Comparison of Traditional (2D) and Stereoscopic (3D) Flood Visualization in supporting Flood Risk Assessment

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Abstract: Stereoscopic 3D visualization expands flood risk assessment by adding depth and realism to the way hydrologic model results are displayed. This study explores the benefits of using stereoscopic 3D visualization in comparison to traditional 2D flood visualization methods to support flood risk assessment. A quasi-experimental approach was used to rate the helpfulness of using 2D and stereoscopic 3D visualizations to answer nine flood risk assessment questions. The results show that both 2D and stereoscopic 3D visualization are effective though sometimes complimentary with each approach having different strengths and weaknesses. Questions of assessing safety showed the greatest differences with 2D maps rated as unhelpful and stereoscopic 3D visualizations rated as helpful. Conclusions suggest that stereoscopic 3D flood visualizations are effective and will likely become more available as 3D modeling technology improves. They also suggest that more research is needed to explore the benefits of stereoscopic 3D flood visualizations for flood risk assessment and for expanding flood risk awareness to more stakeholders in the community.

Keywords: Flood risk, virtual reality, hydrologic modeling, visualization

1 Introduction

Flood visualization has long been an effective motivator at the policy level and is used by advocates of change (FEMA 2022, NOAA 2025). However, while federal, state and local agencies offer mapping visualization of river flooding and sea-level rise, the format of these 2D mapping applications may not be sufficient to fully communicate flood risk to untrained community stakeholders (ZHU et al. 2025, DE SANTIS et al. 2019, RAUTENBACH et al. 2017). Previous studies have called for empirical studies to assess how stereoscopic 3D visualizations affect risk perceptions (KUSTER et al. 2023, SIMPSON et al. 2022, CHARRIERE et al., 2012). Stereoscopic 3D visualization is a game changer in its ability to visualize flooding solutions at human scale as though you are actually present at the scene during the flood (BAKHTIARI et al. 2023). Immersed in their virtual neighborhood, decisionmakers can view 3D flood simulations to better assess flood risk.

This study is a quasi-experiment involving stakeholder participation to determine the acceptance and effectiveness of using stereoscopic 3D visualization to assess pluvial flooding vulnerability. It explores whether public officials and community organizers find stereoscopic 3D visualization as an effective way to visualize flooding and assess flood risks? It also looks at the differences between stereoscopic 3D visualizations and traditional plan, elevation and tabular representations of model results.

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2 Methods

2.1 Flood Scenario Generation

Flooding scenarios in this study are pluvial, representing urban surface water floods caused when stormwater exceeds the capacity of the infrastructure. Older urban neighborhoods such as those in Baltimore, MD are at high risk to pluvial flooding due to a lack of protection. The study area is located at the corner of East Lafayette Ave and North Castle Street in Baltimore, MD. The spatial data used to produce the scenarios was obtained through Open Baltimore (https://data.baltimorecity.gov/) including 2-foot contours, building footprints, edge of pavement, vegetation, soils, aerial photos, stormwater pipe network, property lines, etc. On-site surveys were conducted to verify and update all data. ArcGIS Pro was used to process the data for defining the watershed boundary, populating the WinTR-55 hydrologic model for small watersheds, and running a Hazen-Williams pipe flow model. AutoCAD and SketchUp were used to establish the floodplain cross-sections and flood surfaces. Sketchup and Lumion were used to build and render the 3D model, and Lumion was used to produce the 2D and stereoscopic 3D visualizations. Photoshop was used to optimize the color and contrast for viewing on Meta Quest 3S VR headsets. Pigasus VR Media Player was used to view all visualizations in the VR headset.

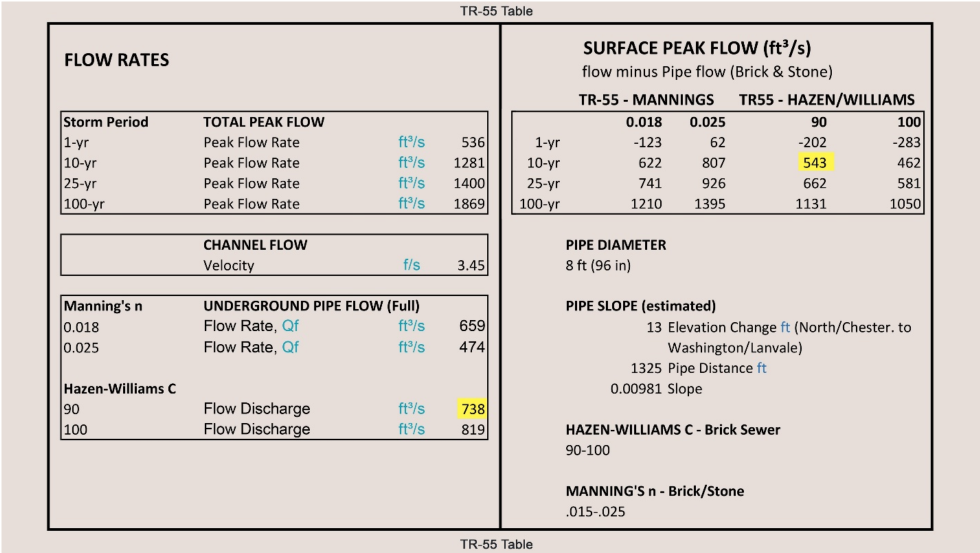
2.2 Sample Population

Participants were recruited using a convenience sample approach to include a balanced mix of users. These include community leaders, public agency professionals, private sector professionals, and community residents. Recruitment included direct email, flyers at targeted professional events, and tabling at community events. Participants were given boxed lunches to compensate for their time.

2.3 Training and Flood Risk Assessment

All participants were trained to use the VR headset to view visualizations prior to completing the flood risk assessment experiment. Visualizations (Figure 1) included a table of hydrologic model results, a 2D plan view of a flooded intersection, a 2D elevation of the intersection, a stereoscopic 3D 360-degree eye-level visualization of the intersection, and a stereoscopic 3D 360-degree aerial view. The flood scenario was a 10-year return period. Nine flood risk assessment questions are presented in section 3.2.

Each of the nine questions required the following tasks, 1) use the headset and five visualizations to answer the question, and 2) rate each of the five visualizations in how helpful they were in answering the question. Each rating question had a choice from one to seven where 1 equaled "not helpful", and 7 equaled "very helpful".



TR-55 Table

FLOW RATES

Storm Period	TOTAL PEAK FLOW		
1-yr	Peak Flow Rate	ft³/s	536
10-yr	Peak Flow Rate	ft³/s	1281
25-yr	Peak Flow Rate	ft³/s	1400
100-yr	Peak Flow Rate	ft³/s	1869

	CHANNEL FLOW		
	Velocity	f/s	3.45

Manning's n	UNDERGROUND PIPE FLOW (Full)		
0.018	Flow Rate, Qf	ft³/s	659
0.025	Flow Rate, Qf	ft³/s	474
Hazen-Williams C			
90	Flow Discharge	ft³/s	738
100	Flow Discharge	ft³/s	819

SURFACE PEAK FLOW (ft³/s)
flow minus Pipe flow (Brick & Stone)

	TR-55 - MANNINGS		TR55 - HAZEN/WILLIAMS	
	0.018	0.025	90	100
1-yr	-123	62	-202	-283
10-yr	622	807	543	462
25-yr	741	926	662	581
100-yr	1210	1395	1131	1050

PIPE DIAMETER
8 ft (96 in)

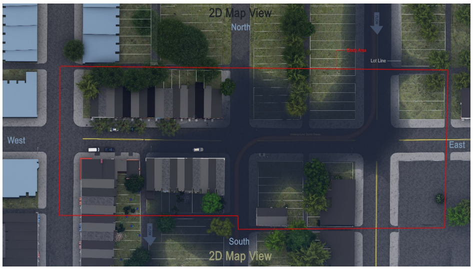
PIPE SLOPE (estimated)
13 Elevation Change ft (North/Chester. to Washington/Lanvale)
1325 Pipe Distance ft
0.00981 Slope

HAZEN-WILLIAMS C - Brick Sewer
90-100

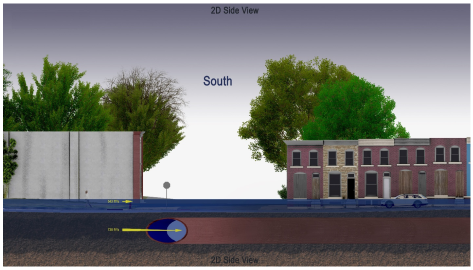
MANNING'S n - Brick/Stone
.015-.025

TR-55 Table

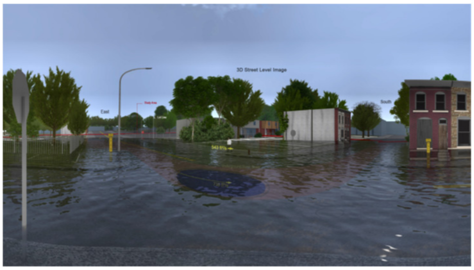
Table



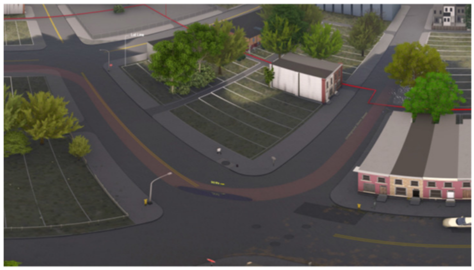
2D Map



2D Elevation



3D 360° Eye-Level View (cropped)



3D 360° Aerial-Level View (cropped)

Fig. 1: Above are the five visualizations that participants viewed in VR headsets to answer flood risk assessment questions. Only the 3D 360-degree visualizations were stereoscopic and fully immersive. All visualizations were viewed within the VR headset. The table and 2D visualizations appeared to participants as if it was an eye-max theatre experience (2D but full screen). The stereoscopic 3D 360-degree views were cropped here for viewing in a standard publication format.

3 Results

3.1 Participant Characteristics

A total of 52 people participated in our study. Mean age was 51.12(SD: 18.07) years old. Forty-five percent of participants were male while fifty-five percent were female. Fifty-eight percent of participants were white, twenty-seven percent were black, eight percent Asian, two percent American Indian or Alaskan native, and six percent other. Eight percent were Hispanic and ninety-two percent non-Hispanic.

3.2 Repeated Measures ANOVA and Pairwise Comparison

The results presented here include the comparison of ratings for each visualization for each of the nine flood risk assessment questions. Preliminary analyses were completed using Repeated Measures Anova. Mauchly's Test of Sphericity (that the variances of the differences between all pairs of groups are equal) was significant for all nine questions, so Greenhouse-Geisser correction was used to test for within-subjects effects. The Greenhouse-Geisser results were significant for all questions indicating that significant differences exist among the visualization ratings for each flood assessment question. Finally, a post-hoc pairwise comparison was completed to determine how each visualization was rated relative to other visualizations. Bonferroni correction was applied. The error bars in the charts below, though technically not correct for within-subjects testing (CUMMING et al. 2007), do offer a good visual approximation of significant differences.

Each graph shows the rating on the Y axis ("not helpful" to "very helpful") and the visualization type on the X axis. The value of 4 was highlighted in red as a neutral value neither very helpful nor not helpful. The graphed points represent the mean value for all observations. The range lines for each mean represents the 95-percentile value.

Question 1: How many vacant lots in the area will be affected by the 10-year flood? (answer: 24, mean: 24.43, SD: 9.975) The ratings (Figure 2) of helpfulness on vacant lots' flood assessment among five visualizations were statistically significant ($F (2.98, 146.23) = 37.07$, $p < .001$, partial $\eta^2 = .65$). Here the "2D Map" and the "3D Aerial" were rated the most helpful while the "Table", "2D elevation" and "3D Eye-Level" were considered less helpful (below the neutral value of 4).

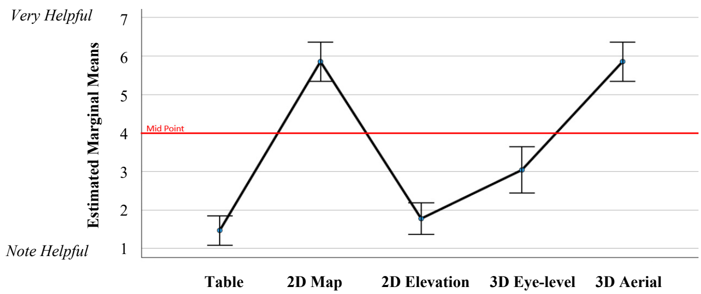


Fig. 2: Graph of estimated marginal means for question 1

Question 2: How many row houses in the area will likely have flood water entering the building? (answer: 15, mean: 18.16, SD: 7.347) The ratings (Figure 3) of helpfulness on row houses' flood assessment among five visualizations were statistically significant (F (2.72, 127,87) = 45.14, $p < .001$, partial $\eta^2 = .49$). Here the "2D Map", the "3D Eye-Level" and the "3D Aerial" were rated the most helpful while the "Table", and "2D Elevation" were considered less helpful.

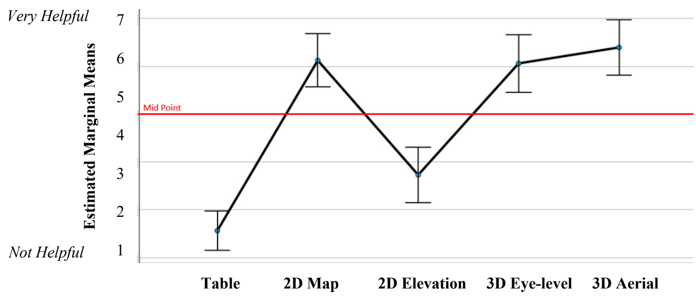


Fig. 3: Graph of estimated marginal means for question 2

Question 3: How safe is it to walk through the flooded intersection during the 10-year flood? (1=not safe to 7=very safe, mean: 1.83, SD: 1.41) The ratings (Figure 4) of helpfulness on walking safety among five visualizations were statistically significant (F (3.55, 170.14) = 57.45, $p < .001$, partial $\eta^2 = .55$). Here the "3D Eye-Level" was rated the most helpful while the "Table" and "2D Map", were considered less helpful. The "2D Elevation" and the "3D Aerial" were neither very helpful nor not helpful.

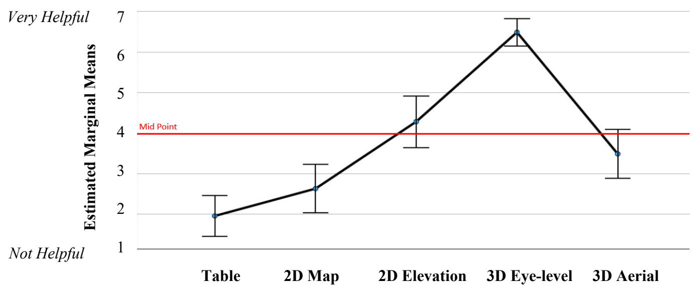


Fig. 4: Graph of estimated marginal means for question 3

Question 4: How safe is it to drive through this intersection during the 10-year flood? (1=not safe to 7=very safe, mean: 1.29, SD: 0.92) The ratings (Figure 5) of helpfulness on drive safety among five visualizations were statistically significant (F (3.18, 149.23) = 53.03, $p < .001$, partial $\eta^2 = .84$). Here the "2D Elevation" and the "3D Eye-level" were rated the most helpful while the "Table" and "2D Map" were considered less helpful. The "3D Aerial" was neither very helpful nor not helpful.

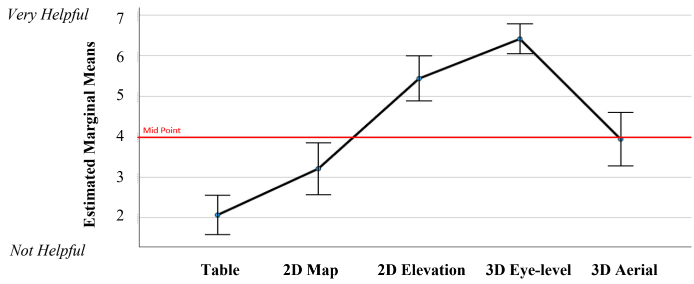


Fig. 5: Graph of estimated marginal means for question 4

Question 5: Which direction is the flood water flowing? (**From**: north 55.8%, east 25%, other 5.8% or less, **To**: south 55.8%, west 25%, other 3.8% or less) The ratings (Figure 6) of helpfulness on the flood water direction among five visualizations were statistically significant ($F(2.72, 133.03) = 19.76$, $p < .001$, partial $\eta^2 = .83$). Here the "2D Map" was rated the most helpful while the "Table" and "2D Elevation" were considered less helpful. The "3D Eye-Level" and the "3D Aerial" were neither very helpful nor not helpful.

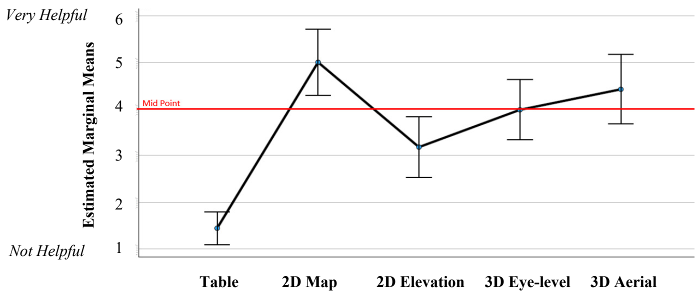


Fig. 6: Graph of estimated marginal means for question 5

Question 6: How fast is the surface water flowing in ft^3/s? (answer: 543 ft^3/s, mean: 586.83 ft^3/s, SD: 223.736) The ratings (Figure 7) of helpfulness on the surface water speed among five visualizations were statistically significant ($F(3.42, 167.57) = 27.84$, $p < .001$, partial $\eta^2 = .72$). Here the "Table", the "2D Elevation", and the "3D Eye-level" were rated the most helpful while the "2D Map" was considered less helpful. The "3D Aerial" was neither very helpful nor not helpful.

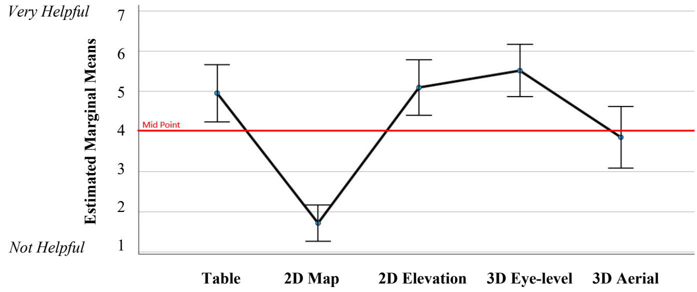


Fig. 7: Graph of estimated marginal means for question 6

Question 7: How would you rate the flood risk at this intersection? (1=no risk to 7=very high risk, mean: 6.51, SD: 0.81) The ratings (Figure 8) of helpfulness on the flood risk among five visualizations were statistically significant ($F(3.18, 155.93) = 15.78$, $p < .001$, partial $\eta^2 = .57$). Here the "2D Elevation", the "3D Eye-Level" and the "3D Aerial" were rated the most helpful while the "Table" and the "2D Map" were neither very helpful nor not helpful.

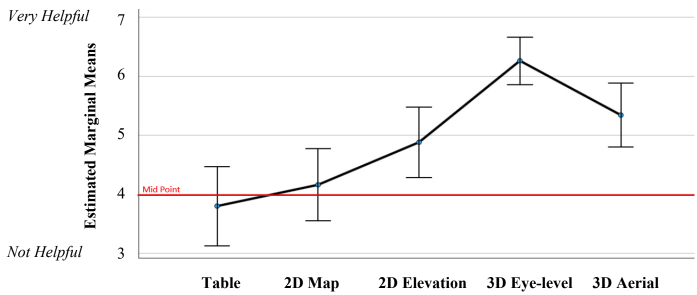


Fig. 8: Graph of estimated marginal means for question 7

Question 8: How extensive is the flood risk in this neighborhood? (1=no risk to 7=very high risk, mean: 5.73, SD: 1.22) The ratings (Figure 9) of helpfulness on the flood risk extensiveness among five visualizations were statistically significant ($F(2.96, 142.01) = 21.39$, $p < .001$, partial $\eta^2 = .31$). Here the "2D Map", the "3D Eye-Level" and the "3D Aerial" were rated the most helpful while the "Table" was considered less helpful. The "2D Elevation" was neither very helpful nor not helpful.

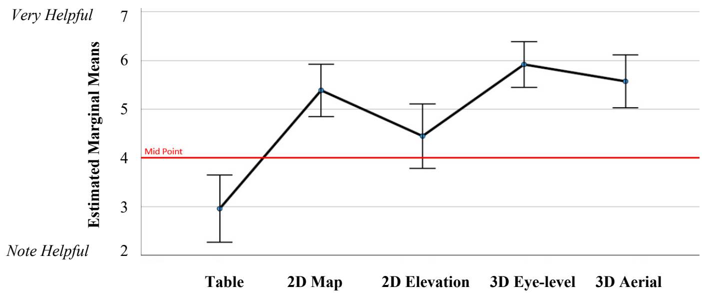


Fig. 9: Graph of estimated marginal means for question 8

Question 9: Overall, how helpful are the following visualizations for assessing flood risk? The ratings (Figure 10) of helpfulness on overall flood risk among five visualizations were statistically significant ($F(2.98, 146.23) = 37.0$, $p < .001$, partial $\eta^2 = .65$). Here the "2D Map", the "2D Elevation", the "3D Eye-level" and the "3D Aerial" were rated the most helpful while the "Table" was neither very helpful nor not helpful.

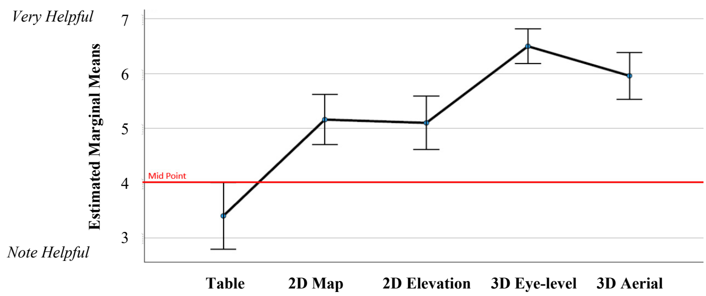


Fig. 10: Graph of estimated marginal means for question 9

Summary Table of Helpfulness: The sum of all questions (Figure 11) that reported a positive value for helpfulness (95 percentile above the estimated marginal means of 4) are shown in the bar graph. Here the "Table" positively supported only one of the risk assessment questions. The "2D map" and "3D Aerial" each supported five questions. The "2D Elevation" supported four questions. And the "3D Eye-level" positively supported seven questions.

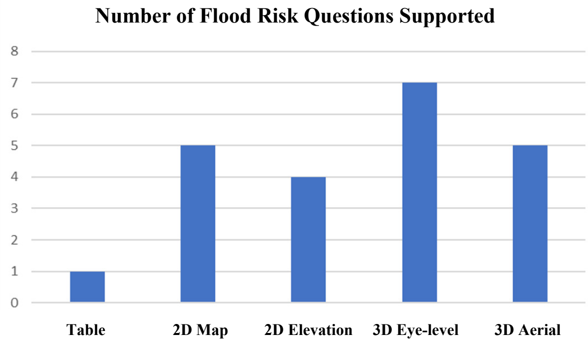


Fig. 11: Number of flood risk questions supported for each visualization

4 Discussion

Two of the key advantages of stereoscopic 3D visualization over 2D maps include depth and realism. People do not experience the world in 2D and so 3D visualizations offer a view of the world that is more compatible with people's everyday experiences. Experiencing flood modeling in stereoscopic 3D has the potential to map onto people's understanding of flood risks with levels of complexity that can only be achieved with depth and realism. The benefits are still largely unknown and should be explored in greater depth. Traditional 2D visualizations have the advantage of simplicity through abstraction. They have been used for flood risk assessment for years with measurable success. The questions are, how much more could be learned about flood risk by expanding flood visualization into three dimensions? How many more people can be included in the decision-making process by making the data more relatable to everyday experiences of the world? How many lives can be saved and how much property can be protected by expanding flood risk assessment capabilities and by communicating flood risk to a greater proportion of affected communities? Current technologies now make it possible to view hydrologic modeling in three dimensions and this study provides evidence that significant benefits exist to using them.

Strengths, weaknesses, and differences between traditional 2D and stereoscopic 3D visualizations were shown to exist. First, with respect to stereoscopic 3D visualizations, these were shown to display modeled flood data in ways that effectively communicate flood risks for flood risk assessment. The "3D Eye-Level" visualization rated highest overall for helpfulness in assessing flood risk but fell short in neighborhood level questions (1, 2, and 8) that required an overall view of the study area. The "3D Aerial" rated high in neighborhood level assessments and overall risk extent but fell short in flood flow and personal safety questions that may be better supported from views closer to the ground. Second, traditional visualizations are also helpful for assessing flood risk. The "2D Map" rated high in neighborhood level assessments and overall risk extent questions but fell short in technical flood flow and personal safety questions. The lack of support for personal safety questions is an important finding because 2D maps are currently the primary visualization technique for flood risk assessment. The "2D Elevation" ratings were mixed for safety and flood flow questions and fell short in neighborhood level questions. Still, it rated high for helpfulness overall. Finally, the data “Table” rated high for flood flow speed, but fell short in neighborhood level assessments, safety assessments, and flood direction. Overall, it did not rate as being useful. Still, all the visualizations were produced using the table information, and hydrologic modelling technicians would likely be skeptical of the visualizations without having it available.

Limitations to this study include a lack of causal information, sampling bias and generalizability, adoption of VR, and modelling costs. First, the results do not provide information as to why participants rated the different visualizations. Knowing the causal relationships would better guide future development. While the causal reasons are not yet clear, we believe the results of this study provide a compelling argument for continued development in this area of visualization. Second, although the sampling approach ensured some level of relevance to likely users of the technology, it is also susceptible to researcher bias. To expand to a larger audience, future sampling should be guided less by convenience and more by generalizability. Third, adoption of VR by municipalities has been slow. Like cell phones of the 1970s, VR headsets can be bulky and costly. Advancements in wireless connections, higher resolution, reductions in cost, etc. continue to bring down barriers to widespread adoption. Research like the study presented here has always been ahead of the market and is critical for further advancement. Meta and Apple are both producing consumer grade VR products and applications. There is reason to be optimistic that widespread adoption throughout government and communities is on the horizon. Finally, it currently takes time and effort (costs) to produce stereoscopic 3D visualizations. However, advancements in producing and rendering highly realistic stereoscopic 3D models efficiently continue at an accelerated rate through drone-based LiDAR scanning and photogrammetry. The costs for producing 3D models are likely to come down in the future, and thus the demand and availability will likely go up.

Future research might build on this study in several ways. First, the visualizations might be expanded to include a range of design solutions. Thus, assessments would build upon existing conditions (this study) by adding visualizations and assessments of future alternative conditions. Second, future studies might include looking at combinations of different visualization types, e.g. stereoscopic 3D visualizations and tables, and to assess the combined effectiveness for answering different types of flood risk assessment questions. The results of this study suggest that combined effectiveness is likely to exist and could be important for guiding infrastructure investments. Finally, a closer look at how different user groups or stakeholders respond to the different visualization techniques would be helpful. Hydrologic modelers may look for different types of information than city council members or community residents. Understanding which visualization techniques best answer typical risk assessment questions, and how each stakeholder group benefits from using the visualization techniques will help guide further development and deployment of them.

5 Conclusion

Together, traditional 2D flood visualizations and stereoscopic 3D visualizations were considered helpful overall in supporting flood risk assessment but with different strengths for each. Stereoscopic 3D visualizations were slightly more supportive overall than 2D traditional visualizations. The 2D map, which is by far the most common flood visualization technique, failed to support assessments of safety to walk or drive through a flooded intersection while stereoscopic 3D visualizations were found to be more supportive. Tabular data provided minimal support for flood risk assessment with respect to the questions used in this study. Nonetheless, all sources of information – tabular, 2D visualizations, and stereoscopic 3D visualizations – provided at least some level of support for answering questions related to flood risk assessment.

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