

**Dear Editor and Reviewers,**

Thank you for the constructive comments and suggestions provided throughout the discussion phase, which we believe have been very helpful in clarifying and strengthening our work. In the following, we provide our detailed, point-by-point responses. All proposed clarifications and improvements will be incorporated in the manuscript accordingly and we give examples of these in italics, with revised text in *bold italics*.

We hope that our replies convincingly demonstrate the novelty and integrated nature of this study. This research constructs a four-stage seismic resilience assessment framework based on the dynamic process of water distribution networks (WDNs) responding to earthquake disasters, and carries out refined and comprehensive assessment of WDNs seismic resilience. This approach aligns closely with the aims and readership of NHESS. We believe that this approach aligns closely with the aims and readership of NHESS.

Please find below our detailed responses. The reviewers' comments appear in black, and our replies are provided in blue.

This manuscript proposes a four-stage framework (preparedness, robustness, recoverability, adaptation) for assessing seismic resilience of urban water distribution networks (WDNs). The authors integrate topological, energy-based, and hydraulic indicators into a multi-attribute system and apply it to two case study networks in China. While addressing an important research gap by incorporating pre-disaster preparedness and long-term adaptation stages, the manuscript suffers from significant methodological and presentation issues that require substantial revision.

### **1. Unclear Novelty**

The abstract and introduction fail to clearly articulate what specific problem this work addresses and how the proposed framework advances beyond existing three-stage approaches. The abstract is vague about implications, and the first clear statement of the research problem appears only in lines 108-115. The manuscript reads as a pipeline of existing procedures rather than a coherent methodological advancement. Novel elements, if present, are obscured by technical details.

We thank the reviewer for their thorough and constructive review. The abstract and introduction have been carefully revised to further clarify the research motivation and the novelty of the proposed method. Furthermore, the research gaps in existing studies are systematically elaborated

in the revised abstract and introduction.

*First, most available studies mainly concentrate on the seismic-induced functional failure and short-term recovery of water distribution networks, while ignoring the pre-disaster preparedness capacity and long-term post-earthquake adaptive improvement ability. It remains challenging to characterize the dynamic evolution of the entire seismic disaster cycle, and there is a particular lack of quantitative quantification for the adaptability improvement during the long-term operation and maintenance period. Second, current evaluation indicator systems mostly depend on individual topological or hydraulic features, without a comprehensive quantitative framework for multi-stage resilience analysis. This results in one-sided evaluation outcomes and fails to provide reliable support for identifying system vulnerable components and implementing targeted optimization and reinforcement schemes. To address the above research gaps, this study develops a four-stage seismic resilience evaluation framework for the full lifecycle evolution of water distribution networks, which divides the resilience evolution into four phases: preparedness, robustness, recovery, and adaptation. The proposed framework extends conventional single-stage or three-stage evaluation paradigms, and enables explicit characterization of the system's adaptive capacity and long-term performance evolution.*

*On this basis, a phased evaluation system is established by integrating multi-dimensional attributes, including network topology, energy reserve, pipeline seismic resistance, hydraulic service level, and recovery duration, realizing refined quantitative assessment of resilience features at each stage. Moreover, an Adaptation Capacity Index (ACI) is proposed to quantify the comprehensive improvement effect of different renovation strategies in the long-term adaptive phase, filling the research gap in the quantitative evaluation of network adaptability. In addition, comparative analyses of two actual water distribution network cases validate the effectiveness of the proposed framework in identifying critical vulnerable nodes and optimizing seismic reinforcement strategies.*

## **2. Methodology**

The seismic hazard analysis (Section 3.1.1) is inadequately described. It remains unclear whether a proper PSHA was conducted or merely a simplified scenario calculation. Using only the Toro et al. (1997) ground motion model is inconsistent with state-of-the-art practice. Figure 8 presents scenario calculations, but Figure 2 mentions PGA sampling without specifying the approach. The fragility model terminology is also problematic, as the described approach differs from standard

seismic fragility conventions.

We thank the reviewer for their thorough and constructive review. The description of seismic hazard analysis in this section mainly emphasizes the application of the method, rather than conducting seismic hazard assessment for specific sites. This subsection primarily aims to generate a spatially incoherent ground motion field and consider the influence of spatial variation in ground motion on pipelines at different locations. The presented formula is only one alternative approach for calculating the peak ground acceleration (PGA), which can be further adjusted according to the characteristics of different regions. In this study, two feasible formulas for PGA calculation are provided, referring to the studies by Boore et al. and Toro et al., respectively. The specific formulas are expressed as follows:

$$\begin{aligned} \ln PGA = & -0.53804 + [-0.6605 + 0.1197(M_w - 4.5)] \\ & \times \ln(\sqrt{R_{jb}^2 + 1.35^2} - 0.01151(\sqrt{R_{jb}^2 + 1.35^2} - 1.0)) \end{aligned} \quad (1)$$

*In the formula, PGA represents Peak Ground Acceleration (g);  $M_w$  is the moment magnitude; and  $R_{jb}$  denotes the shortest horizontal distance from the earthquake rupture.*

$$\begin{aligned} \ln PGA = & 2.20 + 0.81 \cdot (M_w - 6) - 1.27 \ln \sqrt{R_{jb}^2 + 9.3^2} \\ & + 0.11 \cdot \max \left[ \ln \left( \frac{\sqrt{R_{jb}^2 + 9.3^2}}{100}, 0 \right) \right] - 0.0021 \cdot \sqrt{R_{jb}^2 + 9.3^2} \end{aligned} \quad (2)$$

*In the formula, PGA represents Peak Ground Acceleration (g);  $M_w$  is the moment magnitude; and  $R_{jb}$  denotes the shortest horizontal distance from the earthquake rupture.*

*Boore, D.M., Atkinson, G.M. Ground-Motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. Earthq. Spectra, 24, 99-138, <https://doi.org/10.1193/1.2830434>.*

*Toro, G.R., Abrahamson, N.A., Schneider, J.F. Model of strong ground motions from earthquakes in central and eastern North America: best estimates and uncertainties. Seismol. Res. Lett., 68, 41 - 57, <https://doi.org/10.1785/gssrl.68.1.41>, 1997.*

### 3. Indicator weighting

The framework employs multiple indicators at each stage but assumes equal weights when computing aggregate resilience (Section 5.1). This assumption is unjustified, as indicators likely have unequal importance depending on network characteristics and stakeholder priorities. A sensitivity analysis exploring alternative weighting schemes is strongly recommended.

We thank the reviewer for their thorough and constructive review. Indeed, the weight setting of the four stages is affected by multiple factors, such as network characteristics and stakeholder concerns, as pointed out by the reviewer. For instance, greater attention is paid to the preparedness capacity in earthquake-prone regions, more emphasis is placed on the adaptive capacity in rapidly developing urban areas, and higher priority is given to the robustness capacity in cities with aging infrastructure. From the perspective of stakeholders, water network operators tend to focus more on robustness, while governments and the public are more concerned about network preparedness.

In response to this comment, six weight allocation scenarios were designed, and a sensitivity analysis was further carried out. The weights of the four types of indicators were assumed to vary within the range of 0.1 to 0.5, while ensuring that the sum of all weights equals 1. The detailed weight allocation schemes are presented in Table 4, and the corresponding analytical results are illustrated in Figs. 17 and 18.

Tab.4 Four-stage resilience evaluation index weight setting scheme

Scheme	Preparedness ( $R_b$ )		Robustness ( $R_u$ )		Recoverability ( $R_a$ )		Adaptation ( $R_n$ )
	$NEI$	$G_w$	$SSIQ(t_0)$	$\overline{RR}$	$SSIQ(t_3)$	$r$	$ACI$
	a	0.125	0.125	0.125	0.125	0.125	0.125
b	0.200	0.200	0.090	0.090	0.090	0.090	0.140
c	0.090	0.090	0.200	0.200	0.090	0.090	0.140
d	0.090	0.090	0.090	0.090	0.200	0.200	0.140
e	0.100	0.100	0.100	0.100	0.100	0.100	0.400
f	0.150	0.150	0.130	0.130	0.110	0.110	0.220

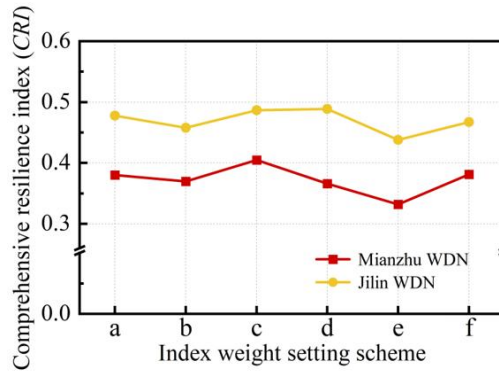


Fig.17 Comprehensive resilience of WDNs with varying weights under renovation measure S3

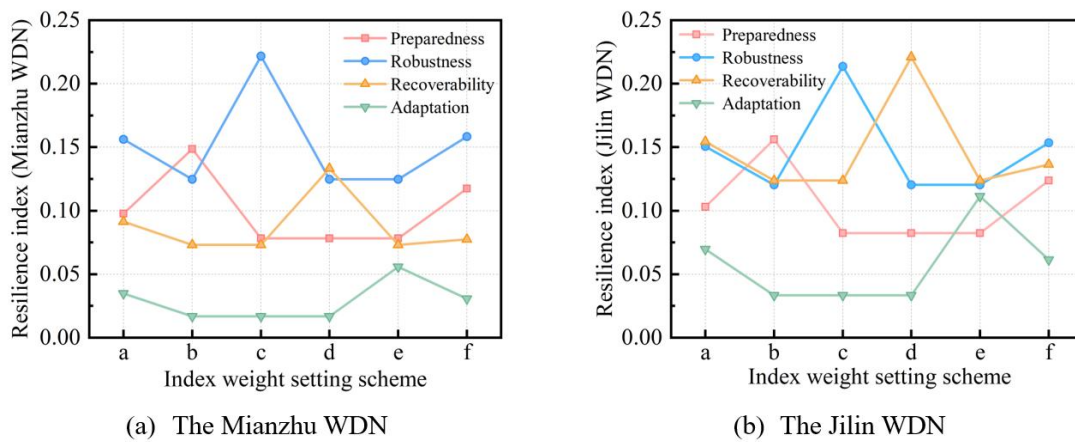


Fig.18 Four-stage resilience change diagram under different weights

#### 4. Adaptation quantification

Equations 16-17 introduce enhancement coefficients without explaining their derivation or calibration. The Adaptation Confidence Index (ACI) is mentioned but not adequately highlighted in results. Meanwhile, Section 5.1 introduces a Resilience Index not discussed in the methodology, creating confusion about the evaluation approach.

We thank the reviewer for their thorough and constructive review. Initially, this study intended to propose an independent indicator for adaptability, enabling separate quantification of water distribution network performance and forming four mutually independent indicators corresponding to the four resilience characteristics. However, it was found that adaptability essentially reflects the long-term performance evolution of the network after earthquakes, such as the construction of new water plants and large-scale pipeline renewal. It differs from pre-disaster preparedness while maintaining inherent connections with preparedness, seismic robustness, and post-disaster recovery capacity.

We introduce the average comprehensive improvement rate (ACI) of the indicators to measure the overall adaptability of WDNs.

$$\eta_{k,m} = \frac{R_{k,m}^{after} - R_{k,m}^{before}}{R_{k,m}^{before}} \times 100\% \quad (3)$$

In the formula,  $\eta_{k,m}$  denotes the improvement rate of the  $m$ -th sub-indicator corresponding to stage  $k$ ;  $R_{k,m}^{before}$  and  $R_{k,m}^{after}$  are the values of the  $m$ -th sub-indicator in stage  $k$  before and after retrofitting, respectively.

$$\Delta R_k = \sum_{m=1}^M \theta_{k,m} \cdot \eta_{k,m} \quad k \in \{b,u,a\} \quad (4)$$

In the formula,  $\Delta R_k$  is the improvement rate of the  $k$ -th stage resilience;  $\theta_{k,m}$  is the weight of the  $m$ -th sub-indicator in stage  $k$  ( $\sum_{m=1}^M \theta_{k,m} = 1$ );  $k$  represents the stage index ( $b$  is preparedness,  $u$  is robustness,  $a$  is recoverability).

$$ACI = \frac{1}{3} \cdot (\Delta R_b + \Delta R_u + \Delta R_a) \quad (5)$$

In the formula,  $ACI$  represent the adaptation index, which quantifies the overall adaptability of the WDN by averaging the improvement rates of the three resilience stages. A higher  $ACI$  indicates stronger adaptability to seismic hazards, as it reflects a greater comprehensive enhancement in preparedness, robustness, and recoverability.

Naturally, alternative indicators can also be considered for adaptability evaluation. For example, the water demand of peripheral network nodes can be randomly increased, and the nodal reliability of the water distribution network under seismic scenarios can be adopted as another evaluation indicator of adaptive capacity. The research framework established in this study is open-ended and not limited to one specific indicator for adaptability assessment. Nevertheless, the selection of evaluation indicators should be conducted with careful consideration and rational justification.

## 5. Statistics

The 200 Monte Carlo iterations lack convergence analysis justification. The case studies present limitations: both networks use only cast iron and plastic pipelines, and the Jilin WDN is small (27

nodes). Despite referencing the 2008 Wenchuan earthquake, there is no reference to the observed damage in the Mianzhu network and no comparison with the results.

We thank the reviewer for their thorough and constructive review. In fact, it is generally difficult to validate the seismic performance of lifeline engineering systems using real earthquake damage data. This difficulty exists not only for water distribution networks, but also for power, gas, transportation and other infrastructure networks. Nevertheless, real seismic disaster events can provide overall verification of network performance to a certain extent. For instance, Reference (Miao & Li, 2022) reported that the reliability of the water distribution network in Mianzhu City after the Wenchuan Earthquake was 0.3410, which is basically consistent with the simulation results obtained in this study. Although the two indicators adopt different names, they share essentially the same physical implication, which indirectly verifies the rationality of the results in this paper.

Concerning the limitations of case studies, we acknowledge that only cast iron and plastic pipes are adopted in the two networks, and the Jilin WDN has a relatively small scale with 27 nodes. We have explicitly stated these limitations in the discussion section and pointed out that more pipe types and larger-scale networks will be considered in future research.

In addition, regarding the convergence of the Monte Carlo simulation, the authors have supplemented the Monte Carlo convergence curves of the two case networks in the revised manuscript. These curves, as shown in Figure 10, further demonstrate that 200 Monte Carlo simulations adopted in this study are convergent and reasonable.

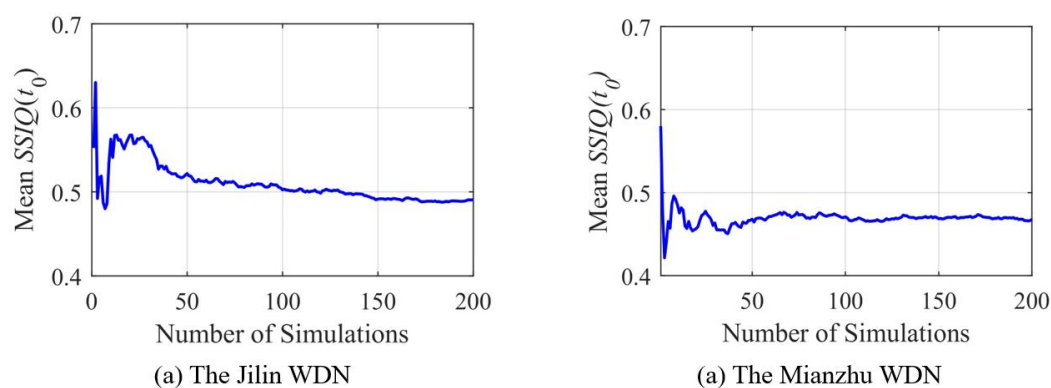


Fig.10 The Monte Carlo simulation convergence curve

*Miao, H., Li, J. Serviceability evaluation of water supply networks under seismic loads utilizing their operational physical mechanism. Earthq. Eng. Eng. Vib., 21, 283–296,*

### **Editorial quality comments**

The introduction is excessively long with extended historical examples (lines 31-47) that could be condensed. Section 2 should be shortened and integrated into the introduction, as it duplicates contextual material. The manuscript contains redundant passages (e.g., lines 175-180 repeating recoverability definition; lines 22-25 repeating information). Figure 1 contains too many visual elements overwhelming the reader. Terminology is inconsistent ("renovation" versus "retrofit"; "seismic fortification intensity" undefined).

We thank the reviewer for their thorough and constructive review. The introduction has been comprehensively reorganized and condensed. Redundant descriptions have been removed, the consistency of technical terminology has been guaranteed, and the innovation of this work has been further highlighted. The detailed revisions are as follows:

First, we acknowledge that the original historical overview (lines 31–47) was overly detailed. We have condensed and streamlined this paragraph, retaining only key historical context that supports the research background, while removing redundant narrative and examples.

As for Section 2, since this section serves as the core theoretical foundation and explicit definition of the four-stage resilience framework in this study, it provides essential theoretical support for the quantitative methods presented in Section 3 and constitutes an indispensable part of the overall methodology. Therefore, we have not merged it into the Introduction. However, we have substantially condensed and revised Section 2 by removing content that overlaps with the Introduction, eliminating redundant descriptions, and streamlining the presentation to make it more concise and focused.

We sincerely appreciate the reviewer's constructive comment on the readability of Figure 1. We have optimized the visual layout and information hierarchy of Figure 1 to improve clarity without losing key information. Specifically, we have streamlined the design by simplifying borders, reducing redundant graphical elements, and using a consistent color scheme across the four stages. The three-layer structure (conceptual framework → cyclic stages → quantitative methods) is now more logically organized, and non-essential background decorations have been removed to avoid visual clutter. We have also shortened some lengthy descriptions and adjusted their positions to prevent overcrowding. These revisions make the figure easier to follow while retaining the

complete logical flow of the proposed framework. The updated version is included in the revised manuscript.

In the end, we have standardized the terminology throughout the manuscript: we unified the use of retrofit and eliminated the inconsistent use of renovation, and we have checked and ensured consistency for all technical terms.

### **Minor Comments**

Literature review lacks critical analysis of cited works. Equation 1 could be omitted. Figure 13 caption incorrectly references only Jilin WDN when showing both networks. The Gini coefficient formulation (Eq. 8) should be verified against standard forms. Provide a reference for the Gini coefficient or specify that it is a novelty.

We sincerely appreciate the reviewer's careful and constructive comments. We have addressed each point as follows:

#### (1) Critical analysis in the literature review

We have added critical analysis of existing studies in the introduction and literature review sections. Specifically, we compare the limitations of traditional three-stage resilience frameworks with our proposed four-stage framework, highlighting gaps in full-cycle resilience assessment and long-term adaptation quantification, which strengthens the novelty and contribution of this work.

#### (2) Omission of Equation 1

We have removed Equation 1 as suggested. This formula presents a general definition of resilience that is not used elsewhere in the manuscript; its deletion does not affect the methodological integrity and helps streamline the presentation.

#### (3) Correction of Figure 13 caption

We have revised the caption of Figure 13 to include both case networks (Jilin and Mianzhu WDNs), clearly indicating that the figure presents results for both networks.

#### (4) Verification and citation of the Gini coefficient (Equation 8)

We have verified the formulation of the Gini coefficient in Equation 8 against standard forms and corrected any inconsistencies. The formula is adapted from the work of Xu et al. (2022) published in *Reliability Engineering & System Safety*, where the Gini coefficient was used to measure the

homogeneity of node importance in metro systems and assess disaster preparedness. Drawing on this idea, we apply the Gini coefficient to water distribution networks to quantify the uniformity of node importance and evaluate preparedness. The revised formula is given as follows:

$$G_w = \frac{1}{2N^2V} \sum_{i=1}^N \sum_{j=1}^N |V_i - V_j| \quad (6)$$

*Xu, Z., Chopra, S.S. Network-based assessment of metro infrastructure with a spatial–temporal resilience cycle framework. Reliab. Eng. Syst. Saf., 223, 108434, <https://doi.org/10.1016/j.res.2022.108434>, 2022.*

**The authors must: (1) clearly articulate the novel contribution beyond combining existing procedures; (2) consider a sensitivity analysis for indicator weighting; (3) clarify the seismic hazard analysis methodology; (4) check Monte Carlo convergence; (5) explain adaptation coefficient derivation; (6) substantially restructure Sections 1-2 for conciseness; and (7) consider validation against real earthquake data.**

The authors sincerely appreciate the reviewer’s valuable and constructive comments, which have greatly helped improve the quality of this manuscript. We have carefully addressed all seven points raised by the reviewer:

1. We have clearly articulated the novel contributions of this work and highlighted its advances beyond the direct combination of existing methods.
2. We have added a sensitivity analysis for the indicator weighting to enhance the robustness of the results.
3. We have further clarified the detailed methodology used for seismic hazard analysis.
4. We have checked and verified the convergence of the Monte Carlo simulations.
5. We have supplemented a clear explanation for the derivation of the adaptation coefficient.
6. We have substantially reorganized and condensed Sections 1 and 2 to improve their conciseness and logical flow.

7. We have strengthened the model validation by comparing the results with real earthquake data where available.

All revisions have been carefully implemented and marked in the revised manuscript. We hope these revisions fully address the reviewer's concerns and meet the standards of the journal.