qualitative

heavy storm periods, as gates of the upstream dams are opened in case of need by the direction of the Han River Flood Control Office (HRFCO), the integrated control for the operation of the pumping stations and reservoirs should be conducted by the RMD in Seoul in cooperation with HRFCO. The concept of reliability proposed in this study focuses on dealing with urban flood hazards, but there is a problem of failure rate data availability on the sewer pipe network, which often occurs in most underground infrastructures. In this study, as the water level of the Han River, which affects sewage drainage in the city, changes greatly during the monsoon season depending on the operating conditions of large-scale dams in the upper reaches of the Han River passing through Seoul, consideration of rainwater pumping stations and reservoirs is essential for evaluating the reliability related to urban flooding. In this study, based on the 2030 Master Plan on Sewerage Rehabilitation (Seoul 2018), we quantify the reliability index by considering five evaluation items, such as the ratio of pipelines with insufficient sewer capacity (based on hydraulic modelling results), the length of the replaced or repaired pipelines per person, the pumping capacities at pump stations, the number of pumping stations, and the area of reservoirs. In the 2030 Master Plan on Sewerage Rehabilitation, the results of hydraulic computation conducted by engineering consulting firms were referred to. The pipes with insufficient flow capacity and the pipes with the minimum velocity not up to the standard value were identified and operated carefully with periodic sewer cleaning before the stormy season. In addition, the subdivision criterion of redundancy 'Treatment capacity of sewage storage facility' is revised to the 'presence/absence of sewage storage facility' in this study, which is sufficient to compare the final resilience evaluation results of each block in the case study, and prevents concerns about overlapping with the indicator belonging to the subdivision criteria of reliability.

The Seoul Metropolitan Government has formulated a basic sewerage rehabilitation plan every 5 years. In the 2030 Master Plan on Sewerage Rehabilitation, the treatment areas were planned based on the 163 drainage districts and 748 small blocks (Seoul 2018), with a total area of approximately 542,742,842 m^2 and a total sewer length of 9,932,508 m. Among them, four small blocks (one block selected randomly in each treatment area, however, block I is an area with a recently established deep stormwater storage-drainage facility, so it was intentionally added for the comparison of the resilience results) were selected for resilience evaluation in this study, and their locations are shown in Figure 2, and the relevant information is shown in Table 2.

Analytic hierarchy process

The AHP was proposed by Satty (1988, 2008). According to the nature of the problem and the overall goal, the AHP decomposes it according to levels, from top to bottom in order of goals, criteria, alternatives, etc. Then, according to

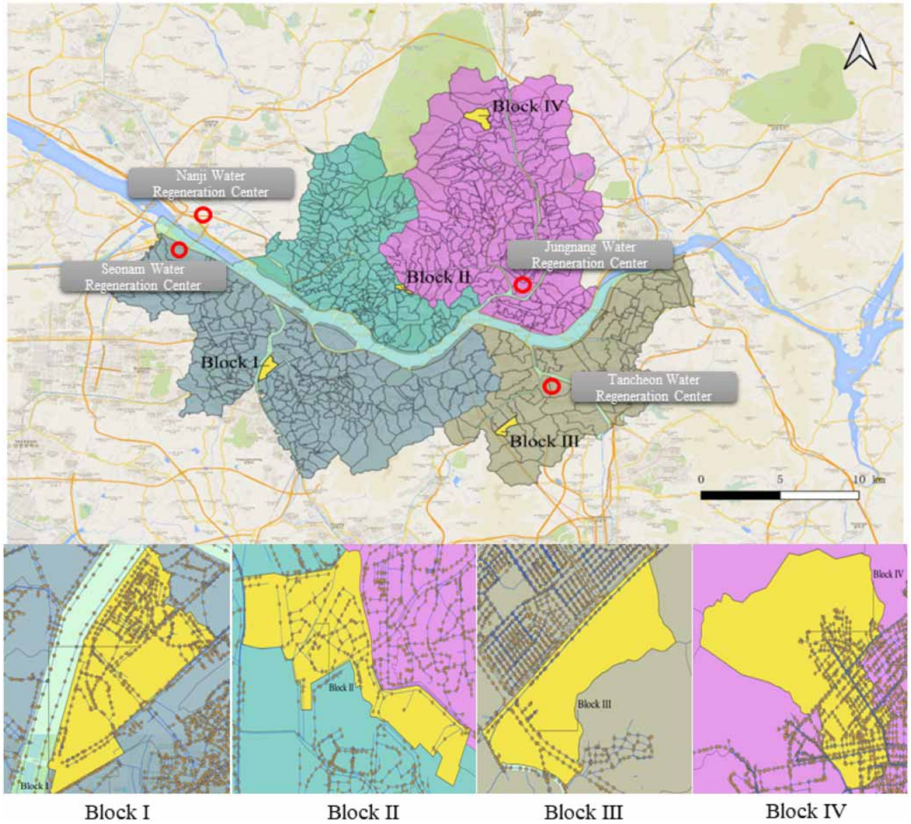


Figure 2 | Four small blocks' sewer networks selected for resilience evaluation. (The red circles indicate the locations of water reclamation centres and yellow sections indicate the locations of small blocks of sewer networks selected in this study.) Please refer to the online version of this paper to see this figure in colour: https://dx.doi.org/10.2166/wst.2023.067.

Table 2 | Information about the selected four small blocks

Evaluation area	Treatment area	Total sewer length (m)	Area (m^2)	No. of sewer pipes	Biochemical Oxygen Demand (BOD) loadings of Combined Sewer Overflows (CSOs) (kg/event)	Flow of wastewater (m^3/s)
Block I	Seonam	17,697.36	1,012,440	329	2,361.83	0.24246
Block II	Nanji	7,166.79	290,416	92	367.98	0.03452
Block III	Tancheon	5,350.28	777,822	46	1,734.03	0.04586
Block IV	Jungnang	20,412.79	1,486,727	410	2,352.06	0.13602

people's subjective judgements, they are compared in pairs to get the index weights. The AHP is based on three principles: (1) construction of a hierarchical structure, (2) priority setting, and (3) logical consistency. First, a hierarchical structure is established. The hierarchical structure has at least three levels: the objective at the top, the (sub-) objectives (criteria and sub-criteria) at the intermediate levels, and the considered alternatives at the bottom. Second, a pairwise comparison matrix ($n \times n$) using Saaty's one to nine fundamental scale is established, which is presented in Table 3 (Saaty 2008). The pairwise comparison matrices are determined in terms of which element dominates the other. The result of the pairwise comparisons is summarized in the pairwise comparison matrix (see Equation (1)). Lastly, the consistency index (CI) of decision-makers, as well as the hierarchy, can be evaluated by means of the consistency ratio (CR). If the CR is lower than 10%, a result can be acceptable. Otherwise, the procedure of pairwise comparison must be repeated until the decision is

Table 3 | Saaty's nine-point scale for pairwise comparison (Saaty 2008)

Comparison intensity	Definition
1	Equally important
3	Moderately more important
5	Strongly more important
7	Very strongly more important
9	Extremely more important
2, 4, 6, 8	Intermediate judgement values
1/2, 1/3,···,1/9	Reciprocals

more consistent. This procedure is explained in detail by Saaty (1988).

$$A = [a_{ij}] = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & a_{nn} \end{bmatrix},\ a_{ii} = 1,\ a_{ji} = \frac{1}{a_{ij}},\ a_{ij} \neq 0 \tag{1}$$

where $A = [a_{ij}]$ is a representation of the intensity of the decision maker's preference for one over another compared alternative a_{ij} and for all comparisons $i, j = 1, 2, \cdots, n$.

In the AHP, when conducting questionnaires to experts, the results would be more acceptable when confronted with an appropriate size of experts like a range of 10–25 (Dehghani Pour 2016; Koohathongsumrit 2018). Therefore, this study conducted a questionnaire survey on 10 experts. The questionnaire survey was conducted from June 24, 2022 to July 8, 2022. Ten questionnaires were sent to the survey subjects consisting of 10 sewer experts including four university professors, three researchers at the research institute of Public Works Department in Seoul, and three professional engineers at consulting firms by e-mail, and a total of 10 questionnaires were collected and put into analysis.

Preference Ranking Organization Methods for Enrichment Evaluation

PROMETHEE (Preference Ranking Organization Methods for Enrichment Evaluation) was developed by Brans & Vincke (1985) to derive priorities between alternatives using the preference function for each criterion and the concept of preference leaving flow and entering flow based on the outranking concept (Brans & Vincke 1985; Brans *et al.* 1986). This method is a relatively new set of multi-attribute decision methods. In 1982, PROMETHEE I (partial ranking) and PROMETHEE II (complete ranking) attracted attention from academia at a conference on auxiliary decision-making tools held at Laval University, Canada. Over the next several years, Professor Brans and Mareschal continued to refine and perfect a series of PROMETHEE techniques, including PROMETHEE III (ranking based on intervals) and PROMETHEE IV (continuous case). A series of algorithms such as designation and continuous case were introduced successively. And the visualized GAIA interactive module proposed in 1988 provided a good graphical representation to support this technique (Mareschal & Brans 1988). In the 1990s, the duo further developed two excellent extension methods: PROMETHEE V (segmentation constraints) and PROMETHEE VI (representation of the human brain). These methods have unique application situations, among which PROMETHEE I and PROMETHEE II are still the most widely used classical methods. The procedure of PROMETHEE I and II is explained as follows:

Step 1: Determination of deviations on the basis of pairwise comparisons.

Define a set of alternatives $A = \{a_i | i = 1, 2, \cdots, n\}$ to the multi-attribute decision problem and suppose that $f_k(a_i)$ represents the evaluation value of the alternative a_i on the considered criterion (f_k). A specific preference function $F(a_i, a_j)$ needs to be defined that translates the deviation between the evaluations of two alternatives (a_i and a_j) on a particular criterion (f_k) into a preference degree ranging from 0 to 1. This preference function is a non-decreasing function of the observed deviation (d) between the evaluations of the alternatives on the considered criterion ($f_k(a_i) - f_k(a_j)$), as shown in

Equations (2) and (3).

$$d = f_k(a_i) - f_k(a_j) \tag{2}$$

$$F(a_i, a_j) = P(f_k(a_i) - f_k(a_j)) \tag{3}$$

Step 2: Application of the preference function corresponding to an index.

Brans & Vincke (1985) proposed six types of preference functions commonly used by decision-makers, which are: usual criterion, U-shape (quasi-criterion), V-shape (criterion with linear preference), level criterion, linear (criterion with linear preference and indifference area), and Gaussian criterion.

Step 3: Calculation of the overall preference index.

The overall preference index $\pi(a_i, a_j)$ can be computed, taking all the criteria into account (see Equation (4)).

$$\pi(a_i, a_j) = \sum_{l=1, i \neq j}^{k} w_l \cdot P_l(a_i, a_j) \quad i, j = 1, 2, 3, \cdots, n, \quad l = 1, 2, 3, \cdots, k \tag{4}$$

where w_l denotes the weight for each criterion, and $\sum_{l=1}^{k} w_l = 1$. In this study, the AHP is used to determine the weight of each criterion (w_l).

Step 4: Calculation of leaving flow and entering flow.

$$\emptyset^+(a_i) = \frac{1}{n-1} \sum_{j=1, j \neq i}^{n} \pi(a_i, a_j) = \frac{1}{n-1} \sum_{l=1}^{k} \sum_{j=1, j \neq i}^{n} w_l \cdot P_l(a_i, a_j) \tag{5}$$

$$\emptyset^-(a_i) = \frac{1}{n-1} \sum_{j=1, j \neq i}^{n} \pi(a_j, a_i) = \frac{1}{n-1} \sum_{l=1}^{k} \sum_{j=1, j \neq i}^{n} w_l \cdot P_l(a_k, a_i) \tag{6}$$

where $\emptyset^+(a_i)$ and $\emptyset^-(a_i)$ denote the leaving and entering flow, respectively, for each alternative.

Step 5: Calculation of net outranking flow.

$$\emptyset(a_i) = \emptyset^+(a_i) - \emptyset^-(a_i) \tag{7}$$

where $\emptyset(a_i)$ denotes the net flow for each alternative.

RESULTS AND DISCUSSION

Demonstration of the AHP

As the opinions of different members of the sewer expert group are consulted, the geometric mean is calculated to combine the evaluation (as suggested by Saaty (2001)). Table 4 shows the results of the weight distribution.

The order of the weights of each criterion obtained by Zhang *et al.* (2022) through the AHP is robustness, rapidity, resourcefulness, and redundancy, whereas the local weight rankings of the reintegrated criteria in this study are resistance, reliability, response and recovery, and redundancy. In addition, the global weight results of the sub-criteria show that the sub-criterion B of reliability is the highest, followed by A1 (good pipelines length ratio), C1 (adequacy of the flow capacity of the bypass pipeline), A2 (percentage of pipelines length that cannot be driven by CCTV), and A3 (traffic complexity). It is found that the sewer experts regard the measures against the urban flooding related to the external river flooding as the most important when the resilience of sewer pipe networks is to be evaluated. It seems because there is a possibility that more damage is foreseen from river flooding than sewer flooding by itself.

Demonstration of PROMETHEE

In this stage, weights and minimum/maximum preferred direction of sub-criteria in Table 4 were prepared to calculate via PROMETHEE. This study selects the sewer networks in four small blocks of drainage area in Seoul, South Korea as the resilience evaluation object. The valuations of the 'A3 (traffic complexity)', 'D1 (allowable restoration time)', 'D2 (accessibility)',

Table 4 | Local weights of resilience indicator 4Rs and global weights of sub-criteria and their rankings

Criteria	Local weights of criteria (a)	Sub-criteria	Local weights of sub-criteria (b)	Global weights of sub-criteria (a * b)	Ranking
Resistance	0.3585	A1 (max)	0.6212	0.2227	2
		A2 (min)	0.2234	0.0801	4
		A3 (min)	0.1553	0.0557	5
Reliability	0.3106	B (min)	1.0000	0.3106	1
Redundancy	0.1564	C1 (max)	0.8079	0.1264	3
		C2 (max)	0.1921	0.0300	8
Response and recovery	0.1745	D1 (min)	0.2571	0.0449	6
		D2 (max)	0.1087	0.0190	11
		D3 (max)	0.0773	0.0135	12
		D4 (max)	0.0568	0.0099	13
		D5 (max)	0.1545	0.0270	9
		D6 (max)	0.1101	0.0192	10
		D7 (max)	0.1846	0.0322	7
		D8 (max)	0.0509	0.0089	14

'D6 (past expenditure to avoid the major accidents)', 'D7 (future budget for restoration)', and 'D8 (technology availability)' are difficult to quantify and their valuations are based upon brainstorm sessions and empirical analysis within the evaluators' team. For this purpose, a 10-point qualitative scale ranging from 1 (very low) to 10 (very high) has been applied (refer to Table 5). For the four qualitative criteria 'C2 (presence/absence of sewage storage facility)', 'D3 (department cooperation plan)', 'D4 (training practice according to the restoration plan)', 'D5 (resource acquisition plan and mobilization capability)', their valuations were based on empirical analysis and social surveys within the evaluators' team. For the four quantitative criteria 'A1(good pipelines length ratio)', 'A2 (percentage of pipelines length that cannot be driven by CCTV)', 'B(reliability)', 'C1 (adequacy of the flow capacity of the bypass pipeline)', their valuations can be obtained directly from the 2030 Master Plan on Sewerage Rehabilitation (Seoul 2018). Among them, the five items considered in determining 'B(reliability)' are the ratio of pipelines with insufficient sewer capacity (40 points), the length of the replaced or repaired pipelines per person (15 points), the pumping capacities at pump stations (15 points), the number of pumping stations (15 points), and the area of reservoirs (15 points), which have a total of 100 points. After each item obtains the maximum and minimum values within the evaluation range, the scores will be allocated proportionally, and the comprehensive results are prioritized from the upper score to the lower score.

The calculation formula is detailed in the notes in Table 6. With this information, the evaluation matrix is constructed.

Table 5 | A 10-point scale proposed for some subdivision factors of the evaluation object

10-Point scale	A3: Traffic complexity (number of intersections/ha)	D1: Allowable restoration time (days)	D2: Accessibility (average buried depth (m))	D6: Past expenditure to avoid the major accidents (one million won/km)	D7: Future budget for restoration (%)	D8: Technology availability (%)
1	>0.9	>7 days	>2.0	<10	10	10
2	0.8–0.9	6–7 days	1.8–2.0	10–15	20	20
3	0.7–0.8	5–6 days	1.6–1.8	15–20	30	30
4	0.6–0.7	4–5 days	1.4–1.6	20–25	40	40
5	0.5–0.6	3–4 days	1.2–1.4	25–30	50	50
6	0.4–0.5	2–3 days	1.0–1.2	30–35	60	60
7	0.3–0.4	1–2 days	0.8–1.0	35–40	70	70
8	0.2–0.3	0.5–1 day	0.6–0.8	40–45	80	80
9	0.1–0.2	0.25–0.5 day	0.4–0.6	45–50	90	90
10	<0.1	<0.25 day	<0.6	>50	100	100

Table 6 | Sample entries of four alternatives in the evaluation project using the PROMETHEE method

Criteria	Sub-criteria	Alternative Block I	Block II	Block III	Block IV
Resistance	A1 (max)[a]	65.38%	52.77%	72.36%	52.78%
	A2 (min)[b]	2.76%	18.56%	0.00%	1.55%
	A3 (max)	9	6	10	9
Reliability	B (min)[c]	33.10%	24.52%	10.28%	22.43%
Redundancy	C1 (max)[d]	84.62%	97.24%	77.64%	97.23%
	C2 (max)	Y	N	N	N
Response and recovery	D1 (min)	8	8	8	7
	D2 (max)	7	6	6	8
	D3 (max)	Y	Y	Y	Y
	D4 (max)	Y	Y	Y	Y
	D5 (max)	Y	Y	Y	Y
	D6 (max)	10	5	1	7
	D7 (max)[e]	8	8	8	8
	D8 (max)[f]	6	6	6	6

[a]Good pipelines length ratio = (length of entire pipelines – length of old defective pipelines)/length of entire pipelines.
[b]Percentage of pipelines length that cannot be driven by CCTV = length of pipelines that cannot be driven by CCTV/length of entire pipelines.
[c]B(reliability) is obtained directly from the 2030 Master Plan on Sewerage Rehabilitation (Seoul 2018).
[d]Adequacy of the flow capacity of the bypass pipeline = length of pipelines with sufficient hydraulic capacity/length of entire pipelines.
[e]Assuming that the target year of the sewerage rehabilitation plan is 2020, the assurance rate of the future budget for restoration is 90%, 2025 is 80%, and 2030 is 70%. The target year of the sewerage remediation rehabilitation plan of the four alternative blocks in this study is 2025, so the assurance rate of the future budget for restoration is assumed to be 80%.
[f]It is assumed that the technical availability of each small block is the same 60% level, due to the fact that in the event of a ground subsidence or flooding accident, the construction must be dominated by manpower and equipment-intensive operations.

Subsequently, for each criterion, a specific preference function is selected and parameter values are defined to compute the degree of preference associated with the best alternative in the pairwise comparison process (Brans & Mareschal 1994). For quantitative assessments, the PROMETHEE guidelines advise applying a linear preference function (V-shape). The V-shape parameter is set within the range of the evaluation index by using the difference between the maximum value and the minimum value of the evaluation index. For qualitative assessments, the usual criterion or the level criterion can be selected. Among them, the preference degree of the traditional level function has only three values of 0, 0.5, and 1. However, some sample data have a large number of qualitative index levels, and the large difference in the number of index levels and the number of preference degrees of the level function can lead to deviations in the results. So, in this case, two more stages are added to the level-type preference function, forming a new preference function-the multi-level preference function, and the preference degrees are divided into five values, 0, 0.25, 0.5, 0.75, and 1. Therefore, the preference functions and thresholds for each evaluation criterion are determined as shown in Table 7.

After the determination of the evaluation matrix and the preference functions, the positive (Φ^+), negative (Φ^-) flows, and the net flow (Φ) values obtained from this evaluation are displayed in Table 8.

Based on PROMETHEE II (complete ranking), the results relate only to net flows and there is no incomparable situation. From the calculation results, the small blocks of selected drainage areas in Seoul rankings appear in the order of Block III, Block IV, Block I, and Block II. This means that Block III shows best resilience, while Block II shows the worst. So, in the future, when the government formulates the sewer network rehabilitation plan, it can give priority to investing in areas with poor resilience.

Sensitivity analysis

The sensitivity analysis has been performed, and the resulting ‘stability intervals’ values are given in Table 9. For each criterion, a stability interval was computed. It indicates the range in which the weights of that criterion can be modified without affecting the PROMETHEE II complete ranking, provided that the relative weights of other criteria are not modified. From the result of the sensitivity analysis, it is clear that ‘presence/absence of sewage storage facility (C2)’ has the greatest impact on the complete ranking. It shows that if the weight of C2 changes in the range of 0–0.0422, the ranking does not

Table 7 | Definition of evaluation criteria

Evaluation criteria				
Criteria	**Sub-criteria**	**Unit(s)**	**Weight**	**Performance function**
Resistance	A1 (max)	%	0.2227	V-shape: $F_1(d) = \begin{cases} \frac{d}{0.1959}, & d \leq 0.1959 \\ 1, & d > 0.1959 \end{cases}$
	A2 (min)	%	0.0801	V-shape: $F_2(d) = \begin{cases} \frac{d}{0.1856}, & d \leq 0.1856 \\ 1, & d > 0.1856 \end{cases}$
	A3 (max)	10-Point scale	0.0557	Deformation of level: $F_3(d) = \begin{cases} 0, & d \leq 0.5 \\ 0.25, & 0.5 < d \leq 1.5 \\ 0.5, & 1.5 < d \leq 2.5 \\ 0.75, & 2.5 < d \leq 3.5 \\ 1, & d > 3.5 \end{cases}$
Reliability	B (min)	%	0.3106	V-shape: $F_4(d) = \begin{cases} \frac{d}{0.2282}, & d \leq 0.2282 \\ 1, & d > 0.2282 \end{cases}$
Redundancy	C1 (max)	%	0.1264	V-shape: $F_5(d) = \begin{cases} \frac{d}{0.1960}, & d \leq 0.1960 \\ 1, & d > 0.1960 \end{cases}$
	C2 (max)	(Y/N)	0.0300	Usual: $F_6(d) = \begin{cases} 0, & d \leq 0 \\ 1, & d > 0 \end{cases}$
Response and recovery	D1 (min)	10-Point scale	0.0449	Deformation of level: $F_7(d) = \begin{cases} 0, & d \leq 0.5 \\ 0.25, & 0.5 < d \leq 1.5 \\ 0.5, & 1.5 < d \leq 2.5 \\ 0.75, & 2.5 < d \leq 3.5 \\ 1, & d > 3.5 \end{cases}$
	D2 (max)	10-Point scale	0.0190	Deformation of level: $F_8(d) = \begin{cases} 0, & d \leq 0.5 \\ 0.25, & 0.5 < d \leq 1.5 \\ 0.5, & 1.5 < d \leq 2.5 \\ 0.75, & 2.5 < d \leq 3.5 \\ 1, & d > 3.5 \end{cases}$
	D3 (max)	(Y/N)	0.0135	Usual: $F_9(d) = \begin{cases} 0, & d \leq 0 \\ 1, & d > 0 \end{cases}$
	D4 (max)	(Y/N)	0.0099	Usual: $F_{10}(d) = \begin{cases} 0, & d \leq 0 \\ 1, & d > 0 \end{cases}$
	D5 (max)	(Y/N)	0.0270	Usual: $F_{11}(d) = \begin{cases} 0, & d \leq 0 \\ 1, & d > 0 \end{cases}$
	D6 (max)	10-Point scale	0.0192	Deformation of level: $F_{12}(d) = \begin{cases} 0, & d \leq 0.5 \\ 0.25, & 0.5 < d \leq 1.5 \\ 0.5, & 1.5 < d \leq 2.5 \\ 0.75, & 2.5 < d \leq 3.5 \\ 1, & d > 3.5 \end{cases}$
	D7 (max)	10-Point scale	0.0322	Deformation of level: $F_{13}(d) = \begin{cases} 0, & d \leq 0.5 \\ 0.25, & 0.5 < d \leq 1.5 \\ 0.5, & 1.5 < d \leq 2.5 \\ 0.75, & 2.5 < d \leq 3.5 \\ 1, & d > 3.5 \end{cases}$
	D8 (max)	10-Point scale	0.0089	Deformation of level: $F_{14}(d) = \begin{cases} 0, & d \leq 0.5 \\ 0.25, & 0.5 < d \leq 1.5 \\ 0.5, & 1.5 < d \leq 2.5 \\ 0.75, & 2.5 < d \leq 3.5 \\ 1, & d > 3.5 \end{cases}$

Table 8 | The results of preference index and flow for PROMETHEE II

π	Block I	Block II	Block III	Block IV
Block I	–	0.3073	0.0990	0.1989
Block II	0.1981	–	0.1456	0.0113
Block III	0.4158	0.5523	–	0.4198
Block IV	0.2365	0.1628	0.1550	–
Leaving flow	0.2017	0.1183	0.4626	0.1848
Entering flow	0.1215	0.1461	0.0571	0.0900
Net flow	0.0803	−0.0277	0.4056	0.0948
Ranking order of resilience index	3	4	1	2

Table 9 | Stability intervals

		Interval	
Sub-criteria	**Initial weight**	**Min**	**Max**
A1: Good pipelines length ratio	0.2227	0.0565	0.2406
A2: Percentage of pipelines length that cannot be driven by CCTV	0.0801	0	Infinity
A3: Traffic complexity	0.0557	0	Infinity
B: Reliability	0.3106	0.2828	0.4993
C1: Adequacy of the flow capacity of the bypass pipeline	0.1264	0.1052	0.2571
C2: Presence/absence of sewage storage facility	0.0300	0	0.0422
D1: Allowable restoration time	0.0449	0	0.1124
D2: Accessibility	0.0190	0	0.3842
D3: Department cooperation plan	0.0135	0	Infinity
D4: Training practice according to the restoration plan	0.0099	0	Infinity
D5: Resource acquisition plan and mobilization capability	0.0270	0	Infinity
D6: Past expenditure to avoid the major accidents	0.0192	0	0.0456
D7: Future budget for restoration	0.0322	0	Infinity
D8: Technology availability	0.0089	0	Infinity

change. The seven sub-criteria of ‘Percentage of pipelines length that cannot be driven by CCTV (A2)’, ‘traffic complexity (A3)’, ‘department cooperation plan (D3)’, ‘training practice according to the restoration plan (D4)’, ‘resource acquisition plan and mobilization capability (D5)’, ‘future budget for restoration (D7)’, and ‘technology availability(D8)’ have the least impact on the complete ranking, and the weight value changes within any range without affecting the ranking result.

In addition, when the weight values of the factors that have a greater impact on the final ranking change outside the stable interval, the final ranking change results are shown in Table 10. For example, when the reliability weight value is on the left side of the stable interval, the ranking will change from Block III, Block IV, Block I, and Block II when the weight value is in the stable interval to Block II, Block IV, Block I, and Block III, when it is on the right side of the stable interval, it will become Block IV, Block III, Block I, and Block II.

CONCLUSIONS

The proposed assessment of sewer network resilience ranking in this study aims to contribute to the rectification of sewer networks and the formulation of disaster prevention policies such as urban flood and ground collapse through the relative resilience ranking calculated by multicriteria decision-making techniques. The AHP method and PROMETHEE family of methods are well-established MCDM techniques. The selection of criteria can also be an important issue in such a selection

Table 10 | Rank changes when weights change outside the stable interval

Sub-criteria	Weight value change range	Ranking
A1: Good pipelines length ratio	[0, 0.0564]	Block IV > Block III > Block I > Block II
	[0.2407, 1]	Block II > Block IV > Block I > Block III
B: Reliability	[0, 0.2827]	Block II > Block IV > Block I > Block III
	[0.4994, 1]	Block IV> Block III> Block I> Block II
C1: Adequacy of the flow capacity of the bypass pipeline	[0, 0.1051]	Block II > Block IV > Block I > Block III
	[0.2572, 0.3535]	Block IV> Block III> Block I> Block II
	[0.3536, 0.4135]	Block IV> Block III> Block II> Block I
	[0.4136, 0.6026]	Block IV> Block II> Block III> Block I
	[0.6027, 1]	Block III> Block II > Block IV > Block I
C2: Presence/absence of sewage storage facility	[0.0423, 0.2449]	Block II > Block IV > Block I > Block III
	[0.2450, 1]	Block I > Block IV > Block II > Block III
D1: Allowable restoration time	[0.1125, 0.4187]	Block II > Block IV > Block I > Block III
	[0.4188, 1]	Block II > Block III > Block I > Block IV
D2: Accessibility	[0.3843, 0. 7321]	Block III > Block IV> Block II > Block I
	[0.7322, 1]	Block II > Block IV > Block III > Block I
D6: Past expenditure to avoid the major accidents	[0.0457, 0.2101]	Block II > Block IV > Block I > Block III
	[0.2102, 0.2884]	Block I > Block IV > Block II > Block III
	[0.2885, 0.4524]	Block I > Block IV > Block III > Block II
	[0.4525, 1]	Block I > Block III > Block IV > Block II

process, and the case of this research can provide a recommendation for other researchers. That is, by considering the various evaluation issues that affect the resilience of the sewer networks, an integrated approach of AHP and PROMETHEE for evaluating the relative resilience of each small block is proposed.

The research results showed that starting from the four issues considered in the prioritization of resilience and selecting index elements corresponding to resistance, reliability, redundancy, response, and recovery can be selected to better characterize the resilience of the sewer network. After determining the 14 sub-criteria, the AHP was used to obtain the importance ranking of each sub-criterion, among which the importance of the sub-criteria of reliability (B), good pipelines length ratio (A1), and the adequacy of the flow capacity of the bypass pipeline (C1) is relatively high. Based on the complete ranking method of PROMETHEE II, the resilience of the four small blocks in the selected drainage areas in Seoul are Block III, Block IV, Block I, and Block II in order from high to low.

Compared with the previous research by Zhang *et al.* (2022), this study added the consideration of urban flood from the perspective of ground collapse. Many studies on resilience of sewer networks lack specificity, and this study quantifies the resilience for specific events (ground collapse and urban flood) and allows the comparison of resilience in different regions, urging new investment and improved operations in regions with weak resilience. It will help designers to specify index and quantify the resilience of the sewer networks. In addition, this paper adapts to qualitative indicators with more levels by improving the level-type preference function, which is more in line with the actual situation. The analysis process of using the PROMETHEE method to rank the resilience of the sewer networks is to set the preference function and parameters according to the subjectivity of the evaluators. Therefore, to ensure the reliability of the analysis, it is necessary to continuously collect the opinions of experts to improve the setting of the preference function and parameters.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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