HydroVerse VR Equipment Hub: An Integrated Virtual Reality Framework for Training and Workforce Development in Environmental Monitoring

Ali Rahmani [1], Yusuf Sermet [2], Ibrahim Demir [2,3]

[1] Informatics, University of Iowa, Iowa City, USA 52246
[2] ByWater Institute, Tulane University, New Orleans, USA 70118
[3] River-Coastal Science and Engineering, Tulane University, New Orleans, USA 70118

Abstract
Environmental monitoring is critical for managing ecosystems and addressing global challenges such as climate change and pollution. However, training professionals in this field is often hampered by remote locations, hazardous field conditions, and limited access to specialized equipment. In response, this paper presents the HydroVerse VR Equipment Hub, an immersive virtual reality framework for training and workforce development in environmental monitoring. This platform provides a safe, interactive learning environment that bridges theoretical knowledge with hands-on practice. It integrates extended reality (XR) technology, photogrammetry-based 3D models of monitoring devices, and artificial intelligence tools—such as the Meta VoiceSDK for voice-guided interaction—to create a dynamic and engaging training experience. Key features include specialized modules for exploring sensor components, practicing equipment troubleshooting, and simulating field deployment scenarios within realistic virtual environments. This approach enables users to safely assemble and calibrate virtual sensors, diagnose faults, and perform monitoring tasks, thereby building technical proficiency and confidence while avoiding the risks and constraints of on-site training. Importantly, the system trains users on existing environmental monitoring devices rather than altering those devices, ensuring that skills learned are directly transferable to real equipment. By enabling experimentation with diverse scenarios and providing immediate feedback (e.g., through voice-guided assistance), the HydroVerse Hub allows trainees to refine their problem-solving strategies before real-world implementation. This immersive training approach has the potential to enhance environmental science education, improve workforce readiness, and inspire similar training innovations in related technical fields.

Keywords: virtual reality, extended reality, learning technology, troubleshooting, environmental monitoring, sensors, IoT

---

1. Introduction

Environmental monitoring plays a foundational role in addressing pressing global issues such as climate change, pollution, and ecosystem degradation (Awewomom et al., 2024; Sermet and Demir, 2023). Accurate data collection and interpretation are essential for informed decision-making, yet the tools and systems used in the field are often complex and difficult to master through conventional means (Means et al., 2009; Kaynak et al., 2025). Traditional training methods, relying heavily on static content, restricted field access, and costly equipment, struggle to provide equitable, hands-on learning experiences (Corter et al., 2007; Emiroglu et al., 2025). These limitations are particularly evident in under-resourced institutions and remote communities, where learners face barriers to accessing equipment, expert instruction, and immersive practice (Singh, 2024). As the need for skilled professionals in environmental fields grows, there is an urgent demand for innovative, inclusive, and accessible training solutions (Tahir et al., 2024; Demiray et al., 2025).

Building on these challenges, existing educational models also suffer from deep structural shortcomings that hinder the development of practical skills (Ahmed et al., 2023). Many programs lack opportunities for hands-on engagement with sensor components and monitoring workflows, while pedagogical models grounded in lectures and diagrams fail to prepare learners for the procedural complexity of field tasks (Owolabi et al., 2024). Safety concerns, logistical constraints, and inconsistent access to field sites further limit experiential learning (Mantai et al., 2021). Even when digital tools are available, they are often fragmented, offering limited interaction or adaptability to different user needs (Marion et al., 2021). These systemic issues reinforce the divide between academic preparation and real-world readiness (Bates et al., 2022).

Extended reality technologies, particularly Virtual Reality (VR), offer a promising alternative (Alnagrat et al., 2022). By simulating real-world tools, sensor components, and monitoring conditions, VR allows learners to practice assembly, calibration, and deployment tasks in a safe and cost-effective digital setting (Yazdi, 2024). These simulations support procedural and spatial skill development through interactive, repeatable workflows that mirror actual field operations (Lawson McLean et al., 2024; Mudiyanselage et al., 2025). Additionally, VR environments can be distributed widely, breaking down geographic and financial barriers to training (Yandrapalli et al., 2025). Their flexibility supports a range of users, from students and educators to technicians and professionals, making learning more inclusive and responsive to individual needs (El Galad et al., 2024).

However, not all digital or immersive tools meet these demands (Siddiqi, 2024). Many platforms (i.e. web, GIS) remain fragmented and limited in scope, focusing narrowly on data visualization or static walkthroughs without enabling true interaction or experiential engagement (Paulino et al., 2024; Yesilkoy et al., 2024). Users often cannot manipulate sensor components, respond to dynamic scenarios, or receive real-time feedback and guidance (Coito et al., 2021). Moreover, most tools fail to adapt to different levels of expertise, offering generic experiences that are not suited for learners with diverse backgrounds or professional goals (Kua et al., 2021).

These shortcomings underscore the need for a more integrated and user-centered solution (Van Velsen et al., 2022).

To address the gaps left by both traditional and existing educational tools, the HydroVerse Equipment Hub was developed as a purpose-built platform for environmental monitoring education and training. This system combines high-fidelity modeling of real-world sensors, modular environments for different learning goals, and realistic urban and environmental simulations (Almutairi et al., 2024). Designed to support hands-on exploration, technical troubleshooting, and context-aware deployment planning, the HydroVerse Equipment Hub offers an immersive, inclusive, and comprehensive approach to preparing the next generation of environmental professionals (Rawat et al., 2024).

The remainder of this paper is organized as follows: Section 2 provides an overview of the background and foundational concepts, highlighting the current state of environmental monitoring education and the role of virtual reality technologies in advancing skill-based learning. Section 3 outlines the methodology, detailing the design principles, system architecture, technological components, and the structured process for creating high-fidelity 3D models using photogrammetry. Section 4 presents the results, emphasizing key features, user engagement outcomes, and the system's capability to simulate real-world scenarios effectively. Section 5 presents a comprehensive evaluation of the system through technical performance analysis, and theoretical framework alignment. Section 6 discusses broader implications for environmental monitoring, training, and interdisciplinary collaboration. Finally, Section 7 concludes with a summary of contributions and outlines future directions, including expanding applications to other domains, enhancing adaptability, and improving accessibility through emerging technologies.

2. Background

Traditionally, training in environmental monitoring has relied on classroom-based instruction and limited practical exposure (Agbor et al., 2025). Lectures and textbook learning are typically supplemented by static demonstrations and infrequent field excursions to illustrate real-world concepts (Lang, 2021). While these conventional methods impart fundamental theoretical knowledge, they offer only restricted hands-on experience with actual monitoring techniques and equipment (Pajo, 2022). Field exercises are logistically challenging and costly to organize, resulting in scarce opportunities for practice that particularly affect learners in under-resourced settings (Shivolo et al., 2024). As a consequence, many students complete such programs with minimal direct exposure to authentic environmental monitoring scenarios, underscoring the need for more accessible and immersive training approaches (Tung, 2025).

Environmental monitoring relies on the integration of environmental science with computational modeling, sensor technologies, and data communication systems to address complex challenges related to ecosystem health, climate resilience, and infrastructure management (Miller et al., 2025; Bhavani & Gajendra, 2024; Fang et al., 2014; Sermet et al., 2020). Over the past decades, advances in computing power and the development of tools such as web systems (Alabbad et al., 2023), Geographic Information Systems (GIS), artificial intelligence (Ram et al., 2025), and virtual reality have significantly expanded the potential of environmental informatics (Ali et al., 2024; Song & Wu, 2021; Safavi, 2024; Demir at al., 2015). These technologies enable more accurate modeling, simulation, and visualization of environmental systems, enhancing both research and operational applications in fields such as air and water quality, disaster response (Cikmaz et al., 2025), and urban planning (Riaz et al., 2023).

Virtual reality has emerged as a powerful tool in education and technical training, particularly in engineering and applied sciences (Sermet and Demir, 2020). By providing immersive and interactive learning experiences, VR enhances students' engagement and understanding of complex concepts (Azzam et al., 2024; Yang et al., 2024). In engineering disciplines, VR-based simulations enable learners to visualize intricate mechanical and structural systems, manipulate virtual components, and conduct experiments in a controlled environment (Soliman et al., 2021; Sermet and Demir, 2019; Daniela et al., 2020). This approach reduces dependency on costly physical laboratories and mitigates risks associated with hands-on training, particularly in hazardous environments (Abulrub et al., 2011). Furthermore, VR has been widely used in simulation, allowing researchers and engineers to develop and test sensor-based devices and complex systems in a virtual space before deploying them in real-world scenarios. This capability is crucial for fields such as robotics, autonomous systems, and environmental monitoring, where accuracy and reliability are critical (Ghazali et al., 2024).

When applied to hydrology, VR has the potential to serve as a transformative tool for education, research, and decision-making in water resource management (Grosser et al., 2022). The ability to simulate hydrological processes in immersive environments allows students and professionals to explore watershed dynamics, groundwater flow, and flood scenarios without the limitations of traditional fieldwork (Demir et al., 2022). Platforms like VR4Hydro have demonstrated how virtual field trips can replicate real-world hydrological settings, enhancing experiential learning while reducing logistical constraints and safety concerns associated with field studies (Grosser et al., 2022). Moreover, VR-based hydrological simulations facilitate better understanding of water management strategies by enabling stakeholders to interact with dynamic models and analyze the impact of different environmental and anthropogenic factors. These applications are particularly beneficial in regions prone to extreme weather events, where predictive simulations can aid in disaster preparedness and response planning (Loucks, 2023; Wagener et al., 2021; Alabbad et al., 2024).

Despite its potential to positively impact learning environments, the integration of VR into environmental monitoring remains an underexplored area (Alotaibi et al., 2024). While existing studies highlight challenges such as high costs, resource requirements, and the need for specialized expertise (Azzam et al., 2024), there is still a gap in practical applications that support experiential learning, informed decision-making, and urban planning in water-related domains. This paper addresses that gap by presenting the design and implementation of the HydroVerse VR Equipment Hub, offering a structured, immersive environment that enhances theoretical understanding, practical skill development, and multidisciplinary collaboration.

3. Methodology

The HydroVerse Equipment Hub was developed through a structured and iterative design process that prioritized realism, usability, and modularity. The system was built using Unreal Engine 5 to enable high-quality rendering and dynamic lighting, while RealityCapture was employed to generate precise 3D sensor models through photogrammetry. CityEngine was used to create a digital twin of Iowa City for contextual deployment scenarios, and VoiceSDK enabled voice-guided navigation and task assistance. Throughout the process, user interaction was refined through feedback loops to ensure intuitive engagement via both controllers and voice commands. The methodological emphasis on modular architecture and adaptive interaction was intended to produce a scalable, immersive learning system capable of replicating real-world workflows in environmental monitoring.

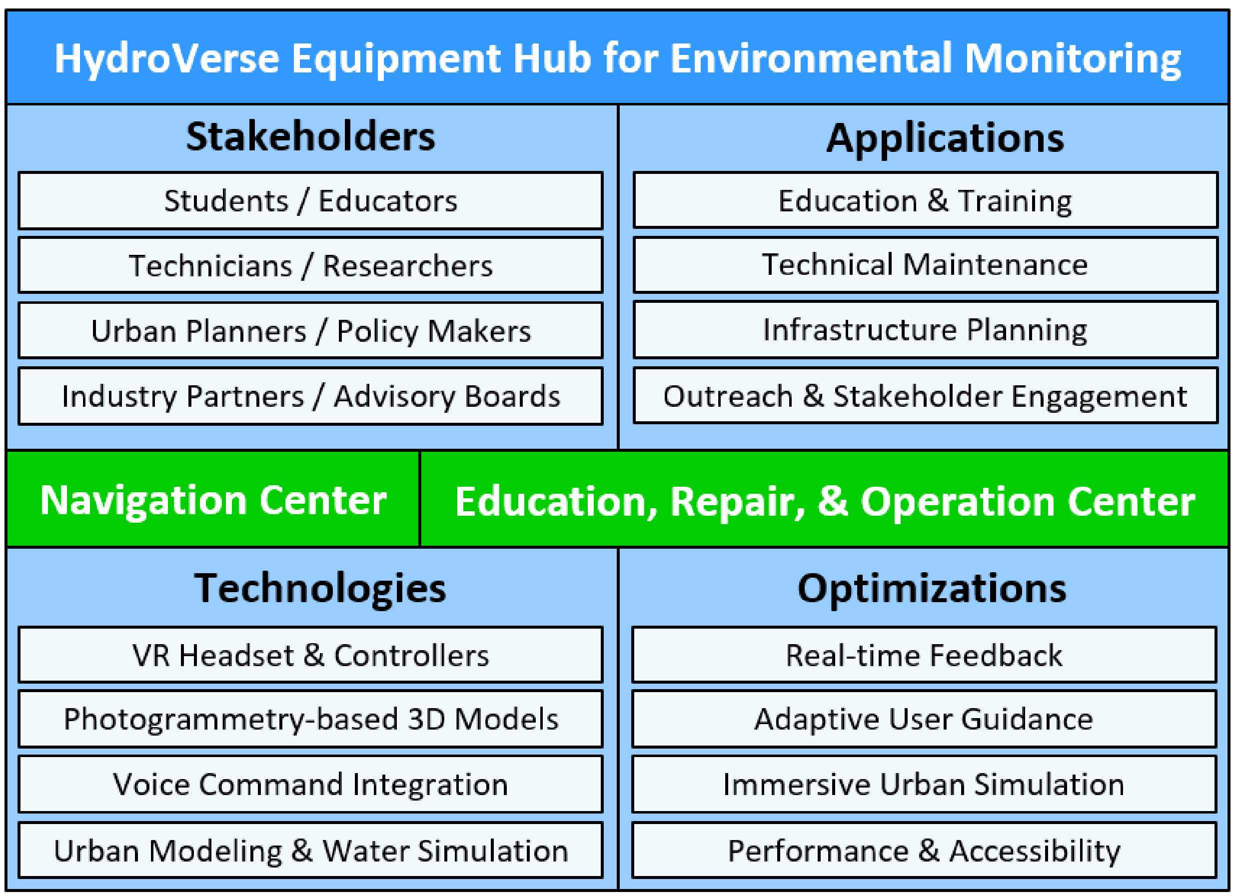


Figure 1: HydroVerse Equipment Hub and its stakeholders, applications, technologies and optimizations

The HydroVerse Equipment Hub offers a structured framework for advancing environmental monitoring through skill-based learning. By integrating virtual reality, photogrammetry, and VoiceSDK, the system bridges theoretical knowledge with practical application. Its three specialized centers—the Education Center, Repair Center, and Operational Center—facilitate interactive simulations, enabling users to explore sensor composition, diagnose faults, and simulate installations. Advanced 3D visualization and voice command navigation enhance accessibility and engagement, ensuring an effective learning environment for students, educators, and professionals. In addition, two main components of this project are water simulation and CityEngine. The water simulation models realistic streamflow within a virtual environment, providing deeper insight into processes. CityEngine exports detailed urban models that are integrated into the HydroVerse Equipment Hub. This integration supports accurate, city-scale environmental monitoring simulations, enhances spatial realism, and enables scenario-based learning. As shown in Figure 1, the HydroVerse Equipment Hub connects diverse stakeholders including students, researchers, policymakers, and industry partners with advanced technologies such as VR, photogrammetry-based 3D models, and urban water simulations.

3.1. Scope and Purpose

This research introduces an innovative, multi-functional VR environment designed to streamline familiarization, learning, and installation processes for specialized hardware across industries, research institutions, and educational settings globally. The platform has been developed to reduce procedural complexity and costs, thereby improving accessibility and instructional effectiveness through immersive AR/VR experiences that can operate on standard PCs and affordable headsets. Manufacturers, companies, and researchers can effortlessly create precise 3D models using common devices such as cameras and smartphones, facilitating detailed user interaction and practical training in a controlled, virtual setting.

The interactive virtual environment supports close examination of hardware components, virtual assembly, installation procedures, and troubleshooting, enabling users to gain comprehensive insight into hardware functionalities and operational scenarios without requiring physical prototypes or on-site training. This significantly mitigates risks and reduces resource investment in physical infrastructure.

The HydroVerse Equipment Hub leverages virtual reality technologies to advance environmental science and monitoring, offering a variety of strategic advantages detailed below:

For students and educators: Enhanced STEM curricula through immersive modules that combine theoretical instruction with interactive simulations of sensor assembly, troubleshooting, and field deployment, significantly improving engagement and retention.

For technicians: Guided virtual scenarios fostering hands-on proficiency in hardware diagnostics and maintenance, minimizing risks, and improving workforce readiness.

For urban planners and engineers: Advanced photorealistic simulations for sensor deployment, enabling evaluation of hydrological performance and spatial constraints prior to physical implementation.

For researchers: Opportunities for detailed investigation into hardware functionality, AI-driven decision support, and human-technology interactions, allowing low-cost experimentation, prototyping, and rapid innovation before production.

For policymakers: A visualization platform to test infrastructure proposals, emergency response strategies, and environmental policies, enhancing communication, stakeholder engagement, and consensus-building.

For Industry Partners and Advisory Boards: the platform establishes robust communication channels between Industries, research institutes and end-users, enabling agile feedback loops to continuously refine products, drive innovation, and enhance market alignment.

3.2. Hardware and Software Components

To enable a high-fidelity VR experience, the VR-based system incorporates a set of advanced hardware and software components. These elements are selected to support real-time rendering, intuitive user interaction, and accurate simulation of scenarios.

Hardware Requirements: The system relies on VR headsets, controllers, and high-performance computing resources to deliver an interactive and responsive environment. The primary VR hardware used during development was Meta Quest 3 headset, which offers wireless functionality, high-resolution displays, and low-latency tracking. These headsets support inside-out tracking, eliminating the need for external sensors while maintaining precise spatial awareness. The Meta Quest Touch Controllers enable accurate hand interactions, allowing users to manipulate virtual components and navigate the simulation environment with ease.

Software Framework: The HydroVerse Equipment Hub is built on a robust software architecture that integrates real-time visualization, high-resolution 3D modeling, and hands-free interaction technologies. At its core, Unreal Engine 5 (UE5) powers the platform, leveraging Nanite and Lumen for high detail rendering and dynamic global illumination. These features allow for real-time physics-based interactions, accurate lighting reflections on water surfaces, and scalability of virtual environments.

For high-resolution 3D asset creation, the system employs RealityCapture, a photogrammetry tool that reconstructs real-world stream sensor components with millimeter-level accuracy. This enables users to interact with photorealistic virtual objects derived from real-world scans. Additionally, Meta VoiceSDK is integrated for voice-controlled navigation, allowing users to interact with the system hands-free. This enhances accessibility, particularly in complex simulations where users need to perform multiple tasks simultaneously. The system also utilizes Epic's Water System in UE5 for dynamic water simulations and CityEngine for modeling realistic urban environments, ensuring an accurate representation of real-world sensor deployment conditions.

3.3. Development Process and Integration

Development followed a structured, iterative cycle aimed at producing a realistic and functional virtual reality environment for environmental monitoring education and training. Each phase addressed specific technical and usability challenges, encompassing 3D model creation, environment design, leveraging tools such as Twinmotion for enhanced visual fidelity, interaction implementation, digital twin integration, and voice control development. These components introduced unique complexities requiring focused solutions. Extensive testing on

Meta Quest devices was conducted throughout the process to optimize system performance, interaction precision, and overall user experience.

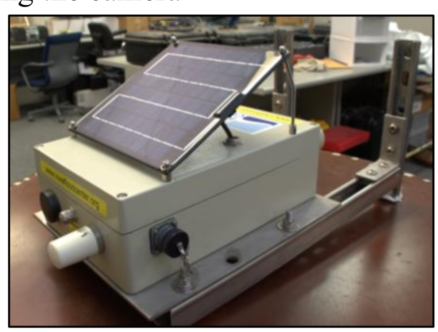
3.3.1. 3D Model Creation and Challenges

The first stage involved creating high-fidelity 3D models of environmental monitoring sensors, a task that proved challenging due to the intricate structure of each sensor. Since these components are composed of multiple pieces, each requiring detailed reconstruction, ensuring geometric accuracy was a significant hurdle. Certain sensor parts featured reflective surfaces, making photogrammetry-based 3D modeling difficult due to light distortions and inconsistent texture mapping. To address this, multiple lighting conditions and camera angles were tested, and additional manual refinements were applied using modeling software to enhance realism. The process comprised several sequential stages, beginning with photographic data acquisition and culminating in textured mesh export.

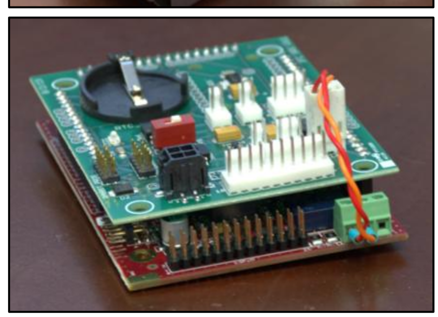
Image Acquisition: To facilitate accurate 3D reconstruction via photogrammetric methods, a structured and controlled image acquisition protocol was employed using a Nikon D5500 DSLR camera across five representative hardware setups. All images were captured indoors using manual camera settings and consistent environmental conditions. The camera was configured to record RAW-format (NEF) images at 6016 × 4016-pixel resolution. ISO sensitivity was fixed at ISO-100 to minimize image noise, and no flash was used to avoid specular reflection. Aperture, shutter speed, and focal length were adjusted to match each object's scale, surface complexity, and lighting requirements. A tripod and delayed shutter release were used to minimize motion blur. The following five scenarios in Table 1 illustrate the range of object types captured.

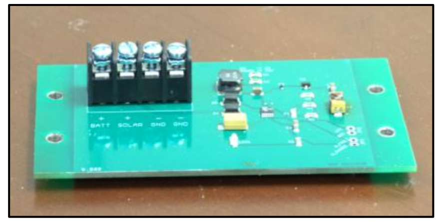
Table 1: 3D captured object types using the camera

Flood Monitoring Sensor Unit: A large enclosure containing a solar panel, padlocks, and reflective metal surfaces was captured using 757 images with a focal length of 18 mm, aperture f/7.1, and 1/5 sec exposure. High image count was necessary to resolve occlusions and surface discontinuities from all sides.

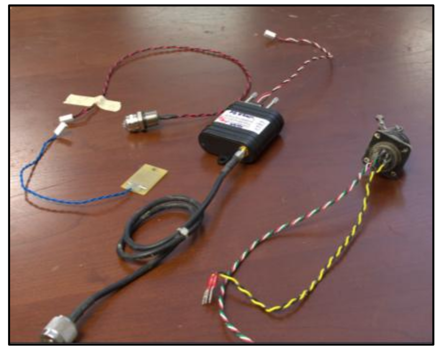


Microcontroller Circuit Board: A compact PCB with densely packed surface-mount components was photographed using 92 images. A 95 mm focal length, f/9 aperture, and 1/3 sec exposure were used to achieve close-up, high-fidelity imaging suitable for resolving sub-millimeter geometries.





Power Distribution Board: This primarily planar circuit board was documented using 42 images. Its relatively simple surface geometry allows for lower coverage. A 75 mm lens at f/9 and 1/2 sec exposure was used to preserve sharpness while minimizing lighting glare.



Sensor and Wiring Assemblies: Thin, flexible cables and connectors introduced significant challenges due to their small diameter, variable curvature, and shadow casting. A 26 mm focal length was selected to provide wider coverage. 96 images were captured using f/9 aperture and 1/4 sec exposure to reconstruct their form in high detail.

In total, 1,274 images were captured across all five cases to ensure comprehensive coverage and accurate 3D reconstruction of objects with varying scales and geometric complexities. A summary of the five sensor imaging cases and their parameters is shown in Table 2.

Table 2: Summary table of imaging parameters

Case	Object Description	No. of Images	Focal Length (mm)	Aperture (f/)	Exposure Time	Notable Challenges
1	Flood Monitoring Sensor Unit	757	18	7.1	1/5 sec	Large size, metallic reflections, complex geometry
2	Microcontroller Circuit Board	92	95	9	1/3 sec	Small scale, high component density
3	Power Distribution PCB	42	75	9	1/2 sec	Planar surface, minor height variation
4	Sensor & Wiring Assemblies	96	26	9	1/4 sec	Irregular shapes, thin wires, shadows
5	Internal View of Sensor Enclosure	287	32	9	1/2 sec	Enclosure shadowing, reflections, tight spaces

Image Preprocessing and Organization: The captured images were transferred to a dedicated workstation and organized into project-specific directories. RealityCapture handles internal camera calibration and lens distortion during the alignment process. File names were optionally standardized for ease of tracking within the workflow.

Photogrammetric Reconstruction in RealityCapture: The modeling process commenced with the import of all images into RealityCapture. The software automatically extracted EXIF metadata and prepared the dataset for alignment. Upon initiating the image alignment step, RealityCapture utilized a feature-based matching algorithm to identify and correlate key points across multiple views. Successful alignment resulted in the generation of a sparse point cloud and a calibrated camera pose for each image. Following alignment, a dense 3D mesh was reconstructed using the software's "Normal Detail" or "High Detail" reconstruction settings. This stage computed the underlying geometry of the scene by estimating depth information from the matched image features, producing a triangulated surface mesh that represents the detailed shape of the object.

Texture Mapping and Model Optimization: Subsequently, the model was textured by projecting the original photographs onto the surface of the mesh. RealityCapture performed UV unwrapping and created a high-resolution texture atlas, effectively fusing photorealistic surface appearance with geometric accuracy. This textured model was then visually inspected for artifacts, misalignments, or incomplete regions. Where necessary, further model refinement was performed. This included manual deletion of background elements or floating geometry, mesh simplification (decimation) to reduce polygon count for real-time rendering, and hole filling to improve mesh continuity.

Model Export: The final output was exported in standard 3D file formats, such as OBJ or FBX, with accompanying texture maps. Additionally, camera alignment data could be exported for applications involving augmented reality, animation, or spatial analysis. The result was a complete, metrically accurate, and visually realistic 3D representation of the physical subject, suitable for use in simulation, analysis, or immersive environments. The 3D modeling process follows a structured photogrammetry workflow as shown in Figure 2.

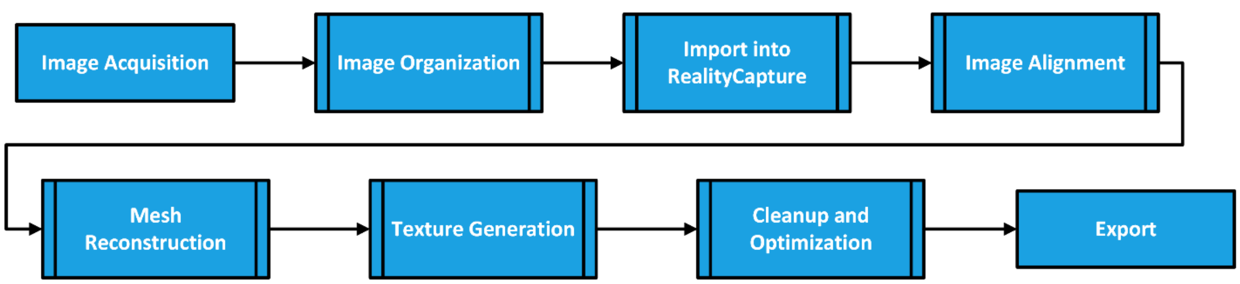


Figure 2: Photogrammetric 3D modeling workflow for environmental sensor reconstruction

3.3.2. Virtual Environment Design

Developing an engaging and functional virtual environment was another key phase. The challenge was balancing realism with usability, ensuring that the lighting was optimal for visibility while maintaining a setting that did not distract users from their tasks. The environment had to include technical tools and workplace elements that reflect a real-world environmental monitoring lab. These additional assets improved contextual understanding but increased computational loads, requiring iterative optimizations to maintain smooth performance in VR.

Interaction Design and Multi-Input Handling: Ensuring intuitive user interaction was a complex process. The system had to integrate hand controllers for precise manipulations while also supporting voice commands for hands-free operation. Combining controller-based selection, object manipulation, and voice-triggered commands required multiple iterations to fine-tune gesture recognition, response timing, and system latency. The goal was to allow users to troubleshoot, repair, and install sensors naturally without unnecessary complexity in interactions.

Integration of Digital Twins and Water Simulation: Another feature of the HydroVerse VR Equipment Hub was the incorporation of digital twins of Iowa City to accurately represent the Iowa River and its hydrological infrastructure. By utilizing CityEngine, realistic urban layouts and hydrological structures were generated, ensuring accurate spatial representation within the simulation. These models were then imported into Unreal Engine, where advanced environmental rendering techniques were applied to enhance realism.

To simulate the visual and physical characteristics of water, Unreal Engine's Water System was implemented, enabling accurate surface representation, reflections, and environmental interactions. However, integrating high-fidelity water rendering introduced significant computational demands, especially on standalone VR devices. To address this, extensive GPU optimizations, level-of-detail (LOD) adjustments, and performance tuning were performed to ensure smooth frame rates without compromising visual quality. The primary challenge was balancing detailed water aesthetics with system efficiency, ensuring users could experience a realistic representation of hydrological elements without excessive processing loads.

Voice Control Implementation and System Guidance: To enhance accessibility, Meta VoiceSDK was integrated for voice commands, system guidance, and real-time encouragement. This feature allowed users to navigate the environment, trigger interactions, and receive instructional feedback without relying solely on controllers. The implementation required extensive testing to ensure voice recognition accuracy across different accents and environments. Additionally, motivational prompts and troubleshooting guidance were introduced to improve user engagement and ensure smooth task execution within the VR environment.

User Interaction and Module Functionality: Within the HydroVerse VR Equipment Hub, users access a centralized main interface, from which they can select specialized modules using either hand controllers or voice commands. Each module presents a distinct set of interactive tasks: users can manipulate 3D sensor models to examine components, follow stepwise procedures to diagnose and repair faults, or position sensors within detailed urban environments for installation planning. Real-time feedback is provided through both visual prompts and voice guidance, enabling users to progress through each workflow and complete assigned tasks within the virtual environment.

Main Interface and Navigation Center: The Main Interface is constructed to provide navigation using both handheld controllers and voice commands. Upon entering the virtual environment, users are presented with a centralized space that visually and interactively connects them to the three core modules: education, Repair, and operation. The interface design emphasizes ease of use and accessibility, accommodating a diverse user base that includes students, technicians, and urban planners. Voice-guided navigation enables hands-free control, allowing users to issue commands for module selection, task initiation, and system guidance, thereby enhancing efficiency and engagement. The interface also integrates real-time instructional support, delivering both task-related prompts and motivational cues to reinforce learning outcomes and user confidence.

Education Center: This center focuses on the animated simulation of sensor composition and decomposition. Within this Hub, users can observe and interact with high-fidelity 3D representations of water level sensors, constructed using photogrammetry techniques via RealityCapture. The modeling process involves capturing extensive photographic datasets from multiple angles, followed by the generation of dense point clouds and textured meshes to recreate the sensor components with high geometric accuracy. This Hub not only illustrates the physical structure and assembly of the sensor but also contextualizes the functional roles of individual components, thereby building foundational knowledge for subsequent troubleshooting and installation tasks. The ability to control these simulations via voice commands further enables users to navigate the decomposition and reassembly processes.

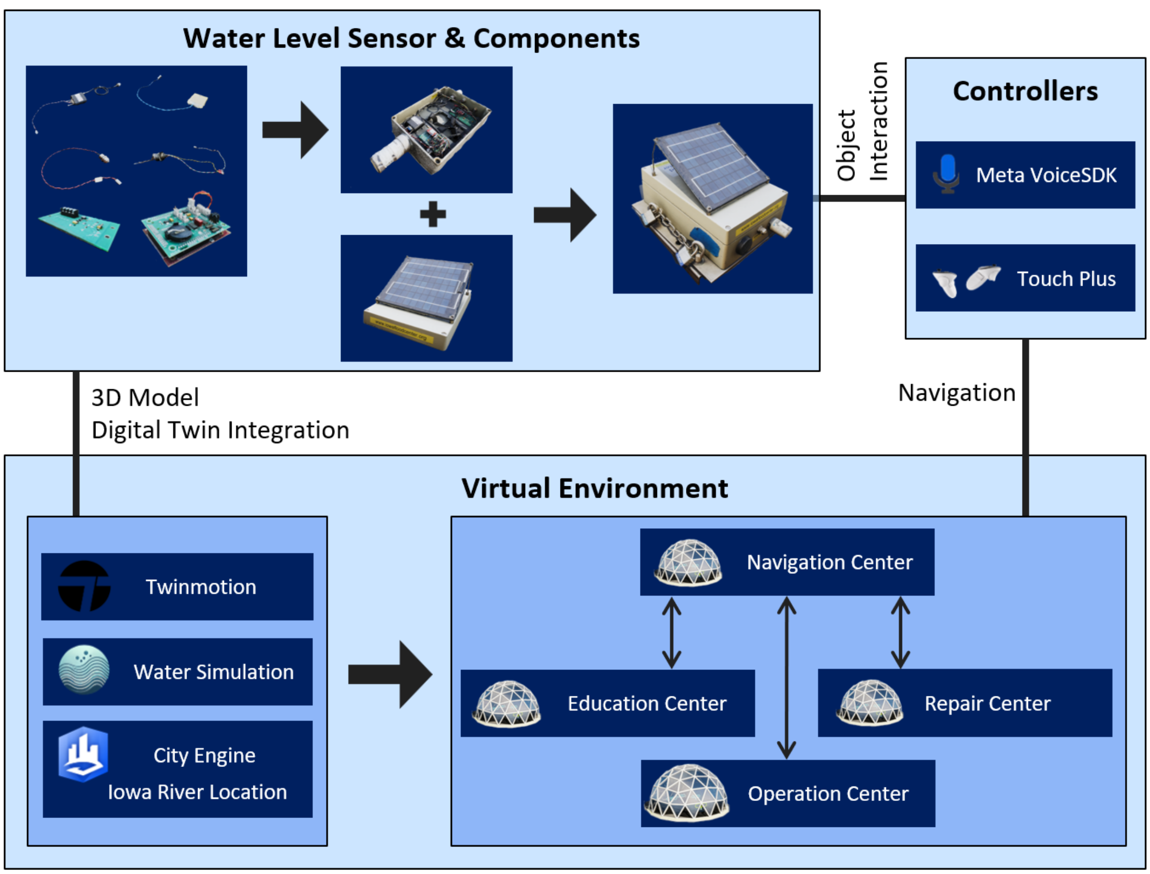


Figure 3: System architecture of the HydroVerse VR equipment hub

Repair Center: The Repair Hub offers a hands-on virtual environment for sensor fault detection and maintenance. Users engage in simulated troubleshooting tasks where they identify alarms, diagnose issues, and perform component replacements. The Hub includes a predefined workflow, implemented through *a Repair Wizard*, which guides users step-by-step through common repair scenarios. Each stage of the repair process is interactive and supported by real-time feedback, both visual and auditory, that informs users of their progress and prompts them toward the next action. This Hub emphasizes technical proficiency by requiring users to apply analytical skills and procedural knowledge within a simulated but realistic context. The integration of hand controllers for precise interaction, coupled with voice-enabled task progression, enhances the realism and accessibility of the repair workflow.

Operation Center: The Operation Center simulates real-world scenarios for sensor placement within urban infrastructure. This Hub incorporates detailed city models generated using CityEngine, including specific geographical locations such as bridges over the Iowa River. These environments provide contextually rich settings for sensor deployment tasks, allowing users to practice positioning and securing sensors under realistic spatial constraints. Unreal Engine's Water System is employed to simulate hydrodynamic behaviors, enabling users to understand environmental factors that influence sensor performance. Through voice guidance, users are led through the installation process, from initial positioning to final verification, fostering familiarity with operational procedures and spatial considerations. The ability to replicate real-world deployment challenges in a virtual setting allows for experiential learning without the risks or resource constraints of physical implementation. Figure 3 depicts the HydroVerse VR Equipment Hub's architecture, highlighting the integration of virtual reality elements, interactive hubs, and advanced visualization technologies that serve as the foundation of the educational system.

4. Results

To evaluate the effectiveness of the HydroVerse VR Equipment Hub, we developed and tested a virtual reality application featuring three core capabilities: high-fidelity 3D sensor visualization, voice command integration, and realistic simulations of environmental monitoring environments. These components were implemented to address essential educational and operational needs across various user groups, including students, technicians, researchers, and urban planners. The overall scene design and its central Main Hub environment are illustrated in Figure 4.

The system was designed to support three primary use cases. It enables assembly exploration by allowing users to disassemble and reassemble detailed 3D models of water level sensors, enhancing their understanding of internal structures and functional relationships. The internal view of the Main Hub that connects users to each functional environment is shown in Figure 5. Additionally, it offers a simulated troubleshooting environment where users can identify faults, receive real-time guidance, and perform virtual repairs on malfunctioning components. Moreover, the platform facilitates infrastructure simulation by replicating real-world sensor installation scenarios within photorealistic urban environments. This feature allows users to evaluate spatial constraints, environmental factors, and deployment strategies in a controlled yet immersive setting.

4.1. Key Features and Capabilities

This section presents the core technical features developed and validated within the HydroVerse VR Equipment Hub. The implementation process emphasized the integration of photorealistic modeling, natural user interfaces, and spatially accurate environmental simulation to enhance user experience and educational effectiveness.

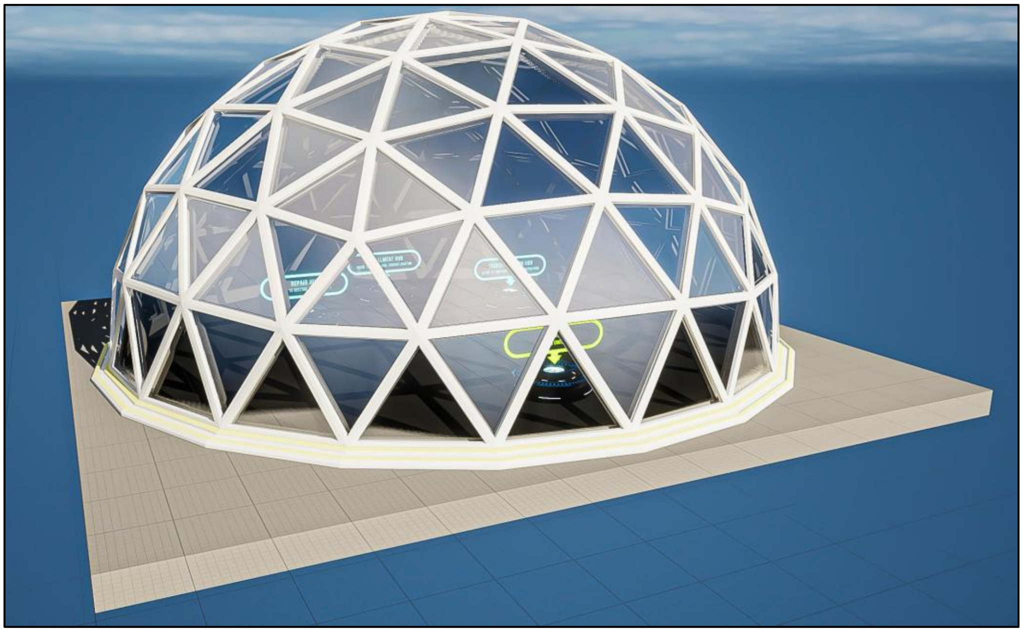


Figure 4: Navigation Center exterior view from a distance

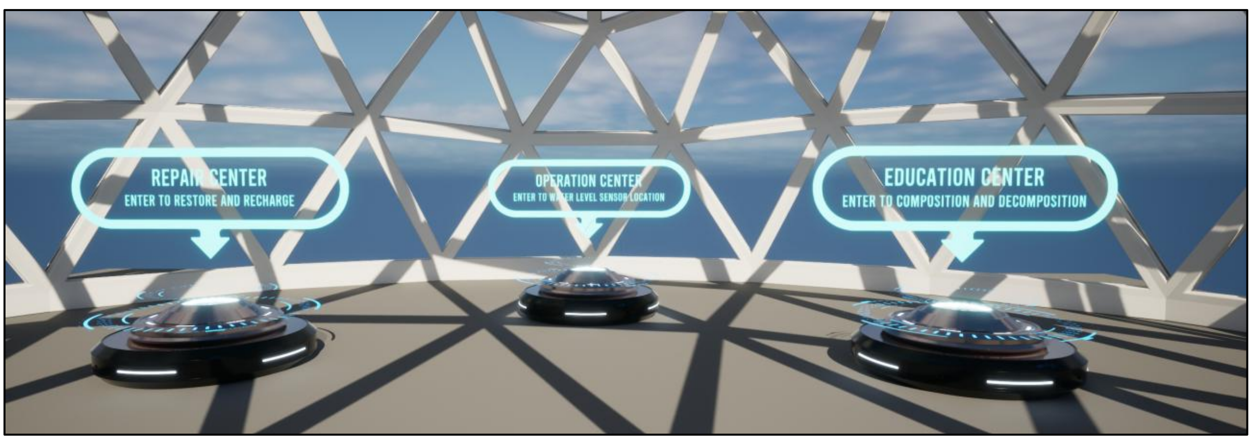


Figure 5: Navigation Center interior view with multiple use case

In the 3D reconstruction process, the number of triangles generated for each object varied significantly depending on the complexity and scale of the subject. The Flood Monitoring Sensor Unit, being the largest and most geometrically complex object, resulted in the highest triangle count at 23,018,154, reflecting the detailed surface information required. In contrast, smaller and simpler components like the Microcontroller Circuit Board and Power Distribution PCB produced significantly fewer triangles—42,693 and 45,953, respectively. Assemblies with intricate geometry, such as the Sensor and Wiring Assemblies, yielded 116,138 triangles, while the Internal View of the Sensor Enclosure, with its confined and reflective structure, generated 428,666 triangles. These results highlight the direct relationship between object complexity and mesh resolution in photogrammetric modeling (Table 3).

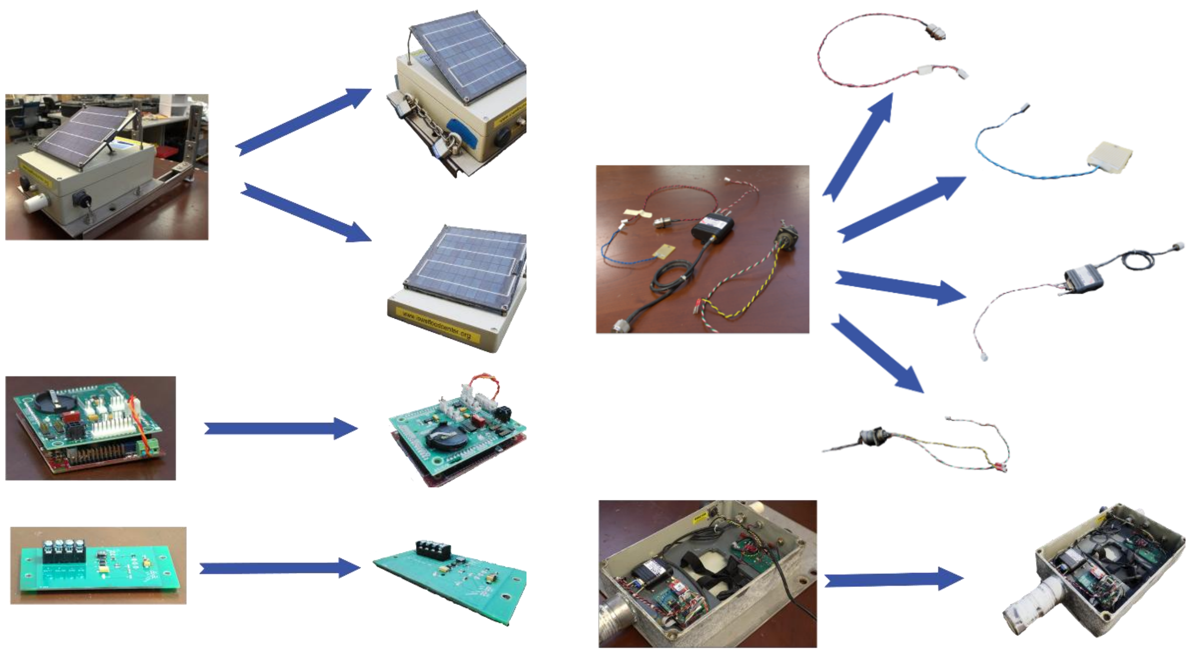


Figure 6: 3D modeling process of the IFC water level sensor using RealityCapture

Table 3: Triangle count summary for photogrammetric sensor models.

Case	Object Description	Number of Triangles
1	Flood Monitoring Sensor Unit	23,018,154
2	Microcontroller Circuit Board	42,693
3	Power Distribution PCB	45,953
4	Sensor and Wiring Assemblies	116,138
5	Internal View of Sensor Enclosure	428,666

High-fidelity 3D Sensor Visualization: To enable detailed exploration of environmental monitoring equipment, a high-fidelity 3D model of the IFC water level sensor was constructed using photogrammetry. The modeling process employed RealityCapture software and involved capturing over 1,274 photographs of the sensor and its components using a Nikon D5500 DSLR camera with controlled lighting and fixed angles to ensure sharpness and consistency. The resulting dataset was processed to produce a dense point cloud, mesh geometry, and fully textured output, accurately replicating the sensor's physical attributes. This visual fidelity allowed precise documentation of structural features and preserved the sensor's form for technical training and analysis. The finalized 3D models were integrated into the virtual environment, offering users an interactive and scalable means to study the sensor at multiple levels of detail. The 3D model of the water level sensor and its components is depicted in Figure 6, providing a detailed visualization of the reconstruction workflow from raw images to a fully textured digital representation. In addition, the education center, where users explore and interact with these models, is depicted in Figure 10c.

Voice Command Integration: Voice command functionality was developed using VoiceSDK to streamline interaction and navigation across the system's modules. Users can issue spoken commands to transition between different hubs—education, repair, and operation—without relying on traditional input devices. This interface reduces friction in user interaction and supports accessibility by enabling hands-free operation. In addition to navigational control, the voice system provides context-aware guidance and spoken feedback. Users receive task instructions, performance cues, and motivational prompts during each stage of the experience, improving task efficiency while supporting user engagement and confidence. This approach proved particularly valuable in maintaining immersion and reducing task complexity in simulation-based training scenarios, such as those found in the Repair Hub shown in Figure 10d.

Realistic Simulations: To replicate realistic environmental monitoring scenarios, the system incorporates high-resolution spatial models and dynamic environmental elements. Using CityEngine, detailed urban representations—most notably the Iowa River corridor—were generated and imported into Unreal Engine to construct accurate virtual infrastructure settings. These environments were enhanced with dynamic water simulation to provide realistic surface behavior, reflections, and flow characteristics. The integration of these tools created a spatially rich and visually coherent simulation space, supporting authentic sensor installation and evaluation scenarios. This feature enables users to assess spatial constraints, test sensor placement strategies, and visualize hydrodynamic conditions in a controlled, immersive environment. The Installation Hub, designed to simulate these real-world deployments, is illustrated in Figure 10e.

4.2. Demonstrated Use Cases

The HydroVerse VR Equipment Hub was developed to enable users from diverse backgrounds—including students, technicians, researchers, and planners—to engage with environmental monitoring technologies through interactive simulations. To illustrate the range and utility of the system, three use cases were conceptualized based on the core functional modules of the platform. These use cases represent how different users can benefit from immersive and task-specific virtual environments for training, analysis, and planning that replicate real-world conditions and workflows.

Sensor Assembly Exploration (Student/Researcher Scenario): Within the education center, users engage in detailed inspection and manipulation of a high-fidelity 3D water level sensor. Through guided decomposition and reassembly tasks (Figure 7), users gain hands-on understanding of how each component contributes to the sensor's operation. The experience enables rotation, isolation, and close-up study of internal parts, supported by voice-command-based guidance.

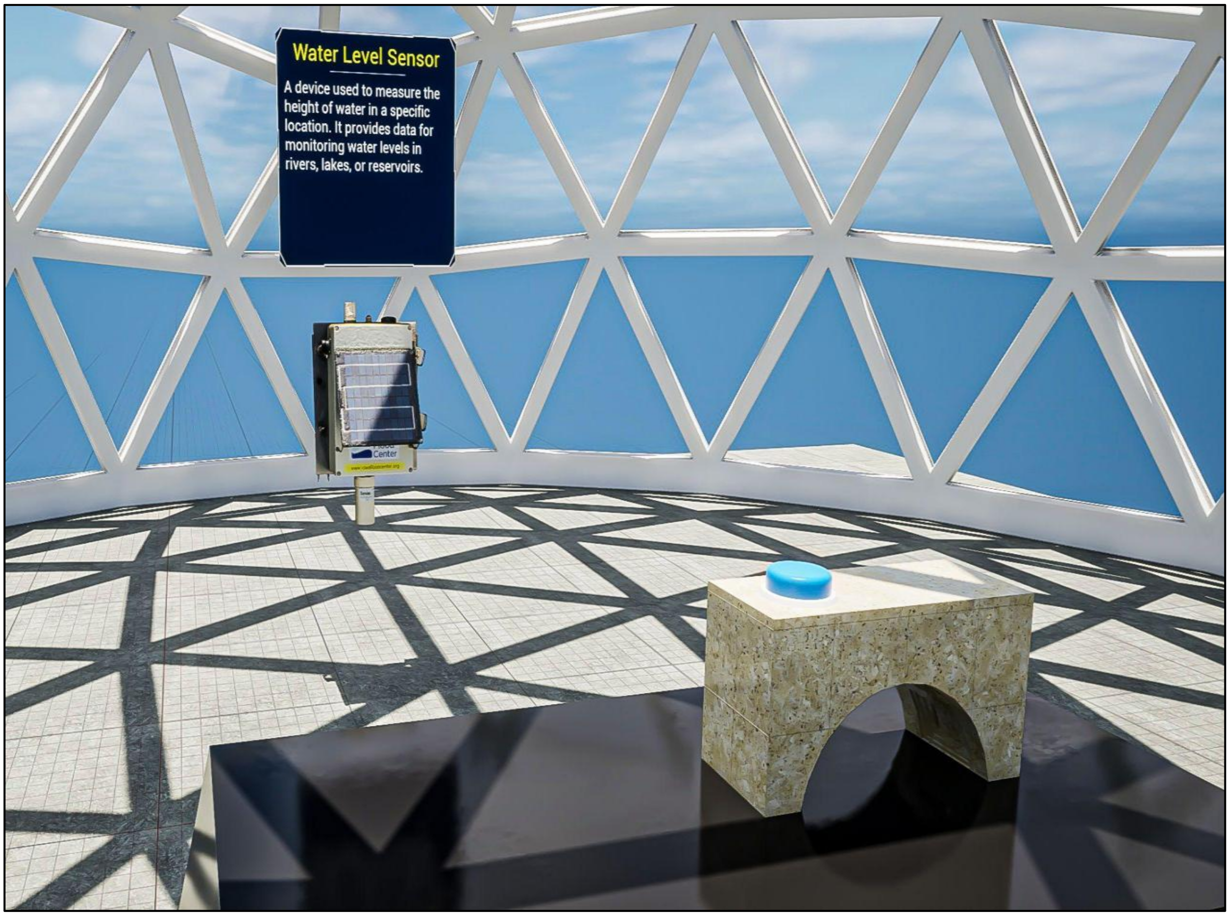


Figure 7: Education center for sensor assembly visualization

This module enhances experiential learning for students, supports design documentation for researchers, and assists technicians in developing familiarity with sensor structures prior to fieldwork. It also provides an opportunity for teams to communicate component-level knowledge in collaborative settings. Figure 8 illustrates this process effectively.

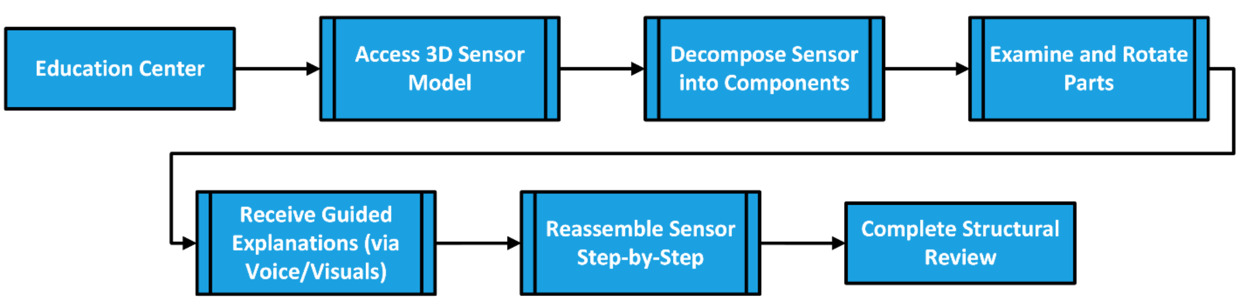


Figure 8: Flowchart of the Education Center within the HydroVerse VR Equipment Hub

Sensor Troubleshooting and Repair (Technician Scenario): The Repair Hub allows users to simulate diagnostic workflows and interactively resolve sensor malfunctions. Upon entering the module, the system alerts direct users to faulty components, triggering a step-by-step troubleshooting process guided by a voice-activated Repair Wizard. Figure 9 illustrates the Repair Center for diagnostic and troubleshooting tasks.

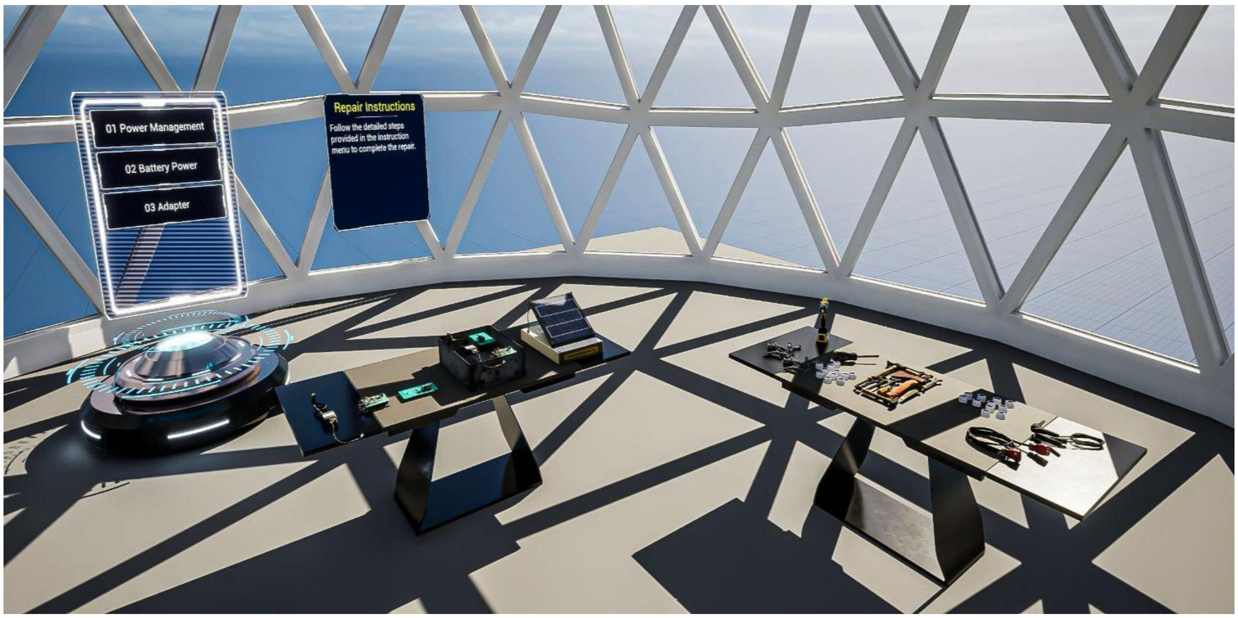


Figure 9: Repair Center for diagnostic and troubleshooting tasks.

Users perform virtual repairs, validate connections, and assess system recovery through simulated outputs. Whether used in technical education, workforce training, or organizational testing, this module supports protocol standardization and allows learners and practitioners to build or evaluate diagnostic competencies in a risk-free environment. Figure 10 depicts the step-by-step workflow of the Repair Module clearly.

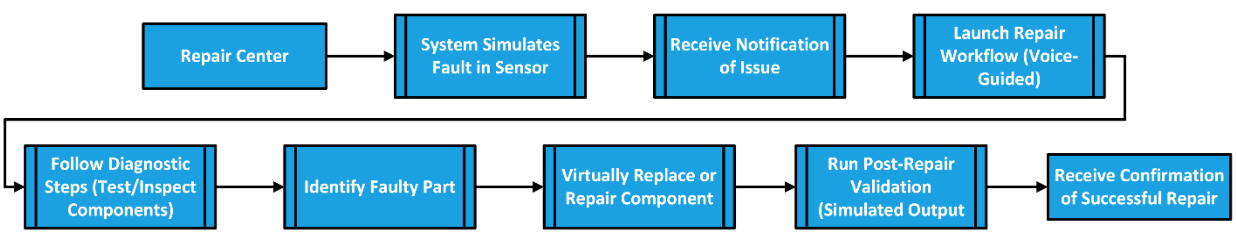


Figure 10: Flowchart of the Repair Center within the HydroVerse VR Equipment Hub

Sensor Installation Planning (Urban Planner/Engineer Scenario): In the Installation Hub, users explore sensor deployment strategies within a spatially accurate, photorealistic urban environment. By navigating city-scale 3D models, users assess spatial constraints, hydrological behavior, and environmental risks related to sensor placement. Real-time interaction with these variables enables strategic planning and iterative testing without physical or logistical limitations. Figure 11 shows the operation center simulating real-world sensor deployment.

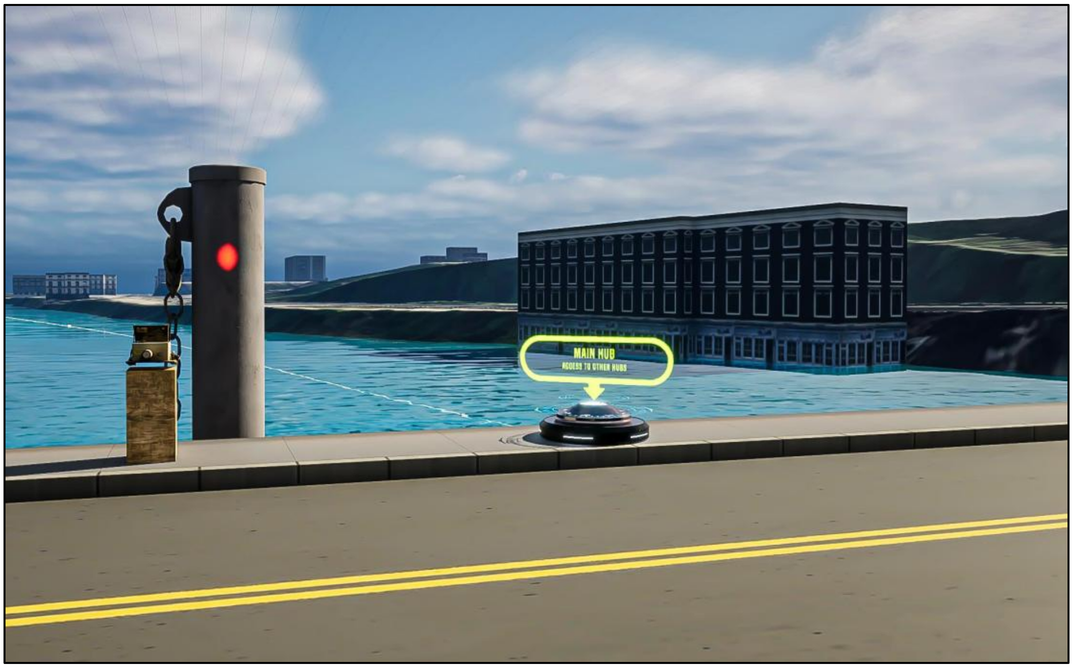


Figure 11: Operation center simulating the real-world sensor deployment

This module is particularly valuable for infrastructure planners, civil engineers, students in urban systems education, and interdisciplinary teams seeking to visualize and optimize environmental monitoring strategies. Figure 12 effectively represents the installation module process.

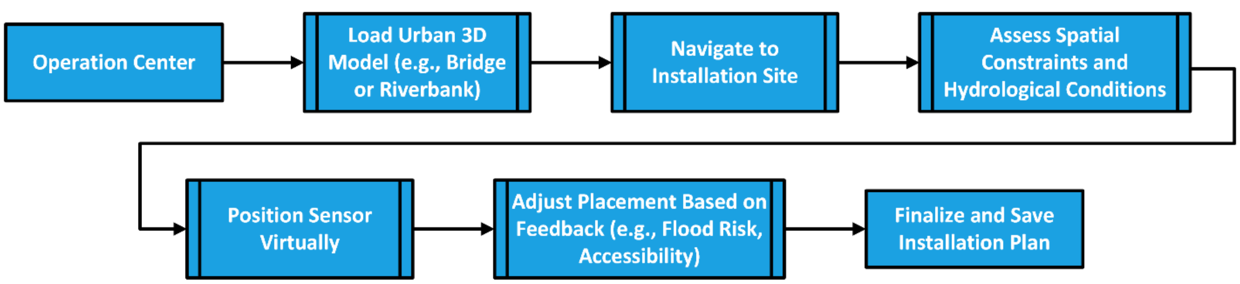


Figure 12: Flowchart of the Operation Center within the HydroVerse VR Equipment Hub

4.3. Evaluation

To assess the effectiveness, usability, and practical value of the HydroVerse VR Equipment Hub, this section presents a structured evaluation covering technical performance, pedagogical grounding, and comparative benchmarking. Through performance metrics, theoretical analysis, and comparison with existing platforms, we explore how the system supports immersive learning, real-world simulation, and interdisciplinary training in environmental monitoring contexts. This comprehensive evaluation provides insight into the platform's readiness for deployment and its potential to transform environmental science education and professional training.

4.3.1. Technical Performance Evaluation

The purpose of the System Technical Performance Evaluation is to assess the computational efficiency, runtime stability, and responsiveness of the HydroVerse VR Equipment Hub under standard PC-VR conditions. This evaluation ensures the application can deliver smooth and immersive experience while maintaining real-time rendering standards, particularly in modules that integrate high-fidelity content such as water simulation and urban-scale models. This section focuses on identifying potential performance bottlenecks and validating the system's readiness for deployment in educational or operational environments.

The evaluation was performed on a desktop system equipped with a Meta Quest 3 headset (via Link), Intel Core i9-14900KF CPU, NVIDIA RTX 4080 SUPER GPU, and 32 GB DDR5 RAM using runtime platform as OpenXR. Four modules were evaluated: the Navigation Center, Education Center, Repair Center, and Operation Center. Performance was analyzed through frame rate tracking, loading time measurements, and system resource usage. It is also important to note that all photogrammetry-based 3D models were optimized for the VR environment—reducing polygon count and texture resolution while preserving visual quality. This optimization ensured that scene complexity did not lead to performance degradation, particularly in real-time operations.

Frame Rate Monitoring: The average frame rates across all modules were well above the VR industry baseline of 90 FPS, confirming the system's ability to support fluid rendering and input response. The Operation Center, which includes both dynamic water simulation and a city-scale model generated using CityEngine, recorded the lowest average (179.67 FPS) due to its complexity. However, this remained within an acceptable threshold, and no instability was observed. Minimum frame rate dips (2.50 FPS) appeared briefly across all scenes, likely tied to background asset loading or shader compilation. These drops did not persist and were not perceptible during normal interactions.

It is required to consider that while the GPU generated high FPS values (above 200 in different centers), the actual display rate is constrained by the headset's refresh rate (e.g., 90Hz–120Hz). Any excess frames beyond the display limit are either dropped or synchronized using technologies such as V-Sync or G-Sync to prevent tearing and maintain visual consistency (Table 4).

Table 4: Frame rate monitoring summary and results

Center	Avg FPS	Min FPS	Comments on Smoothness
Navigation Center	217.33	2.50	Smooth overall, but occasional heavy frame drops
Education Center	210.48	2.50	Generally fluid, rare stutters noticed
Repair Center	210.48	2.50	Consistently responsive, similar drop pattern
Operation Center	179.67	2.50	Slightly lower average, but mostly smooth

Scene Transition Load Time: Most scene transitions occurred almost instantaneously (<0.25 seconds), with the exception of the Operation Center, which required a 3.17-second load due to the inclusion of multiple environmental systems. Despite the longer time, no loading indicator was implemented; adding one could help maintain user immersion. All other modules loaded quickly without user-perceivable delay (Table 5).

Table 5: Scene transition load times and indicator for each scene

Scene/Transition Name	Load Time (s)	Loading Indicator
App launch → Navigation Center	0.12	No
Navigation Center → Education Center	0.22	No
Navigation Center → Repair Center	0.08	No
Navigation Center → Operation Center	3.17	No

System Resource Usage: Resource usage was measured for CPU, GPU, and RAM while interacting with each module. The Operation Center again presented the heaviest load due to real-time hydrological simulation and city-scale digital twin rendering. RAM usage remained stable across all modules, with slight increases in CPU and GPU usage in the more complex scenes. Despite high fidelity, the system did not exceed resource limits, demonstrating effective content and rendering pipeline optimization (Table 6).

Table 6: Resource usage summary

	CPU %	GPU %	RAM Usage	Notes on Stability
Navigation Center	16%	50%	27.3 GB	Stable – moderate usage
Education Center	13%	47%	27.3 GB	Lighter load, steady behavior
Repair Center	19%	53%	27.4 GB	Slightly higher CPU/GPU balance
Operation Center	20%	57%	27.6 GB	Highest CPU/RAM usage; stable performance

4.3.2. Theoretical Framework Analysis

This section evaluates the HydroVerse VR platform from a pedagogical perspective, using established learning theories to assess its potential educational effectiveness (Djordjević et al., 2025; Tisoglu et al., 2025; Lo & Tsai, 2022). Rather than relying on empirical user testing, this evaluation is grounded in theory-driven principles that have consistently demonstrated value in immersive learning environments (Kim et al., 2023). By aligning the platform's interactive features with experiential, constructivist, and cognitive apprenticeship models, we explore how HydroVerse supports learning in principle.

The design of HydroVerse VR is rooted in experiential learning theory, most notably Kolb's model (1984), which posits that knowledge is best retained when learners cycle through concrete experience, reflective observation, abstract conceptualization, and active experimentation (Kee et al., 2024). Within the HydroVerse, learners interact directly with lifelike 3D models of environmental sensors, performing tasks such as equipment assembly, calibration, and installation (De Paola et al., n.d.; Kurbonova, 2023). These hands-on, risk-free experiences allow users to test ideas, correct mistakes, and iteratively refine their understanding. This approach closely mimics the trial-and-error cycles central to experiential learning.

In addition to experiential learning, HydroVerse draws on the principles of constructivist learning theory, as outlined by Piaget and Vygotsky. Constructivism emphasizes that learners build knowledge through interaction with their environment and that learning is most effective when situated in authentic contexts (Nursyam & Pajarianto, 2025). The HydroVerse provides such contexts by simulating realistic environments such as a virtual watershed, an urban setting, and sensor deployment zones where students can explore complex hydrological systems and monitor outcomes (Yin et al., 2024). For instance, users might ask, "What would happen if I installed the sensor in a different location?" and then observe the simulated consequence. This level of interactivity supports hypothesis testing and personal meaning-making, which are core aspects of constructivist pedagogy.

Moreover, the system incorporates key elements of cognitive apprenticeship, a model that emphasizes learning through guided experience. In traditional settings, apprentices learn by watching experts, receiving coaching, and gradually assuming responsibility (Dennen & Burner, 2008). The HydroVerse replicates this approach through integrated voice-guided instructions and contextual feedback. During training modules, learners receive real-time coaching via the VoiceSDK system, which offers step-by-step guidance, verbal explanations, and subtle prompts. This helps them perform procedures accurately while also understanding the rationale behind each step. The process reflects the "modeling, scaffolding, and fading" structure central to cognitive apprenticeship, guiding learners from dependence on instruction toward independent mastery (Collins & Kapur, 2006).

Research in VR education further supports this theoretical alignment. Rossoni et al. (2024) demonstrate that interactive VR applications improve skill acquisition by enabling active, self-paced learning. Yang et al. (2024), in a meta-analysis, show that VR environments significantly enhance practical understanding in science and engineering domains. By combining experiential tasks, immersive contexts, and guided practice, HydroVerse is designed to promote deep learning and engagement without requiring physical classroom tools or access to real-world field sites.

In summary, although this evaluation does not include human-subject testing, the HydroVerse VR platform is firmly grounded in evidence-based educational theories. Its immersive design, scaffolded guidance, and real-time interactivity align with well-established pedagogical models such as experiential learning, constructivism, and cognitive apprenticeship. These foundations indicate that the system is both technically robust and theoretically positioned to support meaningful, skill-based learning in environmental science and sensor training.

5. Discussions

Key benefits of offering a modular, immersive environment for environmental monitoring education include improved learning, multidisciplinary use, realistic virtual training environment and practical application (Ma et al., 2024). Challenges involve hardware limits, voice-3D integration, and user adaptability. The system can support use cases on sensor maintenance, urban planning, and decision support, showing VR's potential to transform environmental monitoring practices.

The HydroVerse VR Equipment Hub offers significant advantages by combining high-fidelity 3D visualization, interactive simulations, and voice command navigation to improve environmental monitoring education and professional training. It allows users to explore detailed sensor designs, perform troubleshooting, and simulate installations in a safe, immersive environment. These features enhance learning efficiency, promote engagement, and support technical skills development without requiring physical equipment (Kushwaha et al., 2024). The system is adaptable for various users, including students, educators, technicians, and urban planners, providing tailored experiences for each group. By simulating real-world scenarios, HydroVerse Equipment Hub enables practical training while reducing risks and resource costs. Its multidisciplinary capabilities support not only education but also urban infrastructure planning and sensor maintenance workflows. Voice-guided navigation improves accessibility, and the platform's flexibility fosters collaboration across fields. Overall, the HydroVerse VR Equipment Hub delivers a scalable, effective tool for advancing environmental monitoring (Sermet & Demir, 2022) through experiential learning and interactive training (Fitrianto & Saif, 2024).

The implementation of the HydroVerse VR Equipment Hub presents several technical and integration challenges that impact its scalability and usability across diverse applications. One of the primary challenges is the demand for high-fidelity simulations, which require significant computational power and advanced hardware to render detailed hydrological models in real time. Accurate representation of sensor components and environmental conditions through photogrammetry and physics-based simulations increases processing requirements (Lei et al., 2024), making it difficult for lower-end devices to support the system effectively (Yin et al., 2024). This challenge is particularly evident in dynamic water simulations (Yang et al., 2021), where real-time fluid interactions impose heavy computational loads, limiting the performance of standalone VR headsets and mid-range computing systems (Murugan et al., 2024).

Another major hurdle is the complexity of integrating voice-controlled navigation with detailed 3D visualization. While voice commands enhance user accessibility and hands-free interaction, ensuring precise recognition and real-time responsiveness in a VR environment is challenging, especially when users have varying accents, speech patterns, or background noise interference. Synchronizing voice input with highly detailed 3D models and interactive components requires robust AI-driven natural language processing and optimized system performance to prevent lag or command misinterpretation (Hromadova et al., 2023).

The adaptability of the system for diverse user groups also poses challenges. The HydroVerse VR Equipment Hub is designed for students, educators, technicians, and urban planners, each with different levels of technical expertise. While experienced users may easily navigate the platform, novice learners may face difficulties in understanding complex VR interactions, troubleshooting procedures, or sensor operations without extensive training. Ensuring an intuitive and accessible interface for all users requires adaptive UI/UX design, guided onboarding experiences, and multilingual support to bridge knowledge gaps and enhance user engagement.

Additional limitations include hardware accessibility and cost constraints. High-performance VR systems, such as Meta Quest headsets and high-end GPUs, are often expensive and not readily available in all educational institutions or technical training centers. This financial barrier limits widespread adoption, particularly in regions with restricted access to advanced computing resources and reliable internet infrastructure. Furthermore, integration with existing educational and professional training programs requires institutional support, curriculum restructuring, and instructor training to maximize the benefits of VR-based learning environments.

Addressing these challenges will require ongoing advancements in hardware optimization, software efficiency, and accessibility strategies. By refining computational resource management, improving AI-driven voice recognition, and developing adaptive learning pathways, the HydroVerse VR Equipment Hub can enhance its usability across a broader audience. Despite these limitations, the system's potential to revolutionize environmental monitoring education and training remains significant, as it continues to evolve to meet the demands of real-world applications (Avsec & Jagiełło-Kowalczyk, 2021).

5.1.Broader Implications for Environmental Monitoring

The HydroVerse VR Equipment Hub has broader implications for environmental monitoring, particularly in sensor maintenance workflows and urban infrastructure planning, as well as fostering interdisciplinary collaboration and research. By providing a realistic and interactive environment, the system enhances the way professionals engage with environmental monitoring technologies, offering new opportunities for education, training, and decision-making.

One of the key impacts is on sensor maintenance workflows, where VR-based simulations allow technicians to diagnose, troubleshoot, and repair sensors in a controlled environment before applying their skills in the field (Casini, 2022). This minimizes errors, improves efficiency, and reduces downtime associated with sensor failures. The ability to simulate real-world conditions enables users to test different maintenance strategies, optimize workflows, and standardize procedures, making sensor upkeep more reliable and cost-effective (Yeganeh et al., 2024).

In urban infrastructure planning, the system provides a platform for engineers and planners to visualize sensor deployment within different environments, such as bridges, water treatment facilities, and flood monitoring sites. By simulating sensor placements and testing their functionality in virtual city models, decision-makers can optimize deployment strategies before physical implementation. This approach enhances the efficiency of infrastructure development, ensuring that sensors are placed in optimal locations for accurate data collection and long-term reliability.

Apart from practical applications, the HydroVerse VR Equipment Hub promotes interdisciplinary collaboration and research by integrating environmental monitoring with computer science, engineering, environmental science, and urban planning. Researchers can use the system to develop new analytical tools (Sharma, 2024), study environmental impacts, and test advanced hydrological models in an interactive setting. The ability to engage experts from different fields within a shared virtual workspace fosters innovation and accelerates problem-solving in water resource management and environmental monitoring.

The system also contributes to the advancement of educational methodologies, providing universities and research institutions with an effective tool for teaching environmental monitoring concepts. By incorporating VR-based experiential learning, students and professionals gain hands-on experience with complex environmental monitoring systems, improving knowledge retention and practical skill development.

As the field of environmental monitoring evolves, the HydroVerse VR Equipment Hub may serve as a catalyst for technological advancement, enabling more efficient sensor management, data-driven infrastructure planning, and cross-disciplinary collaboration. By continuing to expand its applications and refining its capabilities, the system has the potential to shape the future of environmental monitoring research and practice, making water resource management more efficient, adaptable, and data-driven.

6. Conclusion and Future Work

The HydroVerse VR Equipment Hub is a step forward in environmental monitoring education, bridging theoretical knowledge and practical application through immersive, hands-on experiences. Utilizing advanced technologies like game engines, photogrammetry, and voice enabled interaction, the system enables users to explore sensor components, practice troubleshooting, and simulate real-world tasks such as installation and repair. By incorporating interactive hubs—Education, Repair, and Operation—the platform has the potential to promote technical proficiency, build user confidence, and ensure safe and effective learning experiences. It also allows users to investigate various scenarios, potentially fostering deeper understanding and problem-solving skills before facing real-world challenges.

This proposed framework makes significant contributions by redefining skill-based education. It provides a safe and controlled virtual environment where users can interact with complex devices, practice procedures, and gain hands-on experience without the risks associated with real-world scenarios. The system can help users build confidence and expertise, ensuring safety while reducing the likelihood of errors during real-life tasks. Moreover, the ability to simulate diverse installation and repair scenarios enables learners to experiment and develop optimized approaches, enhancing efficiency and preparedness. This innovation not only benefits environmental monitoring education but also creates a scalable model applicable to various technical disciplines.

Future developments can extend the framework's scope to include additional devices, more advanced AI-driven simulations, and broader accessibility for diverse user groups. Enhancing the platform's adaptability to various engineering domains can expand its impact, making it a universal tool for skill development. Moreover, integrating more detailed scenario-based simulations, collaborative features for teamwork, and enhanced customization options can further enrich the learning experience. Addressing technical challenges, such as optimizing resource requirements and ensuring cost-effective implementation, will be critical to fostering inclusivity and scalability.

Looking ahead, emerging VR capabilities will further enrich the platform's realism and effectiveness. For instance, the incorporation of enhanced haptic feedback through gloves or suits that simulate texture, resistance, pressure, and temperature will provide users with a more tactile and physically engaging training environment. This functionality will make it possible to realistically simulate tool handling, component manipulation, and intricate assembly tasks, resulting in deeper engagement and skill mastery.

The adoption of eye-tracking and facial expression recognition will enable more intuitive interactions, such as gaze-based navigation and emotion-aware virtual responses. These features can support improved user feedback, more responsive virtual characters, and the tracking of learner engagement and comprehension during training sessions.

In addition, mixed reality integration will allow virtual objects to coexist and interact with real-world surroundings, enabling users to place virtual equipment within physical spaces or perform hybrid training activities. This blending of physical and digital contexts enhances spatial awareness and prepares users for on-site applications more effectively.

With AI-driven personalization, the learning environment can adapt dynamically to each user's needs. Content can be automatically tailored based on individual performance, learning pace, and user preferences. Virtual instructors and intelligent agents can guide users through troubleshooting tasks, recommend best practices, and deliver personalized challenges to reinforce learning outcomes.

As VR hardware continues to evolve, lighter, more ergonomic headsets will enable longer and more comfortable use, increasing accessibility and usability across diverse educational and professional settings. These improvements make immersive learning more practical for extended sessions, supporting deeper, uninterrupted engagement.

Beyond individual training, the HydroVerse framework provides a strategic model for industry and research. Organizations can develop, test, and validate entire processes such as device assembly, installation, usage, and repair within the virtual environment before committing to physical manufacturing. This not only reduces development risks and costs but also allows for the refinement of workflows, safety protocols, and user training strategies in a controlled and repeatable way.

7. Declaration of Generative AI and AI-Assisted Technologies

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

8. Funding

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

9. Acknowledgement

The authors thank the Iowa Flood Center for providing access to sensor equipment and technical advisory. Special thanks to James Niemeier, Daniel Ceynar, and Witold Krajewski for their expertise and support.

10. Disclaimer

Mention of any brand name in no way implies recommendation of a particular manufacturer or product.

11. References

Abulrub, A. G., Attridge, A. N., & Williams, M. A. (2011). Virtual reality in engineering education: The future of creative learning. IEEE Global Engineering Education Conference (EDUCON), 751–757.

Agbor, C. N., Etan, M. O., Akuji, R. T., & Ogbor, C. O. (2025). Methods Of Teaching Environmental Education for Sustainability. International Journal of Economics, Environmental Development and Society, 6(2), 209-233.

Ahmed, S. F., Alam, M. S. B., Hassan, M., Rozbu, M. R., Ishtiak, T., Rafa, N., ... & Gandomi, A. H. (2023). Deep learning modelling techniques: current progress, applications, advantages, and challenges. Artificial Intelligence Review, 56(11), 13521-13617.

Alabbad, Y., Yildirim, E., & Demir, I. (2023). A web-based analytical urban flood damage and loss estimation framework. *Environmental Modelling & Software*, *163*, 105670.

Alabbad, Y., Mount, J., Campbell, A. M., & Demir, I. (2024). A web-based decision support framework for optimizing road network accessibility and emergency facility allocation during flooding. *Urban Informatics*, *3*(1), 10.

AlGerafi, M. A. M., Zhou, Y., Oubibi, M., & Wijaya, T. T. (2023). Unlocking the potential: A comprehensive evaluation of augmented reality and virtual reality in education. Electronics, 12(3953). https://doi.org/10.3390/electronics12183953

Ali, A., Hadeed, M. Z., Safavi, S., & Ahmad, M. (2024). Leveraging GIS for environmental planning and management. In Global Challenges for the Environment and Climate Change (pp. 308–331). IGI Global. https://doi.org/10.4018/978-1-6684-8485-4.ch016

Almutairi, R., Bergami, G., & Morgan, G. (2024). Advancements and challenges in IoT simulators: A comprehensive review. Sensors, 24(5), 1511.

Alnagrat, A., Ismail, R. C., Idrus, S. Z. S., & Alfaqi, R. M. A. (2022). A review of extended reality (XR) technologies in the future of human education: Current trend and future opportunity. Journal of Human Centered Technology, 1(2), 81-96.

Alotaibi, E., & Nassif, N. (2024). Artificial intelligence in environmental monitoring: In-depth analysis. Discover Artificial Intelligence, 4(1), 84. https://doi.org/10.1007/s44163-024-00184-6

Avsec, S., & Jagiełło-Kowalczyk, M. (2021). Investigating possibilities of developing self-directed learning in architecture students using design thinking. Sustainability, 13(8), 4369. https://doi.org/10.3390/su13084369

Awewomom, J., Dzeble, F., Takyi, Y. D., Ashie, W. B., Ettey, E. N. Y. O., Afua, P. E., ... & Akoto, O. (2024). Addressing global environmental pollution using environmental control techniques: a focus on environmental policy and preventive environmental management. Discover Environment, 2(1), 8.

Azzam, I., El Breidi, K., Breidi, F., & Mousas, C. (2024). Virtual reality in fluid power education: Impact on students' perceived learning experience and engagement. Education Sciences, 14(7), 764. https://doi.org/10.3390/educsci14070764

Barta, S., Gurrea, R., & Flavián, C. (2023). How augmented reality increases engagement through its impact on risk and the decision process. Cyberpsychology, Behavior, and Social Networking. In press. https://doi.org/10.1089/cyber.2022.0087

Bates, R., Brenner, B., Schmid, E., Steiner, G., & Vogel, S. (2022). Towards meta–competences in higher education for tackling complex real–world problems–a cross disciplinary review. International Journal of Sustainability in Higher Education, 23(8), 290-308.

Bhavani, K., & Gajendra, N. (2024). Smart data-driven sensing: New opportunities to combat environmental problems. In Bio-Inspired Data-driven Distributed Energy in Robotics and Enabling Technologies (pp. 17–47). CRC Press.

Casini, M. (2022). Extended reality for smart building operation and maintenance: A review. Energies, 15(10), 3785. https://doi.org/10.3390/en15103785

Cikmaz, B. A., Yildirim, E., & Demir, I. (2025). Flood susceptibility mapping using fuzzy analytical hierarchy process for Cedar Rapids, Iowa. *International journal of river basin management*, *23*(1), 1-13.

Coito, T., Firme, B., Martins, M. S., Vieira, S. M., Figueiredo, J., & Sousa, J. M. (2021). Intelligent sensors for real-Time decision-making. Automation, 2(2), 62-82.

Collins, A., & Kapur, M. (2006). Cognitive apprenticeship (Vol. 291). Educational Encyclopedia.

Corter, J. E., Nickerson, J. V., Esche, S. K., Chassapis, C., Im, S., & Ma, J. (2007). Constructing reality: A study of remote, hands-on, and simulated laboratories. ACM Transactions on Computer-Human Interaction (TOCHI), 14(2), 7-es.

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

De Paola, F., Liso, G., Ronco, A., Speranza, G., Giovannini, A., Napoli, E., & Venturini, G. (n.d.). The digitalization of hydraulic infrastructures: The Smartverse approach. Available at SSRN. https://doi.org/10.2139/ssrn.4979215

Demir, I., Sermet, Y., & Rink, K. (2022). Next generation visualization and communication systems for earth science using immersive reality and serious gaming. Frontiers in Earth Science, 10, 1101538.

Demir, I., Conover, H., Krajewski, W.F., Seo, B.C., Goska, R., He, Y., McEniry, M.F., Graves, S.J. and Petersen, W., (2015). Data-enabled field experiment planning, management, and research using cyberinfrastructure. *Journal of Hydrometeorology*, *16*(3), pp.1155-1170.

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

Dennen, V. P., & Burner, K. J. (2008). The cognitive apprenticeship model in educational practice. In J. M. Spector, M. D. Merrill, J. van Merriënboer, & M. P. Driscoll (Eds.), Handbook of research on educational communications and technology (pp. 425–439). Routledge.

Djordjević, A., Ćirić, M., Milošević, V., Radivojević, D., Zammit, E., Scerri, D., & Gocić, M. (2025). Transforming water education through investment in innovation: A case study on the cost-benefit of virtual reality in water education. Water, 17(13), 1998. https://doi.org/10.3390/w17131998

El Galad, A., Betts, D. H., & Campbell, N. (2024, April). Flexible learning dimensions in higher education: aligning students' and educators' perspectives for more inclusive practices. In Frontiers in Education (Vol. 9, p. 1347432). Frontiers Media SA.

Emiroglu, E., Grant, C. A., Sermet, Y., & Demir, I. (2025). Floodcraft: Game-based Interactive Learning Environment using Minecraft for Flood Mitigation for K-12 Education. *International journal of disaster risk reduction*, 105799.

Fang, S., Da Xu, L., Zhu, Y., Ahati, J., Pei, H., Yan, J., & Liu, Z. (2014). An integrated system for regional environmental monitoring and management based on internet of things. IEEE Transactions on Industrial Informatics, 10(2), 1596–1605.

Fitrianto, I., & Saif, A. (2024). The role of virtual reality in enhancing experiential learning: A comparative study of traditional and immersive learning environments. International Journal of Post Axial: Futuristic Teaching and Learning, 2(2), 97-110. https://journal.amorfati.id/index.php/postaxial

Ghazali, A. K., Aziz, N. A., Aziz, K. A., & Kian, N. T. (2024). The usage of virtual reality in engineering education. Cogent Education, 11(1), 2319441. https://doi.org/10.1080/2331186X.2024.2319441

Grosser, P. F., Xia, Z., Alt, J., Rüppel, U., & Schmalz, B. (2022). Virtual field trips in hydrological field laboratories: The potential of virtual reality for conveying hydrological engineering content. Education and Information Technologies, 28, 6977–7003. https://doi.org/10.1007/s10639-022-11434-5

Hromadova, V., Brida, P., & Machaj, J. (2023). Design of acoustic signal for positioning of smart devices. Sensors, 23(7852). https://doi.org/10.3390/s23187852

Ifenthaler, D., Gibson, D., Prasse, D., Shimada, A., & Yamada, M. (2021). Putting learning back into learning analytics: Actions for policy makers, researchers, and practitioners. Education Tech Research Dev, 69, 2131–2150. https://doi.org/10.1007/s11423-020-09909-8

Kaynak, B., Mermer, O., Sermet, Y., & Demir, I. (2025). HydroSignal: open-source internet of things information communication platform for hydrological education and outreach. *Environmental monitoring and assessment*, *197*(4), 1-21.

Kee, T., Zhang, H., & King, R. B. (2024). An empirical study on immersive technology in synchronous hybrid learning in design education. International Journal of Technology and Design Education, 34(3), 1243–1273. https://doi.org/10.1007/s10798-023-09840-w

Kim, T., Planey, J., & Lindgren, R. (2023). Theory-driven design in metaverse virtual reality learning environments: Two illustrative cases. IEEE Transactions on Learning Technologies, 16(6), 1141–1153. https://doi.org/10.1109/TLT.2023.3241234

Kua, J., Lim, W. S., Teo, W., & Edwards, R. A. (2021). A scoping review of adaptive expertise in education. Medical Teacher, 43(3), 347-355.

Kurbonova, G. (2023). Creating a virtual geographic learning environment and its user assessment (Doctoral dissertation, Palacký University Olomouc). https://theses.cz/id/z6g9op/

Kushwaha, R. S., Civi, A., Inamdar, A., Patil, N., & Chapte, R. (2024). AR indoor navigation. Information Fusion Research, 2(2), Article 6386. https://doi.org/10.59429/ifr.v2i2.6386

Lang, J. M. (2021). Small teaching: Everyday lessons from the science of learning. John Wiley & Sons.

Lawson McLean, A., & Lawson McLean, A. C. (2024). Immersive simulations in surgical training: analyzing the interplay between virtual and real-world environments. Simulation & Gaming, 55(6), 1103-1123.

Lei, Y., Bruno, N., & Roncella, R. (2024). Integrating 3D survey and open datasets for creating low-cost urban digital twins in VR. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, XLVIII-2/W8-2024, 295-302. https://doi.org/10.5194/isprs-archives-XLVIII-2-W8-2024-295-2024

Lo, S. C., & Tsai, H. H. (2022). Design of 3D virtual reality in the metaverse for environmental conservation education based on cognitive theory. Sensors, 22(21), 8329. https://doi.org/10.3390/s22218329

Loucks, D. P. (2023). Hydroinformatics: A review and future outlook. Cambridge Prisms: Water, 1, e10. https://doi.org/10.1017/wat.2023.10

Ma, S., Flanigan, K. A., & Bergés, M. (2024). State-of-the-art review: The use of digital twins to support artificial intelligence-guided predictive maintenance. arXiv. https://arxiv.org/abs/2406.13117

Mantai, L., & Huber, E. (2021). Networked teaching: Overcoming the barriers to teaching experiential learning in large classes. Journal of Management Education, 45(5), 715-738.

Marion, T. J., & Fixson, S. K. (2021). The transformation of the innovation process: How digital tools are changing work, collaboration, and organizations in new product development. Journal of Product Innovation Management, 38(1), 192-215.

Means, B., Padilla, C., DeBarger, A., & Bakia, M. (2009). Implementing data-informed decision making in schools: Teacher access, supports and use. US Department of Education.

Miller, T., Durlik, I., Kostecka, E., Kozlovska, P., Łobodzińska, A., Sokołowska, S., & Nowy, A. (2025). Integrating artificial intelligence agents with the internet of things for enhanced environmental monitoring: Applications in water quality and climate data. Electronics, 14(4), 696.

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

Murugan, S., Ali, M. K., Singari, D., & Kumar, S. P. (2024). Interactive sign language learning system using computer vision and deep learning. 2024 International Conference on Advances in Computing, Communication and Applied Informatics (ACCAI). IEEE. https://doi.org/10.1109/ACCAI61061.2024.10602251

Nursyam, N., & Pajarianto, H. (2025). Theories and educational practice. In Innovations in Educational Robotics: Advancing AI for Sustainable Development (p. 39). IGI Global. https://doi.org/10.4018/978-1-6684-9389-4.ch003

Owolabi, O., Abedoh, H., Abiodun, P., Ikiriko, S., Wemida, A., Duru, C., ... & Ladeji-Osias, J. (2024). Hands-on Learning Pedagogy in Teaching Concepts Relevant in the Analysis, Design, and Maintenance of Transportation Infrastructure Systems. Transportation Research Record, 2678(11), 501-515.

Pajo, B. (2022). Introduction to research methods: A hands-on approach. Sage publications.

Paulino, D., Netto, A. T., Brito, W. A., & Paredes, H. (2024). WebTraceSense—A Framework for the Visualization of User Log Interactions. Eng, 5(3), 2206-2222.

Popescu, I., Jonoski, A., & Bhattacharya, B. (2012). Experiences from online and classroom education in hydroinformatics. Hydrology and Earth System Sciences, 16(3935–3944). https://doi.org/10.5194/hess-16-3935-2012

Sajja, R., Sermet, Y., Cwiertny, D., & Demir, I. (2025). Integrating AI and learning analytics for data-driven pedagogical decisions and personalized interventions in education. *Technology, knowledge and learning*, 1-31.

Rawat, D. B., & Hagos, D. H. (2024). Metaverse survey & tutorial: exploring key requirements, technologies, standards, applications, challenges, and perspectives. arXiv preprint arXiv:2405.04718.

Riaz, K., McAfee, M., & Gharbia, S. S. (2023). Management of climate resilience: Exploring the potential of digital twin technology, 3D city modelling, and early warning systems. Sensors, 23(5), 2659. https://doi.org/10.3390/s23052659

Rossoni, M., Spadoni, E., Carulli, M., Barone, C., Colombo, G., & Bordegoni, M. (2024). Virtual reality in education to enable active learning and hands-on experience. Computer-Aided Design & Applications, 21(2), 258-269. https://doi.org/10.14733/cadaps.2024.258-269

Safavi, S. (2024). Leveraging GIS for environmental planning. Global Challenges for the Environment and Climate Change, 22, 308.

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

Sermet, Y., & Demir, I. (2020). Virtual and augmented reality applications for environmental science education and training. In New perspectives on virtual and augmented reality (pp. 261-275). Routledge.

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

Sermet, Y., & Demir, I. (2022). GeospatialVR: A web-based virtual reality framework for collaborative environmental simulations. Computers & Geosciences, 159, 105010. https://doi.org/10.1016/j.cageo.2021.105010

Sermet, Y., & Demir, I. (2023). Camera-based intelligent stream stage sensing for decentralized environmental monitoring. *Journal of hydroinformatics*, *25*(2), 163-173.

Sharma, S. (2024). Revolutionizing teacher education with cutting-edge digital solutions. In Advancements in Digital Learning and Teacher Training (Chapter 14). IGI Global. https://doi.org/10.4018/979-8-3693-6880-0.ch014

Shihab, S. R., Sultana, N., & Samad, A. (2023). Pedagogy designing with augmented reality: A paradigm shift in educational approaches. Injurity: Interdisciplinary Journal and Humanity, 2(11), 878-892. https://injurity.pusatpublikasi.id/index.php/in

Shivolo, T., Kamina, C. U., Nembenge, G., Nangutuwala, M. M., & Simasiku, F. S. (2024). Evaluating the Teaching of Physical Science Practical Work at a Selected Resource-Constrained Secondary School in Rundu Circuit, Kavango East Region. Journal of Research in Education and Pedagogy, 1(2), 118-131.

Siddiqi, M. M. (2024). Future of digital education: inclusive, immersive, equitable. MediaSpace: DME Media Journal of Communication, 5(01), 8-24.

Singh, R. B. (2024). "Challenges and Coping Strategies of Teaching English in an Under-Resourced Context: A Narrative Inquiry". APPROVED B (Doctoral dissertation, Kathmandu University School of Education).

Soliman, M., Pesyridis, A., Dalaymani-Zad, D., Gronfula, M., & Kourmpetis, M. (2021). The application of virtual reality in engineering education. Applied Sciences, 11(6), 2879. https://doi.org/10.3390/app11062879

Song, W., & Wu, C. (2021). Introduction to advancements of GIS in the new IT era. Annals of GIS, 27(1), 1–4. https://doi.org/10.1080/19475683.2021.1883523

Tahir, U., & Babar, H. (2024). The Role of Policy in Developing a Skilled Workforce for a Green Economy. Green Environmental Technology, 1(2), 78-87.

Tisoglu, S., Sönmez, E., Kaya, K. Y., & Et, S. Z. (2025). Bridging pedagogy and technology: A systematic review of immersive virtual reality's potential in climate change education. Environmental Education Research, 1–31. https://doi.org/10.1080/13504622.2025.2298741

Torresen, J. (2018). A review of future and ethical perspectives of robotics and AI. Frontiers in Robotics and AI, 4, 75. https://doi.org/10.3389/frobt.2017.00075

Tuma, F. (2021). The use of educational technology for interactive teaching in lectures. Annals of Medicine and Surgery, 62, 231-235. https://doi.org/10.1016/j.amsu.2021.01.051

Tung, T. M. (2025). Immersive Education: Leveraging Extended Reality for Environmental Awareness and Action. In Exploring the Impact of Extended Reality (XR) Technologies on Promoting Environmental Sustainability (pp. 373-393). Cham: Springer Nature Switzerland.

Van Velsen, L., Ludden, G., & Grünloh, C. (2022). The limitations of user-and human-centered design in an eHealth context and how to move beyond them. Journal of medical Internet research, 24(10), e37341.

Wagener, T., Savic, D., Butler, D., Ahmadian, R., Arnot, T., Dawes, J., Djordjevic, S., Falconer, R., Farmani, R., Ford, D., Hofman, J., Kapelan, Z., Pan, S., & Woods, R. (2021). Hydroinformatics education – The Water Informatics in Science and Engineering (WISE) Centre for Doctoral Training. Hydrology and Earth System Sciences, 25(5), 2721–2738. https://doi.org/10.5194/hess-25-2721-2021

Wang, M., Yu, H., Bell, Z., & Chu, X. (2022). Constructing an Edu-Metaverse ecosystem: A new and innovative framework. IEEE Transactions on Learning Technologies, 15(6), 685-695. https://doi.org/10.1109/TLT.2022.3210828

Yandrapalli, V. K., & Sharma, S. (2025). Cloud-Powered Distance Learning: Breaking Geographical Barriers in Education. In Cloud Computing for Smart Education and Collaborative Learning (pp. 133-144). Chapman and Hall/CRC.

Yang, C., Zhang, J., Hu, Y., Yang, X., Chen, M., Shan, M., & Li, L. (2024). The impact of virtual reality on practical skills for students in science and engineering education: A meta-analysis. International Journal of STEM Education, 11, 28. https://doi.org/10.1186/s40594-024-00487-2

Yang, D., Yang, Y., & Xia, J. (2021). Hydrological cycle and water resources in a changing world: A review. Geography and Sustainability, 2(2), 115-122. https://doi.org/10.1016/j.geosus.2021.05.003

Yazdi, M. (2024). Augmented reality (AR) and virtual reality (VR) in maintenance training. In Advances in Computational Mathematics for Industrial System Reliability and Maintainability (pp. 169-183). Cham: Springer Nature Switzerland.

Yeganeh, L. N., Fenty, N. S., Chen, Y., Simpson, A., & Hatami, M. (2024). The future of education: A multi-layered Metaverse classroom model for immersive and inclusive learning. Preprints, 202412.2507.v1. https://doi.org/10.20944/preprints202412.2507.v1

Yeşilköy, S., Baydaroğlu, Ö., Singh, N., Sermet, Y., & Demir, I. (2024). A contemporary systematic review of Cyberinfrastructure Systems and Applications for Flood and Drought Data Analytics and Communication. *Environmental Research Communications*, *6*(10), 102003.

Yin, W., Hu, Q., Liu, W., Liu, J., He, P., Zhu, D., & Kornejady, A. (2024). Harnessing game engines and digital twins: Advancing flood education, data visualization, and interactive monitoring for enhanced hydrological understanding. Water, 16(17), 2528. https://doi.org/10.3390/w16172528