Flood Risk Communication via Dynamic, Isometric Street Views

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From 2D to 3D:
Flood Risk Communication via Dynamic, Isometric Street Views

Abstract

There is increasing evidence that climate change will lead to greater and more frequent extreme weather events, thus underscoring the importance of effectively communicating risks of record storm surges in coastal communities. This article reviews why risk communication often fails to convey the nature and risk of storm surge among the public and highlights the limitations of conventional (two-dimensional) storm surge flood maps. The research explores the potential of dynamic street-level, augmented scenes to increase the tangibility of these risks and foster a greater sense of agency among the public. The study focused on Sunset Park, a coastal community in southwest Brooklyn that is vulnerable to storm surges and flooding. Two different representations of flooding corresponding to a category three hurricane scenario were prepared: (1) a conventional two-dimensional flood map ("2D" control group) and (2) a, dynamic, street view simulation ("3D" test group). The street view simulations were found to be (1) more effective in conveying the magnitude of flooding and evacuation challenges, (2) easier to use for judging flood water depth (even without a flood depth legend), (3) capable of generating stronger emotional responses, and (4) perceived as more authoritative in nature.

Keywords:
disaster prevention, risk communication, flood simulation, storm simulation, LiDAR

I. Introduction

Extreme weather has caused some of the largest natural disasters in human history. The leading cause of fatalities from tropical cyclones are storm surges generated by the cyclone's strong winds, which can strike vulnerable coastal areas (NHC, 2024). For example, Cyclone Bhola produced storm surges as high as 10 meters in southern Bangladesh, killing at least 300,000 people (Hossain and Mullick, 2020). Such tragedies occur in highly industrialized countries as well, especially in vulnerable populations, whether due to low income, social exclusion, or other factors (Cutter, 2021). For example, in September 2021, remnants of Hurricane Ida led to 14 deaths in New York City, mostly among Asian immigrants dwelling in unregulated basement apartments (Yuan et al., 2024).

Critically, there is mounting evidence that such events will grow in frequency and magnitude (Knutson, 2020; Emanuel, 2021; IPCC, 2021). This means that, increasingly, coastal communities will be struck with events that possibly none in the community may have ever experienced. What makes these events especially tragic is that much of the loss of life can be averted, as a tropical cyclone's approximate timing, location, and magnitude can be predicted days in advance. While this should enable authorities to warn imperiled communities and issue evacuation notices, many coastal communities are underprepared, resulting in significant loss of life. In many cases, the problem has been attributed to a failure in effective risk communication (Eisenman et al., 2007; Marris, 2005).

Communicating storm surge risk is hindered by a number of important factors, including message clarity (Otto et al., 2018), messenger trustworthiness (Slovic, 1993; Deeming, 2008), overly technical language (Lindell and Perry, 2012), and incomplete messaging that omits information on flood severity and timing (Paul et al., 2010; Saha and James, 2017). Those factors can be compounded by government advisories that the public often assume to be perfunctory, pro-forma bulletins (Lejano et al., 2016). These challenges are further complicated by socio-economic factors that increase people's vulnerability (Cutter, 2012). For example, poverty creates additional vulnerabilities. Social and economic marginalization and language barriers can hinder effective communication and access to vital information and resources. Limited financial resources in low-income communities make preventative measures and recovery difficult. Marginalized communities they are more likely to feature substandard housing in spaces more prone to environmental hazards. In some communities, a high proportion of renters and recent immigrants also contributes to instability and increased vulnerability, as these households often lack long-term support and face greater challenges in accessing assistance.

Some researchers have shown showed that many people are unfamiliar with the concept of storm surge (let alone the term) and are more likely to attribute tropical cyclone danger directly to the winds or rain (GIZ, 2014; Rasquinho, 2014). Large storm surges are generally infrequent events, often unprecedented for a community's current residents (e.g., Colten and Sumpter, 2009). Increasingly severe storms are likely to exacerbate this problem, as previously sized hazard events are absent from both a place's personal and institutional memories (Lejano, Haque, and Berkes, 2021). As such, residents may struggle to form a mental image or concept of such a phenomenon (Lazrus et al., 2016) and the appropriate preparatory actions.

In response, this article presents a study that explored the effectiveness of novel modes of risk communication, primarily using 3D-like simulations of coastal flooding due to storm surge. The following section describes the existing and evolving modalities by which storm surge risk is communicated (e.g., 2D flood maps). Next, an experimental design is described for comparing map comprehension, risk cognition, and other parameters for conventional ("2D") plan-view flood inundation maps versus a ("3D") dynamic, street view simulation. Interpretation of the study results is followed by discussion of potential improvements in risk communication practice that result from this research, including suggestions for additional uses of this approach for planning, emergency response, and other areas of professional practice.

II. Background

This section presents current scholarship on the challenges of mapping storm surge risk, the growing availability of three-dimensional (3D) models and scenes for disaster representation, and how such a 3D approach can better align with the relational model of risk communication, as a potentially more effective alternative for flood risk communication

II.1 Storm Surge Risk Communication via 2D Flood Maps

National Oceanic and Atmospheric Administration (NOAA) and similar organizations use predictive models such as Sea, Lake, and Overland Surges from Hurricanes (SLOSH) to simulate storm surges and provide forecasts for tropical cyclones (Jelesnianski, 1992). Typically, the results are presented in the form of a conventional 2D map image to communicate storm surge risk to public audiences. At the most basic level, 2D maps require labeling and legends to present complex information, but many people lack the training or prior experience to interpret these elements accurately. Additionally, a person's map interpretation abilities are influenced by their backgrounds and cognitive processing (Tolman, 1948; Lynch, 1960; Schiller et al, 2015). The mental images used to interpret maps and guide reactions depend on people's memory, experience, and immediate sensations, as well as the mode of representation of these hazards (Buzsáki and Moser, 2013; Wilhelmi, 2024). Therefore, creating maps that accommodate everyone's cognitive abilities is extremely challenging.

Furthermore, storm-surge flood prediction maps resemble topographic maps, with elevation contours superimposed upon the underlying street base map. Problematically, topographic maps present extra cognitive challenges. For example, Rautenbach, Coetzee and Çöltekin, (2016) found that viewers had difficulty interpreting horizontal and vertical positions and even more problems interpreting map symbology. In addition, representing certain information, such as volumetric data, is particularly challenging with 2D visualization (De Santis, 2019). The less realistic nature of 2D plan-view representations can cause a disconnect between perceived risk and reality, potentially leading to an underestimation of the risk. Consequently, interpretation of topographic maps, including flood maps, is generally challenging and further exacerbated by difficulties in interpreting symbology and positioning.

The problems with 2D mapping can to some extent be mitigated. For example, Morrow et al. (2015) tested various alternative storm surge mappings among different stakeholder groups and found that using a four-color chloropleth map, corresponding to four flood levels, with sufficient well-known landmarks, was readily interpreted. Additionally, Seipel and Lim (2017) demonstrated that factors such as multicolored and high-resolution maps with consistent legends improve understanding and risk communication.

II.2 Storm Surge Risk Communication via 3D Imagery

Increasingly there are also opportunities to represent altered built environment conditions in 3D. These include 3D printing, 3D reconstructions from imagery or laser scanning, and videos of 3D environments to semi- and fully immersive approaches such as virtual reality (VR) and augmented reality (AR). Most employ some skeletal representation of a real space that then undergoes simulation and/or augmentation (e.g. Costabile et al. 2021). The advent of 3D geospatial products, such as Image City and Google Earth, have made such approaches more readily available through internet applications. In fact, over the past decade there has been a tremendous proliferation of these types of approaches with respect to flooding and inundation.

An extensive review of research in 3D flood modeling and depiction efforts was done by Rydvanskiy and Hedley (2020). They noted a high reliance on bespoke software and hardware, as well as an emerging trend to integrate with Geographic Information System platforms (including a proposed workflow by the authors to create 3D geovisualization interfaces as a management strategy for flood risk and similar work by Wu et al. 2019). Notably, some approaches were intended to enable alternative simulations such as that by Wang et al. (2019) to consider a sponge city approach as a means to manage flood risk and the urban drainage model by by Zhi et al. 2020 with its inclusion of 3D building models.

A subsequent review paper by Bakhtiari et al. (2023) focused specifically on urban flood risk management. That work surveyed the areas of Immersive 3D imagery, 3D Web-based visualization, game-based approaches, AR, and digital twins and explored their adoption in engaging various stakeholders (including local councils and insurance companies), across the five key stages of risk management: prevention, mitigation, preparation, response, and recovery. Bakhtiari et al. (2023) reported on papers that considered a wide variety of potential application areas such as conveying certain injury risks, anticipating damage patterns and levels, types of damage, and community-specific vulnerabilities. They found that only 35% of the models were developed to communicate with the public, but that nearly 80% of those were targeted at a local population, such as that by Al Kalbani and Rahman (2021) for monitoring flash flood risks in Salalah, Oman or that by Li et al. 2024 for a portion of the Rhine River in Bonn, Germany. Of note is the web-based visualization work by Saifi and Anandakumar (2024) that may be seen as an extension of the work by Zhi et al. (2020).

Despite the plethora of approaches and models, there have been few head-to-head comparisons of model effectiveness with respect to risk communication. For example, Dang et al. (2023) tested for realism between a pair of 3D visualization approaches using a multi-scale, flood simulation method which is subsequently integrated with panoramic images or videos and dimensionality reduction. 3D flood models with 2D panoramic images, with the authors concluding that without very heavy computational loads, realistic portrayal was not achievable. In that study, only the realism was tested not the effectiveness of the risk communication. Similarly, Zhang et al. (2020) found that flood visualization using virtual 3D printing combined with augmented reality was statistically better for both expert and non-expert stakeholders than only an exclusively AR, but testing against traditional 2D was not considered. In some instances, the superiority of an approach is asserted but not explicitly tested [e.g. Macchione et al. (2019), who explored a range of levels of detail (LOD) for building façade for a river flooding scenario for risk communication, and while they discussed potential pros and cons of a 2D hydraulic simulations within a 3D VR environment for multiple user groups, no testing was conducted].

Despite a paucity of direct testing in flooding scenarios, the general appeal of 3D representations of the built environment is well established. They have been shown to be effective at providing location specific information and mitigate the loss of details and features commonly excluded in traditional 2D maps (Deren, 2009). Furthermore, compared to 2D maps, 3D visualizations are less abstract, more realistic, and require less interpretation and mental workload from the reader (Tavanti and Lind, 2001; Macchione 2019). Such advantages help non-expert viewers avoid confusion as well as reducing the cognitive workload of map interpretation (Al-Kodmany, 2002; Dadi, 2014; Jacquinod and Bonaccorsi, 2019). So it is not surprising that effective visual representation has been proposed as a means to enhance the understanding and management of risks generally (Eppler and Aeschimann, 2009).

Arguably, the inclusion of a vertical dimension can provide viewers with enhanced spatial information about the urban environment (Dransch, 2010; Lai, et al. 2011) or in the case of flooding a more vivid volumetric presentation to help viewers analyze volumetric complexity with hydrological and contextual information (Macchione et al., 2019), thus giving a more accurate representations of inundation (Allen, 2013).

Alternatively, improved understanding of spatial relationships in 3D maps may be attributable to the reduced effort needed in map interpretation (Cockburn and Mackenzie, 2000; Tavanti and Lind, 2001). While 2D maps require labeling and legends to convey risk information, which can cause miscommunication and interpretation problems, 3D maps and direct 3D simulations of real-life scenarios can replace the function of labeling. When a known location is represented, people can easily locate their areas and identify risk-related parameters, such as the height of the water. Vivid visualization of hydrological and meteorological data can achieve deeper understanding, active interaction, and enhanced engagement in risk communication (Helbig, 2014). This was also found by Rickard et al., (2017) where using photographs to depict storm surge conveyed flood risk more effectively than maps. Risk researchers argue that tangible and realistic hazard representations form mental impressions that influence future decision-making - a concept known as the availability heuristic (Keller, Siegrist, and Gutscher, 2006). Generally, it is believed that the realism of hazard depictions better aligns with the experiential and cognitive aspects of actual events, increasing the likelihood of risk-protective behavior (Bishop and Rohrmann, 2003; Sheppard, 2005). Animation has for seismic risk shown to be effective in enhancing attention and perception, (Bostrom, 2008), and according to Harold et al. (2016), increased attention helps the brain comprehend and interpret important information from the graphics.

Finally, models developed by Macchione et al. (2019), De Santis et al. (2019), and Lai et al. (2011) have demonstrated the potential to facilitate informed discussions on mitigation and adaptation options among a wider range of stakeholders, thanks to the volumetrically and visually realistic representations of urban landscapes under flooding scenarios.

II.3 Relational model of risk communication

The technical advancements outlined above may offer additional benefits. Specifically, risk communication has historically employed a one-way transmission of information from experts to a passive public who have a subject matter, knowledge deficit. However, such traditional risk communication often fails in effectively engaging stakeholders and enhancing their understanding and responsiveness to potential hazards (see Balog-Way et al., 2020, for a review).

As an alternative, Lejano (2018) proposed a relational model that views risk communication as a dynamic process where experts, the public, and agencies engage in open communication, treating the public as an equal partner rather than a passive recipient of information. The relational model focuses on interactions and relationships between the communicator and the audience. There are three key elements of that model:

- Contextualization/Personalization: Tailoring the message to the individual's context and experiences, ensuring the information is directly applicable to the audience's life and environment.
- Engagement: Using interactive and immersive methods to capture and retain the audience's attention.
- Empathy: Building emotional connections by incorporating personal stories and experiences.

In principle, 3D AR flood simulations align well with the tenets of the relational model by enabling stakeholders to visualize the potential impacts of flooding in a highly realistic and engaging manner.

Personalization: 3D AR simulations can be customized to reflect the actual neighborhood and personal property of the user. This immediate self-relevance potentially makes the risk information more pertinent and compelling. For instance, users can potentially see how floodwaters would impact their own homes, making the risk more tangible and urgent. Such relevance may enhance the audience's understanding and encourage proactive risk-reductive actions.

Engagement: The immersive nature of AR allows users to visualize the potential impact of flooding in a more engaging manner which captures the audience's attention more effectively than traditional plan-based, 2D maps.

Empathy: 3D AR simulations can incorporate storytelling elements, which may make the experience more relatable. By visualizing the potential impact of floods on their own community, users may develop a deeper emotional connection to the information being presented.

While fully immersive 3D augmented reality (AR) environments may be the most effective way to change personal risk assessments and behaviors, presently the hardware and technical expertise requirements preclude AR from being a scalable approach for widespread modeling and risk communication at the block or even neighborhood scale, especially on a per storm basis. Thus, this paper investigates whether a fixed, isometric view (that is, a 3D-like simulation) of a location dynamically augmented in the form of flood filling could provide a more scalable means to overcome the flood risk communication deficits encountered with 2D inundation maps. In the following sections, we explore the potential for enhanced 3D visualization of storm surge simulations to increase the level of understanding of the public through the direct testing of a static 2D versus a dynamic 3D approach.

III. Methodology

In this paper, we use digital technology to improve risk communication. This is done by comparing a dynamically augmented, isometric street view ("3D") flood representation to a conventional, static ("2D") flood inundation map. The augmented, isometric street view was designed to incorporate the relational model by increasing the contextuality of the representation by allowing the viewer to see the flood as it might appear in reality (as opposed to a map) and including a dynamic component (e.g., rising water) to increase viewer engagement and to enhance the sense of water height and depth. The premise is that enhanced contextualization, engagement, and empathy may provide a more tangible and realistic representation of risks, fostering a deeper understanding and emotional connection among stakeholders. Influenced by the afore-mentioned experience of Hurricane Ida, the researchers sought to test an enhanced mode of risk communication among the Asian immigrant community in a coastal area of New York City (Sunset Park, Brooklyn).

Under the authors' university's Institutional Review Board approval (IRB-FY2018-2147), participants were recruited through local community events with the Chinese-American Planning Council whose mission is to promote the social and economic empowerment of Chinese American, immigrant, and low-income communities in the neighborhood of Sunset Park. Sunset Park, Brooklyn, New York, is a coastal community vulnerable to storm surges and flooding, particularly from extreme weather events exacerbated by climate change (Nguyen and Leichenko, 2022). This area was impacted by Hurricane Sandy, making it a relevant location for studying flood risk communication. All participants either lived or worked in the Sunset Park area to increase the probability that participants are familiar with the simulated street scene. The research team specifically sought out immigrants who may be more isolated and vulnerable during extreme weather conditions. Surveys were created by and administered through Qualtrics. The surveys and recruitment information were provided in both English and Chinese.

Online Survey Design

The study aimed through an online exercise to compare the effectiveness of conventional 2D flood maps with 3D virtual reality flood simulations in engaging non-expert stakeholders and enhancing their flood risk awareness and preparedness. The main hypothesis was that the 3D flood simulation will generate comparable or even better risk evaluation and prompt more proactive actions before and during flood events in the Sunset Park area compared to the traditional 2D flood map. Additionally, it was hypothesized that the 3D flood simulations would be more effective in conveying flood information and generating stronger emotional responses and a greater sense of authoritativeness for non-expert stakeholders. To test this hypothesis, half of the respondents first viewed the conventional 2D flood map, while the other half first viewed the 3D flood simulation (Figure 1).

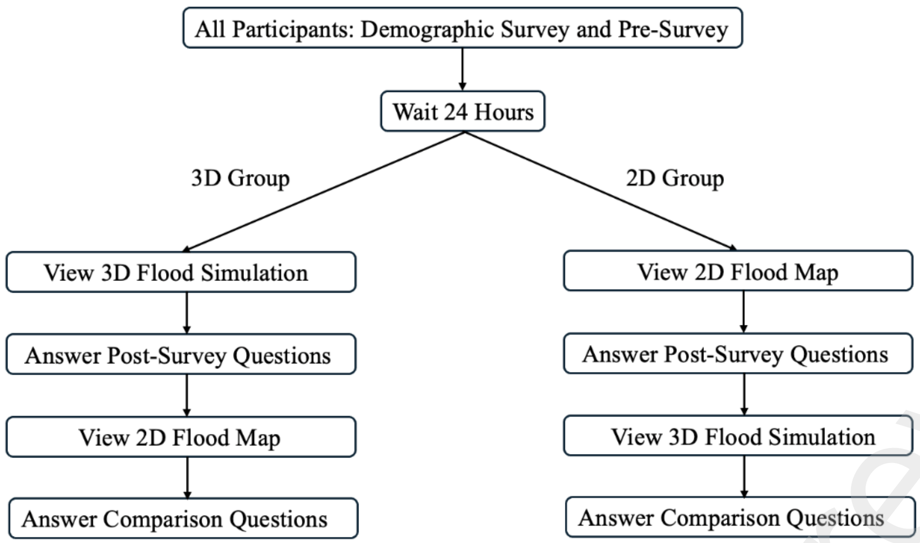

Figure 1. Flow Chart of Survey Procedure

The storm depiction is of a Category 3 Hurricane based on a SLOSH model from the National Hurricane Center[1] with the focus being the intersection of 4th Avenue and 36th Street in Sunset Park Brooklyn, NY. Figure 2 is the 2D flood map version of the location and surrounding areas presented. The map was intended to determine participant comprehension of the potential flooding scenarios during extreme weather events anticipated to occur within the next two decades. The arrow labeled "you are here" in Figure 2 designates the precise intersection of interest and matches with the street view Figure 3. Figure 3 provides a screen capture of the dynamic, 3D flood simulation, which starts with a dry surface and culminates with the maximum flood height (approximately three feet). The scene geometry was captured with a terrestrial LiDAR laser scanner with an integrated camera. This 3D representation was then paired with the commercial flood filling program Inkscape (REF) that was modified to depict a specified rising water level and horizontal water flow.

[1] The SLOSH data can be accessed at https://experience.arcgis.com/experience/203f772571cb48b1b8b50fdcc3272e2c/page/Category-3/

Figure 2. Two-dimensional flood map of the corner of 4th Ave and 36th St in Sunset Park, showing potential flood levels during a Category 3 hurricane; arrow indicates streetview location in Figure 3.

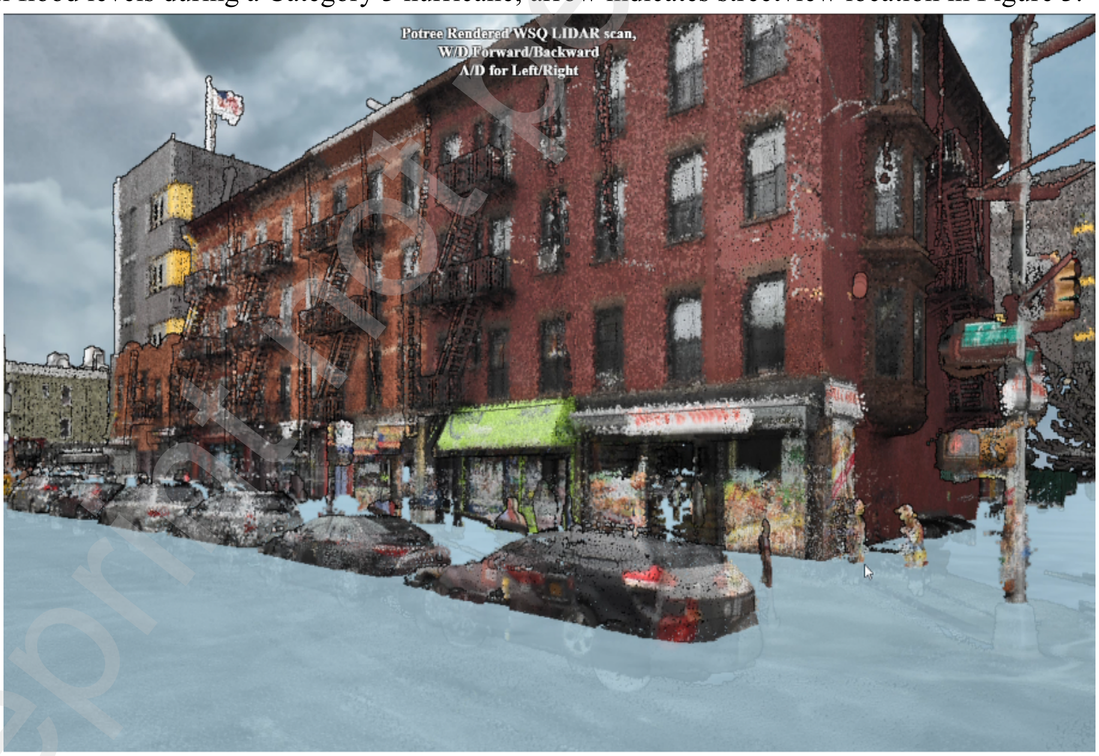

Figure 3. Three-dimensional flood simulation of the same location in Sunset Park, demonstrating the rise of water from a dry surface to a maximum inundation height of three feet.

The flow chart in Fig. 1 shows the study survey procedure. All participants completed a pre-survey that included demographic questions and questions assessing their flood risk perception of a section of the local neighborhood (see subsequent section for questionnaire). After completing the pre-survey, participants were randomly assigned to either the 3D or 2D group. After 24 hours, the 2D group received the traditional 2D flood map of the same area, while the 3D group watched a short video of a 3D flood simulation of an isometric street view of a small section of the 2D coverage area in Sunset Park. Both the still 2D image and the video showed the inundation water at the same level.

Participants then completed a post-survey, which included 11 questions. Nine were identical to those in the pre-survey. The two additional questions assessed the difficulty of using the depiction and understanding the predicted flood level. After completing the post-survey, participants in the 2D group viewed the 3D visualization with flood simulation. Similarly, participants in the 3D group viewed the 2D flood map. Finally, all participants were asked five questions comparing the effectiveness of the 2D and 3D demonstrations in conveying flood information, generating emotional responses, and conveying a sense of authority.

Questionnaire

Survey Questions

The demographic questions solicited personal information (e.g., phone number, preferred gender identity, age), as well as information relevant to flood risk awareness (e.g., duration of residence in Sunset Park, experience with Hurricane Sandy). Phone numbers were used as identifiers to link pre-survey and post-survey responses.

Identical Pre- and Post-Survey Questions (answered on a Likert scale):

1. What level of risk is posed by the predicted flooding in this area of Sunset Park?
2. How much danger (risk to life) would the predicted flood pose to a resident in this area?
3. How likely is it that you would evacuate the area before the storm and stay elsewhere?
4. Sunset Park will experience serious flooding following an extreme weather event.
5. Evacuating Sunset Park during an extreme weather event would be extremely difficult.
6. I will likely start emergency planning (i.e., what to do and how to evacuate during an extreme weather event).
7. I know what Sunset Park would look like during an extreme weather event.
8. I will buy flood insurance.
9. I feel that flood disasters from climate change are things that would mostly happen far into the future or, today, in other countries.

Comparison Questions:

1. For the 2D group: Was the 3D simulation more effective in conveying the magnitude of flooding than the conventional 2D map? Why or why not? For the 3D group: Was the 2D conventional map more effective in conveying the magnitude of flooding than the 3D simulation? Why or why not?
2. Which (2D or 3D) view is easier to use to judge the depth of the floodwater, and why?

3. Which flood map, 2D or 3D, generates more emotional response from you and why?
4. Which flood map, 2D or 3D, do you think is more authoritative, and why?
5. Do you have any suggestions for improving the quality of the 3D flood simulation?

Data analysis

Surveys were administered through Qualtrics, with data collected and linked pre- and post-surveys via participants' contact information. Data analysis was conducted using R statistical software. Normality checks were performed using the Shapiro-Wilk test, and homogeneity of variances was assessed with Levene's Test. For the identical pre- and post-survey questions in Likert scale format, differences in scores (difference = post-score - pre-score) were compared between the 2D and 3D groups before and after participants viewed the different flood maps. Two-tailed independent two-sample t-tests were used to assess the significance of differences in risk awareness, risk prediction, risk evaluation, likelihood to evacuate, emergency planning, and climate change awareness between the two groups.

Additionally, Chi-Square tests were used to evaluate stakeholders' perceptions of the two demonstration types in terms of authority, emotional response, and effectiveness in conveying flood information.

IV. Results

In this section, we present participant demographics (Table 2), differences between the pre- and post-responses for 2D and 3D groups (Table 3), and participants' preferences between the 2D and 3D Views (Table 4).

No significant differences between the 2D and 3D groups were found in terms of age, duration in Sunset Park, years in New York City, gender, connection to Sunset Park, race/ethnicity, education levels, impact of Hurricane Sandy, and impact of other hurricanes/flooding events (Table 2). Thus, the 2D and 3D groups are demographically comparable.

Table 2. Characteristics of Respondents

	2D Group	3D Group	p-value
Age (years)			
Mean ± s.d.	69.55 (± 4.68)	63.47 (± 17.65)	0.8347[a]
Duration in Sunset Park (years)			
Mean ± s.d.	12.92 (± 8.75)	15.00 (± 9.04)	0.5517[b]
Years in New York City			
Mean ± s.d.	19.46 (± 10.23)	20.20 (± 9.90)	0.8478[b]
Gender			

Male	7.69%	7.14%	1.000[c]
Female	92.31%	92.86%	
Connection to Sunset Park			
I live here	75.00%	73.33%	1.000[c]
I study here	0.00%	0.00%	
I work here	16.67%	20.00%	
Other	8.33%	6.67%	
Race/Ethnicity			
Hispanic	0.00%	7.69%	0.1693[c]
Asian/Asian-American	100.00%	84.82%	
Black/African-American	0.00%	0.00%	
White (Non-Hispanic)	0.00%	0.00%	
Other	0.00%	7.69%	
Education			
Less than secondary school	84.62%	68.75%	0.6966[c]
Secondary school diploma	7.69%	12.50%	
Bachelor's degree	7.69%	18.75%	
Graduate degree	0.00%	0.00%	
Impact of Hurricane Sandy			
Definitely not	23.08%	25.00%	0.4513[c]
Probably not	15.38%	18.75%	
Might or might not	0.00%	0.00%	
Probably yes	23.08%	43.75%	
Definitely yes	38.46%	12.50%	
Impact of Other Hurricanes			
Definitely not	33.33%	14.29%	0.2451[c]
Probably not	8.33%	42.86%	
Might or might not	0.00%	14.29%	

Probably yes	25.00%	14.29%	
Definitely yes	33.33%	14.29%	

[a] Mann-Whitney U test
[b] Two sample t test
[c] Fisher's Exact Test
''No answer'' category not included in computation.

Table 3 compares the changes in participants' opinions before and after viewing a single version of the flood prediction (either static 2D for the control group, or dynamic 3D for the test group) As shown in Table 3, there was a significant difference ($p < 0.05$) between the 2D and 3D groups regarding the changes in perceived difficulty of evacuating Sunset Park during an extreme weather event before and after viewing the maps. This suggests that participants in the 3D group, after viewing the 3D flood simulation, perceived evacuation to be significantly more difficult than those in the 2D group, implying that 3D visualizations may be more effective in conveying the challenges associated with evacuation. Additionally, the difference in changes in beliefs about the timing and location of flood disasters from climate change between the 2D and 3D groups is significant but only to a better than 90% level of confidence ($p = 0.058$). Specifically, participants in the 3D group perceived a greater change in their beliefs about the risk of flood disasters due to climate change compared to the 2D group, suggesting that 3D visualizations might be more effective in conveying the urgency and immediacy of climate-related risks. Notably, the difference in perceived danger to life between the 2D and 3D groups was somewhat statistically significant ($p = 0.0896$), at least at a 90% level of confidence, indicating that 3D visualizations may also be more effective in conveying danger severity. No significant differences were found between the 2D and 3D groups regarding (1) changes in the perceived level of risk posed by predicted flooding in Sunset Park, (2) the likelihood of evacuation before the storm, (3) the belief that Sunset Park will experience serious flooding following an extreme weather event, (4) the likelihood of starting emergency planning, (5) knowledge of what Sunset Park would look like during an extreme weather event, or (6) the intention to buy flood insurance. Importantly these were the results after seeing either the 2D or the 3D representation, but not both.

Table 3. Difference between pre- and post- Responses for 2D and 3D Groups
(Group 2D: n = 14, Group 3D: n = 17).

Survey Item	Differences between pre- and post-survey (Mean Difference = Post score - Pre score)	t	p
Level of risk posed by predicted flooding			
Group 2D	0.67	-0.955	0.351
Group 3D	1.53		
Danger to life from predicted flood			
Group 2D	-0.33	-1.78	0.0896
Group 3D	1.25		
Likelihood of evacuating			
Group 2D	-0.08	-0.847	0.404
Group 3D	0.77		
Sunset Park will experience serious flooding			
Group 2D	-1.08	-1.65	0.111
Group 3D	0.77		
Difficulty of evacuating during extreme weather event			
Group 2D	-0.92	-2.21	0.0373*
Group 3D	1.07		
Likelihood of emergency planning			
Group 2D	-0.17	-1.28	0.211
Group 3D	1.00		

Knowledge of Sunset Park during extreme weather event			
Group 2D	-1.00	-1.27	0.215
Group 3D	0.27		
Intention to buy flood insurance			
Group 2D	-0.92	-0.0391	0.969
Group 3D	-0.87		
Belief about timing/location of flood disasters from climate change			
Group 2D	-2.00	-2.02	0.0577*
Group 3D	0.46		

* $p < 0.10$ (90% confidence), ** $p < 0.05$ (95% confidence)
p value is for a two tailed independent two sample t-test.

After filling in the survey questions pertaining to the data shown in Table 3, participants in each group were asked to view the other map (i.e., the 2D group viewed the 3D view, and the 3D group viewed the 2D map). Thus, the last part of the survey asked all participants to compare both representations. As shown in Table 4, after having viewed both the 2D and 3D representations, the majority of participants (95.7%) found the 3D view more effective in conveying the magnitude of flooding, to a statistically significant degree ($p < 0.05$). Additionally, an large majority (92%) found the 3D view easier for judging the depth of floodwater ($p < 0.05$). The majority (88%) reported that the 3D map generated a more emotional response ($p < 0.05$). Furthermore, all respondents (100%) found the 3D map to be more authoritative, indicating a unanimous preference and making statistical testing unnecessary due to the uniform preference.

Table 4. Preferences for 2D and 3D Views (Chi-square test results)

Survey Item	Preference	Percentage	p-value
Which (2D or 3D) view is more effective in conveying the magnitude of flooding?	2D	4.35%	0.0000119*
	3D	95.7%	
Which (2D or 3D) view is easier to use to	2D	8%	0.0000267*

judge the depth of the floodwater?			
	3D	92%	
Which flood map, 2D or 3D, generates more emotional response from you?	2D	12%	0.0001447*
	3D	88%	
Which flood map, 2D or 3D, do you think is more authoritative?	2D	0%	**
	3D	100%	

* $p < 0.01$ (99% confidence)
** All respondents (100%) found the 3D map more authoritative, making statistical testing unnecessary due to the uniform preference.

Participants highlighted several reasons for these preferences through their qualitative responses. Regarding the effectiveness in conveying the magnitude of flooding, they noted that "3D is easier to understand than 2D" and that "the 3D simulation vividly illustrates the severity of flooding". The 3D view was described as "more visual and dynamic", "clear and intuitive", "more accurately showing the height of the floodwater", "more clearly showing the flood situation", and appreciated for its "more realistic and three-dimensional feel". Participants found that the 3D simulation "shows the water level clearly" is "more advanced" and "more scientific". One participant noted that "the 2D map included too many color schemes, which was confusing", highlighting the clarity and effectiveness of the 3D visualization. The only participant who preferred the 2D map explained that it was "easier to read as it broke down which areas would flood the most".

In terms of judging the depth of floodwater, participants emphasized that "3D can quickly see" the flood water depth, with "the 3D video being clearer" and "more realistic". They appreciated that "3D provides more depth and realism", has "higher definition", and a "three-dimensional nature". The 3D view was considered "more advanced, easier to judge building height", and "more intuitive and vivid". They pointed out that the 3D visualization was "more effective in showing the severity of flooding" and that "the 3D map is easier to identify due to comparison with building structures". The 8% of participants who preferred the 2D version did not provide any reasons.

Regarding emotional response, participants found the 3D flood map "more realistic" and providing "more depth and realism". They noted that "3D makes it easier to see water levels" and described it as "more scientific" and "more advanced". The 3D view was seen as "more shocking" with "higher definition". The 3D flood map was said to be "more practical and easier to understand". Participants emphasized the "more visual impact" of the 3D map, noting that "you can see the water rising" and "see water gradually moving in". The 12% of participants who preferred the 2D version provided no reasons.

In terms of authoritativeness, participants mentioned that "3D is closer to reality" and "more dynamic", showing "how the water increases". Seeing flood water reach doors and windows in 3D felt "scarier", creating "more visual impact". They appreciated that "3D provides more depth and realism" and "different angles", making it "more realistic" and ensuring "people know how to keep safe". The 3D map was considered "more advanced" and "more scientific", offering "clearer flood levels" and a better understanding of flood severity.

Lastly, participants also provided several suggestions for improving the quality of the 3D flood map. They recommended "marking the flood height on the dynamic flood map" to make it more specific and suggested the simulation can be "slower and more detailed". While one participant felt that "the quality of the 3D map is pretty good", another suggested improving the "quality and definition to be more intuitive and realistic".

V. Discussion

Traditional 2D maps are known to pose challenges for engaging and educating non-expert stakeholders about potential risks. To increase the accessibility of risk maps, engage both expert and non-expert stakeholders, and effectively enhance their risk awareness and risk-reductive actions, alternative approaches need to be explored and implemented. The research presented herein demonstrated that by fostering a sense of immediacy and personal relevance, 3D representations of simulated events can enhance the effectiveness of risk communication, promoting active engagement and facilitating a more profound understanding of the risks involved. While other research has generated similar street view representations even with cars (e.g. Costabile et al. 2021), the work herein is the first extensive direct comparison with traditional 2D flood map risk communication.

Given the potential of 3D representations to convey flood risks in ways that may address some of the limitations of 2D flood maps, the research team conducted an empirical investigation involving comparison of control and test groups vis-a-vis flood risk cognition. This has implications for how risk communication might be done in the near future. One can envision online applications, resembling Google Maps or Google Earth, that allow viewers to view flood projections but in a simulated 3D view.

This leads to the specific theme of this article, which explores the potential advantages of using augmented, street-level video (simulated 3D) for conveying storm surge risk. Unlike annual monsoons, where communities become accustomed to precipitation-based flooding, extreme storm surges are relative rare. Thus, communities may lack relevant social memory of similar events. The expectation of larger and more frequent tropical cyclones and their affiliated storm surges (Emanuel, 2013; Knutson et al., 2020) reduces the ability of a community to develop an understanding of the degree and kind of risk, which in turn affects their motivation to taking risk-preventive action (Lindell and Perry, 2012).

The results suggest that 3D flood simulations significantly influence participants' perceptions in specific areas, particularly regarding the difficulty of evacuation and the urgency of climate-related risks. This impact can largely be attributed to the personalized and immersive nature of these simulations. By reflecting the actual neighborhoods and properties of users, 3D visualizations create a direct connection between the viewer and the potential impact of flooding. This level of personalization helps individuals feel more understood and connected to the information presented. It makes the risks more immediate and tangible, which in turn leads to stronger and more informed responses compared to traditional 2D maps.

The impact of 3D simulation on other areas, such as overall risk evaluation and preparedness, was not statistically significant. One reason for this could be the limitations in the current version of 3D visualizations. For instance, the 3D simulation only covers a one-block area, which does not provide a comprehensive view of flood distribution in the entire region. This restricted view might have prevented participants from accurately assessing broader risks, including evacuation routes or the full extent of flooding. Consequently, this limitation could negatively affect their overall risk evaluation, preparedness, and likelihood of evacuation.

Moreover, the fact that the 3D simulations provided flood level predictions comparable to the 2D maps highlights their capability to deliver accurate and reliable data in an immersive format, even without direct flood depth information such as a flood depth legend. This level of accuracy, achieved in a more engaging and personalized environment, reinforces the value of 3D visualizations in enhancing users' understanding of flood risks. Presenting complex data intuitively without compromising accuracy shows that 3D tools can be valuable assets in risk assessment and in fostering better-prepared communities.

Additionally, participants overwhelmingly preferred the 3D simulations over the 2D maps for their effectiveness, ease of use, and emotional impact. The unanimous perception of the 3D simulations as more authoritative further underscores their potential in instilling confidence and motivating proactive measures. This superiority in communication suggests that 3D tools can be beneficial for improving public awareness and preparedness in the face of climate-related risks.

While immersive AR may further enhance the realism of a flood situation, the current generation of available technology cannot be cost effectively deployed, as "cardboard" VR is insufficient to support the dynamic nature of the flooding simulation. Conversely, given the prevalence of streetview imagery, OpenStreetMap models, and the recent completion of a national laser scanning data set, much of what was tested in this research could be cost-effectively replicated and disseminated through a regular web-browser on a near real-time basis to reflect emerging hurricane and other inundation threats, as predicted by NOAA.

VI. Conclusions

Promoting the relational model through web-based, dynamic, isometric, streetview flood simulations offers a promising avenue for enhancing risk communication by creating a more inclusive and effective communication strategy that engages and empowers stakeholders to better understand and respond to flood risks. This approach not only provides comparable effects to 2D flood maps in raising risk awareness and encouraging proactive risk-reductive actions but also excels in several areas. It is significantly more effective in conveying the magnitude of flooding and the challenges associated with evacuation. Additionally, it generates stronger emotional responses and is perceived as more authoritative compared to traditional 2D maps. Non-expert stakeholders also found it easier to use for judging the depth of floodwater.

The accessibility of the internet can help offset varying levels of map literacy. For instance, this tool can be used in ESL classes for recent migrants at schools and in community centers for older adults, demonstrating the potential harms of floods and initiating conversations on preparation. This inclusivity is crucial for ensuring that diverse groups, including the most vulnerable, can participate in risk education regardless of their language and educational background. By democratizing risk communication, the entire community, as a whole, becomes better informed and more resilient.

Furthermore, the relational approach to risk communication views the community as active agents of risk knowledge, rather than passive recipients. The localized, web-based tool, being engaging and accessible to vulnerable and low-literacy users, enables a broader range of community members to effectively utilize it, transforming them into active agents of risk knowledge. This facilitates the dissemination of risk information through social networks within the community, promoting engagement and becoming an integral part of the network that advances risk mitigation efforts.

When applying the tool in practice, pairing 3D and 2D visualizations can enhance the effectiveness of information dissemination. For example, 2D maps can provide an overview of the distribution of risk impacts and help people navigate evacuation routes, while 3D simulations can offer a detailed, vivid, and personalized immersive experience that emphasizes the urgency of the risk and encourages proactive risk-reductive actions.

In areas with predicted flood risk, landlords could use the 3D model to educate new renters as part of the leasing process, ensuring they are aware of the risks and prepared from the start. This practical approach helps disseminate critical information to those who need it most, regardless of renters' language and education background. Additionally, installing LED screens in at-risk communities may effectively capture the attention of passersby, showing potential flooding on their block. Unlike 2D maps, which require time and effort to interpret, 3D flood simulations quickly and clearly convey the risks.

Incorporating advanced technologies and innovations can further promote disaster risk reduction including simulating virtual drills for various types of risks, providing participants with experiential learning opportunities. This would be in contrast to traditional drills that often lack realism (e.g. no fire in a fire drill or water in a flood drill). Dynamic, isometric streetviews can offer more realistic scenarios, thereby allowing participants to practice and learn to respond appropriately to risks.

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