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Seismic Performance Assessment of Water Distribution Systems Based on Multi-Indexed Nodal Importance

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Abstract: Seismic performance assessment of water distribution systems (WDSs) based on hydraulic simulation is essential for resilience evaluation of WDSs under earthquake disasters. The assessment is mainly to determine how the water supply will be affected due to pipe breaks caused by the earthquake, with the water supply loss estimated based on the loss of supply to nodes. Existing research works usually use the average or overall performance metric of all user nodes as the system performance indicator without considering user nodes' individual performance and criticality. This paper proposes a framework to evaluate the importance of user nodes considering post-earthquake rescue service and the seismic performance of individual user nodes in the WDS, which supports the pipeline renovation plan to improve the performance of critical user nodes. The importance of user nodes is evaluated by a multi-index model, including the indices for daily service, post-earthquake rescue service, and network topology influence of user nodes. These indices evaluate the importance of user nodes in terms of their roles for daily water service, emergent rescue service, and water transmission to other nodes, respectively. Fragility model of pipelines evaluates the earthquake-induced damages of the WDS, and the seismic performance assessment of the WDS system is performed by the hydraulic model of the WDS with pipeline damages. The proposed framework is implemented in an actual WDS; the results show that the importance classification to user nodes by multi-index approach can identify the critical user nodes for post-earthquake rescue service, which traditional methods may ignore. The importance classification and seismic performance of individual user nodes make it feasible to check the seismic performance of critical user nodes and formulate a targeted pipeline renovation plan to focus limited resources on critical user nodes.

Keywords: water distribution systems; seismic performance analysis; hydraulic simulation; importance of user nodes; multi-index evaluation

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1. Introduction

The water distribution system (WDS) is one of the critical lifeline systems, which provides fundamental resources and services to communities. After a severe earthquake event, the damage of the structural components of WDS, such as pipelines, pump stations, and tanks, may significantly impair the functionality and serviceability of WDS and seriously hamper the post-disaster restoration of communities. According to the statistical analyses of post-earthquake restoration behaviors of infrastructures under 32 global earthquakes from 1960 to 2015 with magnitude ranges from 6.0 to 9.5 [1], the WDS has the longest serviceability shutdown and restoration time among the urban lifeline systems including water, power, gas and telecommunication systems. The seismic performance measure of WDS is a quantitative indicator for failure consequence assessment and provide fundamental evaluation of the system behaviour, which plays an important role in disaster resilience evaluation of WDS.

Many studies have conducted the seismic performance evaluation of WDS, the network connectivity reliability model [2–5] and the water flow-based hydraulic model [6,7] are two widely used evaluation models. The connectivity reliability model, which considers the seismic reliability of pipelines and network topology, is a simplified model and is usually classified as the graph theory approach [8]. It needs less data to establish the model and could provide a reasonable result for the seismic performance evaluation of the WDS [9–13]. The water flow-based hydraulic model is a more complex approach, consisting of the seismic fragility analysis of pipelines, the assessment of the opening area of the leakage on the damaged pipelines, and the hydraulic simulation of the earthquake-damaged WDS [6,14–16]. Shinozuka et al. [9] compared the results of the connectivity reliability measure and that of the flow-based hydraulic simulation measure in a small WDS. It was found out that the water transmission lines are more likely to lose their water supply service before losing connectivity. O'Rourke and his co-workers [6,17,18] have done pioneering works on applying the hydraulic model into the seismic performance evaluation of large-scale WDS by the computer program Graphical Iterative Response Analysis for Flow Following Earthquakes (GIRAFFE) [6]. In their studies, earthquake-induced pipelines damages were simulated by leaks and breaks in the hydraulic model, the parameters of which were verified by the performance of the Los Angeles WDS with monitor data after the 1994 Northridge earthquake [17]. Yoo et al. [19] made a complement to the hydraulic simulation model for seismic performance evaluation of WDS by using pressure-dependent demand (PDD) and pressure-dependent leakage (PDL) techniques.

An important role of seismic performance evaluation of WDS is to provide a basis for pre-and post-disaster intervention such as seismic design, renovation of pipelines, and restoration of the earthquake-induced damages in the WDS. Under the condition of limited money budget and resources investment for the intervention measures, decision-makers should utilize an efficient model to formulate strategies to balance the investment and the seismic performance benefits. As to the pre-earthquake intervention measures, Wang and Au [20] proposed a method to identify critical water supply links to crucial water consumers under earthquake disasters. Their study did not provide methods to determine crucial consumers and the crucial consumers in the case WDS were assumed by the authors. Lee et al. [21] identified the critical path for optimal seismic reliability protection of WDS with limited money budget and resources. The optimal critical path was selected by comparing the system performance increment and the construction costs among 9 candidate paths. Didrik et al. [22] developed a graph-theory-based method to identify critical link elements on the functionality of the whole WDS, which aims to support prioritizing maintenance or rehabilitation activities. The sum of all nodes measured the influence of links on the functionality of the WDS. Li et al. [23] developed a model to evaluate the importance of links in electronic power supply networks considering multi-element failures. These aforementioned studies have focused on determining critical links according to their impacts on the system's overall performance but did not pay attention to the performance of individual users (customers) in the system. Yoo et al. [16] conducted an optimal seismic design of WDS that aims to maximize the system seismic performance subject to the constraints on total pipeline cost and nodal water pressure. The system performance was measured by the overall water supply of the WDS. Li et al. [24] utilized the topology optimization of pipeline networks to minimize the construction cost of pipelines subject to the seismic connectivity reliability constraints at user nodes. In their work, all the user nodes were set with the same reliability constraint, the differential water demand among user nodes was not considered.

As to the post-earthquake recovery, when the waterworks cannot restore water supply to all users in a short time, the prior strategy is to restore water serviceability to critical users (e.g., hospitals, firefighting stations, and shelters for evacuation) [25]. In the 2018 water industry (WDSA/CCWI) Joint Conference, a competition entitled Battle of Post disaster Response and Restoration (BPDRR) was set up for the solutions on the response and service restoration of WDS after five earthquake scenarios [26]. Ten teams participated in the battle and submitted their approaches and results. Diego et al. [26] described the approaches and results presented by the ten teams. One of the consensus reached by participants is that installing more isolation valves would reduce the impact of pipe damages. Zhang et al. [27] proposed a dynamic optimization framework to maximize the resilience of a post-disaster WDS using six different metrics. The metrics include the water supply service restoration of critical users, rapidity of the system recovery, water loss, etc. Balut et al. [28] utilized the ranking approach to prioritize the pipes' importance by a multi-criteria decision method, namely the preference ranking organization method for enrichment evaluation (PROMETHEE). The repair schedule of pipe damages was determined by the PROMETHEE method based on different types of rankings and the weights obtained from expert recommendations. Han et al. [29] used the hydraulic simulation model to simulate the seismic performance during the post-earthquake recovery process of WDS. They developed a dynamic cost-benefit method to determine the post-earthquake recovery sequence of pipeline damages to maximize the overall seismic resilience of WDS.

Given the situation without sufficient budget and resources to improve the overall system performance, decision-makers should formulate the priority strategy to improve the seismic performance of critical user nodes rather than all user nodes. In the studies above on the seismic performance evaluation of WDS, the performance is generally measured either by the system's overall value or by the average metric of all user nodes in the WDS. The performance of individual user nodes has not been studied separately, which disabled the pre-/post-earthquake intervention models on assigning limited resources to the critical user nodes.

This paper provides a framework for seismic performance evaluation of WDS based on the importance classification of user nodes to address this problem. First, a multi-index model that comprehensively considers daily service, post-earthquake rescue services, and the network topology influence is proposed. Then, the seismic performance of individual user nodes is obtained by the hydraulic simulation of WDS. Finally, the pipeline renovation plan aims to improve the seismic performance of critical user nodes under limited intervention investment.

2. Methodology

The framework to evaluate the seismic performance of WDS based on the importance of user nodes includes four main steps: (1) Evaluate the comprehensive importance of user nodes according to a multi-index measure developed in this study; (2) Simulate the seismic damages of pipelines based on the fragility model of pipelines; (3) Simulate the post-earthquake water serviceability (seismic performance) of user nodes by the hydraulic model of the WDS with the damaged pipelines; (4) Check the post-earthquake performance of user nodes based on results from both (1) and (3), and provide pipeline renovation plan to improve the post-earthquake performance of critical user nodes. Figure 1 shows the overall framework. In addition, the probabilistic analysis and Monte Carlo simulation (MCS) were used to simulate the seismic damage states of pipelines in step (2) and water serviceability of user nodes in step (3).

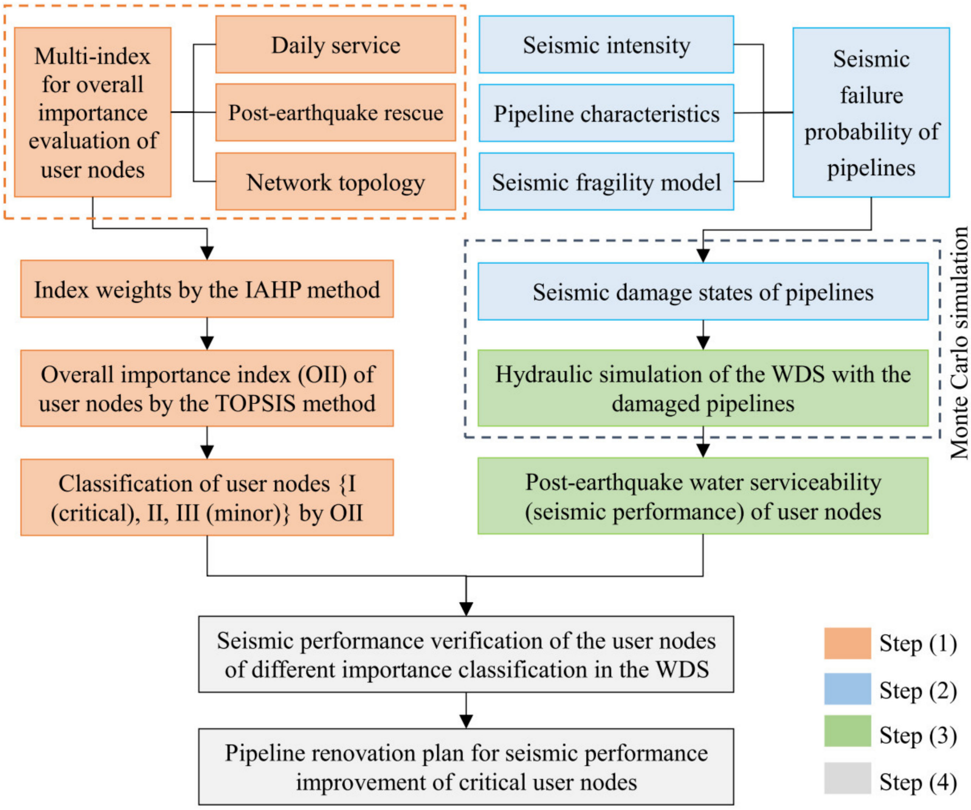

Figure 1. The framework for seismic performance evaluation of WDS based on nodal importance.

2.1. Multi-Indexed Importance Measure of User Nodes

In the geometric topology network of water distribution pipelines, the node element is generally located at the junction of pipelines. The water consumption of users along with a pipeline is usually allocated to the two end nodes of the pipeline. Then the node elements in the network are termed user nodes. A multi-index model is proposed to assess the importance of user nodes by considering their daily service, post-earthquake rescue service, and the influence of network topology. The reason to use these three kinds of indices is based on the cognition that the WDS should provide continuous service in the pre-and post-earthquake period. The report of Applied Technology Council [25] points out that water service should be firstly provided to critical facilities during the short-term phase of disaster restoration, and then gradually restoration to pre-event functionality. Moreover, the research works by Pagano et al. [8] and Yazdani et al. [10] indicate that the topology characteristics measured by the graph theory approach also have a non-negligible influence on the system performance of WDS.

The multi-index evaluation model is proposed and presented in Figure 2. To evaluate the overall importance of user nodes, first, the degree of user nodes' importance, I, are separately evaluated by three main indices (I_i, i = 1,2,3) and their sub-indices. Then, the overall importance of the user nodes is computed based on the index values and index weights by a multi-criteria decision-making method, i.e., the technique for order preference by similarity to an ideal solution (TOPSIS) [30]. TOPSIS is a popular method to identify comprehensive ranking for a set of elements by multi-criteria [31].

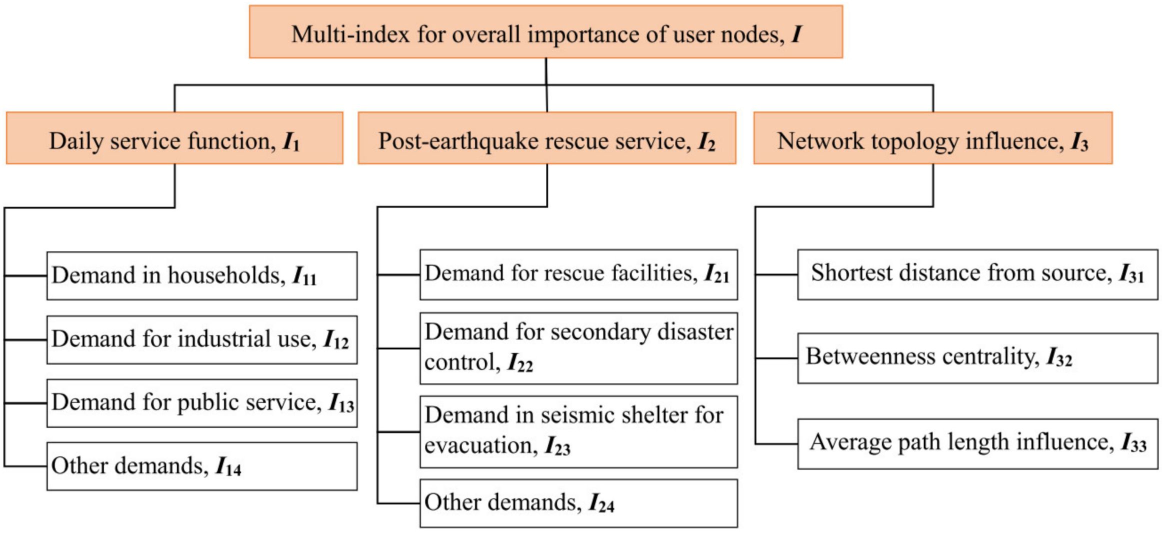

Figure 2. The multi-index model for the overall nodal importance evaluation.

2.1.1. Importance Indices of Daily Service

The daily water demands of an urban WDS generally consist of the household demand, the public service demand, the industrial production demand, and other types of demands, and sub-indices (I_{11}, I_{12}, I_{13}, I_{14}) are used for these demands to evaluate the daily service importance index I_1. Then the value of I_1 can be evaluated by Equation (1). The water demand of the sub-indices I_{1k} ($k = 1, \ldots, 4$) can be evaluated by the following two methods: (i) Use the record data taken from the water meter records of daily water consumption; (ii) Use the regional quota data according to the land type and the unit water demand data provided by water utilities or the water supply planning guidelines, such as the Chinese code for urban water supply engineering planning [32]. User nodes with a much larger daily service importance index I_1 indicate a higher degree of overall importance.

$$I_1(i) = \sum_{k=1}^{4} I_{1k}(i) = \begin{cases} \sum\limits_{k=1}^{4} \sum\limits_{j=1}^{m_k(i)} Q_{ij}; \text{watermeterrecorddata} \\ \sum\limits_{k=1}^{4} \sum\limits_{j=1}^{n_k(i)} A_{ij} \cdot q_j; \text{reginal quota data of water demand} \end{cases} \quad (1)$$

where I_1 (i) is the water demand of daily service at user node i; $m_k(i)$ is the number of water meters corresponding to $I_{1k}(i)$; Q_{ij} is the flow rate at the water meter j; $n_k(i)$ is the number of land types that correspond to $I_{1k}(i)$; A_{ij} is the area of land type j in the service area of node i, which can be determined by constructing Thiessen polygons of the user nodes in the service area of the WDS; q_j is the daily water demand quota of land type j provided by the water supply planning guidelines [32].

2.1.2. Importance Indices of Post-Earthquake Rescue Service

During post-earthquake rescue and restoration, the water demands at user nodes may change significantly from those of daily service under normal conditions. Generally, household and commercial water demands will significantly reduce and disappear, while water demands for post-earthquake rescue will increase tremendously. The post-earthquake water supply to user nodes located in areas for disaster rescue, evacuation shelter, and potential secondary disaster control is more urgent than the others [25,33]. Therefore, the post-earthquake water demands of user nodes can be divided as demand for disaster rescue, secondary disaster control, seismic shelter for evacuation, and other demands. Sub-indices (I_{21}, I_{22}, I_{23}, I_{24}) are used to measure the importance of these demand categories and subsequently used to evaluate the post-earthquake rescue importance of nodes (I_2).

The sub-indices I_{2j} (i) (j = 1, . . . ,4) of user node i can be evaluated according to the facilities or area it serves, namely, facility method or land type method as listed in Table 1.

Table 1. Water demand category for post-earthquake rescue and disaster reduction service.

Demand Categories	Disaster Rescue, I_{21}	Secondary Disaster Control, I_{22}	Seismic Shelter for Evacuation, I_{23}	Other Demands, I_{24}
Facility	Disaster rescue headquarters, hospitals, transportation hub, etc.	Firefighting stations, potential fire site, explosive facilities, etc.	Parks, squares, large-scale stadiums, etc.	Households, commercial and office buildings, factories, etc.
Land type	Land for administrative facilities, medical land, transportation land, etc.	Fire control land, fuel, and gas storage land, etc.	Green space and square, sports land, etc.	Residential, commercial, business, and industrial land, etc.

The post-earthquake water demands of user nodes can be evaluated by Equation (2).

$$I_2(i) = \sum_{k=1}^{4} I_{2k}(i) = \begin{cases} \sum\limits_{k=1}^{4} \sum\limits_{j=1}^{m_k(i)} V_{ij} \cdot g_j; \text{facilitymethod} \\ \sum\limits_{k=1}^{4} \sum\limits_{j=1}^{n_k(i)} A_{ij} \cdot q_j \cdot \alpha_j; \text{landtypemethod} \end{cases} \quad (2)$$

where I_2 (i) is the post-earthquake water demand of user node i; $m_k(i)$ is the number of facilities that correspond to $I_{2k}(i)$; V_{ij} is the volume of facility j; g_j is the unit water demand of facility j; $n_k(i)$ is the number of land types that correspond to $I_{2k}(i)$; A_{ij} is the area of land type j in the service area of node i; q_j is the ordinary water demand quota of land type j provided by the design codes of WDS planning, such as the Chinese code for urban water supply engineering planning [28], and α_j is the adjustment coefficient of post-earthquake water demand for land type j.

According to urban planning on disaster mitigation, the facilities and land type for the post-earthquake service category in Table 1 should be pre-determined. Unit water demand quotas can evaluate the post-earthquake water demands of these facilities. Public service buildings such as hospitals, transportation hubs, schools and sports stadiums are usually constructed with a larger safety factor according to seismic design codes, such as the Chinese seismic design of buildings [34] and ASCE 7-16 of the United States [35]. These facilities are usually pre-selected for post-earthquake rescue service purposes by the urban disaster mitigation plans [36] and the design code of disaster mitigation shelters [37]. It is at the top of the priority list to provide water to these facilities after an earthquake. For the secondary disaster control purpose, it is also necessary to keep water supply to the facilities belong to sub-index $I_{22,}$ as shown in Table 1, which are critical to controlling the post-earthquake fires or explosions. In the "land type" method, the service area of the WDS is divided into individual lands according to the land type category. Their areas and the unit water demand quotas for post-earthquake rescue services can evaluate the post-earthquake water demands of individual lands. The post-earthquake water demands at user nodes can be evaluated either by the "Facility" method or the "land type" method. The facility method requires more information and leads to a more accurate result. The land-type method requires less information and provides an average estimation. Figure 3 presents an illustrative example WDS to introduce the facility method. The network comprises six user nodes (1~6) and nine pipelines (A~G, H, L). The estimation of post-earthquake service demand of user node 5 is illustrated as a typical example according to Table 1 and Equation (2). Figure 4 presents the service land types of the user nodes in the example WDS.

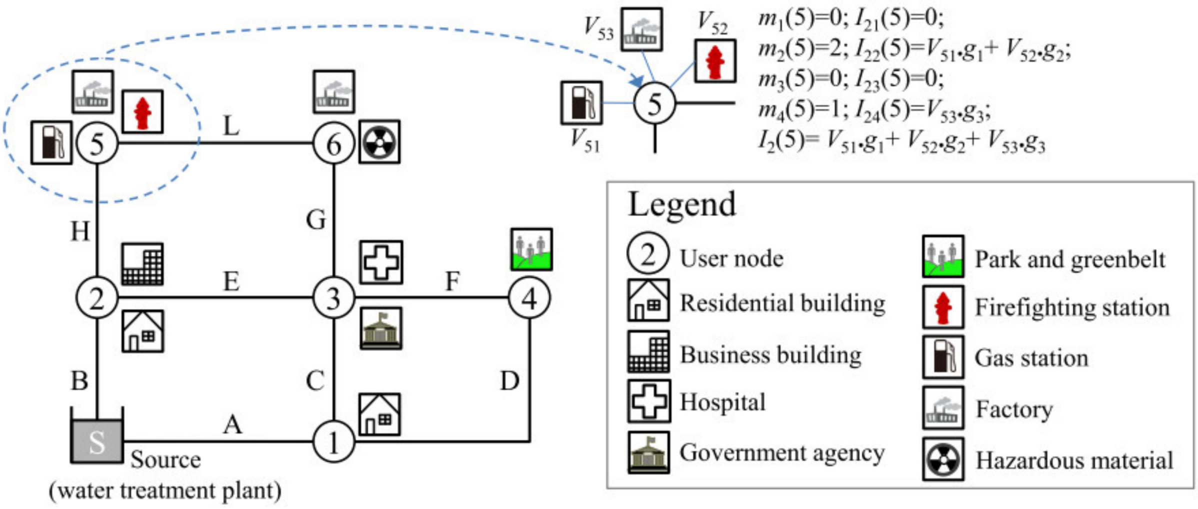

Figure 3. Layout of the example WDS and the service facilities of user nodes.

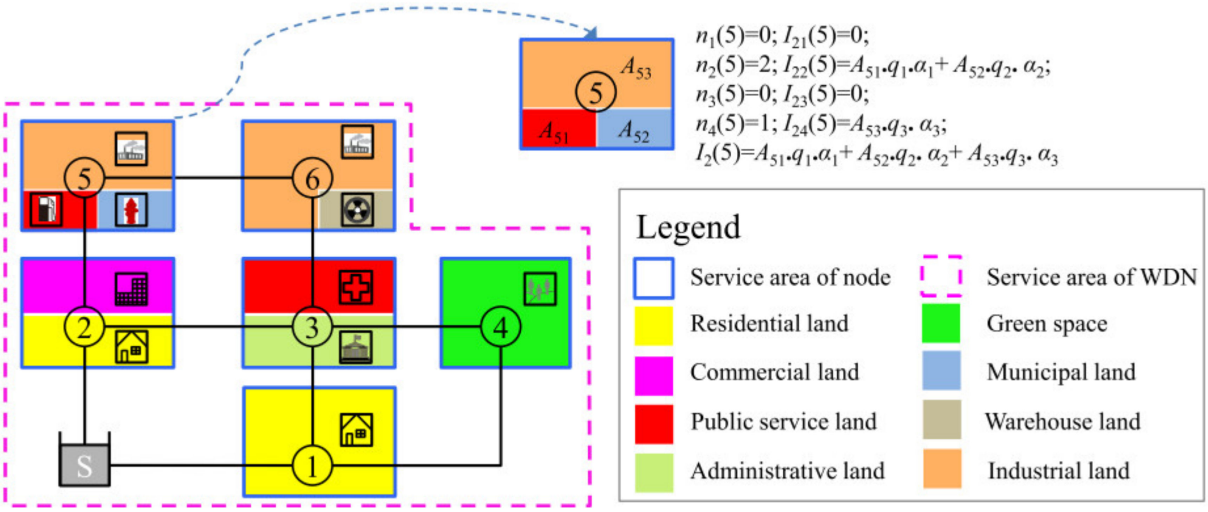

Figure 4. Land types in the service area of user nodes in the example WDS.

2.1.3. Importance Indices of Network Topology

The graph-based metrics can explicitly analyze the inherent topology properties of the WDS, such as connectivity and redundancy. These metrics consider the WDS as a set of multiple interconnected nodes (e.g., demand users, tanks, and reservoirs) and links (e.g., pipes and valves) and have been widely used for WDS performance evaluation [8,11,38]. Giudicianni et al. [39] utilized a topological metric, namely cut-vulnerability, to investigate the critical role of topology-based metrics in the vulnerability analysis of WDS after extreme disasters. In this study, three sub-indices, including "shortest source distance" (I_{31}), "betweenness centrality" (I_{32}), and "average path length influence" (I_{33}), are taken to evaluate the topological importance of user nodes. A network model G(**V**,**E**) consisting of a set of n nodes **V** = $\{v_1, v_2, \ldots, v_n\}$ and a set of m links **E** = $\{e_1, e_2, \ldots, e_n\}$ is utilized to represent the network topology of the WDS. In the node set **V**, element v_s denotes the source node of G, and v_t ($t \in \mathbf{V}$, $t \neq s$) denotes a user node.

(1) Shortest source distance (I_{31}). The shortest source distance of node v_i is defined as the length of the shortest path from source nodes to user node v_i with all links (pipelines) weighted by their lengths:

$$I_{31}(i) = \min\{d(s, v_i)\} \quad (s \in \mathbf{S}) \tag{3}$$

where $d(s,v_i)$ is the length of the shortest path from source node s to user node v_i, which is evaluated by the Dijkstra algorithm [40]; **S** is the set of sources in the WDS, node s denotes an element in set **S**.

The user nodes near the source node always have a much smaller value of $I_{31}(i)$ and are usually located in trunk pipelines, especially for the WDS with the branchlike layout. The smaller values of $I_{31}(i)$ correspond to a much higher importance of user nodes. When evaluating the shortest path $d(s,v_i)$, the weight of network links could be geometric or hydraulic characteristics of the pipelines, such as length, diameter, head loss, flow, and so on. This study takes the length of pipelines as the weight of network links, which is similar to the approach by Torres et al. [41]. Several studies have explored the applications of weighted and unweighted geometric network models of WDS [11,22,38,42–44]. The influence of other weighting approaches on the values of index I31 is worth exploring further research.

(2) Betweenness centrality of user nodes (I_{32}). The sub-index betweenness centrality (BC) has been widely used to assess the centralization of infrastructure networks [45,46]. The BC of node v_i is defined as the number of shortest path visits on v_i from node v_k to v_j ($k \neq j \neq i$; v_k, $v_j \in \mathbf{V}$) [47]. Because network flows from the source to user nodes in the WDS, the BC of user node v_i in the WDS is expressed as:

$$I_{32}(i) = \frac{\sum\limits_{s \neq j \neq i; v_s, v_j, v_i \in \mathbf{V}} N_{s \to j}(i)}{\sum\limits_{s \neq j; v_s, v_j \in \mathbf{V}} N_{s \to j}} \quad (4)$$

where $N_{s\to j}$ is the number of shortest paths from source node v_s to user node v_j ($s \neq j \neq i$), and $N_{s\to j}(i)$ is the number of shortest paths from v_s to v_j passing through node v_i. A user node passed through by a larger number of shortest paths has a larger value of $I_{32}(i)$ and indicates greater importance.

(3) Average path length influence (I_{33}). The average path length is the shortest path between all possible pairs of network nodes [10,11]. This index provided a view of network reachability and efficiency in water transport and was adopted for infrastructure network analysis by Wu and Baker [48]. Given the water transmitted from source to user nodes, the average path length of a WDS network (l_G) is defined as the average length of the shortest paths between sources to user nodes. Based on the network topology with- (G) and without- (G^*i) node v_i and its adjacent links, the average path length influence of a user node v_i is defined as the number of user nodes in network G^*i with the average path length larger than that in network G.

$$I_{33}(i) = \sum_{j=1}^{n} f\left(\frac{1}{n_s}\sum_{s=1}^{n_s} d_{G*i}(s, v_j) > \frac{1}{n_s}\sum_{s=1}^{n_s} d_G(s, v_j)\right) \quad (5)$$

where $I_{33}(i)$ is the average path length influence of user node v_i; n is the No. of user nodes in the network; n_s is the No. of source nodes; $f(*) = 1$ if the judgment * is true and otherwise $f(*) = 0$.

The application results of the three topology indices (I_{31}, I_{32}, and I_{33}) in the example WDS network (Figure 4) are presented in Table 2. The importance ranking to user nodes by I_{31} are {1,2} > {3,5} > {4,6}. The index I_{32} provides a detailed sequence to the user nodes as {2 > 1} > {3 > 5} > {4 = 6}. In index I_{33}, user node 2 has a larger importance than the other nodes. The differences among index values of I_{31}, I_{32}, and I_{33} show that these indices indicate different topology characteristics of the nodes.

Table 2. Topology importance of nodes in the example WDS.

User Node No.	1	2	3	4	5	6
Shortest source distance, I_{31}	1	1	2	3	2	3
Betweenness centrality, I_{32}	1.83	2.17	0.67	0	0.33	0
Average path length influence, I_{33}	0	1	0	0	0	0

2.1.4. Overall Importance Evaluation and Classification of User Nodes

To coordinate the three main indices and eleven sub-indices in Figure 2 to work out the overall importance of user nodes, a multi-criteria decision-making (MCDM) method, namely "Technique for Order Preference by Similarity to an Ideal Solution" (TOPSIS), is utilized. TOPSIS is a popular method to identify comprehensive ranking for a set of elements [30,31]. Among the available MCDM methods, the TOPSIS method has notable advantages in the elements ranking because it only requires the weights of criteria as the subjective input [49].

Before the implementation of the TOPSIS method, the weights of indices should be determined. According to the characteristics of the main indices and their sub-indices; an improved analytic hierarchy process (IAHP) method based on index ranking [50] is utilized to compute the weights of indices I_i, $I_{1j,}$ and I_{2j} (i = 1, 2, 3; j = 1, 2, 3, 4). The IAHP improves the consistency of the comparison matrix by using a sorting and ranking methodology. The ranking of indices I_i, I_{1j} and I_{2j} should be firstly determined, and then the IAHP method is used to obtain the weights of those indices.

When applying the TOPSIS method for the importance ranking of user nodes, user nodes are elements, and sub-indices are treated as the decision criteria of these elements. The assessment of the overall importance of user nodes is then transformed into a MCDM problem. The details of the TOPSIS method can be found in Kim et al. [30] and Certa et al. [51].

After implementing the TOPSIS method, the normalized values of the overall importance of user nodes can be obtained. The importance classification of users can be obtained according to sorting those overall importance values in descending order and intercept the quantiles from the sorted values such as trisection and quartering etc.

2.2. Seismic Fragility of Pipelines

The seismic damages may occur to many facilities in the urban water distribution system, such as pipelines, pumps, and tanks. The seismic damage of pipelines and appurtenances (e.g., valves and joints) scattered in the pipeline network and occupied the majority of the seismic damages in the urban WDS [52]. Therefore, only pipeline damages are considered in the system-level seismic reliability analysis in this study. A similar assumption is also taken in the study by Laucelli and Giustolisi [7] and Romero et al. [18].

The earthquake-induced repairs (damages) of buried pipelines are assumed to follow a Poisson distribution [53]:

$$\text{Prob}\{N = n\} = e^{-RR\cdot L} \cdot \frac{(RR \cdot L)^n}{n!} \tag{6}$$

where n is the number of pipeline damages; RR is the earthquake-induced repair rate (repairs/km) of the pipe evaluated by Equation (8), and L is the length (km) of the pipeline.

The failure probability of an individual pipeline becomes:

$$P_f = 1 - \text{Prob}\{N = 0\} = 1 - e^{-RR\cdot L} \tag{7}$$

Previous research on the seismic fragility of buried pipelines has proposed empirical relationships between the seismic intensity and the average pipe damage ratio [53–55]. According to the post-earthquake reconnaissance of the 1995 Kobe earthquake, Japan Water Works Association [56] suggests that pipe damage caused by ground motion can be expressed as a function of the peak ground velocity (PGV) as:

$$\begin{cases} RR = C_P \cdot C_d \cdot C_g \cdot C_l \cdot RR_0 \\ RR_0 = 3.11 \times 10^{-3} \times (PGV - 15)^{1.30} \end{cases} \tag{8}$$

where C_p, C_d, $C_{g,}$ and C_l are correction factors for pipe material, pipe diameter, ground topography, and soil liquefaction where the pipe is located, respectively. RR is the corrected repair rate (repairs/km) of pipelines; RR_0 is the standard repair rate, and PGV is estimated in the unit of cm/s.

The values of C_p, $C_{d,}$ and C_l are shown in Table 3, and the definition and detail information of those factors can be found in Isoyama et al. [55] and Japan Water Works Association (JWWA) [56]. Since the factor C_p for steel pipe (SP) of 0.3 in Table 3 is fitted by SP damages with small diameters, the recommended correction factor of large-diameter ($\geq$400 mm) SPs of 0.15 by the guideline of American Lifeline Alliance (ALA) [53] is adopted in this study.

Table 3. Correction factors to *RR*.

Category	Description	Correction Factor
Pipe Diameter (mm) C_d	75 100~150 200~450 500~	1.6 1.0 0.8 0.5
Pipe Material C_p	DIP CIP SP ACP	0.3 1.0 0.3 (0.15) 1.2
Ground Topography C_g	Disturbed Hill	1.1
	Terrace	1.5
	Narrow Valley	3.2
	Alluvial	1.0
	Stiff Alluival	0.4
Soil Liquefaction C_l	None Partial Serious	1.0 2.0 2.4

Note: DIP (Ductile iron pipe), CIP (Cast iron pipe), SP (Steel pipe), ACP (Asbestos cement pipe).

ALA guideline [53] divided the pipeline damages caused by the earthquake into two types: leakage and breakage. Leakage means that the pipeline has a rupture or tear, which leads to water losses, while breakage means that the pipeline is completely separated and loses all the water supply capacity. Earthquake damage survey shows that in the pipeline damage caused by the earthquake, leakage accounted for about 80%, and breakage accounted for about 20%. Therefore, the state of the pipelines after an earthquake can be divided into three categories, namely, intact (s_1), water leakage (s_2), and breakage (s_3). Once the seismic failure probability P_f is obtained by Equation (7), then the occurrence probabilities for the three states are 1-P_f (s_1), 0.8P_f (s_2), and 0.2P_f (s_3), respectively.

2.3. Seismic Performance Evaluation of WDS by Hydraulic Simulation

2.3.1. Hydraulic Model of the WDS with Earthquake Damaged Pipelines

Figure 5 shows the hydraulic models of pipeline leakage and breakage. The leakage is modeled by adding an emitter in the middle of the pipeline (Figure 5b). The elevation of the emitter takes the average of elevations at the ends of the pipeline, and the leakage water flow rate (m^3/s) can be obtained according to the orifice flow model as [15,57]

$$Q_L = \mu \cdot A_L \cdot \sqrt{2g \cdot H} \tag{9}$$

where μ is the orifice flow coefficient and takes the value of 0.62; A_L is the opening area of the leakage (m^2), g is the acceleration of gravity (m/s^2), and H is the water pressure at the leakage (m H_2O).

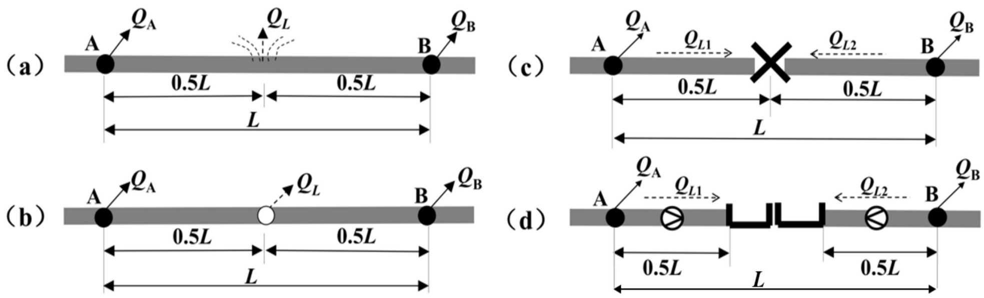

Figure 5. Diagram of pipeline damages and the hydraulic model of damages. (**a**) Diagram of leak. (**b**) Hydraulic mode of leak. (**c**) Diagram of break. (**d**) Hydraulic mode of break.

On determining the opening area, A_L of leakage, the model developed by Shi and O'Rourke [6] is used in this study. Shi and O'Rourke [6] divided the earthquake-induced water pipeline leakage into five types: annular disengagement, round crack, longitudinal crack, local loss of pipe wall, and local tear of the pipe wall. The opening area at the leak orifice and the occurrence ratio of each leakage type are varied according to pipe material and joint characteristics, as shown by Shi and O'Rourke [6].

Two separated broken pipelines model the breakage (Figure 5c) by adding fictitious reservoirs at the ends of the broken pipelines (Figure 5d). A check valve is built into the broken pipeline, allowing water to flow only from the failure pipeline to the reservoir. The elevation of the reservoir is the average of elevations at both ends of the original pipeline.

The pipeline leakages and breakages are added to the original hydraulic model of the WDS. Therefore, the topology of the WDS is accordingly modified to perform post-earthquake hydraulic simulations. The simulation is performed by the open-source software EPANET 2.2 [58] developed by the US Environmental Protection Agency (EPA).

It should be noted that the earthquake-induced leak regards the leak formulated by the earthquake-induced deformation and stress concentration on the pipes or joints, which is different from that in the daily service situation. Even in a daily service situation, the water supply pipeline network usually works with concealed leaks that are difficult to be discovered by the equipment and that have not been discovered in time. These leaks usually occur at the defect and degradation of pipes or joints, which could be induced by many reasons, including intrinsic, environmental, and operational factors [59]. The concealed leaks in daily service situations are not included in the hydraulic model of the WDS in this study.

As shown in Equation (10), the pressure-driven analysis (PDA) approach [60] is applied in the hydraulic simulation of the earthquake-damaged WDS.

$$Q_i = \begin{cases} 0 & , \quad H_i \le H^{\min} \\ Q_{0i} \cdot \sqrt{\frac{H_i - H^{\min}}{H^{\mathrm{req}} - H^{\min}}} & , \quad H^{\min} < H_i < H^{\mathrm{req}} \\ Q_{0i} & , \quad H^{\mathrm{req}} \le H_i. \end{cases} \tag{10}$$

where Q_i is the delivered amount of water at node i; Q_{0i} is the water demand at node i; H_i is the actual pressure (m) at node i; $H^{\min}$ is minimal pressure (m); H^{req} is the pressure (m) required to fulfill the demand at node i.

The ratio of delivered water to water demand at user node i is defined as the post-earthquake serviceability (seismic performance) of user nodes, as shown in Equation (11). The $SI_{\mathrm{Q}}(i)$ is utilized as the performance indicator of individual user nodes. The sum of all $SI_{\mathrm{Q}}(i)$ in Equation (12) is used as the overall system performance indicator of the WDS.

$$SI_{\mathrm{Q}}(i) = \frac{Q_i}{Q_{0i}} \tag{11}$$

$$SSI_{\mathrm{Q}} = \frac{1}{m}\sum_{i=1}^{m} \frac{Q_i}{Q_{0i}} \tag{12}$$

where Q_i is the delivered water at user node *i* obtained from the PDA-based hydraulic simulation; Q_{0i} is the water demand at user node *i* before the earthquake; *m* is the number of user nodes in the WDS.

2.3.2. Probabilistic Analysis by Monte Carlo Simulation

As shown in Equations (6)–(8), the seismic fragility of pipelines is presented by the repair rate (*RR*) and the seismic failure probability (P_f). In the situation of probabilistic analysis, the pipeline works with the probability of 1-P_{f}. Therefore, the Monte Carlo simulation (MCS) is utilized to sample the states of pipelines according to P_{f} and to evaluate the WDS performance probabilistically. Similar approaches were taken by Shi and O'Rourke [6] and Han et al. [29]. The flowchart is built as shown in Figure 6.

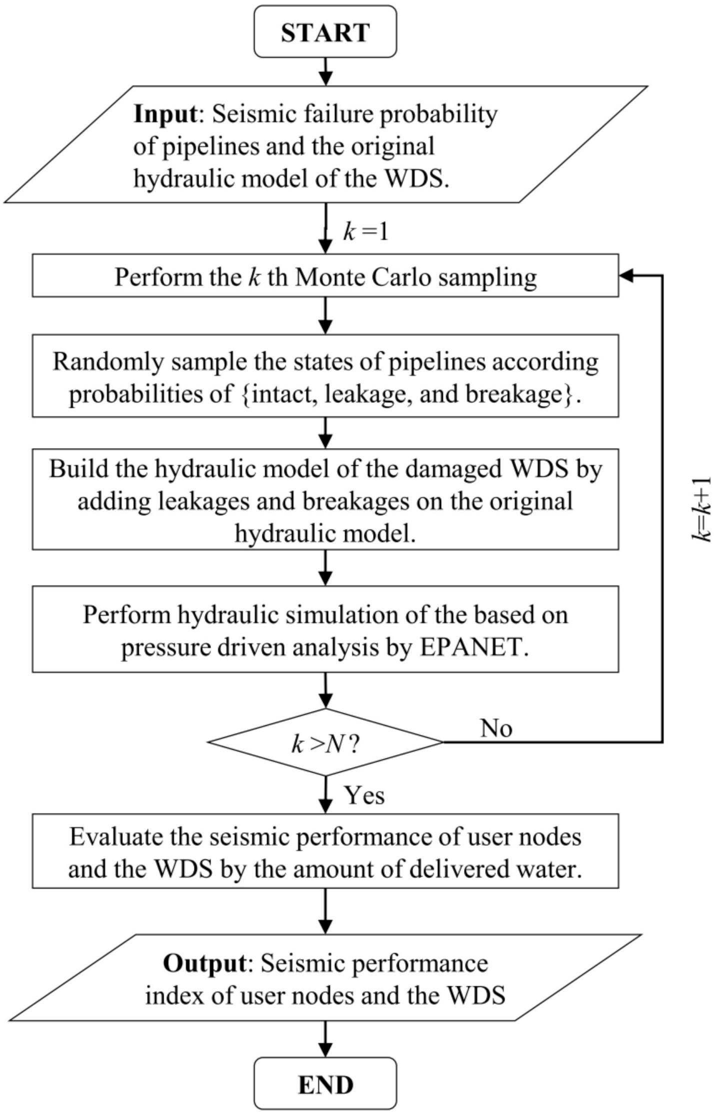

Figure 6. Flowchart of probabilistic seismic performance analysis of WDS based on MCS.

The proposed framework includes several models, such as the improved analytic hierarchy process (IAHP), the multi-criteria decision-making model (TOPSIS), the fragility model of pipeline, and the MCS-based hydraulic simulation of the WDS. Due to insufficient data, an overall validation analysis of all these models cannot be provided. However, all these models have been verified in previous references, respectively. For example, the TOPSIS model was used for nodal importance evaluation in the regional water system by Liu et al. [61]; the fragility model of pipelines and the MCS-based hydraulic model has been applied in the seismic performance assessment of WDN in Los Angeles [6], south Seoul [16], and benchmark cases [12,29].

3. Case Study

The WDS of Z city in southeast China was taken as an application case. As shown in Figure 7, the WDS consists of three sources (water treatment plants R1~R3), 136 user nodes, and 242 pipelines. The service area of the WDS is 41.68 km^2, and the pipelines have a total length of 147.19 km with a diameter range from DN300 to DN2000. Pipeline materials include CIP, DIP, and SP, which vary according to installation year and diameter. The average water supply of the WDS is 5044 LPS, of which the volume from the plants {R1, R2, R3} are {1517 LPS, 1884 LPS, 1643 LPS} respectively.

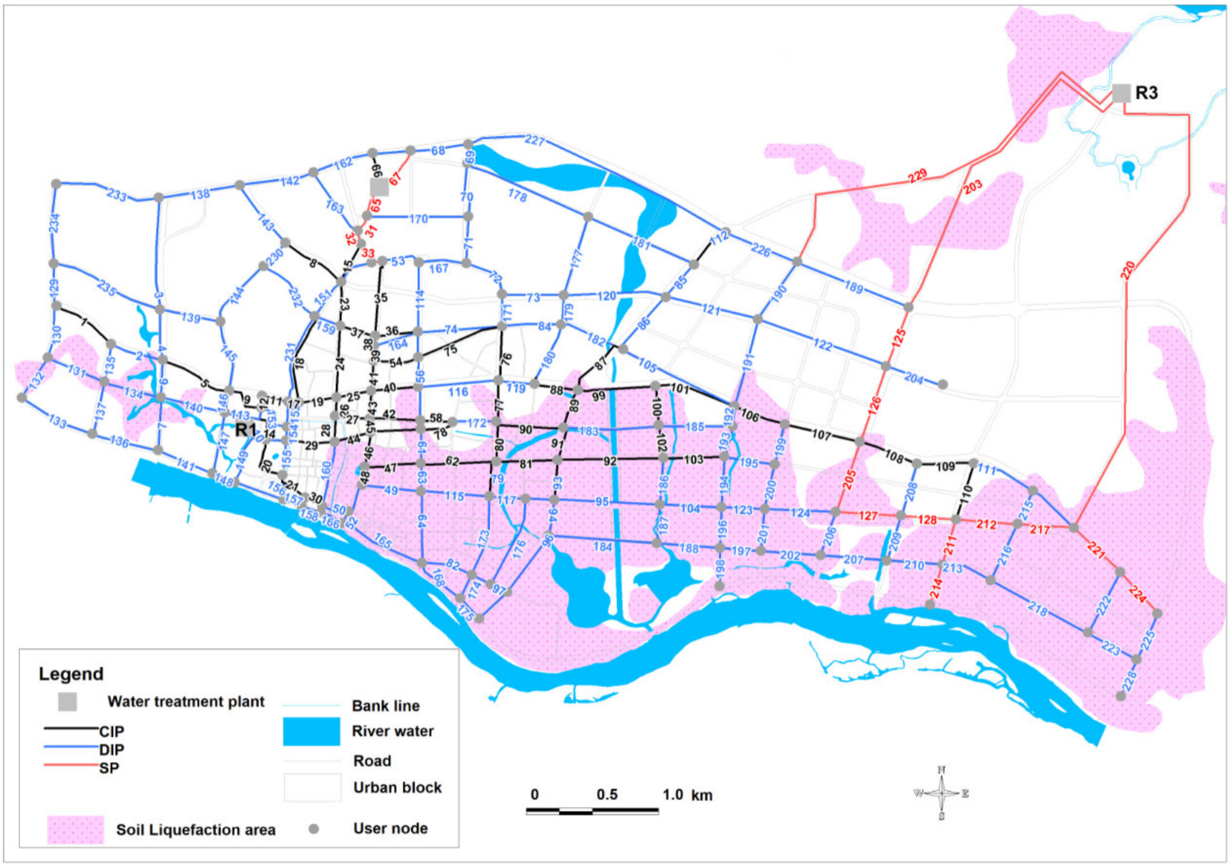

Figure 7. Layout of the WDS in Z city.

According to the seismic ground motion parameter zonation map of China [62], Z city is located in the southeast coastal seismic region. The seismic intensity for the seismic design in Z City is IX degrees. In the Chinese seismic intensity scale [63], the *PGV* value interval of intensity IX is (35, 71) cm/s. The pipeline repair rates to the Chinese seismic intensity degree IX without the correction of ground topography and soil liquefaction are shown in Figure 8. Since WDS is a critical infrastructure system, the *PGV* = 71 cm/s and its corresponding *RR* evaluated by Equation (8) were used for the seismic performance assessment. The construction costs of pipelines varied with diameters are shown in Figure 9. The RR of pipelines under the *PGV* = 71 cm/s are also presented in Figure 9.

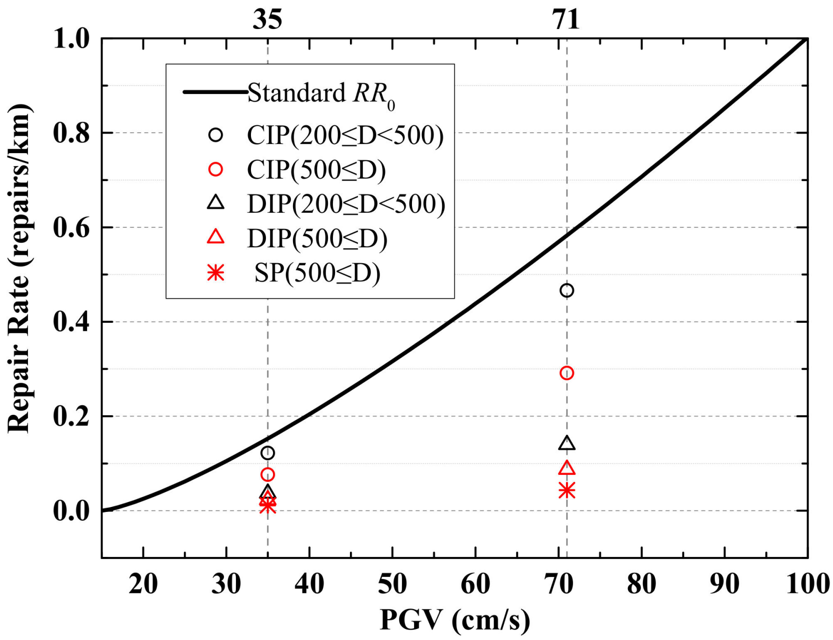

Figure 8. Pipeline repair rates evaluated by the fragility model of JWWA.

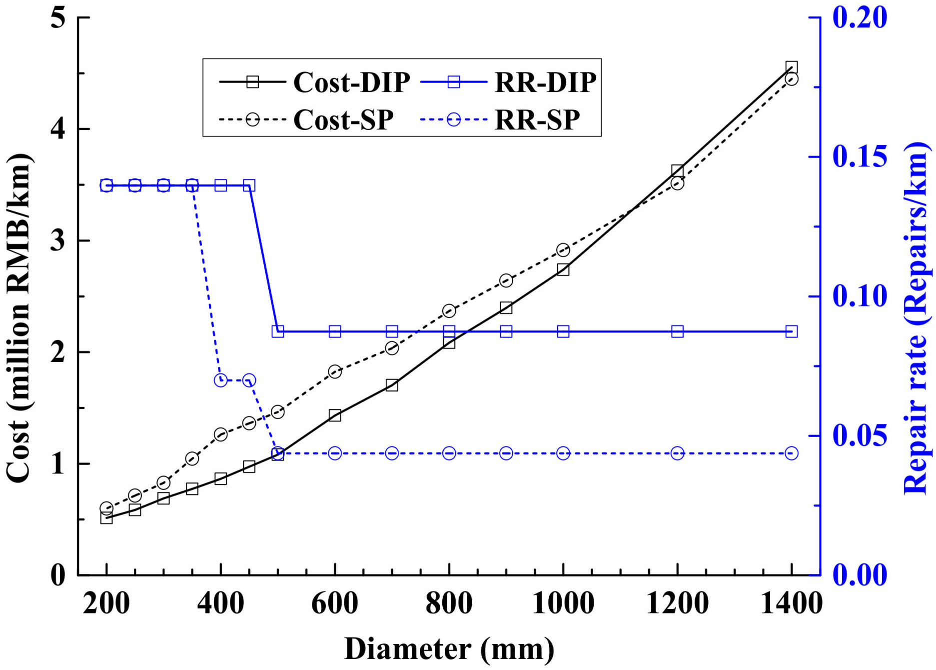

Figure 9. Construction cost and seismic repair rate of the pipelines in Z city.

According to the red marks in Figure 8, for the pipelines with D ≥ 500 mm, the *RR*s from *PGV* = 35 cm/s to *PGV* = 71 cm/s show that the seismic fragility of pipelines performs as SP < DIP < CIP. The comparisons between the *RR*s of pipelines with D < 500 mm and D ≥ 500 mm show that larger diameter and better ductility result in a smaller *RR* of pipelines. The cost data in Figure 9 show that for the pipelines with 400 mm ≤ D ≤ 1000 mm, changing the pipe material from DIP to SP will result in a 50% reduction of *RR*s with the increase of cost by 6.4~45.8%, which shows the efficiency of this approach in improving the seismic resistance of the pipelines in Z city.

The downtown area of Z city is located at the riverside with a flat ground topography, and fine to medium-grained sands, silts and clays are widely distributed in the surficial soils of this area. After the geological investigation, the waterworks of Z city mapped the presumed soil liquefaction areas (Figure 7) under the Chinese seismic intensity IX. According to Table 3, the *RR* correction factor to pipelines in the liquefaction area C_l was 2.40, and the correction factor Cg was set to 1.0. The parameters for the hydraulic simulation of the WDS are shown in Table 4.

Table 4. Parameter setting of the seismic performance analysis model.

Item	Parameter	Value
Seismic hazard intensity measure	Peak ground velocity (*PGV*)	71 cm/s
Pressure driven analysis	H_{min} H_{req}	0 m 20 m
Sampling No. of MCS	N	1000

As for the importance indices of the daily service and post-earthquake rescue service, the land type method and the maximum daily water demand per square kilometer q_j of different land types were evaluated according to the Chinese code for urban water supply engineering planning [32] and is shown in Table 5. The values of adjustment coefficient α_j of water demand were determined according to the post-earthquake reconnaissance in China and are shown in Table 5. According to information from the 2008 Wenchuan Ms 8.0 earthquake [64], downtown Mianzhu city suffered serious damage under seismic intensity IX. One month after the earthquake, the water demands in this area were approximately 30 percent of the daily service demands in normal conditions. The post-earthquake water demands mainly occurred at evacuation shelters located in green spaces and open spaces.

Table 5. Daily water demands and post-earthquake adjustment coefficients.

Land Type	q_j (1000 m^3/km^2.day)	α_j	Land Type	q_j (1000 m^3/km^2.day)	α_j
Residential	19	0.3	Reserved space	10	1.0
Public service	10	2.0	Warehouse	3.5	1.0
Commercial	10	0.3	Municipal	10	2.0
Green space	2.0	5.0	Industrial	20	0.3

When computing the weights of indices by IAHP, it should be noted that decision-makers and experts should determine index ranking, who need to consider a number of factors that will have a notable impact on users' overall importance value. In this study, the importance ranking of the main indices was taken as $I_2 > I_1 = I_3$ since the post-earthquake rescue service is usually believed of great importance. The rank of the sub-indices set for daily service was taken as $I_{13} > I_{11} > I_{12} > I_{14}$ considering that the node serves a large population has greater importance. The rank of sub-indices set $\{I_{2j}\}$ were taken as $I_{23} > I_{21} > I_{22} > I_{24}$ given the fact that the water demands of seismic evocation shelters were the most urgent requirements to be satisfied during the emergency response period in the 2008 Wenchuan earthquake [64], and the rank of sub-indices set $\{I_{3j}\}$ were taken as $I_{33} > I_{32} > I_{31}$. The scaling value sets {0,1,2} and {0,1,2,3} were utilized for the computation of the weight for the indices set with 3 and 4 indices, respectively. The individual weights of each index set and the integrated weights of the sub-indices are shown in Table 6. The integrate weights $w_{ij}{}^*$ of the sub-indices were evaluated by $w_{ij}{}^* = w_i \times w_{ij}$.

Table 6. The individual and integrate weights of indices.

Main Indices Weight (w_i)		Sub-Indices Weight (w_{*j})		Integrate Weight (w_{ij})
I_1	0.25	I_{11}	0.2819	0.0705
		I_{12}	0.2000	0.0500
		I_{13}	0.3677	0.0919
		I_{14}	0.1504	0.0376
I_2	0.50	I_{21}	0.2819	0.1410
		I_{22}	0.2000	0.1000
		I_{23}	0.3677	0.1839
		I_{24}	0.1504	0.0752
I_3	0.25	I_{31}	0.2599	0.0650
		I_{32}	0.3275	0.0819
		I_{33}	0.4126	0.1032

4. Importance Classification of User Nodes

The land type method evaluated the water demands for the daily service and post-earthquake rescue service at user nodes. Land types in the service area of the WDS in Z city are shown in Figure 10.

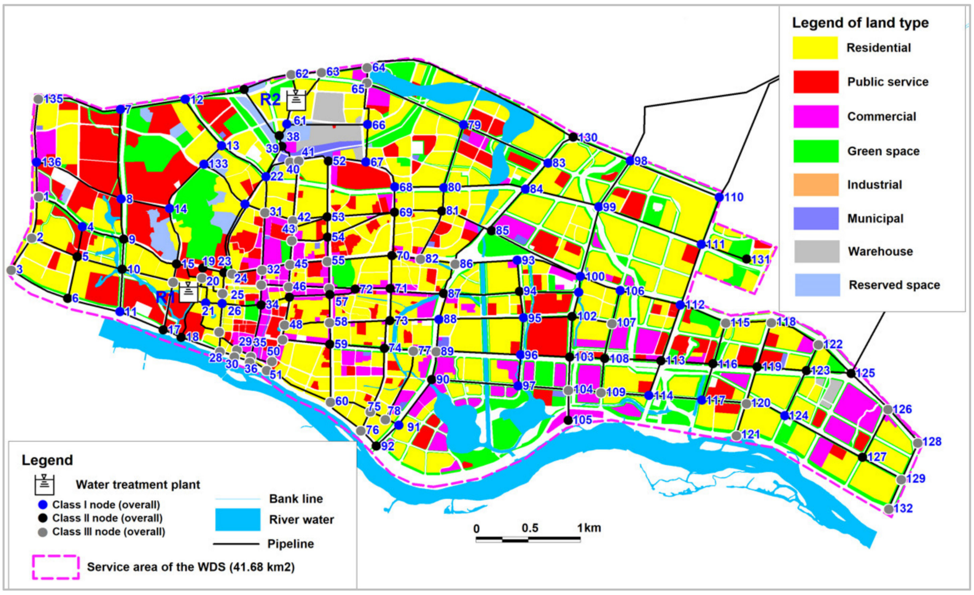

Figure 10. Land types in the service area of WDS in Z city and the overall importance of user nodes.

Thiessen Polygons separated the service area of each user node. The water demands at the public service lands, the reserved spaces, and the municipal lands in Figure 10 were classified as public service demand in Table 5. The water demands of industrial lands and warehouse lands in Figure 10 were classified as industrial demand in Table 5. The post-earthquake water demands of rescue service at user nodes were evaluated by Equation (2) and Table 1. Parameters n_i and A_{ij} in Equation (2) were determined according to geographical information in Figure 10.

According to the integrated weights of indices in Table 6, the water demand adjustment coefficients in Table 5, and the land types presented in Figure 10, the importance of user nodes for daily service, post-earthquake rescue service, and network topology influence was shown in Figure 11a–c, respectively. Figure 11d presents the overall importance of user nodes evaluated by the TOPSIS method, which includes all sub-indices. To sort these importance values in descending order, the user nodes were divided into three classifications {I, II, III} by the 30% and 60% fractiles, the importance classification to user nodes are shown in Figures 10–12. The top 10 importance nodes through the importance values by different indices are listed in Table 7 and shown in Figure 11.

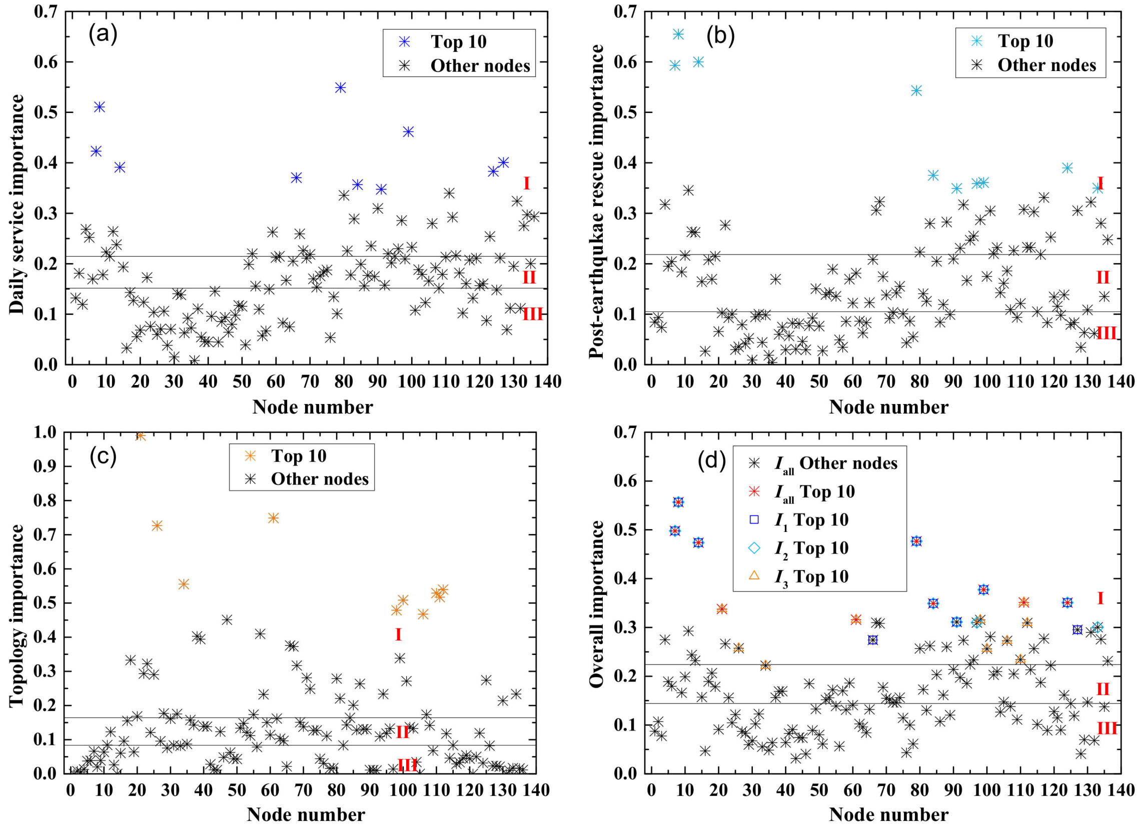

Figure 11. Importance values and classification of nodes obtained by TOPSIS. (**a**) Daily service (I_1). (**b**) Post-earthquake rescue service (I_2). (**c**) Network topology influence (I_3). (**d**) Overall importance of all indices.

Table 7. Top 10 ranked nodes by different indices.

Nodal Rank		1	2	3	4	5	6	7	8	9	10
Index	I_1	79	8	99	7	127	14	124	66	84	91
	I_2	8	14	7	79	124	84	99	97	133	91
	I_3	21	61	26	34	112	110	111	100	98	106
	I_{all}	8	7	79	14	99	111	124	84	21	61

The shading numbers mark the same elements in line $I_1/I_2/I_3$ and the line I_{all}.

Figure 12a,b shows that the user nodes with a larger service area, nodes 7, 14, and 80, usually hold the class I importance for both daily service and post-earthquake rescue service. A comparison between Figure 11a,b indicates a notable difference in nodal importance between the two figures exits at nodes from 60 to 90 because their water demand changes after the earthquake. For the nodes from 60 to 90, the numbers of user nodes in classes {I, II, III} are {12,14,5} in Figure 11a, while the corresponding numbers in Figure 11b are {7,13,11}. There are noticeable differences in the numbers of user nodes in classes I and III between Figure 11a,b, which can be explained through the land types in the service areas of nodes 60 to 90 (Figure 10). The service areas of these nodes are mainly composed of residential lands. The water demands of these nodes are relatively high for daily service but change to small values after an earthquake due to the movement of people from residential areas to the evacuation shelters in other places. Similar results are also shown in Figure 12a,b. The user nodes 10, 53, and 90 hold class I importance for daily service but the class II importance for post-earthquake service because the service area of these nodes is mostly residential commercial lands. The post-earthquake service importance classes of user nodes 55, 103, 114 are larger than that of daily service because their service areas are mainly green space and public service lands.

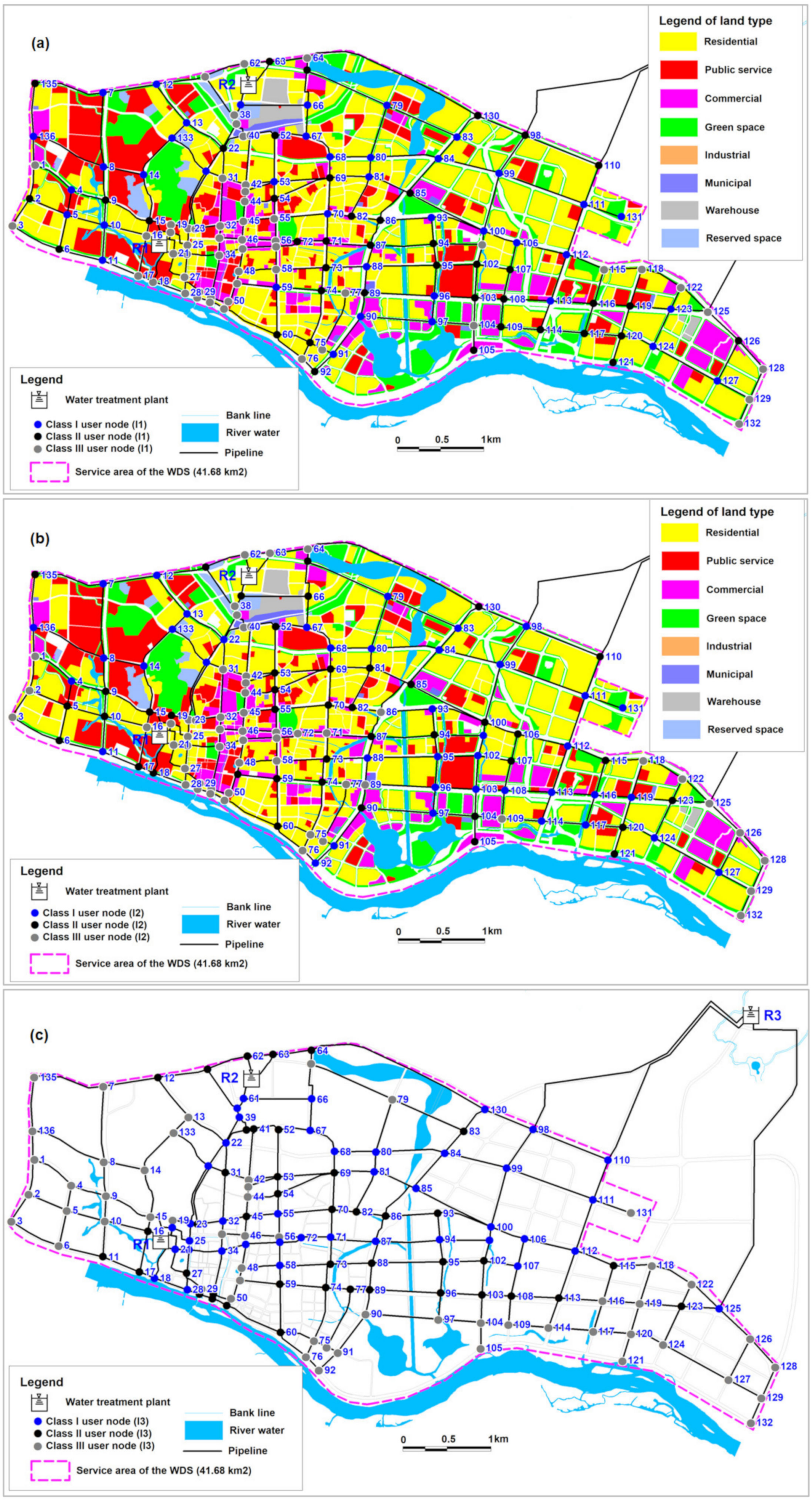

Figure 12. Importance classification of user nodes by the three main indices. (**a**) Daily service (I_1). (**b**) Post-earthquake rescue service (I_2). (**c**) Network topology influence (I_3).

The nodal importance values in Figure 11d are similar to those in Figure 11a,b but are different from those in Figure 11c. As shown in Figure 12, the locations of class I user nodes identified by the network topology index are different from those identified by the daily service indices and post-earthquake service. In Figure 12c, the class I user nodes are mainly located nearby the source nodes and on the paths from the source to other user nodes. Therefore, the importance classification to user nodes by multi-index approaches differs from that of a single type importance index. The data in Table 7 show the number of user nodes in the intersections of the top 10 sets between I_{all} and $\{I_1, I_2, I_3\}$ are {7,7,3}, which indicate the different emphases of the network topology index and other indices. Although the topology indices hold smaller weights in Table 6, they bring a non-negligible influence on the overall importance (Figure 11d).

The overall importance evaluated by multi-index includes various factors and thus provides a more reasonable classification to user nodes. The importance classifications based on daily service or topology index may not identify important user nodes for post-earthquake rescue service, and the importance classification provided only by the indices of post-earthquake disaster rescue may not be practical for daily service. For the top 10 nodes ranked by the overall importance values, nodes 79, 84, 99, and 124 mainly provide water service to the larger areas with the land type of residential. These areas require much more water for ordinary service. Nodes 7, 8, 14, and 79 provide water service to a relatively large area where the majority of land type is public service. These areas require much more water demand for post-earthquake rescue service, as presented in Tables 1 and 5. While nodes 21, 61, and 111 are identified because of their locations near the sources, and their network topology influences are much greater.

5. Seismic Performance of the WDS and Pipeline Renovation Plan

The seismic failure probability (P_f) of pipelines was calculated according to Equations (6)–(8), and the information is in Table 3 and Figure 7. Then, the water supply performance (SI_Q) of user nodes was evaluated according to the hydraulic simulation of the WDS with earthquake-induced pipeline damages and the MCS method. Figure 13 shows the simulation results as a whole, Table 8 shows the statistical information of $SI_Q(i)$ for the user nodes of different importance classification.

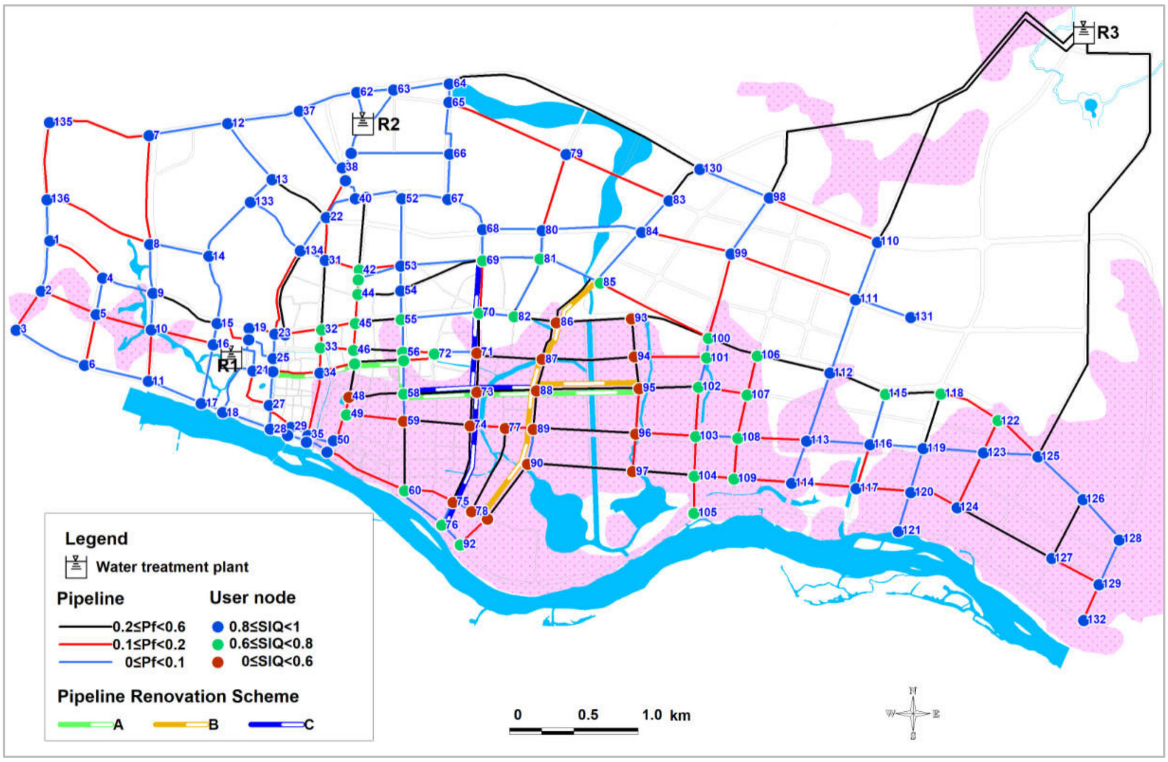

Figure 13. Seismic performance of the original WDS and the pipeline renovation schemes.

Table 8. Seismic performance of user nodes.

Classification of User Nodes		Class I	Class II	Class III	All
Original WDS	SSI_Q	0.8180	0.7869	0.8022	0.8018
	No. of $SI_Q < 0.6$	6	7	6	19
Renovation Scheme A Cost = 7.72 million RMB	SSI_Q	0.8411	0.8221	0.8320	0.8314
	No. of $SI_Q < 0.6$	2	4	2	8
	Nodes of $SI_Q < 0.6$	{88,93}	{74,87,90,94}	{77,89}	
Renovation Scheme B Cost = 6.92 million RMB	SSI_Q	0.8402	0.8124	0.8195	0.8231
	No. of $SI_Q < 0.6$	2	3	4	9
	Nodes of $SI_Q < 0.6$	{88,93}	{73,74,94}	{48,77,78,89}	
Renovation Scheme C Cost = 6.64 million RMB	SSI_Q	0.8374	0.8184	0.8235	0.8258
	No. of $SI_Q < 0.6$	4	3	2	9
	Nodes of $SI_Q < 0.6$	{88,93,95,97}	{87,90,94}	{77,89}	

As shown in Table 8, the average SI_Q of all user nodes in the "Original WDS" is 0.8018, indicating that the WDS has a relatively greater value of seismic performance. However, the SI_Q of individual user nodes shows that there are 19 user nodes with $SI_Q < 0.6$ in the WDS, which includes six nodes {88,91,93,95~97} of importance class I and need to be paid more attention for interventions. As shown in Figure 11, the SI_Q of nodes {73~78,86~91} are less than 0.60. The reason is that the adjacent pipelines of these nodes are located in the earthquake-induced liquefaction area, which results in a relatively larger failure probability of these pipelines, for example, the seismic failure probabilities (P_f) of CIP pipelines {44~48,62,77,80,81,88~92} are greater than 0.2.

In order to improve the SI_Q of individual user nodes, especially for the Class I nodes with $SI_Q < 0.6$, three renovation plans for the pipelines with large P_f values in the liquefaction area were proposed. According to Table 3 and Equation (8), replacing the CIP and DIP pipelines with SP pipelines can reduce the RR and P_f of the pipelines and increase the SI_Q of user nodes. When formulating the renovation schemes of pipelines, the following aspects are considered: (i) Prioritize the renovation of CIP pipelines in the liquefaction; (ii) Choose the main pipeline in the water supply path to user nodes; (iii) Replace the original pipeline with a new SP pipeline along the original path; (iv) Due to budget constraints, the length of the renovated pipeline is about 3% of the total pipeline length of the WDS. According to the above principles, three renovation schemes {A, B, C} were made for selection. The length of the renovated pipelines in schemes {A, B, C} is {4.23 km, 4.21 km, 4.17 km} respectively. Figure 13 shows the pipelines of these three schemes. Table 8 gives the pipeline construction costs and the SI_Q of user nodes of these three schemes.

As for the selection of the pipeline renovation schemes, the seismic performance of individual user nodes and their importance classification has a significant impact on the decision-making. If the average SI_Q of all nodes (SSI_Q) and the construction costs are taken as decision criteria, the cost of Scheme C is the smallest (6.64 million RMB) with the $SSI_Q = 0.8258$, which is better than the SSI_Q of Scheme B (0.8231), so Scheme B should be excluded accordingly. However, if the importance classification of user nodes are considered and the SI_Q of Class I user nodes are taken as decision criteria, scheme C holds the smallest SSI_Q (0.8374) of Class I user nodes and the largest number (4) of Class I user nodes with $SI_Q < 0.6$. Therefore, Scheme C should be excluded accordingly. For Scheme A and Scheme B, if the number of critical user nodes with $SI_Q < 0.6$ is selected as the decision criteria, the number of Class I and Class II user nodes with $SI_Q < 0.6$ in Scheme B is 5, and the corresponding number of Scheme A is 6, so Scheme A should be excluded accordingly. It can be seen from Figure 13 that the pipelines of Scheme B are nearby the Class I user nodes {88,91,93,95,96,97}, so it can provide better improvement of SI_Q to these critical user nodes. Finally, Scheme B is proposed for the seismic performance improvement of critical user nodes. Generally speaking, determining the seismic renovation plan of pipelines is a complex decision process that should consider technical, economic, and social aspects. The comparisons above show that the seismic performance evaluation of the WDS considering the importance of classification to user nodes provides technical information for the water supply utilities and decision-makers to focus the limited resources on the seismic performance of critical user nodes.

6. Conclusions and Remarks

This paper proposes a framework for the seismic performance evaluation of water distribution systems (WDSs) based on importance classification to user nodes. A multi-index model is presented to evaluate the overall importance of user nodes. The seismic hazard to the WDS is probabilistically simulated by the fragility model of pipelines and Monte Carlo simulation. The hydraulic simulation on the WDS with earthquake damages is performed to evaluate the seismic performance of individual user nodes. The proposed framework is implemented in an actual WDS in China. The following conclusions can be made:

- The importance classification to user nodes by the multi-index measures is different from those by a single importance index; the multi-index approach can identify the critical user nodes for post-earthquake rescue service, which may be ignored by the indices for daily service and network topology influence.
- Seismic performance of individual user nodes provides insightful information of the WDS performance than the average or overall value of the system. The locations of critical user nodes with poor performance provide a target for pre-disaster interventions.
- The seismic performance evaluation of the WDS considering the importance of classification to user nodes has a notable impact on the selection of pipeline renovation schemes. The proposed framework provides a novel perspective for the decision-makers to focus the limited resources on the seismic performance improvement of critical user nodes.

The multi-index model to evaluate the overall importance of users presented in this study provides a reference method to classify user nodes in WDS. Other indices can be introduced, and model applications in various WDSs are needed in the future to improve the validity of the model. The seismic performance is measured by the hydraulic analysis of the WDS in this study. Water quality indicators (such as water age, residual chlorine content) may also bring no-negligible effects on the seismic performance of the WDS and should be included in further studies. The overall seismic security of the WDS should be ensured not only by the seismic safety of pipelines but also by the seismic safety of water supply facilities such as tanks, water treatment equipment, and pumping station, and the effect of the damages of the facilities should be considered in the future. Other practical assumptions made in this research include the availability of power supply to the WDS. This aspect affects the functionality of the water treatment and pump stations and needs to be explored further.

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