sustainability

MDPI

Article

Precondition Study of a Sponge City: Comprehensive Assessment of the Vulnerability of an Urban Rainwater System

Lei Li [1], Cuimei Li [1,*], Hao Wang [2] and Fei Xu [1]

[1] School of Environmental Science and Engineering, Suzhou University of Science and Technology, Suzhou 215009, China; 2113022013@post.usts.edu.cn (L.L.); 2311022007@post.usts.edu.cn (F.X.)
[2] China Institute of Water Resources and Hydropower Research, Beijing 100038, China; wanghao@iwhr.com
* Correspondence: cuimeili@usts.edu.cn

Abstract: This study introduces the concept of urban rainwater system vulnerability and identifies the indicator factors that affect the vulnerability of rainwater systems. Using the analytic hierarchy process (AHP), an index system for the vulnerability assessment of the rainwater system was established, and a vulnerability assessment model for the rainwater system was constructed. By integrating vulnerability degree, recurrence period, and water depth of ponding, a vulnerability assessment framework for urban rainwater systems was developed. Taking a newly developed urban area in the Suzhou High-Tech Zone as an example, we calculated the vulnerability degree of the urban rainwater system in this area to be 0.6497, indicating a high level of vulnerability and poor system safety. When encountering rainfall with a recurrence period $p > 5$ years, the city is likely to experience severe waterlogging. Through the analysis and evaluation of the rainwater system's vulnerability, while clarifying the current state of the rainwater system, it can provide a scientific reference basis for the system's upgrade, transformation, and optimized operation and management. Although the selection of factors may not be entirely comprehensive, this method allows for adjustments based on the composition and operation of different rainwater systems.

Keywords: vulnerability; urban rainwater system; analytic hierarchy; weight value; assessment system

Citation: Li, L.; Li, C.; Wang, H.; Xu, F. Precondition Study of a Sponge City: Comprehensive Assessment of the Vulnerability of an Urban Rainwater System. *Sustainability* **2024**, *16*, 3897. https://doi.org/10.3390/su16103897

Academic Editor: Miklas Scholz

Received: 19 March 2024
Revised: 21 April 2024
Accepted: 30 April 2024
Published: 7 May 2024

1. Introduction

Since 2013, China has initiated extensive construction projects focused on sponge city development [1–3]. The first set comprised 16 pilot cities, followed by a second batch of 14 cities, generating widespread enthusiasm for the undertaking, with annual direct funding of over ten billion CNY (Chinese currency yuan) from the central government of China. Virtually every local government has established a dedicated office for overseeing sponge city construction and management, ensuring the systematic execution of all related projects, including planning, design, and subsequent construction [4,5]. The urban rainwater system is a crucial component of sponge city infrastructure, and its stability and reliability are directly related to the sponge city's flood prevention and drainage capabilities. However, there has been a notable absence of theoretical frameworks employed to evaluate plans or designs and assess the vulnerability of existing rainwater systems prior to the commencement of construction work [6].

Vulnerability has progressively emerged as a focal point in the realm of global environmental change and sustainable development, gaining prominence as a hot topic in research [7]. As an innovative research paradigm with widespread applications across various disciplines, vulnerability is capturing increased academic attention. Numerous scientific initiatives, including IHDP, IPCC, and IGBP, have incorporated vulnerability research into their agendas [8,9]. To our knowledge, the scientific investigation of vulnerability originated in the field of natural disaster research, with Timmerman introducing the concept to geoscience back in 1981 [10]. Vulnerability has been widely studied in socio-hydrology, economics, medicine, ecology, and many other fields [11–14].

Vulnerability is commonly characterized as the condition of being open, exposed, or prone to injury or attack. In catastrophology, Zheng thought that damage and loss predominantly result from natural disasters [15]. Spielman thought that vulnerability describes combinations of social, cultural, economic, political, and institutional processes that shape socioeconomic differentials in the experience of and recovery from hazards. Energy vulnerability, intended as the exposure of an energy system to adverse events and change, often overlaps with other energy policy concepts such as resilience, security, poverty, justice, and sustainability [16]. Gatto and Busato improved the understanding of vulnerability in economics, energy, and sustainability studies [17]. Subsequent scholarly explorations have coalesced around the conviction that sensitivity and adaptability to external changes stand as pivotal constituents of vulnerability. Consequently, positioned at the nexus of diverse disciplines and reliant upon interdisciplinary research and inquiry, the concept of vulnerability has undergone a profound transformation from its initial simplicity to a comprehensive definition that embraces both intrinsic and extrinsic natural and social factors. To attain a more nuanced grasp of vulnerability, it becomes imperative to integrate human initiative adaptability into vulnerability research. The discernible impact of human agency on the composition and mitigation of vulnerability is now acknowledged as considerably more profound than in previous considerations.

The concept of engineering vulnerability has primarily found application in municipal infrastructure systems, notably in power transmission grids, water treatment plants, and metro networks to characterize the inherent capacity of these systems to endure the adverse impacts of disaster events [18–23]. However, vulnerability research in the context of rainwater systems remains relatively nascent, with only analogous studies focusing on drainage capacity or the sustainability of such systems. Ke delved into the analysis of restoring forces and proposed a novel method for comprehensively assessing the resilience of drainage systems under various disturbance events [24]. In a similar vein, Lin undertook an assessment of the drainage capacity of rainwater systems, presenting recommendations aimed at mitigating the risk of flooding [25].

In recent years, the discernible increase in instances of waterlogging stemming from rainfall events has become particularly pronounced, especially in rapidly evolving urban centers. Currently, there exists no definitive method for precisely delineating the tolerance or anti-interference capacity of a rainwater system, and research dedicated to understanding the vulnerability of these systems remains scarce. Against this backdrop, assessing the vulnerability of rainwater drainage systems becomes particularly critical. Consequently, this paper endeavors to fill this research gap by developing a vulnerability calculation method and assessment system for urban rainwater systems, drawing inspiration from research findings on other infrastructure systems. The established assessment system enables an indirect evaluation of safety levels and disaster-bearing capabilities, providing assessment results that furnish specific and efficacious measures for reducing system vulnerability during the engineering process. It can provide a scientific basis for the optimization and upgrading of the system, contributing to the sustainable development of the city.

2. Methods

2.1. Evaluation Factors

The vulnerability of an urban rainwater system encompasses its susceptibility to interference and its capacity to adapt to external environmental changes, exemplified by a scenario where a property struggles to discharge water promptly during rainfall. Upon a comprehensive analysis of factors influencing a rainwater system, these factors can be categorized into two primary components: the physical and the social. The physical part pertains to the inherent structure of the system, encompassing elements such as inlet holes, gullies, pipes, lifting pump stations, detention tanks, and more. On the other hand, the social component involves the impact of human behavior on the system's operational processes. Vulnerability, as a characteristic value of the entire system, necessitates the integration of each component that contributes to determining the system's susceptibility.

2.1.1. Physical Factors

Physical vulnerability refers to the susceptibility of a system's functionality to be affected by external disturbances or impacts, as determined by the inherent physical characteristics of the rainwater system. The level of physical vulnerability directly influences the degree of the system's overall vulnerability.

In selecting the physical factors for the vulnerability evaluation index in this study, several critical components of the system were considered. These factors include the setting position, relative elevation, and the collecting and releasing capacity of the gutter inlets or outlets, which can significantly impact the ponding depth on road surfaces. Additionally, the water transmission dynamics within the pipe network were also taken into account. The size of pipes plays a decisive role in drainage capacity, and increasing the pipe diameter not only increases capacity but also adds a regulating volume to the pipe network. The slope of a pipeline has been acknowledged for its effects on deposition and flushing, further influencing drainage capacity. Furthermore, the regulatory and storage capacity of pumping stations or other storage structures have been recognized as vital components, particularly in the context of extraordinary rainstorm events.

2.1.2. Social Factors

Social vulnerability primarily denotes the extent of measures taken by human society to mitigate the threats posed by heavy rainfall to urban areas and to enhance the rainwater system's capacity to cope with such precipitation events. Under conditions where the hazard agents are constant, the greater the intensity of the measures implemented, the lower the social vulnerability of the stormwater system, and, consequently, the lesser the impact of heavy rainfall on the city.

Determining indices for the social component poses challenges due to the intricate interplay within a complex social environment. Considering the urban context, this paper identifies four key facets encapsulating these influences: (1) the construction and renovation of drainage pipe networks, along with daily operation and maintenance, constitute managerial-level influences. Heightened managerial proficiency significantly enhances a system's adaptability to external changes, thereby elevating its safety level; (2) the presence of green spaces and impermeable pavements in a city exerts a substantial impact on flood flux and the peak time of rainfall runoff. Urbanization has notably escalated impermeable surfaces, imposing a substantial burden on drainage systems [26]; (3) sanitation levels indirectly affect drainage system performance. Regular road surface cleaning and unblocking gutter holes prove effective in ensuring swift system functionality upon rainfall; and (4) disaster prevention levels and operating environments, determined by government investment in infrastructure, directly influence the scale of a rainwater system. The profound impact of these social factors on a rainwater system necessitates careful consideration.

2.1.3. Assessment Framework

In the absence of a clear understanding of the mechanisms underlying vulnerability formation, the index system is currently the most commonly employed method for vulnerability assessment. In delineating the causes of vulnerability and the associated characteristics of formation, a hierarchical assessment method was employed to establish the vulnerability value of a disaster body. As a primary statistical method for comprehensive analyses, the analytic hierarchy process (AHP) method was chosen to construct the vulnerability hierarchy system [27,28]. This methodology ascertains the indicators for vulnerability analysis based on the causes and characteristic manifestations of the vulnerability of disaster-prone entities and establishes an index system for vulnerability assessment. Subsequently, it determines the weights of each indicator through expert consultation or methods such as the analytic hierarchy process (AHP). Finally, it constructs a vulnerability assessment model using relevant mathematical methods to calculate the comprehensive vulnerability index, also known as the vulnerability degree, which characterizes the extent of vulnerability of disaster-prone entities. This approach can be applied to evaluate individual disaster-prone entities, multiple entities, as well as entire disaster-prone systems. Upon categorizing the factors into two distinct parts, the rainwater vulnerability system's hierarchy comprises three layers, as illustrated in Figure 1. The top layer serves as the target layer, presenting the vulnerability value. The second layer, the logical layer, comprises sub-indices that differentiate the principal components. The bottom layer, the index layer, encompasses each factor contributing to the assessment [29].

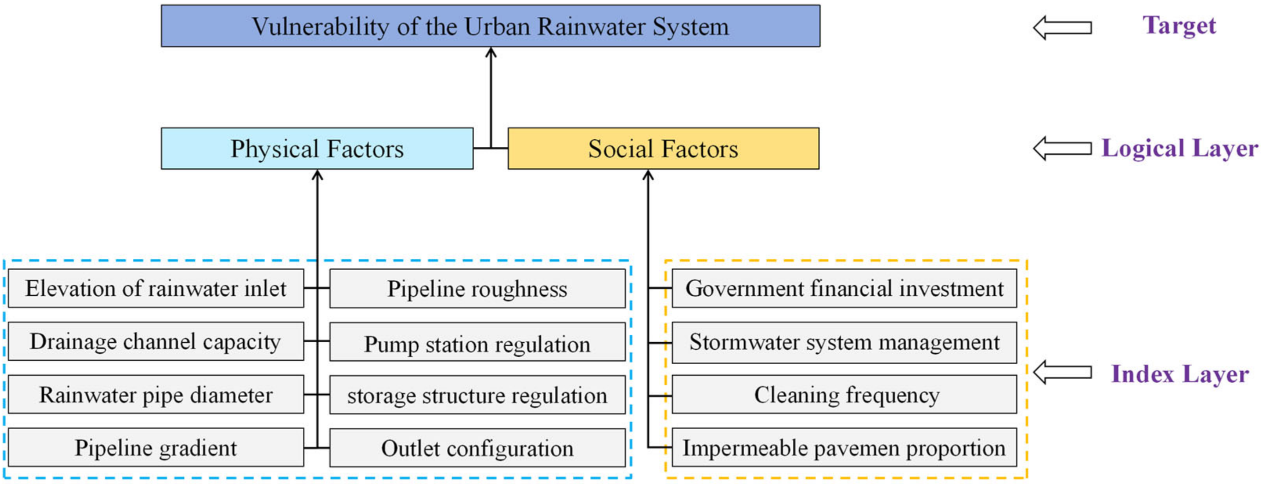

Figure 1. Framework of the assessment system.

2.2. Weight Value of Factors

A weight value represents the local or global priority of a factor to its system. To determine the weight, the relationships among all factors in the group need to be taken into account. The steps to ensure the weight value are important in a synthetic evaluation model.

In consideration of the rainwater system's constitution and operating characteristics, the structural model was constructed based on the framework previously built using the AHP method. The weight value was calculated using a judgment matrix; however, both the judgment value and matrix should have been checked through a consistency test.

For the successful construction of a vulnerability assessment framework for the rainwater system, the selection of both internal and external factors, as well as the analysis of corresponding indicative values, weights, and judgment matrices, are conducted through the method of providing questionnaires to experts for specialized surveys and then evaluating and judging the scores.

2.2.1. Judgment Matrix

Within a certain category, all of the factors are interrelated but are quite different from one another. By giving them a numerical value, a judgment value of the importance intensity can represent the significance of the factors [30]. In Table 1, B_i and B_j represent two different evaluation factors, and the intensity of importance is divided into five ranges, where $f(B_i/B_j)$ and $f(B_j/B_i)$ are the values of intensities and $f(B_i/B_j)$ means the judgment value of the importance of element B_i relative to element B_j.

Table 1. Judgment value from the intensity of importance.

Intensity of Importance Compared between B_i and B_j	$f\left(B_i/B_j\right)$	$f\left(B_j/B_i\right)$
Equal importance	1	1
Moderate importance	3	1
Strong importance	5	1
Very strong importance	7	1
Extreme importance	9	1

Note: The intensities of 2, 4, 6, and 8 can be used to express intermediate values. And the intensities of 1.1, 1.2, 1.3, etc., can be used for elements that are very close in importance.

According to the relative importance of a rainwater system, b_{ij} and M can be calculated using the initial judgment value given in Table 1.

The formulas for the judgment value and matrix are as follows:

$$b_{ij} = \frac{f\left(B_i/B_j\right)}{f\left(B_j/B_i\right)} \quad (i, j = 1, 2, \ldots, n) \tag{1}$$

$$\text{M} = \begin{bmatrix} b_{11} & \cdots & b_{1n} \\ \vdots & \ddots & \vdots \\ b_{n1} & \cdots & b_{nn} \end{bmatrix} \tag{2}$$

2.2.2. Consistency Check

In order to verify the soundness and accuracy of the initial value, the result of b_{ij} and M must be checked through numerical consistency. The consistent matrix should observe the following steps:

1. The matrix $B = \left(b_{ij}\right)_{n \times n}$ should be a tolerance matrix that meets the following conditions:

$$\begin{cases} b_{ii} = 1\,, & \forall\, i \in \{1, 2, \ldots, \text{n}\}\,; \\ b_{ij} \cdot b_{ji} = 1\,, & \forall\, i, j \in \{1, 2, \ldots, \text{n}\}\,; \\ b_{ij} \cdot b_{jk} = b_{ik}\,, & \forall\, i, j, k \in \{1, 2, \ldots, \text{n}\}\,; \end{cases} \tag{3}$$

2. If matrix B meets the conditions, then we define the corresponding eigenvector as $\mathscr{W}_i$:

$$\mathscr{W}_i = \sqrt[n]{\prod_{j=1}^{n} b_{ij}} \tag{4}$$

If the maximum eigenvalue $\lambda_{max} = n$, the weight vector w is the collection of $\mathscr{W}_i$:

$$\mathscr{W} = [\mathscr{W}_1, \mathscr{W}_2, \ldots, \mathscr{W}_n]^T \tag{5}$$

3. Calculation of Consistency check [31].

The judgment matrix formed based on actual problems may not achieve absolute consistency. Therefore, it is necessary to verify the consistency of the judgment matrix and calculate the consistency index (*CI*) of the matrix:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{6}$$

If the consistency index $CI = 0$ and the maximum eigenvalue $\lambda_{max} = n$, then the judgment matrix has complete consistency. Conversely, when $CI \neq 0$, the larger the CI is, the worse the consistency of the judgment matrix is.

To ascertain the attainment of a desirable level of consistency within the judgment matrix, it is essential to compare the CI with the average random consistency index (RI)

of the same order. Matrices of the first and second orders inherently exhibit complete consistency, whereas matrices beyond the second order necessitate the use of the ratio of CI to RI for assessing satisfactory consistency levels. Generally, the random consistency ratio of the judgment matrix is represented by CR:

$$CR = \frac{CI}{RI} \tag{7}$$

When $CR < 0.10$, it is considered that the consistency of the judgment matrix meets the requirements. Otherwise, adjustments to the judgment matrix are indispensable until it aligns with the stipulated requirements [32–34].

The average random consistency index of each order is shown in Table 2.

Table 2. Average random consistency index.

n	0	1	2	3	4	5	6	7	8	9
RI	0	0	0.52	0.89	1.12	1.24	1.36	1.41	1.46	1.49

If the weight vector successfully passes the normalization check, this signifies that the values of b_{ij} and M can be utilized in the subsequent steps. This indicates that the AHP method can be employed to select and assign the evaluation factors of vulnerability.

For a hierarchical analysis of the system, we amalgamate the factor weight $\mathscr{W}_c$ with the criteria weight $\mathscr{W}_B$ to derive a cohesive weight value, structured in the order of vulnerability:

$$\mathrm{W}_i = \mathscr{W}_B \cdot \mathscr{W}_c = [\mathscr{W}_1, \mathscr{W}_2, \ldots, \mathscr{W}_n] \tag{8}$$

The derived weight value serves as a poignant indicator of each factor's significance in both the composition and operation of the system. It stands as fundamental data pivotal for calculating the vulnerability of rainwater systems.

2.3. Vulnerability Calculation

2.3.1. Mathematical Model

Vulnerability is represented by V and comprises basic index vulnerability values V_i, which is portrayed through a comprehensive representation of each factor using the weighted average method. Mitigating the influences of distinct dimensions was accomplished through the use of a relative method, resulting in representative values for these factors.

Within this framework, akin factors are consolidated, less impactful elements are excluded, and the parameters essential for this model are determined as follows: h_a, q_a denote the relative elevation and flow capacity of gutter inlet holes; d_a and i_a represent the diameter and slope of pipes; Q_a signifies the regulation quantity of the pump station; T_a embodies the storage capacity of the detention tank; O_a characterizes the outfall setting condition; C_a reflects the financial investment situation; S_a denotes the proportion of impermeable pavement; G_a gauges the management level of the stormwater system by the government; and P_a signifies the cleaning frequency of the urban target region. The corresponding weight values for each factor are denoted as $\mathscr{W}_h$, $\mathscr{W}_q$, $\mathscr{W}_d$, $\mathscr{W}_i$, $\mathscr{W}_Q$, $\mathscr{W}_T$, $\mathscr{W}_O$, $\mathscr{W}_C$, $\mathscr{W}_S$, $\mathscr{W}_G$, and $\mathscr{W}_P$.

The magnitude of the vulnerability characteristic values for each indicator reflects the performance quality of that component within the system. A larger characteristic value indicates good performance and low vulnerability of the component, whereas a smaller value indicates poor performance and high vulnerability. It is important to note that the characteristic value only reflects the vulnerability of that particular component within the indicator system, which has its limitations.

Upon finalizing the characterization of both physical and social factors, the corresponding weights were organized in the target layer from Equation (2), and the formulation of the mathematical model for calculating the vulnerability value of the urban rainwater system is expressed as Equation (9):

$$\begin{aligned} V = V_{Physical} + \quad V_{social} \\ = h_a \mathscr{W}_h + q_a \mathscr{W}_q + d_a \mathscr{W}_d + i_a \mathscr{W}_i + Q_a \mathscr{W}_Q + T_a \mathscr{W}_T + O_a \mathscr{W}_O \\ + C_a \mathscr{W}_C + S_a \mathscr{W}_S + G_a \mathscr{W}_G + P_a \mathscr{W}_P \end{aligned} \tag{9}$$

The comprehensive reflection of indicator vulnerability is represented by the product of the characteristic value and the weight value, also known as the vulnerability degree. This vulnerability degree refers to the internal vulnerability within the system, indicating the contribution value of that indicator to overall system vulnerability; the greater the vulnerability degree, the more significant the impact of the indicator on system vulnerability, and vice versa. The magnitude of internal vulnerability is not used to measure the size of system vulnerability and is not used for comparison of vulnerability levels. The comparison of vulnerability degrees pertains to the comparison of system vulnerability, which is a comparison of the system's comprehensive performance.

2.3.2. Vulnerability Assessment

The vulnerability value serves as a reflection of a system's capability to handle an imminent storm. A lower vulnerability value signifies a heightened safety level, implying the system's ability to withstand more robust rainfall. Conversely, elevated vulnerability values indicate a city's diminished ability to weather a storm, thereby escalating the likelihood of a flood. It is crucial to establish an evaluation standard for vulnerability grounded in pre-generalized assessments of an urban rainwater system. This standard should not only account for the vulnerability degree value but also align with existing standards for flood control, rainfall drainage, or other relevant benchmarks. Notably, the return period serves as a pivotal indicator of rainfall intensity, crucial in storm sewer system design and a prevalent index for discussing urban water flooding concerns. However, the return period solely conveys rainfall intensity without capturing a storm system's capacity to collect and transfer water. In this regard, vulnerability emerges as a precise assessment criterion for evaluating a storm system's ability to collect, transfer, and discharge rainwater. This indicator proves invaluable in assessing capability and analyzing the safety level of a storm system, whether it is already established or not.

The return period (P) refers to the average P-year rainfall event, where a larger P value indicates a greater intensity of rainfall and consequently a higher volume of stormwater runoff. The recurrence period P of a stormwater system denotes the scale of the constructed system's capability to handle a storm with a P-year recurrence interval. When the rainfall recurrence interval exceeds the system's recurrence period, the volume of rainfall surpasses the drainage capacity of the stormwater system, potentially leading to the formation of surface water accumulation. Under a given rainfall recurrence interval P, the shallower the ponding depth (H) and the shorter the retention time (T), the better the system's overall performance and the lower the vulnerability. Conversely, a deeper H and longer T signify poorer overall system performance and higher vulnerability.

Recognizing the paramount influence of the return period (P) on the scale of a rainwater system, this study adopts the return period and vulnerability degree as fundamental indices, complemented by depth and ponding retention time as referential benchmarks. The vulnerability assessment standard, meticulously formulated in Table 3, integrates technical codes for urban flooding prevention and control, urban rainwater tion, and retention engineering, along with insights from urban waterlogging patterns observed over the last two decades. By referencing the calculated vulnerability values in the standard table, we can discern the system's capacity to withstand various rainfall intensities, assessing ponding depth and retention time. This analysis elucidates the safety level of an urban rainwater system.

Table 3. Vulnerability assessment reference standards.

Vulnerability Value	Description	Security Level
$V \in [0.9, 1.0]$, Very high	$P = 1$ a, $H \geq 0.15$ m, $T > 1$ h, Water flooding events may occur easily	Weakest Lv. 1
$V \in [0.6, 0.9]$, High	1 a $\leq P < 5$ a, 0.15 m $\leq H < 0.4$ m, 1 h $\leq T < 2$ h, Easy to meet small-scale waterlogging	Low Lv. 2
$V \in [0.4, 0.6]$, Medium	5 a $\leq P < 10$ a, $H \leq 0.15$ m, $T < 1$ h, Rainfall runoff may not be drained in a short time	Normal Lv. 3
$V \in [0.1, 0.4]$, Low	10 a $\leq P < 50$ a, $H \leq 0.15$ m, $T < 1$ h, Waterlogging will appear but disappear in a short time	High Lv. 4
$V \in [-0.03, 0.1]$, Very low	$P \geq 50$ a, $H \leq 0.15$ m, $T < 1$ h, Waterlogging may occur in an extraordinary storm	Highest level Lv. 5

Note: *P*: the return period, where 'a' denotes 'age', is expressed in years; *H*: depth of rainfall ponding, meter; *T*: duration time of water ponding, hour.

In China, the majority of rainwater systems have been tailored for a return period ranging from two to ten years, exhibiting notable disparities in compositions with regard to this temporal parameter. To streamline calculations, system designs often opt for a uniform period, neglecting the overarching regional distinctions and overlooking vulnerability assessments and safety analyses. It is imperative that the scientific vulnerability assessments of existing rainwater systems serve as a foundational step for any reconstruction endeavors. This approach holds profound significance in enhancing the capacity to prevent flooding and mitigate the impact of storm events.

Low vulnerability of the rainwater system indicates that the system possesses stable performance and strong response capabilities when combating rain-induced flood disasters. This ensures that rainwater generated within the city can be promptly drained, reducing the risk of water accumulation and internal flooding, thereby enhancing the city's safety. Conversely, high vulnerability of the rainwater system suggests that the system exhibits poor stability when dealing with urban flood disasters. The system's normal operational state is more prone to disruption, and its response capabilities are diminished, leading to a delay in the drainage of rainwater within the city and an increased risk of internal flooding. This, in turn, lowers the overall safety of the city.

3. Case Study

The case study area surveyed in this investigation is a typical newly developed urban area located in the Suzhou High-Tech Zone, a city situated in the lower reaches of the Yangtze River in China. The region has a northern subtropical humid monsoon climate with abundant rainfall. The typical rainstorms are predominantly concentrated in the months from June to August. Against a backdrop of rapid urbanization, the underlying surface exhibits significant variability in water permeability, leading to a surge in flood events triggered by storms in recent years. The total area of the region is 7.32 hectares, primarily composed of residential buildings, lawn areas, flower beds, roads, and small squares. The impervious area accounts for 5.70 hectares, representing 78% of the total regional area. To the south of the area lies a small river, while the east and west sides are bordered by main drainage pipes along the roads, which collect rainwater discharged into the river through the eastern and western trunk pipes. The drainage network is equipped with three stormwater inlets, distributed in the southeast, southwest, and due south directions of the area. The regional schematization is depicted as shown in Figure 2.

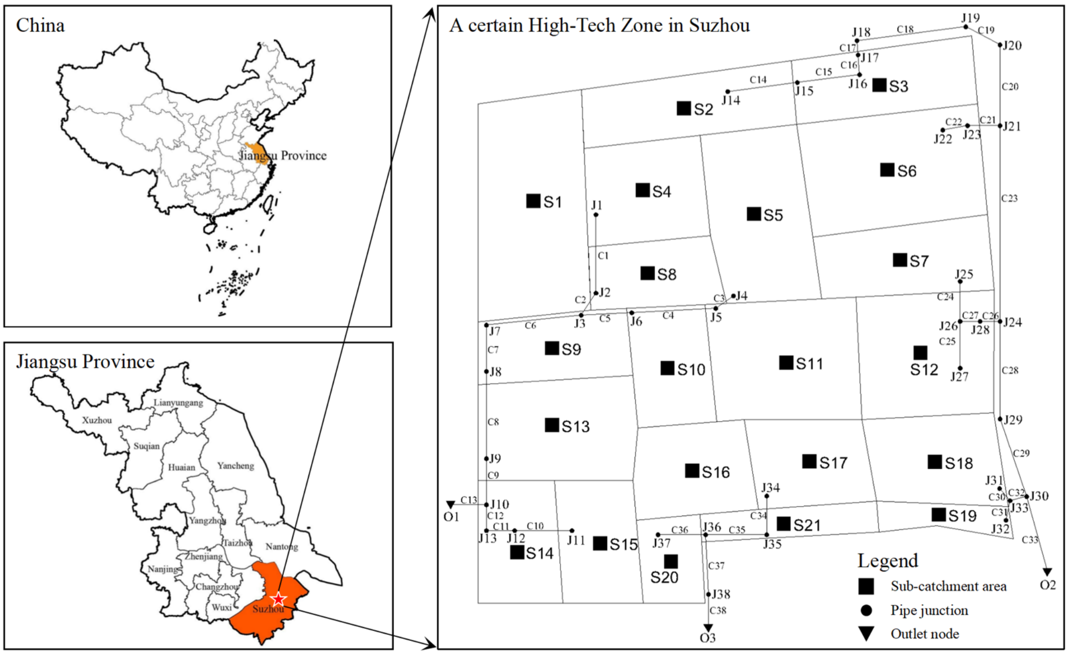

Figure 2. Geographical location and profile of the study area. S1–S21 represent the sub-catchment area; J1–J38 denote the pipe junction; C1–C38 signify the pipe segment; O1–O3 represent the outlet mode.

The entire residential complex is schematized into 21 sub-catchment areas, 38 pipe segments, and 41 nodes, which include three outlets.

By selecting such a region as the research area for evaluating the vulnerability of an urban rainwater system, our aim is to propose designs and plans geared towards mitigating the impact of flooding and storm events in the current study area and similar urban regions.

3.1. Calculation of Vulnerability

Each factor involved in the vulnerability calculation process is transformed into a dimensionless value ranging from 0 to 1, representing its normalized reference range. This reference range can be established through experiential judgment, data statistics, expert evaluations, standards, regulations, and similar criteria. Relative elevation is determined by the difference between ground and rainwater inlet elevations, with the ground elevation taken as the average around the inlets (within two meters). In this instance, the average relative elevation h_a was 0.18. The drainage capacity of a standard rain inlet fell within the range of 10 to 30 L/s. Utilizing statistics on the type and quantity of main inlet holes, the flow capacity q_a was determined as 0.64 and the characterization of the outfall setting condition O_a was evaluated as 0.68. Examination of rainwater system design drawings and files provided by the local regional council allowed us to ascertain the scale and slope of the pipeline, setting the values of d_a and i_a at 0.68 and 0.35, respectively. Furthermore, the storage capacity of the detention tank T_a and the regulation quantity of the pump station Q_a were confirmed as 0.90 and 0.80, respectively.

The characteristic values of social factors were predominantly acquired through thorough investigation, data analysis, and experience-based definitions. In this case, the values of G_a, S_a, P_a, and C_a were ultimately established as 0.65, 0.75, 0.50, and 0.45, respectively.

$$M_1 = \begin{bmatrix} 1 & b_{Physical/Social} \\ b_{Social/Physical} & 1 \end{bmatrix} = \begin{bmatrix} 1 & 6/4 \\ 4/6 & 1 \end{bmatrix} \quad (10)$$

Based on the computation, the maximum eigenvalue (λ_{max}) is 2, and the random consistency ratio (CR) is 0, which is less than 0.10. The hierarchical sorting results align with the consistency requirements.

In the process of determining weight values, the initial step involves constructing a judgment matrix within the same layer of the assessment framework. For instance, a matrix in the logical layer between the physical and social components can be established based on their respective judgment values, denoted as M_1. The matrices for physical and social factors are represented as M_2 and M_3 in Tables 4 and 5. Subsequently, the weight vector is derived using these matrices.

Table 4. Judgment matrix of physical factors.

M_2	*h*	*Q*	*O*	*d*	*i*	*Q*	*T*
h	1	2/4	2/3	2/9	2/1	2/6	2/7
q	4/2	1	4/3	4/9	4/1	4/6	4/7
O	3/2	¾	1	3/9	3/1	3/6	3/7
d	9/2	9/4	9/3	1	9/1	9/6	9/7
i	1/2	¼	1/3	1/9	1	1/6	1/7
Q	6/2	6/4	6/3	6/9	6/1	1	6/7
T	7/2	7/4	7/3	7/9	7/1	7/6	1
$\lambda_{max} = 7;\ CR = 0 < 0.10$							

Note: *h* denotes the relative elevation; *q* represents the flow capacity of gutter inlet holes; *O* characterizes the outfall setting condition; *d* represents the diameter; *i* denotes yjr slope of pipes; *Q* signifies the regulation quantity of the pump station; *T* embodies the storage capacity of the detention tank.

Table 5. Judgment matrix of social factors.

M_3	*G*	*S*	*P*	*C*
G	1	6/5	6/3	6/7
S	5/6	1	5/3	5/7
P	3/6	3/5	1	3/7
C	7/6	7/5	7/3	1
$\lambda_{max} = 4;\ CR = 0 < 0.10$				

Note: *G* gauges the management level of the stormwater system by the government; *S* denotes the proportion of impermeable pavement; *P* signifies the cleaning frequency of the urban target region; *C* reflects the financial investment situation.

All of the assignment, weight, and vulnerability values mentioned and calculated in this instance are presented simply in Tables 6 and 7.

Table 6. Characterization and weight values of physical and social factors.

Hierarchy	Factors						
Physical Index	h_a 0.18	q_a 0.64	O_a 0.68	d_a 0.65	i_a 0.35	Q_a 0.90	T_a 0.80
	$\mathscr{W}_h$ 0.0375	$\mathscr{W}_q$ 0.0750	$\mathscr{W}_O$ 0.0563	$\mathscr{W}_d$ 0.1687	$\mathscr{W}_i$ 0.0187	$\mathscr{W}_Q$ 0.1125	$\mathscr{W}_T$ 0.1313
Social Index	G_a 0.65	S_a 0.75	P_a 0.50	C_a 0.45			
	$\mathscr{W}_G$ 0.1143	$\mathscr{W}_S$ 0.0952	$\mathscr{W}_P$ 0.0571	$\mathscr{W}_C$ 0.1333			

In accordance with the rainwater system vulnerability assessment model, the vulnerability of urban rainwater systems comprises two integral components: physical vulnerability $\left(V_{Physical}\right)$ and social vulnerability (V_{Social}). The calculated values for $V_{Physical}$ and V_{Social} stand at 0.4155 and 0.2342, respectively.

Table 7. Calculation of physical and social vulnerability.

Hierarchy	Factors							V_i	V_{system}
Physical Index	$h_a \cdot \mathscr{W}_h$ 0.0068	$q_a \cdot \mathscr{W}_q$ 0.0480	$O_a \cdot \mathscr{W}_O$ 0.0383	$d_a \cdot \mathscr{W}_d$ 0.1097	$i_a \cdot \mathscr{W}_i$ 0.0065	$Q_a \cdot \mathscr{W}_Q$ 0.1013	$T_a \cdot \mathscr{W}_T$ 0.1050	$V_{Physical}$ 0.4155	0.6497
Social Index	$G_a \cdot \mathscr{W}_G$ 0.0743	$S_a \cdot \mathscr{W}_S$ 0.0714	$P_a \cdot \mathscr{W}_P$ 0.0286	$C_a \cdot \mathscr{W}_C$ 0.0600				V_{Social} 0.2342	

3.2. Results and Discussion

Referring to Table 3, when V_{system} falls within the range of 0.6–0.9, the rainwater system is classified as having a high level of vulnerability. Upon encountering rainfall with a recurrence interval of 1 to 5 years, the ground will experience water accumulation with depths ranging from 0.15 m to less than 0.4 m, and the duration of water accumulation will be between 1 h and less than 2 h, leading to minor internal flooding in the area.

Analyzing the vulnerability of the case study area from a comprehensive perspective of the rainwater system reveals a value of 0.6497, indicating high vulnerability and suggesting that the system has poor drainage performance, with a low capacity to handle heavy rainfall. When encountering rainfall with a recurrence interval greater than 5 years ($p > 5$ a), severe water accumulation is likely to occur, which could significantly impact public life. In order to conduct an analysis of the vulnerability composition of the case study rainwater system and to draw specific conclusions, the proportion of each component is represented in the pie chart depicted in Figure 3.

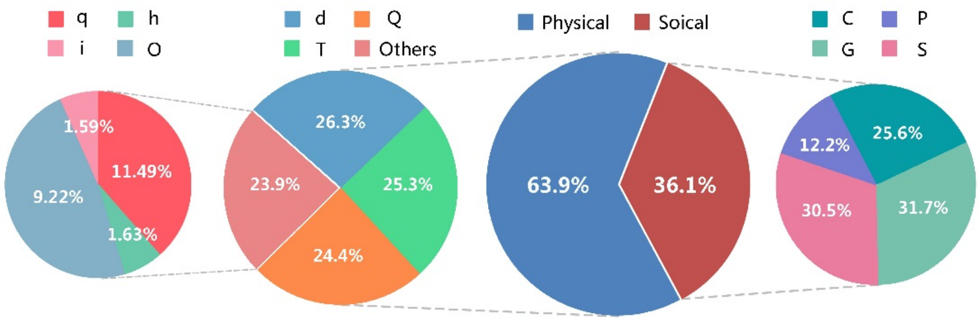

Figure 3. Distribution proportions of vulnerability in the case. *h* denotes the relative elevation; *q* represents the flow capacity of gutter inlet holes; *O* characterizes the outfall setting condition; *d* represents the diameter; *i* denotes the slope of pipes; *Q* signifies the regulation quantity of the pump station; *T* embodies the storage capacity of the detention tank; *G* gauges the management level of the stormwater system by the government; *S* denotes the proportion of impermeable pavement; *P* signifies the cleaning frequency of the urban target region; *C* reflects the financial investment situation.

Upon scrutinizing the calculations derived from the data presented in Table 7 and the graphical representations in Figure 3, the physical vulnerability of the rainwater system in the area under study was found to be 0.4155, accounting for 63.9% of the system's overall vulnerability. The proportion of physical vulnerability within the overall system vulnerability is substantial, indicating a significant influence on the system's comprehensive vulnerability. An examination of the components contributing to the system's physical vulnerability reveals that the diameter of rainwater pipes, the regulatory capacity of pump stations, and the storage capacity of detention basins constitute a considerable share of the physical vulnerability at 26.3%, 23.9%, and 25.3% respectively. The sum of these three components is 75.5%, indicating that their performance is decisive for the physical functionality of the rainwater system. To reduce the system's vulnerability, improve the performance of the rainwater system, and enhance its safety, the focus should primarily be on these three aspects at the physical level of the system to achieve a noticeable improvement in system vulnerability.

The high proportion of physical vulnerability in this area relative to the overall system vulnerability indicates that the rainwater system's drainage capacity is far from meeting the actual requirements. This reflects insufficiencies in the design of the rainwater system, as the design is meant to determine the scale of the system's components, which in turn dictates the comprehensive drainage capacity of the system. Therefore, to enhance the safety of the rainwater system, reduce its vulnerability, and achieve the goal of withstanding heavy rainfall, it is necessary to reduce the system's physical vulnerability from the initial design stage. According to the analysis of vulnerability calculations, it has been determined that the impact of various physical factors on the vulnerability of the rainwater system in this study, from the most significant to the least, is as follows: the diameter of rainwater pipes, the storage capacity of the detention tank, the regulation quantity of the pump station, the flow capacity of gutter inlet holes, the outfall setting condition, the relative elevation, and the slope of pipes.

The social vulnerability of the rainwater system in the area is 0.2342, representing 36.1% of the system's overall vulnerability. Although the proportion of social vulnerability within the system is relatively smaller than that of physical vulnerability, its impact on the system's overall vulnerability cannot be overlooked, as it influences the performance of the drainage system to a certain extent. From the components contributing to the area's social vulnerability, the management level of the rainwater system, the proportion of impermeable pavement, and the financial investment situation have significant contributions at 31.7%, 30.5%, and 25.6% respectively. The sum of these three components is 87.8%, indicating that they have a substantial impact on the determination of the rainwater system's social vulnerability. Measures to reduce the social vulnerability of the rainwater system should be targeted at these three areas, where the effects achieved would be the most direct and significant.

The social vulnerability of the rainwater system takes into greater account the impact of human subjective proactivity on the system's vulnerability. Through their initiative, humans can mitigate the encroachment of the surrounding environment on the rainwater system. For instance, relevant authorities should enhance management efforts, repair and reinforce damaged system structures, and dredge pipes, or by increasing the area of permeable road surfaces and improving groundwater infiltration capabilities, humans can reduce the formation of surface runoff. This, to a certain extent, decreases the drainage load on the rainwater system, which is beneficial for maintaining the effectiveness of its functions. After the construction of the rainwater pipe network system, with the physical vulnerability essentially determined, reducing social vulnerability is a highly feasible approach to lowering overall system vulnerability and can achieve significant results.

In our study, the vulnerability of the system was intricately designed based on the physical composition and potential integration, as illustrated in the schematic diagram presented in Figure 4.

It is evident that the vulnerability of the rainwater system is not a singular metric; rather, it is a comprehensive indicator that encompasses both the system's inherent physical attributes and its closely related social attributes. This approach provides an objective and holistic reflection of the influencing factors affecting the operation of the rainwater system, both internal and external. It allows for a deeper understanding of the rainwater system and offers clearer insights into the frequent occurrence of urban waterlogging; the high vulnerability of the rainwater system leads to urban water accumulation and internal flooding. The genesis of urban waterlogging is attributable to both the physical components of the rainwater system and the subjective proactivity of human actions. The assessment of the rainwater system's vulnerability can elucidate the causes of urban waterlogging and provide a basis for decision-making in managing and mitigating such incidents.

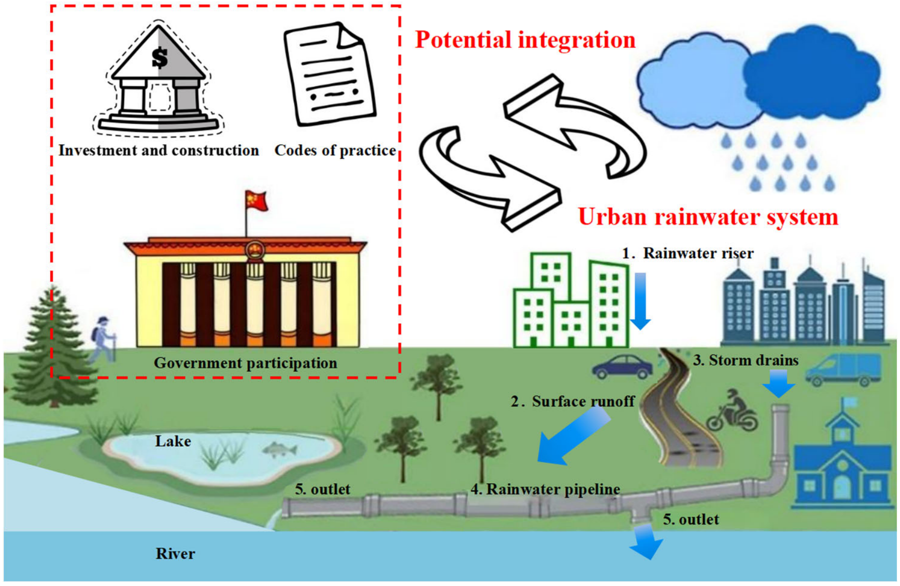

Figure 4. Physical composition and potential integration of an urban rainwater system.

4. Conclusions

This study introduces the concept of urban rainwater system vulnerability and identifies the indicator factors that influence the vulnerability of the rainwater system. Utilizing the analytic hierarchy process (AHP), an index system for the vulnerability assessment of the rainwater system was established, and a vulnerability assessment model for the rainwater system was constructed. This provides a methodological reference for evaluating the vulnerability of the rainwater system and determines the priority order of the most important criteria and sub-criteria in the implementation of rainwater system projects. The urban rainwater system vulnerability calculation model is as follows: the physical vulnerability is $V_{Physical} = h_a \mathscr{W}_h + q_a \mathscr{W}_q + d_a \mathscr{W}_d + i_a \mathscr{W}_i + Q_a \mathscr{W}_Q + T_a \mathscr{W}_T + O_a \mathscr{W}_O$, the social vulnerability is $V_{social} = C_a \mathscr{W}_C + S_a \mathscr{W}_S + G_a \mathscr{W}_G + P_a \mathscr{W}_P$, and the system vulnerability is $V_{system} = V_{Physical} + V_{social}$.

Preliminary standards for the vulnerability assessment of rainwater systems have been established, categorizing the vulnerability of rainwater systems into five levels: $V \in [0.9, 1.0]$, indicating very high vulnerability; $V \in [0.6, 0.9]$, indicating high vulnerability; $V \in [0.4, 0.6]$, indicating moderate vulnerability; $V \in [0.1, 0.4]$, indicating low vulnerability; $V \in [-0.03, 0.1]$, indicating very low vulnerability. The characteristics of rainwater systems with different levels of vulnerability under rainfall conditions were described, and the system performance and safety performance of rainwater systems under various vulnerability levels were determined. The analysis method for the results of the vulnerability assessment was elucidated. Through the analysis and evaluation of rainwater system vulnerability, not only was the current state of the rainwater system clarified, but a scientific reference basis was also provided for the upgrading, transformation, and optimized operation and management of the rainwater system.

A typical newly developed urban area within the Suzhou High-Tech Zone was selected as the subject of study. An evaluation model for the vulnerability of the rainwater system in this area was constructed, and a vulnerability assessment of its rainwater system was conducted. The calculations determined the following: the physical vulnerability of the rainwater system in the area is 0.4155, the social vulnerability of the residential community is 0.2342, and the overall vulnerability of the community's system is 0.6497, which is indicative of high vulnerability, poor system performance, and low safety performance. When the area encounters rainfall with a recurrence interval of $1 \leq p < 5$ years, the community is susceptible to minor internal flooding.

In conducting a vulnerability assessment of the rainwater system, it was found that in the analysis of physical vulnerability, the diameter of rainwater pipes, the storage capacity of the detention tank, and the regulation quantity of the pump station play a decisive role in the system. To enhance system performance and increase safety against storm surges and flood events, designers should focus primarily on increasing the diameter of the pipes and the design scale of the storage structures, which can effectively reduce the system's vulnerability. Under conditions where the physical aspects are essentially determined, reducing the overall comprehensive vulnerability by lowering social vulnerability can achieve better results. Social vulnerability is mainly concerned with considering the impact of human initiatives. Relevant authorities should strengthen management, actively repair damaged components, and dredge rainwater inlets and pipes. Increasing the permeable area will reduce surface runoff, which can also reduce system pressure and extend the lifespan of its components.

However, within the assessment system, the selection of factors may not be comprehensive, and the determination of weight values is, to some extent, contingent upon human consciousness. The design of the hierarchical structure depends not only on the nature of the decision-making process participants but also on their knowledge, judgment, and experience. However, even after construction, it can be modified to accommodate new standard concepts, and factors can be added, removed, or altered to suit different regions. Vulnerability research should be practical, especially in engineering design or system assessment. Subsequent research on assessment systems should pay attention to the logic and comprehensiveness of the selected indicators, require a more objective quantification of weights, and conduct deeper exploration and improvement in the construction of hierarchical structures and assessment systems.

Author Contributions: Conceptualization, C.L. and L.L.; methodology, C.L.; formal analysis, L.L. and F.X.; investigation, L.L.; data curation, F.X.; writing—original draft preparation, L.L.; writing—review and editing, C.L. and H.W.; visualization, H.W. and F.X.; supervision, H.W.; project administration, C.L.; funding acquisition, C.L. All authors have read and agreed to the published version of the manuscript.

Funding: The study was funded by two Technology Support Project, including Suzhou Water Resources and Water Science and Technology Project (Project No. 2022008): Exploration of Zero-Energy Consumption and Low-Carbon Exhaust Outlet Ecological Management Technology and Integrated Equipment and Suzhou Social Development Science and Technology Innovation Key Project (Project No. 2022SS09): Research and Development of Low-Carbon Intelligent Outlet Outflow Ecological Management Equipment and System and Application Demonstration.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data generated or analyzed during this study are included in this published article.

Acknowledgments: The study was supported by a grant from the "333" High-level Talents Cultivation Project of Jiangsu Province.

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

References

1. Chikhi, F.; Li, C.; Ji, Q.; Zhou, X. Review of Sponge City implementation in China: Performance and policy. *Water Sci. Technol.* **2023**, *88*, 2499–2520. [CrossRef] [PubMed]
2. Li, C.; Zhang, Y.; Wang, C.; Shen, R.; Gisen, J.I.A.; Mu, J. Stormwater and flood simulation of sponge city and LID mitigation benefit assessment. *Environ. Sci. Pollut. Res.* **2023**. [CrossRef] [PubMed]
3. Nguyen, T.T.; Ngo, H.H.; Guo, W.; Wang, X.C.; Ren, N.; Li, G.; Ding, J.; Liang, H. Implementation of a specific urban water management—Sponge City. *Sci. Total Environ.* **2019**, *652*, 147–162. [CrossRef] [PubMed]
4. Yin, D.; Xu, C.; Jia, H.; Yang, Y.; Sun, C.; Wang, Q.; Liu, S. Sponge City Practices in China: From Pilot Exploration to Systemic Demonstration. *Water* **2022**, *14*, 1531. [CrossRef]

5. Hongyong, L.; Zujie, L. Research on Project Management Mode of Sponge City. *Sci. Technol. Manag. Res.* **2018**, *38*, 232–236. [CrossRef]
6. Li, J.; Jiang, Y.; Zhai, M.; Gao, J.; Yao, Y.; Li, Y. Construction and application of sponge city resilience evaluation system: A case study in Xi'an, China. *Environ. Sci. Pollut. Res.* **2023**, *30*, 62051–62066. [CrossRef]
7. Zang, T.; Wang, Z.; Wei, X.; Zhou, Y.; Wu, J.; Zhou, B. Current Status and Perspective of Vulnerability Assessment of Cyber-Physical Power Systems Based on Complex Network Theory. *Energies* **2023**, *16*, 6509. [CrossRef]
8. Ishtiaque, A.; Estoque, R.; Eakin, H.; Parajuli, J.; Rabby, Y. IPCC's current conceptualization of "vulnerability" needs more clarification for climate change vulnerability assessments. *J. Environ. Manag.* **2022**, *303*, 114246. [CrossRef] [PubMed]
9. Glp, G.L.P. Science Plan and Implementation Strategy. *Environ. Policy Collect.* **2009**, *20*, 1262–1268. [CrossRef]
10. Timmerman, P. *Vulnerability, Resilience and the Collapse of Society: A Review of Models and Possible Climatic Applications*; Institute for Environmental Studies, University of Toronto: Toronto, ON, Canada, 1981.
11. Gordon, B.L.; Koebele, E.A.; Rego, J.J.; Harpold, A.A.; Ajami, N.K. Adaptable and comprehensive vulnerability assessments for water resources systems in a rapidly changing world. *J. Environ. Manag.* **2024**, *352*, 119958. [CrossRef]
12. Chen, B.; Zeng, N.; Tam, K.P. Do social networks affect household financial vulnerability? Evidence from China. *Financ. Res. Lett.* **2024**, *59*, 104710. [CrossRef]
13. Sheikh, J.; Allotey, J.; Kew, T.; Khalil, H.; Galadanci, H.; Hofmeyr, G.J.; Abalos, E.; Vogel, J.P.; Lavin, T.; Souza, J.P.; et al. Vulnerabilities and reparative strategies during pregnancy, childbirth, and the postpartum period: Moving from rhetoric to action. *eClinicalMedicine* **2024**, *67*, 102264. [CrossRef] [PubMed]
14. Ma, L.; Hou, K.; Tang, H.; Liu, J.; Wu, S.; Li, X.; Sun, P. A new perspective on the whole process of ecological vulnerability analysis based on the EFP framework. *J. Clean. Prod.* **2023**, *426*, 139160. [CrossRef]
15. Zheng, H.; Deng, Z.; Guo, L.; Liu, J.; Liu, L.; Li, T.; Zheng, H.; Zheng, T. Assessment of Building Physical Vulnerability in Earthquake-Debris Flow Disaster Chain. *Int. J. Disaster Risk Sci.* **2023**, *14*, 666–679. [CrossRef]
16. Spielman, S.; Tuccillo, J.; Folch, D.; Schweikert, A.; Davies, R.; Wood, N.; Tate, E. Evaluating social vulnerability indicators: Criteria and their application to the Social Vulnerability Index. *Nat. Hazards* **2020**, *100*, 417–436. [CrossRef]
17. Gatto, A.; Busato, F. Energy vulnerability around the world: The global energy vulnerability index (GEVI). *J. Clean. Prod.* **2020**, *253*, 118691. [CrossRef]
18. Forsberg, S.; Thomas, K.; Bergkvist, M. Power grid vulnerability analysis using complex network theory: A topological study of the Nordic transmission grid. *Phys.-Stat. Mech. ITS Appl.* **2023**, *626*, 129072. [CrossRef]
19. Mohseni-Bonab, S.; Kamwa, I.; Rabiee, A.; Chung, C. Stochastic optimal transmission Switching: A novel approach to enhance power grid security margins through vulnerability mitigation under renewables uncertainties. *Appl. Energy* **2022**, *305*, 117851. [CrossRef]
20. Barros, M.; Leitao, J.; Aranha, T.; Simsek, S.; Buley, R.; Fernandez-Figueroa, E.; Gladfelter, M.; Wilson, A.; Capelo-Neto, J. Icyano: A cyanobacterial bloom vulnerability index for drinking water treatment plants. *Water Supply* **2020**, *20*, 3517–3530. [CrossRef]
21. Kerpelis, P.; Alexakis, D.; Golfinopoulos, S. A Qualitative Approach to the Seismic Estimation of Wastewater Treatment Plants and Potential Impacts on the Hydrosphere. *Water* **2022**, *14*, 3225. [CrossRef]
22. Pan, S.; Yan, H.; He, J.; He, Z. Vulnerability and resilience of transportation systems: A recent literature review. *Phys.-Stat. Mech. ITS Appl.* **2021**, *581*, 126235. [CrossRef]
23. Zhang, D.; Du, F.; Huang, H.; Zhang, F.; Ayyub, B.; Beer, M. Resiliency assessment of urban rail transit networks: Shanghai metro as an example. *Saf. Sci.* **2018**, *106*, 230–243. [CrossRef]
24. Ke, Q.; Lin-Sen, W.; Tao, T. Resilience Assessment of Urban Rainwater Drainage Systems. *China Water Wastewater* **2016**, *32*, 6–11. [CrossRef]
25. Lin, L. Assessment of Flood Drainage Capacity of Typical Stormwater Gully System in Hefei City. *China Water Wastewater* **2014**, *30*, 150–154. [CrossRef]
26. Guan, X.; Wang, J.; Xiao, F. Sponge city strategy and application of pavement materials in sponge city. *J. Clean. Prod.* **2021**, *303*, 127022. [CrossRef]
27. Ramanathan, R. A note on the use of the analytic hierarchy process for environmental impact assessment. *J. Environ. Manag.* **2001**, *63*, 27–35. [CrossRef] [PubMed]
28. Huang, I.; Keisler, J.; Linkov, I. Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. *Sci. Total Environ.* **2011**, *409*, 3578–3594. [CrossRef]
29. Dos Santos, P.; Neves, S.; Sant'Anna, D.; de Oliveira, C.; Carvalho, H. The analytic hierarchy process supporting decision making for sustainable development: An overview of applications. *J. Clean. Prod.* **2019**, *212*, 119–138. [CrossRef]
30. Krajnc, D.; Glavic, P. A model for integrated assessment of sustainable development. *Resour. Conserv. Recycl.* **2005**, *43*, 189–208. [CrossRef]
31. Alonso, J.; Lamata, M. Consistency in the analytic hierarchy process: A new approach. *Int. J. Uncertain. Fuzziness Knowl.-Based Syst.* **2006**, *14*, 445–459. [CrossRef]
32. Ghorbani, M.K.; Hamidifar, H.; Skoulikaris, C.; Nones, M. Concept-Based Integration of Project Management and Strategic Management of Rubber Dam Projects Using the SWOT–AHP Method. *Sustainability* **2022**, *14*, 2541. [CrossRef]

33. Hamidifar, H.; Ghorbani, M.K.; Bakhshandeh, M.A.; Gholami, S. A multi-criteria multidimensional model for optimal selection of rural water supply systems. *AQUA—Water Infrastruct. Ecosyst. Soc.* **2023**, *72*, 1042–1056. [CrossRef]
34. Saaty, T.L. A scaling method for priorities in hierarchical structures. *J. Math. Psychol.* **1977**, *15*, 234–281. [CrossRef]