

Re-imagining River Basin Management through an Immersive Reality-Enabled Digital Twin – Dolo Ado, Somalia

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Levels of hunger and malnutrition are at record highs. Without urgent action, many more lives and livelihoods will be lost. Many of the 500 million small-scale producers who provide a third of the world's food on 83% of the world's farms are affected. With science, we can co-design the innovations they need to produce more and better food with fewer resources, adapt to the changing environment, and protect natural resources.

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Abstract

The Somali region of Ethiopia, particularly Dolo Ado, faces a volatile environmental landscape characterized by unpredictable weather patterns and severe flood risks that drive displacement and humanitarian crises. Traditional 2D mapping often fails to convey the visceral urgency required for effective decision-making. This study introduces an immersive, reality-enabled Digital Twin designed to bridge the gap between data forecasts and actionable decisions, specifically investigating the potential of Virtual Reality (VR) as a tool for Anticipatory Action (AA) in flood risk management.

The researchers employed a technical development framework centered on high-fidelity UAV photogrammetry and game engine integration. Data was acquired using a consumer-grade DJI Mavic Pro 2 drone to capture a 16.4 km² area of the floodplain with a Ground Sampling Distance (GSD) of 1–5 cm. To manage the massive datasets (>6 GB), the study utilized a rigorous optimization pipeline involving Blender for mesh polygon reduction and texture baking, reducing asset size to under 800 MB for real-time performance.

The simulation is powered by Unreal Engine 5.5.4, utilizing the Cesium plugin for dynamic terrain streaming. The system models two specific flood scenarios, the extreme flood events of November 2019 and the moderate flood of April 2023, visualizing not only hydrological data but also socio-economic impacts such as displacement and infrastructure damage.

The resulting Digital Twin offers dual-mode accessibility, functioning as both a tethered PC VR experience for high immersion and a desktop application for broader accessibility. By overlaying impact layers onto the 3D environment, the tool allows stakeholders to visualize the human dimension of flooding, shifting focus from abstract flow rates to tangible livelihood disruptions.

The study demonstrates that consumer-grade photogrammetry can generate high-relative-accuracy Digital Twins in resource-constrained settings, though it notes limitations regarding "Uncanny Valley" visual artifacts in photogrammetric meshes. To address these fidelity issues and move toward a fully operational system, the paper proposes integrating Procedural Content Generation (PCG) using Generative AI tools and connecting the system to real-time hydrological API streams (e.g., Hec-Ras) to transition from simulating past events to monitoring future risks.

Introduction

The Imperative for Anticipatory Action in the Somali Region the Somali region, nested within the Horn of Africa, faces a volatile security and environmental landscape. Its geographic location renders it highly vulnerable to climatic shocks, particularly in recent years where weather patterns have become increasingly unpredictable. Heavier precipitation events have resulted in growing water run-off, significantly heightening the risk of both flash floods and riverine flooding.

This environmental instability has severe humanitarian consequences. River floods occurring when water overflows riverbanks due to prolonged rainfall are currently one of the primary drivers of environmental migration in Somalia. As of January 2021, the Somali region of Ethiopia hosted over 884,000 internally displaced persons (IDPs) across 408 sites, a crisis driven partially by these climatic shocks. With approximately 2.8 million poor people at risk, Ethiopia is ranked as a global "hot spot" where poverty and vulnerability to flooding critically coexist.

Virtual Reality as a Decision-Support Tool

Virtual Reality (VR) has emerged as a powerful tool for bridging this gap. Research indicates that Immersive Virtual Reality (iVR) significantly increases users' accuracy in estimating flood risks and enhances their perception of danger compared to traditional 2D maps. VR simulations, often used as "Serious Games," offer a safe environment to train stakeholders in emergency response, increasing their self-efficacy and preparedness.

Despite these proven benefits, no VR simulation of this kind has previously been documented in the academic literature for the Somali region. This project addresses that gap by introducing an immersive, reality-enabled Digital Twin.

Study Area: Dolo Ado

The research is contextualized in Dolo Ado, located near the Ethiopia-Somalia border. This area is a critical focal point as it hosts significant refugees and host communities and is prone to seasonal flooding that disrupts livelihoods and infrastructure. Given the severe flood risk environment and the high density of vulnerable populations, Dolo Ado presents an ideal setting to test the efficacy of immersive technology in flood risk management.

Aims and Objectives

Primary Aim

The primary aim of this research is to examine the potential of Virtual Reality (VR) as a tool for Anticipatory Action (AA) in flood risk management. Specifically, the project seeks to determine if a VR-enabled Digital Twin can be effectively adopted by stakeholders in Dolo Ado to enhance their decision-making processes regarding flood preparedness and mitigation.

Specific Objectives

To achieve this aim, the study focuses on the following objectives:

- **Evaluate Stakeholder Perception:** To investigate how professionals in the public, private, and humanitarian sectors perceive the usefulness, trust, and efficiency of VR technologies for flood disaster preparedness.

- **Analyze Behavioral Responses:** To analyze user perceptions and behavioral responses to immersive flood visualizations, determining if VR experiences can effectively bridge the gap between data forecasts and actionable decisions.
- **Visualize Socio-Economic Impacts:** To move beyond physical water mapping by visualizing the human dimension of flooding including displacement, infrastructure damage, and livelihood disruption thereby fostering a deeper understanding of flood consequences among decision-makers.
- **Develop a Scalable Framework:** To demonstrate the technical feasibility of using high-resolution photogrammetry data and game engine (Unreal Engine 5) to create accessible, dual-mode high-fidelity (VR and Desktop) simulations for data-scarce regions.

Literature Review

Flood risk management in Somali region, Ethiopia

Somali's geographic location, nested within the Horn of Africa makes it vulnerable to security developments (Destrijcker et al., 2023). The Somali region's climate has been unpredictable over the past years with heavier precipitation resulting in growing water run-off heightening the risk of flash floods and river floods (Destrijcker et al., 2023). (Destrijcker et al. (quoted in The World Bank and UN Habitat) provides a critical perspective on the impact of climate change by informing how varied and more intense rainfall combined with drier soil will increase the risk of flooding, affecting agricultural production and livestock. Moreover, as of January 2021 the Somali region of Ethiopia is home to 884,642 internally displaced persons (IDPs) in 408 sites partially due to climatic shocks (Alexion et al., 2021). With 2.8 million poor people at risk of flooding, Ethiopia is ranked among the "hot spots" where poverty and vulnerability to flooding coexist in a 2022 study Legass et al. (2025 quoted in (Rentschler et al., 2022). With this information in hand, it is evident that flood risk management (FRM) is required to mitigate the devastating impacts of floods in the Somali region of Ethiopia. According Klijn et al., (2015) the definition of flood risk is not a straightforward one and may prioritize different variables according to the context in which it is used. Natural scientists view it as the probability of flooding in relation to the consequences of flooding, whereas social scientists frame a definition around the flood and the vulnerability of the area and society.

River floods are the most common and one of the main causes of environmental migration in Somalia, which happens when water overflows a riverbank due to a prolonged period of rainfall. (Momeni et al., 2022)

Anticipatory Action (AA) refers to acting ahead of a predicted hazard to prevent or reduce the impacts on communities before they fully unfold (Grace, 2024). This is very different from the actions taken after a disaster has occurred. Although natural disasters, such as floods, cannot be prevented, even if their occurrence is predictable, measures can be taken to mitigate their impact before they arise.

An example of this type of measure is vulnerability and exposure mapping through identifying high-risk communities, especially informal settlements, low-lying areas, or areas with poor drainage and incorporating socioeconomic data, such as poverty, disability, and access to infrastructure, to prioritize the most vulnerable for quick response.

Table 1: Comparison between responsive and anticipatory action (Chaves-Gonzalez et al., 2022)

	Responsive	Anticipatory
Timeline	After a shock	Before shock or peak impact
Basis for action	Observed humanitarian impacts	High risk of imminent shock and/or early indicators of weather impacts
Financing	Upon request	Pre-agreed
Activities	Selected to address currently existing needs, based on what is feasible and available at that point in time	Pre-agreed; timed to mitigate the impact of shock; additional time to plan may allow for a wider set of possible activities
Trigger	Needs-based: assessed humanitarian impacts	Risk-based: Pre-agreed levels of risk (predicted or observed)
Challenges	Aid delivery may be more difficult after a shock such as a storm or flood; beneficiaries may lack the resources to protect themselves against the shock itself (e.g., to move out of the danger zone before a storm)	Forecasts and risk/early warning data not available for all contexts or hazards; forecast skill or lead time may be insufficient; the situation on the ground may differ from the projection
Opportunities	Further acceleration of aid delivery Reduction in uncertainty on the specific nature, scale, location of impacts	Lead time enables consultation and inclusion of communities in planning Earlier aid delivery empowers local people to decide and act on the best way for them to respond to the shock

Vulnerability and exposure mapping is an important method to inform AA for flood risk management, however in the recent years, there has been a search for identifying ways for a better representation of hazard, vulnerability, and exposure, along with spatial science (e.g. GIS: Geographic Information Systems) which is even more difficult for floods because of the reduced preparation time after rainfall (Alves et al., 2021). The end-user of these technologies should also remain inclusive and accessible to flood victims, as one of the challenges in implementing AA are gaps in knowledge and skills according to a study by (Weingärtner et al., 2022). There is an opportunity to improve and find new ways to better visualize flood risk scenario, a gap this research study seeks to contribute to.

Virtual Reality (VR) applications in flood risk management

There is a rising increase in the use of Virtual Reality (VR) Digital Twin's (DT) to aid in floods in risk for anticipatory action., early warning systems and early response. DT's are virtual representations of real-world objects or environments.

Prevalent examples of VR used in similar research include Simpson et al. (2022) study on immersive storm surge flooding and using VR as a tool for risk perception. The results of the study showed that IVR (immersive Virtual Reality) increased users' accuracy when estimating flood heights in the real-world case studies.

D'Amico et al. (2023) study focused on a non-immersive VR Serious Game (SG) to improve' knowledge and self-efficacy in case of a flood disaster by subsequently increasing awareness around safety during floods and understanding associated human behavior. The study concluded that VR and Serious Games SGs training offer powerful tools to prepare users for disasters and improve their emergency response by providing immersive, engaging, and safe methods of learning.

Mol et al. (2022) uses immersive VR to examine whether a simulated disaster can stimulate people to invest in risk reducing measures in the context of flooding. The study found that one potential way to increase risk perception is to use VR simulations of floods.

Panggabean (2023)'s study on a VR flood disaster simulation. Findings reported that the VR flood simulator succeeded in increasing players' awareness and preparedness in dealing with flood disasters. Oyishi et al. (2022) FloodVis offers a means of visualizing possible future flood risks in VR. User can enter a virtual surrounding to interact with the data, examine the temporal evolution, and compare alternative development pathways. Conclusions of the research are that this type of visualization can enable the sense of presence, and this might be an asset helping people to prepare for the worst. None of the participants in the study disagrees with this statement.

Based on the positive feedback from previous case studies of VR flood simulations that have been produced through empirical research, have surveyed participants and identified areas of improvement for better results, this can be an innovation worth undertaking in the context of the Somali region who have battled with the flood issue. Especially given that no VR simulation has been found in academic literature in the Somali region. This research will this be the first of this kind in this region adding to its novelty.

Dolo Ado Town Flood Risk Management

Dolo Ado is located near the Ethiopia-Somali border and is home to many refugee and host communities. With 300-500 mm annual average rainfall and 20-45 degrees Celsius range of temperature, the Somali region climatically falls in either semi-arid or arid zones. (Betts et al., 2021)

Strong rains can lead to localized flooding in one part of a region while another simultaneously experiences drought.

Dollo Ado and Dolo bay are some of the districts that host flood induced internally displaced people (IDPs) on a seasonal basis. (Easton-Calabria et al., 2023)

Since 1990, Somalia has endured over 30 extreme weather events, encompassing 12 droughts and 19 floods, triggering two significant famines in 1991–92 and 2011. These disasters led to more than 3.2 million new displacements (Momeni et al., 2024). The 2025 Somalia Humanitarian Needs and Response Plan estimates that 5.98 million people will need assistance in 2025. It will require US\$1.4 billion, a 10 per cent reduction from 2024 (OCHA, 2024). The flood risk environment of Dolo Ado town in Somali make it a good setting to conduct this research study in as it is a place that could really benefit from an intervention of this kind.

This research seeks to examine the potential of VR for AA for floods in Dolo Ado for stakeholders to adopt as part of their decision-making process.

Methodology

This study employed a technical development framework focused on creating a high-fidelity, immersive Digital Twin for the Dolo Ado region. Data collection, cloud point data optimization, and the incorporation of hydrological situations in a real-time game engine environment comprised of the methodology's structured pipeline.

Data Acquisition: UAV Photogrammetry

To generate a high-fidelity 3D terrain model of the Dolo Ado floodplain, an extensive aerial survey was conducted using Unmanned Aerial Vehicles (UAVs).

- **Instrumentation:** Data was captured using a DJI Mavic Pro 2 equipped with an RGB sensor for geotagged imagery. While the platform is non-RTK (Real-Time Kinematic), it was selected for its agility and ability to produce high relative accuracy and strong local shape fidelity.
- **Flight Parameters:** Flights were conducted at a low altitude of approximately 100 meters Above Ground Level (AGL) (approx. 330 ft) to achieve a Ground Sampling Distance (GSD) of 1–5 cm. This centimeter-scale resolution was critical for capturing floodplain micro-topography and settlement features essential for accurate flood modeling.
- **Mission Planning:** The survey covered a large volume area of approximately 16.4 km², prioritizing flood corridors, riverbanks, and vulnerable infrastructure (specifically east of the main road) over general coverage.
 - **Block-Based Acquisition:** To manage the massive dataset (approx. 47,287 images, ~460 GB), the mission was structured into ~22 mapping blocks. This block-based approach ensured consistent lighting conditions, maintained sufficient forward/side overlap to reduce occlusions in dense vegetation, and kept processing batches tractable.

Photogrammetric Processing & Optimization

The raw aerial imagery was processed using DroneDeploy to generate the core geospatial outputs: a dense point cloud, an orthomosaic, and a Digital Surface Model (DSM).

- **Quality Control (QC):** A rigorous manual QC process was implemented prior to processing. Images with motion blur, exposure outliers, or those dominated by low-texture surfaces (such as open water) were removed to prevent noise and voids.
 - **Water Surfaces:** Recognizing the inherent weakness of photogrammetry over transient, specular water surfaces, the reconstruction focused on hydraulically meaningful edges riverbanks, embankments, and channels where stable geometry is most critical for flood modeling.
- **Iterative Reconstruction:** Processing was executed in blocks (approx. 10,000 images per batch) to minimize failure risk and improve stability. The workflow involved camera calibration, bundle adjustment, and dense reconstruction. Where warping or seam artifacts appeared, input data was revisited and pruned rather than relying on downstream "fixing."
- **Output Generation:** The primary output was a high-density point cloud. However, the initial photogrammetry data was extremely heavy (>6 GB with >100 texture maps), rendering it unfeasible for direct import into a real-time VR engine.

Technical Framework

Data Pipeline & Preparation

Terrain & Environment

The IWMI VR flood visualizer (Figure 1) starts with a strong base of terrain and environmental data from high-resolution **UAV photogrammetry** of the Dolo Ado area, collected by Mitchell McTough, Sandra Ruckstuhl, Abdulkarim Seid, Alemseged Tamiru Haile, Meron Teferi Taye, Elizabeth Wamba (McTough et al., 2025). The scans are rich elevation data and are processed into optimized 3D meshes for real-time rendering. Since the initial photogrammetry data was extremely big (>6 GB) and was accompanied by more than 100 texture maps, importing it directly into Unreal Engine would have been unfeasible, both from a performance and memory standpoint. Moreover, the raw meshes obtained from point clouds had very high vertex density and were not suitable for VR, where frame rate is paramount.

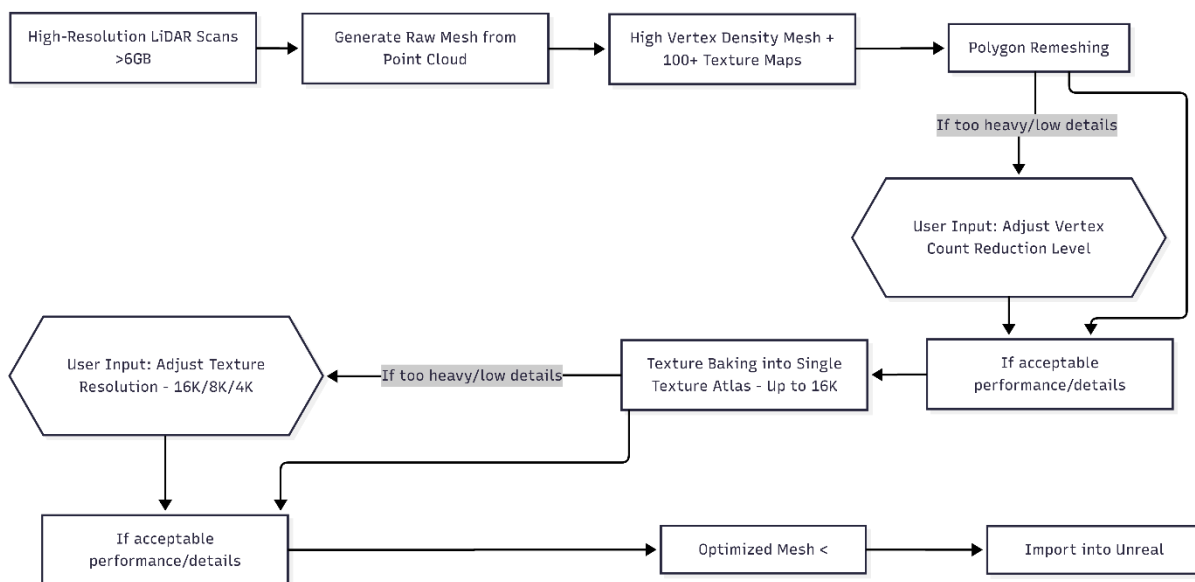


Figure 1: Point Cloud pre-processing system pipeline

To address this, the following post-processing pipeline was applied. It is detailed in step-by-step guideline as follows:

Mesh Optimization

The original high-poly mesh was polygon-reduced and retopologized using Blender remeshing tools by applying Smooth Normals modifier as, retaining key terrain details while dramatically lowering the vertex count.

Reduce the "High Vertex Density Mesh" to a manageable polygon count without losing the silhouette of the terrain.

Import Raw Data:

- Import raw mesh (OBJ/FBX) into Blender.
- *Note:* Ensure scene units are set correctly (usually Metric) to match Unreal Engine scale.

Duplicate for Baking (Source vs. Target):

- Defining the imported mesh to High_Poly_Source
 - Duplicate and redefine the copy to Low_Poly_Target since it needs the original High_Poly_Source to bake the high-quality details onto the optimized mesh later.

Polygon Reduction (The "Remeshing" Step):

- Select Low_Poly_Target, add a **Decimate Modifier** (Mode: *Collapse*), and adjust the **Ratio** to balance detail with vertex count before applying. Ratio: Reduce the ratio (e.g., 0.5 for 50% reduction, 0.1 for 90%).
- User Input Loop (from diagram): Check the viewport wireframe. If the terrain looks too blocky, increase the ratio. If it is still too heavy (high vertex count), decrease it.
- Apply the modifier when satisfied with correct geometry alignment (edges, vertices and faces)

Smoothing Normals:

- Apply **Shade Smooth**, enabling **Auto Smooth** in Data Properties if shading artifacts occur.

Texture Baking:

All the original texture maps were combined into one 16K texture atlas. This maintained visual detail while drastically lowering draw calls in Unreal Engine.

UV Unwrapping the Optimized Mesh:

- applying **Smart UV Project** with a small margin (0.001–0.01) to organize the layout and prevent bleeding on the selected Low_Poly_Target.(Figure 2)

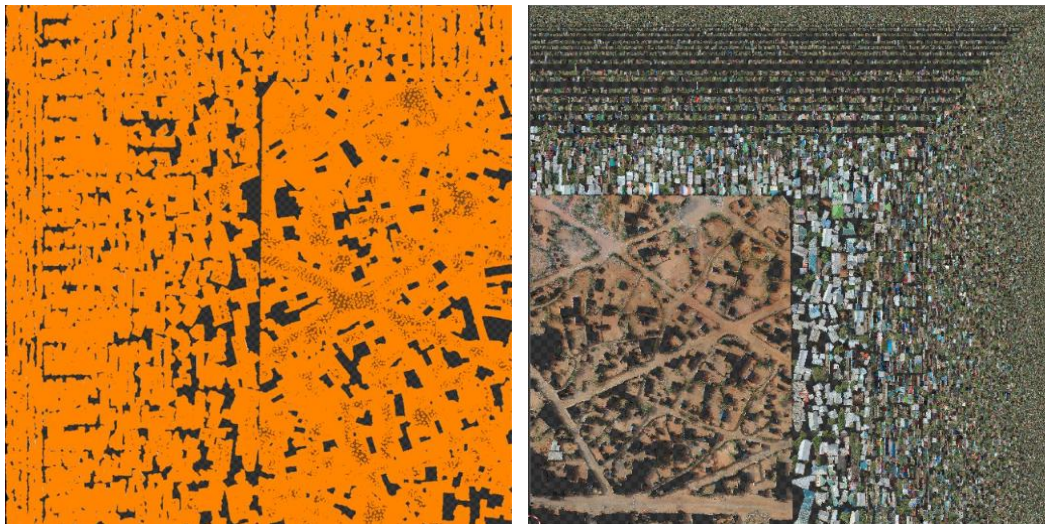


Figure 2: 16K texture compression into single output image

Preparing the Destination Material:

- Create a new material in the Shader Editor containing a disconnected, **selected Image Texture Node** set to your target resolution (e.g., 16K).

Final Asset Packaging:

The mesh, now less than 800 MB in size, retained the fidelity required for flood visualization but was lightweight enough for Cesium streaming and real-time VR playback.

The integration of Cesium into Unreal improves terrain management by dynamically streaming only the tiles that are currently visible, allowing for efficient visualization of extensive geographical regions without taxing.

The following image (Figure 3) depicts the preprocessed point cloud resulting in a well topologized single 3D mesh.



Figure 3: Finalize 3D Mesh with a compact texture preset (Preprocessed)

Flood Event Data

For the simulation, the authors conducted an extensive search for reliable reports, publications, and news articles documenting flood events in the Dolo Ado area. Because the region has very few hydrological monitoring stations nearby, official datasets on flood levels and impacts are limited, especially for precise local measurements. As a result, much of the information had to be gathered from regional field assessments, hydrological summaries from upstream stations, and community-level impact studies. After compiling and cross-checking these sources, two significant flood events, in November 2019 and April 2023, were selected as primary scenarios. Each event was processed to include parameters such as estimated river height, water spread, affected population, and damage. These were then structured into scenarios within the VR environment, allowing users to explore each event's extent and socio-economic impacts in an immersive, decision-support context.

Engine & Platform

Unreal Engine 5.5.4 powers the VR visualizer, offering state-of-the-art graphics rendering, physics simulation, and VR support. Its robustness allows for the seamless integration of heavy assets such as photogrammetry scanned

terrains, while also enabling real-time interaction and high-fidelity visualization crucial for immersive flood simulations.

The application is built to run on a Windows PC with a powerful GPU, ensuring smooth rendering and real-time interaction even with large datasets. Users interact with the simulation through a tethered PC VR headset, which provides a high-immersion experience without overburdening the headset's internal processing. Alternatively, the PC's output can be cast to the VR headset, maintaining performance while delivering a rich visual experience. This setup also prepares the system for future scalability, as more data and advanced features are added.

System Requirements

VR Application (Meta 3/PC VR)

Recommended Requirements

- Operating System: Windows 10/11 (64-bit)
- Processor: Intel i5-10400 / AMD Ryzen 5 3600 or better
- Graphics Card: NVIDIA GTX 1660 Ti / RTX 2060 or AMD RX 5600 XT or better
- RAM: 16 GB or more
- Storage: SSD with at least 20 GB free space
- Connectivity: USB 3.0 + stable internet (for Cesium streaming)

Desktop Application (Non-VR, runs on Intel integrated GPU)

Recommended Requirements

- Operating System: Windows 10/11 (64-bit)
- Processor: Intel i5 or newer
- Graphics Card: Intel Iris Xe / entry-level NVIDIA or AMD GPU
- RAM: 8 GB or more
- Storage: SSD with at least 15 GB free space
- Display: 1080p or higher monitor

Architecture is designed with future growth in mind. Larger photogrammetry data areas can be seamlessly added thanks to Cesium's tile-based streaming. Additionally, Unreal Engine's GPU computing capabilities allow for future integration of fluid simulations, which will enhance realism by modeling the physical behavior of floodwaters. These scalable features ensure the platform can grow in complexity without sacrificing user experience.

Navigation & Controls (Figure 4)

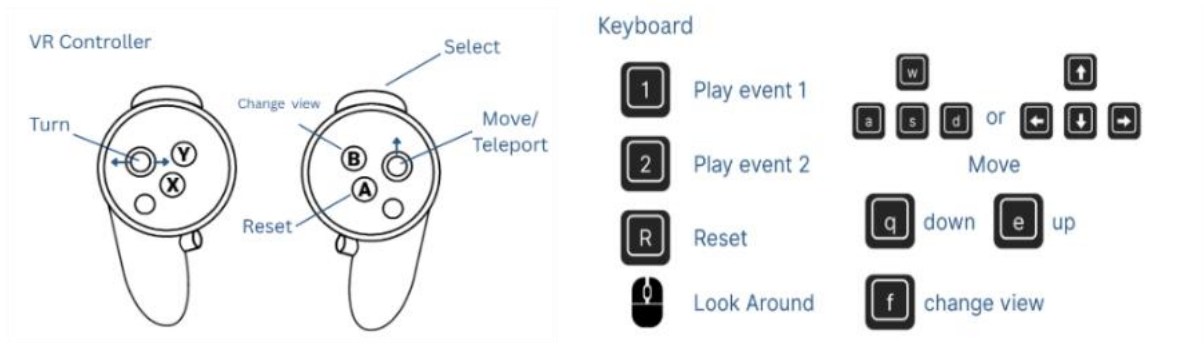


Figure 4: Key controllers outline with key bindings

VR Mode

In VR mode, intuitive controller-based navigation enhances user engagement. Users can teleport for smooth locomotion, minimizing motion sickness and allowing for fast movement across the terrain. Snap rotation provides comfort during exploration, and key functions such as event selection and position reset ensure that users remain oriented and in control. A scenario selection widget is embedded into the VR experience, allowing users to interact with the content naturally and efficiently.

Desktop Mode

For users without VR headsets, desktop mode provides a comparable experience using keyboard and mouse controls. Standard navigation keys (WASD and arrow keys) allow free movement, while function keys trigger scenario playback, vertical movement, view changes, and scene resets.

This dual-mode functionality ensures the application is accessible to a wide range of stakeholders, regardless of hardware availability.

Visualization Features

Flood Scenarios

The application currently includes two flood scenarios: the November 2019 extreme flood and the April 2023 flood (Figure 5). These scenarios are designed with distinct flow rates and corresponding assumed water heights to give users contrasting experiences of flooding severity.

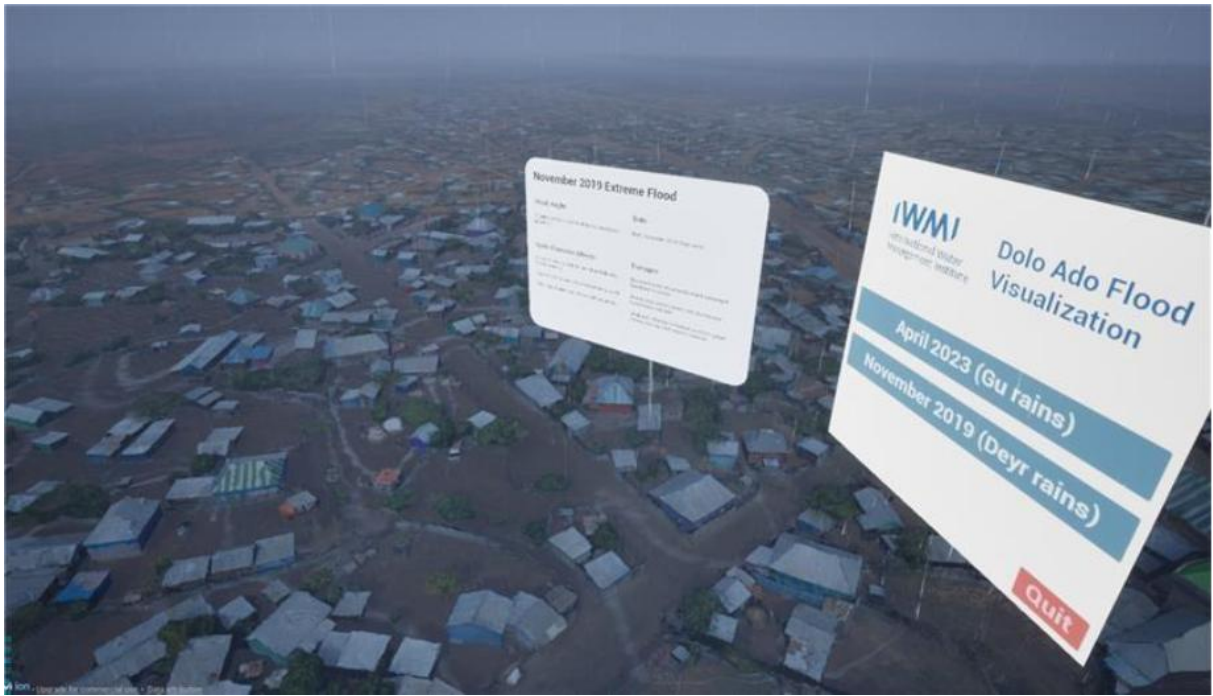


Figure 5: Scenario Selection in the demonstration of the Flooding events

- **April 2023 (Normal Flood):** Assumes a flow rate of $\sim 250 \text{ m}^3/\text{s}$, corresponding to an estimated water rise of around **2 m above bank level**. This represents a more moderate flood, allowing users to experience a “typical” high-water event.
- **November 2019 (Extreme Flood):** Assumes a flow rate of $\sim 400 \text{ m}^3/\text{s}$, corresponding to a significantly higher estimated water rise. This visualizes an extreme flooding situation where riverbanks are breached, farmlands are inundated, and widespread displacement occurs.

Because the Dolo Ado area has very limited direct hydrological observations (e.g., no reliable stage height records from nearby monitoring stations), these heights are assumed values derived from flow depth relationships and proxy information such as reports, satellite imagery, and photogrammetry scan-based terrain models. The two levels serve primarily as mock solutions to demonstrate how VR can visualize both normal and extreme floods, rather than as precise measurements of past events.

In addition to hydrological visualization, the authors have integrated **socio-economic impact data** into each event. This includes agricultural losses, infrastructure damage, household displacement, food security risks, and health outcomes. By pairing the physical flood scenarios with their corresponding social and economic consequences, the VR experience emphasizes the **human dimension of flooding**, showing not only where water rose, but also how it disrupted livelihoods, reduced harvests, displaced families, and increased dependency on aid.

The objective of the project is to showcase the capability of VR as a tool for visualizing both the physical dynamics and the socio-economic effects of floods. When higher-resolution or gauge-based datasets become available, these assumptions can be updated easily, enabling the simulation to transition from a demonstration model to a fully data-driven decision-support system.

Information Delivery

To enhance comprehension, each scenario is accompanied by voiceover narration that explains what happened and why it matters. These narrations are designed for non-technical users and include important details about flood impacts. Additionally, a visual UI panel presents structured information, such as flood heights, timelines, affected populations, and infrastructure damages, making it easy to digest critical data.

Impact Layers

Visual impact layers overlay flood-related information onto the 3D environment. These include water rise visualizations, displacement maps, and socio-economic effects such as damage to infrastructure, agriculture, and health services. This layered approach enables users to visualize multiple dimensions of a flood event simultaneously, enhancing understanding and engagement.

Future enhancements are planned to increase realism and interactivity. Fluid simulations will model real-time water behavior, providing a physically accurate depiction of flood movement. A timeline slide will enable users to scrub through the timeline of each flood event to observe progression and retreat. Map overlays showing risk zones and vulnerability indicators will further support decision-making and planning.

Performance & Optimization

Terrain Streaming via Cesium

The use of Cesium's dynamic terrain streaming ensures that only the necessary portions of the terrain are loaded into memory. This allows the application to render high-resolution environments without overloading the system, making it ideal for VR use where frame rate and performance are critical.

Prepared for Larger AOIs

The platform is designed to handle larger Areas of Interest (AOIs) beyond the initially scanned regions. Streaming tiles from adjacent areas enable the visualizer to scale up to regional or national flood scenarios without significant performance loss. This ensures flexibility for future applications that may require broader geographic coverage.

High-Performance Hardware

To support the computational demands of VR, high-resolution terrain, and fluid dynamics, the application runs on high-performance PCs equipped with capable GPUs. This hardware setup not only ensures a smooth user experience but also prepares the system for upcoming features such as real-time fluid simulations and the integration of even larger datasets.

The VR Flood Visualizer provides a technically robust and immersive platform for visualizing past flood events in the Dolo Ado region. Its foundation on photogrammetry and real flood data, coupled with scalable architecture and high-performance rendering, makes it an essential tool for flood risk awareness, stakeholder training, and anticipatory decision-making. With planned features like fluid simulation and expanded AOI coverage, the tool is positioned to support broader applications in disaster risk reduction and environmental planning.

Discussion and Learnings

Enhancing Situational Awareness and Risk Perception

The primary contribution of this study lies in its shift from traditional 2D static mapping to immersive 3D visualization. It is expected that the use of high-fidelity VR will lead to a statistically significant increase in "perceived risk" among stakeholders. Unlike flat displacement maps, the immersive model allows users to experience the scale and depth of inundation relative to local landmarks, fostering a more visceral and accurate understanding of flood urgency.

Viability of Consumer-Grade UAVs in Resource-Constrained Settings

This study critically evaluates the trade-off between absolute geodetic accuracy and visual fidelity in humanitarian data capture. While photogrammetry scan-based aerial surveys offer superior penetration of vegetation and water surfaces, their cost and logistical complexity often render them inaccessible in fragile contexts like Dolo Ado. Our results demonstrate that consumer-grade RGB photogrammetry (e.g., DJI Mavic Pro 2), when executed with a rigorous block-based flight plan and high overlap (>75%), can yield centimeter-scale Ground Sampling Distance (GSD) sufficient for effective flood visualization.

However, this approach presents distinct technical limitations regarding hydrological features. The inherent specular reflection of water surfaces resulted in "noise" and geometric voids in the raw point cloud, necessitating a manual "hydro-flattening" post-processing step to ensure hydraulic credibility. Despite this manual overhead, the workflow proves that high-relative-accuracy Digital Twins can be generated without prohibitive capital investment, effectively democratizing access to high-resolution flood risk data for developing nations.

Technical Standardization for Data-Scarce Environments

A significant output of this research is the development of an optimized data pipeline for humanitarian settings. By demonstrating how raw, heavy photogrammetry scans can be optimized through decimation, baking, and streaming via the Cesium for Unreal plugin, this paper contributes to a repeatable technical blueprint. This allows other researchers to deploy high-quality Digital Twins in regions with limited high-speed internet or specialized hardware.

Strengthening Anticipatory Action (AA) Triggers

This work expects to provide a visual bridge for "trigger-based" financing. By visualizing specific community-informed flood scenarios (April 2023 vs. November 2019), the tool serves as a pedagogical asset for policymakers to pre-approve/renovate financing protocols. For example, re-evaluating prevailing infrastructure solutions for that AOI. Seeing the potential breach of a specific riverbank in a VR environment makes the abstract numbers of a forecast (e.g., cubic meters per second/ flow rate) immediately actionable.

Current Limitations on Maintaining Authenticity and the Fidelity of the Environment

While the photogrammetric reconstruction provided a high-accuracy terrain model, a significant limitation observed was the "Uncanny Valley" effect, a phenomenon where realistic but imperfect 3D renders trigger cognitive dissonance in users. Despite centimeter-level accuracy, the drone-derived mesh often displayed "melting" artifacts on vertical structures (e.g., building facades, vegetation) and noisy textures on water surfaces. These visual imperfections can break the immersion for stakeholders, shifting their focus from the risk (the flood) to the glitch (the melted house). To bridge the gap between "data accuracy" and "visual believability," this research proposes a transition to a new dimension with Procedural Content Generation as a next step.

Conclusion and Future Directions

Synthesis of the Technical Framework

This paper presents a robust conceptual and technical framework for re-imagining river basin management in the Dolo Ado region. By integrating advanced game engine technology (Unreal Engine 5) with localized hydrological scenarios, the project has successfully created a "Reality-Enabled Digital Twin." This tool addresses the chronic gap between humanitarian data and human decision-making, offering a platform where displacement risks and infrastructure vulnerabilities can be visualized before they occur.

Methodological Limitations

It is acknowledged that the current iteration relies on community-reported historical flood markers rather than the actual sensor data retrieved by the gauges situated in that specific region.

The path toward a fully operational, real-time Digital Twin for the Somali region involves three critical steps:

Maintain Realism and Fidelity:

Since drone mapping is limited in resolution when generating and refining it into a fine 3D mesh, it lacks visual appeal as expected (Figure 6). Hence, adopting novel frameworks related to Procedural Content Generation (PCG) would be the ideal solution, utilizing high-resolution 3D assets generated using open-source Gen AI tools (Tencent Hunyuan 3D, n.d.)

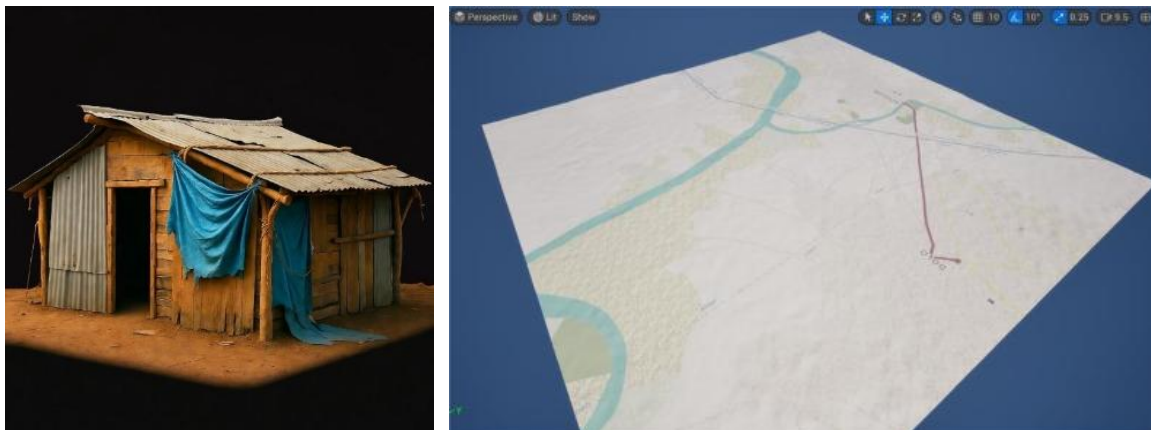


Figure 6: Procedural Biome and Content Generation using Gen AI tools in Dolo Ado

Automating Asset Placement via Point Cloud Classification:

To address the "melting" artifacts observed in vertical structures and fully leverage the potential of Procedural Content Generation (PCG), future development will incorporate a semantic classification pipeline using MATLAB's Lidar Toolbox. While the current photogrammetric mesh provides a continuous visual surface, it lacks the semantic distinction required to separate the "ground" from "buildings."

By utilizing the Simple Morphological Filter (SMRF) algorithm and terrain classification techniques available in MATLAB (MathWorks, n.d.), the project aims to algorithmically segment the raw point cloud data into discrete

classes: ground, vegetation, and buildings. This process will allow for the automatic extraction of building footprints and centroids, specifically targeting refugee camp tents and resilience infrastructure.

Once classified (Figure 7), these spatial coordinates will be exported as structured data points to drive Unreal Engine's PCG framework. Instead of relying on the low-fidelity photogrammetric mesh for shelter representation, the engine will use these data points to procedurally spawn the high-fidelity, GenAI-created 3D assets at their exact real-world locations.

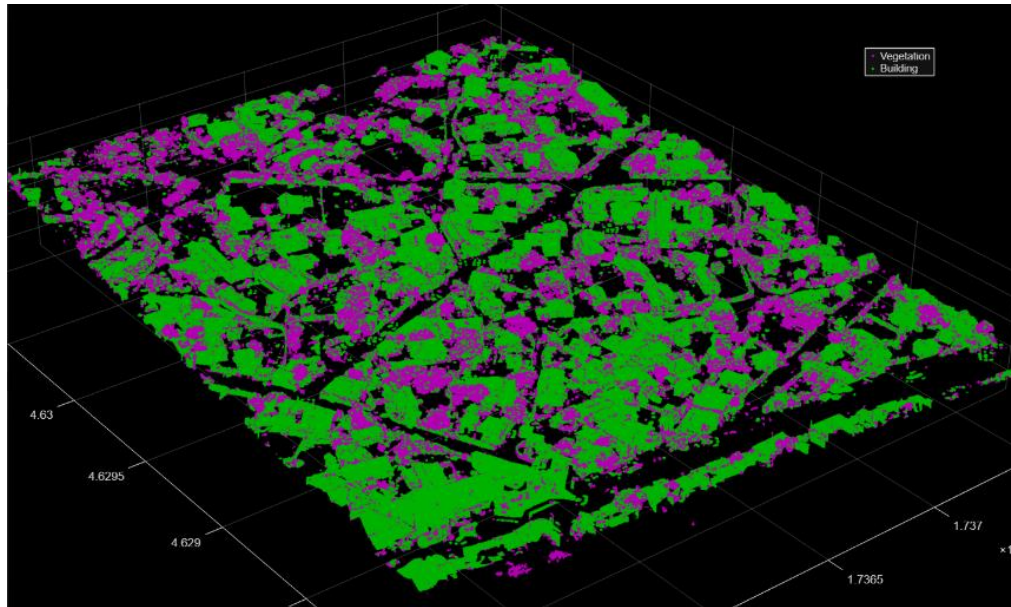


Figure 7: Point cloud classification trials

Real-Time API Integration:

Future development will prioritize connecting the Unreal Engine blueprint to live data streams, such as the Hec-Ras model Integration. This would transition the tool from a "simulation of past events" to a "live dashboard of future risks."

Socio-Economic Layering: There is a need to integrate deeper socio-economic metadata, such as gender-disaggregated displacement statistics and crop maturity levels, to visualize not just the presence of water, but the exact cost to human livelihoods.

Conclusion

In an era of increasing climate volatility, the ability to anticipate and visualize disasters is essential for resilience. This Digital Twin framework represents a critical step toward inclusive, data-driven, and proactive water resource management in one of the world's most climate-vulnerable regions.

References

- Alves, P. B. R., Djordjević, S., & Javadi, A. A. (2021). An integrated socio-environmental framework for mapping hazard-specific vulnerability and exposure in urban areas. *Urban Water Journal*, 18(7), 530-543.
- Betts, A., Omata, N., & Sterck, O. (2021). Transnational blindness: International institutions and refugees' cross-border activities. *Review of International Studies*, 47(5), 714-742.
- Chaves-Gonzalez, J., Milano, L., Omtzigt, D. J., Pfister, D., Poirier, J., Pople, A., ... & Zommers, Z. (2022). Anticipatory action: Lessons for the future. *Frontiers in Climate*, 4, 932336.
- Creswell, J. W., & Creswell, J. D. (2017). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage publications.
- D'Amico, A., Bernardini, G., Lovreglio, R., & Quagliarini, E. (2023). A non-immersive virtual reality serious game application for flood safety training. *International journal of disaster risk reduction*, 96, 103940.
- Easton-Calabria, E., Ahmed, A., Mohamed, D., & Singh, A. (2023). Anticipatory action in complex crises: lessons from Ethiopia.
- Grace, J. (2024). *Lessons learned: Anticipatory action in a protracted crisis*. Save the Children.
- McTough, M., Worku, T., Abdella, M., & Belay, O. (2025b, July 24). *Taking science to difficult places: field notes from Ethiopia's Dolo Ado - IWMI*. International Water Management Institute (IWMI). <https://www.iwmi.org/news/taking-science-to-difficult-places-field-notes-from-the-dolo-ado/>
- Mol, J. M., Botzen, W. W., & Blasch, J. E. (2022). After the virtual flood: Risk perceptions and flood preparedness after virtual reality risk communication. *Judgment and Decision Making*, 17(1), 189-214.
- Momeni, R., Bircan, T., & King, R. (2022). Environment-induced internal displacement. *The case of Somalia (Deliverable 4.3)*, 870661-H2020.
- Momeni, R., Bircan, T., King, R., & Santos, E. Z. (2024). Deciphering climate-induced displacement in Somalia: A remote sensing perspective. *PloS one*, 19(8), e0304202.
- OCHA. (2024). SOMALIA Monthly Humanitarian Update. PG. 1-4. (Accessed - file:///C:/Users/n.langa/Downloads/Monthly%20Humanitarian%20Update-Dec-2024%20-%20final.pdf).
- Oyshi, M. T., Maleska, V., Schanze, J., Bormann, F., Dachsel, R., & Gumhold, S. (2022). FloodVis: Visualization of Climate Ensemble Flood Projections in Virtual Reality. In *EnvirVis@ EuroVis* (pp. 1-9).
- Panggabean, F. M. (2023). Enhancing Flood Disaster Preparedness Through Virtual Reality: A VR-based Flood Simulator Game. *Engineering, Mathematics and Computer Science Journal (EMACS)*, 5(2), 69-72.
- Simpson, M., Padilla, L., Keller, K., & Klippel, A. (2022). Immersive storm surge flooding: Scale and risk perception in virtual reality. *Journal of Environmental Psychology*, 80, 101764.
- "Tencent Hunyuan 3D." *Tencent Hunyuan 3D*, <https://3d.hunyuan.tencent.com>. Accessed 16 Dec. 2025.
- Weingärtner, L., Humphrey, A., Sheikh, M., & Levine, S. (2022). Obstacles to and opportunities for anticipatory action in Somalia. *Supporting Pastoralism and Agriculture in Recurrent and Protracted Crises (SPARC)*.
- Zhang, Jie, et al. "A Literature Review of the Research on the Uncanny Valley." *Cross-Cultural Design. User Experience of Products, Services, and Intelligent Environments*, edited by Pei-Luen Patrick Rau, vol. 12192,

Springer International Publishing, 2020, pp. 255–68. *DOI.org (Crossref)*, https://doi.org/10.1007/978-3-030-49788-0_19.



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