VRFIS: An Immersive Framework for Real-Time Flood Monitoring, Visualization, and Interactive Environmental Analysis

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Abstract

The rapid evolution of Mixed Reality (MR) technologies, particularly Virtual Reality (VR), offers powerful new means of visualizing and interacting with geographic and environmental data. This paper presents Virtual Reality Flood Information System (VRFIS), an immersive information platform developed using Unreal Engine 5 and Google Photo Realistic 3D Tiles to enable real-time exploration of high-resolution geospatial datasets across the United States. VRFIS integrates photorealistic terrain rendering, dynamic environmental simulation, and multimodal interaction within a fully immersive 3D environment, allowing users to visualize, query, and interpret complex environmental phenomena with unprecedented realism and spatial context. By coupling high-fidelity visualization with live data streams from authoritative sources such as USGS and NOAA, the system delivers an intuitive decision-support and educational tool for environmental science, hydrology, urban planning, and geography education. The results demonstrate how next-generation virtual reality environments, exemplified by VRFIS, can enhance spatial awareness, promote experiential learning, and improve data-driven decision-making in environmental and geospatial domains.

Keywords: Digital Twin, Environmental Decision Support, Hydrology, Virtual Reality, Real-Time Environmental Data, Unreal Engine, Geospatial Visualization

1. Introduction

The visualization and interpretation of environmental and geospatial data are fundamental to effective planning, monitoring, and decision-making in domains such as hydrology, urban development, and climate analysis. Traditional 2D and web-based GIS platforms, including ArcGIS Online, Google Earth, and CesiumJS, have broadened access to spatial information, yet they remain constrained in their ability to manage complex, multiscale, and dynamic datasets. Many web-based systems offer limited analytical functions and basic cartographic tools, reducing their usefulness for advanced modeling or real-time analysis (Fast & Hossain, 2020; Luo et al., 2018). Integrating heterogeneous data such as sensor networks, LiDAR, or building information models is often difficult, and client-side resource limits further restrict scalability and interactivity (La Guardia & Koeva, 2023; Yang et al., 2023; Pavelka & Landa, 2024). Even 3D web viewers typically lack the realism and depth perception needed to represent volumetric processes like flooding, groundwater movement, or urban microclimates (Liao et al., 2017).

To overcome these constraints, immersive technologies, virtual reality (VR), augmented reality (AR), and mixed reality (MR), are gaining traction as powerful tools for environmental science, hydrology, and urban planning (Daniela, 2020). By immersing users directly within interactive 3D environments, virtual reality systems enable intuitive exploration of complex spatial relationships and temporal dynamics. They consolidate multivariate data such as precipitation, streamflow, or terrain elevation into unified visual experiences that improve comprehension and engagement (Mudiyanselage et al., 2025; Rambach et al., 2021; Cho & Park, 2023). These environments also support scenario testing, allowing stakeholders to visualize flood events, infrastructure changes, or climate impacts safely and repeatedly (Argo et al., 2025). Beyond scientific analysis, immersive technologies enhance communication, education, and participation by translating technical models into accessible, experiential formats that foster collaboration and inclusivity (Berigüete et al., 2024; Shehadeh et al., 2025; Aguayo & Eames, 2023).

The rapid development of game engines and photorealistic mapping frameworks has further expanded what is possible in this space. Engines such as Unreal Engine 5 provide advanced lighting, physics, and interaction systems that support realistic rendering and natural movement within large-scale geospatial scenes (Laksono & Aditya, 2019; Haibt, 2024; King et al., 2023). When coupled with streaming technologies like Google 3D Tiles, these platforms can visualize entire cities or landscapes with high fidelity and real-time responsiveness (Würstle et al., 2022). Together, they enable the creation of digital twins, interactive virtual replicas of real-world locations, used increasingly for urban planning, archaeology, and environmental monitoring (Kaynak et al., 2025). The democratization of these tools through open data standards and affordable hardware is making immersive geospatial visualization more accessible than ever before (Demir & Szczepanek, 2017).

Despite these advances, current systems rarely achieve a seamless integration of live environmental data, photorealistic rendering, and intuitive multimodal interaction within a single unified framework. Most VR or web-based visualization projects emphasize visual realism but lack the data synchronization, scalability, or analytical depth needed for continuous environmental monitoring and decision support (Zhao et al., 2021). Consequently, there is a critical need for platforms that combine high-fidelity visualization with real-time data ingestion and user-centered interactivity.

To address these gaps, this study presents Virtual Reality Flood Information System (VRFIS), an immersive information framework that merges Unreal Engine 5 with Google Photo Realistic 3D Tiles to visualize real-time hydrologic and environmental data from authoritative sources such as the USGS and NOAA. VRFIS integrates voice-driven and AI-assisted interaction, enabling users to query, explore, and analyze spatial data within a fully immersive virtual environment. Its modular architecture supports both educational and professional applications, ranging from virtual field instruction to data-driven decision support in environmental management. This framework advances spatial understanding, enhances user engagement, and aligns with emerging paradigms of Digital Twin environments and AI-augmented immersive analytics.

The remainder of this paper is organized as follows: Section 2 reviews related work in immersive geospatial systems; Section 3 details the system methodology and architecture; Section 4 presents results and discussion; and Section 5 concludes with implications and future directions.

2. Related Work

Virtual and augmented environments have become increasingly important for geospatial visualization, enabling immersive, interactive experiences that extend beyond traditional 2D representations (Sermet & Demir, 2020). They allow users to explore complex spatial datasets such as terrain models, urban environments, or environmental systems within fully three-dimensional contexts (Edler & Kersten, 2021; Lochhead & Hedley, 2021). Cross-reality systems now combine touch-based 2D displays with head-mounted 3D visualization, permitting seamless switching between flat and immersive perspectives for analyzing molecular structures, point clouds, or environmental data (Zhao et al., 2025). Augmented-reality enhancements to physical data sculptures further enrich spatial understanding by adding interactive overlays and contextual annotations (Engert et al., 2025). Empirical studies confirm that AR and VR visualization improves user engagement and comprehension of spatial information relative to traditional desktop interfaces (Hou et al., 2024).

Multiple technologies underpin these immersive visualization environments. Game engines such as *Unity3D* and *Unreal Engine* provide real-time rendering, physics-based lighting, and flexible interaction frameworks suitable for both planetary-scale and site-specific applications (Lee et al., 2020). Web-based systems built on HTML5 and WebGL, such as *CesiumJS*, *three.js*, and *X3DOM*, enable plugin-free 3D visualization in browsers, supporting interactive analysis across platforms (La Guardia et al., 2024; Krämer & Gutbell, 2015).

Open-source collaborative platforms such as GeospatialVR further extend these capabilities by dynamically generating real-world 3D environments, integrating hazard and sensor layers, and supporting multiuser interaction for remote decision-making and virtual incident command operations (Sermet & Demir, 2022). *CesiumJS* in particular supports large-scale urban models, streaming of 3D Tiles, and IoT integration for digital-twin applications (La Guardia, 2025;

Evangelidis et al., 2018). Other frameworks such as *GeoScope* extend these capabilities to massive 3D city models and real-time rendering (Zhang et al., 2011). Recent initiatives like *AI4GEO* employ artificial intelligence and big-data analytics to automate 3D geospatial data generation (Brunet et al., 2021).

Immersive environments have proven especially valuable in environmental science, hydrology, and urban infrastructure management, where they improve communication and analysis of complex spatial processes (Rahmani et al., 2025a). In flood modeling, VR platforms enable the overlay of real-time or simulated flood data onto panoramic imagery and 3D city models, enhancing realism for experts and the public (Dang et al., 2023; Alene et al., 2024). Immersive VR training platforms have also been developed for workforce preparation in environmental monitoring, enabling users to interact with photogrammetry-based equipment models, practice troubleshooting, and simulate field deployment tasks in a safe, guided virtual environment (Rahmani et al., 2025b). Virtual simulations have been used to represent avalanches, landslides, and flash-flood dynamics, linking numerical model outputs to intuitive visual representations (Spero et al., 2022).

In urban contexts, 3D models and VR systems facilitate infrastructure planning, vulnerability assessment, and risk communication by embedding spatial and socio-environmental data into interactive visualizations (Schröter et al., 2018; Saran et al., 2018). Serious-game approaches have been adopted for flood awareness and safety training, improving preparedness and knowledge retention (D'Amico et al., 2023; Sajja et al., 2025b; Demiray et al., 2025). Related VR disaster-preparedness systems incorporate real-time and historical hazard conditions, gamified emergency-response scenarios, and voice-based interaction to improve public awareness and support first-responder training (Sermet & Demir, 2019). More broadly, 3D simulations enable real-time scenario analysis in smart-city planning and disaster-risk reduction, offering planners and decision-makers an intuitive interface for exploring sustainable development options (Jamei et al., 2017). Tools like Hydro3DJS, a modular 3D visualization library for hydrology and climate data, highlight how web-based immersive approaches can support both professional analysis and learning (Sajja et al., 2025d).

Recent efforts have also focused on integrating authoritative environmental data sources into immersive visualization. Systems such as NOAA's READY provide real-time meteorological data and model outputs for emergency management and air-quality applications (Rolph et al., 2017), while NOAA's National Centers for Environmental Information have migrated ocean-exploration data into cloud-based 3D web scenes for collaborative analysis (Ruby et al., 2020). Mobile AR applications now stream live hydrologic and meteorologic annotations, such as rainfall intensity or sensor readouts, using smartphone sensors and open APIs (Haynes et al., 2018). Service-oriented frameworks built on the OGC SensorThings API provide standardized access to real-time environmental sensor networks for visualization and simulation (Zhang et al., 2023).

More recently, extended-reality systems such as MetIVA enable immersive exploration of dynamic earth-science data with real-time streaming and multi-user interaction (Zhang et al., 2025). Collectively, these examples illustrate a growing convergence between immersive interfaces, sensor integration, and environmental analytics, principles further extended in AI-enabled systems such as the Educational AI Hub, which delivers conversational, data-driven assistance for environmental science education (Sajja et al., 2025a).

Parallel advances in digital-twin frameworks have transformed how environmental and infrastructure systems are represented and managed. In flood prediction, digital twins combine hydrologic and meteorologic data with AI and deep learning to simulate flood dynamics, assess risk, and guide emergency planning (Manocha et al., 2025; Ghaith et al., 2022). They support real-time monitoring, situational awareness, and optimization of evacuation routes for disaster resilience (Kim et al., 2025). For climate visualization and infrastructure monitoring, digital twins replicate environmental impacts on buildings and energy systems, supporting predictive maintenance and adaptation planning (Chen et al., 2024).

Immersive digital-twin models developed in modern game engines further enhance public understanding and stakeholder engagement through accessible, realistic visualizations of environmental processes (Yin et al., 2024; Bakhtiari et al., 2023). Nonetheless, persistent challenges remain in data harmonization, model validation, and cybersecurity when integrating heterogeneous real-time data (Setijadi Prihatmanto et al., 2025; Astarita et al., 2024). Complementary research in multi-agent AI frameworks, such as the Multi-Hazard Tournament for collaborative flood-mitigation planning, demonstrates how conversational and agent-based systems can enhance environmental decision-making (Kadiyala et al., 2025).

At the same time, domain-specific large language models (LLMs) and embedding systems are advancing the analytical backbone for environmental data processing. HydroLLM-Benchmark provides a standardized evaluation framework for LLMs in hydrology (Kizilkaya et al., 2025), while HydroEmbed introduces fine-tuned sentence-embedding models to improve retrieval and semantic matching in scientific Q&A systems (Sajja et al., 2025e). Broader bibliometric analyses reveal rapidly expanding research on LLM applications in hydrology, climate modeling, and environmental policy, underscoring challenges in transparency and data ethics (Sajja et al., 2025c). These developments suggest a clear trajectory toward integrating LLM-powered analytics with immersive visualization and decision-support systems.

Collectively, prior research demonstrates significant progress in combining immersive visualization, geospatial analytics, and environmental modeling. However, most existing systems remain fragmented, focusing on either photorealistic rendering or analytical integration but rarely achieving both in real time. Few frameworks fully incorporate authoritative datasets from agencies such as USGS and NOAA or provide seamless multi-modal interaction through voice and AI-driven analysis. This study advances the field by introducing VRFIS, which unifies real-time environmental data ingestion with high-fidelity visualization using Unreal Engine 5 and Google 3D Tiles, supported by adaptive interaction modalities. By bridging immersive realism, dynamic analytics, and educational usability, VRFIS addresses enduring limitations in existing geospatial visualization and environmental decision-support platforms.

3. Methodology

This section outlines the methodological framework adopted for the development of VRFIS, detailing its objectives, architectural design, data integration workflow, and interactive control mechanisms. The methodology emphasizes the translation of environmental and geospatial information into an intuitive, photorealistic, and interactive virtual environment. Each component, from data ingestion to user interaction, was designed to enhance accessibility, analytical value, and spatial understanding for research, decision-making, and education.

3.1. Scope and Purpose

This section presents the methodological framework for developing VRFIS, emphasizing how geospatial and environmental data were translated into an interactive, photorealistic, and analytically rich virtual environment. The design process integrates visualization science, game-engine engineering, and data-driven modeling to support research, decision-making, and education. Each methodological layer, from data acquisition and synchronization to rendering, interaction, and user testing, was organized to maximize realism, responsiveness, and interpretability. The system leverages the combined strengths of Unreal Engine 5 and Google Photo Realistic 3D Tiles, establishing a flexible architecture that enables real-time environmental visualization across multiple spatial and temporal scales.

The primary scope of this project is to transform how users interact with complex geographic and environmental datasets by replacing static, two-dimensional analysis with immersive, experiential exploration. Built to serve environmental scientists, urban planners, policymakers, and educators, the platform allows users to navigate and interrogate spatial information across the United States in a realistic 3D environment. Photorealistic rendering and real-time data streaming facilitate examination of phenomena such as coastal flooding, watershed dynamics, and urban microclimates, while intuitive controls enhance spatial awareness and cognitive engagement. By offering a unified digital-twin environment that fuses analytical accuracy with visual fidelity, the framework bridges scientific modeling, environmental education, and decision support. Although the system operates within the current computational limits of Unreal Engine 5 and Google 3D Tiles, it establishes a foundation for future extensions, such as AI-driven analytics, collaborative multi-user environments, and adaptive educational modules, positioning immersive technologies as a new standard for geospatial data interaction.

3.2. System Design and Architecture

VRFIS is built upon a modular and scalable architecture designed to integrate real-time environmental data with photorealistic visualization and multimodal user interaction. Its design philosophy emphasizes interoperability, scientific accuracy, and user immersion, combining advanced rendering technologies with dynamic data ingestion from authoritative sources. The architecture aligns with three foundational pillars: (i) data integration, ensuring continuous and reliable access to environmental datasets from USGS, NOAA, and other providers; (ii) visualization and rendering, leveraging Unreal Engine 5, Google Photo Realistic 3D Tiles, and

Cesium for Unreal to deliver geospatially precise and high-fidelity environments; and (iii) interaction and control, enabling intuitive engagement through controllers, voice commands, and AI-assisted interfaces. These elements form a unified ecosystem that transforms environmental data exploration into an interactive, analytically rigorous, and educationally enriching experience.

3.2.1. Overall Architecture

VRFIS follows a modular architecture integrating real-time environmental data acquisition, photorealistic rendering, and multimodal user interaction within a unified virtual-reality environment. The system is developed in Unreal Engine 5, chosen for its real-time rendering capabilities, dynamic lighting, and native VR optimization. Its layered structure separates data integration, visualization, and interaction control, ensuring scalability and extensibility across research and educational use cases.

At the core of the architecture, environmental and geospatial data are streamed from authoritative sources into a photorealistic 3D representation of the United States. The visualization pipeline combines Google Photo Realistic 3D Tiles for detailed terrain and infrastructure rendering with Cesium for Unreal Engine for precise geospatial alignment and coordinate management. A dedicated data-synchronization layer handles API communication, caching, and update management, guaranteeing minimal latency during immersive exploration.

User embodiment and control are managed through the VR Pawn framework in Unreal Engine, enabling natural movement, teleportation, and interactive engagement via hand controllers or voice input. Together, these components form a responsive environment that bridges analytical accuracy, scientific visualization, and intuitive human interaction. Figure 1 illustrates the overall system architecture, showing the integration between the Unreal Engine core, data sources, visualization stack, and the diverse application domains supported by the framework.

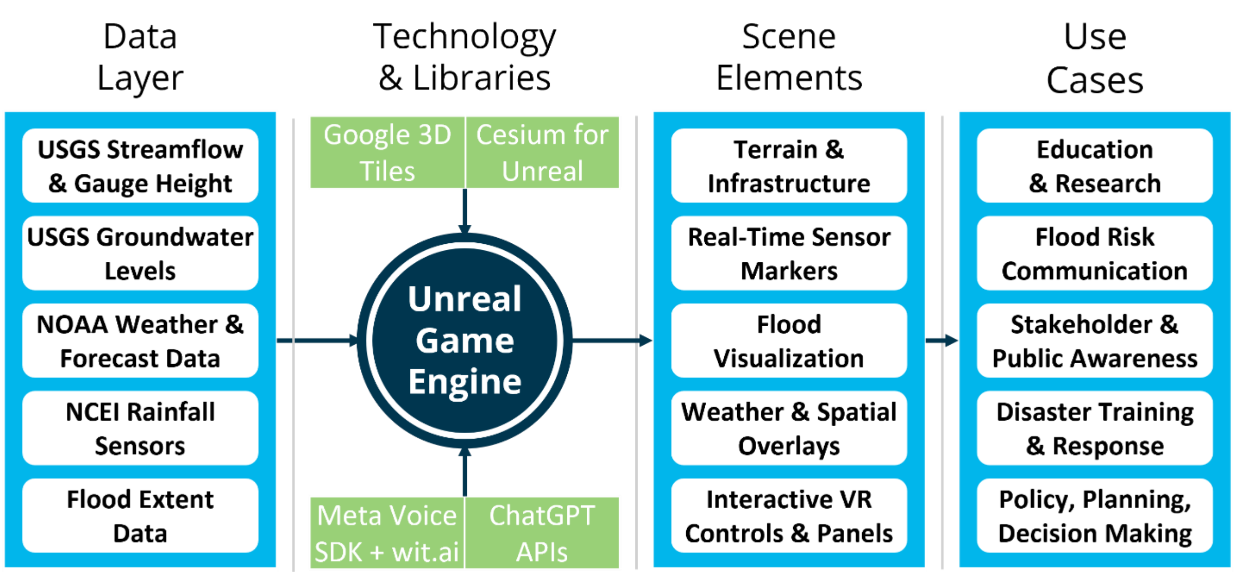

Figure 1. System architecture and components of the VRFIS

The framework integrates real-time environmental data (USGS, NOAA, RWIS) with photorealistic 3D visualization in Unreal Engine 5 using Google 3D Tiles and Cesium for Unreal. Supporting modules such as Google Maps APIs and Voice SDK enable interactive control, dynamic simulation, and educational applications across environmental research, planning, and decision support.

3.2.2. Data Integration and Sources

VRFIS integrates a comprehensive set of APIs to provide real-time, high-fidelity environmental data. These APIs collectively enable the visualization of hydrologic, meteorologic, and geospatial phenomena within a single immersive environment, ensuring both analytical accuracy and experiential engagement. The system incorporates multiple authoritative data streams to ensure accurate and up-to-date environmental representation. The primary data sources include: (i) the USGS Instantaneous Values (IV) Service, which provides real-time hydrologic data, including streamflow, water quality, and groundwater levels, from thousands of monitoring sites across the United States, supporting visualization of live hydrologic conditions and flood-risk assessment; (ii) the USGS Site Service, which supplies detailed metadata such as coordinates, sensor types, and site descriptions to ensure accurate spatial placement and contextual representation of monitoring sites within the VR environment; (iii) the USGS Groundwater Service, delivering groundwater-level observations from a nationwide well network to support coupled surface–subsurface hydrologic analysis; (iv) the NOAA Forecast and Alerts Service, providing meteorological forecasts and severe-weather alerts to enable real-time simulation of storms, droughts, and other weather-driven events; (v) the NOAA National Centers for Environmental Information (NCEI) Rain Sensors, offering both historical and live precipitation data to animate rainfall events and analyze precipitation-driven processes such as runoff and inundation; and (vi) the Iowa Road Weather Information System (RWIS), delivering road-surface data, including temperature, precipitation, visibility, friction, and ice indices, to support transportation safety analyses and assessment of storm impacts.

Table 1. Summary of data sources integrated into the VRFIS

Provider	Service	Data
USGS	Instant Value	Various parameters (i.e., Gage height, Streamflow etc.)
	Site Service	Site information
	Ground water	Various parameters (i.e., Gage height, Dissolved oxygen, etc.)
NOAA	Forecast	Temperature, Dewpoint, Relative humidity
	Alert Service	Alerts
	NCEI	Rain site information
IDOT	RWIS	Surface Condition, Ice Percentage, Friction Index, Route ID
FEMA	Flood Maps	FloodMaps TIN

Additionally, flood-extent data from FEMA are integrated through a FloodMaps API, referred to here as the *FloodMaps* module. This custom service generates region-specific triangulated irregular network (TIN) or GeoJSON datasets that model flood extents under varying hydrologic conditions. The resulting data are dynamically streamed into Unreal Engine, where they are procedurally converted into 3D meshes for interactive flood visualization and analysis. This internal service enables flexible, on-demand generation of high-resolution flood layers without dependence on external data pipelines. The system's API integration layer handles all asynchronous data retrieval, preprocessing, and synchronization, ensuring continuity between data ingestion and visualization updates.

3.2.3. Rendering and Visualization Architecture

High-fidelity rendering and spatial accuracy form the core of the VRFIS visualization architecture, enabling realistic and data-driven representations of geographic environments. The system leverages the combined strengths of Google Photo Realistic 3D Tiles, Cesium for Unreal SDK, and Unreal Engine 5's advanced rendering pipeline to deliver photorealistic, georeferenced, and interactive scenes. This architecture ensures that users experience a scientifically faithful and visually compelling environment that supports both exploration and analysis.

The visualization workflow begins with the Google Photo Realistic 3D Tiles dataset, which provides globally available, photogrammetric models of terrain and built infrastructure. These 3D Tiles are streamed dynamically into Unreal Engine through Cesium's tile-loading architecture, optimizing level-of-detail (LOD) transitions and minimizing latency even at national or continental scales. The streaming process allows seamless movement from regional overviews to detailed urban areas without performance degradation, supporting continuous immersion during exploration or analysis.

Integration of Cesium for Unreal SDK ensures that all geospatial features are accurately positioned using real-world coordinates. Key Cesium components enhance both precision and usability, including: (i) the Fly-To Component, which enables smooth, camera-driven transitions to any selected location on the virtual globe, supporting rapid inspection of points of interest; (ii) the Coordinate Conversion tool, which translates between geographic (latitude/longitude) and Unreal Engine's Cartesian coordinate system to maintain consistent spatial alignment across datasets; and (iii) the Origin Shift mechanism, which dynamically re-centers the world origin near the active region to mitigate floating-point precision loss, a common challenge in large-scale 3D environments.

Flood-extent datasets from the FloodMaps module are incorporated directly into this rendering pipeline. Retrieved as GeoJSON or TIN files, these datasets are programmatically converted into procedural meshes within Unreal Engine. Specialized water-material shaders simulate depth variation, reflection, and transparency, producing visually distinct flooded regions that enhance interpretability. Real-time georeferencing ensures these flood layers overlay precisely with terrain and infrastructure data, maintaining analytical validity.

To sustain performance and realism, Unreal Engine 5's Nanite virtualized geometry and Lumen global illumination systems are employed. Nanite enables efficient rendering of massive, high-detail assets without manual optimization, while Lumen provides dynamic lighting and reflections that respond to environmental context and user movement. Together, they create a visually coherent environment that balances scientific accuracy with immersive realism.

3.3. Interaction and Control Mechanisms

VRFIS supports a multimodal interaction framework that enables users to intuitively engage with environmental data through hand controllers, interface panels, voice commands, and conversational AI. These mechanisms collectively enhance accessibility, realism, and analytic depth within the virtual environment, allowing seamless exploration and analysis of complex geographic and environmental datasets.

3.3.1. Controller-Based Interactions

The system employs the VR Pawn architecture in Unreal Engine 5 to represent the user within the virtual environment. The VR Pawn integrates motion tracking, collision detection, and camera components to create a responsive and immersive user embodiment. Key elements include: (i) Motion Controller Components, which translate real-world hand movements into precise virtual actions, enabling object manipulation, selection, and pointing; (ii) Input Mapping and Response, which associates controller buttons and gestures with predefined actions, such as grabbing, teleporting, or activating interface elements, through Unreal Engine's input-mapping system; (iii) Haptic Feedback, which delivers tactile responses based on user interaction, reinforcing realism through physical cues such as vibration during contact or resistance events; and (iv) Pre-configured Components, including VR-specific cameras and motion sensors that ensure head tracking and hand-movement detection function seamlessly across compatible hardware.

For navigation, the Teleportation and Locomotion module minimizes motion sickness by allowing users to point to a target location and instantly reposition the VR Pawn. This mechanism combines comfort with precision and is supplemented by scalable customization options, developers can add new sensors, modify controller mappings, or extend scripts for enhanced input modalities such as eye-tracking or adaptive haptics.

3.3.2. User Controls and Navigation

VRFIS incorporates an integrated menu-based control interface to facilitate data access and environmental interaction. Four main components provide structured interaction capabilities:

Navigator: Governs system navigation and enables voice-mode activation for hands-free control, allowing users to switch between modes and access system functions efficiently.

Weather Panel: Displays real-time meteorological parameters such as temperature, humidity, wind speed, and diurnal light changes through a day/night toggle, providing a continuously updated view of environmental dynamics.

Sensor Toggle Buttons: Allow users to activate or deactivate environmental sensors (e.g., streamflow, groundwater, rainfall, or reservoir data) to customize the visualization according to their analytical needs.

Location Selector: Enables users to focus on specific geographic areas by selecting from a dropdown list or performing direct search queries, automatically re-centering the virtual scene on the chosen location.

This combination of visual and interactive controls ensures that users, from researchers and urban planners to educators, can access and manipulate the data most relevant to their analytical or instructional objectives.

3.3.3. Voice-Based Interactions

To expand accessibility and streamline interaction, the system integrates voice-command functionality using the *Meta Voice SDK* in conjunction with *wit.ai*. Users can issue natural-language commands to navigate the environment, toggle sensors, or modify visualization parameters. Spoken input captured by the headset is transcribed via the Meta Voice SDK and interpreted by wit.ai, which extracts user intent and entities. Primary configurations include: (i) Intents, defining the purpose of commands, such as *navigate_to_place*, *sensor_control*, *turn_on_switch*, and *turn_off_switch*; (ii) Entities, representing specific parameters (e.g., *location*, *operation_name*, *switch*) extracted from user utterances; and (iii) Utterances, a trained dataset of example phrases such as "Fly to New York City," "Activate the rain sensors," or "Disable the flood map." Once wit.ai identifies intent and parameters, the system uses the Google Reverse Geocoding API to resolve place names into precise geographic coordinates, enabling geospatial navigation through the Cesium engine.

3.3.4. AI Integration layer

To augment voice interaction with reasoning and analysis capabilities, the system integrates ChatGPT APIs for both conversational and visual understanding tasks.

Voice Based ChatGPT Integration: Enables real-time dialogue between the user and the system. Voice input, captured and processed through the Meta Voice SDK and wit.ai, is interpreted by ChatGPT to retrieve or summarize environmental data, respond to contextual queries, and adjust visualization settings. Custom optimization for accent variation, background noise, and latency ensures natural conversation without disrupting immersion.

Image Based Search: Powered by the *ChatGPT Vision API*, allows users to capture in-scene screenshots or object views within the VR environment. These images are analyzed to identify objects, interpret environmental elements, and return descriptive or analytical insights directly to the VR interface. Visual feedback is designed to appear seamlessly within the 3D scene, enriching environmental exploration and supporting educational use cases that rely on contextual interpretation and visual accuracy.

4. Results and Discussion

4.1. System Interface and Visualization Overview

VRFIS presents an integrated, data-driven virtual environment designed for intuitive environmental exploration and analysis. Figures 2–5 show the system's primary user-interface components and the visual outputs that link real-time data to immersive spatial representation.

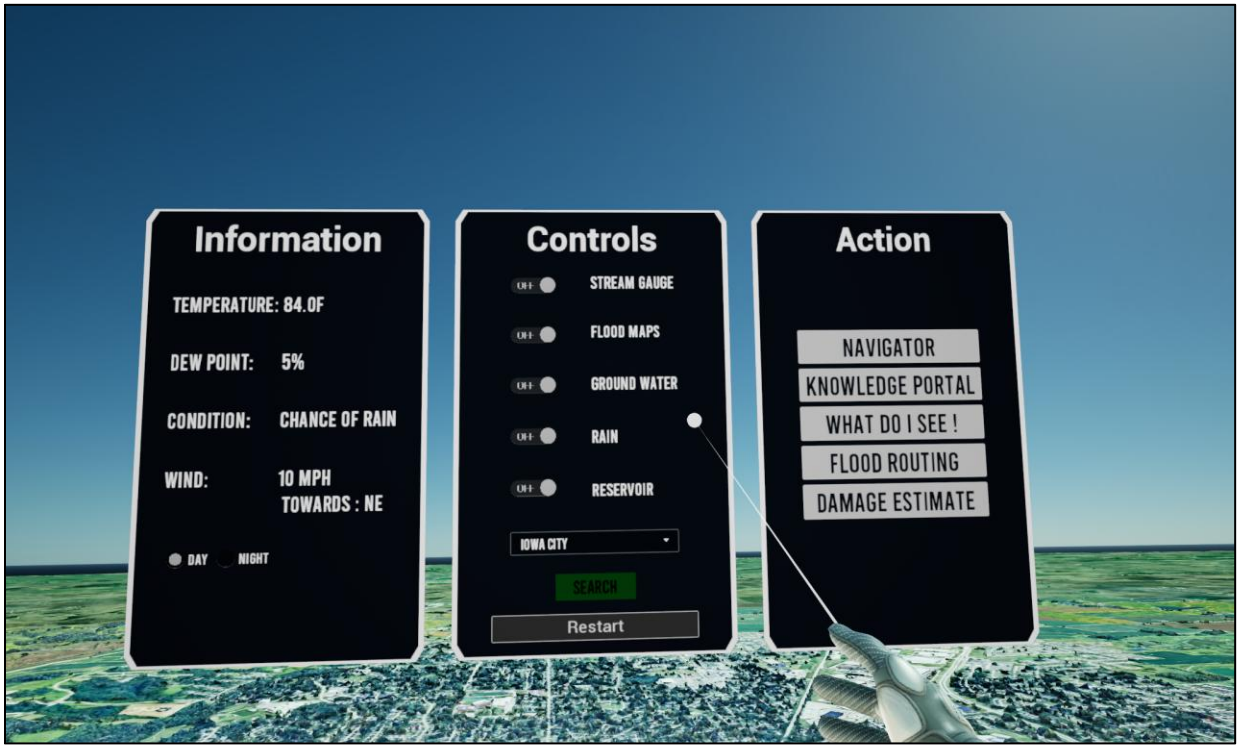

Figure 2. The control panel which includes panels for weather information, controls switch sensors and voice command center

As shown in Figure 2, the main control interface organizes environmental and navigation functions into three coordinated panels, *Information*, *Controls*, and *Action*. The Information panel displays real-time meteorological variables such as temperature, dew point, and wind speed, while the Controls panel manages data-layer visibility, enabling users to toggle between hydrologic datasets (e.g., stream-gauge readings, groundwater levels, flood maps, rainfall, and reservoir data). The Action panel provides quick access to system utilities such as the Navigator, Knowledge Portal, and Flood Routing functions. Together, these panels create a structured, ergonomic interface that allows users to interact with multiple data layers simultaneously while maintaining immersion.

Figure 3 illustrates the spatial rendering of *USGS monitoring sites* within the virtual environment. Each marker corresponds to a real sensor location and provides interactive metadata including discharge, gage height, and stream-gauge identification. This visualization enables the user to interpret hydrologic conditions in geographic context, linking live sensor measurements to their physical surroundings and supporting both analysis and instruction on flood-risk awareness.

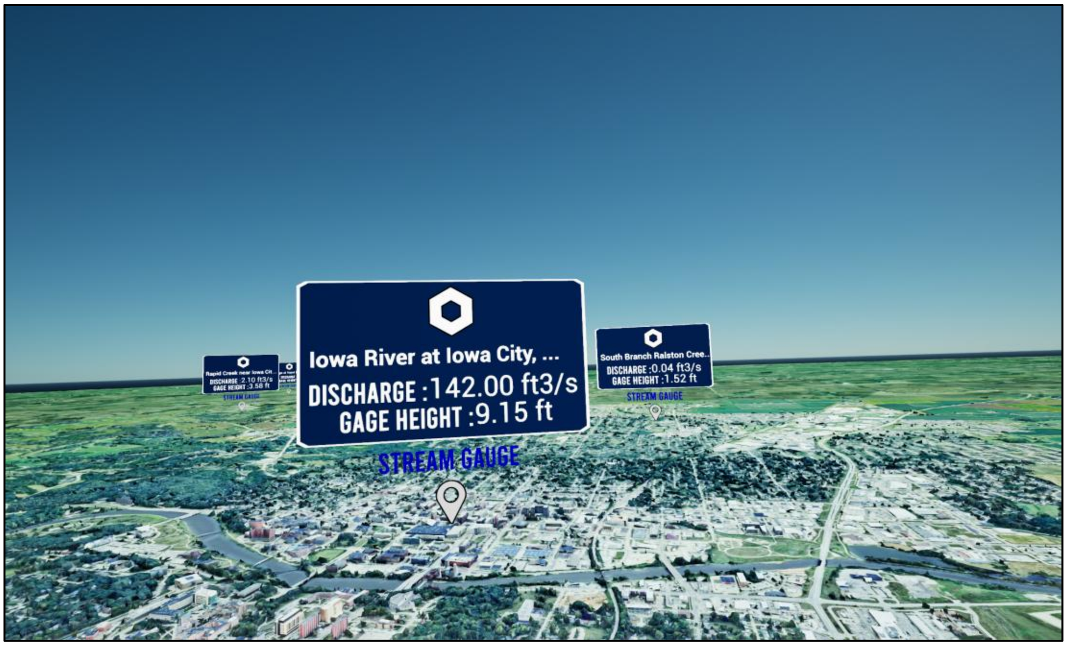

Figure 3. USGS Sensor location marker with information panel

The photorealistic environmental rendering shown in Figure 4 depicts the Iowa River at Iowa City using Google 3D Tiles streamed through Cesium for Unreal. The integration of topographic and urban-infrastructure data creates a high-fidelity view of the landscape, allowing users to assess inundation patterns, infrastructure exposure, and hydrologic connectivity. The realism of these renderings enhances spatial understanding for planners and researchers studying flood dynamics or urban-watershed interactions.

Figure 4. Flood Map of Iowa River at Iowa City

4.2. System Demonstration and Evaluation

VRFIS was introduced and discussed in an exploratory, formative evaluation setting through oral presentations at two professional venues: the 12th International Congress on Environmental Modelling and Software (iEMSs) and the 60th Anniversary Joint Water Resources Conference organized by the American Water Resources Association (AWRA), the Universities Council on Water Resources (UCOWR), and the National Institutes for Water Resources (NIWR). Across these events, the system was presented to an audience of over 40 stakeholders from federal agencies (e.g., USGS representatives), state agencies, academic institutions, and private-sector firms developing commercial water-resources and visualization solutions.

Attendees included hydrologists, water-resources engineers, floodplain managers, GIS and geospatial analysts, environmental modelers, educators, and technology developers working on decision-support and visualization tools for agencies and municipalities. Following each presentation, feedback was obtained through question-and-answer sessions and informal follow-up discussions in which participants commented on data integration, usability, realism, and potential application domains. Although no formal questionnaires or structured usability instruments were administered, these interactions provided targeted, domain-informed insights that guided the identification of strengths, limitations, and priority areas for future development.

Data Integration and Accuracy: Participants consistently commended the integration of multiple data sources (USGS Instantaneous Values, NOAA forecasts, and flood alerts) into a unified, spatially coherent environment. Stakeholders from agencies and consulting firms in particular emphasized that being able to see hydrologic and meteorologic information "in one place" helped them mentally connect river conditions, rainfall patterns, and warning products. At the same time, several attendees asked detailed questions about refresh rates, latency, and provenance indicators (e.g., timestamps, source labels), underscoring that real-time or near-real-time updates alone are not sufficient unless users can clearly judge how current and trustworthy the displayed data is. These discussions highlighted that data synchronization, explicit communication of update times, and visible indicators of data reliability are central to user confidence in the visualizations.

User Experience and Interface: The interface was widely praised for its intuitiveness and clarity in navigating complex geospatial layers, especially by users with limited prior VR experience. Many attendees reported that basic operations, such as flying to a location, toggling data layers, and opening sensor pop-ups, were easy to discover and perform. More advanced users, including GIS specialists and modelers, expressed interest in deeper control and direct access to advanced Cesium functionalities such as the Fly-To and Coordinate Conversion components, as well as precise coordinate readouts and finer-grained layer management. This contrast between novice and expert expectations highlighted the need to balance a clean, approachable interface with pathways to more technical tools, and it reinforced the importance of user-centered design that can accommodate differing levels of expertise.

Educational Applications: Educators and outreach-oriented participants expressed strong interest in adopting the system as an immersive teaching and communication tool. They described potential use cases ranging from introductory demonstrations of watersheds and floodplains to advanced, scenario-based exercises in university hydrology and urban-planning courses. Several noted that VRFIS could effectively support "virtual field trips," enabling students to visit locations they might not physically reach and to explore real sensor data in context. Comments emphasized that the ability to move through a landscape, see infrastructure at risk, and interrogate live data in situ could improve engagement and help learners internalize abstract concepts such as recurrence intervals, watershed connectivity, and floodplain dynamics. A number of attendees also suggested that structured guidance, such as stepwise tasks or on-screen prompts, would be valuable in a classroom setting to channel student exploration toward specific learning objectives.

Realism and Immersion: The use of Google Photorealistic 3D Tiles was praised across stakeholder groups for delivering high levels of detail and spatial fidelity, allowing users to recognize familiar landmarks and assess terrain and infrastructure in a way that felt closely aligned with the real world. Participants commented that this realism increased their sense of presence and made it easier to discuss potential impacts with nontechnical audiences who might struggle to interpret traditional maps. At the same time, some attendees cautioned that highly realistic backgrounds could lead users to assume that all overlaid information (e.g., flood extents) is equally precise, even when derived from simplified scenarios or coarse-resolution inputs. Others expressed interest in more interactive environmental behaviors, such as seeing water levels rise along streets or riverbanks, indicating that users are attuned not only to visual fidelity but also to how convincingly dynamic processes are represented in the immersive environment.

Scalability and Performance: Some participants raised concerns about maintaining smooth performance when exploring large geographic areas, dense urban scenes, or multiple active data layers. We reported potential issues such as occasional frame-rate drops, brief pauses while tiles loaded, and visual clutter when many sensors were displayed simultaneously, particularly on mid-range hardware. These potential issues were especially of interest among attendees who imagined deploying VRFIS in classroom, training, or agency settings where hardware may not be top-tier. Such feedback stressed that perceived usefulness is closely tied to responsiveness and comfort in VR, and that users are sensitive to delays, sudden changes in detail, or visual overload when operating at regional or national scales.

Potential for Collaboration: Participants from planning agencies, consulting firms, and research organizations expressed strong interest in extending the system into multi-user, collaborative environments. They envisioned joint sessions in which planners, modelers, emergency managers, and community representatives could inhabit the same virtual space, explore flood scenarios together, and use shared views to support discussion and decision-making. Several attendees noted that a shared immersive environment could facilitate communication across disciplines and with nontechnical stakeholders, by enabling everyone to "look at the same thing" while discussing trade-offs, vulnerabilities, and proposed interventions. This feedback underscored that stakeholders see VRFIS not only as an individual analysis tool but also as a potential platform for collaborative planning, training, and stakeholder engagement.

4.3. Challenges and Recommendations

The development and deployment of VRFIS revealed several technical and design challenges that inform future enhancements.

Data Integration Complexity: Incorporating multiple live APIs, especially from USGS and NOAA, posed synchronization challenges. Maintaining real-time consistency and minimizing latency across hydrologic, meteorologic, and flood data streams required careful optimization of the data-handling layer. Differences in temporal resolution, data formats, and update schedules further complicate seamless integration, occasionally leading to short-lived mismatches between displayed layers. Future work will focus on implementing a more robust middleware layer with standardized data schemas, event-driven synchronization, and prioritization strategies (e.g., critical alerts vs. background updates), as well as tools for monitoring API health and automatically handling outages or degraded service.

Performance Optimization: Achieving high visual fidelity while sustaining real-time frame rates was a persistent challenge, particularly when rendering large-scale datasets. Balancing graphical realism with computational efficiency remains a core technical goal for future iterations. In dense urban areas or when multiple dynamic layers are enabled, rendering demands can exceed the capabilities of typical VR hardware, increasing the risk of discomfort or motion sickness. Planned improvements include more aggressive and adaptive level-of-detail management, selective streaming of tiles and data layers based on user focus, and GPU-aware resource allocation strategies to dynamically adjust visual complexity while preserving smooth and comfortable VR experience.

User Interaction and Feedback: Designing an interface accessible to both novice users and experts proved difficult. Feedback underscored the need for customizable user interfaces and adaptive complexity levels to better accommodate different use cases. Some users preferred minimal controls and guided workflows, while others requested deeper, more technical access to parameters and analytics. Future development will prioritize role-based interface configurations (e.g., “educator,” “student,” “analyst,” “planner”), in-system tutorials and onboarding, as well as configurable dashboards that allow users to tailor control panels, data overlays, and AI assistance to their experience level and task requirements.

System Limitations: The reliability of the visualizations depends on the accuracy and completeness of source data. Gaps or inaccuracies in upstream datasets can propagate to visual outputs and may not always be obvious to end users. Moreover, the system’s reliance on Unreal Engine 5 and Google 3D Tiles imposes certain constraints on flexibility and dataset compatibility, such as limited support for proprietary formats or custom simulation meshes without additional preprocessing. Future work will explore broader interoperability through standardized geospatial formats and OGC-compliant services, as well as mechanisms for flagging data quality issues directly within the VR environment. In parallel, modularizing the platform to support alternative rendering backends and tile providers will reduce dependence on any single technology stack and facilitate long-term maintainability.

Data Quality and Uncertainty: The accuracy and interpretability of VRFIS outputs are fundamentally constrained by the quality, continuity, and resolution of upstream datasets. At present, the system visualizes nominal values without explicitly representing uncertainty, confidence intervals, or data gaps. This can lead users to overestimate the precision of the displayed information, particularly during extreme events when sensor performance may degrade. Future work will focus on incorporating uncertainty visualization and metadata surfacing to better communicate data reliability.

Hardware Constraints: The immersive experience and high-fidelity rendering in VRFIS currently require relatively powerful hardware, including a dedicated GPU, sufficient system memory, and a tethered or high-end standalone VR headset. On lower-specification systems, users may encounter reduced frame rates, simplified level-of-detail, or restricted scene complexity, which can diminish immersion and analytical usefulness. Comprehensive optimization for a wider range of devices, including standalone headsets and mid-range workstations, remains an important step toward broader accessibility and deployment in educational and professional settings.

Network Dependence and Reliability: VRFIS relies on continuous internet connectivity for streaming Google Photorealistic 3D Tiles and retrieving real-time data from USGS, NOAA, and other APIs. High latency, limited bandwidth, or intermittent connectivity can result in delayed tile loading, incomplete data layers, or inconsistent updates, particularly in bandwidth-constrained environments such as field deployments or developing regions. While basic caching strategies alleviate some of these issues, future enhancements will emphasize more robust offline modes, adaptive data throttling, and resilient synchronization mechanisms to maintain usability under variable network conditions.

5. Conclusion

VRFIS developed using Unreal Engine 5 and Google Photo Realistic 3D Tiles represents a major advancement in the visualization and interaction of geographic and environmental data. By leveraging virtual reality's immersive and spatial capabilities, the system provides the means of exploring complex, multi-source datasets in contextually rich environments. This approach enables users to interpret environmental processes, assess hydrologic and meteorological conditions, and engage with spatial information more intuitively than through traditional 2D or web-based platforms.

The project demonstrates the transformative potential of immersive technologies across disciplines such as environmental science, hydrology, urban planning, and geography education. Real-time integration of authoritative data sources, from USGS, NOAA, and RWIS, combined with high-fidelity rendering, establishes a foundation for analytical precision and experiential engagement. Feedback from demonstrations and academic audiences highlights the system's strengths in realism, interactivity, and educational value, affirming its promise as both a research and teaching tool.

At the same time, this work has revealed opportunities for enhancement, particularly in the areas of data integration, system performance, and user adaptability. To address these, future development will focus on: (i) Improved real-time synchronization and caching to ensure low-latency, stable updates across data streams; (ii) Performance optimization for large or multi-layered geographic scenes through adaptive level-of-detail management; (iii) Customizable user interfaces and collaborative functionality, enabling multiple users to interact and analyze data simultaneously within the same immersive environment; and (iv) Expanded environmental simulations, including dynamic scenario modeling for floods, rainfall, and land-use change to support predictive and educational applications.

In conclusion, VRFIS demonstrates potential for how environmental and geographic data can be visualized, analyzed, and communicated. By bridging photorealistic rendering, real-time data analytics, and AI-assisted interaction, the framework moves beyond visualization to serve as an intelligent decision-support and educational platform. Continued refinement and expansion will position such immersive and intelligent endeavors as a cornerstone technology for next-generation environmental research, public communication, and experiential learning.

Declaration of Generative AI and AI-Assisted Technologies

During the preparation of this manuscript, the authors used ChatGPT, based on the GPT-5 model, to improve the flow of the text, correct grammatical errors, and enhance the clarity of the writing. The language model was not used to generate content, citations, or verify facts. After using this tool, the authors thoroughly reviewed and edited the content to ensure accuracy, validity, and originality, and take full responsibility for the final version of the manuscript.

Competing Interest Declaration

The authors declare no relevant financial or non-financial interests.

Data Availability

All data produced and analyzed in the manuscript are readily available and presented in the manuscript.

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Contributions

Uditha Herath Mudiyanselage: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Original Draft, Software, and Visualization. **Jerry Mount**: Writing - Original Draft, Software. **Ramteja Sajja:** Validation, Visualization, and Writing - Review & Editing. **Yusuf Sermet:** Writing - Review & Editing, Methodology, Conceptualization, Software, Supervision, Funding acquisition, and Validation. **Ibrahim Demir:** Writing - Review & Editing, Conceptualization, Project administration, Funding acquisition, and Resources.

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