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Drones, virtual reality, and modeling: communicating catastrophic dam failure

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ABSTRACT
Dam failures occur worldwide and can be economically and ecologically devastating. Communicating the scale of these risks to the general public and decision-makers is imperative. Two-dimensional (2D) dam failure hydraulic models inform owners and floodplain managers of flood regimes but have limitations when shared with non-specialists. This study addresses these limitations by constructing a 3D Virtual Reality (VR) environment to display the 1976 Teton Dam disaster case study using a pipeline composed of (1) 2D hydraulic model data (extrapolated into 3D), (2) a 3D reconstructed dam, and (3) a terrain model processed from UAS (Uncrewed Airborne System) imagery using Structure from Motion photogrammetry. This study validates the VR environment pipeline on the Oculus Quest 2 VR Headset with the criteria: immersion fidelity, movement, immersive soundscape, and agreement with historical observations and terrain. Through this VR environment, we develop an effective method to share historical events and, with future work, improve hazard awareness; applications of this method could improve citizen engagement with Early Warning Systems. This paper establishes a pipeline to produce a visualization tool for merging UAS imagery, Virtual Reality, digital scene creation, and sophisticated 2D hydraulic models to communicate catastrophic flooding events from natural or human-made levees or dams.

Abbreviations: ASDSO: Association of State Dam Safety Officials; DEM: digitalelevation model; EWS: Early Warning System; HEC-RAS: Hydrologic EngineeringCenter-River Analysis System; HMD: Head-Mounted Display; NOAA: NationalOceanic and Atmospheric Administration; Reclamation: Bureau of Reclamation; United States Agency; SfM: Structure from Motion; 1D: one-dimensional; 2D:two-dimensional; 3D: three-dimensional; UAS: Uncrewed Aerial System (drone); US:United States; USACE: United States Army Corps of Engineers; VR: VirtualReality

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1. Introduction

Earthen dam failures threaten rapidly growing downstream populations. There is an emerging global risk because the world's dam infrastructure is aging (Perera et al. 2021). Given the infrastructure in the United States (US) is similar to other countries, and the US consistently ranks in the top three

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countries by the number of dams (current estimates indicate there are 90,500 dams), this study focuses specifically on a representative earthen dam in the US with a robust data set: the Teton Dam failure (Mulligan, van Soesbergen, and Sáenz 2020; USACE 2019).

Additionally, of the 90,500 dams in the US, it is estimated that by 2030 over 60,000 dams will be 'high hazard,' meaning their failure could result in the loss of life (ASDSO 2021). Within the US, dam failures have occurred in all 50 states, leading to fatalities and severe life safety consequences (Aureli, Maranzoni, and Petaccia 2021). Moreover, dam failure is one of many hazards that is predicted to be magnified by climate change (Fluixá-Sanmartín et al. 2019). Studies indicate that climate change can increase precipitation levels which can lead to higher inflow into reservoirs, creating increased structural loading that could lead to dam failure (e.g. Fluixá-Sanmartín et al. 2019; Bahls and Holman 2014; Loza and Fidélis 2021; Tabucanon et al. 2021). Because the probability of dam failure and associated flooding hazard risk is increasing, it is essential for the public to understand the associated hazards and for researchers to communicate with citizens and industry professionals. Virtual Reality (VR) offers a 3D method for visualizing geo-referenced data and 2D hydraulic modeling data in an intuitive way using raw UAS data to form an environment for visualizing scientific information for social applications, targeting non-specialist users like students or policymakers.

It has been established that risk perception and behavioral responses are often influenced by experience with flooding (Siegrist and Gutscher 2008). Further, it has been established through the Early Warning System (EWS) and disaster management research that risk communication efforts can be enhanced by understanding risk perception (Fakhruddin et al. 2020; Zhong et al. 2021).

For example, studies have focused on improving citizen disaster awareness through VR fire disaster trainings (Ooi, Tanimoto, and Sano 2019). For natural disasters, such as dam failures, there is not yet an established correlation between improved disaster awareness and improved citizen preparedness. The general public does not have personalized experience with dam failure flooding, probably because dam failures are not common. This could make citizen responsiveness to EWS difficult. This paper presents a pipeline to generate a VR environment which could be used to personalize the users experience with flooding.

The development of appropriate strategies for risk communication is part of an overarching formulation of flood risk management in the US. US Federal agencies have been developing multifaceted communication tools combining ESRI products and mapping. However, programs do not yet capitalize on a framework using drone photogrammetry and VR, which has the potential to increase citizens' preparedness (Oe and Yamaoka 2021).

A VR environment creates an area for a user to experience risk assessment personally and creates a window of attention for a user to experience terrestrial flooding in urban areas (Costabile et al. 2021). Recent work by Macchione and Costabile highlights a methodology combining terrestrial and airborne laser scanning with 2D modeling to generate 3D flood hazard maps in urban areas (for enhancing risk communication; Macchione et al. 2019; Costabile et al. 2021). This study builds off of their work, to package a risk communication tool using VR for dam failure simulation.

This novel pipeline has the potential to produce virtual environments of different locations and use it for effective dam and levee failure risk communication. Currently, maps are informed by 2D numerical models, commonly employed by floodplain managers to simulate the flow resulting from a dam failure (i.e. Brunner 2016; ASDSO 2021; USACE 2019). Such results can provide information on flood wave arrival time, flood extent, and wave water surface elevation (e.g. Urzică et al. 2021; Spero and Calhoun 2020; Toapaxi Alvarez and Quilumbaquin 2021).

2D numerical modeling commonly uses historical dam failures as case studies (Aureli, Maranzoni, and Petaccia 2021). Having previously been used for these models and with accompanying reference and aerial data available from the United States Geological Survey and the Bureau of Reclamation, we selected the Teton Dam failure for this study (Spero and Calhoun 2020; Aureli, Maranzoni, and Petaccia 2021). The Teton Dam failure event also has historical importance; the dam failure took 11 lives, is considered the largest failure of a Reclamation project and still has a notable influence on US dam mitigation measures (Chadwick 1976).

Virtual environments are produced for VR experiences as part of a digital production or computer science process commonly referred to as a production pipeline (or 'pipeline'). Pipelines can be created to combine technologies, demonstrating steps by a processor to perform an instruction. More specifically, they consist of collections of tools, processes, and tasks organized into a specific sequence taking digital inputs and through both human and computer programs converting them into a final digital media output. VR digital production pipelines typically yield a shareable virtual environment consisting of geometry, imagery, audio, software code, and metadata that can be loaded into a VR Headset to create an immersive experience (Kang and Choi 2018).

Scientific disciplines also use pipelines (or 'workflows' in other parlance), for solving complex problems and transforming input data into finalized data for communication and decision making. These pipelines are typically used for scientific problems that are complex, requiring multiple users and programs to produce actionable results (Deelman et al. 2018).

Combining digital production pipelines with scientific workflows allow interdisciplinary teams to produce more broadly accessible results from disparate data, building on one of the primary goals of Digital Earth (DE): interfacing education with 3D virtual scientific information to help people understand the Earth (Van Genderen 1999; Liu et al. 2020).

1.1. Innovation of current work

In this paper, we show that the VR environment pipeline can be used to communicate historical disasters (informed by real-world data) to the public. VR is an evolving technology that creates fully immersive virtual environments, including vision and sound (Kei 2018). In 1968 Sutherland and Sproull coined the term Head-Mounted Displays to describe devices for this purpose (HMDs; Sutherland 1968). Despite the incredible advancements since 1968, VR application in the communication of dam failure hazards has not been explored to potential.

Standalone headset systems have become light and affordable, enabling researchers to develop scenarios for the general public which can be viewed in such mundane areas as parking lots, office buildings, and public forums (Alawa et al. 2021; Concannon, Esmail, and Roduta Roberts 2019). In this work, we have chosen to investigate dam failure simulation using an HMD (the Oculus Quest 2) as the primary hardware component for demonstrating VR as a communication tool for natural hazards and disasters. We use the 1976 Teton Dam scene (Figure 1) as a case study, but also demonstrate our constructed pipeline is extensible to other devices due to its low computational cost. This study's methods can also be used for static VR applications such as CAVEs (Cave Automatic Virtual Environment; Cruz-Neira et al. 1992; Cruz-Neira, Sandin, and DeFanti 1993).

1.1.1. Overview of Virtual Reality and related works

Advancements in computational power allow the creation of complex VR environments. However, a knowledge gap exists in the computational limitations of standalone HMD for visualizing realistic environments. Therefore, this study has two focuses. First, investigating if a 3D model of a real-world scene constructed through remote sensing techniques (Structure from Motion, 'SfM') will improve terrain viewed in VR (Niedzielski 2018). Second, determining the limitations of the Oculus Quest 2 by using geospatial data to create a compelling VR environment. As the Oculus Quest 2 is a newer technology, we further the state of current research by assessing advantages and limitations. Building a lower computational cost environment can extend hazard communication to mobile devices (i.e. phone or tablet).

In the past several years, widespread affordability and availability of VR hardware has led to VR use in disaster research and communication of human-made and geologic hazards such as flooding, mining, urban fires, volcanoes, landslides, and earthquakes (e.g. Rydvanskiy and Hedley 2020;

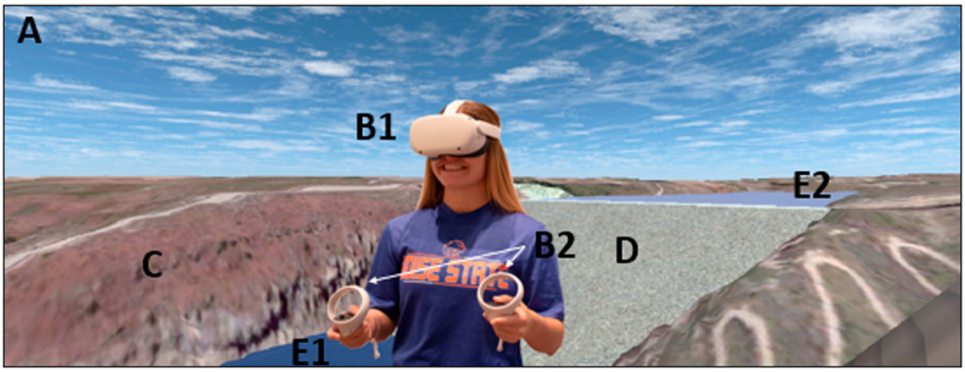

Figure 1. Sketch with Oculus Quest 2 headset and hand controllers in the Teton Dam environment. (A) VR scene or VR environment, (B) Oculus Quest 2 VR Headset where (B1) is the Head Mounted Display (HMD) and (B2) denotes the Oculus Quest 2 controllers, (C) VR terrain, (D) VR Teton Dam, (E) Cloth Textures simulating water where (E1) is downstream and (E2) is the reservoir volume.

Denby et al. 1998; Isleyen and Sebnem Duzgun 2019; Tucker et al. 2018; Asgary, Bonadonna, and Frischknecht 2020; Havenith 2021; Gong et al. 2015). Applications range from singular disciplines (civil engineering, computer science, geosciences, geophysics) to multidisciplinary, often combining a STEM field with social science applications like risk analysis. As an example, VR was used to simulate specific mine operator hazards such as underground fires and explosions. This hazard awareness training was for professional development and emergency situation preparedness (Denby et al. 1998). As a hazard assessment tool, VR environments simulating mining roof fall events enabled users to determine appropriate mitigation measures (Denby et al. 1998; Isleyen and Sebnem Duzgun 2019). For urban fire research, Tucker et al. studied the effects of accessible information of hazards on evacuee behavior in VR during a burning building emergency, demonstrating VR efficacy in reducing anxiety typically experienced in evacuations and showed that providing targeted training experiences decreases evacuation time (2018). VR has been used in volcanology to simulate volcanic phenomena for emergency managers and teachers in Italy (Asgary, Bonadonna, and Frischknecht 2020). Similar research has been used for landslide geologic mapping and modeling in 3D, notably using Radar and LiDAR as input data (Havenith 2021).

Adding to applications (such as communicating technical understanding of natural hazards and disasters to emergency planners and first responders), VR research in computer science typically focuses on more technical aspects of immersion such as cybersickness. Several recent studies analyzed methods for preventing dizziness (cybersickness) in 3D disaster scenes or analyzed effects of dizziness enhancing VR environment realism (e.g. Cummings and Bailenson 2016; Hu et al. 2018; Kennedy et al. 1993; Gong et al. 2015). In the case of Hu et al., a riverine flooding VR model was used when investigating how to pair the left and right eye synchronicity to minimize user dizziness or sickness (Hu et al. 2018; Kennedy et al. 1993). Another study used VR cybersickness to their advantage, as they were simulating earthquakes which often cause dizziness and enhanced the panic in users earthquakes can cause (Gong et al. 2015).

For a more discipline-specific application, in the geosciences VR field, flooding VR models have used rigorous integration of geospatial data to visualize flood models (Rydvanskiy and Hedley 2020). Since 2011, efforts have been made to develop a 3D virtual environment for communication flooding events (Lai et al. 2011). As technology has progressed, the environments have linearly improved as well (Leskens et al. 2017). For coastal flooding, there has been further development allowing for the visualization of storm surge flooding based on 3D numerical simulations (Liu et al. 2018). In 2019, Macchione et al. introduced the method of representing 2D hydraulic simulations within a 3D VR environment (2019). In our study, we build on efforts like Macchione et al. to render the 3D environment in Blender (2019). Building on that work, Costabile et al. used terrestrial and airborne laser scanning combined with 2D modeling to generate 3D flood hazard maps (Costabile et al. 2021).

The literature and research demonstrate that technological advancements provide the infrastructure to facilitate hazard and disaster visualization and data accessibility. With continuous improvements in HMDs, VR systems offer the opportunity for seamlessly integrating historical data to improve communication among industry, academia, and the general public (Liu et al. 2020; Foresman 2008). This study shows a valuable way for visualizing and communicating 2D hydraulic calculations of the 1976 Teton Dam failure using a geo-referenced 3D terrain model inside a VR headset (Oculus Quest 2).

1.1.2. Dam break modeling in Virtual Reality

Zhu et al. (2015) presented the first investigation of dam break informed VR 3D modeling. Zhu et al. modeled a dam-break, focusing on the real-time simulation of risks (2015). The results obtained by Zhu et al. indicate their methods improve the efficiency of dam-break risk assessment. Our study is unique from previous applications as it provides a method that could potentially be used to bridge the communication barrier between experts and non-specialists. A Virtual Geographic Environment (VGE) has been used to reproduce dam-break floods, using post-disaster information to design their visualization (Li et al. 2021). but their case study mentioned that high-precision DEM data and computational efforts (using the 2D cellular automata method) could improve the model further (Li et al. 2021). In Yu et al., the authors integrated a Computational Fluid Dynamic (CFD) model into their VGE visualization system for tailings dam failures (2021). A comprehensive review of VR for visualization and assessing the intersectionality with geohazards can be found by Havenith (2021).

Other advances in VR research have focused on public perception and community resilience. For example, Li et al. used an augmented scene to depict debris flows and then a questionnaire to survey the public and determine their perception (2020). This research extends to geosciences and geography education, where students can develop media literacy (Prisille and Ellerbrake 2020). Students can also use VR for developing science fluency. Assimilation of Big Data for VR is another ongoing sub-field in geoscience education, with Argo3D creating immersive VR for earth sciences (Gerloni et al. 2018).

1.2. Teton Dam study area and case study selection

The Teton Dam was located on the Teton River in Eastern Idaho on the Northeast edge of the Snake River Plain. The Teton Dam is 93 m tall with 289,374,408 m^3 volume in the reservoir (Chadwick 1976), it was the most prominent structural collapse in US history (Mattox et al. 2018). The Teton Dam failed on 5 June 1976, and was one of the costliest dam failures in US history, with damage estimates ranging from 400 million to 1 billion dollars (Solava and Delatte 2003). The Teton Dam failure event also instigated the creation of agencies and groups that monitor dam safety, such as the Association of State Dam Safety Officials (ASDSO 2021). The Teton Dam disaster was selected as a case study because it is historically significant with widespread effect. The Teton Dam disaster changed how dams were designed and monitored in the US. The disaster also has abundant data that is publicly accessible, when combined with the results from the 2D numerical models (Spero 2021) it forms a robust case study.

1.2.1. Teton Dam site geomorphology

The change in geomorphology of the Teton Canyon following the breach event was considered for this study because the steep canyon walls experience consistent erosion, and landslides are commonplace (Reclamation 2000). According to Reclamation's Geomorphology report, the Teton Dam failure activated more than 200 landslides (Schuster and Embree 1980; Reclamation 2000). These landslides submerged the reservoir with approximately 3.6 million ft^3 of debris having slid to the canyon floor (Magleby 1981; Reclamation 2000). This change poses a challenge for generating an accurate 3D model of the pre-breach Teton Dam topography, which is an unavoidable source of uncertainty. In this work, we assume that in its entirety, the geomorphology is largely unchanged, and acknowledge that our model does not reflect the topography as it was in 1976.

High-resolution geo-referenced topographic data and detailed historical records are preconditions to modeling or creating a VR environment that represents the real world. This study used the SfM reconstruction to generate geo-referenced mesh terrain files in several resolutions ; however, the coarsest resolution (i.e. smallest file) was ultimately used for computational performance considerations (Reclamation 2015; USGS 2015). Other available data include public historical archives containing abundant information such as dam blueprints containing specific information on breach geometry (Figure 2) (Chadwick 1976).

The resolution of data can assist in overcoming some of the technological hurdles in VR environment creation, by providing more realistic terrain for users. However, some obstacles still exist as those who construct VR environments must balance the need for high-resolution terrain with a computational expense. Movements in the virtual space can help communicate complex processes, but the technical endeavor of creating a convincing environment is challenging. This study also determines what elements are necessary for a dam failure VR environment to make it believable and safe for all users.

1.3. Study objectives

With current resources lacking the ability to identify spatially and temporally changing features for researchers and resulting communication to the public, this project aims to investigate three technical questions with underlying objectives:

(1) Can this study create a VR pipeline using drone photogrammetry and VR methods informed by numerical modeling results?
(2) How best can we emulate 3D water movement using the VR Unity platform at the low computational expense?
(3) Is VR technology capable of being a mechanism for teaching about dam failure?

The underlying objectives associated with the technical questions involve (i) determining the elements necessary to create a convincing dam failure in VR for users; (ii) creating an open-source pipeline for researchers and industry professionals alike to develop VR dam failure environments of their own; (iii) exploit inexpensive commercial off-the-shelf SfM technology to generate high-resolution VR terrain; (iv) ascertain the visualization capabilities of the Oculus Quest 2 headset and

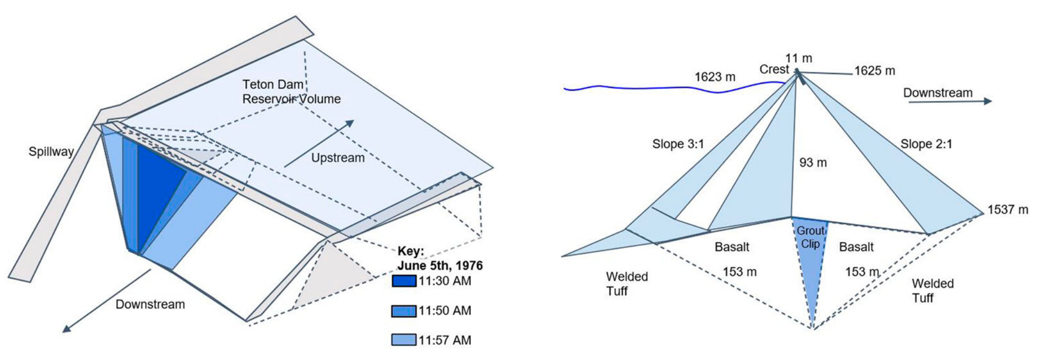

Figure 2. Digital schematics of the Teton Dam created from historical blueprints. The Teton Dam crest was 93 m high, 914 m long, and 11 m wide. This dam stored a volume of 355,242,240 m^3 along the Teton River, only reaching 289,374,408 m^3 volume before failing (Department of the Interior 2006).

potential limitations for processing on an HMD. The objectives contribute to answering the two technical questions and provide the technical foundation for future work studying the effectiveness of VR as a communication tool in (dam failure) disaster preparedness.

2. Approach

Using digital technology to support dissemination of science to non-specialists requires a robust and straightforward methodology. This study creates the VR Teton Dam failure environment using a pipeline to construct an infrastructure for widespread use and application, which is freely available. Through this workflow, the communication of dam failure hazards is significantly improved (Figure 3).

2.1. System workflow and data availability

In the process of developing the interactive virtual environment for users to explore a dam failure simulation, we also set up a workflow solution that simplifies the process of integrating earth systems simulations into virtual environments. This simplifies the process for future work exploring creating other dam failures in VR, demonstrating what could happen if particular future dams were to fail. This process also provides useful resources for educating interested individuals about national infrastructure. Additionally, this simplifies the process of creating virtual environments for earthquakes and other additional natural hazards.

The system workflow (see Figure 3) consists of a small pipeline of data flow, a collection of commodity software and tools, and a small amount of customized software to allow for source data to be integrated smoothly into the virtual environment.

We utilized Blender, Unity, Adobe Creative Suite, and the Oculus Quest 2 as our commodity tools with customized Unity scripts and Python software for data conversion, exchange and environment creation.

2.1.1. Data availability statement

The data that supports this study and findings, including source code and primary digital assets, are stored in a GitHub repository and made publicly available in https://github.com/MEC402/tetondamvr (DOI:10.5281/zenodo.4915654; Cutchin et al. 2021).

2.2. UAV remote sensing and high-resolution topographies for hydrogeologic modeling and Virtual Reality environment

The first step in generating a hydrogeologic and VR-ready model was to process drone imagery collected by Reclamation using SfM technology (Reclamation 2015). Using Agisoft Metashape^{TM} software (LLC, Agisoft 2006), over 10,000 geo-referenced photos were coaligned at high quality and mild depth filtering. Water reflection (glint) points and other outlier points were removed manually

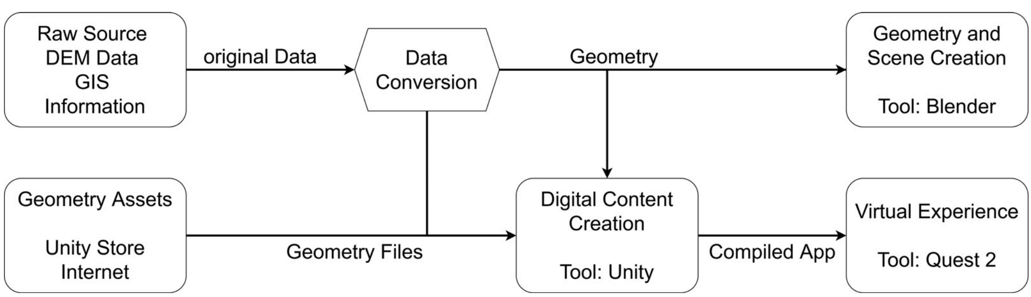

Figure 3. The system workflow diagram. The system workflow integrates raw source materials through conversion tools into commodity software tools for producing digital content that is delivered to VR devices for interactive viewing.

to ensure a hydro-flattened model. Following other iterative alignment optimizations, a dense point cloud (11.5 million points) was generated (AgiSoft 2018). A triangulated mesh was generated and a concomitant colorized texture was generated as a realistic and high-resolution terrain base. Several spatial extents and resolutions were investigated to ensure that we used a sufficiently high-resolution image while still performing at a high-level refresh rate. The terrain model was placed at the Teton Dam overlook, next to the left abutment. The drone photogrammetry flight included the current canyon overlook where visitors can see the site of the Teton Dam failure (Figure 4).

2.3. Mathematical model development

A 2D GeoClaw model and HEC-RAS model were the inspiration for the VR model construction (Spero 2021). GeoClaw (Clawpack Development Team 2020) is a 2D hydraulic modeling software that uses the depth-averaged shallow water equations SWE to simulate a propagating flood wave over topography using adaptive mesh refinement (Clawpack Development Team 2020). On the other hand, HEC-RAS (HEC-RAS 2021) (Hydrologic Engineering Center-River Analysis System) is a hydraulic modeling software developed by the US Army Corps of Engineers (USACE) and can use either the Full Momentum version of the depth-averaged SWE or the Diffusion version; the HEC-RAS Teton Dam model utilizes the Full Momentum equation set (e.g. Brunner 2016; Spero 2021). HEC-RAS is considered a standard for dam failure modeling and is accessible through a graphical user interface compared to GeoClaw, which is accessible through a command line. The GeoClaw model has been used to simulate two dam failures for validation including the Malpasset Dam failure and the Teton Dam Failure (George 2011; Spero and Calhoun 2020). For the Teton Dam model, it was validated for dam-break flood modeling through comparison with historical observational and gauge data (Chadwick 1976) and compared with the HEC-RAS model results (flood depth, flood wave arrival time, maximum flow depth, and lateral flood extent over a topography (Spero 2021).

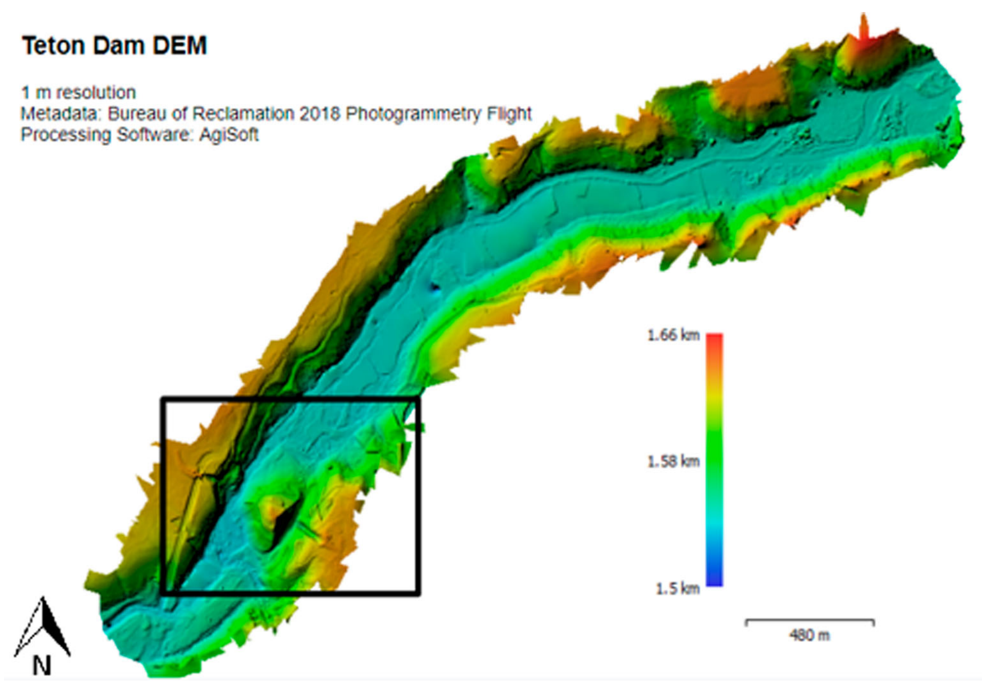

Figure 4. TetonDamPhoto.topo processed with AgiSoft MetashapeTM software into a Digital Elevation Model (DEM) at approximately 1m spatial resolution (elevation relative to sea level). The black box denotes the location of the Teton Dam site (Spero and Calhoun 2020). Data courtesy of Reclamation, UAS flight Reach 01 (Reclamation 2015).

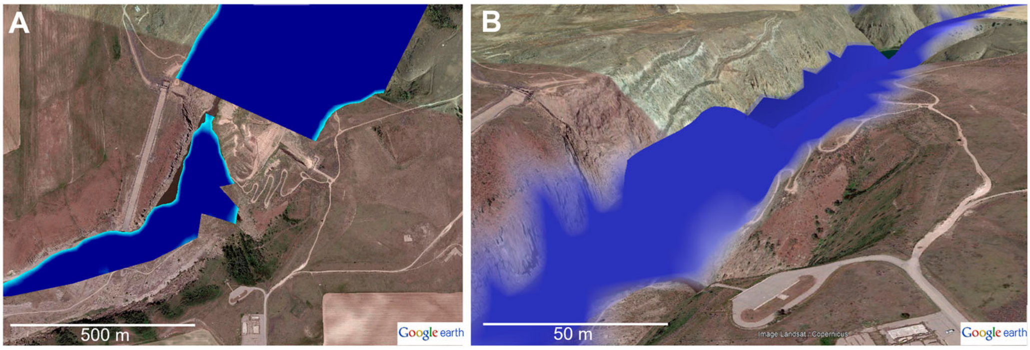

Figure 5. (A) HEC-RAS 2D model of Teton Dam Failure displayed on Google Earth. (B) GeoClaw 2D model of Teton Dam Failure projected in 3D from Google Earth, 2D pixels. The pixels stretch across Teton Canyon, but do not represent water in a meaningful 3D way. Models sourced from Spero and Calhoun (2020) and Spero (2021). These models are 2D SWE hydraulic models and therefore do not simulate debris or sediment (i.e. broken dam pieces), rather they inform the hydraulics portion of the research using an instantaneous breach analysis.

For VR applications, these two 2D models were used as the basis for understanding the flood wave interactions with local topography. The simulated VR flood also used historical data (photographic records of the breach geometry; Chadwick 1976) to inform the parts of the simulation not captured in the 2D models (Figure 5). The GeoClaw and HEC-RAS models provided a basis for understanding flood wave lateral extent and water surface elevation (depth of wave) fluctuations over time, which are critical data to generate a historically accurate 2D model validated 3D representation of the dam failure.

The results from these 2D depth-averaged shallow water solvers were exported and viewed on Google Earth as .KML files (.PNG images animated based on time-step output). Ideally, a workflow could take .KML files from the desktop version of Google Earth to Google Earth VR. However, although this would be an ideal workflow, there is currently no user ability or support from Google to open .KML or .KMZ files in Google Earth VR. Due to this limitation, this study used the 2D results to inform the 3D dam outburst flood by tracking the precise location of the flood wave with incremental time stepping.

Once the user enters the overlook, the Unity system settings trigger the VR simulation which begins 30 s before the dam failure and then depicts 15 s of dam failure involving blocks falling and the underlying dam eroding, before stabilizing to show up to an hour of the reservoir water flooding the canyon immediately downstream.

This study used the 2D models to inform the hydraulics portion of the 15 s of dam failure. In the numerical models, the first time step symbolizes the instantaneous failure of the dam. Using the first five time steps from both the GeoClaw and HEC-RAS models informed the VR simulation from the pulled .JPG results. Since the GeoClaw and HEC-RAS models used 10 m resolution and models were in 2D, the results were coarse. However, the results were high enough resolution to extrapolate into the third dimension manually in the Unity software using the textures. Thus, the quantitative numerical modeling results inform the VR model. Figure 5 shows the HEC-RAS 2D model and the GeoClaw 2D model results (.PNG on Desktop Google Earth), with the outburst flood wave.

2.4. Virtual Reality development methods

The VR environment development workflow generation consists of acquiring the terrain data, building fundamental structures, generating the animations, and exporting it to the Oculus Quest 2 headset. This workflow (Figure 6) can various hazards by adapting the key elements and terrain data to the desired environment.

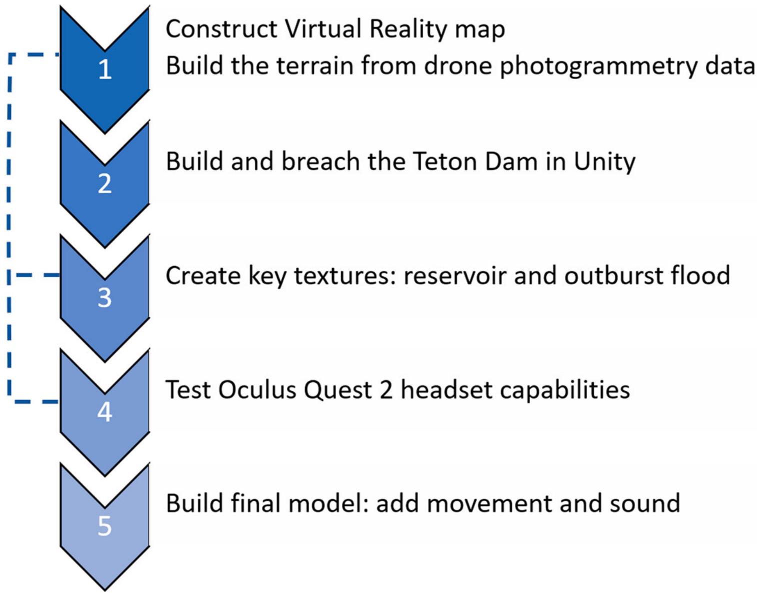

Figure 6. Chronological VR environment development workflow: top to bottom. (1) Construct the VR map using a terrain model generated from UAS SfM imagery. During this step, we determine the user locations and needed historical data. (2) This study builds and breaches the Teton Dam in Unity. (3) We create key textures for the reservoir water and for the outburst flood based on historical images. We also test different terrains when layering the textures in the environment. (4) Test Oculus Quest 2 headset capabilities include its ability to compile with high-resolution terrain; iteratively changing terrain and textures as needed. (5) Build the final model adding user movement and a soundscape.

2.4.1. Terrain generation and constructing the Virtual Reality map

The first two steps in the method (Figure 6) were to construct the VR map. This study used three terrains, because of varying terrain resolutions. This study sourced terrain from two USGS DEMs, but this data did not offer high enough resolution for realistic terrain or canyon definition based on pixel side (30 and 10 m; USGS 2015). Therefore, this study considered other options and a high-resolution photogrammetric terrain ('TetonPhoto.topo') was selected as the basis for the model (Figure 4). TetonPhoto.topo was generated from drone photogrammetry data as a part of the pipeline. For the VR map, we layered the three topographies with the lowest resolution on the bottom and the highest resolution terrain on the top. Then, we determined the user placement within TetonPhoto.topo, and necessary historical data for dam failure parameterization. This study used a three iteration method for refining the VR environment.

Methods for importing the terrain mesh onto the Oculus Quest 2 involved testing different domain sizes and resolutions to balance the enhanced speed of interaction of the headset and the demanding computational requirements. Although five terrains were iteratively tested, ultimately a small domain (15 m × 15 m) with low resolution (50 cm) was used; balancing resolution, domain size, and Oculus Quest 2 capabilities. This study begins by importing the mesh terrain as an '.obj' file (standard geometry file format for 3D models) into the Unity (Unity 2021) environment as the texture asset of the project. Unity has benefits and cross-platform capabilities, allowing our code and the VR environment to be adapted to multiple mixed reality platforms. Then, the texture is loaded into the center of the scene.

Consequently, the orientation and scaling of the mesh are often misaligned if one directly projects the texture onto the mesh. In this study, a new shader tool was generated, which casts the surface onto the mesh, which allows sliders to adjust the texture dimensions and orientation. This study aligns the RGB terrain image with the topography using terrain features such as the dam spillway and the remnants of the dam's shell and core.

2.4.1.1 Virtual Reality map. Designing the user experience first depends on the user placement and viewpoints, which depend on the terrain. For example, the viewpoint and movement area limits what the user will see and therefore, because some parts of the scene will never be visible, they can be discarded to decrease the environment's computational cost. The user placement determines which historical information can be presented and, subsequently, noticed and processed efficiently by users (Seinfeld et al. 2020). Determining the geographical context within the topographic domain allows the ability to emulate the historical dam failure disaster. For example, placing a user at the base of the canyon during the dam failure would affect perceived depth cues and the users' visuospatial information. Another parameter for selection user placement is the resolution of the terrain. For example, in 30 m resolution topography (downstream portion of the Teton Dam domain), the user would not be able to distinguish any natural features and the terrain would be flat in all directions. Therefore, choosing a location within the high-resolution TetonPhoto.topo was paramount.

In this study, the Teton Canyon overlook was chosen for user placement within the confines of the high-resolution terrain; a location next to the right abutment of the Teton Dam. At the right abutment overlook, users can detect visual stimuli such as the water movement in the reservoir and the outburst flood while not directly engaging with the flood water or evacuation behavior. The right abutment overlook also was the location of a local radio show broadcast that warned citizens downstream of the dam to evacuate when the dam breached 5 June 1976, at 11:57 am (BYU 2016). Therefore, this spot allowed for a unique soundscape implementation. Another motivation for choosing the overlook was that users can visit there in-person, and with the mobile headset, they could view the dam failure in VR space in the real-life position, rare in VR (as virtual worlds are often not related to the 'real' world). Allowing users to 'time travel' to 1976 and stand or sit in the same position as the Reclamation engineers is a unique aspect of this study.

2.4.2. Build and breach the Teton Dam

The task of creating and rendering the dam breach in VR can be broken down into three main steps:

(1) Create the scaled model of the Teton Dam
(2) Fracture the model into pieces to mimic the parts of the dam that broke off
(3) Construct a system to initiate the dam collapse (time-dependent)

This study conducts Steps 1 and 2 in Blender (Roosendaal 1994), a free, open-source 3D creation suite, and Step 3 in the Unity engine. The first step was creating the dam using reference pictures of the Teton Dam and historic blueprints (Figure 2) as a base for the scale and size of the dam. Then, this study used historical photos to generate an earthen texture for the dam's appearance to provide a realistic look (Figure 7).

The second step focused on fracturing the dam using a built-in tool in Blender called Cell Fracture. To fracture the mesh of the dam into hundreds of smaller pieces, this study composed several computationally intensive scripts which denoted a trigger zone and separated out individual pieces

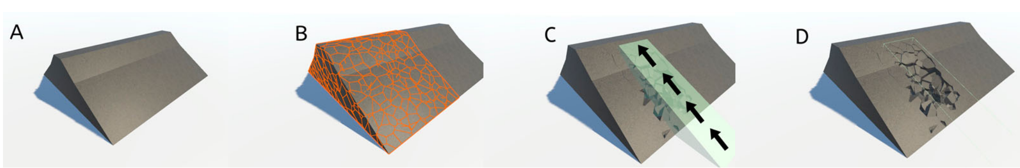

Figure 7. (a) Unfractured Teton Dam model created in Blender (b) Fractured dam model produced from Blender's Cell Fracture tool (c) Collapsing of the fractured dam model in Unity. The black arrows denote the direction the trigger zone is moving in relation to the dam. (d) The fractured pieces move downstream in the opposite direction of the black arrows (upstream).

of the dam; scripts are housed in the open-source repository associated with this study (Cutchin et al. 2021) (Figure 7(b)).

Further, for the third step, a script was created that runs during the simulation. The script moves a trigger zone towards the dam (Figure 7(c)). Every piece inside the trigger zone is pulled down and out of its initial position. The trigger zone would then cause the other nearby parts to break loose and simulate the dam collapsing. We modeled the VR dam breaching based on historical images and the outflow flood wave on 2D hydraulic models (GeoClaw and HEC-RAS). Simulating the dam's collapse with these three steps is the most efficient process for modeling large-scale fracturing involving many pieces,

2.4.3. Create key textures: reservoir and outburst flood

Various studies exist on the simulation of water in diverse environments within VR. However, the Oculus Quest 2 hardware (GPU) limitations do not allow for high computational costs. Therefore, this study used low computational techniques, which optimized the environment simulation performance at the cost of decreasing some of the quality. This study generated custom Unity shaders for the water flow and Unity's cloth system to shape the uncontrollable release of the impounded water. These custom shaders represent the flood after the dam breach and keep the computational cost low by eliminating the use of particle systems (Table 1).

For simulating the water flow for the outburst flood and underlying river, this study uses shaders to project two water textures on top of each other with different moving speeds in the same direction, which can provide a flowing water visual effect (Figure 1-E1; Supplementary File 1). On the contrary, the reservoir water (Figure 1-E2) does not have flow and only shows small waves. In this study, a sinusoidal texture movement is applied, rather than using one-directional movement. Since there is no data about the historical water height during the breach aside from historical photographs, this study manipulated the textures' normal vectors to shift the planes' vertex positions providing a more realistic water simulation.

A Unity cloth system was used to anchor vertices at the sides of the plane to fix them in place, at a similar angle to the historical flood wave. Then, the Unity cloth system was used to anchor vertices at the sides of the plane to fix them in place. However, the rest of the vertices were loose for movement. The environment gravity pulls down the vertices and generates a convex shape simulating the historical breach geometry.

Furthermore, we implemented two Unity particle systems in the VR scene. The first emulates water sprays at the dam's base simulating the dam-break wave front. The second particle system is located at the top of the dam, where the water passes through the partial breach. These particle systems were shaped and colored accordingly to simulate the water behavior at different locations. Then, as the active dam storage outbursts into the downstream canyon, turbulent river water is manufactured by water textures. The textures disperse in a semi-spherical shape, with the tan color representing the occurring advection, the sediment, and water mixing.

2.4.4. Build choices and model implementation on Oculus Quest 2 headset

The Teton Dam VR environment was tested on the Oculus Quest 2 VR headsets with 6GB of memory and a Qualcomm Snapdragon XR2 Platform as CPU. Oculus Quest 2 allows for both seated and

Table 1. This table summarizes the VR environment criteria evaluation for the Teton Dam case study.

Criteria	Model I	Model II	Final model
Refresh Rate	72 Hz	90 Hz	90 Hz
Particle Systems[a]	10 s × 5000 p	5 s × 1000 p	7 s × 1000 p
Terrain Resolution	35 mm	25 cm	50 cm
User Movement with Controller	No	No	Yes
User Hand Tracking	No	No	Yes
Terrain Size	15 m × 20 m	15 m × 20 m	15 m × 15 m

Note: [a]Terrain pertains to the size and resolution of TetonPhoto.topo – the terrain generated from drone photogrammetry. 's' stands for system and 'p' stands for particle.

stationary play and room-scale play. This study used player movement, both (i) allowing the user to move around the scene with the controllers in the static mode and (ii) letting the user walk around the scene in a 2.74 m × 2.74 m space with at least a 2 m × 2 m obstacle-free area. Therefore, this tool used universal design criteria to enable accessibility to various users with differing ability levels.

Although these specifications are state of the art among commercial VR headsets, for a photo-realistic rendering, it is weak. Therefore, to achieve the desired frame rate, we had to reduce the size of the terrain and switch to a shader-based water simulation rather than the particle-based one. However, we used a limited number of particles (170 per spray × 4 sprays = 680 particles) to add realism to the water when the Teton Dam breaches. In creating the water shaders to simulate the flood, this study was limited to Unity core shader components as Oculus Quest 2 only supports the core shaders in the Unity shader pipeline.

The soundscape consists of three overlaying sounds: a waterfall recording, Don Ellis radio broadcast from the Teton Dam overlook during 5 June 1976, and a white water river recording (BYU 2016). The sounds were overlaid and then inserted into the VR environment with the radio broadcast configured to play once the scene starts and a user enters the Teton Dam site. Furthermore, the soundscape integrates with the user proximity to the dam (ability to see the failure) and is synced then with the physical failure of the VR Teton Dam. It was critical to include the soundscape as it provides a clear cue for orientation and the user can establish self-presence (i.e. the user is cued when the dam will fail by the sound; Sutcliffe and Deol Kaur 2000).

2.5. Iterative improvements to Virtual Reality dam failure environment

Determining elements necessary to construct a convincing dam failure VR environment, iterations assessing realism were necessary and ultimately improved the model significantly. The lightweight model contained a low-resolution terrain, no soundscape or user movement (head rotation only), two textures (reservoir and resultant flood), and one particle system (Table 1). Although the model performed well, the simulation was unrealistic without sound, containing no indicators to orient users of the impending dam failure. VR environments require user autonomy and environment interaction. Therefore, the lightweight model was used to support iterative model improvement, ensuring rapid development of user autonomy.

The second model used a similar approach, but included: (i) higher resolution topography, (ii) user movement with two defined walking areas and cameras allowing multiple vantage points, and (iii) several small particle systems used at the interface of the two textures to model the sharp wave front originated by the sudden dam-break occurring as the dam failed. However, the second model lacked an audible indicator of impending dam failure to users; it would abruptly breach.

The third model oriented users using a soundscape, specified in VR space by proximity to the dam using the Oculus Quest 2 hand-held controllers for tracking within the environment (Figure 7). We used the simulation to measure the VR models inundation depth (base of the canyon to the height of the flood wave) upon the dam breaking based on the model scale and the VR reservoir model water surface elevation of the initial wave. We measured the wave's travel time by timing when the flood wave arrival time downstream 0.8 km, the Western edge of the VR user viewpoint. Once both values were within historical range, ±1 m compared to the historical value of 15.24 m depth and ±2 s for the arrival time of 5 s, respectively (Chadwick 1976), the model was considered sufficiently refined.

3. Results

This paper documents the dam failure VR pipeline, which interfaces various technologies to create a user-friendly environment that fully immerses the user into the environment in order to communicate the Teton dam hazard. As compared to Augmented Reality environments, the immersion of VR environments provide a higher presence sensation and therefore, the communication of the hazard is stronger.

We assessed specific elements necessary for a realistic dam failure VR environment from the iterative process to generate a model. The evaluation criteria for the Teton Dam VR model are summarized in Table 1. Specifically, this study analyzed three VR characteristics. First, we assessed the model's performance regarding the model components that allow for user presence: VR camera field of view of 90° to ensure a correct environment immersion and visualization within the device's limits, and soundscape to add audio feedback from Don Ellis (BYU 2016). Second, we evaluated the user perception model components, frame refresh rate, panoramic 3D displays of terrain. With higher resolution we would achieve a better environment visualization at the cost of computational cost, however, since we primarily evaluated our models over the Oculus Quest 2;, the screen resolution is fixed at 1832 × 1920 per eye. One of the most important aspects of VR is the environment's frame refresh rate. With a low refresh rate, wearing an HMD may induce motion sickness in the user thereby limiting the ability to communicate to a large audience. A high refresh rate ensures a smooth user experience with reduced motion sickness at the expense of computational cost so the selected 90 Hz balances low hardware requirements without a high impact on the user's experience. Third, we focused on user interaction with the environment through user movement with the controller and user hand tracking. Allowing the user to have free limited movement in the environment increases the immersion sensation and as a result, a better communication of the dam breach hazard.

The final Teton Dam VR model oriented users using a soundscape, specified in VR space by proximity to the dam using the Oculus Quest 2 hand-held controllers for tracking within the environment (Figure 7). We also compared the 2D numerical modeling results from HEC-RAS and GeoClaw to the VR water simulation system (the coupled particle system and textures). Additionally, the comparison between the historical data and the VR model for the arrival time downstream 0.8 km showed an arrival time of 7 s, within ±2 s of the historic 5 s. The flood wave depth is within ±1 m of 15.24 m value (Chadwick 1976), with calculations indicating a value of 16 m, as it reaches about $\frac{1}{6}$ from the base of the canyon to the top (107 m) of the flood wave; there is uncertainty in the calculation of this value of ±0.5 m. Additionally, from a visual comparison, the initial dam breach mirrors the historical blueprints and the lateral extent of the outburst flood.

Initial interactions with users indicate that the soundscape cues users to the impending dam failure, and the dam failure was realistic. Interacting with users also demonstrated that this VR environment could be a tool for improving understanding of hazards, improving community resilience. We define community resilience as the public's ability to anticipate hazards, adapt to changing conditions, and anticipate potential hazard scenarios because of improved scientific literacy (National Institute of Standards and Technology 2021).

4. Conclusions

Below we outlined the two technical questions of this survey and the associated conclusions. This freely available pipeline delineated in this paper allows non-specialists in computer science to take full advantage of this tool. This is reproducible research and results are recreatable.

(1) Can we create a VR pipeline using drone photogrammetry and VR methods informed by numerical modeling results?

This study indicates that VR is a technology that can be employed to simulate 3D dam failure. One step of the VR pipeline creation involved assessing the visualization capabilities of the Oculus Quest 2 headset and its limitations for processing for VR. This study indicates that VR is a technology that can be employed to simulate 3D dam failure. We produced a pipeline that takes historical images and terrain data as input to build a low computational cost VR environment to communicate the Teton Dam failure. The iterative assessments demonstrated that model realism could be achieved with high-resolution terrain, soundscape, user movement (walking areas and head movement), multiple vantage points, particle systems, and water textures (reservoir and resultant flood). In addition, the pipeline used the 2D GeoClaw and HEC-RAS hydraulic models to ensure timing similarities to the numerical simulation and the historical data. Although the 2D numerical models do not include the sediment or the failing dam blocks as they only model water, there were timing similarities. From the reservoir parameterization in VR and the 2D models, we see the canyon and water surface elevation scale aligned with the historical 15 m value (Chadwick 1976). For the VR scene, the flood wave flow produced values similar to those depicted in historical photographs and those in the simulation. The portion of the pipeline informed by the numerical modeling results showed similar visuals between the Unity environment, the HEC-RAS results, and historical photographs. Therefore, we can create a VR pipeline combining drone photogrammetry and VR methods efficiently that depicts accurate results.

As for compelling advantages and remaining limitations of this workflow, the Oculus Quest 2 headset was found to have limitations in loading and compiling the highest resolution terrains and processing an outburst flood composed of particle systems rather than textures. For an HMD, its accessibility balances with the limitations of the system framework. Another limitation of this workflow is that the limitation of this method is that the Unity game development environment loads the model mesh without any imagery or a texture file. An advantage of this workflow is that it was designed to reach more users at the cost of visualization quality, but has been considered realistic. For those interested in visual quality, the environment could be drastically improved (up to 3 cm), if the headset, or visualizing technology (AR or CAVE) could process at necessary speeds.

(2) Is VR technology capable of being a mechanism for teaching about dam failure? The final Teton Dam failure VR environment transports users to the Teton Dam overlook during the 5 June 1976 dam failure. Initial results demonstrated that the performance of the VR Oculus Quest 2 headset is satisfactory with the Teton Dam environment, on functionality and user–environment interaction based on user feedback. User feedback indicates that the soundscape induces emotional reactions aligned with a heightened perception of dam failure and realism. The integration of handheld controllers lends to user autonomy and potentially stronger body ownership in the fully immersive environment as the user is visually represented in the environment. Communication using VR requires a realistic environment. This study found the geo-referenced terrain, the Blender dam, the Unity features (water textures and environment), and soundscape simulate a natural dam failure environment on the Oculus Quest 2 HMD. To conclude, we analyzed the VR model to determine if the developed pipeline was capable as a communication tool. We focused on analyzing three VR characteristics to ensure we met high-fidelity criteria within the low computational cost environment. (1) We identified the model components that allow for user presence, composed of VR field of view, soundscape. (2) We focused on perception, affected by pixel density/eye, refresh rate, and panoramic 3D terrain displays -- size and resolution. (3) We focused on user interaction with the controller and user hand tracking (Table 1). At this stage, the pipeline demonstrates fidelity with the possibility of executing them in limited hardware devices such as HMD and mobile devices.

5. Discussion of future work

As a multidisciplinary study, goals moving forward encompass directions involving computer science, social sciences, and geoscience education. This study outlines its open-source workflow, so VR dam failure environments in addition to the Teton Dam can be constructed and used as communication tools with non-specialists. Therefore, goals branching directly from this UAS to VR disaster environment pipeline include (i) investigating the application of this workflow to other historic earthen dam failures and (ii) application to other flooding hazards like levee failure or failure of natural dams.

5.1. Improving existing Virtual Reality simulation

For improving the existing VR simulation of the Teton Dam failure, this study recommends a photo capture session at the Teton Dam site to improve the immediate topography under and around the users. Although the current Teton Dam VR environment allows for head tracking, fixed viewpoints, and positional audio contributing to a realistic simulation, the existing model can be enhanced with greater processing ability. The SfM terrain provided from UAS imagery, while agreeing with historic photos, was not collected for this purpose. Texture and topography capture for both simulation and visual modeling could further be improved with a UAS collection specifically for this purpose. An advantage of our workflow is that other 2D dam failure models that exist already have a skeleton framework (flood wave progression, wave depth, and arrival time) for the application of our VR model workflow. Future work could also concern modeling dams that have not yet failed or breached, communicating to legislators the threat that exists, and the potential hazards downstream.

5.2. Application to floodplain management

In the US, current methods for floodplain management communication focus predominantly on using maps to show citizens potential scenarios if flooding (or dam failure) would occur. For example, the FEMA flood risk communication tool kit leverages traditional communication strategies (newspapers, radio, television) in addition to 1D maps. Since current methods do not yet involve 3D communication methods, this novel VR pipeline (using (i) remote-sensing outputs, (ii) 2D modeling results, and (iii) VR technology) is an opportunity for flood hazard and flood risk management to communicate with the general public.

There is also an opportunity to further research into the overlap between disaster awareness and dam failure modeling with Early Warning Systems (EWS). With investment on many fronts (government, community, academic, businesses), it is critical to have cross-sector collaboration in exploring VR's potential to (i) personalize user risk, (ii) enhance risk perception and awareness, and (iii) improve community resilience through improved citizen preparedness and understanding of this hazard. From our pipeline, future work could determine where VR fits in the 'integrated system of hazard monitoring, forecasting and prediction, disaster risk assessment, communication and preparedness activities systems and processes' aspects of EWS (UN Office for DRR 2022).

5.3. Future technical work

As technology continues to improve, opportunities will exist for further use of the state-of-the-art textures and shaders (reservoir and outflow dam breach) created by this study. Textures could be used to simulate other dam failures in VR. For example in the US, one could model historic dam failures such as the Oroville Dam (California, US), the Ka Loko Reservoir Dam (Hawaii, US), and the Swift Dam (Montana, US). Worldwide, failures such as the Banqiao Dam (Henan, China) and the Panjshir Valley Dam (Kabul, Afghanistan) could also be modeled. This study also finds that, as current VR and GPU capabilities increase, the resolution of the virtual environments developed can become much more accurate and more realistic. The Oculus Quest 2 ran into issues running higher resolution environments as it relies on an on-board GPU, the size and weight of which is limited due to headset constraints. Other current generation VR headsets, such as the Valve Index and HTC Vive Pro 2, do not suffer from these issues and can run higher resolution environments. However, they require the headset to be tethered to a PC, thus they are not as portable and are more expensive in base cost and in cost of needed for a PC that can run them. In the future, the on-board GPUs will get better, thus allowing new untethered VR headsets to run better environments. Further, with advancements in VR hardware and more economical costs, simulating other earthen dam failures or flooding geohazards could use web services or other fundamental technologies such as cloud computing (parallel computing in a distributing computing architectural paradigm).

Dam failure hazards transcend organizations and traditional academic discipline-specific silos such as those posed by academia, industry professionals, and the general public. Key advancements in scientific research regarding dam failure need to be communicated to the public to improve science literacy and understanding. This study's findings provide useful insights into the value of using VR environments for disaster composition and communication, building on the original goals of Digital Earth. This methodology can synthesize historical data of a disaster into an interactive environment with the functionality available to different audiences. This paper outlines a workflow and open-source repository for 3D dam failure modeling and communication with minimal requirements or capabilities required. The Teton Dam failure VR simulation demonstrates the efficacy of the Oculus Quest 2 headset and the simulation. The stereoscopic graphics pop out at users, creating a unique experience (Figure 8). SfM terrain generation from UAS flights shows

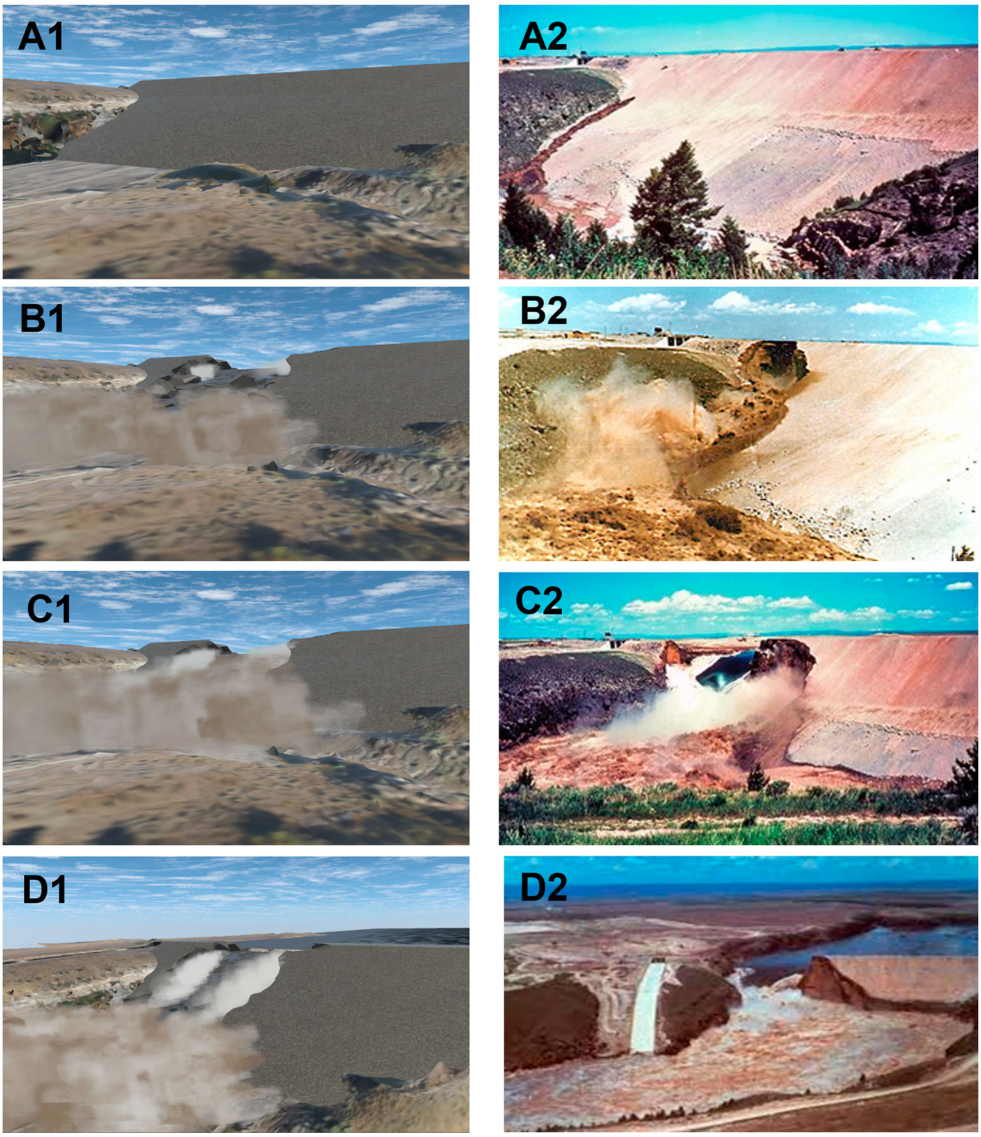

Figure 8. Time series of the Teton Dam failure in the VR environment where the terrain background in TetonPhoto.topo (as seen in Figure 4). The outburst flood wave is informed by the 2D numerical modeling data (Figure 5). In this series, (1) denotes the VR model and (2) denotes historical photographs sourced from Chadwick (1976). (a) 11:50 am before the dam failure, where the user can survey surroundings. (b) 11:55 am, the Teton Dam fails as chunks of the dam fall into the canyon. The reservoir begins to flood the 91.4 m deep canyon; the geometry of the dam failure portrays historical photos (1D) in 3D. (c) 11:57 pm depicts the dam post-failure as the reservoir continues to empty the reservoir storage downstream in agreement with historical archives. (d) 12:00 pm depicts the maximum breach of the dam with the left abutment completely disintegrated. Accessible at: https://github.com/MEC402/tetondamvr.

that inaccessible areas can be modeled in high-resolution and transport socioeconomically diverse groups to visualize disasters that have occurred remotely and hazards that could occur in remote areas. The system's sensory stimuli are realistic, the soundscape providing key sensory cues orienting users to the failing dam. The system's rendering display allows for an objective and measurable output simulation. Overall, our workflow is low cost and demonstrates the capability of representing the historical Teton Dam failure event. The immersive soundscape, immersion fidelity, and agreement with historical data contribute to real-world visual stimuli of the 1976 Teton Dam failure and exemplify the opportunity this workflow can provide to other reconstructions of dam failures.

Supplemental data

Supplemental data for this article can be accessed from the interactive WebGL environment http://mec402.boisestate.edu/teton—dam/ or by viewing the supplementary video file of the VR environment https://doi.org/10.6084/m9.figshare.17267783.

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