

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.

Specific comments:

1) L15: WDN need to be defined before its first use

We sincerely appreciate the reviewer's careful and constructive comments. The authors have redefined "*water distribution networks (WDNs)*" in the first sentence of the abstract. Meanwhile, a clear definition has also been provided in the introduction section of the main text as "*As a critical lifeline engineering system, urban water distribution networks (WDNs)...*".

2) L22: What does ACI stand for?

We sincerely appreciate the reviewer's careful and constructive comments. In this paper, ACI denotes the **Adaptation Capacity Index**, a quantitative indicator for characterizing the adaptability of water distribution networks during the long-term post-disaster adaptation stage. The full formal name and interpretation of this indicator have been supplemented and clarified in the revised manuscript.

3) L23-27: Repetition

We sincerely appreciate the reviewer's careful and constructive comments. The relevant textual descriptions in the abstract have been revised and rephrased accordingly.

4) L66: WDN should be defined in the abstract or in the title already

We sincerely appreciate the reviewer's careful and constructive comments. The specific definition of WDNs has been supplemented in the abstract, which is stated as: *As a typical engineering system, the seismic resilience of urban water distribution networks (WDNs)...*

5) Table1: This table needs more horizontal separators to see which equations belong where. No definition of variables etc! Without this the eqs are of little use. Their font is too small.

We sincerely appreciate the reviewer's careful and constructive comments. Necessary horizontal dividing lines have been added to all tables in the revised manuscript. Also, a table of variable descriptions has been added at the end of the paper.

6) L109: What do you mean by "actual earthquake processes" ?

We sincerely appreciate the reviewer's careful and constructive comments. The expression "actual earthquake processes" in the original text was intended to describe the real response process of water distribution networks facing seismic disasters. This phrase has now been revised to "*the process of the WDN responding to earthquake disasters*" in the revised manuscript.

7) L109-110: By only adding a fourth stage, does the proposed approach really solve this issue?

We sincerely appreciate the reviewer's careful and constructive comments. According to the definition of resilience proposed by the National Academy of Sciences, resilience encompasses four fundamental characteristics: preparedness, robustness, recoverability, and adaptation. Based on this definition and an in-depth analysis of the response process of water distribution networks in real earthquake events, this study conducts a refined multi-stage and multi-dimensional evaluation of the seismic resilience of water distribution networks in view of their phased characteristics under seismic disasters. The resilience performance of the network at each stage is explicitly clarified. Compared with single-stage and single-index evaluation methods, the proposed framework can better reflect the seismic vulnerable links of water distribution networks

and provide a decision-making basis for subsequent network optimization and rehabilitation.

8) L116-117: “entire seismic process of water distribution networks” I don’t understand this. Suggest rephrasing.

We sincerely appreciate the reviewer’s careful and constructive comments. The original expression “*the entire seismic process of water distribution networks (WDNs)*” in the manuscript is indeed inaccurate. We have carefully reviewed the linguistic presentation throughout the paper and removed this inappropriate statement accordingly.

9) L136-137: Since you include the robustness during the EQ event, it should read “before, during and after an earthquake”.

We sincerely appreciate the reviewer’s careful and constructive comments. The relevant expression in the manuscript has been revised to: *this study categorizes the evolution of WDN functionality before, during and after an earthquake into four sequential stages...*

10) L1411: what is meant by “developing seismic codes” ? computer code? emergency procedures?

We sincerely appreciate the reviewer’s careful and constructive comments. The intended meaning of the original expression in the manuscript refers to formulating criteria for seismic design. Considering the inappropriate wording, we have revised it to “***establishing seismic design specifications***”.

11) L157: “several seconds to hours” a rather days and even weeks in case of larger earthquakes.

We sincerely appreciate the reviewer’s careful and constructive comments. Indeed, the recovery process following major earthquakes may last for several days or even weeks. The original text only described the general scenario and lacked rigor. We have now supplemented the explanation with the following sentence: *For a catastrophic earthquake, such disruptions may even persist for several days or weeks.*

12) L165-166: Do you mean maps of supposed peak ground acceleration etc are used in these simulations?

We sincerely appreciate the reviewer's careful and constructive comments. In the simulation, this study takes into account the spatial incoherence of the seismic ground motion field and calculates the PGA values of pipelines at different locations for the subsequent evaluation of pipeline seismic damage ratio and other parameters. Nevertheless, the epicenter location adopted in the analysis is assumed.

13) L179-180: You wrote this sentence already at the end of the previous paragraph.

We sincerely appreciate the reviewer's careful and constructive comments. There is indeed repetitive content in this part, and the redundant statement has been deleted accordingly.

14) L181: WDN recovery rate needs to be defined somewhere, suggest to add here a reference to the equation where it is defined.

We sincerely appreciate the reviewer's careful and constructive comments. The detailed definition and corresponding calculation formula of the WDN recovery rate have been supplemented in Section 3.4, which are stated as follows:

Finally, to quantify the recovery efficiency of the WDNs, the recovery rate is defined in this study as the ratio of the service performance improvement value of the damaged network to the total recovery time during the recovery process. The calculation formula for the WDN recovery rate r is as follows:

$$r = \frac{\Delta SSIQ}{\Delta T} \quad (1)$$

15) L195: I guess you only modelled these upgrades rather than actually employing them.

We sincerely appreciate the reviewer's careful and constructive comments. Indeed, the water distribution network renovation measures mentioned herein are further simulated on the case networks in subsequent chapters to compare the improvement effects of different upgrading strategies. Since this study focuses on establishing a more comprehensive and accurate resilience evaluation framework for water distribution networks, the proposed renovation measures are not implemented in practical engineering applications, which belongs to the scope of network optimization research.

16) Fig:1: Second panel, interior graphics of the circle is too small. Panel 3 needs more

explanation/description. Key needs to be larger. Where is the variable description?

We sincerely appreciate the reviewer's careful and constructive comments. Regarding the issue that the figure inside the circle in the second part of Figure 1 is too small, we have revised the presentation form of this part in the revised manuscript by replacing the small diagram inside the circle with text description to improve readability.

For the description of the third part of Figure 1: the formula here is only a general schematic representation of the seismic resilience quantification method for water distribution networks. The detailed descriptions of all variables are provided in the subsequent formula derivations in the main text, so they are not repeated in the figure to avoid redundancy. In the revised manuscript, we have added a brief note in the figure caption to guide readers to refer to the subsequent text for detailed definitions.

17) L200: "assessment of WDNs" ? word missing?

We sincerely appreciate the reviewer's careful and constructive comments. This part has been revised to: *Quantitative method for four-stage resilience assessment of WDNs*.

18) Fig.2: first box starting with "Input": The repair rate should logically be part of the recovery phase, right? I guess it should rather be renamed to damage rate here.

We sincerely appreciate the reviewer's careful and constructive comments. We have revised "**the repair rate**" to "**the damage rate**" in the figures.

19) Is SSIQ a usual abbreviation for this variable? If not, I suggest a single letter abbreviation.

We sincerely appreciate the reviewer's careful and constructive comments. *SSIQ* is a widely adopted performance indicator for water distribution networks, namely the **System Serviceability Index of Quantity** (Xu et al., 2025; Hou et al., 2024; Song et al., 2022) , which can also be referred to as the system water supply satisfaction rate (Hou, B. et al., 2024). The detailed explanation of this indicator has been supplemented in the revised manuscript.

Xu, C., Ma, T., Hou, B., Ma, X., Miao, H., Du, X. Seismic fragility model for the system-level performance evaluation of water distribution systems. Soil Dyn. Earthq. Eng., 199, 109695, <https://doi.org/10.1016/j.soildyn.2025.109695>, 2025.

Hou, B., Yang, C., Wu, S., Miao, H., Xu, C. Seismic retrofit optimization of water distribution systems based on the reduction of uncertain damage scenarios. *Int. J. Disaster Risk Reduct.*, 112, 104756, <https://doi.org/10.1016/j.ijdr.2024.104756>, 2024.

Song, Z., Liu, W., Shu, S. Resilience-based post-earthquake recovery optimization of water distribution networks. *Int. J. Disaster Risk Reduct.*, 74, 102934, <https://doi.org/10.1016/j.ijdr.2022.102934>, 2022.

20) L232-233: Here you should offer some justification.

We sincerely appreciate the reviewer's careful and constructive comments. We have added the following explanatory content in the revised manuscript:

Leakage and water supply interruptions caused by pipe damage are the dominant factors governing the hydraulic performance and service capacity of water distribution networks. In contrast, pumping stations, reservoirs, and other structures are designed with higher seismic fortification levels; even if damaged, they can be fully restored within a short period and exert limited impact on the overall system. Accordingly, this study focuses only on pipeline damage, neglecting impacts on secondary components such as pumping stations and valves.

21) L235: I strongly suggest to replace the term “repair rate” with “damage rate” when you want to quantify the damage of the pipeline network. By the way, technically speaking the use of the term “rate” implies some form of time dependency in its definition, which is not the case here.

We sincerely appreciate the reviewer's careful and constructive comments. The variable notation *RR* has been uniformly replaced with **damage rate** throughout the entire manuscript.

22) L242: Please add the used correction coefficients.

We sincerely appreciate the reviewer's careful and constructive comments. Regarding the selection of correction coefficients in the *RR* calculation formula, we have supplemented relevant descriptions in Section 4.1 as follows:

This study assumes that the service areas of both WDNs are flat terrain and neglects permanent ground deformation risks such as soil liquefaction and fault rupture. The pipe materials consist

of two types: gray cast iron pipes and plastic pipes. Therefore, for Equation (4), the parameters C_a , C_b , and C_m are all taken as 1.

23) L250-252: How do you justify this assumption?

We sincerely appreciate the reviewer's careful and constructive comments. This assumption is derived from investigations conducted by the National Institute of Building Sciences. Statistical results indicate that **80% of post-earthquake pipeline damage manifests as leakage, and 20% as complete breakage**. We have added the corresponding reference in Section 3.1.3 and revised the statement to:

According to surveys by the National Institute of Building Sciences (FEMA, 2003), approximately 80% of pipeline damage after earthquakes is characterized by leakage, while the remaining 20% involves pipe breakage. Therefore, this study assumes that 80% of the randomly generated damage points are leakage points and 20% are breakage points.

24) Fig.3: Fonts could be larger. What is Q_{leak} ?

We sincerely appreciate the reviewer's careful and constructive comments. In the figure, Q_{leak} represents the leakage flow rate of the pipeline.

25) L271: "n" I suggest to use a different index variable because you already used n for the number of damages above.

We sincerely appreciate the reviewer's careful and constructive comments. We have changed the index variable n to a new notation in Line 271 to eliminate symbol repetition and confusion with the previously defined number of damages. The relevant contents have been carefully revised throughout the manuscript.

26) L272: "which can be determined according to actual conditions and managers' requirements." Please specify.

We sincerely appreciate the reviewer's careful and constructive comments. Supplementary explanations have been added to clarify the weight determination principle in the revised manuscript. The two weight coefficients in the node importance calculation formula correspond respectively to the proportion of nodal water demand and nodal betweenness centrality. In

practical engineering applications, their values can be flexibly assigned according to regional water supply characteristics and actual management preferences: When focusing on water supply service reliability, a larger weight is assigned to the proportion of nodal water demand; when emphasizing the topological structural importance of the pipe network, a higher weight is set for nodal betweenness centrality. In this study, the weight combination adopted in the example is given and illustrated, which can also be adjusted adaptively for different engineering scenarios.

27) L279: Here you use damage rate. Keep consistency in variable naming.

We sincerely appreciate the reviewer's careful and constructive comments. The variable *RR* has been uniformly renamed as damage rate throughout the manuscript.

28) L293: "NEI" Here and elsewhere, why using these multi-letter abbreviations? What is Q_{req} ?

We sincerely appreciate the reviewer's careful and constructive comments. We have supplemented the explanation that this variable denotes the actual water supply quantity of node i in the manuscript.

29) L295: "NEI represents the energy index considering pipeline diameter uniformity" is this the Todini index?

We sincerely appreciate the reviewer's careful and constructive comments. *NEI* is the modified Todini index. On the basis of the original index proposed by Todini, it further incorporates a correction coefficient that reflects the uniformity of pipe diameters.

30) L306: "damage rate" a time should be part of its definition if its a rate, right?

We sincerely appreciate the reviewer's careful and constructive comments. In this paper, damage rate is a specific term in the field of earthquake engineering. It refers to the probability or proportion of structures (such as water supply pipelines, buildings, and network components) suffering seismic damage of varying degrees under a given ground motion intensity (e.g., PGA, seismic fortification intensity), and it is irrelevant to the time dimension.

31) L311: *RR* has already been defined above.

We sincerely appreciate the reviewer's careful and constructive comments. This index is one of

the evaluation indicators for robustness, namely the average seismic damage rate of pipelines, which is calculated as the mean value of the seismic damage rates of all pipelines.

32) L313: this is not the right eq. reference.

We sincerely appreciate the reviewer's careful and constructive comments. We have conducted a full-text proofreading and corrected the expressions of formula symbols throughout the manuscript.

33) L321: " Q_{reg} " a definition should come at the first usage. It would be good to have the units also defined for the other variables.

We sincerely appreciate the reviewer's careful and constructive comments. The parameter Q^{req} has already been defined in the preceding formulas, and a corresponding explanation is also provided here: Q^{req} represents the basic water demand volume of water-demanding node i .

34) L342: WDN has already been defined

We sincerely appreciate the reviewer's careful and constructive comments. We have revised the full manuscript and removed the duplicate definitions.

35) L359-360: Just put the variables in parentheses to the description above the equation, then you could delete this sentence.

We sincerely appreciate the reviewer's careful and constructive comments. The expression here has been refined accordingly.

36) L363: I guess this study doesn't actually enhance the resilience of the WDN but is rather modelling the enhancement, right? Please clarify.

We sincerely appreciate the reviewer's careful and constructive comments. Indeed, this study focuses on realizing the four-stage seismic resilience evaluation of water distribution networks (WDNs), rather than conducting further optimization and enhancement. Therefore, this paper only lists three different rehabilitation measures to simulate the resilience improvement process of the water distribution network. The relevant description in the manuscript has been revised to:

In this stage, based on the multi-dimensional evaluation indicators proposed in the preceding

three stages, targeted renovation measures are adopted to simulate WDNs retrofitting, and the resilience level of the WDN after improvement is quantitatively calculated.

37) L365: suggest replacing “implemented” with “modelled” .

We sincerely appreciate the reviewer’s careful and constructive comments. The corresponding statement has been updated in the manuscript.

38) Fig.4: check grammar and spelling e.g. “topology” not “topological” of WDN, “peak” instead of “pack” .

We sincerely appreciate the reviewer’s careful and constructive comments. We have corrected the grammatical and spelling errors in the figures.

39) L388: what’s the population size of Jilin?

We sincerely appreciate the reviewer’s careful and constructive comments. The Jilin water distribution network adopted in this study is a hypothetical benchmark network, not a real urban system. It was obtained from the open-source water distribution system database (University of Kentucky, WDST). Therefore, there is no corresponding real-world population data. We have clarified this point in the revised manuscript (Line 388) to avoid misunderstanding.

40) General comment: please consider adding a table where all variables are listed i.e. with abbreviation, name and unit.

We sincerely appreciate the reviewer’s careful and constructive comments. We have added a nomenclature table of variables at the end of the manuscript to improve the readability and clarity of this paper.

41) L391: “simplification” a Please specify.

We sincerely appreciate the reviewer’s careful and constructive comments. The term "simplification" here refers to abstracting the complex actual water distribution network into a topological graph. Specifically, the actual layout, curvature, slope, burial elevation, and tortuous routes of pipelines are neglected. All pipelines are uniformly abstracted as linear topological edges, while the geometric forms of auxiliary structures such as valve chambers, inspection wells, pipe

elbows, and tee fittings are omitted. In the revised manuscript, this expression has been replaced with “*After topological abstraction*”.

42) L415-417: This is only true for the Jilin WDN. In Mianzhu there are several nodes in the center that are equally important. But more importantly, why are the nodes directly attached to the sources so unimportant? If they are damaged the entire system shuts down.

We sincerely appreciate the reviewer’s careful and constructive comments. Indeed, regarding the identification method of critical nodes in water distribution networks, this study takes both nodal water demand and node degree into consideration. Nodes with a high proportion of water demand and a low node degree are defined as critical nodes. The original calculation formula is expressed as follows:

$$V_i = w_1 \cdot \frac{Q_i^{req}}{\sum_{i=1}^n Q_i^{req}} + w_2 \cdot \left(1 - \frac{D_i}{\max\{D_1, D_2, \dots, D_n\}} \right) \quad (2)$$

In the formula, V_i represents the importance index of Node i ; Q_i^{req} represents the basic water demand of node i ; n is the number of user nodes; D_i is the degree of node i , i.e., the number of pipelines connected to this node; w_1 and w_2 are weight coefficients with $w_1 + w_2 = 1$, which can be determined according to actual conditions and managers’ requirements.

Nevertheless, as pointed out by the reviewer, such a definition of node importance is unreasonable. Degree centrality only focuses on the local connectivity of a node while ignoring its global topological location. Therefore, we have revised this formula for node importance calculation in this paper. The second term of the original formula is replaced with betweenness centrality, which refers to the proportion of the shortest paths between all node pairs that passthrough node i . The revised calculation formula for node importance is given as follows:

$$V_i = \alpha_1 \cdot \frac{Q_i^{req}}{\sum_{i=1}^n Q_i^{req}} + \alpha_2 \cdot \sum_{s \neq i \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}} \quad (3)$$

In the formula, V_i represents the importance index of Node i ; Q_i^{req} represents the basic water demand of node i ; n is the number of user nodes; σ_{st} is the number of shortest paths from node s to node t ; $\sigma_{st}(i)$ is the number of paths passing through node i ; α_1 and α_2 are weight coefficients with $\alpha_1 + \alpha_2 = 1$, which can be determined flexibly according to actual engineering focus:

prioritizing water supply demand or the topological importance of the WDN.

43) Fig.7: This is completely counterintuitive. Nodes at the periphery shouldn't be that important. Am I missing something? It would help when you write in the caption again what V_i and MCB_j are. The “seismic fortification intensity” has not been defined.

We sincerely appreciate the reviewer’s careful and constructive comments. Indeed, edge nodes should not be assigned such high importance. The authors have revised the calculation formula for critical nodes in the revised manuscript. The spatial distribution map of the final critical components is presented as follows:

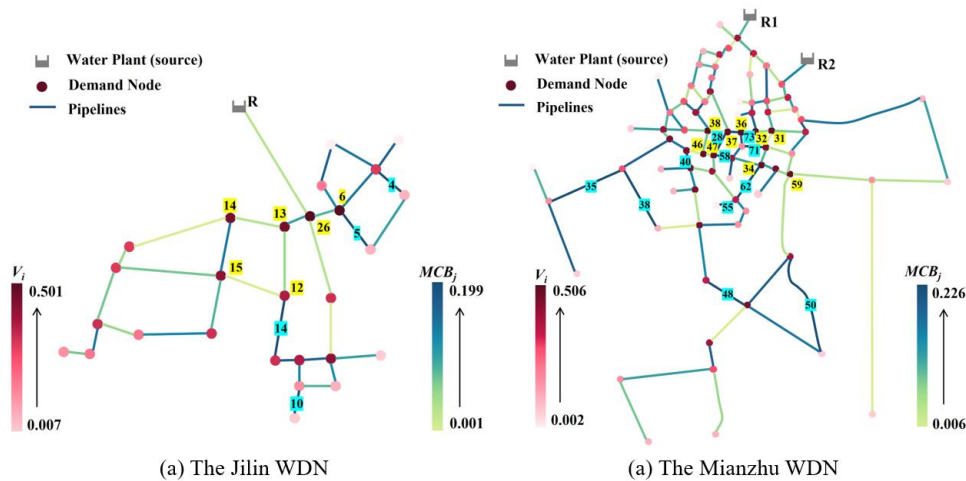


Figure 7. Spatial distribution of WDNs component importance (The darker the color, the higher the importance of the component. For the identification of key pipelines, it is assumed that the current seismic fortification intensity is X)

The term “seismic fortification intensity” represents the local seismic fortification intensity of the research area, which has been annotated in the figure caption.

44) L422: “seismic hazard analysis” ÷ is this coming from official estimates or is this a randomly chosen PGA field? Are there seismogenic faults in the vicinity of these WDNs that have been studied?

I suggest replacing “the effect of spatial incoherence of the” with “a spatially varying”.

We sincerely appreciate the reviewer’s careful and constructive comments. The relevant expression has been revised to “*a spatially varying ground motion field*” in the manuscript. In

addition, the seismic hazard analysis in this study is only adopted to determine the site PGA. Neither of the two selected water distribution network examples considers fault traversal. This explanation has been supplemented in Section 4.1:

This study assumes that the service areas of both WDNs are flat terrain and neglects permanent ground deformation risks such as soil liquefaction and fault rupture. The pipe materials consist of two types: gray cast iron pipes and plastic pipes. Therefore, for Equation (4), the parameters C_b , C_l , and C_m are all taken as 1.

45) L424: “ground motion field” do you mean PGA?

We sincerely appreciate the reviewer’s careful and constructive comments. The statement in this context refers to the PGA distribution of each pipeline within the water distribution network.

46) L427: wrong equation ref. it is actually eq 11.

We sincerely appreciate the reviewer’s careful and constructive comments. The corresponding content has been revised in the manuscript.

General comment: I suggest to use more active language and simpler sentences.

We sincerely appreciate the reviewer’s careful and constructive comments. We have fully polished the manuscript by using more active language and simplifying sentence structures to make the writing clearer and easier to understand.

47) L431: This implies that you assume the other correction factors to be equal, right? You should state this here.

We sincerely appreciate the reviewer’s careful and constructive comments. In this study, it is assumed that the two water distribution networks share identical terrain conditions and soil liquefaction characteristics, thereby yielding identical correction factors for both networks. Supplementary explanations have been added in Section 4.1, as follows:

This study assumes that the service areas of both WDNs are flat terrain and neglects permanent ground deformation risks such as soil liquefaction and fault rupture. The pipe materials consist of two types: gray cast iron pipes and plastic pipes. Therefore, for Equation (4), the parameters C_t ,

Cl, and *Cm* are all taken as 1.

48) L434: earthquake magnitudes, better separate the caption from the text in the manuscript.

We sincerely appreciate the reviewer's careful and constructive comments. Following your suggestions, we have made corresponding adjustments in the manuscript to clearly distinguish the figure captions from the main text paragraphs.

49) Fig.10: text in figure is too small.

We sincerely appreciate the reviewer's careful and constructive comments. We have adjusted the font size of the text in the figure, and the revised figure is presented below:

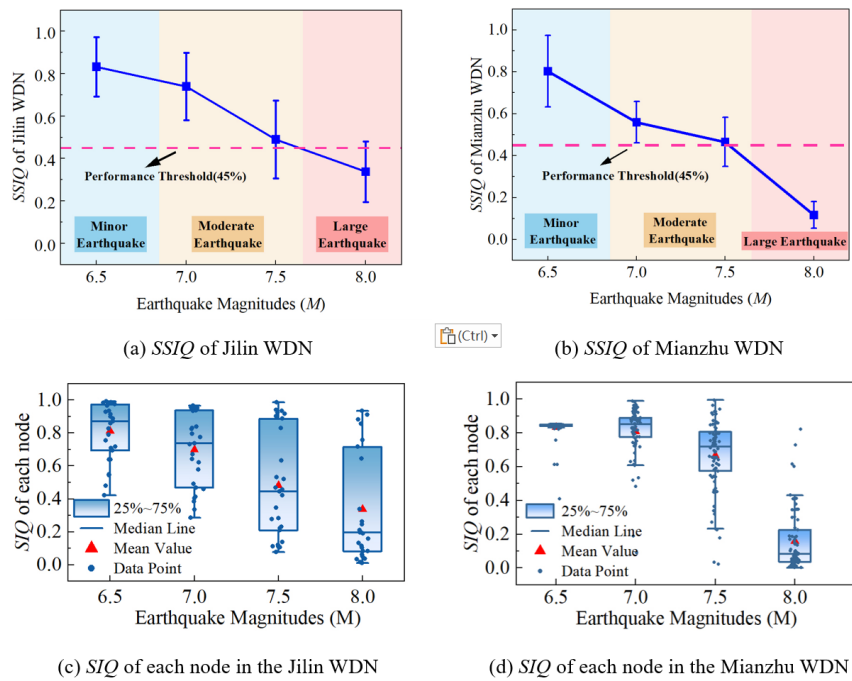


Figure 11. Water supply satisfaction rate under different earthquake magnitudes

50) L465-467: But this is only true for the Jilin WDN, because the Mianzhu WDN reaches more than 0.95.

We sincerely appreciate the reviewer's careful and constructive comments. We have corrected the recovery curves of the two water distribution networks under the M_w 7.0 earthquake scenario. It is evident that at 72 hours, the service performance of both networks exceeds 0.9, indicating an almost full functional recovery. The revised interpretation is summarized as follows:

Under an M_w 7.0 earthquake, both networks show a rapid rise in SSIQ within 72 hours, reaching mean values above 0.90, indicating that most service functionality can be restored within three days.

51) Fig.11: suggest to color code the lines like the bars

We sincerely appreciate the reviewer’s careful and constructive comments. We have revised the figure, and the updated version is presented below.

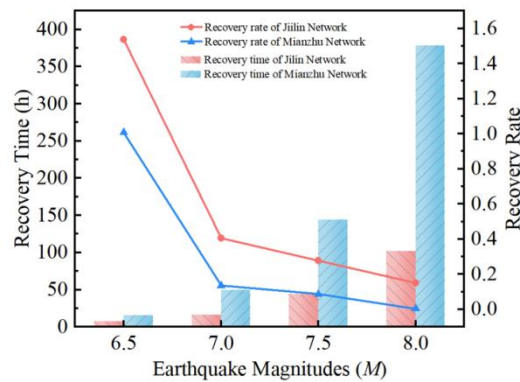


Fig. 12 The WDNs’ recovery time and recovery rate under different magnitudes

52) Fig.12: does it make sense that the μ +sigma curves all go beyond 1?

We sincerely appreciate the reviewer’s careful and constructive comments. Since the standard deviation σ characterizes the dispersion degree of data and has no inherent upper or lower bounds, the sum $\mu + \sigma$ may exceed 1 when the mean value μ is close to 1 (e.g., $\mu = 0.95$) while $\sigma = 0.1$. As the SSIQ is a normalized performance metric, its error range ($\mu \pm \sigma$) should theoretically be constrained within the boundary of 0 and 1. Accordingly, we have reprocessed the raw data and truncated the error range strictly within the interval [0, 1]. The revised figure is presented below.

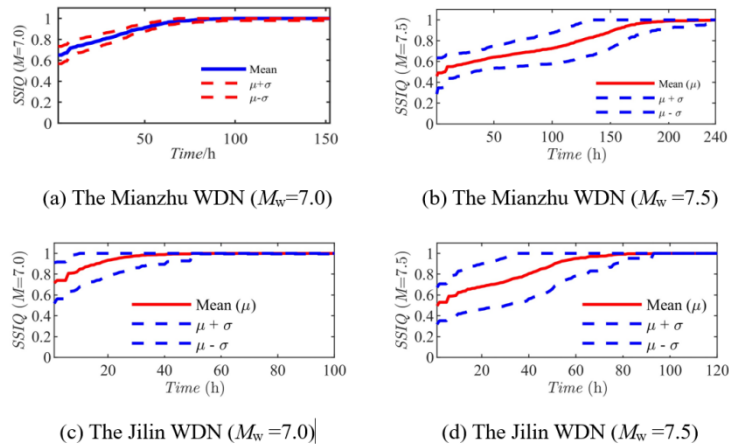


Fig. 13 Mean performance recovery curves and one standard deviation error bars of WDNs under different magnitudes

53) L482: Do you mean modelled?

We sincerely appreciate the reviewer's careful and constructive comments. Indeed, this study only simulates different renovation strategies for the benchmark water distribution networks and evaluates the corresponding post-retrofitting resilience performance, rather than implementing actual physical reconstruction of the networks.

54) Table2: "The key pipelines" instead of "The pipelines of key pipelines".

We sincerely appreciate the reviewer's careful and constructive comments. The erroneous expression has been corrected in the manuscript.

55) Fig13: What is the red curve in the background?

We sincerely appreciate the reviewer's careful and constructive comments. In the figure, the red portion represents the pipeline importance index MCB_j , while the blue bar chart denotes the failure frequency of pipelines obtained from 200 Monte Carlo simulations. Relevant explanations have been supplemented in the revised figure.

56) Fig:16: What is growth rate?

We sincerely appreciate the reviewer's careful and constructive comments. The term "growth rate" refers to the improvement rate of the resilience indicator at each stage. We have corrected this error in the figure accordingly.