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Review and rebuttal of the paper

Three roles of evacuation simulation in life-safety-oriented flood disaster management

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Editor handling the paper: Miguel Esteban

The reviewers remain anonymous.

Reviewer A

(Comment) This Short Communication organizes the roles of evacuation simulation in flood disaster management into three categories: diagnostic, experimental, and optimization. The proposed framework could provide a useful basis for discussing the societal roles of evacuation simulation and directions for its future development. I therefore believe that publication of this Short Communication and dissemination of its perspective would be valuable to the readership of the journal.

The reviewer has no major comments on the manuscript. However, the following points should be addressed before publication.

(Answer) The author sincerely thanks the reviewer for taking the time to review this Short Communication and for providing constructive comments. The manuscript has been revised accordingly, as detailed in the responses to each comment below.

The authors state that the three roles are "not entirely new or mutually exclusive" (Page 3, Line 1), while Figure 1 presents the three roles side by side. I felt that the relationships among the three roles are not discussed very explicitly. At the same time, some parts of the manuscript appear to imply that these roles may be applied sequentially—for example, diagnostic simulation may first identify evacuation problems, experimental simulation may then test possible measures to address those problems, and optimization may subsequently be used to identify preferable or optimal measures. If this interpretation is consistent with the authors' intention, I suggest adding some discussion of the relationships among the three roles. Even if they are not necessarily sequential, clarification of how they relate to and overlap with one another would help readers better understand the proposed framework.

The author thanks the reviewer for this helpful comment. The author agrees that the relationships among the three roles were not sufficiently explicit in the original manuscript. The intended framework is flexible: the three roles can be applied independently when addressing a specific planning question, sequentially when diagnosis leads to the testing of possible measures and subsequently to optimization, and iteratively when proposed or optimized measures are reassessed under different assumptions or conditions.

To clarify these relationships, *Figure 1* has been revised to show both possible sequential and feedback relationships among the three roles. The updated figure and caption are as follows:

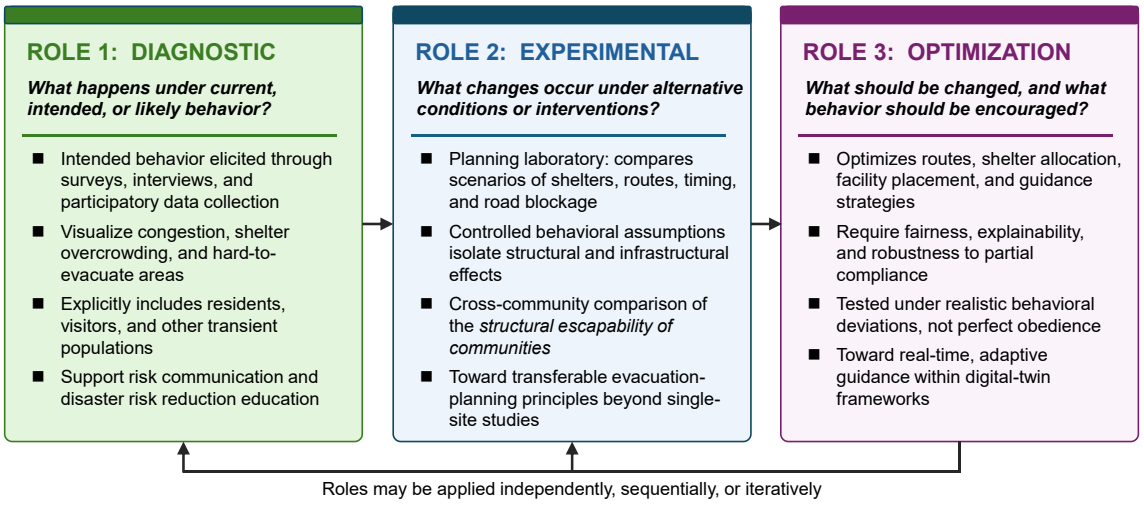


Figure 1: Three roles of evacuation simulation in life-safety-oriented flood disaster management. The arrows indicate possible sequential and iterative relationships among the roles and do not represent a mandatory workflow.

Additionally, the final paragraph of the Introduction has been revised to state that the roles may be applied independently, sequentially, or iteratively:

"The three roles are not presented as entirely new or mutually exclusive. They can be applied independently, sequentially, or iteratively, depending on the planning purpose. For example, diagnostic simulation may identify evacuation problems, experimental simulation may then examine possible measures, and optimization may subsequently search for more effective solutions. Measures identified through these processes can also be reassessed through the diagnostic or experimental roles under revised behavioral, population, or hazard assumptions. By organizing existing and emerging applications into these three roles, this Short Communication provides a framework for the wider and responsible use of evacuation simulation under its current limitations."

Furthermore, the Concluding perspective now emphasizes that the framework is intended to support a flexible planning process rather than to prescribe a fixed sequence. Specifically, the following text has been added as the 5th paragraph of the Concluding perspective:

"Taken together, the three roles are intended to support a flexible planning process rather than to prescribe a fixed sequence. Their value lies in linking problem identification, comparative testing, and solution development, while allowing repeated reassessment as conditions and assumptions change."

The title refers broadly to "flood disaster management." Flood disasters include tsunamis, storm surges, riverine floods, pluvial floods, and compound flooding. The conditions surrounding evacuation can differ considerably among these hazards. For example, tsunami evacuation may need to begin within a very short time after an earthquake, whereas evacuation associated with rainfall-induced flooding may, in some cases, be supported by forecasts and warnings issued considerably before inundation. Accordingly, the relative importance and application of evacuation simulation may also differ depending on the type of flood hazard. I recognize that this is a Short Communication focused primarily on presenting the three roles, and therefore a detailed discussion for each type of flood disaster is not necessary. Nevertheless, given the broad scope indicated by the title, some brief discussion of this point would be useful.

The author thanks the reviewer for raising this point. The author agrees that evacuation conditions vary considerably depending on the type of flood hazard, and that these differences affect the application of evacuation simulation. Accordingly, the following paragraph has been added to the Concluding perspective, immediately before the final paragraph:

"Evacuation conditions differ considerably among the hazards to which this framework applies. Near-field tsunamis may allow only a short interval, often from several minutes to a few tens of minutes, between the earthquake and tsunami arrival, whereas riverine floods, storm surges, and some distant tsunamis may provide substantially longer warning lead times. Flash and pluvial floods can also involve short and uncertain lead times. Such differences affect assumptions regarding warning response, departure timing, travel mode, and the spatial and temporal scales represented in evacuation simulations, and may therefore influence both the relative importance of the three roles and how they are applied in practice. Nevertheless, the three roles remain applicable across these hazards because they are defined by the purpose of the analysis rather than by the characteristics of a specific hazard."

In the discussion of the experimental role, the concept of "structural escapability of communities" is introduced and emphasized in italics. I find this idea very interesting and potentially important as one direction for the application of evacuation simulation. However, the concept appears somewhat abruptly, without a specific reference or explanation of its origin. The authors should clarify whether this concept has already been proposed or discussed in previous studies, or whether it is a new concept that the authors intend to propose in this Short Communication. If it is newly proposed here, a brief explanation of its novelty and its relationship to existing concepts in evacuation research would help readers understand its significance.

The author thanks the reviewer for this comment and for the interest in this concept. The *structural escapability of communities* is a new concept proposed in this Short Communication. The author agrees that this was not stated sufficiently clearly in the original manuscript.

Section 2.2 has therefore been revised to explicitly identify *structural escapability* as a concept proposed in this study and to distinguish it from previous studies examining the effects of urban form on evacuation outcomes. The novelty does not lie in recognizing that urban structure influences evacuation, which has been demonstrated in previous studies. Rather, the concept compares the capacity for timely evacuation across communities under common hazard and behavioral conditions. This helps isolate the influence of community structure on evacuation performance.

The revised passage in Section 2.2 reads as follows:

"Beyond local planning, this controlled use of evacuation simulation can move evacuation research beyond single-site scenario studies toward comparative analyses across communities. When behavioral assumptions are held constant across multiple communities, differences in simulated evacuation performance can be interpreted not only as scenario-specific outcomes but also as evidence of how the physical structure of a community supports or constrains rapid mass movement. In this sense, this Short Communication proposes the concept of the structural escapability of communities, defined as the capacity of urban form, including street networks, topography, population distribution, high-ground accessibility, and shelter placement, to help exposed populations reach safety within the available time.

The premise that urban structure affects evacuation outcomes is not itself new. Previous studies have examined how urban morphology, street networks, evacuation routes, and shelter configurations influence evacuation performance [41, 42], and León et al. [43] compared seven coastal cities and ranked built-environment attributes as predictors of evacuation outcomes. The concept proposed here differs in its purpose and definition. Rather than evaluating evacuation performance as the combined result of site-specific hazard, behavioral, and urban conditions, structural escapability seeks to isolate the contribution of community structure by applying common hazard and behavioral conditions across communities. This controlled comparison allows evacuation performance to be interpreted as a relative characteristic of community structure under a specified time constraint. The concept therefore provides a basis for comparing communities and, ultimately, for identifying structural characteristics that consistently facilitate or hinder timely evacuation."

References:

León, J., & March, A. (2014). Urban morphology as a tool for supporting tsunami rapid resilience: A case study of Talcahuano, Chile. *Habitat International, 43*, 250–262. https://doi.org/10.1016/j.habitatint.2014.04.006

León, J., & March, A. (2015). An urban form response to disaster vulnerability: Improving tsunami evacuation in Iquique, Chile. *Environment and Planning B: Urban Analytics and City Science, 43*(5), 826–847. https://doi.org/10.1177/0265813515597229

León, J., Gubler, A., & Ogueda, A. (2022). Modelling geographical and built-environment attributes as predictors of human vulnerability during tsunami evacuations: A multi-case-study and paths to improvement. *Natural Hazards and Earth System Sciences, 22*(9), 2857–2878. https://doi.org/10.5194/nhess-22-2857-2022

Reviewer C:

(Comment) Thank you for this opportunity in reviewing this paper which is well organized and covers the whole process of evacuation simulation. Please find below some suggestions I believe that can improve completeness the current draft.

(Answer) The author sincerely thanks the reviewer for taking the time to review this Short Communication and for providing constructive suggestions. The manuscript has been revised accordingly, as detailed in the responses to each comment below.

Different stakeholders use evacuation simulation results differently. It may be good to arrange explanations for each of them. You may consider applying this in conclusion section if it is too difficult to apply in the main body.

The author thanks the reviewer for this suggestion. The author agrees that the three roles are used differently by different stakeholders, and that this point was not addressed in the original manuscript. Accordingly, the following paragraph has been added as the 6th paragraph of Section 3:

"The three roles may also serve different purposes for different stakeholders. Local authorities, planners, and disaster management agencies can use simulation to identify evacuation problems, compare possible measures, and develop evacuation routes, facilities, and guidance strategies. Researchers can use these roles to examine evacuation mechanisms and derive more generalizable planning knowledge through comparative analysis. For residents and visitors, simulation results can support risk communication, preparedness, and understanding of evacuation options. In all cases, the assumptions and limitations of the simulation should be communicated together with its results to avoid presenting simulated outcomes as predictions of what will actually occur."

Diagnostic role: As this paper focuses on water-related disasters which as different warning time for evacuation. For example, we have some days or hours for flood or storm surge warning but only minutes or hours for tsunami warning. Thus, it may be good to mention about this point too.

The author thanks the reviewer for this comment. The author agrees that the time available for warning and evacuation differs considerably among flood hazards and that these differences affect how evacuation simulation is applied.

This point was also raised by Reviewer A (Comment #2). Since differences in the time available for warning and evacuation affect the assumptions of all three roles rather than the diagnostic role alone, this issue has been addressed in the Concluding perspective rather than in Section 2.1, so that it applies to the framework as a whole. Specifically, the following paragraph has been added to the Concluding perspective, immediately before the final paragraph:

"Evacuation conditions differ considerably among the hazards to which this framework applies. Near-field tsunamis may allow only a short interval, often from several minutes to a few tens of minutes, between the earthquake and tsunami arrival, whereas riverine floods, storm surges, and some distant tsunamis may provide substantially longer warning lead times. Flash and pluvial floods can also involve short and uncertain lead times. Such differences affect assumptions regarding warning response, departure timing, travel mode, and the spatial and temporal scales represented in evacuation simulations, and may therefore influence both the relative importance of the three roles and how they are applied in practice. Nevertheless, the three roles remain applicable across these hazards because they are defined by the purpose of the analysis rather than by the characteristics of a specific hazard."

Experimental role: I think there are some issues that you may also include such as these points:

1) Interaction between human and vehicles or among vehicles.

2) Horizontal evacuation and vertical evacuation. I believe this paper focuses on horizontal evacuation but there is some time that needs to be considered for walking up to higher floor of buildings.

3) Difficulty in estimating number of population and also variation against day time/night time or seasonal variation.

4) People might act differently to what they answered in the questionnaire survey.

The author thanks the reviewer for these suggestions, which have been incorporated into Sections 2.1 and 2.2 as follows.

(1) To address the interaction between pedestrians and vehicles, as well as interactions among vehicles, a new paragraph has been added to Section 2.2. Three relevant studies have also been added to the reference list. The new paragraph begins as follows:

"For instance, evacuation may involve not only pedestrians but also evacuees using vehicles. Interactions among vehicles can cause traffic congestion, while interactions between vehicles and pedestrians can also affect evacuation movement and safety. Examining how the mix of evacuation modes and the interactions among them affect evacuation times and casualty rates is therefore an important experimental application, and several studies have addressed this issue [33–35]."

(2) The distinction between horizontal and vertical evacuation has also been addressed in the same newly added paragraph of Section 2.2, following the text added in response to point (1):

"The relative effectiveness of horizontal and vertical evacuation can be examined in the same way, although assessing vertical evacuation requires a more detailed representation of the evacuation process, including the time needed to enter a building and ascend to a safe floor."

(3) The author agrees that estimating the exposed population is difficult and that population size and distribution can vary substantially by time of day and season. Section 2.1 (5th paragraph) already discusses transient populations that may be absent from residential demographic data and notes variations associated with time of day, season, weather conditions, holidays, and local events. Following the reviewer's comment, the treatment of such variation as an experimental condition has also been added to the same new paragraph of Section 2.2, following the text described in points (1) and (2):

"Another important application is to examine how differences in the size and distribution of the exposed population, as well as the time at which an event occurs, affect evacuation outcomes and casualty rates [9]."

(4) The author agrees that stated intentions may differ from actual behavior. Since this issue concerns the interpretation of simulated outcomes obtained under stated or intended behavior, it has been addressed in Section 2.1 rather than Section 2.2. The following paragraph has been added after the 2nd paragraph of Section 2.1:

"However, caution is required when interpreting such outcomes. Intended evacuation behavior stated in questionnaires or interviews may differ from actual behavior under real hazard conditions [28]. Diagnostic simulation does not resolve this discrepancy. Its value lies in making the assumed behavior explicit, so that simulated outcomes can be interpreted as consequences of clearly stated assumptions rather than as predictions of what will actually occur."

References:

Di Mauro, M., Megawati, K., Cedillos, V., & Tucker, B. (2013). Tsunami risk reduction for densely populated Southeast Asian cities: analysis of vehicular and pedestrian evacuation for the city of Padang, Indonesia, and assessment of interventions. *Natural Hazards, 68*, 373–404. https://doi.org/10.1007/s11069-013-0632-z

Fraser, S. A., Wood, N. J., Johnston, D. M., Leonard, G. S., Greening, P. D., & Rossetto, T. (2014). Variable population exposure and distributed travel speeds in least-cost tsunami evacuation modelling. *Natural Hazards and Earth System Sciences, 14*(11), 2975–2991. https://doi.org/10.5194/nhess-14-2975-2014

Hasegawa, N., & Takabatake, T. (2024). The role of vehicular considerations in tsunami shelter location optimization. *International Journal of Disaster Risk Reduction, 110*, Article 104607. https://doi.org/10.1016/j.ijdrr.2024.104607

Kim, K., Kaviari, F., Pant, P., & Yamashita, E. (2022). An agent-based model of short-notice tsunami evacuation in Waikiki, Hawaii. *Transportation Research Part D: Transport and Environment, 105*, Article 103239. https://doi.org/10.1016/j.trd.2022.103239

Sun, Y., Nakai, F., Yamori, K., & Hatakeyama, M. (2016). Tsunami evacuation behavior of coastal residents in Kochi Prefecture during the 2014 Iyonada Earthquake. *Natural Hazards, 85*, 283–299. https://doi.org/10.1007/s11069-016-2562-z

Optimization role: I think it is also important to mention that the real event might be bigger than the simulation, so we need to educate users or let them keep in mind to have such ability to make decisions for such situations.

The author thanks the reviewer for this important point. The author agrees that actual disaster conditions may exceed those assumed in optimization and that this limitation should be clearly communicated to users of optimized guidance. The following text has therefore been added to the 4th paragraph of Section 2.3:

"Such communication should also convey that actual disaster conditions may exceed those assumed in the optimization. Evacuees and emergency managers should therefore understand these limitations and be prepared to adapt their decisions when actual conditions differ from those assumed."

Will it be useful to discuss evacuation simulation with the official warning and explain a bit more about disaster education using VR/AR technology?

The author thanks the reviewer for these suggestions.

Regarding official warnings, the focus of this Short Communication is on how evacuation simulation is used, and a full discussion of warning systems would extend beyond this scope. However, the author agrees that responses to official warnings are directly relevant to evacuation simulation because they affect evacuation departure timing. The following text has therefore been added to the 1st paragraph of Section 2.1:

"Among these behavioral inputs, the intended responses to official warnings are particularly important, since departure timing strongly affects whether evacuation can be completed within the available time. Collecting information on whether, and how quickly, people would act on an official warning provides a basis for representing departure timing in simulations rather than simply assuming it."

Differences in warning lead time among flood hazards are also discussed in the Concluding perspective, in the paragraph added in response to Comment #2 from Reviewer C.

Regarding disaster education using VR and AR, these technologies were already discussed in the final paragraph of Section 2.1 and in the 7th paragraph of the Concluding perspective. Following the reviewer's suggestion, their potential contribution to disaster risk reduction education has been stated more explicitly in the 7th paragraph of the Concluding perspective.

"In particular, VR and AR can support disaster risk reduction education by allowing people to experience evacuation situations that are difficult to reproduce in conventional drills."