An Immersive Hydroinformatics Framework with Extended Reality for Enhanced Visualization and Simulation of Hydrologic Data

Uditha Herath Mudiyanselage[1,3], Eveline Landes Gonzalez[2,3], Yusuf Sermet[3], Ibrahim Demir[3,4,5]

[1] Computer Science, University of Iowa
[2] Informatics, University of Iowa
[3] IIHR Hydroscience & Engineering, University of Iowa
[4] Civil and Environmental Engineering Department, University of Iowa
[5] Electrical and Computer Engineering Department, University of Iowa

Corresponding Author: Yusuf Sermet, msermet@uiowa.edu

Abstract

This study introduces a novel framework, with the use of Extended Reality (XR) systems in hydrology, particularly focusing on immersive visualization of hydrologic data for enhanced environmental planning and decision-making. The study details the shift from traditional two-dimensional data visualization methods in hydrology to more advanced XR technologies, including virtual and augmented reality. Immersive information systems facilitate dynamic interaction with real-time hydrological and meteorological datasets for various stakeholders and use cases and paves the way for metaverse and digital twin systems. This system, accessible via web browsers and virtual reality (VR) devices, allows users to navigate a 3D representation of the continental United States, engaging with detailed environmental data. The paper addresses the current limitations in hydrological visualization, methodology, system architecture while discussing the challenges, limitations, and future directions to extend its applicability to a wider range of environmental management and disaster response scenarios, highlighting the potential of XR systems in transforming data visualization and its future applications in hydroinformatics.

Keywords: Hydrology, Data Visualization, Immersive Environments, Digital Twin, Metaverse

1. Introduction

Historical practices of data collection and visualization in hydrology were firmly rooted in two-dimensional methodologies. These traditional approaches often relied on graphical representations, primarily in the form of graphs, which served as the cornerstone for analytical procedures and the extraction of meaningful insights (Linsley, 1978; Demir at al., 2009). Nevertheless, the inexorable march of technological progress brought about a transition towards computational techniques, leading hydrological research towards the adoption of physical and statistical models (Ramirez et al., 2022).

It is noteworthy that as computational methodologies gained prominence, the evolution of data visualization techniques was also significantly influenced by technological advancements. An illuminating review of this transformation can be found in the work of Ladson et al. (2018), which not only elucidates the process of creating such visualizations but also proposes avenues for enhancement. Despite the prevalence of graphical methods in the field, a paradigm shift occurred with the ascendancy of data-driven analyses (Li and Demir, 2022).

Hydrological data is inherently complex, characterized by multifaceted attributes, including multivariate properties, temporal dependencies, diverse origins, and data from various sources or models and simulations (Kehrer, 2011). Compounded with growing efficiency in data collection, the intricate nature of hydrological data has presented formidable challenges to researchers and decision-makers (Kehrer, 2011). The voluminous and multivariate nature of these datasets has made the extraction of critical insights a daunting task, thus hindering the potential to apply the data effectively (Chalh et al., 2015; Demir et al., 2022).

In the realm of environmental management and planning, hydrological data plays a pivotal role in supporting intricate decision-making processes, with a pronounced emphasis on the social dimensions of water resource management (Xu et al., 2022). This emphasis is rooted in the imperative need for decisions regarding water resources to align with the understanding, consent, and endorsement of local stakeholders, encompassing water managers, landowners, and residents (Alabbad et al., 2024). Given this critical focus on comprehension and stakeholder engagement, effective representation of data assumes paramount significance in this field (Carson et al., 2018).

This study introduces an innovative framework utilizing Extended Reality (XR) to transform the visualization of hydrologic data in environmental planning and decision-making. This framework leverages the Unity Engine and Mapbox Maps Software Development Kit (SDK) as the base and WebXR exporter and Virtual Reality Tool Kit (VRTK) SDK for dynamic interaction with real-time hydrological and meteorological data. This system, accessible via web browsers and VR devices, enables users to navigate a 3D representation of the continental United States, interactively engaging with detailed environmental data from federal agencies like United States Geological Survey (USGS) and National Oceanic and Atmospheric Administration (NOAA).

The project marks a significant shift from traditional 2D data visualization methods in hydrology to more advanced XR technologies, encompassing virtual and augmented reality

(Daniela, 2020). This approach not only enhances the comprehension of complex hydrologic data but also facilitates collaborative planning and informed decision-making in environmental management and disaster response scenarios.

2. Related Work

A promising avenue that has gained prominence in recent years is the adoption of XR systems. While XR systems have witnessed substantial adoption in various realms (Hughes et al., 2005; Cheok et al., 2009), there still remains untapped potential for diverse applications in the hydrological sciences. Creating virtual realities often necessitates the use of visualization construction tools, which, while valuable, have been critiqued for their limitations in user manipulation and control (Korkut & Surer, 2023). Furthermore, the utilization of visualization-based software libraries has mitigated the complexities of creating graphical visualizations, albeit at the cost of requiring a certain degree of familiarity with technological systems (Korkut & Surer, 2023).

Augmented and virtual reality applications present an opportunity to develop fully immersive experiences to recreate real-time and historical disaster scenarios (Yildirim et al., 2022) in a controlled experimental environment that allows repetition. In the environmental sciences, applications of XR technology have proliferated with a strong emphasis on education. This can be exemplified by the Virtual Hydrology Observatory, which is designed to augment student learning by offering immersive field experiences from within the classroom setting (Su et al., 2009). Other projects extend the concept to virtual field trips, enabling users to explore geographic locations that are relevant and representative to current topics of study. Such is the case with VR4Hydro, which allows for digital tours within the catchment of the Gersprenz river in an immersive fashion (Grosser et al., 2023). XR technology is also being explored for its utility in hydrological visualizations, as evidenced by Hedley et al., who integrates augmented reality technology into the visualization of geographic and hydrological information, facilitating real-time data exploration while navigating a modeled terrain (Hedley et al., 2002).

In the realm of XR technologies for environmental disaster management and response, significant strides have been made. Sermet and Demir (2019) presented Flood Action VR, a virtual reality tool designed for disaster awareness and emergency training, integrating real-time weather data and gamification strategies. They further expanded their research by emphasizing the integration of XR in environmental education, disaster management, and data visualization to enhance decision support and public awareness (Sermet and Demir, 2020).

Another notable contribution is from Demiray et al. (???), who developed FloodGame, an interactive 3D serious game on flood mitigation for disaster awareness and education. This web-based game focuses on educating users about flood mitigation strategies, using realistic 3D environments to foster community resilience and engagement. Further, XR technology has been effectively used in data visualization and situational analysis, as illustrated by Ready et al. (2018), Haynes et al. (2018), and Macchione et al. (2019), showcasing its utility in presenting complex environmental data in an accessible format.

In immersive disaster simulation, Kawai et al. (2015) introduced an AR-based tsunami evacuation drill system that challenges users to navigate disaster scenarios within time constraints. Iguchu et al. (2016) developed a gamified disaster evacuation training framework, enhancing disaster response education by immersing users in various scenarios. Finally, Wang et al. (2019) utilized VR to simulate floods, integrating hydrological models into a 3D environment, providing a realistic experience of flood scenarios. These developments underscore the immense potential of XR systems in revolutionizing the visualization and understanding of hydrological data, opening doors for innovative applications to environmental planning and decision making.

2.1. Gaps and Limitations in Previous Approaches

While the adoption of XR technology in the field of hydrological visualization has been steadily increasing (Demir et al., 2022), the predominant focus of these endeavors has been the enhancement of educational experiences. Many of these initiatives are tailored for classroom settings and involve providing students with some means of visualizing and exploring hydrological processes. Notably, a dearth of efforts exists concerning the development of digital systems for hydrological visualization that directly cater to the support of environmental policy formulation, strategic planning, and informed decision-making.

Furthermore, there appears to be a limited number of models that not only facilitate data visualization but also foster face-to-face interactions centered around the data. Augmented reality emerges as a compelling candidate for enabling such interactions (Sermet et al., 2018). AR's unique capacity to encourage collaborative engagement surpasses the capabilities of VR enhancements, making it a particularly promising avenue (Hedley et al., 2002). Moreover, AR seamlessly integrates into pre-established workflows, a characteristic that further enhances its appeal in the context of hydrological visualization (Hedley et al., 2002).

The remainder of this paper is organized as follows. Section 3 will discuss the methods used to create the virtual environment. Section 4 presents the products of our development along with a discussion of the available features. Section 5 presents a summary of our work as well as highlighting plans for future research.

3. Methodology

This project is part of an ongoing effort to create open information system frameworks that have widespread applications to various situations with the ultimate goal of enhancing environmental planning and decision making. One significant step towards this goal was the development of HoloFlood (Demir et al., 2018). HoloFlood is an XR framework designed to simulate flooding events, which are displayed upon surfaces like a hologram. It also provides property-specific estimations for structural and content damage as well as information regarding the population being affected. Stakeholders can use HoloFlood as a decision support tool for disaster planning and response, as it visualizes how a particular area may be affected by different types of flooding (Sermet, 2020).

Building on the developments made through HoloFlood, which was designed to facilitate collaborative, face-to-face planning, the next step involved GeospatialVR advancing this objective by establishing a generalized framework that is aimed at enabling immersive visualizations of floods, fires, and other environmental hazards (Sermet and Demir, 2022). In the context of this paper, the project's goal is to allow for seamless integration of data that supports a large variety of use cases focused on environmental planning, decision making, and emergency response.

The concept of immersion within the context of this project pertains to the extent to which a user perceives the digitally rendered environment as convincingly real. User immersion holds a pivotal role in the framework of this project, supported by empirical evidence demonstrating its capacity to enhance cognitive performance and mitigate the undesirable effects associated with simulation use, often referred to as 'simulation sickness' (Mostajeran et al., 2023).

For systems of this nature to be deemed effective and fit for serious use, it becomes imperative that users experience a profound level of immersion within the digital realm. Without this immersion, there exists a risk of rendering the developed systems unwieldy or evoking a sense of the uncanny, both of which can detrimentally affect the overall user experience (Roberts & Patterson, 2017). By using XR as an integral component of hydrological visualization, our overarching objective is to construct an intuitive workflow that empowers users with an enhanced capability to visualize complex environmental data and processes. It is our hope that creating such a system will pave the way for a more seamless and intuitive data visualization experience that can be used in many relevant scenarios.

3.1. Scope and Purpose

This project endeavors to enhance the immersive visualization of hydrological processes with a specific focus on the continental United States. The primary objective is to enable the visualization of hydrological phenomena and pertinent information throughout the region, thereby providing valuable insights for stakeholders involved in water resources planning. These stakeholders encompass a broad spectrum of individuals and organizations impacted by hydrological events.

While the project primarily caters to planners and decision-makers, its utility extends to a wider audience. The application dynamically generates 3D models to represent terrain and relevant infrastructure, adapting in real-time as users navigate the interface to display terrain tiles visualizing the landscape of the continental United States. All 3D modeling and generation for this process is executed locally, leveraging client-side hardware resources, and eliminating the need for resource-intensive server-side preprocessing.

The application draws upon data from sensors maintained by the United States Geological Survey (USGS) to present real-time information on local weather conditions, stream height, and discharge. By implementing this framework, we contribute to an ongoing endeavor to revolutionize the field of hydrological visualization, facilitating collaborative planning and response to climate-related disasters.

Through the development of this application, we aim to address the following key questions: a) what data sources are most effective for creating immersive hydrological visualizations?; b) how can XR be used to enhance hydrological data visualizations?; c) how can user immersion be created, maintained, and leveraged in data visualization?; and d) what are the future prospects and potential improvements that can be made in the use of XR systems for hydrological data visualization?

3.2. Data Sources

This section delves into the exploration of data sources that significantly contribute to the functionality and efficacy of the immersive hydroinformatics framework. It outlines the process of selecting appropriate map providers, detailing the criteria and considerations that informed this selection, including the evaluation of features such as data availability, geospatial calculation capabilities, and cross-platform compatibility. Furthermore, the section presents an overview of the integration of real-time sensor data, explicating the methodologies employed to incorporate and visualize hydrological and meteorological data from third-party providers.

3.2.1. Review of Map Providers

In the field of interactive geospatial applications, selecting an appropriate map provider is crucial. This is because the available SDKs and libraries consist of different capabilities and cater different requirements. Providers offer a range of services, including the provision of a high-precision WGS84 globe, geospatial calculations, cross-platform compatibility (such as Unity and Unreal game engines, and JavaScript), open-source geospatial data standards, and data pipelines for geospatial information, such as 3D vector tiles. Moreover, they typically feature active community forums where users can find collaborative support for solving problems.

During the project's planning phase, several map providers were evaluated by developing prototypes. The chosen map providers, namely Cesium, Mapbox, and Google's Photogrammetry 3D data, were assessed based on a range of features and services provided such as availability of data, capability of geospatial calculations and cross-platform compatibility.

Cesium: Cesium, a prominent map provider, extends beyond its mapping services to offer various geospatial functionalities. Notably, it has pioneered the development of a standardized format for 3D geospatial objects known as 3D vector tiles. Furthermore, Cesium Ion, an associated service, provides hosting for these vector tiles and streamlines the process of programmatically converting datasets into 3D vector tiles. Unity and Unreal developers can visualize these datasets through Cesium's dedicated SDK. Additionally, Cesium offers certain basic 3D data for free such as OpenStreetMap Building data.

Mapbox: Mapbox, another map provider, stands out for its extensive capabilities. It offers 3D buildings data and the ability to dynamically load and view any location with precision by providing longitude and latitude coordinates. Beyond basic mapping, Mapbox includes valuable features such as live traffic data and bathymetry. Users can choose from various terrain options, including flat terrain and terrains with elevation data. Mapbox displays a high accuracy in precision calculations when working with coordinates, allowing for precise placement of pointers and markers. Nevertheless, Mapbox has faced criticisms regarding the frequency of SDK updates, the last of which dated back to 2019. This has necessitated manual adjustments when integrating the SDK into new projects such as deleting deprecated components and replacing deprecated methods. Despite this, Mapbox continues to provide support through its forums and offers a free tier during prototype development.

Google's Photorealistic 3D Tiles: A unique offering for geospatial data comes from Google in the form of Photorealistic 3D Tiles. This dataset represents a 3D mesh model of the world, meticulously created from satellite imagery and Google Street View. Though experimental during the time of development, it exhibited impressive smoothness and precision. This dataset adheres to Cesium's open standard and is hosted on Cesium's platform, requiring Google's map API with an authentication key for access. One of its standout features lies in its remarkable precision when placing different objects on the terrain. These objects seamlessly integrate with the landscape, even following its elevations. Google's Photorealistic 3D Tiles are observed to offer the best support for accurate visualization of spatial data that support environmental decision making and disaster response, while providing limited capabilities to modify individual entities.

In choosing a map provider for the application, Mapbox emerged as the preferred choice for several compelling reasons. Foremost, Mapbox boasts an abundance of data, ensuring a rich and comprehensive foundation for our visualization needs. The platform's free tier allows for substantial exploration and development work. Moreover, Mapbox's intuitive functions cater specifically to geospatial-based calculations and data manipulation, streamlining the development process and enhancing the system's capabilities. Additionally, the community support surrounding Mapbox also was weighted in.

3.2.2. Spatiotemporal Data

Incorporating real-time sensor data is a pivotal aspect of the application's functionality, particularly for the purpose of visualizing hydrological data. To enable this, various REST APIs were seamlessly integrated, facilitating the display of real-time data from third-party providers while accurately geolocating it within the application's terrain. The application relies not only on data fetched from external APIs but also on information available through the map provider.

USGS Discharge and Weather API: One of the key components of the hydrological data integration is the utilization of the United States Geological Survey (USGS) REST API for water bodies. This API serves as a vital resource for accessing real-time data concerning water bodies across the United States, precisely pinpointed to their geographic locations. When a user loads a specific location within the application, the USGS API is invoked to retrieve pertinent information about the water bodies encompassed within a square area of 10 square kilometers. Subsequently, the application instantiates markers that are positioned at the exact geographic coordinates of these water bodies. These markers actively display dynamic data, including critical parameters such as discharge rate and flow velocity.

In addition to hydrological data, real-time weather information plays a crucial role in enhancing the application's functionality. To this end, a weather API was thoughtfully integrated, offering continuous updates on meteorological conditions. Users can readily access this real-time weather data through a dedicated weather panel within the application. The weather panel is designed with user-friendliness in mind, presenting an array of weather-related information, including temperature and current weather conditions. These details are presented with an intuitive and visually engaging interface, featuring distinct icons that correspond to various weather conditions.

Incorporating Data Provided by Mapbox: Within the application, we leverage Mapbox's diverse dataset, offering users the choice between terrain views, including both street and satellite perspectives, depending on their preferences. This versatility extends to the representation of urban landscapes, with a rich assortment of detailed building data that further enhances the user experience. To ensure users have an enhanced understanding of urban conditions, we seamlessly integrate live traffic data from Mapbox. This dynamic feature displays traffic information on roadways, categorizing congestion levels into three distinct tiers: severe, moderate, and low. This aids users in planning their hydrological exploration routes effectively and efficiently. Additionally, we don't limit our geographical scope to land; the application also incorporates bathymetry data, extending our visualization capabilities to underwater landscapes, further broadening our understanding of hydrological systems and the interconnectedness of water bodies.

3.3. System Architecture

The system architecture of the application under consideration primarily hinges on the Unity game engine, specifically Unity version (2022.3). Unity is chosen for its exceptional support of lightweight applications and cross-platform capabilities, which aligns with our vision of creating a lightweight and device-agnostic framework. Figure 1 presents the overview of the system architecture.

This application is designed to be accessible through web browsers to ensure broad accessibility. Moreover, the application offers immersive experiences through various VR devices. To enable this compatibility, the "WebXR exporter" SDK for Unity is utilized. Rigorous testing has been conducted with devices such as Oculus Quest and Magic Leap to verify compatibility. Furthermore, the application harnesses the VRTK to seamlessly integrate the controllers of the VR device. The VRTK SDK's device-agnostic design is instrumental in capturing inputs from different controller types. This design choice was made to ensure a standardized and seamless experience for users across various VR environments.

The system architecture of the application reflects a methodical blend of advanced technology and inclusivity. Unity, combined with the WebXR exporter and VRTK, forms the foundation for a versatile, immersive, and user-friendly environment. This architectural approach aims to deliver a comprehensive and standardized user experience.

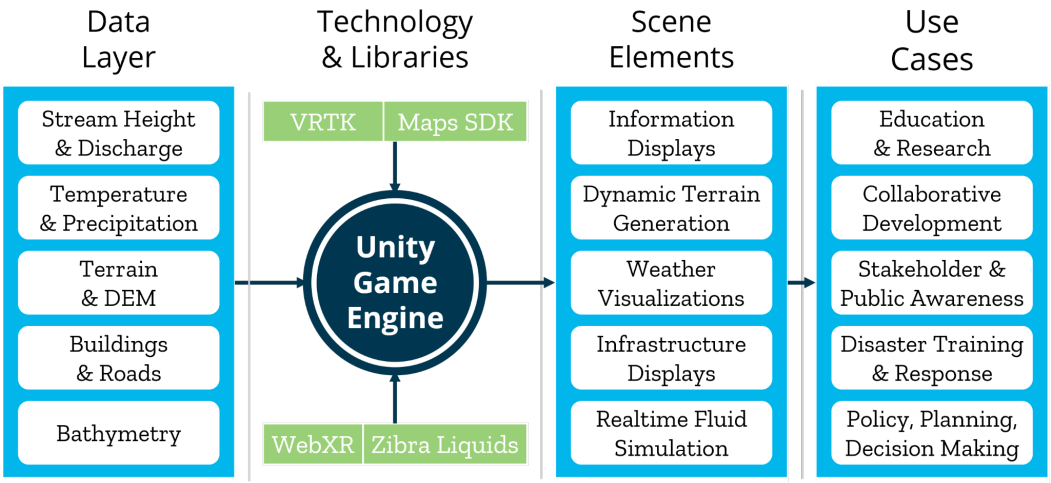


Figure 1. System architecture and components with sample datasets and use cases

Game Manager Component: In the context of Unity applications, a game manager serves as a central component responsible for managing the application's states and logic. It acts as a coordinator, ensuring seamless communication between various modules of the game. In our application, the game manager module plays a pivotal role in controlling the available features. While the invocation of third-party APIs is delegated to a dedicated module, it is always initiated through the game manager. This design choice is attributed to the dynamic loading of the map, where the need for API invocation is contingent on specific conditions. Moreover, the game manager module also houses the control logic necessary to handle the dynamic zooming feature. This logic enables the application to respond to user-initiated zooming actions by adjusting the map's level of detail, enhancing visuals when the camera is focused on smaller areas and reducing image quality when zooming out to save on performance.

WebXR Exporter and Multiplatform Support: WebXR is an innovative, open-source SDK that allows developers to export a WebGL build of the Unity games. This application utilized the WebXR exporter to produce the final build for direct use by other platforms. This build is hosted on a static web host, making it accessible to PCs and VR devices through web browsers. Hosting the finished build in this way reduced the necessity of having separate builds catered to the particular needs of individual devices and platforms.

Dynamic Location Update: The application offers the ability to update the map dynamically in response to user requests. Users can input longitude and latitude values, enabling the application to load any desired location, even locations outside of the continental United States. This functionality is achieved through the utilization of the AbstractMapScript.UpdateMap() method, a feature provided by Mapbox. Notably, this method streamlines the process by eliminating the need for map re-initialization. Furthermore, it facilitates the conversion of longitude and latitude values into world coordinates. The application also allows for dynamic zooming capabilities. Users can navigate the scene both horizontally and vertically, effectively zooming in or out. The application intelligently adjusts the level of detail displayed based on the user's zoom level. Similar to the map updating function, this dynamic zooming feature is also managed by the AbstractMapScript.UpdateMap() method provided by Mapbox.

3.4. Immersive Hydrological Visualizations

This section discusses the strategies used to create a sense of immersion in the digital environment. It first describes the methods used to create immersive precipitation, and then move on to the use of real-time fluid simulation. Lastly, it details the visualization of critical hydrological infrastructure.

3.4.1. Rainfall and Snowfall Animations

Rainfall and snowfall animations were created using Unity's inbuilt particle system. Rain particles were simulated by giving the particles a three-dimensional start size that varied within a range along the Y axis. The particles were then given a linear velocity over time that could take on a range of values, allowing for variability between the velocity of different particles. The snow particle system was created with the same method used to create the rainfall particle system, though range values for the particle size and velocity were adjusted to allow the look and behavior of the particle system to conform more to that of snowfall.

These particle systems were simulated within the world space, rather than the local space. Doing this allowed for the particle system to be moved without affecting the positions of particles after they have been emitted. This was particularly important because the particle systems are attached to the main camera, and thus, move within the world as the main camera moves. This was done to increase the presence of the particles without needing to simulate the particles over an incredibly large range within the game space.

A C# class was created to control the relevant visual settings of the particle systems. This control was achieved by attaching the class as a script component to the appropriate particle systems. Serialized variables within this class allowed for easy modification of the particle system's emission rate over time, simulation speed, maximum particle count, and Transform component axis-rotation values.

3.4.2. Water Animation

Many solutions were considered for water simulation within the virtual environment. Initially, water had been simulated by using a plane with animated normal maps and reflections to give the plane the illusion of waves, ripples, and flow. Although this method of water simulation looked realistic and supported user immersion, it was fundamentally flawed. This method did not support our vision of visualizing complex hydrological processes because the plane that was employed could not be compelled to behave like an amorphous body of water. For this reason, this method was utilized, and we decided to work on real-time fluid simulation solutions.

Water simulation within the virtual environment was achieved using the off-the-shelf Zibra Liquids asset. This asset allowed for real-time fluid simulation, which could be used to visualize fluid behaviors within the virtual environment. To fully integrate this asset into our digital environment, we had to first resolve incompatibilities between the Maps SDK and the Zibra Liquids asset. All colliding object instances must be defined within the Unity editor before running the fluid simulation. This results in dynamically generated object instances, such as those utilized by our terrain generation method, being unable to be added to the array of meshes for which complex collision interactions would be calculated. This problem was partially circumvented by disabling the instance of the fluid simulation, programmatically adding the newly generated terrain tiles to the array of objects for which collisions would be processed, and then enabling the fluid simulation instance. A new problem arose however when terrain became too complex to be simulated using the collision systems provided by the plugin. For these reasons, integration of real-time fluid simulation is a feature considered still in development.

3.5. User Experience, Interaction and User Control

The web application, accessible through a PC and Virtual Reality (VR) devices, has been meticulously designed to ensure seamless user interaction across different platforms. The VRTK is used predominantly for managing inputs from the VR devices, while the Unity input system caters to keyboard based interactions, complemented by independently developed modules for input handling. Users have the flexibility to navigate through the scene, able to switch from an aerial view to a closer, ground view on command. The WASD keys on the keyboard facilitate movement within the scene, following conventions set by other immersive digital experiences. For VR devices, the thumbstick controller is configured for navigation, and users have the option to teleport between locations, further enhancing the interactive experience of visualizing hydrologic data.

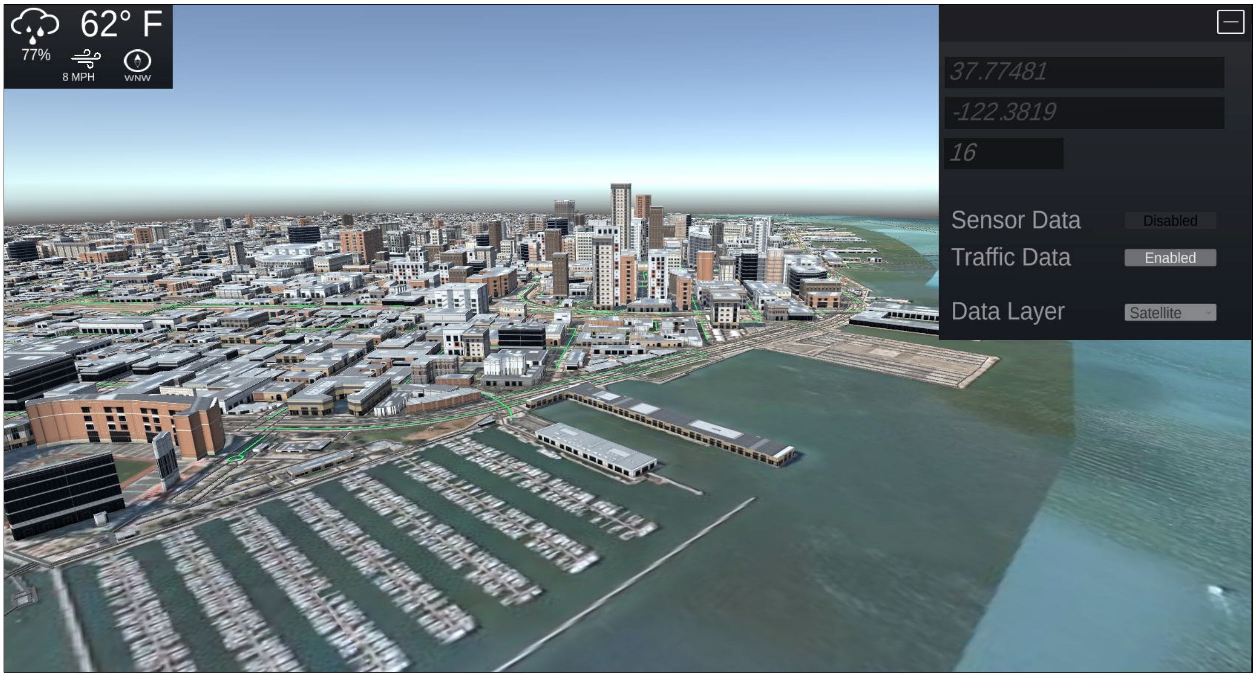
The primary user interface serves as a central hub for users to orchestrate all activities within the application. This interface allows the user to input latitude and longitude values of a specific location and to dynamically load the location corresponding to the latitude and longitude entered. Additionally, the interface includes toggle options that allow users to seamlessly access and view USGS information panels, as well as real-time traffic and weather information. There are two types of information panels utilized in the application for data comprehension: panels displaying USGS data and the one showing weather data. The USGS information panel, designed as a prefabricated element (prefab), is instantiated at each sensor location within the virtual environment.

4. Results and Discussions

This study presents the development of an immersive hydroinformatics framework, integrating XR technologies. This framework, leveraging the Unity engine alongside the Mapbox Maps SDK, renders a detailed 3D representation of the continental United States and incorporates real-time data from the USGS API and a weather API. This facilitates an interactive environment for users to engage with hydrological and meteorological data, aiming to enhance understanding of complex hydrological phenomena through visualization. Designed for accessibility, the system is accessible within a web browser and is compatible with various VR devices, thereby supporting a wide user base including researchers, decision-makers, and educators.

4.1. Mapbox Maps SDK Integration

Mapbox's rich and diverse dataset has supported the presented application's functionality and visualization prowess and proved to be an effective data source for visualizing the continental United States (Figure 2). Placement of models representing infrastructure is highly accurate, creating an effectively representative scale model of real space. There were few instances where the Maps SDK inhibited the display of data from other sources. Furthermore, there was one notable instance where the Maps SDK presented an issue, stemming from incompatibilities with the fluid simulation plugin. Another concern regarding the Maps SDK is the potential for future support. As of the writing of this paper, there have been few major updates made to the Maps SDK that support our future vision for the project.



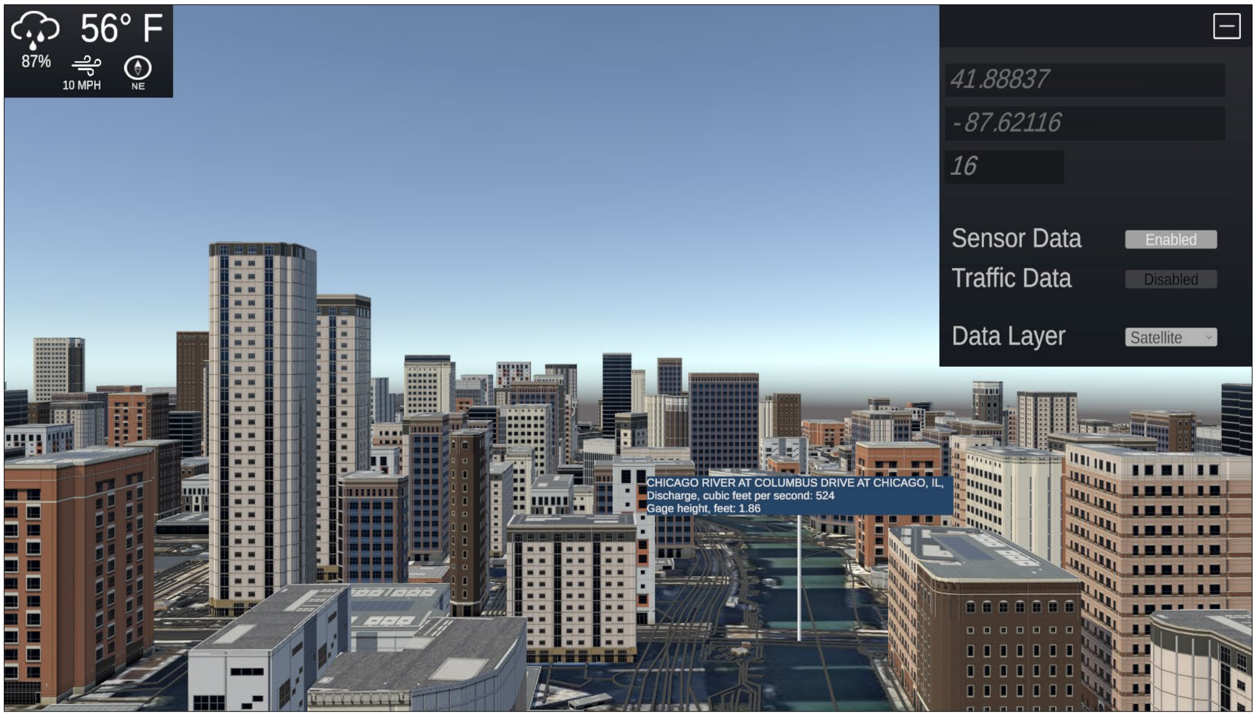
37.77481
-122.3819
16

Sensor Data: Disabled
Traffic Data: Enabled
Data Layer: Satellite

Figure 2. 3D map view generated via Mapbox along with input and information panel.

4.2. USGS API for Discharge and Weather Data

By integrating the USGS weather and discharge APIs, the application supports users with instant access to crucial hydrological data, enhancing their understanding of the surrounding water bodies (Figure 3). Additionally, the inclusion of bathymetry data, visualized as raster data, offers a comprehensive view of underwater terrain features, further enriching the users’ spatial awareness and comprehension of aquatic ecosystems (Figure 4). Stream characteristics data are presented to users in a simple and effective format and markers allow users to visualize where the data is coming from, improving user spatial comprehension. By offering up-to-the-minute meteorological insights, the application equips users with invaluable information, enabling informed decision making and effective planning. By visualizing relevant data, it is our vision that in-person and remote planning be enhanced with exceptional comprehension of environmental conditions. Future work on this system will focus on improving the graphics of the information panels used to present the data. Significant effort will be made to unify all stylistic aspects of the project to avoid diminishing user immersion through stylistic inconsistencies.



41.88837
-87.62116
16

Sensor Data: Enabled
Traffic Data: Disabled

Data Layer: Satellite

CHICAGO RIVER AT COLUMBUS DRIVE AT CHICAGO, IL,
Discharge, cubic feet per second: 524
Gage height, feet: 1.86

Figure 3. Weather information from the USGS Weather API being displayed in the user view along with stream conditions from the USGS Discharge API.

4.3. Immersive Visualization Systems

The presence of rainfall (Figure 5) and snowfall (Figure 6) particle systems is not crucial to the display of hydrological data, but it is important for the creation and maintenance of user immersion. The presence of these systems gives the digital environment a sense of realism and dynamism, which allows users to become more immersed in the simulated world than they could with the absence of dynamic weather (Roberts & Patterson, 2017). User immersion is a key consideration to this model, as it has been found to increase cognitive performance and reduce the adverse effects of simulation use (Mostajeran, Fischer, Steinicke, et al., 2023). The visualization of precipitation in this project is currently a static, visual phenomenon and does not have complex interactions with the terrain or with other data visualization and simulation systems. Future work on this system will prioritize implementing default visualizations that correspond to real-world weather data, thus allowing users to see local weather conditions in real time, then configure these visualizations if they choose to do so. Additionally, future work will aim to connect the weather visualizations to the fluid simulation system, allowing for a more seamless and holistic simulation of complex hydrological interactions.

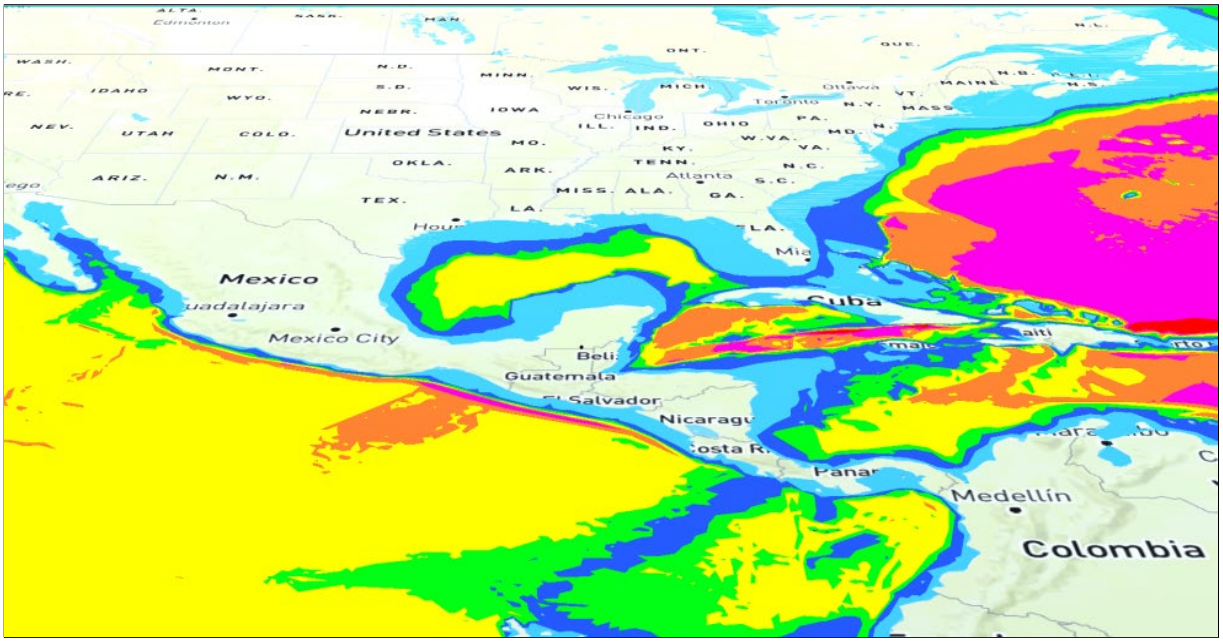


Figure 4. Bathymetry data for lakes and water bodies

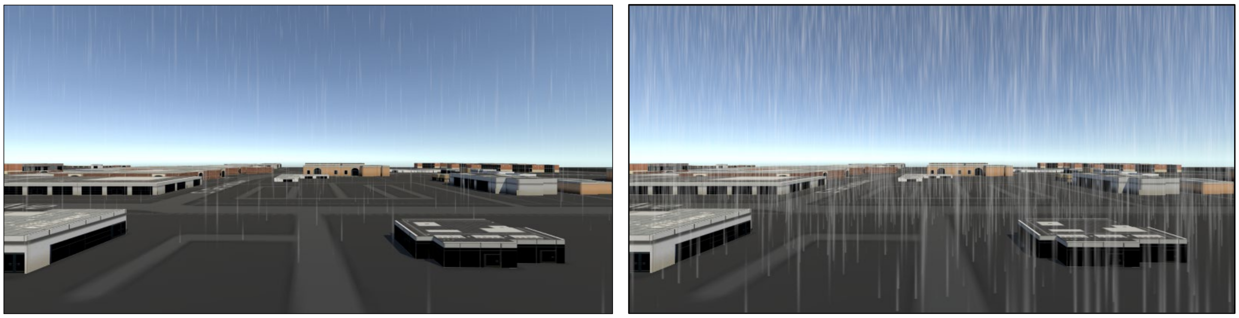

(a) (b)

Figure 5. Rainfall particle system at: (a) low; and (b) high intensity configurations.

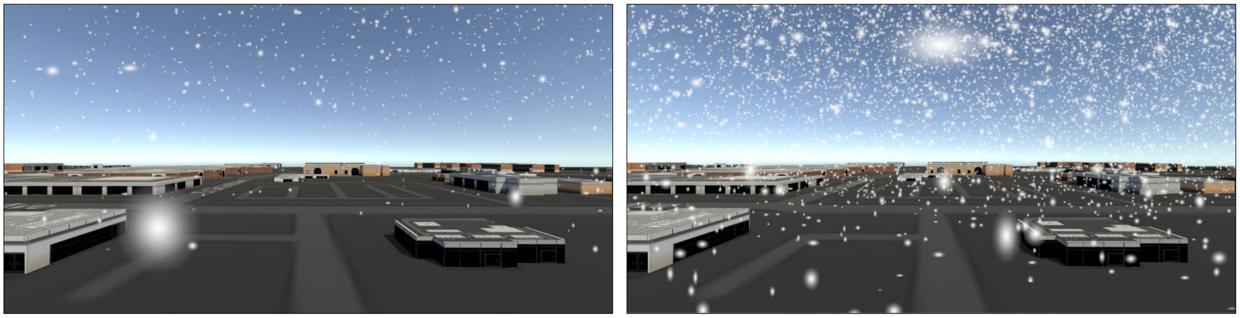
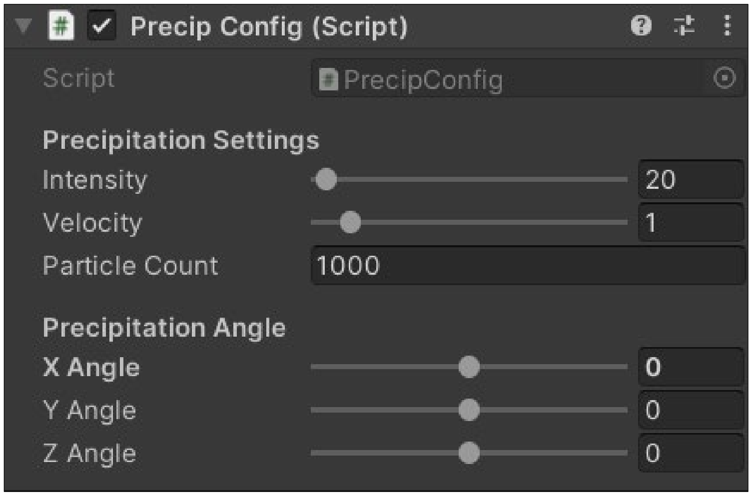

(a) (b)

Figure 6. Snowfall particle system at: (a) low; and (b) high intensity configurations.

The precipitation configuration script (Figure 7) allows users to control aspects of the particle system that are relevant to the graphical attributes of the precipitation. By implementing this script, other factors of the particle system that are not relevant can be stripped, reducing the likelihood of users becoming confused when trying to adjust the precipitation attributes. Allowing users to control these graphical attributes should allow for visualization to be catered to the needs of the user and their specific scenario. Additionally, this script acts as the foundation for implementing control of these graphical systems during runtime. Future work on this project will make these attributes accessible to users within the game world through a control panel user interface. This would allow these attributes to be configurable on the fly, without needing to be initialized before runtime or modified in the Unity editor. The configuration script is easily modifiable and can be changed to accommodate other visualizations that use Unity's particle system.

The Zibra Liquids plugin provided effective real-time fluid simulation. The fluid is simple enough to configure and can be controlled well via scripting. The major issue with using this plugin was the inability to add collisions to the simulation at runtime. This limitation, although partially resolved, has been quite a setback to the progress of this application due to terrain provided by the Maps SDK being entirely dynamically generated. Additionally, because terrain tiles can display a wide variety of topographic features, often the prebuilt collision boxes provided were not enough to create entirely emergent visualizations of hydrological processes. The 'Neural Colliders' offered by the plugin allow for the generation of more complex collision meshes, but this is more suited towards facilitating collisions between key set piece assets. Because the process of creating these neural colliders must be done through the Zibra AI servers, it is not practical to generate these collision meshes for each terrain tile at runtime.



☑ Precip Config (Script)

Script: PrecipConfig

Precipitation Settings

Intensity: 20

Velocity: 1

Particle Count: 1000

Precipitation Angle

X Angle: 0

Y Angle: 0

Z Angle: 0

Figure 7. Configurable attributes of the configuration script.

Another concern for fluid simulation was considerations of scale. The Zibra Liquids plugin simulates fluids using a large number of particles. Increasing the volume of fluid to be simulated increases the particle count, thereby increasing the need for computer processing power. To simulate large scale hydrological processes such as floods, the volume of fluid must be strategically scaled in such a way that an accurate representation of the event can be created while also operating within the limitations of available hardware. How these simulations can be most effectively scaled is a consideration for future work on this project. As the development of this application progresses, it may become necessary to utilize fluid simulations provided through other means. We expect that the generalized nature of the project will allow for seamless integration of new simulation systems, thus allowing this project to be expanded upon with the addition of other environmental visualizations.

4.4. User Interaction and Control

An important aspect of the user experience is the application's accessibility. Throughout development, we have taken action to make this application available to as many modes of use as possible. This was greatly facilitated by the use of the WebXR exporter for the creation of the WebGL build. The WebGL build exhibited incredible adaptability, seamlessly accommodating a plethora of VR devices. Because WebXR has such a device-agnostic nature, developers can bypass the need to incorporate additional packages for supporting particular devices (such as the Oculus Integration package). Using a unified build greatly increases compatibility and reduces development complexity, but also comes with the cost of limiting the use of device specific technology. The application may be able to run on many devices, but it is unlikely that the application will make the most of the technology it is being deployed on.

Within the application, users are given the ability to move their position in three-dimensions via controls or web interface, allowing for seamless navigation of the generated scenes. This design choice ensures a consistent and user-friendly experience that aims to accommodate users and their viewing needs and preferences. Currently, the application best supports web and VR users with controls built in to accommodate for these methods of viewing. To fully achieve our goal of a device-agnostic framework, effort must still be made to allow for seamless user interaction for AR users. To achieve this, a user interface will be crafted and rendered within the world space and combined with the capabilities of the VRTK to provide users with intuitive and accessible control over the application.

In addition to these needs, we must acknowledge the absence of control mechanisms optimized for mobile devices, such as touch-based interfaces and mobile browser compatibility. This gap in the system's design restricts the accessibility and usability of the application on widely used mobile platforms. Additionally, the VR component of the system does not support activation via mobile VR headsets, further limiting its applicability in mobile contexts. These shortcomings, while notable, also present opportunities for enhancement and refinement that shall be addressed in subsequent developments of the project.

4.5. Evaluation of Findings

The development and implementation of the immersive hydroinformatics framework yielded insights that directly respond to the research questions posited in this paper (Section 3.1).

Regarding the question about the most effective data sources for creating immersive hydrological visualizations, the integration of the USGS API and weather API proved to be paramount. The selection of Mapbox as the map provider, as detailed in the consideration of various map providers, facilitated a rich and dynamic visualization platform. This choice was initiated by the accurate rendering of hydrological phenomena and the seamless integration of real-time data, pointing to the effectiveness of these data sources in enhancing the immersive experience.

In response to focusing on how XR can be utilized to enhance hydrological data visualizations, the use of the Unity engine and Mapbox Maps SDK, alongside VR devices, created a multi-dimensional and interactive environment. The application's ability to dynamically generate 3D models and visualize real-time data within an immersive setting exemplifies the potential of XR technologies in transforming hydrological data visualization.

Concerning on the development, maintenance, and leverage of user immersion in data visualization, the incorporation of real-time weather conditions and fluid simulations significantly contributed to user engagement. The visualization of rainfall and snowfall animations, as well as the simulation of water behavior using the Zibra Liquids asset, not only enhanced the realism of the environment but also facilitated a deeper understanding of hydrological processes, thereby addressing the pivotal role of immersion in data visualization.

Lastly, with respect to identifying future prospects and potential improvements in the use of XR systems for hydrological data visualization. The discussion on integrating additional hydrological phenomena, such as percolation and soil moisture, into the framework suggests a pathway for expanding the application's capabilities. Moreover, the emphasis on refining user interfaces and ensuring cross-platform compatibility highlights the ongoing need to enhance accessibility and user experience. These findings underscore the framework's capacity to address the initial research questions, demonstrating the considerable promise of XR technologies in hydrological visualization and the potential for future advancements in this field.

5. Conclusions

The development of this framework marks a significant stride towards the realization of our vision for an immersive information system. Through the integration of the Maps SDK with USGS stream data into the Unity engine, a milestone was achieved wherein relevant hydrological information is presented within its spatial context, enhancing the cognitive understanding of local conditions. Users now possess the capability to seamlessly traverse the continental United States in the virtual realm and dynamically visualize hydrological data from streams equipped with USGS sensors. This not only encompasses stream conditions but also provides real-time updates on local weather parameters, including temperature, wind speed and direction, and precipitation conditions. Additionally, dynamic weather visualizations allow for a greater level of immersion to be achieved by giving the digital environment a sense of dynamism.

Ongoing efforts are directed towards refining the user experience, emphasizing an intuitive and accessible interface adaptable to diverse user devices while upholding functionality. Our future development priorities center on ensuring complete compatibility across all data visualization and simulation systems, both current and prospective. The seamless integration of real-time fluid simulations with dynamically generated terrain stands as a crucial objective to accurately depict intricate hydrological processes. Subsequent phases will explore the incorporation of additional facets of the hydrological cycle, such as percolation and the direct accumulation of precipitation particles, seamlessly interwoven into the fluid simulation.

A paramount consideration in the project's design is its openness and generalizability. While currently focused on hydrological data, the framework is designed to empower users to incorporate new data APIs for spatial contextualization. Users have the flexibility to adapt the project to showcase a spectrum of information, from drought patterns and forest fire coverage to soil erosion and transport. This versatility extends the utility of the framework, allowing prospective researchers to explore disaster simulations. Researchers may further leverage this framework for visualizing diverse natural disasters, including tornadoes, fires, hurricanes, fostering applications in data visualization, environmental planning, education, disaster training, and beyond.

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