Hydro3DJS: A Modular Web-Based Library for Real-Time 3D Visualization of Watershed Dynamics and Digital Twin Integration

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Abstract

Effective visualization of hydrological data is critical for addressing challenges such as flood risk, water resources management, and climate adaptation. This study introduces Hydro3DJS, a modular, web-based 3D visualization library that integrates real-time environmental data with interactive digital twin capabilities. Developed using JavaScript, WebGL, and Google Maps API, the tool enables dynamic simulation of hydrological and atmospheric processes, including rainfall, flood events, and infrastructure exposure, within a spatially accurate and browser-accessible interface. The system supports live data ingestion from sources like USGS and NOAA and renders terrain-aware water dynamics, customizable 3D infrastructure, and sensor overlays. We demonstrate its functionality through two use cases: a rural flood scenario featuring multi-hazard elements, and an urban simulation of a 100-year flood event with real-time stream gauge integration. A usability study with 20 domain experts confirmed the platform's value for planning, analysis, and stakeholder communication, while also identifying areas for future enhancement in performance and interoperability.

Keywords: 3D hydrological visualization, Web-based geospatial tools, Digital Twin, WebGL, Watershed management, real-time data integration

Highlights

- A 3D web-based library visualizes rainfall and flooding using real-time geospatial data.
- The tool supports interactive 3D models of dams, levees, and urban infrastructure.
- Usability testing showed strong opportunity in flood planning and stakeholder outreach
- The library runs in browsers with no plugins, ensuring cross-platform accessibility.
- User study identified key visualization gaps and informed future feature design.

1. Introduction

Visualizing hydrological data plays a critical role in both scientific research and practical environmental management, serving as a bridge between complex, multidimensional datasets and actionable insights (Demir & Szczepanek, 2017). In an era of rapidly increasing climate risks, flood frequency, and global water scarcity, the need for robust, user-friendly visualization tools has never been more urgent. Effective hydrological visualization enables researchers, policymakers, and the general public to interpret data, anticipate impacts, and implement timely interventions (Xu et al., 2019). Tools such as WaterVis have demonstrated their value in managing large hydrological datasets and supporting early flood warning systems, enhancing both the speed and clarity of environmental decision-making (Marbouti et al., 2018; Rivera & Ramos, 2024). These web platforms exemplify the growing reliance on digital tools to interpret water-related phenomena and reinforce the demand for scalable, interactive solutions that work across technical domains and user expertise levels (Yesilkoy et al., 2024).

In parallel, emerging technologies such as Extended Reality (XR), which include virtual and augmented reality environments, have introduced new modes of engaging with hydrological systems (Sermet & Demir, 2020). These immersive platforms allow for dynamic, spatially situated interactions with real-time data, enabling users to explore flood dynamics, infrastructure exposure, and watershed conditions in ways that traditional maps and graphs cannot offer (Mudiyanselage et al., 2025). Research into web-based XR tools, such as GeospatialVR, has expanded the potential for collaborative hydrological analysis, particularly in stakeholder-driven planning contexts (Sermet & Demir, 2022). These advancements represent a meaningful shift from static, two-dimensional (2D) methods toward more engaging, multidimensional representations of environmental systems (Rink et al., 2014).

Despite these developments, many standard hydrological tools remain limited by their reliance on static 2D graphics, which can obscure important spatiotemporal dynamics and hinder the communication of non-steady flow phenomena. Techniques such as flow steadification attempt to compensate for these limitations, but they often involve complex pre-processing steps and still fall short in representing real-time behavior (Wolligandt et al., 2020). Additionally, the nonlinear and heterogeneous nature of hydrological systems further complicates static modeling, necessitating visualization tools that are adaptable, multiscale, and sensitive to contextual changes (Gentine et al., 2012; Laidlaw et al., 2001). Research has shown that even when key flow structures or critical points are visualized, no single 2D method adequately supports all analytical needs in hydrology, reinforcing the need for novel approaches (Manfreda et al., 2023).

On the other hand, digital twin (DT) technologies have emerged as a transformative approach in hydrological visualization and modeling, particularly within water resources management. Traditionally, hydrological modeling relied on empirical and physics-based approaches to simulate water flow, precipitation patterns, and watershed dynamics with extensive computational needs (Singh, 2018; Agliamzanov et al., 2020). However, these models often faced limitations due to static inputs, lack of real-time adaptability, and challenges in integrating diverse benchmark datasets (Demir et al., 2022). The emergence of DT technology offers a groundbreaking solution to these challenges by providing dynamic, real-time, and predictive insights into hydrological systems (Henriksen et al., 2022). By creating a digital replica of a watershed, river basin, or dam (Qiu et al., 2022; Shao et al., 2025), DTs enable continuous monitoring and proactive management of water-related events (Park et al., 2023). This approach is already proving transformative in water resource management, offering enhanced capabilities for urban water security, wastewater treatment optimization, and infrastructure resilience planning (Huang et al., 2024; Lumley et al., 2024; Shehadeh et al., 2024).

Digital twins have also demonstrated value in climate risk mitigation, where they integrate high-resolution geospatial data with predictive models to simulate and respond to hydrological extremes (Kim et al., 2023). However, despite their potential, several barriers hinder the widespread adoption of digital twins in environmental science. These include concerns around model accuracy, the complexity of real-time data integration, and the need for high-performance computational infrastructure (Li et al., 2024). Without addressing these issues, digital twins risk remaining confined to research settings or highly resourced organizations, limiting their broader utility.

Simultaneously, platforms such as Google Maps and Google Earth Engine (GEE) have become foundational in democratizing access to geospatial hydrological data. Their cloud-based infrastructures support rapid deployment, cross-platform accessibility, and integration with remote sensing data, making them ideal for both research and operational use. Studies have successfully leveraged Google Maps to enhance streamflow modeling and visualization, integrating high-resolution imagery and geographic data into hydrological simulations (Wang et al., 2013; Li & Demir, 2024).

GEE, with its cloud computing capabilities, has further enabled scalable flood risk assessments and global water quality monitoring, driven by satellite data and machine learning algorithms (Sellami & Rhinane, 2024; Amani et al., 2020). These platforms provide a critical foundation for expanding hydrological modeling into browser-based environments, particularly when combined with WebGL and custom 3D rendering libraries. Advances in Geographic Information Systems (GIS)-based procedural modeling and 3D scene generation have also allowed the creation of richly detailed, interactive simulations of urban and rural water systems (Pepe et al., 2021; Xu et al., 2025). While promising, many of these tools face persistent issues related to data integration, real-time responsiveness, and usability across disciplines, particularly when targeting non-expert users or decision-makers.

Considering the current state of hydrological visualization tools and technologies, there is a clear and growing need for scalable, intuitive platforms that bridge the gap between scientific data and real-world decision-making. Existing systems often lack the ability to dynamically represent hydrological phenomena in a spatially grounded, real-time, and interactive manner, especially within the context of widely accessible platforms like web browsers. Furthermore, many solutions require steep learning curves or specialized software, which limits their adoption in practice. These gaps are particularly consequential in high-stakes scenarios such as flood forecasting, infrastructure planning, and emergency management, where timely and intelligible data interpretation can have significant consequences. Thus, the development of a modular, browser-compatible, 3D hydrological visualization tool that integrates with widely used geospatial platforms represents both a technical and a societal imperative.

This research aims to address the existing gaps in hydrological visualization by introducing a web-based 3D hydrological visualization library built with JavaScript, WebGL, and Google Maps. The primary objective is to create a visualization tool that enables real-time, interactive exploration of hydrological data in geospatially accurate environments. The tool supports modular integration of real-time environmental datasets, including river discharge, rainfall patterns, and flood zones, with visual elements such as 3D infrastructure models and dynamic water animations.

In addition to technical development, the study seeks to evaluate the tool's usability and effectiveness through structured user feedback gathered from environmental scientists, engineers, and policy professionals. These insights inform refinements to the system and support its application across a range of contexts, from academic research to public outreach and disaster preparedness. The broader goal is to contribute a scalable, accessible solution to the ongoing evolution of digital twins and interactive hydrological modeling, while also aligning with recent efforts that explore the role of AI in hydrology-related education and certification contexts (Sajja et al., 2025b; Sajja et al., 2025d).

This paper is structured as follows: Section 2 reviews relevant studies in hydrological visualization, digital twin systems, and geospatial integration. Section 3 describes the system architecture and methodology used in developing the Hydro3DJS library. Section 4 presents implementation results and two representative use cases that demonstrate the tool's key features in rural and urban flood scenarios. Section 5 concludes with a discussion of the library's contributions, current limitations, and future development directions, including improvements in scalability, interactivity, and integration with predictive modeling frameworks.

2. Related Work

Understanding and managing water resources requires the synthesis of complex hydrological data, which has been increasingly supported by a growing suite of visualization tools (Sit et al., 2021). Traditional 2D and 3D hydrological visualization systems have served as essential platforms for interpreting environmental data, enhancing both scientific insight and operational planning (Oyshi et al., 2022; Kaynak et al., 2025). Tools such as the Hydrological Visualization and Analysis System (HyVAS) allow researchers to process and analyze high-resolution spatial and temporal datasets related to hydrological parameters like soil moisture, which are fundamental to water management and agricultural applications (Jangyodsuk et al., 2015).

Similarly, the Groundwater Visualization System (GVS) has provided means for constructing three-dimensional models of subsurface conditions, translating abstract groundwater data into intelligible visuals for both experts and non-specialist stakeholders (James et al., 2009). These platforms exemplify how visualization supports multi-scale understanding of hydrological dynamics, contributing to more transparent communication between scientists, decision-makers, and the public.

Beyond enhancing comprehension, visualization systems have also proven instrumental in education, community engagement and policy development (Ewing et al., 2022). Interactive platforms like the 3D Water Atlas demonstrate the potential of combining geospatial groundwater data with immersive environments to foster public trust and active participation in water governance (Wolhuter et al., 2019). Similarly, AI-based learning systems have been developed to enhance student understanding of environmental systems and provide targeted academic support using conversational interfaces (Sajja et al., 2025a; Sajja et al., 2025c). Likewise, ecohydrological modeling in 3D settings has emphasized the importance of capturing interactions between hydrology and ecosystems, which is critical for managing sustainability goals and understanding biophysical feedback loops (Kaczorowski et al., 2006).

GIS-based applications, such as HydroVIS, have further supported education and operational decision-making by integrating hydrological modeling with multimedia and spatial mapping, allowing end-users to explore both scientific outputs and real-world implications in tandem (Streit et al., 1999). Despite these contributions, many of these platforms still face considerable limitations. These include high computational demands, steep learning curves associated with specialized software, and limited support for real-time or multi-format data integration, which restrict their adaptability and wider adoption in dynamic or interdisciplinary contexts.

The evolution of visualization in hydrology has also been shaped by advances in data collection and analysis. The integration of image-based monitoring, remote sensing, and AI-driven technologies has ushered in a new era of visual analytics frameworks that combine computational power with human-centered interpretation. These innovations have significantly improved the responsiveness and accuracy of hydrological assessments, enabling stakeholders to visualize complex processes like flood propagation, sediment transport, or drought evolution with greater clarity and precision (Manfreda et al., 2023). These frameworks, particularly when integrated with GIS and cloud-based cyberinfrastructure, facilitate a more holistic understanding of environmental systems, bridging the gap between simulation outputs and policy insights (Xu et al., 2022; Alabbad et al., 2024).

Augmented reality (AR) further enhances this interactivity by allowing real-time simulations of water risks in situ, a capability especially valuable in emergency response, infrastructure planning, and public communication (Pajorová & Hluchý, 2022). However, despite these gains, key challenges persist, including poor data quality, difficulties in aligning heterogeneous datasets, and the continued complexity of hydrological system behavior. These issues are compounded by interdisciplinary barriers, especially between hydrologists, computer scientists, and interface designers, which can slow innovation and impede collaborative tool development (Clark, 1998; Gregory et al., 2020). To overcome these limitations, several researchers have proposed for visualization tools that support rapid prototyping, interactive data exploration, and more flexible deployment across platforms and user contexts (Lotteraner et al., 2023).

In parallel with the advancement of visualization tools, digital twin technologies have gained substantial momentum as a paradigm for integrating real-time data, simulation, and environmental modeling. A digital twin refers to a virtual replica of a physical system that is continuously updated with data streams and analytical outputs, creating a closed loop of monitoring, forecasting, and decision support. Originally developed in engineering and manufacturing sectors, digital twins have since been adapted for environmental applications and hydrological systems, including rivers, watersheds, groundwater aquifers, reservoirs, floodplains, and even urban water infrastructure (Uluiburotu & Rabuka, 2024; Vasumathi et al., 2022; Rigon et al., 2022).

These systems are typically structured around three interconnected layers: the physical layer (representing the real-world system), the transmission layer (which manages data flow and integration), and the virtual layer (responsible for simulation and visualization) (Zheng et al., 2023). AI-driven planning frameworks have also emerged in this space, simulating stakeholder behavior and decision dynamics to enhance mitigation strategies (Kadiyala et al., 2025). These virtual models can simulate the complex dynamics of water flow, storage, distribution, and interaction with both natural and man-made environments. By integrating real-time sensor data, advanced analytics, machine learning, and predictive modeling, DTs can mirror current hydrological states, forecast future conditions, and support effective decision-making processes.

Within the water sector, digital twins have been applied to a diverse array of planning and operational scenarios. Utilities and municipalities have implemented digital twin frameworks to monitor pumping efficiency, optimize distribution networks, and improve fault detection across water infrastructure systems (Bernard, 2024). Urban resilience initiatives in regions such as Orange County, California, and Victoria, Australia, have deployed spatially explicit digital twins augmented with GIScience tools to enhance flood preparedness and long-term infrastructure planning (Sabri et al., 2023).

Wastewater management systems have also benefited, with platforms like Future City Flow and TwinPlant integrating collection and treatment networks to reduce energy use and prevent overflow during storm events (Lumley et al., 2024). Notably, the Eindhoven Water Resource Recovery Facility (WRRF) in the Netherlands represents a large-scale operational digital twin implementation that utilizes automated data pipelines and real-time scenario modeling to manage urban water systems effectively (Daneshgar et al., 2024). While these cases highlight the transformative impact of digital twins, broader adoption is still hindered by organizational barriers, including a shortage of digital competencies in the workforce and a lack of standardized models for different hydrological contexts (Mercer, 2024).

Equally important to the evolution of digital twins in hydrology is their integration with universally accessible geospatial platforms such as Google Maps and Google Earth Engine (GEE). These platforms provide a familiar interface for many users while offering powerful capabilities for spatial analysis and real-time data integration (Choi et al., 2005; Alabbad et al., 2023). For example, studies have demonstrated the successful coupling of Google Maps with hydrological models like IHACRES, allowing for interactive streamflow prediction and high-resolution terrain modeling with minimal technical overhead (Yuan & Cheng, 2007). GEE extends these capabilities by enabling large-scale flood risk assessments and time-sensitive disaster response through satellite imagery and digital elevation models (Agrawal et al., 2024). It also supports water quality monitoring and global hydrological assessments using advanced remote sensing techniques combined with cloud-based machine learning algorithms (Galodha et al., 2024). These developments have paved the way for more inclusive and accessible visualization tools, reducing the technical barriers traditionally associated with hydrological modeling and mapping.

Furthermore, 3D modeling within GIS environments has significantly expanded the depth and analytic value of environmental visualizations. Advances in procedural modeling techniques have enabled the creation of complex urban and topographic scenes that support both visualization and spatial querying, which are critical for applications in urban planning and disaster management (Zhou & Hu, 2024). Tools like CityEngine have facilitated the rapid generation of city-scale 3D models, supporting a range of use cases from academic campus simulations to regional infrastructure planning (Tsiliakou et al., 2014). In hazard preparedness, WebGIS-based platforms have successfully simulated flood and tsunami events, offering interactive, building-level assessments that support targeted risk mitigation (Hong & Tsai, 2020). While powerful, such systems often struggle with challenges such as computational load, integration of real-time data, and the need for specialized expertise, which limit their scalability and use in resource-constrained settings.

As AI tools become more embedded in hydrology, there is a growing need for standardized evaluation frameworks to assess their effectiveness. Benchmarks such as HydroLLM-Benchmark provide a systematic approach for evaluating large language models on domain-specific tasks like flood prediction, hydrological modeling, and water cycle comprehension (Kizilkaya et al., 2025). These benchmarks help ensure transparency, accuracy, and relevance in AI-driven hydrological applications, supporting more responsible integration into research and decision-making contexts.

Together, these bodies of work illustrate a clear trajectory from static 2D visualization techniques toward more intelligent, integrated, and immersive platforms for hydrological analysis. They also underscore persistent barriers, including the need for real-time data pipelines, modularity, interdisciplinary collaboration, and broader accessibility, that must be addressed to realize the full potential of digital twin frameworks in water-related fields. This study contributes to this evolving research landscape by introducing a web-based, modular 3D hydrological visualization library that integrates real-time data with Google Maps API. By prioritizing interactivity, spatial accuracy, and cross-platform accessibility, the proposed tool aims to support both scientific inquiry and applied decision-making in water resources, offering a practical and scalable solution to long-standing challenges in environmental visualization.

Existing geospatial platforms such as Google Earth, CesiumJS, and Mapbox GL support 3D terrain rendering and object overlays, but they do not offer native capabilities for hydrological animations or real-time flood visualization. These platforms primarily focus on static elevation models or navigation, with limited or no support for terrain-coupled water surface rendering, animated rainfall, or hydrological mesh deformation. Hydro3DJS extends these limitations by introducing real-time flood animation, atmospheric simulation, and object-level interaction in a unified web interface.

3. Methodology

The methodology for this research involved the design, development, and evaluation of a web-based 3D hydrological visualization library intended to enhance the communication of water-related phenomena through intuitive and spatially accurate representations. The development approach emphasized modularity, real-time responsiveness, and seamless integration with authoritative data sources and widely adopted geospatial mapping platforms. This section details the architectural design, implementation strategies, data processing workflows, user interface elements, and validation processes employed to ensure cross-platform compatibility, scalability, and relevance to hydrological visualization use cases. By combining cutting-edge web technologies with domain expert feedback, this methodology establishes a strong foundation for both technical deployment and practical application in environmental monitoring and decision-making.

3.1. Architecture

The 3D hydrological visualization library was developed using a JavaScript-based architecture built around modular components to enable real-time interactivity, scalability, and flexible integration with geospatial data platforms such as Google Maps. The system architecture, illustrated in Figure 1, is composed of five core modules: Hydrological Data Sources, Data Processing, Visualization App, WebGL Engine, and User Interface Controls. These components form a coherent pipeline that supports the flow of hydrological information from ingestion through to 3D rendering in the browser.

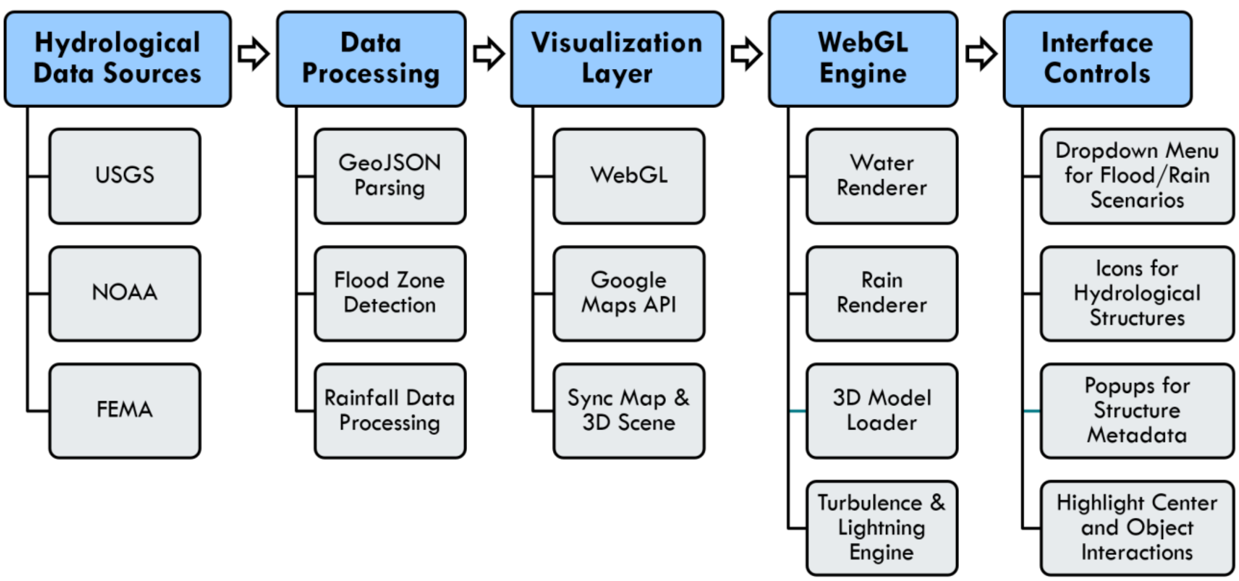

Figure 1: System Architecture of the 3D Hydrological Visualization Library

Hydrological Data Sources include publicly accessible datasets from authoritative providers such as the U.S. Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), and the Federal Emergency Management Agency (FEMA). These sources provide a rich and diverse range of hydrological data, including streamflow, rainfall, flood zones, and environmental hazard indicators through cloud computing providers (Seo et al., 2019). The incorporation of these datasets ensures the tool can support a wide variety of operational and research scenarios, from forecasting flood risks to simulating the impact of infrastructure on water dynamics (Yildirim et al., 2022).

The Data Processing component uses a client-side pipeline for lightweight preprocessing of raw input data. Spatial data, primarily in GeoJSON format, is parsed to identify hydrologic features such as flood zones and precipitation extents. Terrain-aware thresholds are applied to detect hydrologically significant zones, while precipitation data is processed to inform the rendering of rainfall effects. The entire processing pipeline is implemented using browser-compatible JavaScript modules to support real-time updates with minimal latency and no reliance on back-end servers.

Visualization App combines Google Maps API for geospatial referencing with WebGL for hardware-accelerated 3D rendering. The map-to-scene synchronization mechanism ensures that user actions such as zooming or panning the map directly correspond to updates in the 3D scene, maintaining spatial coherence and enhancing the user experience.

The WebGL Engine is responsible for rendering all dynamic hydrological and environmental visual elements, including water and rain animations. It also supports the incorporation of 3D models such as levees, culverts, and dams for contextual enrichment. The engine employs shaders and custom lighting to create realistic environmental conditions, including turbulence, shadow casting, and water reflections, thereby enhancing immersion and spatial awareness.

User Interface Controls enable direct interaction with the visualization environment. A dropdown menu allows users to toggle between predefined flood and rainfall scenarios, while icons and toggle switches manage the visibility of different hydrological structures. Interactive features, such as clickable objects and animated metadata popups, facilitate exploration and understanding. Additional controls support object highlighting and scene manipulation, allowing users to focus on specific areas of interest for more detailed analysis.

The overall architecture reflects a balance between performance, usability, and extensibility. The use of WebGL ensures efficient rendering in any modern browser without requiring additional plugins. Meanwhile, the modular architecture allows developers to independently update or extend each system component, whether by adding support for new data formats, incorporating more complex simulation models, or enhancing rendering capabilities. Accessibility and performance optimization were also key design criteria, and the application supports full functionality on both desktop and mobile devices.

3.2. 3D Visualization Engine

The development of the 3d visualization engine leveraged modern web technologies and geospatial libraries to create an interactive 3D environment capable of rendering hydrological phenomena in real time. The primary programming language used was JavaScript, supported by WebGL for rendering and the Google Maps JavaScript API for geographic base mapping. These technologies were chosen for their cross-platform compatibility, performance efficiency in browsers, and extensive developer support. The modular structure of the codebase allows easy maintenance and scalability, making it adaptable for different hydrological use cases.

A key feature of the tool is its support for custom 3D models, which represent hydrological infrastructure such as dams, levees, and urban buildings. These models were designed using industry-standard 3D file formats including glTF, FBX, and OBJ. Once imported, they are spatially aligned with the Google Maps terrain using latitude, longitude, and elevation data. This spatial anchoring allows users to visualize how water behaves in topographically accurate environments, making the simulation more realistic and context sensitive. Elevation alignment ensures that structures interact appropriately with rendered hydrological phenomena, enabling more realistic simulation of water behavior and structural impacts during flood scenarios.

To simulate dynamic events, such as rainfall and water movement for flooding, the system uses animated shaders within the WebGL framework. Rainfall effects are generated through particle systems and vertex animations, while floodwater animations use mesh deformations and fragment shaders to convey depth, velocity, and direction. These animations are scenario-driven and update in real time in response to user selections, providing a temporal layer to the visualizations that help users understand how conditions evolve over time and space.

The tool also allows users to highlight areas of interest by overlaying translucent layers onto the map. These highlight zones may represent evacuation areas, flood-prone zones, or infrastructure at risk. Object highlighting functionality brings attention to selected map elements and triggers animations or metadata displays, enabling deeper exploration of localized risks and interventions. Metadata, such as flood stage levels or structural vulnerability, is displayed in intuitive popup windows that follow modern UI standards for clarity and responsiveness.

Another core capability of the tool is real-time data integration. The system connects to external APIs and data streams from organizations like USGS and NOAA, allowing the visualization to reflect live river discharge rates, precipitation levels, and flood warnings. The tool effectively transforms from a static simulator into a real-time operational dashboard, empowering users to monitor ongoing events and respond quickly to changes. This live data pipeline supports operational use cases such as emergency planning, infrastructure monitoring, and public information campaigns.

3.3. Data Integration in System Workflow

The primary function of the visualization library is to present existing hydrological data in an interactive and engaging 3D environment. Importantly, the system is designed as a visual representation layer only; it does not conduct hydrological analysis, computations or modeling. Its focus is on translating data, whether historical or real-time, into spatially accurate, visually rich formats that can be easily interpreted by experts and stakeholders alike. Hydrological data is sourced from agencies such as the USGS, NOAA, and FEMA. These sources provide a wide range of data, including river discharge, rainfall amounts, flood hazard zones, and environmental sensor metadata. These datasets are typically formatted in GeoJSON or other standard spatial formats and are suitable for immediate ingestion by the visualization engine.

Once data is acquired, it undergoes preprocessing using lightweight routines that operate directly in the browser. GeoJSON files are parsed to identify geometric features such as polygons and multipolygons representing areas affected by flooding or rainfall. These geometries are then passed to specialized functions within the visualization library, such as addWater() and addRain(), which convert them into animated visual effects. These effects are enhanced using WebGL shaders to provide realistic environmental cues such as surface ripples, flow direction, and rainfall density.

In addition to environmental overlays, the tool supports 3D object rendering via the addModel() function, which accepts widely used 3D file formats including GLTF, FBX, and OBJ. This feature allows users to incorporate infrastructure models such as bridges, levees, turbines, and buildings directly into the scene. Developers can position, scale, and orient these models using transformation methods like setPos() for setting geographic position, setRot() for adjusting orientation, and setScale() for controlling the size. The library also supports both static and animated 3D objects, including turbines (addTurbine()), stationary boats (addStaticBoat()), and path-following boats (addTravelBoat()), enhancing the realism and contextual detail of simulations.

A utility function, highlightCenter(), is provided to place a visual marker at the center of the current map view, aiding in spatial reference and navigation. Overall, the system is designed to maintain minimal computational overhead while providing high-quality 3D renderings, making it suitable for web-based deployment across a variety of platforms and user contexts. By focusing exclusively on visualization, the library ensures maximum flexibility and ease of integration with existing hydrological datasets and platforms.

3.4. User Feedback and Testing

To evaluate the usability and practical applicability of the developed 3D hydrological visualization library, a case study was conducted using a prototype flood information system tailored to Iowa City, Iowa. This location was selected for its well-documented vulnerability to flooding (NWS, 2009; USGS, 2010) and the availability of high-resolution hydrological data from authoritative agencies such as the U.S. Geological Survey (USGS) and the Federal Emergency Management Agency (FEMA). The prototype implementation served as a comprehensive demonstration of the library's key functionalities, including real-time rainfall data integration, incorporation of digital elevation models, rendering of 3D infrastructure, and scenario-based flood simulation, all within a geospatially referenced user interface.

To assess the effectiveness and usability of the tool from the perspective of intended end users, a structured usability survey was designed and administered to a group of 35 stakeholders. Participants were recruited primarily from the Iowa Institute of Hydraulic Research (IIHR), the Iowa Flood Center (IFC), and the Iowa Water Center (IWC). These organizations represent a broad cross-section of professionals in hydrology, environmental science, civil engineering, water resources planning, and municipal policy. Participants were selected based on their expertise in water resources and experience working with hydrological data and visualization tools.

Instead of requiring hands-on interaction with the live tool, participants were provided with a curated set of demonstration materials. These included pre-recorded video walkthroughs, annotated screenshots, and narrative explanations that highlighted the system's features, visualization techniques, and interactive capabilities. The demonstration content was designed to simulate real-world use cases and provide an in-depth understanding of the tool's potential, particularly in visualizing hydrological scenarios involving rainfall, flooding, and critical infrastructure vulnerability.

Following this demonstration, participants completed a multi-part online questionnaire designed to capture both quantitative and qualitative feedback. One section of the survey asked respondents to rate the relevance of five primary use cases on a five-point Likert scale (1 = Not Relevant, 5 = Very Relevant). The evaluated use cases included flood map visualization, real rainfall data integration, highlighting custom objects affected by floods, displaying scenarios with 3D infrastructure models, and bathymetry visualization based on cross-sectional survey data. These use cases were selected to reflect the tool's core functionalities and their potential applicability to both routine and emergency hydrological tasks.

In addition to rating relevance, participants were asked to provide background information on their fields of expertise and their frequency of visualization tool usage. This contextual data helped in analyzing responses according to disciplinary lens and experience level. Respondents were allowed to select multiple domains of expertise, which revealed that many had interdisciplinary backgrounds combining hydrology, computer science, environmental planning, and data science. The survey also asked users to indicate their primary purposes for using visualization tools, options included data analysis, public communication, report generation, research, and education or training. Participants were able to select more than one category, reflecting the multifunctional nature of hydrological visualization tools in professional contexts.

The survey concluded with an open-ended question that invited participants to describe the most significant challenges they face when visualizing water-related events. This qualitative prompt aimed to elicit unstructured insights into the technical, conceptual, and communication barriers encountered in real-world workflows. The responses highlighted a wide spectrum of obstacles ranging from data interoperability and rendering performance to challenges in stakeholder engagement and interdisciplinary communication.

Collectively, the feedback gathered through this structured evaluation provided valuable information on the strengths and limitations of the visualization library, both from a usability standpoint and in terms of real-world applicability. The insights gained informed not only the refinement of the tool itself but also contributed to a broader understanding of the needs and expectations of hydrological visualization users. The following section presents the detailed results of this evaluation and synthesizes the themes and technical challenges identified through user feedback, which serve as guiding principles for future development and enhancement of the platform.

4. Results and Discussion

This section presents the outcomes of implementing and evaluating the Hydro3DJS library. The results are structured into three parts. First, Section 4.1 introduces two case studies, rural and urban, used to demonstrate the system's capabilities in real-world hydrological visualization scenarios. These examples highlight dynamic water rendering, infrastructure modeling, and integration with live sensor data. Second, Section 4.2 summarizes findings from a structured usability study involving domain experts, including relevance ratings for specific use cases and user engagement patterns. Finally, Section 4.3 outlines technical and user-identified challenges, focusing on performance limitations, interaction constraints, and opportunities for improvement. Together, these results illustrate both the practical utility of Hydro3DJS, and the broader challenges involved in hydrological data visualization on the web.

4.1. Case Study: Interface-Driven Hydrological Visualization Scenarios

To demonstrate the capabilities of the Hydro3DJS library in applied settings, we present two representative use cases that showcase how the system integrates geospatial data, dynamic rendering, real-time streams, and infrastructure modeling. These examples, one rural and one urban, highlight the flexibility and extensibility of the library for diverse hydrological visualization goals, including planning, analysis, and communication.

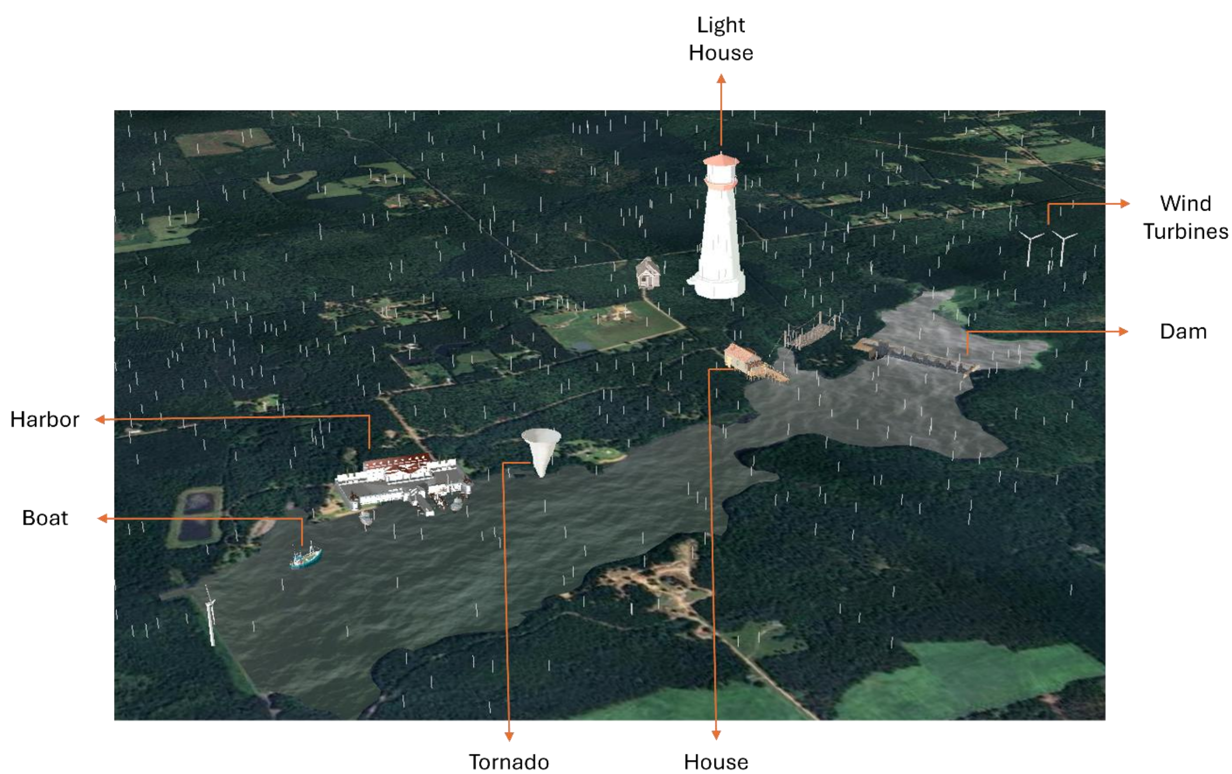

Figure 2. Interactive 3D flood simulation with rain, infrastructure, and water dynamics

Use Case 1: Rural Watershed Simulation with Custom 3D Elements

The first use case simulates a rural watershed environment with key hydrological and structural components rendered in a 3D scene (Figure 2). The scenario includes a combination of dams, wind turbines, a harbor, boats, and a lighthouse, along with animated rainfall and floodwater effects. These assets are loaded using Hydro3DJS functions such as addModel(), addRain(), and addWater(), and positioned using geographic coordinates for accurate spatial alignment.

Users interact with the scene via a modular control panel, enabling or disabling individual components to tailor the visualization for specific analysis tasks. For example, stakeholders can simulate infrastructure vulnerability by toggling flood effects while examining how water interacts with nearby levees or turbines. Each visual element is designed to demonstrate a core feature of the library, from realistic water animations to metadata-linked popups and model animations.

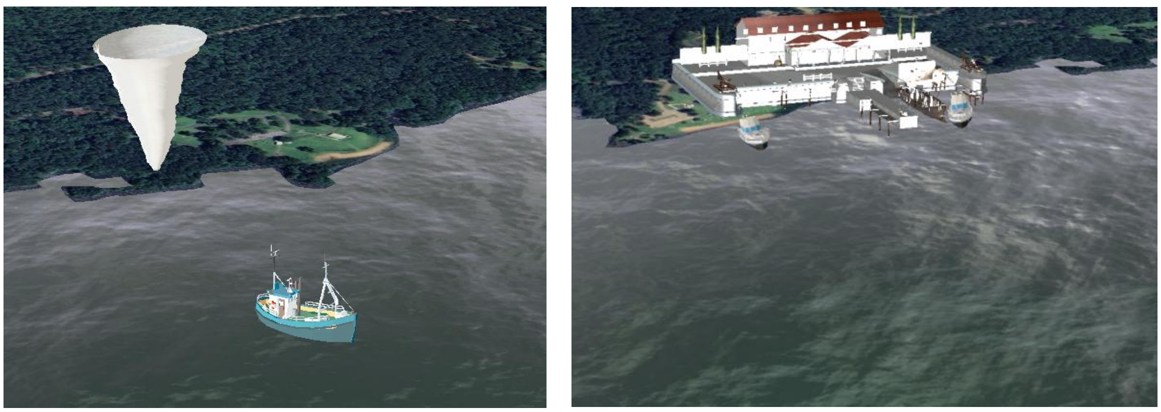

Figure 3. (a) Simulated tornado and vessel interaction on floodwater near shoreline (b) Close-up of harbor and docked boats with animated floodwater surface

To highlight visual fidelity and composability, Figure 3a presents a close-up view of a tornado simulation interacting with floodwater and a nearby vessel, an example of multi-hazard visualization. Figure 3b shows detailed rendering of a harbor facility with docked boats, illustrating Hydro3DJS's support for complex infrastructure modeling over animated water surfaces. This scenario illustrates the use of Hydro3DJS as a sandbox for flood education, rural risk assessment, and multi-object spatial visualization, particularly in areas where critical infrastructure is co-located with natural water bodies.

Use Case 2: Urban Flood Visualization for a 100-Year Event

The second use case focuses on an urban environment, downtown Iowa City, where the system simulates a 100-year flood event to visualize inundation and infrastructure exposure at street-level resolution (Figure 4). This scenario demonstrates the ability of Hydro3DJS to visualize historical or projected flood zones alongside real-time sensor overlays, providing both planning and operational value.

Flood extents are rendered using elevation-aware mesh deformation, with the 100-year flood polygon derived from FEMA and local hydrodynamic models. 3D water fills low-lying areas, illustrating how key city infrastructure, including roads, public buildings, and waterfront developments, would be affected under a severe flood event. Users can interact with the environment using pan and zoom tools, select predefined locations, or enter custom coordinates for precise spatial targeting.

Figure 4. Urban flood visualization showing projected 100-year flood extents

To illustrate specific interface capabilities, Figure 5a shows a close-up view of the integrated sensor overlay, where clicking on a monitored river section reveals live USGS stream gauge readings and flood alert status. This real-time interaction adds situational awareness to the scene and enables timely decision-making. In contrast, Figure 5b highlights the full spatial extent of a simulated 100-year flood event, showing widespread urban inundation that affects critical transportation routes and industrial zones. Together, these views demonstrate how Hydro3DJS bridges predictive modeling and operational monitoring within a single browser-based platform.

Figure 5. (a) Sensor integration (b) Inundation extent under a 100-year flood event

One of the core features of this scenario is the integration of live USGS stream gauge data. Users can click on flood-affected rivers to open contextual popups showing real-time water levels, historical trends, and flood alert status. This bridges the gap between predictive simulation and live monitoring, offering a decision-support tool that can assist during emergency response and risk communication efforts. This example underscores the system's use in urban planning, infrastructure preparedness, and community-facing flood outreach.

4.2. Usability Findings

To assess the usability and domain relevance of the 3D hydrological visualization library, a structured survey was distributed to 35 professionals working in water-related fields. Of these, 20 participants completed the survey, yielding a response rate of approximately 57%. All respondents completed the full questionnaire, which consisted of both quantitative items, such as use case relevance ratings, and open-ended qualitative feedback prompts. Participants represented a broad spectrum of disciplinary backgrounds, including hydrology, computer science, environmental science, urban planning, disaster management, and data science.

Participants reviewed curated demonstration materials that included annotated screenshots and video walkthroughs showcasing the tool's primary functionalities. These materials covered real-time rainfall integration, flood animation rendering, interactive 3D model displays, and infrastructure overlays. After reviewing the demonstrations, participants were asked to rate the relevance of five visualization use cases on a 5-point Likert scale, where 1 represented "Not Relevant" and 5 represented "Very Relevant." The use cases evaluated were flood map visualization, highlighting flood-affected infrastructure, integrating real rainfall data, rendering scenarios with 3D objects, and bathymetry visualization based on river cross-sections.

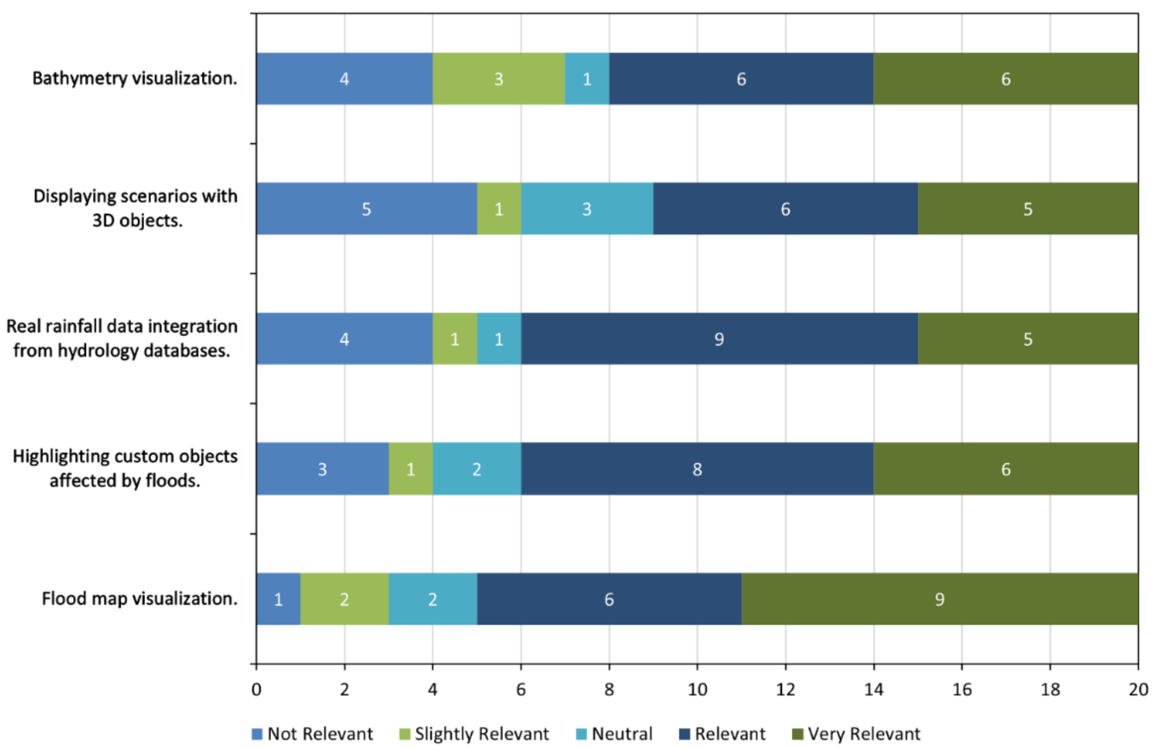

Figure 6. Relevance ratings for five visualization use cases

As shown in Figure 6, flood map visualization, rainfall integration, and infrastructure highlighting emerged as the most relevant use cases, receiving the highest average scores. Notably, 9 out of 20 respondents rated flood map visualization as “Very Relevant,” while over 60% of participants rated the top three use cases as either “Relevant” or “Very Relevant.” Although bathymetry visualization received more varied ratings, it still attracted interest, with over 50% of respondents assigning a positive score. This suggests that while some visualization types may have niche applicability, they still contribute meaningfully to specialized workflows such as hydraulic modeling or geomorphic analysis

The disciplinary composition of the participant pool is shown in Figure 7. Participants could select multiple fields to reflect their interdisciplinary expertise. Seven participants selected hydrology, eight identified with computer science, and seven were aligned with data science. Other domains included environmental science, disaster management, urban planning, and related engineering disciplines such as hydraulics and electrical engineering. The diversity in professional background reinforces the broad potential of the tool to serve cross-cutting needs, from technical modeling and analysis to stakeholder engagement and public communication.

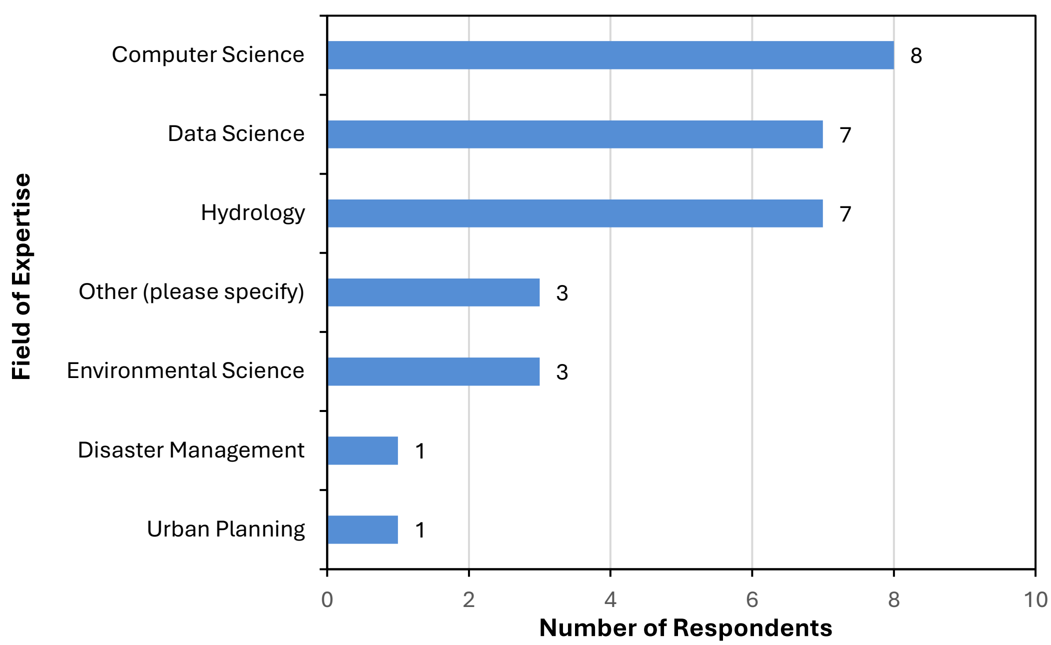

Figure 7. Distribution of participants by field of expertise

Participants also reported their frequency of visualization tool use, shown in Figure 8. A majority, 11 out of 20 respondents, reported using such tools on a daily basis, while others indicated weekly or monthly use. This high level of engagement affirms the critical role visualization plays in their workflows and underscores the need for tools that offer intuitive interfaces, real-time responsiveness, and scientific accuracy.

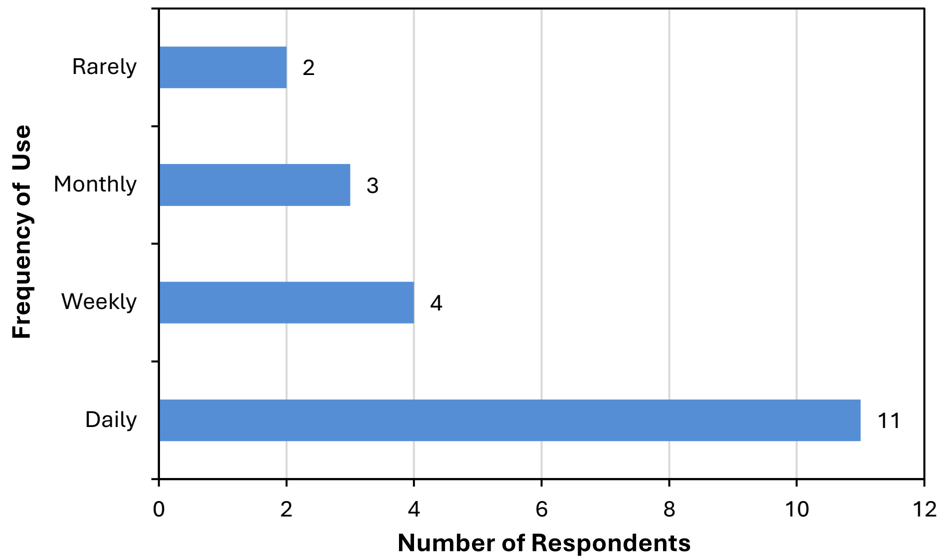

Figure 8. Frequency of visualization tool usage among respondents

When asked to identify the primary purposes for using visualization tools, participants selected from five categories: data analysis, report generation, public communication, research, and education or training. As shown in Figure 9, the most frequently selected purposes were data analysis and research, each chosen by 16 respondents. These were followed by report generation (9), education/training (8), and public communication (8). One participant selected "Other," specifying "data visualization" as their primary focus. These results emphasize the need for flexible tools that can serve diverse objectives, from scientific analysis to educational outreach, within the same interface.

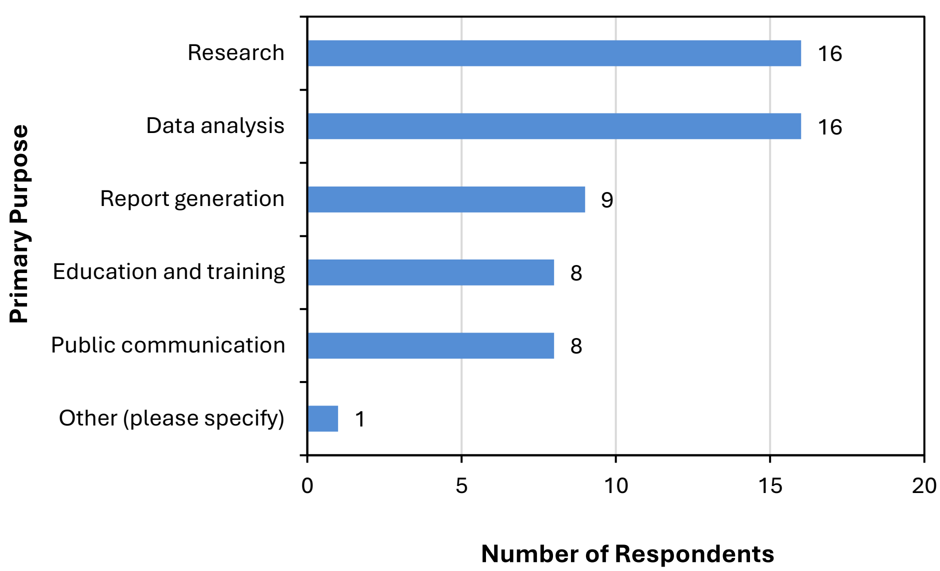

Figure 9. Primary purposes for using visualization tools

4.3. Challenges and Limitations

4.3.1. Technical Challenges

While the prototype was well received for its visual clarity, interactivity, and accessibility, several technical limitations were identified during both the development and evaluation phases. One of the most significant challenges related to rendering performance. The system experienced inconsistent frame rates and elevated memory consumption when tasked with large GeoJSON datasets, high-polygon 3D models, or overlapping visual effects such as rain, floodwater, and infrastructure animations.

These resource-intensive conditions particularly impacted performance on lower-end or older devices, revealing the need for further optimization. Potential improvements in rendering efficiency include geometry simplification, level-of-detail techniques, progressive loading of 3D assets, and optimized use of fragment shaders. For example, water and rain effects could benefit from simplified mesh generation and shader reuse. Additionally, future development may explore WebAssembly or GPU-accelerated computation to offload some of the visualization processing from the main JavaScript thread.

Another limitation was the passive nature of the current simulation interface. Although users can observe hydrological phenomena and toggle between preconfigured scenarios, they are not able to manipulate environmental parameters in real time. Participants expressed a desire for adjustable controls, such as modifying rainfall duration, changing water level thresholds, or defining the geographic scope of flooding. The absence of scenario editing capabilities was noted by several participants a constraint in exploratory analysis and stakeholder workshops, where dynamic simulations and "what-if" testing are often essential.

Minor browser compatibility issues were also observed. While the tool performs consistently in mainstream browsers like Chrome and Firefox, slight discrepancies in rendering order, lighting effects, or performance metrics emerged across environments. Addressing these inconsistencies will require cross-browser testing and fallback strategies to ensure accessibility and reliability in varied use cases, including mobile and offline deployment scenarios.

4.3.2. User-Identified Visualization Challenges

Open-ended responses from participants further illuminated the challenges faced in hydrological visualization practice. A recurring theme was the complexity of working with large, heterogeneous datasets. Several respondents noted the computational load required to simulate and render water behavior accurately, especially under real-time constraints. One user described the difficulty of "handling high volume of data for high accuracy," while another cited the "high computational load for real-time physical simulations" as a major barrier to broader adoption.

Another concern involved the fidelity of raster-based visualizations. Several participants commented on the spatial imprecision and oversimplification introduced by cell-based rendering methods, particularly in flood modeling applications. One respondent pointed out that raster methods often "lose precision and liability," making it difficult to interpret subtle transitions in elevation or flow velocity. These concerns reflect a broader dissatisfaction with traditional hydrological visualization methods, which often obscure critical spatial and temporal variability due to oversimplified data representations.

Integration of infrastructure models with hydrological data was also cited as a persistent challenge. Respondents emphasized the need for better alignment between flood scenarios and 3D representations of real-world objects such as culverts, levees, and bridges. One participant observed that "integration with real 3D objects" was difficult to achieve, especially when modeling infrastructure impact zones or simulating cascading failure scenarios. The difficulty of visualizing interactions between dynamic water bodies and static infrastructure was highlighted as a key area for improvement.

Several respondents expressed concern over the usability of current tools, particularly in communicating technical analyses to non-expert audiences. Issues such as visualizing multiple data types, stream direction, and historic event reconstruction were cited as difficult to implement effectively in current workflows. One participant commented, "*When I present technical analysis to the public, I want to show them everything that went into the study, but they don't need that and often get overwhelmed.*" This underscores the importance of striking a balance between transparency and simplicity, especially when visualization tools are used for public communication, policy engagement, or emergency briefings.

Additional user comments highlighted challenges such as the lack of automation in content generation, difficulties in capturing stream directionality, and poor support for historic data visualization. Some users pointed to the burden of manual data formatting and validation, citing it as a major time sink that detracts from analytical work. Others flagged issues with tool interoperability, where mismatches in data formats or coordinate systems required extensive preprocessing. Together, these insights offer a clear roadmap for future development: more robust data integration, improved rendering performance, increased parameter interactivity, and adaptive visualization tailored to different audiences.

5. Conclusion and Future Work

This study introduced a web-based 3D hydrological visualization library designed to improve the way water-related phenomena, such as rainfall, flooding, and infrastructure exposure, are represented, communicated, and explored. Through a structured usability survey involving 20 professionals across diverse domains such as hydrology, environmental science, computer science, and urban planning, the research identified key priorities in hydrological visualization. Use cases such as flood map rendering, integration of real-time rainfall data, and highlighting flood-affected infrastructure emerged as particularly relevant and valuable. At the same time, the survey revealed critical limitations in existing visualization tools, including computational bottlenecks, insufficient support for dynamic interactivity (real-time simulations), and challenges in effectively conveying complex information to non-expert stakeholders.

The developed library addresses many of these challenges by offering a browser-based, modular platform that enables real-time, 3D rendering of hydrological data within a geospatially accurate environment. Unlike traditional modeling tools that require specialized software or high-end hardware, this system operates entirely within modern web browsers without the need for plugins, making it broadly accessible. The tool supports animated simulations of rainfall and floodwater, custom 3D model integration, infrastructure overlays, and live data visualization from sources such as the USGS and NOAA. By focusing on visualization rather than analysis, the platform minimizes computational overhead while maintaining flexibility and usability across a wide range of users and scenarios.

Looking ahead, the next phase of development will focus on significantly expanding the library's interactivity, scalability, and integration capabilities. One of the highest priorities is the implementation of real-time scenario control and parameter tuning. Future versions of the tool will allow users to adjust simulation variables such as rainfall intensity, event duration, infrastructure resilience, and geographic extent directly within the interface. This will support interactive "what-if" analyses and scenario planning, capabilities that are especially valuable for researchers, municipal planners, emergency response teams, and educators.

To increase the tool's applicability across larger and more complex geographic areas, future development will also incorporate automatic integration of spatial datasets from external sources, including municipal sensor networks, high-resolution terrain models, and global satellite feeds. This will allow the system to operate at regional or national scales, supporting use cases in disaster preparedness, infrastructure planning, and real-time monitoring. Furthermore, future iterations will explore integration with machine learning and predictive analytics frameworks. By coupling hydrological models with forecast data, the tool could enable visualization not only of current environmental conditions but also of likely future outcomes, thereby supporting early warning systems and proactive risk mitigation strategies.

Another key area of enhancement involves immersive visualization through extended reality (XR) technologies, including both augmented and virtual reality (AR/VR). These capabilities will allow users to experience hydrological scenarios at human scale, whether by projecting flood extents onto real-world landscapes via AR or exploring inundated urban environments through VR simulations. Such immersive environments can enhance engagement, particularly for training, outreach, and stakeholder communication.

User customization and content flexibility will also be prioritized in future updates, including for uploading custom datasets, defining user-specific infrastructure elements, and tailoring the visual interface for different audiences. These enhancements will enable more targeted use of the tool in settings such as public meetings, classroom education, and technical planning workshops.

Collectively, these future directions aim to transform the library into a comprehensive, intelligent, and extensible visualization platform. By offering an accessible yet scientifically robust environment for exploring hydrological phenomena, this work contributes meaningfully to the growing convergence of digital twins, environmental informatics, and web-based visualization. The continued refinement and expansion of the system will empower diverse stakeholders to better understand, communicate, and respond to water-related challenges in a world where resilience, foresight, and collaboration are more important than ever.

Software Availability

Name	Hydro3DJS
Developers	Zitong Wang, Ramteja Sajja, Yusuf Sermet
Contact information	https://hydroinformatics.uiowa.edu
Software Required	Web Browser
Program language	JavaScript, HTML, CSS
Availability & Cost	The software is free to use and can be accessed via https://github.com/uihilab/Hydro3DJS

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Ethics Approval and Consent to Participate

This study was approved by the Human Subjects Office Institutional Review Board (IRB), approval number 202411391. Informed consent was obtained from all participants prior to the administration of the survey. Participation was entirely voluntary, and all individuals were fully informed about the purpose and procedures of the study. The authors affirm that this work was conducted in accordance with established ethical standards.

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