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A Framework for Creating Virtual Reality Models for More Effective Coastal Flood Risk Communication

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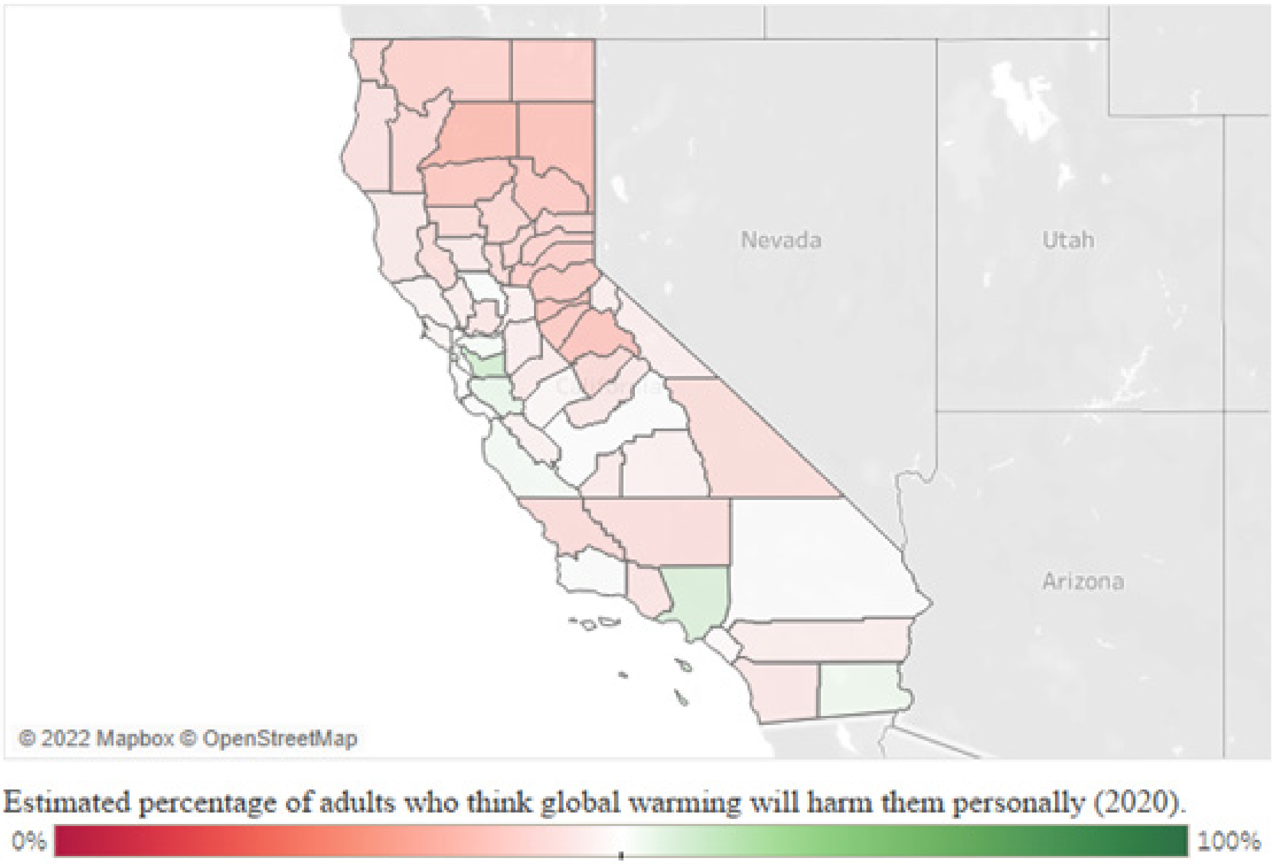
Coastal cities are exposed to increasing risks of flooding from sea-level rise. Climate change is expected to double the frequency of coastal flooding within the next decade, and some areas could experience floods of a magnitude 100 times higher than currently (Vitousek et al., 2017). People living in at-risk areas often ignore the impact of climate change on flood intensity and frequency. Immersive visual storytelling techniques proved promising and powerful tools to engage with and raise awareness of flood hazards. Here, we are introducing a framework to use Virtual Reality (VR) to reach better people living in coastal cities and help them understand the impact of climate change on their community. We developed a virtual experience in which people can be immersed in a coastal flood and experience its intensity. We used a combination of UAV imagery and digital photogrammetric techniques to create a virtual environment in which people can recognize real locations in their neighborhood and used GIS flood data to apply a water texture in Unity3D to create the flood levels.

1. Introduction

Coastal cities are exposed to a wide range of hazards. Among them, flooding is being magnified by global warming and its related effects, such as rising sea levels and changes in extreme precipitation events (Cheng et al., 2014). Coastal flooding often results from combined events, such as high precipitation, storm surge, high tide, and sea-level anomalies. This, alongside increased urban development in affected areas, means the number of coastal residents at risk for flooding is expected to increase. Currently, 200,000 people live in low-lying coastal areas in California (Crowell et al., 2010), and an additional 204,000 people are projected to be at risk by 2050 (McGranahan et al., 2007). Despite this increased risk being well documented in academic literature, climate change is not yet considered a direct and personal threat to many people living in these areas. A 2020 survey from the Yale Program on Climate Change Communication shows that while a large majority of Americans believe that climate change is happening (72% National, 77% California) and changing the weather (64% National, 69% California), it is still considered a far and future issue (71% National, 76% California). Only 43% of Americans think they will be personally impacted by climate change (50% California) (Desssler et al., 2016; Leiserowitz et al., 2015; Mcdoughall et al., 2011; Howe et al., 2015). Despite the frequent and stronger droughts, wildfires, floods, and heatwaves, most of California does not feel impacted directly and immediately by climate change (Fig-1).

The disconnect between the public's flood risk perception and the flooding's relationship to climate change has been extensively studied. For instance, it has been observed that flood risk communications in Europe were not accompanied by personal preparedness (O'Sullivan et al., 2012) or knowledge of the local flood risk (Bubeck et al., 2012). The feeling of helplessness, or inability to manage the uncontrollable, has been attributed as one of the causes of such dissonance (Paton & Johnston, 2001). The high trust in centralized governmental agencies managing hazards might also cause this lack of interest (Cannon et al., 2021). Moreover, the psychological distance between the

Figure 1.
Percentage of people who think climate change will impact them during their lifetime. Visualization of the data from the Yale Climate Opinion 2020 using Tableau's software.



public and climate change is extremely high: the long-term projections used by climate scientists or policymakers (such as 2035, 2050, or 2100) or the apparent small-scale climatic changes (objective of 1.5oC degree warming, current global sea-level rise of 3–4 mm/yr) gives the wrong impression to people that climate change is a slowly emerging issue only for future generations (Spence et al., 2015; Loy et al., 2020). Finally, terminology such as centennial flood or return period is not understood and has little to no meaning for people (Burningham et al., 2008; Chowdhury et al., 2011; Taylor et al., 2014). Research in individuals' risk perceptions has gained interest in improving risk communication strategies (Baan & Klijn, 2004; Siegrist & Gutscher, 2006; Plattner et al., 2006). Traditional visualization tools to inform people of coastal flood risk suffer from different flaws, such as assuming that people will process the information analytically (Marx et al., 2007). However, it was shown that the human brain prioritizes personal experiences over gathered analysis or statistical information (Marx et al., 2007). For instance, it has been shown that people who previously experienced a flood are more likely to be concerned about climate change (Whitmarsh, 2008). Consequently, many flood communication tools have failed to inform people about their risk, and there is a need to deliver risk information in a way that allows users to develop an informed judgment of their risk (Rollason et al., 2018).

Experts have been researching the best ways to reduce flood losses for years. Like other risk domains, flood risk management has increased interest in risk perception and communication research. Immersive Virtual Environments (IVE) have proved to be an effective tool in communicating flood risk in the past. Realistically 3D virtual environments can add drama to the scenarios while adhering to the representation of accurate scientific information (Olsen et al., 2016;). It provides a direct-to-user hands-on experience of the subject matter within the environment of interest. By being fully immersive and located in a place they know, we aim to make people more emotionally connected to the issue they are experiencing. The information interactively provided will also give them valuable information on why and how these floods are happening and changing in intensity. Pairing a persuasive message with a personal experience is potentially a valid and

Figure 2.
Left: area surveyed by the drone, view from the Drone Deploy Application. Right: ground view of the study area.

more effective technique to raise climate change awareness (Gustafson et al., 2020). By creating both affective (emotional) and cognitive (analytical) responses (Bostrom, 2003), VR is seen as a promising multifaceted tool to communicate climate change risk. By showing simulated flood scenarios in a photorealistic 3D environment that closely resembles a real place, people may better understand the impact of those scenarios in the real world. 3D modeling can create extremely realistic environments but is limited to faithfully reproducing an existing location. There are two main techniques to create realistic 3D models: The first uses a 3D scanner, which can produce high-resolution models but doesn't perform well over water. In contrast, the second uses only RGB imagery from different angles (stereovision) to estimate the 3D coordinates of each point. This last technique, called photogrammetry-stereovision or stereophotogrammetry (Wesencraft et al. 2019), is used in this paper since it is focused on coastal areas. This technique allows multiple photos of real-world objects to author game-ready assets and can realistically and faithfully reproduce landmarks near the coast. Photogrammetry is the reconstruction of object properties (i.e., shape, orientation, size, relative position, textures) based on images. Considering those, we propose a framework to augment two-dimensional traditional flood maps into a three-dimensional photorealistic virtual and immersive environment.

Previous attempts have been to use such technology to improve communication, especially flood risk communication. For instance, VR was used to improve flash flood evacuation in Japan (Fujimi, 2020) and in the UK (Skinner, 2020). It was shown that users could better understand complex phenomena, such as flash floods. Research in Taiwan has shown that when compared to static maps or visual presentations, VR programming increased the communication efficiency between the public and the government on a flood diversion infrastructure (Lai et al., 2011). According to the Construal Level Theory (Trope & Liberman, 2010), the perceived or psychological distance is defined by four dimensions: the temporal distance, the physical distance, as well as the social distance, and the hypothetical distance. While the previous studies are focusing on closing the temporal and physical distance, they lack the social, and hypothetical distances. Social distance can be reduced by choosing a place familiar to the user rather than a generic building, for instance a famous monument or a local public place. Hypothetical distance can be reduced by allowing the user to choose a set of climate change scenarios rather than a fixed one.

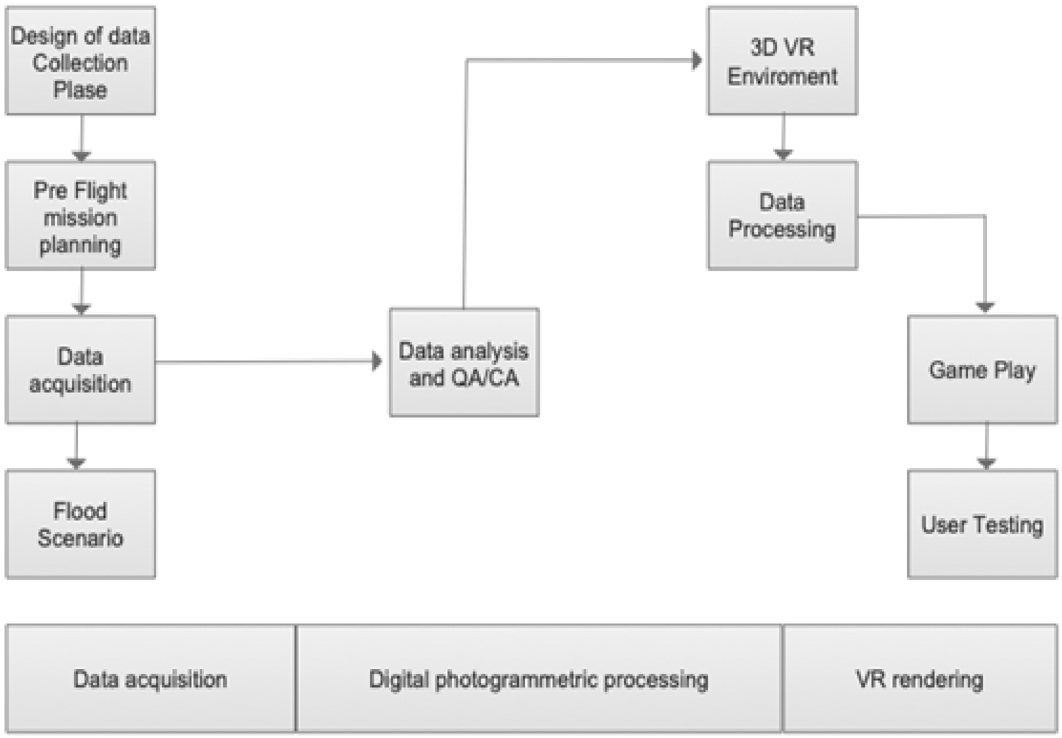
The goal of this paper is to introduce a framework to visualize flood scenarios in environments that resemble the real world, using drones as a tool to collect 3D data, and VR as a tool to create 3D immersive environments.

2. Data and methods

2.1. Study area

The study area is at the "Little Corona Del Mar" beach, located in Southern California. It has a total surface area of 10 acres, and the UAV covers 12 acres (see Figure 2). Residents of this coastal area experienced a relatively recent major flood (centennial) in January 2005, which impacted 355 properties (Gallien et al., 2011) and is still in people's memory. The area

Figure 3.
Framework developed for creating a photorealistic 3D and interactive environment.



exhibits several human constructions (staircase, lifeguard stands), several geological features (cave, sea stacks, cliffs), and it is a widely known beach among Orange County residents.

Due to its popularity, recent flood, and easy-to-recognized features, this location is a great choice to implement a flood VR experience, in which residents will be able to recognize local features, remember past flood experiences, and create a more personal and empathic connection with the environment. We will also be able to test the effectiveness of the VR experience as a risk communication tool for people familiar with relevant oceanic concepts (tide levels, wave patterns) otherwise unknown to more inland residents.

2.2. Overall workflow

The overall workflow consists of a data acquisition phase using an Unmanned Aerial Vehicle (UAV), data processing using digital photogrammetric techniques, flood data selection and rendering into an immersive virtual environment, the experience design to create an interactive environment, and finally user testing (pre and post survey) to identify learners' existing knowledge and whether the VR experience was effective in creating awareness about coastal flooding.

2.3. Data acquisition phase

The data acquisition phase has been divided into four interconnected phases: (1) design of the data collection phase, (2) Pre-flight mission planning, (3) data collection, and (4) data analysis and quality control.

The design of the data collection phase is the most critical step to ensuring a safe, data-producing flight. It is the role of the Pilot in Control (PIC) to assess the key parameters affecting the quality of the data produced, such as meteorological conditions, local topography, and sensor performance. It is also responsible for knowing current flight regulations, legislation, and safety protocols. Depending on the spatial and temporal resolution needed and the desired data precision, the PIC creates the mission plan while accounting for camera settings, flight paths, and battery management. The PIC also defines the optimal conditions for data collection using the UAV, such as low tide, to capture more rock structures at the beach, morning, and overcast days to minimize the shadows that can interfere with the digital photogrammetric process.

The pre-flight mission plan consists of the reconnaissance of the area that will be surveyed to identify potential hazards (e.g., powerlines) and problematic areas for the project's objectives (e.g., cave, benches, fire pits for our project will require a higher level of details and ground imagery). During this step, we identified all potential hazards, such as possible collisions with standing objects, structures that could alter the remote-control signal, and the presence of people or animals (birds) that could require attention. We also identified the objects or areas that require special attention when collecting imagery because of their shape or topography. Some areas were not accessible by UAV and will have to be surveyed using a DSLR camera.

The data collection phase involves flying the UAV on an automated path using the DJI Waypoint application. For this project, we set up a linear path for image acquisitions with Ground Control Points (GCP) to properly align and scale the study area. Aerial imagery was acquired by a DJI Mavic Pro 2 at 3 level altitudes (20m, 30m, and 50m). We used manual settings for the camera to avoid high ISO (camera's sensitivity to light) and noise and saved the images in RAW format. We set up a front overlap of 70%, a linear path, and a combination of nadir and oblique imagery to generate more accurate and realistic 3D reconstructions. DJI WayPoints were used to define the trajectory of the UAV, and all images were acquired automatically.

The data analysis and quality control phase are critical to ensure the project's success. Despite the growing trend for using UAVs to collect data, currently, there are no universal standards and procedures to ensure the data's quality. For this reason, we implemented the following methods to ensure data reliability: mapping all imageries to ensure that the UAVs correctly recorded the GPS coordinates; qualitatively assessing the luminosity and level of glare over the oceans, and in case of high levels, postponing the flying plan, and finally quantitatively assessing the blur of each image and removing the low-quality ones or rescheduling the flying plan. There are many different methods to detect blur in imagery (Pertuz et al., 2013). We implemented a method based on the variance of the Laplacian on detecting blur (Pacheco et al., 2000) using the cv2.Laplacian function from the OpenCV library in Python to detect blurry images and exclude them.

2.4. 3D processing and rendering.

The general workflow to obtain Digital Surface Model (DSM), Digital Terrain Model (DTM), or 3D Model from UAV imagery is: (1) creating a low-density point cloud using camera orientations and locations, (2) creating a high-density

Figure 4.
CoSMoS data visualization around the area of interests for two scenarios of Sea Level Rise.w

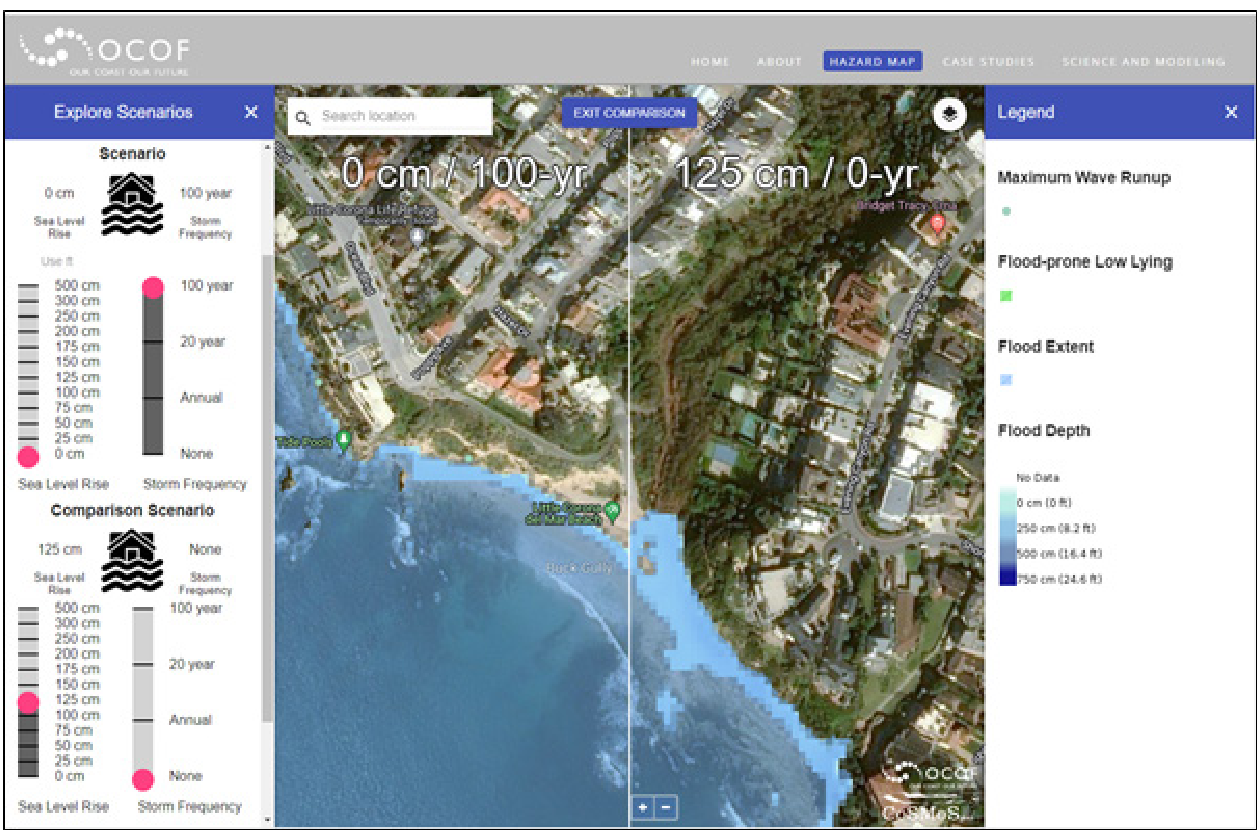


Table 1.
Scenario description for a non-expert user

Scenario	Sea Level Rise	Description for the use
S1	0 cm	Current world conditions, equivalent to the 2005 flood.
S2	50 cm	World where sea level rise has reached 50cm. This sea level rise is the most likely by the end of the century if global warming is contained to 2 to 3 Celsius (RCP 4.5) or by 2050 if global warming is around 4.5 Celsius (RCP 8.5)
S3	150 cm	World where sea level rise has reached 150cm. This sea level rise is the most likely by the end of the century if global warming reaches 4.5 Celsius (RCP 4.5) or by 2050 if global warming is around 4.5 Celsius (RCP 8.5)
S4	200 cm	World where sea level rise has reached 200cm. This sea level rise is the most likely by the end of the century if no action is taken (scenario H++)

point cloud, (3) generating a georeferenced mesh from the point clouds, and (4) applying the texture on the mesh. We used the commercial software Autodesk Reality Capture (ReCap) to generate a georeferenced 3D Model on the cloud with texture (colors) out of the UAV imagery. After scaling the model, we verified the quality of the output by comparing one virtual object's dimensions (a rock) on the model with its actual dimensions to ensure no wrapping or distortion of the 3D model. After validation of the DSM, we manually edited the 3D model using Maya 3D to smooth the object's surfaces and fill any holes in the model using ReCap's automated functions. The 3D objects generated by Autodesk ReCap were exported into Unity 3D, a virtual reality platform, along with the rest of this model's assets. Unity3D has been chosen due to its support for advanced physics (such as waves) which are essential for a realistic rendering.

Flood information were queried from the Coastal Storm Modeling System (CoSMoS) dataset (Barnard et al., 2018), which consists of detailed projections of storm-induced coastal flooding and erosion for both current and future sea-level rise (SLR) scenarios. The flood heights were extracted from the 100-years return period raster files using ESRI ArcGIS and summarized to water heights to feed the Unity3D software. We chose several scenarios of sea level rise and related them to several scenarios in California (Griggs et. Al., 2017).

Finally, the application was implemented in C# on Unity3D and visualized using Oculus Rift virtual reality headset, as detailed in the results section.

2.5 Virtual Reality development

This phase formed the core of the whole research process; It included converting the images and videos obtained with

Figure 5.
Foliage modeling on the 3D model.

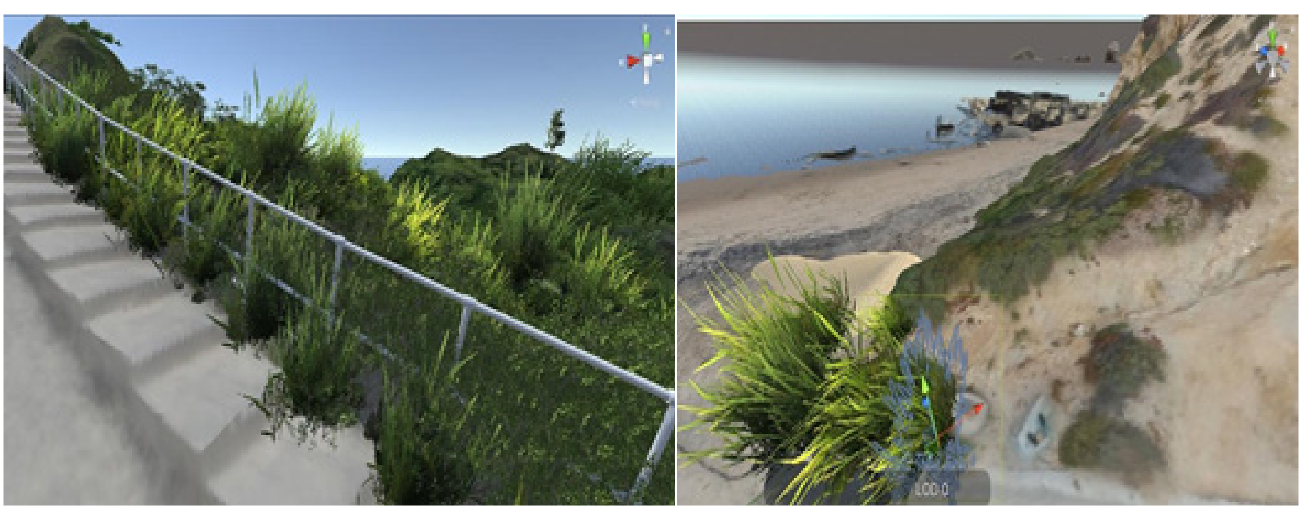


Figure 6
Final rendering of the VR environment

high-resolution cameras and drones to realistic 3D models in Reality-Capture software, 3D modeling smaller objects in Maya, using these 3D models in Unity to create a virtual environment that can be walked around freely like a virtual game, providing the audience with a six degree of freedom. The gamification involved coding the scene using the C# script to enable the audience's movement in a virtual environment. The scene enables the simulation of rising waves and tides at the beach, providing a first-hand experience to the audience to create awareness about the grim situation.

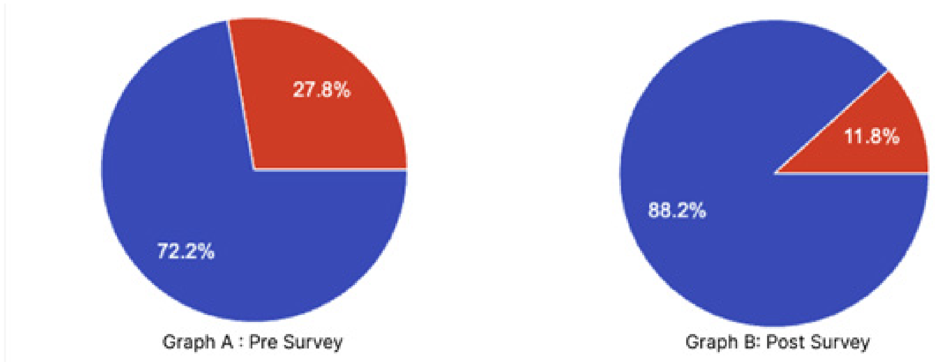
The next step involved creating realistic terrain from the Height/UV map using the Terrain to Object plugin in Unity. We created vegetation that resembled the one that Newport beach has. Finally, we used C# in the unity development environment to Gamify the environment where the audience could press the button to increase the water level and see the impact and hear the narration about different scenarios. The data about water rise was taken from the CoSMoS dataset. The audience is always provided with a narration in the background to give information about the flood rise in each scenario. We created a hype- realistic VR scene of the Newport beach, mapping the exact flora and fauna found on the beach. Although the 3D model from the Reality Capture gave us a high-quality UV map, it flattened all the foliage and high poly organic objects. As a result, we had to use some foliage from the Unity asset store and place them on the UV map. The foliage was placed on the UV map specifically selected based on the color, type of foliage, and its exact location, and motions were added to the leaves for realism.

3. Testing

We conducted a testing session with around seventeen participants; the main focus of our demography was young adults, who can play a pivotal role in creating awareness and achieving the goal of sustainable development. The

Figure 7.
Participants experiencing VR scene in Oculus headset

Figure 8.
The two graphs show an increase in the number of participants that feel concerned about increasing sea levels



participants were hired from San Jose State University and pursuing their undergrads.

We conducted surveys in two stages; the first stage helped us to understand the current level of understanding about the sea level rise and climate change and how it is affecting major decisions in the life of students. We found that almost 60% of participants felt that rising sea levels are not affecting their daily lives. This data showed us that very little awareness about the rising sea level directly or indirectly impacts our lives. On the contrary, almost 78% of participants agreed that they are affected by climate change. We need to make it obvious that climate change and Sea level rise are both issues that go hand in hand; very little effort is being put into making people aware of the consequences of rising sea levels.

The post-survey was aimed at getting insights into the VR application created and its effect on understanding the situation of sea level rise. About 88% of the participants found the application relevant in creating awareness about the rising sea level.

The experience got a positive response from the participants; all the participants found the experience informative and made them more aware of the consequences of rising sea levels. About 70% of participants did not encounter navigating the scenes. Our efforts to keep the effect of motion sickness to a minimum showed with 70% stating they did not face any dizziness or motion sickness.

4. Results

The 3D model was created using a combination of UAV and DSLR imagery with photogrammetry techniques. The image acquisition phase took 30 min using two sets of batteries. The imagery was taken in the morning when lighting conditions were ideal. One challenge of mapping the coastal environment is the surface roughness of the water layer created by the waves so that two images taken within one second would be dramatically different and create uncertainties in the digital photogrammetric process resulting in model errors. We took this into account by capturing images on a day with low tide, featuring as much of the landscape as possible while also minimizing potential problems caused by capturing the ocean. We obtained a total of 680 aerial photographs and removed 12 images with a high level of blur using the method mentioned in the previous section. We then processed the remaining images using photogrammetry software and obtained a high-resolution georeferenced 3D model (Figure 9). The processing time in the cloud (AutoDesk ReCap) took 3 hours for the 10 acres. Merging UAV and DSLR data were challenging, and we decided to process the two imagery sources separately. High-resolution DSLR ground imagery was processed to create separate 3D objects that were later integrated into the DSM.

The flood information has then been integrated into Unity so that the correct water level can be rendered. The hypothetical level under a sea-level rise in 2035 and 2050 has also been integrated. The final VR environment and flood scenario were implemented; we could virtually experience the 2005 flood under current and future climate conditions (Figure 10).

The combination of UAV and DSLR imagery created high-resolution surfaces with texture in most areas of interest, with some high-resolution objects when needed. All geological features (rocks, caves) and topographic features (sand dunes) were correctly captured by the UAV and rendered in Unity. The added water layer due to different sea-level and tide conditions has been rendered in Unity with visual effects, such as surface roughness and waves. We decided, however, not to include wave interactions with an object, people, and surfaces such as walls or cliffs. Such interaction (droplet projections) requires more data, such as current velocities, which were not directly available and would add another scenario level (high tide, low tide, wind conditions, etc.). However, adding flow conditions, such as velocities, and interactions with people, for instance, resistance to walking due to the wind or waves), would further improve the VR experience of the flood and the comprehension of the severity of the event. Vegetation was the most challenging as many small bushes and most small plants were either not fully captured in 3D or were captured as 2D assets. Capturing these 3D features would require adding an unnecessary and considerable amount of time and data. For these reasons, we decided to cut them out and add similar-looking vegetation features that were pre-modeled. Overall, using a ground based DSLR, it is necessary to model these complex features that cannot be fully captured by UAVs separately. These objects should be identified during the pre-flight mission steps so UAV and DSLR imagery is captured simultaneously and in similar lighting conditions.

Figure 9.
Overall view of the case study area (3D model).

Figure 10.
Details of the simulation: Left: High tide in 2005; Right: High tide with 50cm SLR

The results of the user testing are encouraging: the survey prior to the test revealed that only 60% of the participants (10 out of 17) felt that rising sea levels are not affecting their daily lives but 76% agreed that they are affected by climate change. Past the VR experience, about 88% of the participants found the application useful in raising awareness about sea level rise. All the participants agreed that the VR experience was informative and provided useful context to the data shown.

Finally, most (70%) of the participants stated having a positive experience, free of motion sickness or dizziness during the navigation and transition from one scenario to another one.

5. Discussion

This DSM was made possible by combining UAV and DSLR imagery, photogrammetric software, and 3D modeling to create a georeferenced, photorealistic model. Compared with their real-life counterparts, the objects depicted in this DSM are appropriately proportioned and accurately textured. VR has been used for experiential learning, as mentioned before; however, few can capitalize on a user's personal experiences and enhance the VR experience. By providing high-resolution details of a public place (beach) where users may have some sentimental attachment, we aim to personalize the VR experience to create a more immersive experience with emotional responses. Moreover, by using the georeferenced DSM into Unity and adding a layer of water with a parametric height, we can easily translate any flood scenario from a shapefile (ArcGIS, QGIS) into a 3D immersive experience.

These results provide several recommendations. One major challenge of climate change resilience is to increase local stakeholders' (local government, communities) participation in their risk mitigation strategies (Frazier et al., 2010). While a high-resolution local flood model exists, static or interactive web maps might not effectively engage most people. Visualizations, such as a preliminary model or an artistic mockup, have increased local stakeholders' engagement in infrastructure development (Assaf et al., 2002; Wang et al., 2019). In effect, however, much of this awareness media is often created by centralized governmental institutions or agencies, which may not account for the local community's specific environmental conditions or needs. The framework presented could help to engage the various local stakeholders by providing an accessible and provocative experience of the different flood scenarios (different return periods, sea wall heights proposed, or climate change scenarios), set in a location known to many within the community. It would furthermore create a space for two-way communication between local communities, which are knowledgeable on local environmental conditions, and centralized agencies, who provide a deeper understanding of the exogenous factors depicted by the framework. Several studies suggest that community-based adaptation measures can be more beneficial (Dumaru, 2010; McNamara et al., 2020). Another challenge is the multidisciplinary nature of flood risk mitigations, which makes it very challenging for the different stakeholders to understand the mechanism underlying coastal floods: sea-level rise, change in precipitation patterns, change in land use and runoff, green infrastructure, engineered infrastructure… The proposed framework is intended to help the different stakeholders better understand the impacts of each of these parameters by experiencing it.By using a consumer grade drone (less than $2000), and free software (Unity 3D, AutoDesk ReCap, free for small non-profit usages), the framework can be replicated in local communities without heavy investments on hardware and software.

We acknowledge that this study has several limitations. First, VR can induce dizziness in some users, so the experience should be calibrated to minimize this effect. Additionally, there is the risk that the program does not appeal to residents. For this reason, the VR experiment should be tested on a representative sample of the population of this paper's case study area, and a survey and robust analysis should be conducted to determine VR's real effectiveness in conveying awareness. Such analysis will be the object of a separate study as it will require testing several scenarios of climate changes and several technical and sensory features of the VR experience.

6. Conclusion

Climate change awareness does not always translate into personal risk awareness, especially in an age where climate-induced hazards are growing increasingly common. While more and more coastal residents understand the global changes in climate thanks to education and scientific outreach, too few are yet aware of the change in hazard frequency and severity at the local level. This paper presented a framework to augment a 2-dimensional flood map into a 3-dimensional photorealistic interactive environment. The framework developed successfully uses UAVs for imagery collection and processing and integrates different quality control and quality assurance steps. Currently, our project is limited to one type of scenario (Sea-Level Rise) over a small non-residential area. However, the framework is generic and can use any type of flood scenario saved in a 2D shapefile, such as sea-level rise, high tide, high precipitation, levee failure, seawall breach, or any combination. Adding a scenario will require no extra work to create the water layers but additional time and resources to create the narrative of the experience.

In future research and with appropriate flight authorizations, we plan to map a residential area protected by a sea wall and test the tool's effectiveness in communicating flood risks under different scenarios of sea-level rise and sea wall height. We will develop the VR Experience with an appropriate narrative in which the user will be able to visualize a historical flood and its projected level under a different scenario of climate change, levee failures, or infrastructure upgrade with the ultimate objective to better explain to people how the current change in climate will impact their local community.

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