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Diagnosis and Prioritization of Vulnerable Areas of Urban Ecosystem Regulation Services

Dongwoo Lee [1], Kyushik Oh [2,*] and Jungeun Suh [2]

[1] Research Institute of Spatial Planning & Policy, Hanyang University, Seoul 04763, Korea
[2] Department of Urban Planning and Engineering, Hanyang University, Seoul 04763, Korea
* Correspondence: ksoh@hanyang.ac.kr

Abstract: Rapid urbanization and population growth have led to drastic degradation of urban ecosystem regulation services (ERS). Urgently needed is the identification of vulnerable areas where ERS are being intensively deteriorated, and preparation of measures to respond to them. This study developed a framework to diagnose and prioritize vulnerable areas of urban ERS. The vulnerability of urban ERS that include carbon storage capacity, flood-risk mitigation capacity, and heat stress reduction capacity was diagnosed with a resolution of 100 m × 100 m grid. Priority areas to improve urban ERS were delineated using hot spot analysis, and the diagnosed results of the urban ERS were categorized by eight combination types including exposure, sensitivity, and adaptability. The spatial and societal problems included in the priority areas were further investigated by overlaying hot spot areas with eight combination maps. Finally, spatial management measures for the priority areas were suggested based on the analysis results. From the detailed diagnosis results of the vulnerable ERS areas, this study provides a framework to link the concept of ERS vulnerability with urban planning. Furthermore, effective spatial planning guidelines can be prepared to improve urban ERS by spatially delineating priority areas to improve urban ERS vulnerability.

Keywords: urban ecosystem regulation services; vulnerability diagnosis; hotspot analysis; spatial combinations; urban planning

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1. Introduction

The idea of ecosystem service (ES) emerged in the 1970s, and definitions and meanings of ES have been developed through literature research [1,2] to the 1990s. One of the most widely used definitions was established by millennium ecosystem assessment [3], which states that ES includes the benefits that humans receive from nature for human health and wellbeing [4,5]. The functions of ES are categorized as "provisioning, regulating, cultural, and supporting". Based on this conceptual framework, research has been mainly conducted by focusing on quantifying the social and economic value of ES, trade-offs among functions of ES, and mapping methods [6]. Based on scientific research results, there have been continuous attempts to apply the concept of ES as a planning and design tool to achieve sustainability [7–9].

In particular, ecosystem regulating services (ERS), including purification of air and water, climate regulation, carbon sequestration, and runoff mitigation and flood control, serve to promote safe environments for citizens [10–12]. ERS are often useful in improving environmental quality of urban spaces while mitigating unwanted negative impacts due to human development. Therefore, efforts are increasing worldwide to improve the multiple functions of ERS using urban planning [13,14]. Despite these efforts however, ERS are often ignored or undervalued in the planning process because most results of studies related to urban ERS assessment have been mainly focused on quantitative "explanations" of current urban ERS conditions rather than practical "applications" in urban planning [14,15].

In order to enhance ERS through urban planning, areas that have high vulnerability should be spatially delineated [16,17]. Vulnerability assessment studies in the field of ecology have been relatively recently launched compared with other social science studies [18]. Moreover, the definition of ecosystem vulnerability is applied differently according to the purpose of each study and generally, it is defined as the degree of experiencing harm due to exposure to hazards [19]. The conceptual ecosystem vulnerability diagnosis model consisting of exposure, sensitivity, and capacity to recover was developed by Van Straalen [20]. This model has also been applied as a basic analysis framework for the International Panel of Climate Change (IPCC) vulnerability assessment. Applying this conceptual model, studies on ecosystem vulnerability have been mainly diagnosed on the regional scale for specific systems such as river basins, coal fields, watersheds, wetlands, and mountain regions [18]. Through such studies, vulnerable areas of ecosystem degradation [21,22] and the potential impact on ecosystems by land use changes including urban development, restoration projects, etc. [23] have been analyzed. Recently, attempts to involve social and economic factors in ecosystem vulnerability diagnosis have been increasing. However, vulnerability assessments have still mainly focused on natural and physical factors, while population and social infrastructure have received little consideration [24,25]. Furthermore, most studies have primarily focused on the vulnerability of natural ecosystems at the regional scale (low resolution), and thus it remains difficult to specify as to which spaces are at risk in entire urban spaces [26]. Such limitations make it less effective to apply vulnerability assessment results directly to urban planning.

On the other hand, identifying priority areas to improve environmental quality in urban planning has been an important research topic for decades. The spatial occurrences and frequency of environmental problems, or accessibility to environmental goods and services, have been mainly analyzed to identify priority areas. Traditionally, ES research focused on the investigation of priority areas for conservation [27,28]. In recent years, the provision of green infrastructure (GI) to improve existing ERS has been widely conducted in the urban planning process [14,29,30], and research to identify priority areas for GI supply to mitigate flood risk and urban heat islands is also being actively conducted [31–34]. Such efforts stem from the fact that environmental inequality for citizens has a direct negative effect on the health as well as safety of citizens [35,36]. Thus, more efforts are being made to supply environmental goods and services to the identified priority areas. In this regard, spatial and societal problems in priority areas should be investigated to ensure the effectiveness of the improvements [37].

As mentioned above, the importance of ERS is increasing as a planning element to achieve the sustainability of cities. Due to the drastic degradation of urban ERS by rapid urbanization, urgently needed is the identification of priority areas where ERS are being intensively deteriorated. Systematic and concrete investigation of spatial and societal problems in priority areas is also necessary in order to establish effective improvements. However, studies that diagnose and prioritize vulnerable areas of ERS in detail for entire urban areas are still insufficient.

The purpose of this study was to develop a framework to diagnose and prioritize vulnerable areas of urban ERS that can be utilized in urban planning. To achieve this, a framework of vulnerability diagnosis of urban ERS was established, and the priority areas needing improvement were delineated by hot spot analysis. Spatial and societal problems were also investigated by combining the urban ERS vulnerability diagnosis results to determine why the priority areas have high vulnerability. Finally, this study suggests future spatial management measures to reduce ERS vulnerability in priority areas.

2. Materials and Methods

This study consists of four parts: (1) definition of urban ERS vulnerability concepts and establishment of an urban ERS vulnerability diagnosis framework, (2) diagnosis of urban ERS vulnerability, (3) prioritization of areas of high vulnerability, and (4) suggestions for spatial management measures for these areas. The detailed process is presented in

Figure 1. Among the urban ERS, this study selected carbon storage capacity (CSC), flood mitigation capacity (FMC), and heat stress reduction capacity (HSRC) as urban ERS indices because they have been emphasized through national environmental research under the direction of the Korea Ministry of Environment [38].

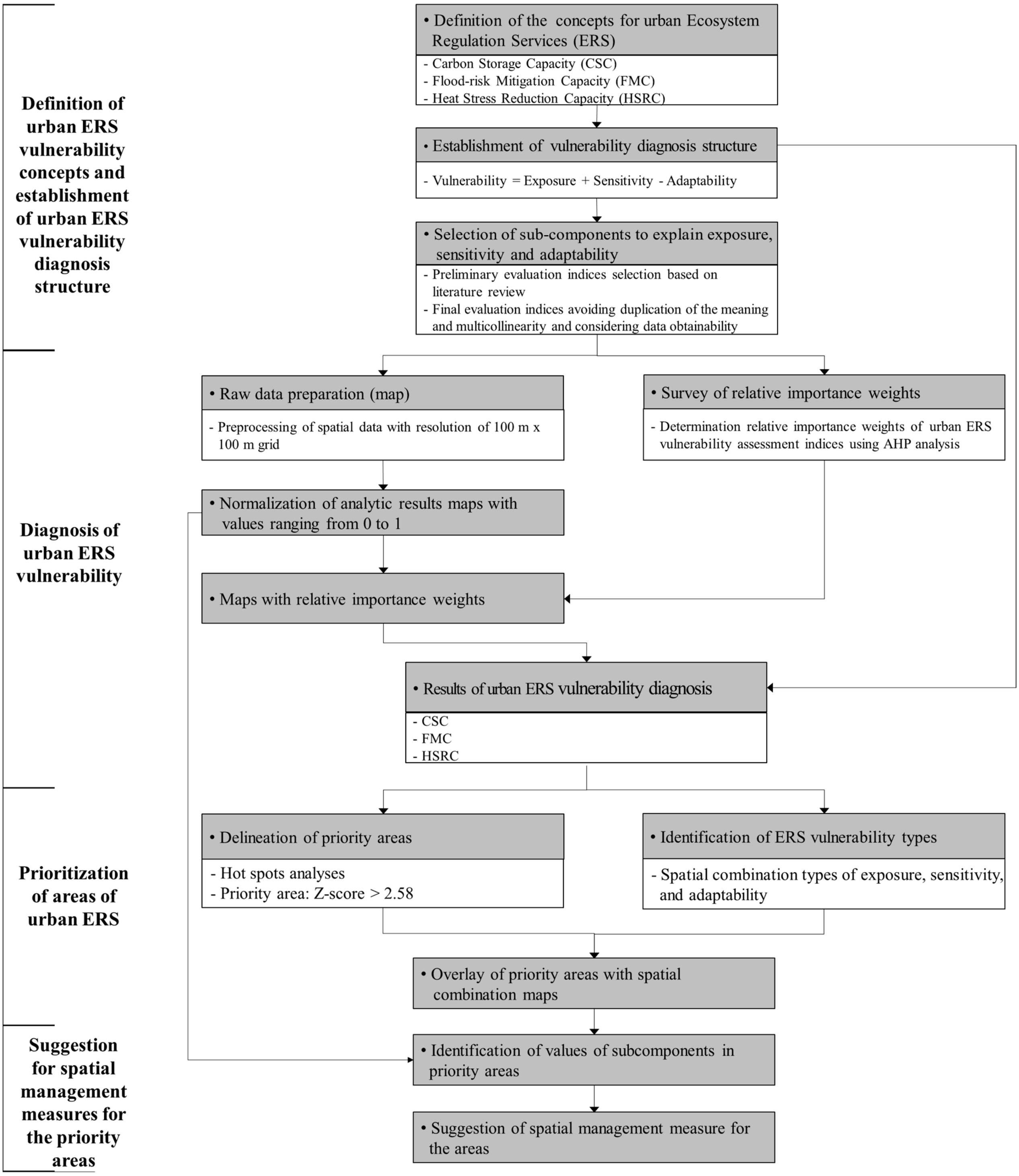

Figure 1. Framework to diagnose and prioritize vulnerable areas of urban ERS.

2.1. The Study Area

This study was conducted in the city of Suwon located in South Korea. Suwon is a basin-type city with a population of 1.19 million and a total area of 115 km^2 (Figure 2). Urbanization has resulted in a population increase of about 100,000 people over the last 10 years. At the same time, the natural land cover, including forests and agroforestry, has decreased by about 9 km^2, while the urbanized area has increased by about 6 km^2. A decrease in natural land cover has resulted in a reduction in carbon storage. Moreover, the continuous expansion of the urbanized area has contributed to the exacerbation of heat islands and extreme temperatures. Furthermore, over the past decade, immense damage has been caused by torrential rains that have been occurring year after year, and thus active measures to restore ERSs are urgently needed. The military facility areas located in the southern area were excluded from the analysis due to legal limitations prohibiting access.

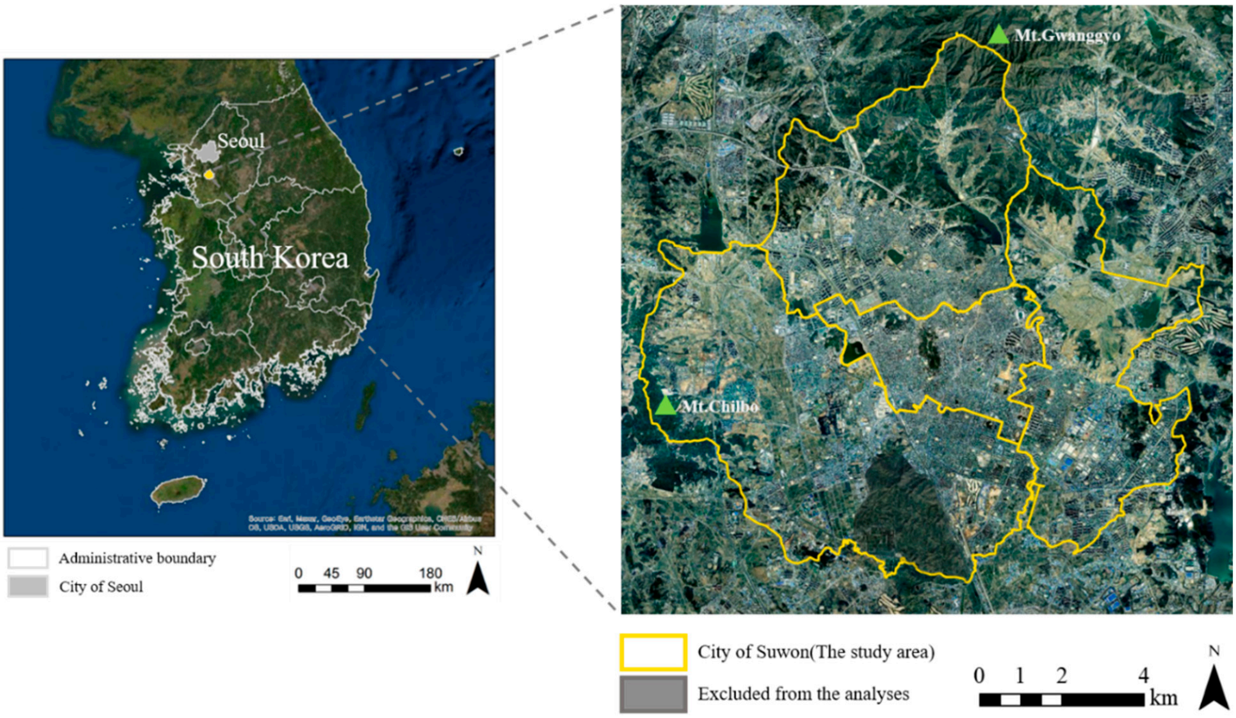

Figure 2. The study area: Suwon, South Korea.

2.2. Definition of Urban ERS Vulnerability Concepts and Establishment of the Urban ERS Vulnerability Diagnose Framework

Vulnerability of urban ecosystems has been defined as the "potential for loss or harm" [19], "the degree to which system, subsystem, or system components are likely to experience harm due to exposure to hazards" [39,40], "the possibility that a particular space will be damaged by external pressures" [21,22], "the possibility that external pressures will cause negative changes in natural, human, economic and social factors" [18,41], and "the side effects of natural disasters and environmental changes" [42]. Based on these ideas of vulnerability assessment, this study defined the vulnerability of ERS in the urban area as "the potential for negative changes in urban space components due to exposure". As mentioned, the three ERS indices that are currently emphasized by the Korea Ministry of Environment were selected for this study. Based on the definition of ERS vulnerability, the vulnerability of CSC, FMC, and HSRC are defined in Table 1.

Table 1. Vulnerability concepts for CSC, FMC, and HSRC.

	CSC	**FMC**	**HSRC**
Definitions	Areas with high potential to reduce carbon storage capacity in urban spaces	Areas where flooding in urban space may generate casualties and property damage	Areas where the deterioration of urban thermal environment can cause human health problems

In line with the IPCC assessment system for evaluating vulnerability assessment [43], this study employed a basic analysis structure based on the function of exposure, sensitivity, and adaptability, as shown in the following Equation (1).

$$\text{Vulnerability} = \text{Exposure} + \text{Sensitivity} - \text{Adaptability} \tag{1}$$

Exposure is a term that describes the negative impact a place or environment is subjected to, such as interference from outside a specific space, climate change, environmental change, etc. Meanwhile, sensitivity refers to the factors that render humans vulnerable to negative impacts, the degree to which humans react to stimuli, and the conditions that may leave humans at risk of such adverse effects. On the other hand, adaptability is defined as the capability to adjust to or resist potential harm, withstand outside interference, and continue functioning [22,42,44]. This study defines ERS exposure as "factors that cause direct and indirect negative impacts on urban ecosystems", sensitivity as "factors that respond easily (or quickly, or significantly) to exposure", and adaptability as "factors that resist exposure and reduce or cope with potential impacts". The concepts of exposure, sensitivity, and adaptability of urban ERS indices are outlined in Table 2.

Table 2. Three dimensions for urban ERS vulnerability diagnoses.

	CSC	**FMC**	**HSRC**
Exposure	Areas exposed to risk of carbon storage capacity loss	Areas exposed to flooding risk	Areas exposed to thermal environment deterioration
Sensitivity	Areas prone to carbon storage capacity loss	Areas prone to flood reaction	Areas prone to reaction from thermal environment deterioration
Adaptability	Areas where degraded carbon storage capacity can be restored or managed	Areas where flooding can be mitigated or managed	Areas where the deteriorated thermal environment can be restored or managed

Based on previous studies, subcomponents that elaborate upon each dimension of exposure, sensitivity, and adaptability per urban ERS index were further developed. The subcomponents were selected, and duplication of the meanings and multi-collinearity were avoided while considering data obtainability. The value ranges of the subcomponents were determined considering absolute minimum and maximum values of subcomponents, references or threshold values, and data distribution of cities similar to the study area. The selected subcomponents and their ranges are presented in Tables 3–5.

Table 3. Subcomponents for the CSC vulnerability diagnosis.

Dimensions	Subcomponents	Units	References	Scale (Min–Max)
Exposure	Vegetation cover ratio (inversed value)	%	[45,46]	0–100%
	Impervious surface area ratio	%	[47,48]	0–100%
	Ongoing and proposed development projects *	-	[47,48]	0–1
Sensitivity	Soil erosion potential	Class	[49,50]	0–3 grade
	Vegetation age class (aged vegetation)	Class	[46,51]	1–9 grade
	Long-term unexecuted facility area ** ratio	%	[52,53]	0–100%
Adaptability	Green space area ratio	%	[46,48]	0–100%
	Number of street trees	Number	[54,55]	0–132
	Budget ratio of greening and ecosystem restoration projects	%	[46,56,57]	1.07–5.74%

* Subcomponents for CSC exposure seem to be neutral in value. However, human-induced urban developments in the study area often deteriorate ecological value and the functionality of the areas substantially. Therefore, the exposure aspect for CSC in this study implies adverse impacts on urban ERS. ** Long-term unexecuted facility area: Areas designated by local governments for use as parks and green spaces but that have not been implemented for a long time. Most of them are left as vacant areas filled with trees and grassland. The areas are likely to be changed to built-up areas, and if developed, they can cause carbon storage reduction due to the large amount of soil loss.

Table 4. Subcomponents for the FMC vulnerability diagnosis.

Dimensions	Subcomponents	Units	References	Scale (min-max)
Exposure	Number of days of heavy rainfall	Days	[58,59]	0–8 days
	Impervious surface area ratio	%	[58,59]	0–100%
	Annual flooding frequency	Times	[60,61]	0–8 times
Sensitivity	Lowland area	m	[62–64]	11.30–148.16 m
	Proximity to water body	m	[58,65]	0–100 m
	Population density	Persons/ha	[59,66]	0–2997 persons/ha
Adaptability	Flood treatment facility capacity	m^3/min	[58,59]	0–3000 m^3/min
	Green space area ratio	%	[63,65]	0–100%
	River improvement ratio	%	[60,67]	0–100%

Table 5. Subcomponents for the HSRC vulnerability diagnosis.

Dimensions	Subcomponents	Units	References	Scale (Min–Max)
Exposure	Number of days of extreme heat	Days	[68,69]	0–20 days
	Number of days of tropical nights	Days	[69,70]	0–18 days
	Impervious surface area ratio	%	[71–73]	0–100%
Sensitivity	Vulnerable age population ratio (age > 65 or age < 5)	%	[69,74]	0–100%
	Low-income population ratio	%	[69,74]	0–10.13%
	Health-related vulnerable population ratio (cardiovascular, respiratory and cerebrovascular)	%	[75,76]	0–15.78%
Adaptability	Accessibility to emergency medical and rescue facilities	m	[77,78]	0–2080 m
	Proximity to green spaces and water bodies	m	[79–81]	0–447.21 m
	Accessibility to cooling centers	m	[76,82]	0–300 m

2.3. Diagnosis of Urban ERS

To link the study results with urban planning, all analytic data and results were prepared with the resolution of a 100 m × 100 m grid (polygon), which is the same size as the reference grid resolution for land suitability assessment used for urban management planning in South Korea. The analytic methods to prepare subcomponents have been presented in Appendix A. Because the selected subcomponents have different measurement units and characteristics, the process of normalizing the subcomponents for the urban ERS vulnerability assessment is required. The normalization of subcomponents is calculated by using the Min-Max method (Equation (2)), and all of the subcomponents are converted to the same range (0–1).

$$I = \frac{X - min(X)}{max(X) - min(X)} \quad (2)$$

X: Raw score of the indicator, *min (X)*: Minimum value of the indicator, *max (X)*: Maximum value of the indicator.

Based on an expert survey conducted in 2021, the relative importance (weight) of the ERS vulnerability assessment index was determined via the use of an analytic hierarchy process (AHP) analysis. The questionnaire involved respondents consisting of 60 professionals who are engaged in urban planning and environment management, including 30 academics and researchers and 30 government officials in the city of Suwon. Detailed information on the expertise and responsibilities of the expert group and survey results are given in the Appendix B.

Having used the developed diagnosis method, subcomponents, and relative importance (weight), the vulnerability of urban ERSs was evaluated. Three subcomponents per dimension were used, which were normalized in the range of 0–1 so that exposure, sensitivity, and adaptability had a distribution ranging between 0–1. Thus, the vulnerability assessment results would have a range of −1 (if exposure and sensitivity are both 0 and adaptability is 1) to 2 (if exposure and sensitivity are both 1 and adaptability is 0).

2.4. Prioritization of Vulnerable Areas of Urban ERS and Suggestions for Spatial Managements

Hot spot analysis (Getis-Ord Gi*) [83] was applied to confirm where the areas of high vulnerability are spatially clustered (Equation (3)). Hot spot analysis could determine locations of statistically significant hot spots and cold spots. Thus, the urban ERS vulnerability results by Equation (1) were inputted as x_j in Equation (3) to identify spatial clustering of high or low urban ERS vulnerability. A Z score (Gi*) and *p*-value for each grid were returned by hot spot analysis. According to the Z score, when Z > 2.58, which corresponds to the 99% confidence level, it is regarded as a significant high value spatial clustering. In this study, areas with a Z score > 2.58 were determined as significant aggregations of high urban ERS vulnerability (priority areas).

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,\,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,\,j}}{S\sqrt{\frac{\left[n \sum_{j=1}^{n} w^2{}_{i,\,j} - \left(\sum_{j=1}^{n} w_{i,\,j}\right)^2\right]}{n-1}}} \tag{3}$$

$$\overline{X} = \frac{\sum_{j=1}^{n} x_j}{n},\ S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - \left(\overline{X}\right)^2}$$

where *xj* is the vulnerability value of grid *j*, and *wij* is the spatial weight between grid elements *i* and *j* (adjacent is 1, non-adjacent is 0), and n is the total number of grids.

From each urban ERS, eight combinations were derived from the upper and lower value maps of exposure, sensitivity, and adaptability results (Table 6). The resulting maps of eight combinations were then overlaid with the priority area maps.

Table 6. Combination of the vulnerability assessment results.

Type	Exposure	Sensitivity	Adaptability	Type	Exposure	Sensitivity	Adaptability
A	▲	▲	▲	E	▼	▲	▲
B	▲	▲	▼	F	▼	▲	▼
C	▲	▼	▲	G	▼	▼	▲
D	▲	▼	▼	H	▼	▼	▼

▲: Higher than mean, ▼: Lower than mean.

Overlaid results can provide a basic clue as to what kinds of dimensions should be mainly considered in improving priority areas. However, to establish concrete and practical measures to reduce urban ERS vulnerability in priority areas, subcomponents that increase ERS vulnerability should be further investigated. If the mean value of any subcomponents in priority areas became higher than the value corresponding to a Z score of 2.58 in the study area, the subcomponents were classified as major factors to cause high ERS vulnerability. Thus, normalized values corresponding to a Z score of 2.58 in the study area were confirmed for each subcomponent. The mean value of each subcomponent for each priority area was calculated, and the mean values were compared with normalized values corresponding to a Z score of 2.58 in the study area. For example, if the normalized value of the impervious surface ratio corresponding to a Z score of 2.58 in the study area was 0.63, and the mean value of impervious surface ratios in priority areas was 0.83, the impervious surface ratio turned out to be a major factor to increase urban ERS vulnerability. The spatial management strategies including land use management and GI installation in priority areas were then developed based on characteristics of the identified subcomponents.

3. Results

3.1. The Results of Urban ERS Diagnosis

The vulnerabilities of CSC, FMC, and HSRC were diagnosed with a resolution of 100 m × 100 m grid. CSC vulnerability showed a range of −0.63 to 1.05, with the mean value being 0.26. In addition, the vulnerability score distribution for FMC ranged from −0.56 to 0.87, with the mean value being 0.15. Finally, the vulnerability of HSRC ranged from −0.59 to 1.18, with the mean value being 0.15. Among the three kinds of dimensions, exposure was found to be a major dimension in increasing vulnerability of all urban ERS. On the other hand, sensitivity was relatively low compared with other dimensions. Such results mean that measures to reduce exposure should be prepared with priority to reduce urban ERS vulnerability in the study area (Table 7).

Table 7. Descriptive statistics of vulnerability diagnosis of urban ERS.

Indices	Vulnerability	Mean	Median	Min	Max.	S.D.
CSC	Exposure	0.47	0.49	0.04	1.00	0.18
	Sensitivity	0.07	0.00	0.00	0.60	0.09
	Adaptability	0.28	0.19	0.08	0.69	0.20
	Vulnerability	0.26	0.36	−0.63	1.05	0.32
FMC	Exposure	0.34	0.34	0.03	0.81	0.15
	Sensitivity	0.09	0.01	0.00	0.80	0.15
	Adaptability	0.28	0.26	0.00	0.70	0.18
	Vulnerability	0.15	0.19	−0.56	0.87	0.31
HSRC	Exposure	0.38	0.38	0.06	0.73	0.17
	Sensitivity	0.16	0.00	0.00	0.81	0.22
	Adaptability	0.39	0.43	0.00	0.88	0.20
	Vulnerability	0.15	0.15	−0.59	1.18	0.42

The study area is a basin type in which mountainous areas surround the city, with urban development occurring mainly in the center. This topographic condition had an influence on the vulnerability diagnosis results. The areas with relatively high exposure and the most negative impacts on urban ERS vulnerability were mainly distributed in the central part of the study area. The results of the sensitivity assessment of three urban ERS indices show spatially different distribution patterns. It was found that the sensitivity of CSC is high in areas with great soil erosion potential. The highly sensitive areas of FMC are distributed in lowland areas near the streams. In addition, in the case of HSRC, sensitivity is high in residential areas at the center of the densely populated area. As a result, the areas that have relatively high urban ERS vulnerability are distributed in the central part of the study area for all the three urban ERS indices (Figures 3–5).

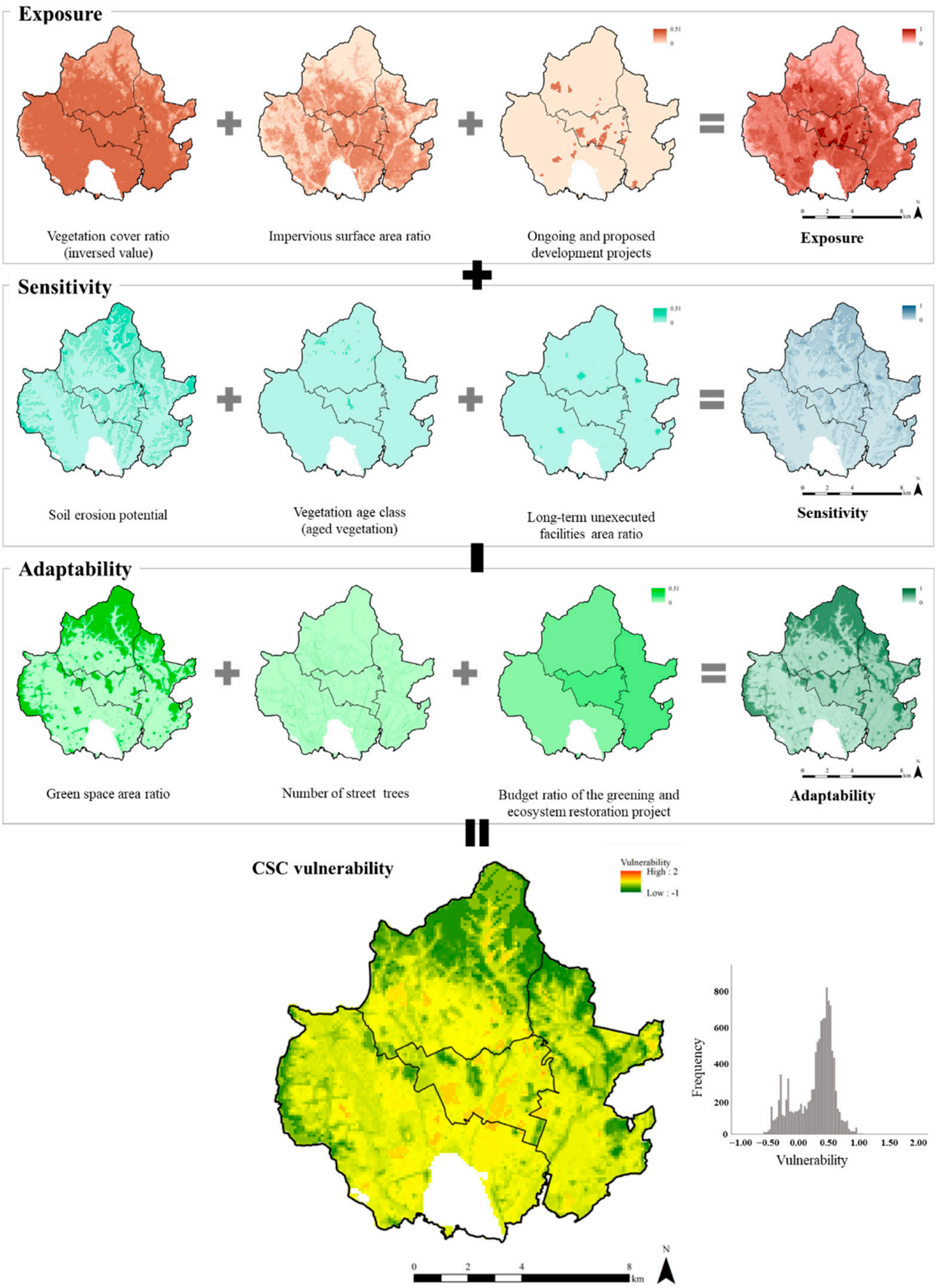

Figure 3. CSC vulnerability diagnosis.

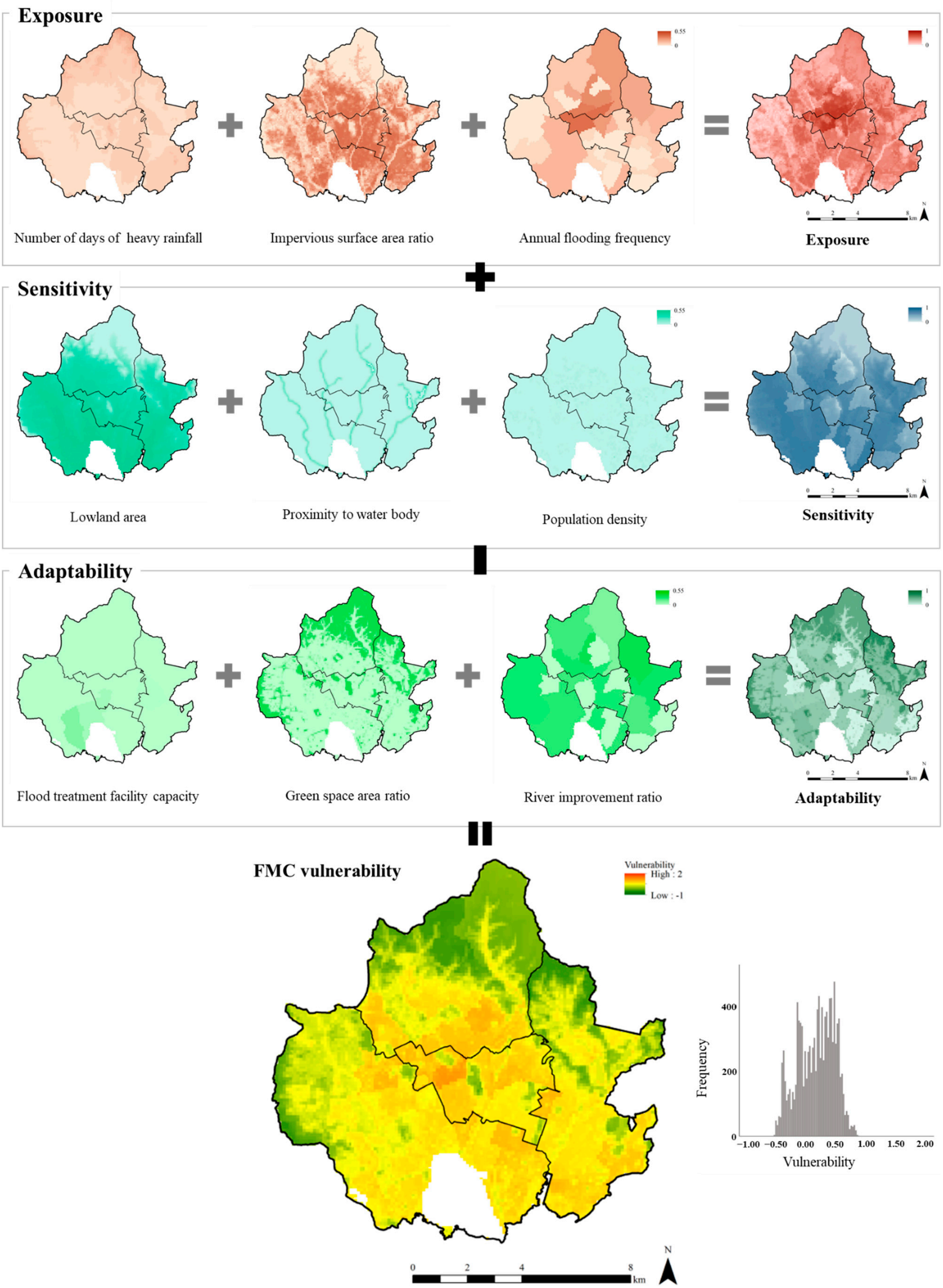

Figure 4. FMC vulnerability diagnosis.

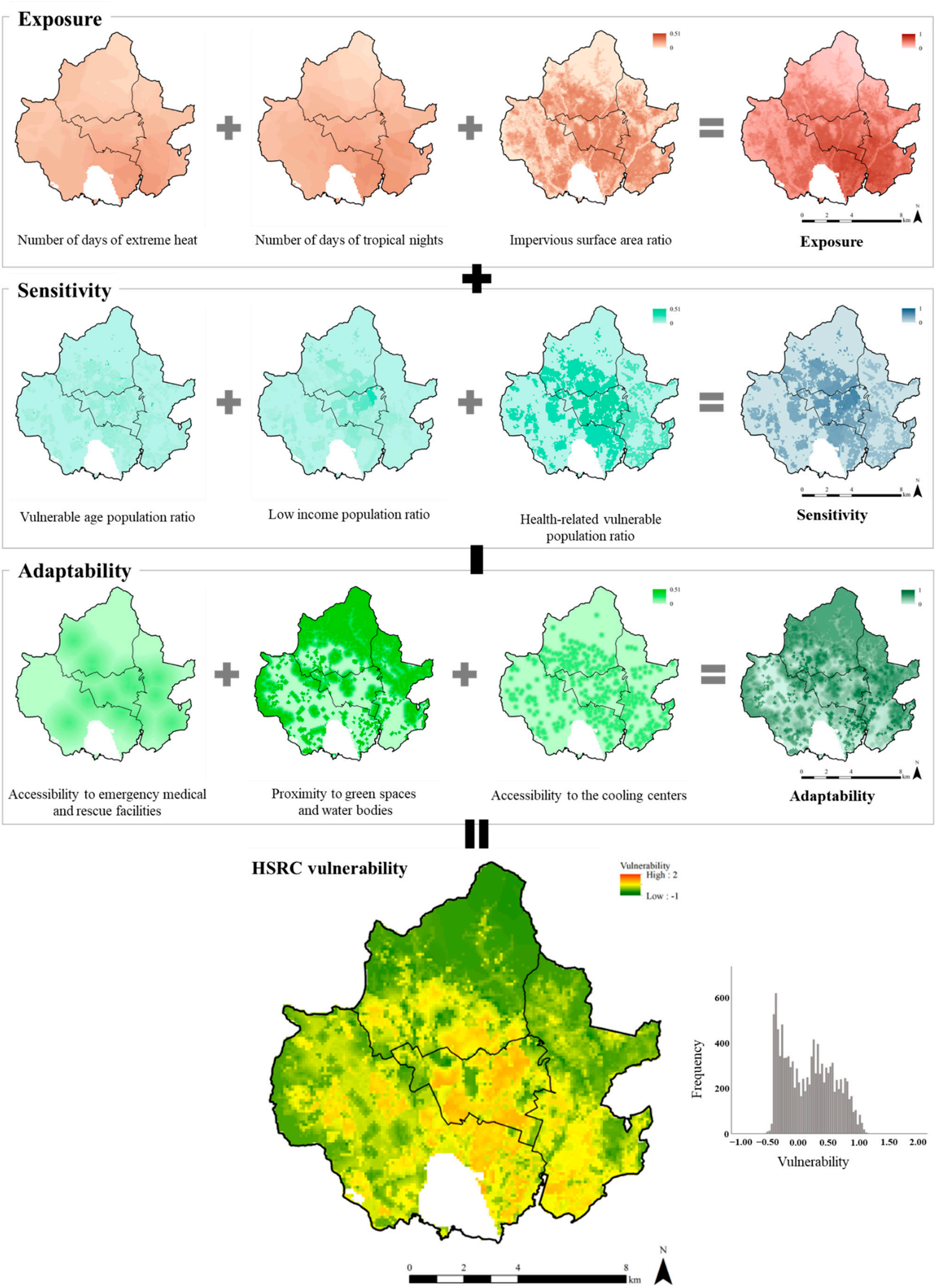

Figure 5. HSRC vulnerability diagnosis.

3.2. The Results for Priority Areas of High Urban ERS Vulnerability

As mentioned, urban spaces where improvement is most urgently needed among the vulnerable areas were identified through the hot spot analysis. The total priority areas in the diagnosis results of CSC, FMC, and HSRC comprised 1213 ha (10.02%), 2309 ha (19.32%), and 2321 ha (19.14%) of the study area, respectively (Table 8). It was confirmed that hot spot areas were mainly distributed in highly urbanized central parts of the study area (Figure 6a). The combination types of exposure, sensitivity, and adaptability were analyzed to investigate the spatial and societal problems to determine why priority areas have high vulnerability (Figure 6b). Type B of CSC, FMC, and HSRC, which is expected to be the most vulnerable, was found to be distributed across 12.98% (1488 ha), 11.91% (1365 ha) and 34% (2228 ha), respectively, of the study area.

Table 8. The spatial combinations and vulnerability in the priority areas.

Indices	The Priority Area (ha)	Spatial Combinations Type	Area (%)	Vulnerability (Mean)	Dimensions (Mean) Exposure	Sensitivity	Adaptability
CSC	1213 ha	Type B	5.29 ha (43.61%)	0.68	0.67	0.15	0.00
		Type D	6.84 ha (56.39%)	0.60	0.73	0.14	0.13
FMC	2309 ha	Type A	2.19 ha (9. 36%)	0.52	0.47	0.40	0.35
		Type B	7.94 ha (33.95%)	0.55	0.44	0.29	0.18
		Type D	8.76 ha (37.45%)	0.53	0.59	0.02	0.08
		Type F	4.5 ha (19.24%)	0.52	0.25	0.38	0.12
HSRC	2321 ha	Type A	2.45 ha (10.57%)	0.55	0.57	0.51	0.53
		Type B	16.9 ha (72.94%)	0.80	0.56	0.46	0.22
		Type D	3.43 ha (14.81%)	0.47	0.59	0.00	0.12
		Type F	0.39 ha (1.68%)	0.65	0.36	0.51	0.22

Figure 7 shows the overlaid results of priority areas with a spatial combination map. Based on the three urban ERS indices, Type B and Type D were identified as having the greatest distributions in the priority areas (Table 8). It was found that 100% of the priority areas of CSC belonged to Type B and Type D. In addition, more than 70% of the priority areas were confirmed to belong to Type B and type D in the case of HSRC and FMC. In addition, as presented in the satellite image in Figure 7, it was found that the priority areas were mainly filled with many buildings and roads. Such urbanized areas have a very high impervious area ratio, while there are few natural elements that can improve the urban ERS. Therefore, the amount of carbon emissions is very high due to energy consumption, and the CSC is relatively insufficient (Figure 7a). In addition, such areas increase the volume of surface runoff by reducing the amount of water infiltration into the ground. Because streams in those areas run faster and higher during heavy rainfall, the probability of flood risk is drastically increased (Figure 7b). Such urbanized areas degrade the thermal environment by retaining longwave thermal radiation and reducing evaporation. Furthermore, massive anthropogenic heat is added directly, resulting from human activities including modes of transportation and the use of air conditioners, and therefore, the heat stress of citizens is increased (Figure 7c).

3.3. Suggestions for Spatial Management Measures for the Priority Areas

As mentioned, the major subcomponents in the priority areas that increase ERS vulnerability were investigated (Table 9). In all ERS vulnerability indices except Type F of FMC, the impervious surface area ratio was proved to be the major factor increasing urban ERS vulnerability.

Because the priority areas have already been highly urbanized, further urbanization is likely to continue in the future. In this regard, existing green spaces and small parks should be preferentially conserved to prevent additional ERS degradation. In the long term, urban design should be highly considered to reduce building coverage ratios and increase green space ratios when redevelopments are carried out. In particular, urban development in potentially high soil erosion areas (Type B in CSC) could cause heavy carbon storage loss. The developments in lowland areas (Type A and Type F in FMC) could also bring about additional flood damage during heavy rainfall. The local government should prohibit drastic land use changes in those areas. If urban developments are inevitable, alternatives to minimize the vulnerability of urban ERS should be prepared.

The priority areas are filled with many buildings and roads, and as a result, introducing new large urban forests and parks to decrease the impervious surface ratio is not feasible. Therefore, applicable areas for additional small GI, including street trees, green roofs, porous paving material, etc., should be analyzed and applied in the priority areas. It has already been determined that introducing GI has multiple effects that enhance urban ERS. Additional carbon storage and infiltration of rainfall is possible if planting is ensured in priority areas. At the pedestrian level, trees have the advantage of reducing the amount of sensible heat due to the shadow effect. If the local government of a city provides financial incentives including subsidies and tax credits for residents to plant on their private land, such multiple effects will be further increased.

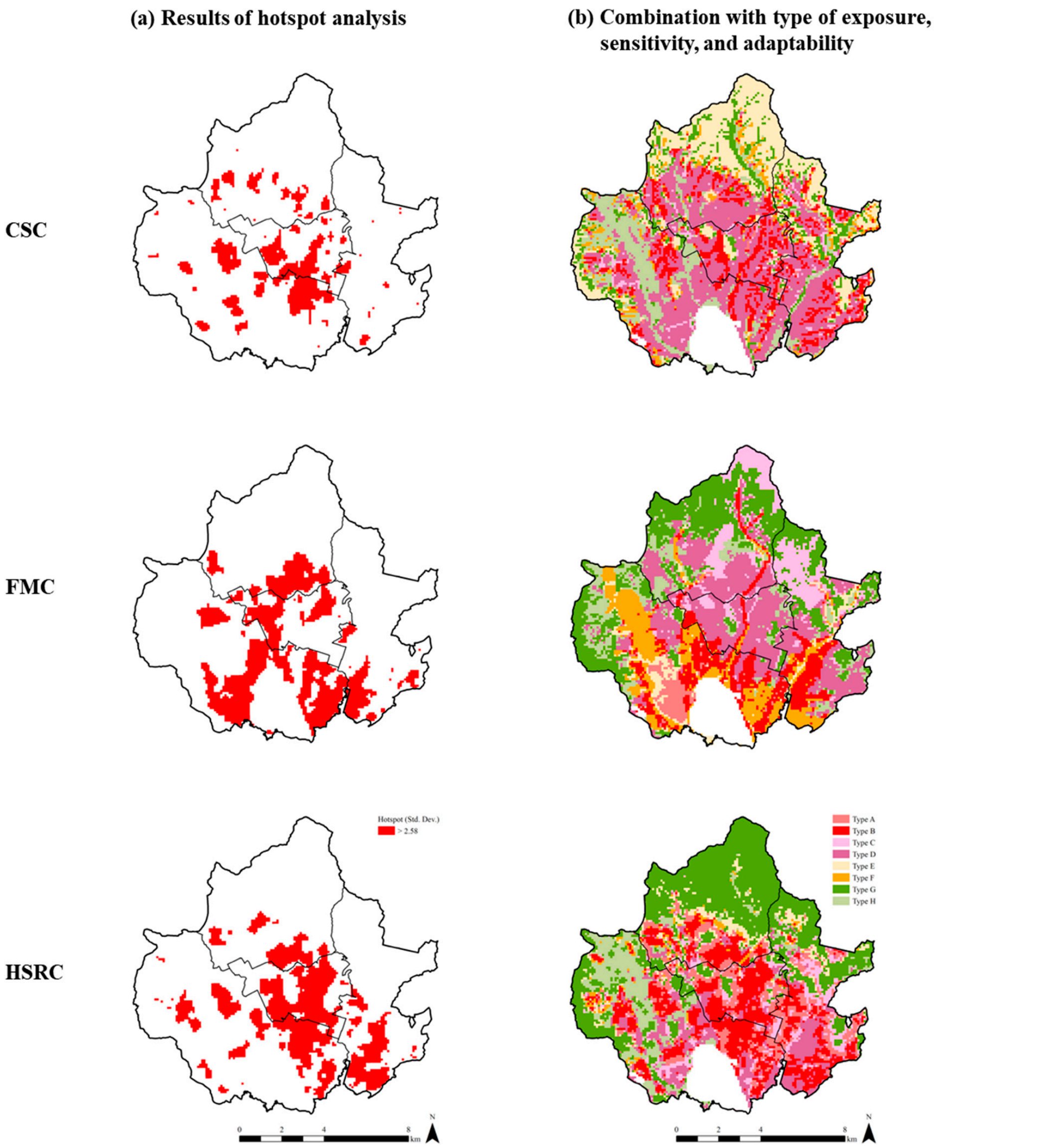

Figure 6. Results of hotspot analysis and combination with type of exposure, sensitivity, and adaptability.

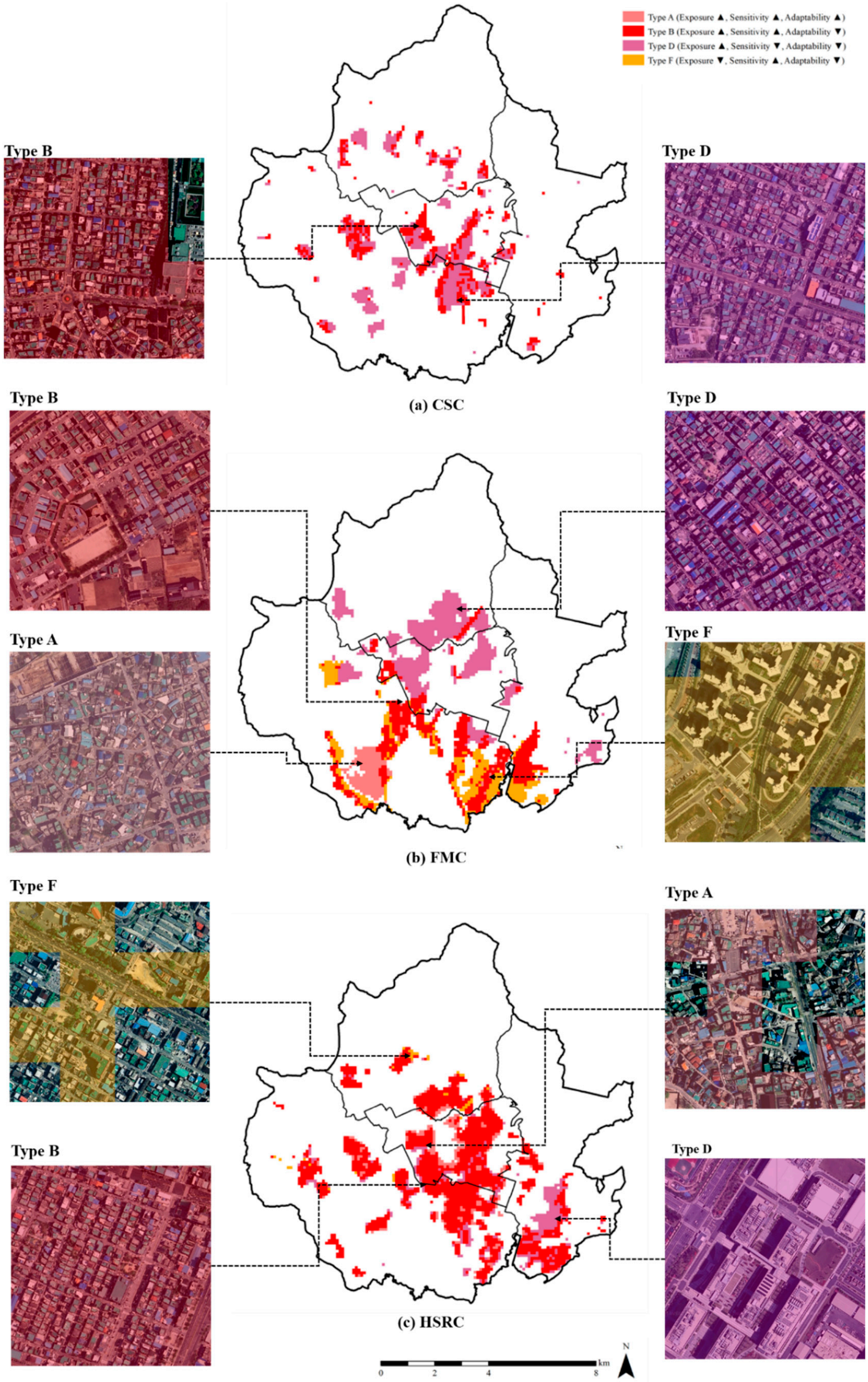

Figure 7. Overlaid results of priority areas with spatial combination maps (a: CSC; b: FMC; c: HSRC). Note: The uncolored areas in the satellite imagery (Type A of HSRC, Type B of CSC, Type F of FMC and HSRC) mean that those areas do not belong to a presented spatial type.

Table 9. Mean values of subcomponents in the priority areas.

Indices	Dimensions	Subcomponents	Type A	Type B	Type D	Type F
		Vegetation cover ratio (inversed value)		**0.99**	**0.99**	
	Exposure	Impervious surface area ratio		**0.87**	**0.86**	
		Ongoing and proposed development projects		0.14	0.31	
		Soil erosion potential		**0.35**	0.00	
CSC	Sensitivity	Vegetation age class (aged vegetation)	-	0.00	0.00	-
		Long-term unexecuted facilities area ratio		0.00	0.00	
		Green space area ratio		**0.00**	**0.01**	
	Adaptability	Number of street trees		**0.05**	**0.04**	
		Budget ratio of greening and ecosystem restoration projects		0.45	0.42	
		Number of days of heavy rainfall	0.14	0.18	0.19	0.17
	Exposure	Impervious surface area ratio	**0.81**	**0.78**	**0.89**	0.37
		Annual flooding frequency	0.38	0.29	**0.58**	0.19
		Lowland area	**0.68**	0.46	0.01	**0.58**
FMC	Sensitivity	Proximity to water body	0.02	0.07	0.01	**0.16**
		Population density	0.03	**0.48**	0.07	0.04
		Flood treatment facility capacity	0.30	**0.04**	**0.01**	**0.01**
	Adaptability	Green space area ratio	**0.08**	**0.01**	**0.02**	**0.03**
		River improvement ratio	0.71	0.51	**0.21**	**0.31**
		Number of days of extreme heat	**0.35**	**0.35**	**0.42**	0.21
	Exposure	Number of days of tropical nights	**0.61**	**0.60**	**0.70**	**0.37**
		Impervious surface area ratio	**0.89**	**0.86**	**0.77**	**0.60**
		Vulnerable age population ratio	**0.19**	**0.17**	0.00	**0.21**
HSRC	Sensitivity	Low-income population ratio	0.32	0.26	0.00	0.33
		Health-related vulnerable population ratio	**0.88**	**0.82**	0.00	**0.85**
		Accessibility to emergency medical and rescue facilities	0.53	0.49	0.39	0.37
	Adaptability	Proximity to green spaces and water bodies	0.60	**0.03**	**0.01**	**0.05**
		Accessibility to cooling centers	0.44	0.39	**0.15**	0.41

Bold: Main factors that cause high ERS vulnerability (mean value > Z score 2.58 in study area).

Finally, social welfare services provided by local governments are also needed to improve HSRC. It has been confirmed that there are many health-related groups (suffering from cardiovascular, respiratory, and cerebrovascular problems) and age-related groups (age > 65 or age < 5) vulnerable to extreme heat events that live in Type A Type B, and Type F areas. As a result, it is necessary to enhance monitoring and disaster information services for the chronically ill in those areas. Therefore, it is necessary to apply not only traditional measures including green infrastructure, but also to introduce welfare policies to improve HSRC. Moreover, local governments should consider providing visiting-care services because it may be difficult for the chronically ill who are elderly and living alone to obtain disaster information.

4. Discussion and Conclusions

Improvement of ERS in urban areas could be achieved through an organic combination with urban planning. However, the complexity of analysis of urban ERS has become a barrier for practical application to urban planning [84]. In particular, in the urban planning process, improvements to maximize the effects of ERS should be established, as there may be limited budgets and time constraints [85]. This study developed a relatively clear framework to diagnose urban ERS vulnerability and prioritize vulnerable areas. The results from the urban ERS diagnosis and for priority areas provide key information where improvement should be applied as a priority. The fact that the priority areas are mainly distributed in highly urbanized areas seems to align with observations from previous studies. However, as presented in Figure 7, although the priority areas of each dimension were partially similar, the spatial distribution of each dimension was different. Furthermore, as presented in Table 9, the main subcomponents increasing urban ERS vulnerability in each dimension and their intensity were different. Such results imply that affordable and distinct measures for each dimension and spatial type should be applied to reduce urban ERS vulnerability.

The overlaid results for the priority areas and combination map enabled the identification of the current issues of the priority areas and the formulation of customized improvement measures. Urban planners will be able to control the urban development type and intensity in the priority areas so that urban ERS will not be seriously damaged in the process of establishing land use planning. Additionally, as presented in the results, concrete and practical measures including GI applications to reduce urban ERS vulnerability in priority areas could be prepared by investigating major subcomponents that increase ERS vulnerability. This study linked the results of urban ERS diagnosis and urban planning by providing a stepwise process to reduce urban ERS vulnerability through the diagnosis of urban ERS vulnerability in the preparation of measures.

Most vulnerability assessment studies have analyzed vulnerability on a large scale (1–5 km^2 or greater) due to problems in obtaining data, and subsequently, only identify the approximate locations and causes of vulnerability. While such an analysis can serve as a reference point for macro-spatial planning, it lacks the specificity necessary for micro-spatial planning [86,87]. Spatially distinguished information to explain ERS is necessary in urban planning to enhance urban ERS [88,89]. This study used GIS spatial analysis methods such as overlay, proximity analysis, etc., to assess the micro-spatial data and construct most of the analysis subcomponents with a 100 m $\times$ 100 m resolution. The results of these specific analyses were also compiled to diagnose the vulnerability of the ERS in urban areas, which provided a basis for the establishment of specific improvement plans.

However, this study has the following limitations. Due to an absence of analytic data availability, this study did not consider air purification, noise reduction, and waste treatment, which are also important aspects of ERS. With the advent of low-cost and high-efficiency sensors, many sensors measuring urban ERS have been put into trial operation in cities in recent years. If such measurements can be gathered and analyzed, it may be possible to determine the vulnerability of other ERS in the future. The results of the vulnerability diagnosis still present only the relatively vulnerable areas and do not provide an absolute answer to the question of whether or not the areas in question are severely problematic. The usefulness of this study will be further enhanced if the results can be verified through the acquisition of relevant data and long-term monitoring. In addition, as priority areas were mainly distributed in highly urbanized areas under the developed analysis framework, another limitation of this study is that measures for suburban areas that require systematic management of urban ERS were not presented. If an analysis framework that can clearly identify areas sensitive to urban ERS changes (such as suburban or rural areas) is developed through further studies, more systematic and effective urban ERS management will be possible.

As the climate change crisis grows, interest in ERS has been steadily increasing in the urban planning field. Climate regulation and natural disaster regulation are closely related to maintaining a safe urban environment. Based on an assessment of both natural and social factors, this study diagnosed the vulnerability of ERS. By conducting a detailed study using GIS spatial analysis, it was possible to ensure the scientific nature and concreteness of the diagnosis results. Furthermore, the spatial and societal problems in priority areas were also investigated to suggest spatial management measures. The developed framework to diagnose and prioritize urban ERS could be utilized in urban planning to improve the health of urban ecosystems.

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Appendix A Analytic Methods for Raw Data Preparation

Table A1. CSC.

Dimensions	Subcomponents	Analytic methods
Exposure	Vegetation cover ratio (inversed value)	GIS overlay analysis application to distribute the vegetation cover by the grid in the biotope map of the study area and results were inversed
	Impervious surface area ratio	GIS overlay analysis application to distribute the ratio of impervious surface areas in the biotope map by the grid
	Ongoing and proposed development projects	GIS spatial query application to identify ongoing and proposed development projects
Sensitivity	Soil erosion potential	GIS overlay application to distribute the erosion data in soil maps by the grid
	Vegetation age class (aged vegetation)	GIS overlay application to input tree ages in biotope map by the grid
	Long-term unexecuted facility area ratio	GIS overlay application to calculate the area occupied by the long-term unexecuted facilities in the grid
Adaptability	Green space area ratio	GIS overlay application to calculate the area occupied by the green spaces in the grid
	Number of street trees	GIS spatial query application to calculate the number of street trees in the grid
	Budget ratio of greening and ecosystem restoration projects	Allocation of ratio of budget for each region corresponding to park and green space development, ecosystem restoration, and tree planting projects by the grid

Table A2. FMC.

Dimensions	Subcomponents	Analytic Methods
Exposure	Number of days of heavy rainfall	Extraction of the number of days of heavy rainfall from measurement data, with calculation carried out via interpolation in the GIS
	Impervious surface area ratio	GIS overlay analysis application to distribute the ratio of impervious surface areas in the biotope map by the grid
	Annual flooding frequency	GIS spatial query application to input the inundation frequency by the grid
Sensitivity	Lowland area	Extraction of the areas below the planned flood level from DEM data after calculating the average flood level based on the planned flood level caused by rivers
	Proximity to water body	Multiple ring buffer tool application in GIS to calculate the distance from water bodies
	Population density	Application of the source material
Adaptability	Flood treatment facility capacity	Distribution of regional statistical data into the grid
	Green space area ratio	GIS overlay application to calculate the area occupied by the green spaces in the grid
	River improvement ratio	Reallocation of regional statistical data into the grid

Table A3. HSRC.

Dimensions	Subcomponents	Analytic Methods
Exposure	Number of days of extreme heat	A temperature of 33 °C or above during summer days is selected from the measurement data, and calculation is carried out via interpolation in the GIS
	Number of days of tropical nights	Extraction of days with the lowest temperature of 25 °C or above on summer days from the measurement data, and calculation via interpolation in the GIS
	Impervious surface area ratio	GIS overlay analysis application to distribute the ratio of impervious surface areas in the biotope map by the grid
Sensitivity	Vulnerable age population ratio (age > 65 or age < 5)	Application of source material
	Low-income population ratio	Reallocation of regional statistical data by the grid
	Health-related vulnerable population ratio (cardiovascular, respiratory and cerebrovascular)	Equal distribution of regional statistical data by the grid
Adaptability	Accessibility to emergency medical and rescue facilities	Calculation of the distance from emergency medical and rescue facilities using the multiple ring buffer tool application in the GIS
	Proximity to green spaces and water bodies	Calculation of the distance from green spaces and water body boundaries using the multiple ring buffer tool application in the GIS
	Accessibility to cooling centers	Calculation of the distance from cooling centers using the multiple ring buffer tool application in the GIS

Appendix B

Table A4. Survey Respondents' Fields of Expertise.

Classification		Total		Expert		Local Government Officers	
		Frequency (Persons)	Ratio (%)	Frequency (Persons)	Ratio (%)	Frequency (Persons)	Ratio (%)
Fields of expertise	Environment	12	20.0	4	13.3	8	26.7
	Architecture	5	8.3	2	6.7	3	10.0
	Landscape/ecosystem	19	31.7	10	33.3	9	30.0
	Urban	15	25.0	11	36.7	4	13.3
	Administration	5	8.3	1	3.3	4	13.3
	Civil engineering	3	5.0	2	6.7	1	3.3
	Transportation	1	1.7	0	0	1	36.
Total		60	100	30	100	30	100

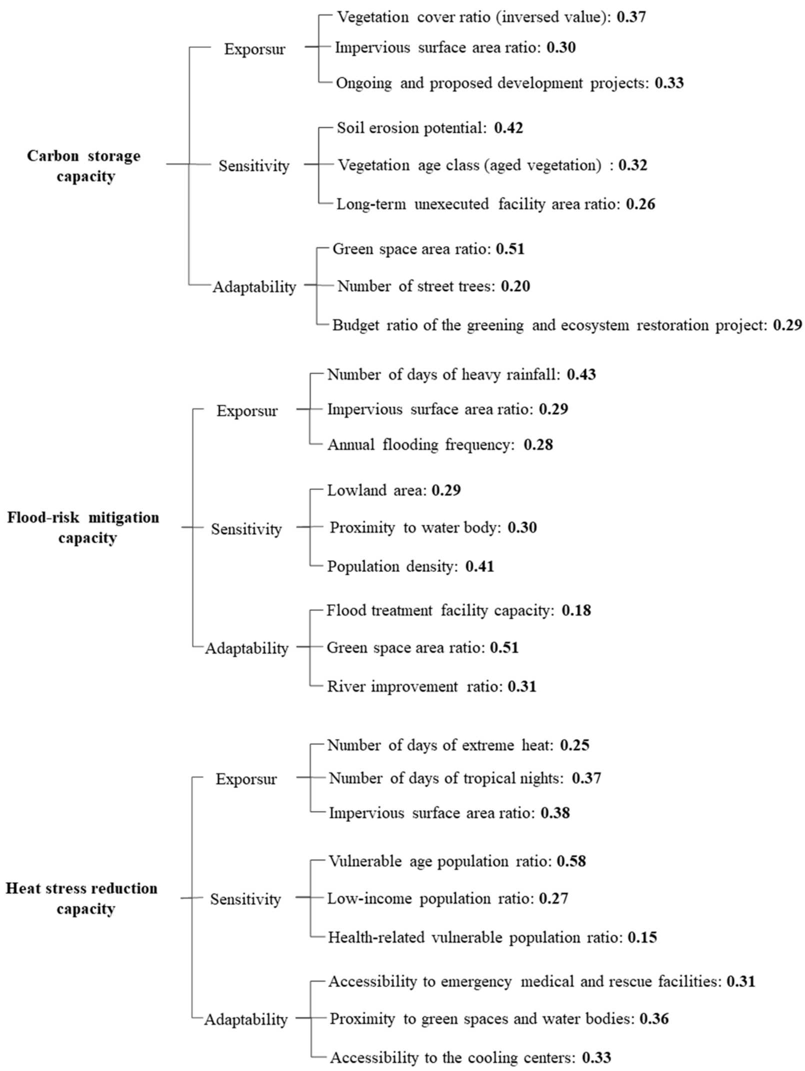

Figure A1. The Relative Importance (Weight) of Subcomponents to Diagnose Urban ERS. Note: All survey results met the consistency ratio (CR) * < 0.1. * The CR is the most representative index to identify whether respondents answered the survey with consistency. Generally, when the CR is less than 0.1, the researcher can judge if the survey results meet the consistency standard. In this study, the CR values of each dimension were identified, and results that met the standard were applied to calculate the relative importance (weight).

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