FloodSim Sandbox: An Immersive Interactive Simulation Framework for Urban Flood Risk Management

Eveline L. Gonzalez[1], Ramteja Sajja[2], Yusuf Sermet[2,3], Ibrahim Demir[2,4]

[1] IIHR Hydroscience & Engineering, University of Iowa, Iowa City, IA, USA 52246
[2] ByWater Institute, Tulane University, New Orleans, LA, USA 70118
[3] Pediatrics, School of Medicine, Tulane University, New Orleans, LA, USA 70118
[4] River-Coastal Science and Engineering, Tulane University, New Orleans, LA, USA 70118

Corresponding Author: Ramteja Sajja, rsajja@tulane.edu

Abstract

FloodSim Sandbox is an AI-augmented, immersive digital twin framework for real-time flood visualization, analysis, and decision support. Developed within Unreal Engine 5, it integrates multi-source geospatial data, physically based fluid simulation, and multimodal AI reasoning to model flood dynamics in a high-fidelity digital twin of Iowa City. The system procedurally generates terrain and infrastructure using CityEngine and OpenStreetMap data, employs the Fluid Flux plugin for hydrodynamic simulation, and incorporates a HAZUS-based damage model calibrated with FEMA flood map data. A multimodal AI subsystem interprets visual and quantitative simulation data to deliver scene-specific risk assessments, mitigation strategies, and explainable insights. Interactive visualization, including responsive human and vehicle game characters, enhances engagement and supports scenario-based exploration of flood behavior. A user study for framework evaluation with environmental professionals confirmed the system's usability and effectiveness compared to traditional 2D flood information tools. Collectively, FloodSim Sandbox provides capabilities for enhancing flood risk communication, participatory education, and adaptive planning by uniting simulation, visualization, and AI-driven analysis within a single digital environment.

Keywords: AI-driven Decision Support, Data Visualization, Digital Twin, Extended Reality (XR), Flood Management, Flood Simulation, Hydrodynamic Modeling, Virtual Reality (VR)

1. Introduction

Traditional flood management strategies, including levees, dams, and static two-dimensional flood mapping systems, face growing limitations under changing climate and land-use conditions. Structural measures can reduce flood damage for specific design events but often struggle with rare, compound, or rapidly evolving flood scenarios (Shah et al., 2018). Levees and dams may also create a false sense of security, encouraging development in flood-prone areas while transferring risk downstream or increasing consequences when design thresholds are exceeded (Baecher & Galloway, 2021). Conventional two-dimensional flood maps further limit effective risk communication and decision support by representing floods as static extents, failing to capture dynamic interactions among flow, infrastructure, and human behavior (Shah et al., 2018). As a result, many studies emphasize the need to complement traditional flood defenses with adaptive, data-driven, and nature-based approaches that can respond to nonstationary and uncertain flood regimes (Fan et al., 2025; Vojinovic et al., 2021).

In response to these challenges, digital twin technologies have emerged as a promising framework for advancing flood modeling and decision support (Kaynak et al., 2025). Originally developed in industrial contexts such as manufacturing and aerospace, digital twins provided real-time virtual representations of physical assets for monitoring, optimization, and predictive maintenance (Maimour et al., 2024). Advances in sensing, data integration, and simulation have enabled their extension to environmental and hydrological systems, where they support dynamic watershed modeling, real-time flood monitoring, and interactive visualization of evolving conditions (Yin et al., 2024). Environmental digital twins are increasingly applied to agricultural water management, ecosystem monitoring, and climate adaptation planning, integrating meteorological and sensor data for predictive analysis and scenario exploration (Alves et al., 2023). Recent work further highlights the importance of incorporating weather and climate information into digital twins to support risk-based decision-making under climate uncertainty (Dale et al., 2023). While challenges remain related to scalability, interoperability, and the complexity of modeling natural systems, digital twins are clearly transitioning from industrial optimization tools toward platforms focused on resilience and sustainability (Li et al., 2024).

Parallel advances in immersive visualization technologies, including virtual reality, augmented reality, and extended reality, are transforming how environmental processes are communicated and understood (Daniela, 2020). By enabling users to interact directly with dynamic, data-driven simulations, immersive environments translate abstract environmental data into intuitive spatial experiences that enhance comprehension and engagement (Huang et al., 2021a). Empirical studies demonstrate that immersive virtual reality experiences can improve environmental awareness and understanding more effectively than traditional media, even when visual realism is limited (Thoma et al., 2023; Rahmani et al., 2025a). These technologies also support embodied and experiential learning by accommodating diverse cognitive and sensory preferences, fostering self-directed exploration and deeper engagement with complex environmental systems (Aguayo & Eames, 2023; Rahmani et al., 2025b). The integration of narrative elements, real-time data, and interactive exploration further enhances emotional resonance and supports participatory decision-making in environmental management and education (Yang et al., 2025; Wang & Caneparo, 2025).

The remainder of this paper is organized as follows. Section 2 reviews prior research on digital twins, immersive visualization technologies, and their integration within environmental and hydrological applications. Section 3 details the methodology, describing the FloodSim Sandbox system architecture, data sources, and interactive components, including Unreal Engine 5, real-time fluid simulation, and multimodal AI analysis. Section 4 presents the system results, covering visualization performance, interactivity, analytical capabilities, and an integrated discussion of implications and limitations. Section 5 concludes the paper with key insights and outlines future directions for advancing AI-driven, immersive digital twin systems for flood visualization and urban resilience.

2. Related Work

Digital twin (DT) technology originated as a means of creating virtual representations of physical objects, processes, or systems that remain continuously linked to their real-world counterparts (Tao et al., 2019; Sajja et al., 2025d). Early adoption occurred primarily in manufacturing and industrial settings, where DTs supported real-time monitoring, optimization, and predictive maintenance within Industry 4.0 paradigms (Onaji et al., 2022). In these environments, DTs integrate sensor data, simulation models, and control logic to improve operational efficiency, reduce downtime, and enable safe experimentation without disrupting physical assets (Javaid et al., 2023; Fantozzi et al., 2025). The incorporation of artificial intelligence and machine learning further expanded DT capabilities by enabling automated anomaly detection, adaptive optimization, and data-driven decision support in complex industrial systems (Huang et al., 2021b; Kadiyala et al., 2025). As a result, DTs have become a cornerstone of digital transformation in smart manufacturing ecosystems (Attaran et al., 2023).

At a conceptual level, DTs are commonly defined by three core principles: real-time synchronization, predictive modeling, and system optimization. Real-time synchronization ensures that digital replicas continuously reflect the evolving state of physical systems through live data streams from sensors and IoT devices (Walton et al., 2024). Predictive modeling enables DTs to simulate future system states, evaluate alternative scenarios, and anticipate failures using physics-based models and data-driven analytics (Rasheed et al., 2019). System optimization integrates these predictions into decision loops that prescribe or automate actions to improve performance, reliability, and lifecycle management (Kapteyn et al., 2021). Together, these principles distinguish DTs from static simulations by enabling adaptive, closed-loop interaction between digital and physical domains (Segovia & García, 2022).

Building on industrial success, DT adoption has expanded into environmental and infrastructure domains, where real-time monitoring and predictive analysis support resilience and sustainability planning (Sermet et al., 2020). In both industrial and environmental contexts, DTs enable predictive maintenance by forecasting component degradation and optimizing intervention schedules based on continuous sensor feedback (Van Dinter et al., 2022). These capabilities are particularly valuable for remote or hazardous systems, where direct inspection is difficult or costly (Abdullahi et al., 2024). The same foundational mechanisms, data synchronization, simulation, and visual analytics, are increasingly being adapted for smart water management, environmental monitoring, and climate adaptation (Wahab et al., 2024; Sit et al., 2021).

In parallel, extended reality (XR), encompassing virtual, augmented, and mixed reality, has emerged as a powerful medium for learning, communication, and decision support. XR environments provide immersive, multisensory experiences that enable users to interact directly with three-dimensional simulations, significantly improving engagement and conceptual understanding compared to traditional 2D representations (Papanastasiou et al., 2019). Empirical studies show that XR enhances spatial reasoning, procedural learning, and critical thinking across domains such as engineering, medicine, and environmental science (Tang et al., 2020). Compared to conventional instructional methods, immersive environments also increase motivation and support collaborative problem solving, although challenges related to cost, accessibility, and cognitive overload remain (Durden, 2025).

The effectiveness of XR is grounded in established educational frameworks. Embodied cognition emphasizes learning through physical and sensory engagement, aligning closely with XR's immersive affordances (Lee, 2025). Experiential learning models further support XR adoption by encouraging iterative cycles of exploration, reflection, and experimentation within simulated environments (Crogman et al., 2025). Socio-constructivist and inclusive pedagogical frameworks extend these ideas by emphasizing collaboration, personalization, and accessibility, enabling XR to support diverse learner populations when thoughtfully designed (Abeywardena, 2023).

Within environmental science and hydrology, DT and XR technologies are increasingly integrated to improve flood prediction, watershed management, and climate-risk communication. Hydrological DT frameworks combine real-time sensor data with hydraulic and machine learning models to forecast floods and support proactive water management decisions (Park & You, 2023). In urban drainage systems, DTs enable real-time detection and adaptive control of flooding by integrating monitoring data with optimization algorithms (Bartos & Kerkez, 2021). Cognitive DT approaches further enhance watershed-scale forecasting by incorporating semantic knowledge structures and cross-domain data integration (Feng et al., 2025). These systems support scenario-based planning and participatory decision-making, strengthening preparedness and resilience (Henriksen et al., 2022).

Embodied digital twins extend environmental DTs by coupling spatial realism with live data streams in immersive environments. By integrating high-fidelity 3D models, IoT data, and advanced rendering engines, these systems enable intuitive, real-time interpretation of complex environmental processes (Arsiwala et al., 2023). Applications include urban air-quality monitoring, where digital twins visualize pollution dispersion using computational fluid dynamics and live meteorological inputs (Teutscher et al., 2025). In hydrology, game-engine-based digital twins create interactive watershed representations that support flood monitoring, education, and stakeholder engagement through spatially contextualized visualization (Yin et al., 2024; Demiray et al., 2025).

Several platforms exemplify the integration of digital twins with hydrological data. The Iowa Flood Information System (IFIS) integrates real-time weather and streamflow observations with interactive flood mapping to support forecasting and risk assessment (Demir et al., 2018). Related systems, such as Flood Action VR (Sermet & Demir, 2019) and GeospatialVR (Sermet & Demir, 2022), combine hydrological simulations with immersive visualization to enhance disaster awareness, collaborative analysis, and public communication. These frameworks demonstrate how real-time data, simulation, and visualization can be unified to improve situational awareness and decision-making.

Immersive visualization tools have further advanced flood modeling by transforming simulation outputs into navigable 3D environments. XR-based systems integrate terrain, precipitation, and streamflow data to allow users to explore flood extent, depth, and dynamics interactively (Mudiyanselage et al., 2025). Tools such as Submerse generate realistic virtual scenes from storm surge simulations, enabling emergency managers to analyze flooding behavior using intuitive spatial interfaces (Boorboor et al., 2024). Other VR-based approaches improve flood-risk communication by translating complex hydrodynamic processes into accessible experiential representations for non-expert audiences (Macchione et al., 2019).

Beyond visualization, XR supports stakeholder engagement and emergency preparedness by enabling shared, interactive environments for planning and training. Narrative-driven XR platforms allow users to explore evacuation strategies and policy scenarios, improving collective sensemaking during disaster planning (Arizala et al., 2025). XR-based training simulations replicate high-stress emergency conditions in safe virtual environments, enhancing response readiness and decision quality (May et al., 2024). Systematic reviews confirm XR's effectiveness for disaster management and risk communication while emphasizing the importance of stakeholder co-design for long-term adoption (Khanal et al., 2022).

A complementary line of research links AI-enabled education to environmental and hydrological domains, demonstrating how conversational agents, retrieval-augmented generation (RAG) pipelines, and domain-aligned evaluation can support learning with complex scientific data and tools. An end-to-end Educational AI Hub shows that course-specific assistants integrated with learning management systems can improve engagement and conceptual understanding across disciplines, including environmental sciences, when rigorously evaluated for retrieval accuracy, question–answer correctness, and hallucination control using structured parsing and code-execution mechanisms (Sajja et al., 2025a).

In professional training contexts, an AI-assisted framework for Floodplain Manager certification delivers adaptive quizzes, dynamic flashcards, and high-accuracy question answering tailored to certification requirements, demonstrating measurable gains in vocational preparation for flood management roles (Sajja et al., 2025b). To support rigorous assessment of foundation models in hydrology, the HydroLLM Benchmark introduces a domain-specific question suite spanning multiple formats to quantify model competence on hydrologic knowledge, revealing strengths and limitations relevant to trustworthy educational and decision-support applications (Kizilkaya et al., 2025). Building on this evaluation foundation, HydroEmbed demonstrates that domain- and task-specialized sentence embeddings significantly improve semantic retrieval and answer composition for hydrology by aligning training losses with multiple assessment formats, enabling more reliable RAG pipelines for scientific education and analysis (Sajja et al., 2025c).

Despite the rapid evolution of DT and XR technologies, several limitations persist. Existing systems often rely on static simulations without real-time feedback, lack integration between AI and physics-based models, and provide limited accessibility for non-technical users. Moreover, while many frameworks achieve high visual realism, few combine interactive immersion, user customization, and AI-based reasoning for decision support. The FloodSim Sandbox addresses these gaps by unifying real-time flood simulation, geospatial modeling, and AI-driven analysis in an interactive digital twin environment. Its design emphasizes multimodal interaction, real-time fluid dynamics, and customizable data ingestion, supporting diverse use cases from research and planning to education and public engagement. By bridging immersive visualization, AI-based insight generation, and participatory interaction, FloodSim Sandbox advances the state of the art in digital twin–based environmental modeling and sets the stage for future innovations in AI-assisted urban resilience, embodied environmental planning, and XR-enabled citizen science.

3. Methodology

The FloodSim Sandbox system follows a modular architecture that integrates digital twin generation, real-time fluid simulation, and multimodal AI analysis within an immersive 3D environment. The architecture (Figure 1) is structured around four sequential stages: (i) data ingestion and scene construction, (ii) dynamic hydrodynamic simulation, (iii) AI-driven analysis and decision support, and (iv) interactive visualization for user engagement. This modular design enables interoperability between geospatial, simulation, and AI components while maintaining extensibility for research, education, and decision-support applications.

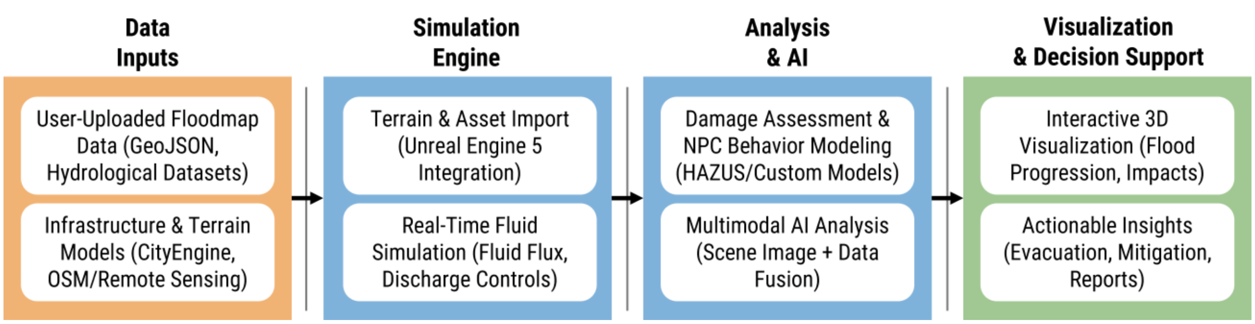

Figure 1. Architecture and components of the FloodSim Sandbox application

Figure 1 illustrates this end-to-end pipeline, from user-provided and geospatial data ingestion through digital-terrain generation, multimodal AI analysis, and interactive 3D visualization that supports actionable insights such as mitigation and evacuation planning. Beyond this linear process, the FloodSim Sandbox is supported by a modular, component-based architecture that integrates multiple data sources and simulation frameworks under a unified environment. Figure 2 illustrates how Unreal Engine 5 functions as the central hub, coordinating interactions between data, visualization, and analysis modules.

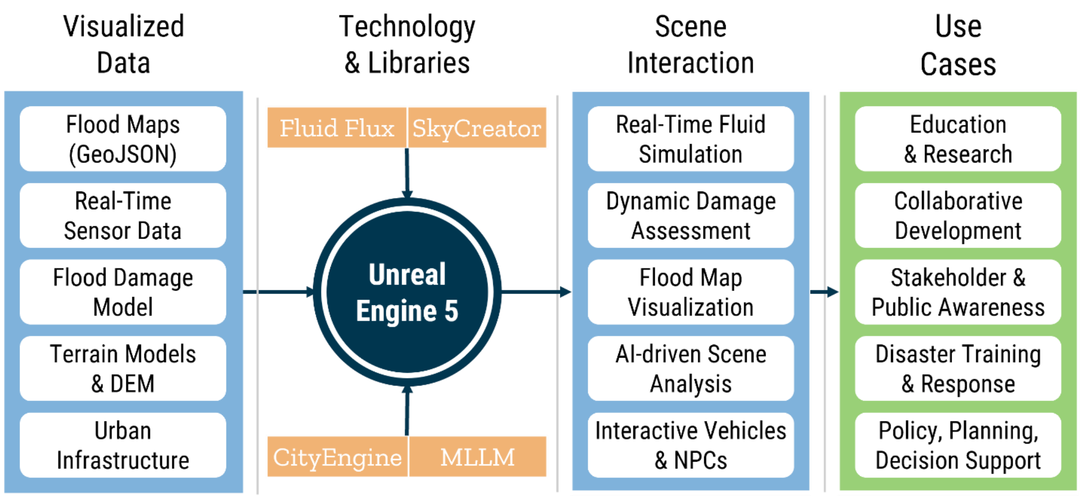

Figure 2. Modular architecture and component integration of the FloodSim Sandbox

All data layers, including flood maps, sensor data, damage models, terrain models, and urban infrastructure, converge within Unreal Engine 5, which interfaces with external systems such as CityEngine (for procedural city modeling), Fluid Flux (for hydrodynamic simulation), SkyCreator (for environmental rendering), and MLLM (for multimodal AI analysis). Together, these subsystems enable real-time flood simulation, damage analytics, AI-driven interpretation, and stakeholder-focused visualization for advancing research, education, and policy-oriented decision support.

3.1. Data and Resources

The FloodSim Sandbox framework relies on a combination of geospatial, hydrological, and environmental datasets to construct an accurate and interactive digital twin environment. These datasets are integrated across multiple software platforms and standardized into interoperable formats suitable for simulation and visualization. The data and resources outlined below form the foundation for terrain generation, hydrodynamic modeling, and real-time analysis, ensuring that the system maintains both scientific accuracy and immersive usability.

3.1.1. Infrastructure

Accurate representation of urban topography and infrastructure is fundamental to realistic flood simulation and intuitive user interaction. The platform employs ESRI's ArcGIS CityEngine to procedurally generate city infrastructure using OpenStreetMap (OSM) data. After defining a geographic extent of interest, features such as roads, buildings, and terrain elevation are automatically populated within the 3D scene. The digital topography is modeled at 8 k resolution to capture fine-scale detail essential for realistic fluid propagation. Satellite imagery provides terrain textures to enhance spatial realism and facilitate recognition of the virtual space with its real-world counterpart.

Once generated, the data is exported to Unreal Engine 5 via the Datasmith plugin, preserving per-asset metadata for interactivity. A custom automation script assigns actor components to every infrastructure element, enabling user interaction. When a user selects a building, either by mouse or XR controller trigger, the attached Datasmith metadata are retrieved through blueprint nodes and displayed via a 3D actor widget rendered in world space (Figure 3). The panel automatically orients toward the user, ensuring legibility across desktop and XR devices.

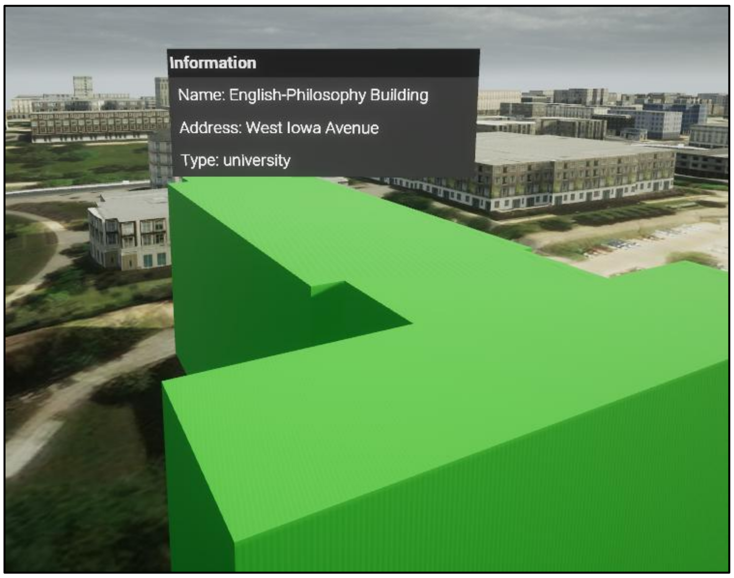

Figure 3. Infrastructure data integration with 3d models and textures from OpenStreetMap

3.1.2. Flood Map Visualization

Once the base terrain is generated, users can integrate their own hydrological data to visualize flood extents within the digital environment. The application accepts GeoJSON files, imported through the C++ DesktopPlatform module. File contents are stored within the GameInstance class to persist between scenes. When the simulation begins, the GeoJSON string is parsed by a Floodplain actor, which extracts geographic coordinates and converts them into engine world space using the Georeferencing plugin. A procedural mesh component generates the flood surface by iterating over coordinate triplets and constructing triangular mesh segments. The flood map is displayed using a vibrant and dithered material that enhances visual clarity and prevents aliasing (Figure 5). Dithering also avoids rendering conflicts with the Fluid Flux transparency system, allowing proper visualization even when submerged. User controls permit real-time adjustment of floodmap height or the option to disable visualization entirely to support alternate analytical views.

3.1.3. Flood Damage Model

To estimate potential losses, the system integrates a HAZUS-based flood damage model calibrated for the Iowa City watershed. Content and structural damages are modeled based on depth – damage functions and gage height using HAZUS methodology. These damage estimated are embedded in a gage collocated with the USGS stream sensor for the Iowa River. As fluid levels vary during simulation, real-time height readings (converted to feet) feed the models to compute damage estimates in USD, which are displayed dynamically in the analysis menu. As the real-time fluid simulation adjusts the water level at various points in the scene, the height above the gage actor is measured periodically using a component from the Fluid Flux plugin library. This height is measured in Unreal Engine's units, so this distance is converted into feet before being used as an input in the content and structure damage models. From this input, damage is calculated in USD and set as separate variables which are displayed in a user interface analysis menu.

3.2. Scene Interaction

The Scene Interaction module defines how users experience and manipulate the simulated flood environment. It links the hydrodynamic engine, AI analysis tools, and interactive entities, allowing real-time observation, experimentation, and feedback. Through simulation control, visualization toggles, and responsive virtual agents, users can explore cause–effect relationships between flood dynamics, infrastructure damage, and human behavior in a scientifically grounded yet immersive setting.

3.2.1. Fluid Simulation

Flood dynamics are simulated using the third-party Fluid Flux library, selected for its physically based shallow-water modeling and seamless integration with Unreal Engine. A simulation domain is defined to encompass the terrain, where the plugin generates a height map for hydrodynamic interactions among the landscape, built structures, and movable entities. Fluid inflow and outflow are controlled by two modifier actors: an upstream inflow source and a downstream outlet. The user can select one of three upstream discharge values representing normal, flood, and extreme flood conditions. The downstream actor continuously removes fluid to prevent unrealistic accumulation, ensuring conservation of flow within the digital domain. The resulting fluid behavior exhibits realistic propagation, pooling, and interaction with static and dynamic assets, supporting both educational and analytical use. This physically grounded simulation framework allows researchers and learners to explore scenario variability and sensitivity to discharge conditions in an interactive environment.

3.2.2. Damage Visualization

Damage to infrastructure is represented visually using a custom overlay material applied to objects in the scene. Visualization of this material is dependent on user toggling. To enable this visualization, each building in the scene was equipped with the Fluid Interaction actor component included in the Fluid Flux plugin. Upon selection, a custom actor component will measure the model extent of the building it is attached to. The Fluid Interaction component is then used to measure the height of the simulated fluid in relation to the building's position. This height is then expressed as a ratio of the building's total vertical extent, effectively computing the building's percentage of coverage from the simulated fluid.

The overlay material is a custom material which contains a red and green color and a linear interpolation node. When the overlay material is applied to the building, the previously measured ratio is used as the alpha for interpolating between the two colors. This process is repeated for every building in the scene, resulting in the visualization illustrated by Figure 7. Additional damage visualizations were explored using Unreal Engine's chaos physics system. Using this system, assets were created that could split along their mesh to simulate more realistic destruction for infrastructure. Implementing this system proved to be cumbersome, and the results raised performance concerns when integrated within the large, simulated scene, so ultimately these visualizations were not implemented. Alternative visualizations using Unreal Engine's Chaos Physics system were explored to simulate structural failure, but performance limitations prevented their inclusion in the large-scale environment.

3.2.3. Multimodal AI Analysis

To support intelligent interpretation and decision support, FloodSim Sandbox integrates a multimodal AI pipeline built on GPT-4o-mini. The model processes both visual and structured simulation data to generate contextual flood assessments. When the user requests an analysis, Unreal Engine's SceneCapture2D component captures an orthographic aerial view of the current simulation, while key simulation variables are serialized into a JSON object containing: (i) water levels at critical infrastructure points; (ii) discharge rates, stream velocities, and cumulative damage estimates; (iii) affected infrastructure (buildings, roads, utilities), and (iv) NPC and evacuation statistics.

The captured image (encoded in PNG → Base64) and JSON data are sent to a middleware interface that constructs a multimodal prompt for GPT-4o-mini. The prompt includes the image, simulation state, and user query (e.g., "Analyze damage, identify at-risk zones, and recommend mitigation strategies.") The model's response is parsed into structured outputs covering: (i) building-level and sector-level damage assessments; (ii) prioritized risk zones visualized via heatmaps; (iii) evacuation and mitigation recommendations, and (iv) explanatory reasoning highlighting uncertainty or confidence levels. Results are visualized in the analysis menu with interactive overlays, for example, highlighting evacuation routes or color-coding at-risk structures. System logs preserve all AI recommendations and underlying data for reproducibility and evaluation against expert benchmarks.

3.2.4. Non-Player Characters

To enhance realism and illustrate behavioral dynamics, the simulation incorporates both vehicle and human NPCs that react adaptively to flood conditions. Vehicle NPCs are generated using Unreal Engine's Chaos Vehicle plugin, enabling realistic physics-based motion along spline paths (Figure 4). Spline actors are placed in flood-prone areas to demonstrate traffic disruption. Vehicles continuously measure their lateral distance to the spline and adjust steering to maintain trajectory alignment. Upon scene reset, vehicles return to their original positions for repeatable simulations.

Figure 4. Vehicle Spline Actor

Human NPCs employ Unreal Engine's Navigation Mesh system to navigate autonomously among predefined waypoints, simulating pedestrian movement in urban settings. When encountering floodwater, NPCs detect the flow direction and flee toward higher ground at increased speed before resuming a wandering pattern once safe (Figure 10). These responsive behaviors enhance engagement, illustrating human–environment interaction and the cascading effects of flood events on mobility and safety.

3.3. Study Design

To assess the effectiveness and usability of the tool from the perspective of its intended end users, a structured usability survey was designed and administered to stakeholders with expertise in hydrology, environmental science, civil engineering, and water resources planning. Participants were primarily recruited from the Iowa Institute of Hydraulic Research (IIHR), Iowa Flood Center (IFC), and Iowa Water Center (IWC), organizations that represent a broad cross-section of professionals and researchers engaged in hydrologic modeling, environmental visualization, and flood management. Recruitment was conducted through a mass email invitation distributed to institutional mailing lists within the IIHR, IFC, and IWC. The message was addressed to affiliated faculty members, research staff, postdoctoral researchers, and graduate students working on water-related research and applications. The email included a brief overview of the FloodSim Sandbox, a short video demonstration, and a survey link for voluntary participation.

The evaluation aimed to assess how effectively the FloodSim Sandbox supports understanding of flood processes, spatial relationships, and decision-making compared to conventional non-immersive visualization systems. The survey was conducted on Qualtrics, a secure web-based platform equipped with IP verification and session tracking to prevent duplicate submissions. The survey collected both quantitative and qualitative feedback. Respondents were asked to rate the system across multiple dimensions, including interface usability, clarity of visualization, and comparative effectiveness against standard 2D flood-mapping tools. Demographic questions captured participants' professional background and experience with hydrological data to identify potential differences in perception across user groups.

Core survey items followed a Likert scale with options Much Better, Better, No Difference, Worse, and Much Worse. During data analysis, the two positive responses (Much Better and Better) were combined into a single "Better" category, and the two negative responses (Worse and Much Worse) were merged into a single "Worse" category. This consolidation simplified interpretation by emphasizing overall directional trends in user perception while maintaining the neutrality of No Difference as a distinct baseline. One additional question asked participants to rate the likelihood of adopting immersive visualization technologies in their daily professional activities. A final open-ended question invited participants to share detailed impressions, suggestions, or concerns about the system's functionality and potential applications.

4. Results and Discussion

The FloodSim Sandbox system successfully integrates real-time fluid simulation, digital terrain modeling, and dynamic flood damage visualization within a digital twin of Iowa City, the project's pilot site. Users can upload custom flood maps, simulate variable hydrological conditions, and visualize resulting impacts on infrastructure in real time. By translating GeoJSON-based spatial data into Unreal Engine 5, the system allows dynamic exploration of flood stages and their effects on urban environments. Together, these capabilities provide an interactive and data-driven medium for assessing flood risks in a controlled virtual setting.

4.1. Flood Map Visualization

The procedural flood map, generated from user-uploaded GeoJSON files, rendered accurately within the digital environment (Figure 5). Users can dynamically adjust water height to represent diverse flood stages, observing terrain and infrastructure responses in real time. The use of dithered materials enhanced visual clarity by distinguishing inundated areas from dry terrain, even during overlapping fluid conditions. This clarity also supports downstream AI analysis by enabling clean segmentation of flooded zones. Performance profiling indicated occasional frame-rate reductions during intensive rendering, primarily due to inefficiencies in the procedural mesh texturing method. Current mesh generation creates numerous material instances, which increases GPU load. Optimizing this process could improve runtime performance in future iterations.

Figure 5. Flood map GeoJSON visualized with procedural mesh

4.2. Real-Time Fluid Simulation

The Fluid Flux plugin produced physically realistic flood propagation that interacted dynamically with terrain and infrastructure (Figures 6a and 6b). Water behavior reflected expected hydrodynamic properties such as pooling, flow redistribution, and overtopping of low-lying structures. Vehicles exhibited buoyancy and displacement, while human NPCs responded adaptively to rising water levels. Predefined discharge rates corresponding to normal, flood, and extreme flood conditions effectively represented a range of hydrological scenarios. The resulting extents aligned closely with those predicted by the IFC flood maps, validating both visual and physical plausibility. Limiting discharge to preset values also improved compatibility with head-mounted display (HMD) modes, ensuring stable real-time visualization.

4.3. Damage Visualization

The flood damage model, derived from HAZUS datasets for the Iowa river watershed, dynamically updated in response to simulated water levels (Figure 7). Buildings within flood zones displayed color-coded overlays corresponding to structural and content damage severity. The visualization provided intuitive feedback, enabling users to assess infrastructure vulnerability at a glance. Occasional overestimation occurred for procedurally modeled buildings where geometry deviated from real-world proportions. Nevertheless, the system effectively conveyed spatial damage distribution, supporting both educational and analytical use.

Figure 6. (a) Flood simulation at low stage conditions (b) Flood simulation at high stage conditions

Figure 7. Color coded building damage information

4.4. AI-based Virtual Expert Analysis

The multimodal AI subsystem, powered by GPT-4o-mini, demonstrated strong performance in analyzing simulated flood scenarios and generating actionable recommendations (Figure 8). The model fused high-resolution scene imagery with structured simulation data, such as discharge rate, velocity, and damage estimates, to deliver context-aware outputs in real time. The AI successfully identified evolving risk zones, predicted infrastructure vulnerabilities, and recommended mitigation actions. Compared to rule-based baseline analysis, it more effectively detected non-obvious conditions such as: (a) roadways at imminent risk of isolation by increasing downstream flow; (b) NPC populations unable to reach shelters due to dynamic route blockages; and (c) critical facilities (e.g., hospitals, emergency response centers) nearing structural thresholds. Outputs included prioritized evacuation routes, resource deployment guidance, and scenario diagnostics with interpretable reasoning (e.g., "Flood severity in the eastern sector is projected to exceed thresholds within 15 simulated minutes; evacuation advised for buildings A34–A59").

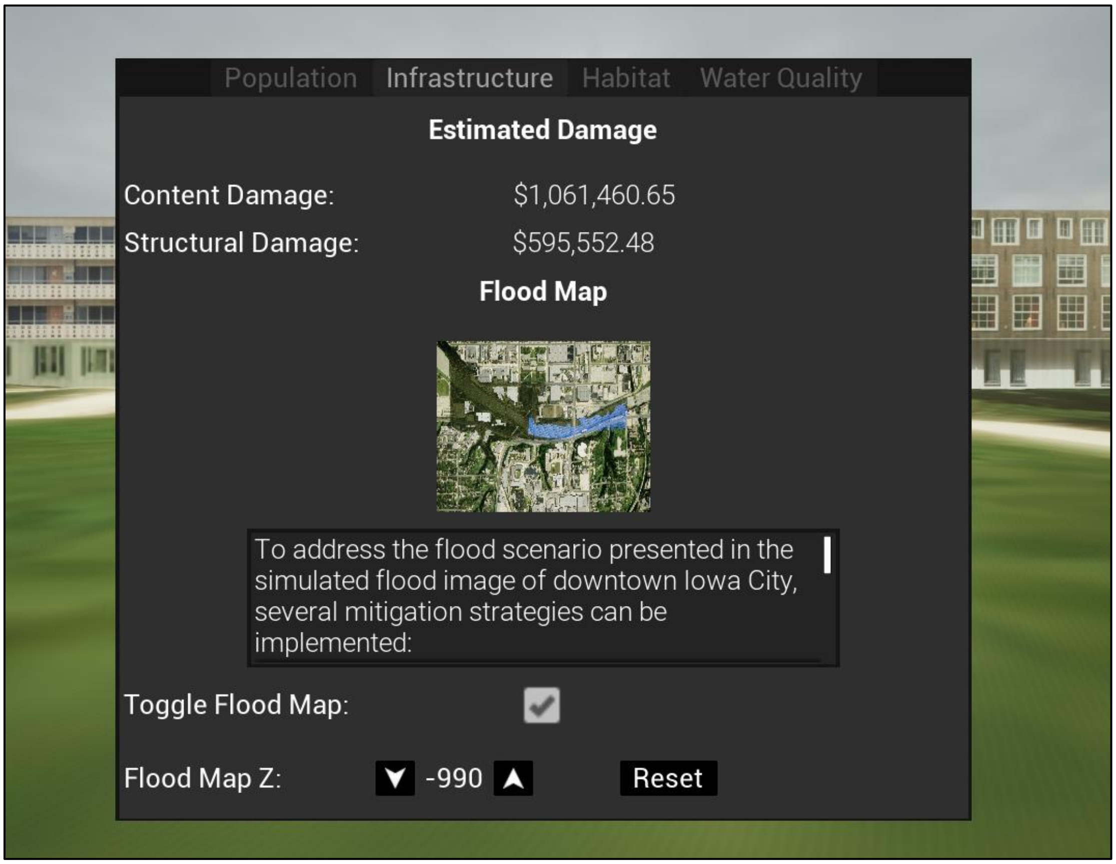

Figure 8. AI-driven analysis menu showing flood extent interpretation, risk prioritization, and mitigation guidance

4.5. Non-Player Characters

The integration of NPCs introduced behavioral realism into the simulation. Pedestrian NPCs autonomously evacuated flood zones based on detected water flow direction and speed, visually representing human mobility patterns under crisis conditions. Vehicle NPCs navigated predefined spline paths (Figure 9) until submersion triggered fluid-interaction physics, resulting in buoyancy, drift, or displacement depending on terrain slope and flow velocity. These interactions produced a dynamic environment where human and vehicular responses evolved alongside hydrodynamic conditions, enhancing both immersion and pedagogical value (Figure 10).

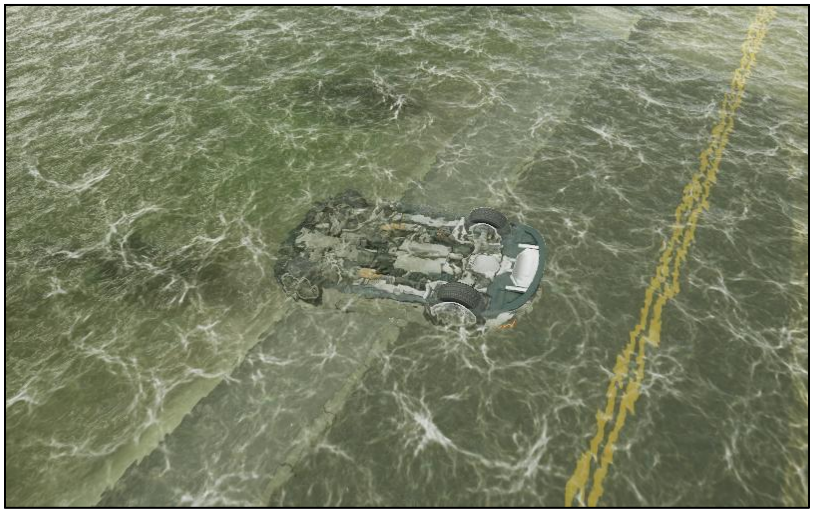

Figure 9. Vehicle path disrupted by fluid simulation

Figure 10. A humanoid NPC evacuating the area due oncoming flood

4.6. User Evaluation and Perception Analysis

A majority of participants perceived the immersive visualization to be substantially more effective than traditional 2D flood information systems for communicating flood-related damages. As shown in Figure 11, 82% of respondents rated the FloodSim Sandbox as Better than conventional visualization methods, while only 6% reported No Difference and 12% considered it Worse. This strong positive response suggests that the immersive 3D environment enhanced participants' understanding of spatial damage patterns and the relative severity of flood impacts compared to flat map-based tools.

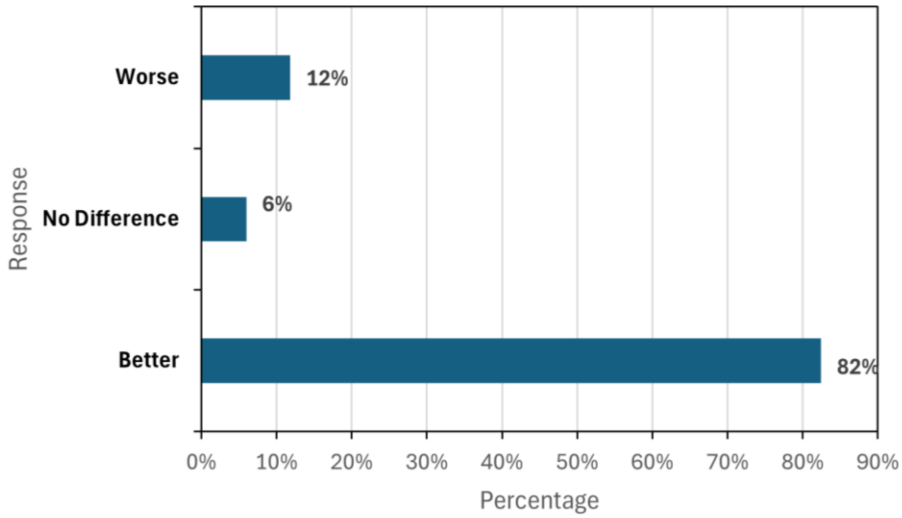

Figure 11. Participant ratings of the visualization's effectiveness in communicating flood-related damages (n = 17)

Participants also rated the immersive interface as easier to use than conventional 2D systems for flood visualization. As shown in Figure 12, 76% of respondents indicated that the FloodSim Sandbox offered a Better user experience, while 12% reported No Difference and 12% rated it as Worse. These findings suggest that the system's interactive 3D environment and intuitive controls enhanced navigation and data interpretation compared to traditional flood information interfaces.

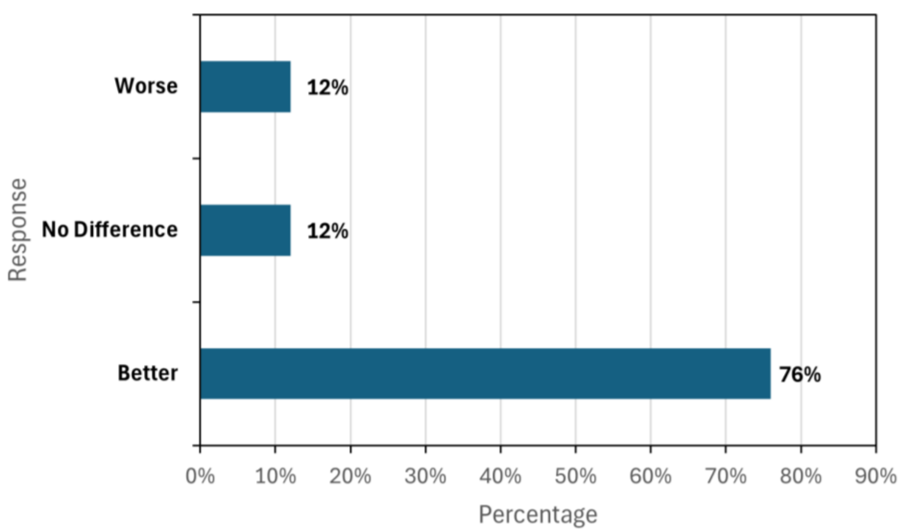

Figure 12. Participant ratings of interface usability compared to non-immersive visualization methods (n = 16)

Participants overwhelmingly reported improved comprehension of flood hazards when using the immersive 3D environment compared to traditional 2D tools. As shown in Figure 13, 88% of respondents rated their understanding of flood dynamics as Better, while only 6% observed No Difference and 6% rated it Worse. These findings indicate that interactive and spatially continuous visualization enhanced users' ability to interpret flood severity, flow direction, and exposure relationships within the scene.

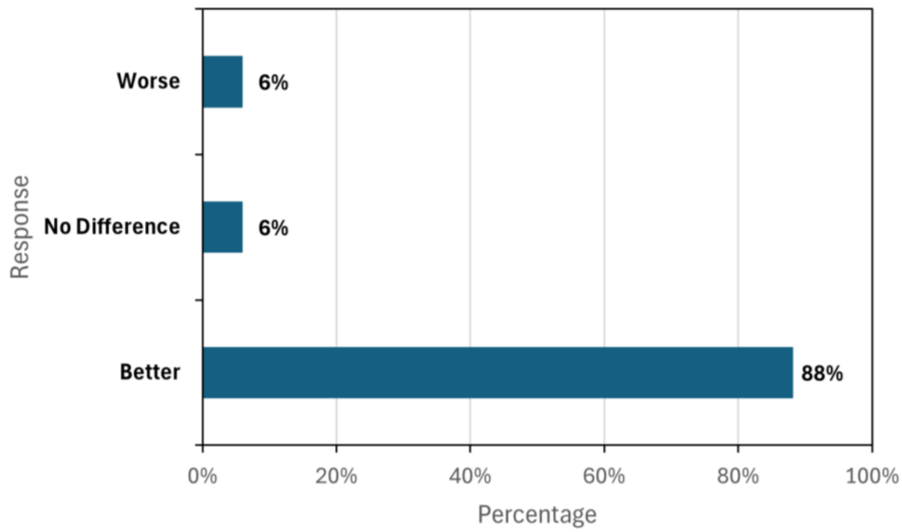

Figure 13. Participant ratings of comprehension improvement in the immersive environment (n = 17)

Participant backgrounds represented a diverse range of disciplines relevant to flood research and environmental analytics. As illustrated in Figure 14, the majority (53%) identified with Computer Science, followed by Data Science (18%), Environmental Science (12%), and Hydrology (12%), with a smaller proportion (5%) identifying as Disaster Analysts. This spread in participant fields of expertise highlights the interdisciplinary appeal of the FloodSim Sandbox and its adaptability across technical and applied domains.

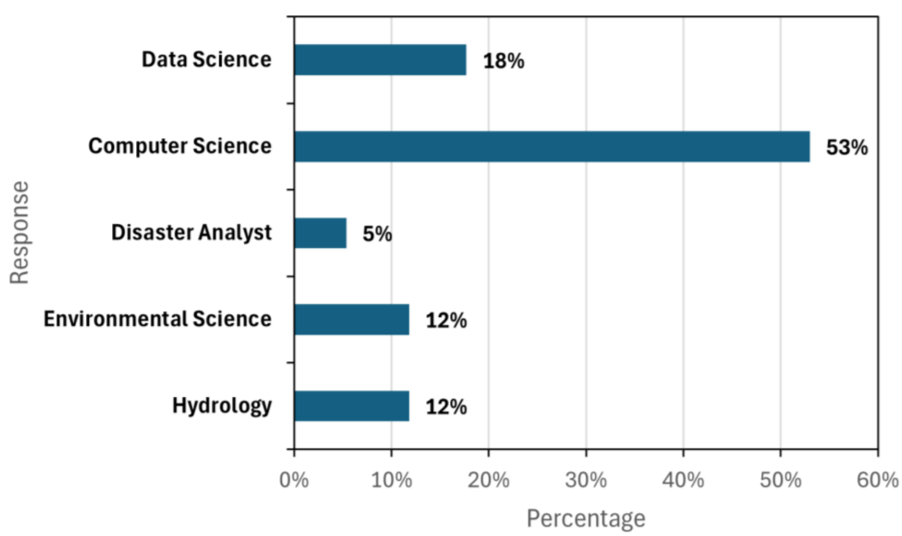

Figure 14. Distribution of participant fields of expertise (n = 17)

Participants reported varied levels of engagement with hydrological data, reflecting a balance between frequent practitioners and occasional users. As shown in Figure 15, 31% of respondents worked with hydrological data daily, 25% monthly, and 19% weekly, while 19% indicated never and 6% rarely. This distribution suggests that the evaluation captured perspectives from both expert users and individuals less familiar with hydrological workflows, supporting a comprehensive usability assessment.

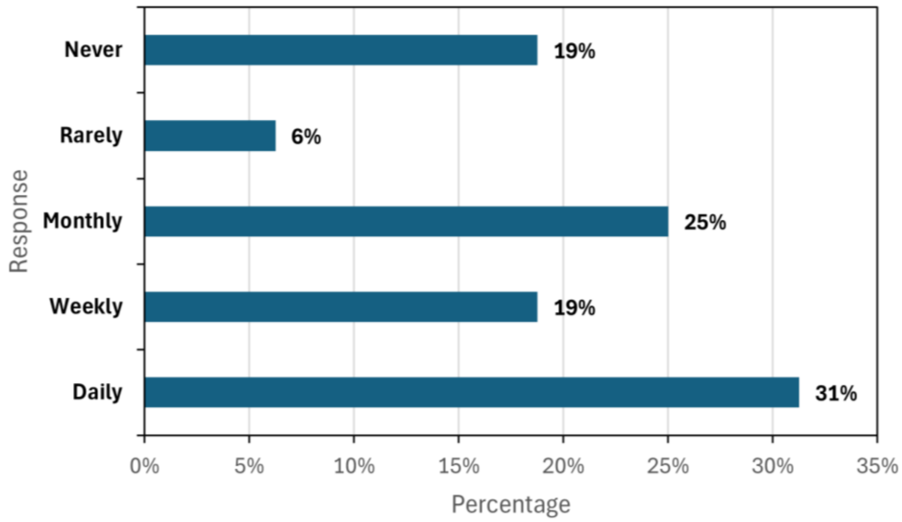

Figure 15. Participant frequency of working with hydrological data (n = 16)

When asked about the likelihood of adopting immersive visualization tools in their professional workflows, responses indicated cautious optimism. As illustrated in Figure 16, 36% of participants selected Likely or Very Likely, 35% responded Maybe, and 30% indicated Unlikely or Very Unlikely. These results suggest that while many respondents recognize the potential of immersive technologies, broader adoption may depend on accessibility, integration with existing systems, and demonstrated value in operational contexts.

As seen from the responses, participants generally perceived the immersive visualization as more effective, engaging, and intuitive than traditional 2D systems for understanding flood dynamics. A large majority rated the tool as Better in terms of visualization quality, usability, and hazard comprehension, reflecting its ability to communicate spatial and temporal flood processes more clearly. Despite varied professional backgrounds, including computer science, environmental science, and hydrology, participants shared similar positive impressions of the platform's interactivity and realism. While attitudes toward adopting immersive tools into professional workflows were more mixed, with roughly one-third expressing clear intent to adopt and another third remaining neutral, these results suggest a growing openness toward integrating immersive technologies in flood management and education.

Exploratory statistical analysis suggested that the frequency of hydrological data handling did not significantly influence perceptions of visualization effectiveness (p = 0.109), usability (p = 0.587), hazard comprehension (p = 0.835), or likelihood of adoption (p = 0.285). Similarly, participant profession showed no statistically significant effect on perceptions of effectiveness ($p = 0.938$) or usability ($p = 0.505$). While the sample size ($n = 17$) limits the statistical power of subgroup comparisons, these results preliminarily indicate that the FloodSim Sandbox was viewed favorably across the diverse disciplines and experience levels represented in the study, suggesting potential for broad accessibility.

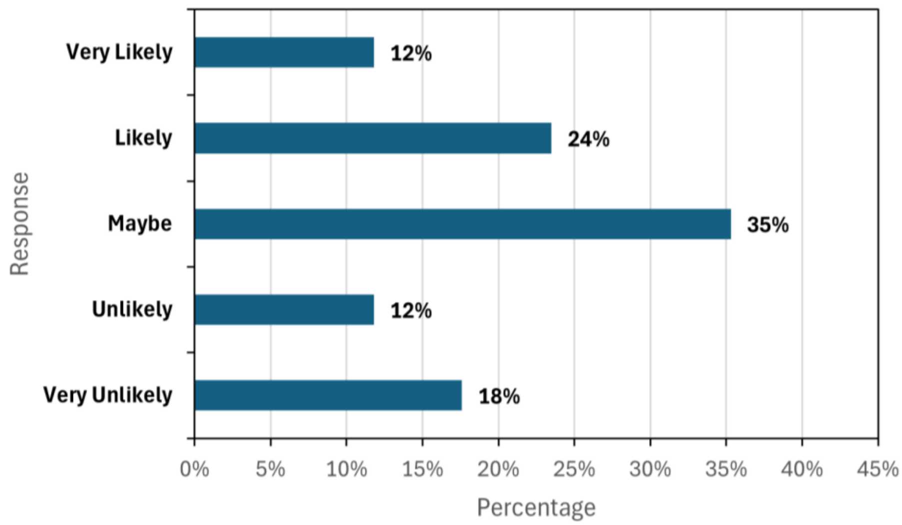

Figure 16. Participant likelihood of adopting immersive visualization tools in future workflows (n = 17)

In addition to the quantitative findings, open-ended responses provided qualitative insights into how participants envisioned the tool's broader value and areas for enhancement. Several respondents highlighted its strong potential as an educational and outreach platform, emphasizing its usefulness for local and state decision-makers, students, and community engagement initiatives. Others noted that if the system could seamlessly integrate new datasets, such as updated digital elevation models or revised design flows, it could serve as a valuable resource for flood prediction, stakeholder communication, and planning support. Participants also suggested incorporating real-time quantitative feedback, such as building-specific color-coded damage indicators or capacity thresholds, to complement the qualitative visualizations. Collectively, these comments reinforce the platform's relevance across professional, educational, and public domains, while offering constructive directions for future interface refinement.

5. Discussions

The FloodSim Sandbox demonstrates how the convergence of digital-twin technology, immersive visualization, and multimodal AI analysis can enhance urban flood understanding and decision support. Results from the user evaluation (Section 4.6) reinforce this integration, showing that participants found the system significantly more effective, usable, and intuitive than conventional 2D flood information systems. Developed using Unreal Engine 5 and tested on a digital twin of Iowa City, the system integrates hydrodynamic simulation, geospatial data ingestion, and AI-driven analysis into a unified 3D environment. This framework bridges the long-standing gap between static flood-risk mapping and interactive, experiential modeling.

Advancements in Digital Twin Based Flood Simulation: Recent work has shown that digital twins can synchronize environmental models with real-world data to improve flood prediction and risk communication (Yin et al., 2024). FloodSim Sandbox extends this capability by coupling procedural city generation through CityEngine with real-time fluid dynamics via Fluid Flux. This integration enables physically plausible flow propagation, pooling, and terrain interaction within a photorealistic virtual cityscape. The resulting environment mirrors the "embodied digital twin" concept identified in current hydrological visualization research (Yin et al., 2024), but with added support for user-defined data and dynamic interaction. Through adjustable discharge parameters and user-uploaded flood maps, the system transforms simulation into an exploratory, scenario-based process, supporting both technical and educational applications.

Integration of User Data and Multimodal AI Analysis: A key innovation is the incorporation of a multimodal AI analysis pipeline powered by GPT-4o-mini. By merging structured simulation variables (e.g., discharge, damage metrics) with orthographic scene imagery, the AI module generates interpretable analyses and mitigation recommendations. This multimodal approach parallels emerging digital-twin research emphasizing cognitive or "smart" twins that couple physics-based simulation with data-driven reasoning (Feng et al., 2025; Kim et al., 2025). The integration of user-supplied GeoJSON flood maps introduces a participatory element, enabling researchers, planners, and citizens to visualize personalized scenarios. Together, these features illustrate how AI can bridge quantitative modeling and qualitative decision support within immersive environments.

Human-Environment interaction and Educational Potential: The inclusion of NPCs introduces behavioral realism that enhances both comprehension and engagement. Vehicle and pedestrian agents dynamically respond to floodwater velocity and depth, illustrating cascading effects on mobility and safety. Such embodied interaction supports environmental communication and public education, key outcomes emphasized by immersive hydroinformatics frameworks (Arizala et al., 2025). By situating users within a responsive virtual city, FloodSim Sandbox facilitates intuitive understanding of complex flood processes and reinforces preparedness behaviors relevant to climate-driven flood risks. These outcomes were reflected in the user survey, where participants reported improved hazard comprehension and engagement when interacting with the immersive 3D environment.

Limitations and Future Work: While the platform demonstrates robust functionality, several limitations highlight avenues for future enhancement. First, simulation resolution constraints required balancing performance and accuracy; fluid solver resolution was reduced to maintain real-time interactivity across large urban domains. Integrating adaptive-mesh or GPU-accelerated solvers could improve hydrodynamic precision without compromising frame rate. Second, damage modeling using HAZUS parameters provided valuable estimation capability but introduced uncertainty at building scale due to procedural geometry differences and generalization. Future iterations could incorporate structure-specific vulnerability curves or integrate empirical calibration data from local flood reports to refine these estimates.

Third, reliance on third-party plugins, including Fluid Flux and SkyCreator, accelerated development but may limit scalability and customization. Transitioning to in-house modules for hydrodynamics, rendering, and asset management would enhance extensibility and platform longevity. Fourth, performance optimization remains an area for improvement. Frame-rate drops during procedural-mesh rendering indicate a need for asynchronous instancing and optimized material management. In addition, the framework currently focuses on simulating and visualizing immediate flood impacts. Expanding to multi-hazard or long-term recovery modeling, for example, erosion, sediment transport, or infrastructure restoration, would extend its value for planning and research.

Future work will also enhance the AI-driven interface: AI-generated overlays and explanations will be visualized directly in the UI, allowing users to interact with these outputs, such as clicking on a building to view tailored risk and mitigation summaries calculated from AI analysis. This planned feature aims to deepen transparency, interpretability, and engagement within the simulation, further bridging real-time analytics and user-driven decision support. Finally, integrating AR capabilities alongside VR could enable on-site visualization of flood scenarios, supporting participatory planning and stakeholder communication across diverse settings.

Broader Implications: FloodSim Sandbox represents a practical advancement in the development of AI-integrated, immersive digital twins for environmental resilience. By combining real-time simulation, interactive visualization, and explainable AI within a unified framework, the system enhances flood modeling from traditional analytical approaches toward more accessible and participatory applications. This integration supports classroom instruction, stakeholder engagement, and professional training, aligning with ongoing initiatives in immersive hydroinformatics and climate-risk education (Yin et al., 2024). Empirical findings from the user evaluation further validate the platform's accessibility and cross-disciplinary appeal, underscoring its readiness for broader deployment in educational and professional contexts.

6. Conclusion

FloodSim Sandbox presents an integrated framework that combines digital-twin technology, real-time fluid simulation, and multimodal AI analysis to advance urban flood visualization, education, and decision support. Developed within a high-fidelity digital twin of Iowa City, the system demonstrates how hydrodynamic modeling and interactive visualization can be unified to provide an intuitive, data-driven understanding of flood dynamics. User evaluation results further confirmed the framework's effectiveness and usability, with most participants reporting enhanced comprehension, engagement, and satisfaction compared to traditional 2D systems.

The platform's ability to ingest user-provided GeoJSON flood maps and render them as procedural 3D visualizations within Unreal Engine 5 represents a significant advancement over conventional two-dimensional mapping systems. The incorporation of physically based simulation through Fluid Flux enables realistic interactions between floodwaters and urban infrastructure, while AI-driven analysis using GPT-4o-mini adds an interpretive layer that supports real-time assessment, mitigation planning, and scenario exploration. By including human and vehicular non-player characters that respond dynamically to flood conditions, the system extends beyond traditional visualization tools to simulate behavioral and logistical dimensions of flooding. This integration enhances engagement and situational understanding for researchers, educators, and planners alike.

Future work will focus on extending the framework's scalability and precision through advanced hydrological solvers, improved damage-model calibration, and in-house simulation modules. Additional development of interactive AI features, such as user-triggered overlays and building-specific mitigation summaries, will further strengthen decision transparency and stakeholder participation. The planned integration of AR components will also enable on-site visualization and participatory risk assessment. FloodSim Sandbox contributes a novel, interdisciplinary platform that bridges scientific modeling, immersive visualization, and AI-based interpretation. As climate change continues to intensify hydrological extremes, such systems provide a foundation for more informed decision-making, adaptive planning, and experiential learning in flood risk management and environmental resilience.

Funding

This project was funded by the National Oceanic and Atmospheric Administration (NOAA) via a cooperative agreement with the University of Alabama (NA22NWS4320003) awarded to the Cooperative Institute for Research to Operations in Hydrology (CIROH).

Competing Interests

The authors declare that they have no competing interests.

References

Abd Wahab, N. H., Hasikin, K., Lai, K. W., Xia, K., Bei, L., Huang, K., & Wu, X. (2024). Systematic review of predictive maintenance and digital twin technologies challenges, opportunities, and best practices. *PeerJ Computer Science*, *10*, e1943.

Abdullahi, I., Longo, S., & Samie, M. (2024). Towards a distributed digital twin framework for predictive maintenance in industrial internet of things (IIoT). *Sensors*, *24*(8), 2663.

Abeywardena, I. S. (2023). OXREF: open XR for education framework. *International Review of Research in Open and Distributed Learning*, *24*(3), 185-206.

Aguayo, C., & Eames, C. (2023). Using mixed reality (XR) immersive learning to enhance environmental education. *The Journal of Environmental Education*, *54*(1), 58-71.

Alves, R. G., Maia, R. F., & Lima, F. (2023). Development of a Digital Twin for smart farming: Irrigation management system for water saving. *Journal of Cleaner Production*, *388*, 135920.

Arizala, J. L., Permito, J., Escopete, S. E., Niño, J. K., & Deja, J. A. (2025). Designing RoutScape: Geospatial Prototyping with XR for Flood Evacuation Planning. *arXiv preprint arXiv:2505.06045*.

Arsiwala, A., Elghaish, F., & Zoher, M. (2023). Digital twin with Machine learning for predictive monitoring of CO2 equivalent from existing buildings. *Energy and Buildings*, *284*, 112851.

Attaran, M., Attaran, S., & Celik, B. G. (2023). The impact of digital twins on the evolution of intelligent manufacturing and Industry 4.0. *Advances in Computational Intelligence*, *3*(3), 11.

Baecher, G. B., & Galloway, G. E. (2021). US Flood risk management in changing times. *Water Policy*, *23*(S1), 202-215.

Bartos, M., & Kerkez, B. (2021). Pipedream: An interactive digital twin model for natural and urban drainage systems. *Environmental Modelling & Software*, *144*, 105120.

Boorboor, S., Kim, Y., Hu, P., Moses, J. M., Colle, B. A., & Kaufman, A. E. (2024). *Submerse: Visualizing storm surge flooding simulations in immersive display ecologies. IEEE Transactions on Visualization and Computer Graphics, 30*(9), 6365–6377.

Crogman, H. T., Cano, V. D., Pacheco, E., Sonawane, R. B., & Boroon, R. (2025). Virtual reality, augmented reality, and mixed reality in experiential learning: Transforming educational paradigms. *Education Sciences*, *15*(3), 303.

Dale, K. I., Pope, E. C., Hopkinson, A. R., McCaie, T., & Lowe, J. A. (2023). Environment-aware digital twins: Incorporating weather and climate information to support risk-based decision-making. *Artificial Intelligence for the Earth Systems*, *2*(4), e230023.

Daniela, L. (2020). New perspectives on virtual and augmented reality. New Perspectives on Virtual and Augmented Reality. Routledge.

Demir, I., Yildirim, E., Sermet, Y., & Sit, M. A. (2018). FLOODSS: Iowa flood information system as a generalized flood cyberinfrastructure. *International journal of river basin management*, *16*(3), 393-400.

Demiray, B. Z., Sermet, Y., Yildirim, E., & Demir, I. (2025). FloodGame: An interactive 3D serious game on flood mitigation for disaster awareness and education. Environmental Modelling & Software, 188, 106418.

Durden, J. M. (2025). Environmental management using a digital twin. *Environmental Science & Policy*, *164*, 104018.

Fan, C., Hou, J., Li, X., Song, G., Yang, Y., Liang, X., ... & Lu, P. (2025). Efficient urban flood control and drainage management framework based on digital twin technology and optimization scheduling algorithm. *Water Research*, 123711.

Fantozzi, I. C., Santolamazza, A., Loy, G., & Schiraldi, M. M. (2025). Digital twins: Strategic guide to utilize digital twins to improve operational efficiency in Industry 4.0. *Future Internet*, *17*(1), 41.

Feng, H., Mu, R., & Cheng, Y. (2025). *The application of digital twin technology in the evaluation of environmental design solutions. IEEE Access, 13,* 139053–139061.

Henriksen, H. J., Schneider, R., Koch, J., Ondracek, M., Troldborg, L., Seidenfaden, I. K., ... & Stisen, S. (2022). A new digital twin for climate change adaptation, water management, and disaster risk reduction (HIP digital twin). *Water*, *15*(1), 25.

Huang, J., Lucash, M. S., Scheller, R. M., & Klippel, A. (2021a). Walking through the forests of the future: using data-driven virtual reality to visualize forests under climate change. *International Journal of Geographical Information Science*, *35*(6), 1155-1178.

Huang, Z., Shen, Y., Li, J., Fey, M., & Brecher, C. (2021b). A survey on AI-driven digital twins in industry 4.0: Smart manufacturing and advanced robotics. *Sensors*, *21*(19), 6340.

Javaid, M., Haleem, A., & Suman, R. (2023). Digital twin applications toward industry 4.0: A review. *Cognitive Robotics*, *3*, 71-92.

Kadiyala, L., Sajja, R., Sermet, Y., Muste, M., & Demir, I. (2025). *AI-driven decision-making for water resource planning and hazard mitigation using automated multi-agents*. Journal of Hydroinformatics, 27(7), 1217–1237. https://doi.org/10.2166/hydro.2025.042

Kapteyn, M. G., Pretorius, J. V., & Willcox, K. E. (2021). A probabilistic graphical model foundation for enabling predictive digital twins at scale. *Nature Computational Science*, *1*(5), 337-347.

Kaynak, S., Kaynak, B., Mermer, O., & Demir, I. (2025). City-scale digital twin framework for flood impact analysis: Integrating urban infrastructure and real-time data analytics. Urban climate, 64, 102640.

Khanal, S., Medasetti, U. S., Mashal, M., Savage, B., & Khadka, R. (2022). Virtual and augmented reality in the disaster management technology: a literature review of the past 11 years. *Frontiers in Virtual Reality*, *3*, 843195.

Kim, Y., Oh, J., & Bartos, M. (2025). Stormwater digital twin with online quality control detects urban flood hazards under uncertainty. *Sustainable Cities and Society*, *118*, 105982.

Kizilkaya, D., Sajja, R., Sermet, Y., & Demir, I. (2025). Toward HydroLLM: a benchmark dataset for hydrology-specific knowledge assessment for large language models. *Environmental Data Science*, *4*, e31.

Lee, J. M. (2025). Embodied Learning in Architecture: A Design Studio Model Utilizing Extended Reality. *Buildings*, *15*(13), 2158.

Li, W., Ma, Z., Li, J., Li, Q., Li, Y., & Yang, J. (2024). Digital twin smart water conservancy: Status, challenges, and prospects. *Water*, *16*(14), 2038.

Macchione, F., Costabile, P., Costanzo, C., & De Santis, R. (2019). Moving to 3-D flood hazard maps for enhancing risk communication. *Environmental modelling & software*, *111*, 510-522.

Maimour, M., Ahmed, A., & Rondeau, E. (2024). Survey on digital twins for natural environments: A communication network perspective. *Internet of Things*, *25*, 101070.

May, B., Milne, R., Dalton, G., Meenaghan, A., & Shawyer, A. (2024). An exploratory study on manifesting decision-inertia in a 360-degree extended reality terrorist incident. *Cognition, Technology & Work*, *26*(3), 401-416.

Mudiyanselage, U. H., Gonzalez, E. L., Sermet, Y., & Demir, I. (2025). An Immersive Hydroinformatics Framework with Extended Reality for Enhanced Visualization and Simulation of Hydrologic Data. *Applied Sciences*, *15*(10), 5278.

Onaji, I., Tiwari, D., Soulatiantork, P., Song, B., & Tiwari, A. (2022). Digital twin in manufacturing: conceptual framework and case studies. *International journal of computer integrated manufacturing*, *35*(8), 831-858.

Papanastasiou, G., Drigas, A., Skianis, C., Lytras, M., & Papanastasiou, E. (2019). Virtual and augmented reality effects on K-12, higher and tertiary education students' twenty-first century skills. *Virtual Reality*, *23*(4), 425-436.

Park, D., & You, H. (2023). A digital twin dam and watershed management platform. *Water*, *15*(11), 2106.

Rahmani, A., Sermet, Y., & Demir, I. (2025a). HydroVerse VR Equipment Hub: An Integrated Virtual Reality Framework for Training and Workforce Development in Environmental Monitoring. EarthArxiv, 10573. https://doi.org/10.31223/X54J2X

Rahmani, A., Sermet, Y., & Demir, I. (2025b). HydroVerse Education: An AI-Assisted Education Framework for Immersive Learning and Training Environments. EarthArxiv, 11231. https://doi.org/10.31223/X5FV02

Rasheed, A., San, O., & Kvamsdal, T. (2020). *Digital twin: Values, challenges and enablers from a modeling perspective. IEEE Access, 8,* 21980–22012.

Sajja, R., Sermet, Y., & Demir, I. (2025a). *End-to-end deployment of the Educational AI Hub for personalized learning and engagement: A case study on environmental science education. IEEE Access, 13,* 55169–55186.

Sajja, R., Pursnani, V., Sermet, Y., & Demir, I. (2025b). *AI-assisted educational framework for floodplain manager certification: Enhancing vocational education and training through personalized learning. IEEE Access, 13,* 42401–42413.

Sajja, R., Sermet, Y., & Demir, I. (2025c). *Domain-specific embedding models for hydrology and environmental sciences: Enhancing semantic retrieval and question answering*. Water Science & Technology, 92(9), 1328–1342. https://doi.org/10.2166/wst.2025.156

Sajja, R., Mermer, O., Sermet, Y., & Demir, I. (2025d). *Hydro3DJS: A modular web-based library for real-time 3D visualization of watershed dynamics and digital twin integration*. Environmental Modelling & Software, 176, 106853. https://doi.org/10.1016/j.envsoft.2025.106853

Segovia, M., & Garcia-Alfaro, J. (2022). Design, modeling and implementation of digital twins. *Sensors*, *22*(14), 5396.

Sermet, Y., & Demir, I. (2019). Flood action VR: a virtual reality framework for disaster awareness and emergency response training. In *ACM SIGGRAPH 2019 Posters* (pp. 1-2).

Sermet, Y., & Demir, I. (2022). GeospatialVR: A web-based virtual reality framework for collaborative environmental simulations. *Computers & geosciences*, *159*, 105010.

Sermet, Y., Villanueva, P., Sit, M. A., & Demir, I. (2020). Crowdsourced approaches for stage measurements at ungauged locations using smartphones. Hydrological Sciences Journal, 65(5), 813-822.

Shah, M. A. R., Rahman, A., & Chowdhury, S. H. (2018). Challenges for achieving sustainable flood risk management. *Journal of Flood Risk Management*, *11*, S352-S358.

Sit, M., Langel, R. J., Thompson, D., Cwiertny, D. M., & Demir, I. (2021). Web-based data analytics framework for well forecasting and groundwater quality. Science of the Total Environment, 761, 144121.

Tang, Y. M., Au, K. M., Lau, H. C., Ho, G. T., & Wu, C. H. (2020). Evaluating the effectiveness of learning design with mixed reality (MR) in higher education. *Virtual Reality*, *24*(4), 797-807.

Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). *Digital twin in industry: State-of-the-art. IEEE Transactions on Industrial Informatics, 15*(4), 2405–2415.

Teutscher, D., Bukreev, F., Kummerländer, A., Simonis, S., Bächler, P., Rezaee, A., ... & Krause, M. J. (2025). A digital urban twin enabling interactive pollution predictions and enhanced planning. *Building and Environment*, 113093.

Thoma, S. P., Hartmann, M., Christen, J., Mayer, B., Mast, F. W., & Weibel, D. (2023). Increasing awareness of climate change with immersive virtual reality. *Frontiers in Virtual Reality*, *4*, 897034.

Van Dinter, R., Tekinerdogan, B., & Catal, C. (2022). Predictive maintenance using digital twins: A systematic literature review. *Information and Software Technology*, *151*, 107008.

Vojinovic, Z., Alves, A., Gómez, J. P., Weesakul, S., Keerakamolchai, W., Meesuk, V., & Sanchez, A. (2021). Effectiveness of small-and large-scale Nature-Based Solutions for flood mitigation: The case of Ayutthaya, Thailand. *Science of the Total Environment*, *789*, 147725.

Walton, R. B., Ciarallo, F. W., & Champagne, L. E. (2024). A unified digital twin approach incorporating virtual, physical, and prescriptive analytical components to support adaptive real-time decision-making. *Computers & Industrial Engineering*, *193*, 110241.

Wang, J., & Caneparo, L. (2025). Building Bridges to the Future: Synergies Between Art and Technology in Communicating Urban Evolution Under Climate Change. *Sustainability*, *17*(12), 5389.

Yang, Y., Sannusi, S. N., & Ahmad Rizal, A. R. (2025). Exploring the role of immersive media technologies in environmental communication: A case study of underwater earth projects. *Environmental Communication*, *19*(3), 432-448.

Yin, W., Hu, Q., Liu, W., Liu, J., He, P., Zhu, D., & Kornejady, A. (2024). Harnessing Game Engines and Digital Twins: Advancing Flood Education, Data Visualization, and Interactive Monitoring for Enhanced Hydrological Understanding. *Water*, *16*(17), 2528.