Research on a Metaverse-Based Virtual Simulation Training Platform for Hydrology Education

Xin Zhong[1], Xiaobo Sun[2], Zhenmei Yan[3], Qiaoxia Wang[1]

1 Sichuan water conservancy vocational college, Chengdu 610000, Sichuan Province, China

2 Neijiang Hydrology and Water Resources Survey Center of Sichuan Province, Neijiang City 641000, Sichuan Province, China

3 Hydrology and Water Resources Management Station of Jiangjin District, Chongqing 402260, Chongqing Municipality, China

Abstract: The rapid advancement of Metaverse technologies has opened up new opportunities for innovation in higher education. Hydrology, a discipline that relies heavily on field practice and experimental training, faces persistent challenges such as limited access to field resources, high operational costs, safety risks, and difficulties in effectively teaching abstract hydrological concepts. To address these issues, this paper proposes the design of a Metaverse-based virtual simulation training platform tailored to hydrology education. The platform integrates multiple emerging technologies—including virtual and augmented reality (VR/AR), digital twins, artificial intelligence (AI), the Internet of Things (IoT), blockchain, and cloud computing—into a multi-layered architecture comprising perception, network, content, and application layers. Key modules such as virtual field practice, virtual laboratories, collaborative training, and AI-driven tutoring provide students with immersive, interactive, and repeatable learning experiences. This approach not only enhances the effectiveness of practical teaching but also supports personalized learning, collaboration, and innovation. The study further explores the platform's application prospects and the challenges it faces, including technical, content-related, pedagogical, and ethical considerations. Overall, the proposed platform aims to enrich hydrology education by bridging the gap between theory and practice, while providing a sustainable pathway for cultivating innovative talents in water resources engineering.

Keywords: Metaverse; Virtual Simulation; Hydrology Education; Immersive Learning

1. Introduction

The Metaverse, as a new form of the Internet, has attracted wide attention in the field of education in recent years [1]. 2021 is regarded as the first year of the metaverse, witnessing a surge in people's demand for virtual spaces [2]. The Metaverse integrates emerging technologies such as Virtual Reality (VR), Augmented Reality (AR), and Artificial Intelligence (AI), constructing an immersive three-dimensional digital space [3]. This fusion of the virtual and real environment is considered to have the potential to disrupt traditional teaching models and provide a learning experience beyond reality [4]. Many researchers have pointed out that the Metaverse is expected to become a future trend in education, empowering innovation and transformation in teaching [5]. For disciplines such as Hydrology and Water Resources Engineering, which emphasize field practice, the virtual simulation training platform enabled by the Metaverse may become a key pathway to overcoming teaching bottlenecks [6]. Based on an overview of the educational technology background of the Metaverse, this paper analyzes the pain points in hydrology teaching, proposes the conceptual framework of a virtual simulation training platform based on the Metaverse, and explores its application prospects and the challenges it faces [1,3].

2. Technical Background

2.1 Concept and Related Technologies of the Metaverse

The Metaverse is essentially a virtual shared space supported by multiple digital technologies, whose key features include immersion, interactivity, and decentralization. At the technical level, the Metaverse integrates extended reality technologies such as VR/AR to create realistic three-dimensional virtual environments; combined with 3D modeling and digital twin technologies, it can reproduce real-world scenes and experimental objects in virtual space. Artificial intelligence is integrated to enable intelligent interactions, such as virtual tutors and intelligent NPCs, thereby improving the level of intelligent teaching. The Internet of Things (IoT) and blockchain are also utilized to support real-time data synchronization and digital asset management, ensuring the connection between the physical and virtual worlds and the trustworthiness of virtual resources [3,5]. Park and Kim (2022) classified the Metaverse system into three levels: hardware, software, and content. The hardware includes head-mounted displays (HMDs), sensors, and other devices; the software encompasses rendering engines, network architecture, and interaction interfaces; and the content refers to virtual scenes and educational resources. At the same time, Metaverse education platforms involve three dimensions: user interaction, implementation models, and application scenarios [3]. Overall, the construction of educational Metaverse platforms requires the integration of multiple fields of new technologies to form an ecosystem of deep integration between the "real world" and "virtual space" [5].

2.2 Characteristics of Hydrology Education and Virtual Simulation

The discipline of Hydrology and Water Resources Engineering emphasizes field observation and experimental operations, but traditional teaching is greatly constrained by conditions such as site availability, climate, and safety. For example, hydrology courses often require field practices like river water level and discharge observations or rainfall-runoff experiments, which are complex and difficult to conduct frequently. Some extreme hydrological scenarios (such as heavy rainfall and floods) are nearly impossible to fully demonstrate through field teaching. Virtual simulation technology provides a potential solution to these issues: through digital twin technology, watershed environments can be replicated, allowing rivers, rainfall stations, and other settings to be reproduced on computers, enabling students to conduct "virtual fieldwork" without leaving campus [6]. VR-based simulations can also realistically reproduce the operation processes of hydrological instruments, allowing students to repeatedly practice skills such as water level measurement and velocity observation. Moreover, simulation environments can safely present hazardous scenarios such as flood progression, offering learning experiences that traditional teaching cannot achieve. With the development of Metaverse technologies, it has become possible to virtualize hydrology teaching content and bring experimental processes online, laying the technical foundation for building a virtual simulation training platform for hydrology education.

3. Teaching Pain Points

The main challenges in hydrology education are concentrated in the area of practical teaching.

Limited field practice resources: Many universities lack permanent hydrological field laboratories, making it difficult for students to gain timely practical experience in real environments [6]. Even when field practice is available, factors such as weather, hydrological conditions, and safety concerns limit the frequency and scope of practice. Especially during the COVID-19 pandemic, field investigations and experiments were temporarily suspended, which severely affected teaching outcomes.

High cost and risk of traditional experiments: Hydrological experiments often involve large-scale facilities such as flumes and pumps, which are costly to build and maintain, and improper operation can pose safety hazards. Large-scale watershed experiments or extreme hydrological processes (such as flood simulations) are almost impossible to conduct in real-life settings.

Abstract and monotonous teaching methods: Many hydrological concepts and processes have large spatiotemporal scales and are highly abstract. Relying solely on classroom lectures and two-dimensional charts makes it difficult for students to truly understand them, resulting in insufficient cultivation of practical skills and innovative thinking.

These pain points urgently call for new teaching approaches. A virtual simulation training platform based on the Metaverse, by providing immersive and interactive practice environments, has the potential to overcome these bottlenecks. Students can conduct multiple “experiments” in a virtual environment without concerns about space or safety, thereby achieving a close integration of theory and practice. For example, the study by Grosser et al. (2023) demonstrated that using VR-based virtual field trips to explore watershed topography and hydrological facilities allows students to experience fieldwork in an immersive way, effectively stimulating learning interest and serving as a beneficial supplement to real-world field practice.

In summary, the introduction of Metaverse technologies is expected to ease the constraints of resource availability and safety in hydrology practice teaching, thereby enhancing students’ participation in practice and improving their mastery of professional skills.

4. Platform Architecture Design

4.1 Overall Design Concept

In response to the above teaching needs, this paper proposes a virtual simulation training platform for hydrology based on Metaverse technologies, aiming to create an immersive practice-oriented teaching environment that integrates teaching, learning, practice, and assessment. The platform architecture follows a typical layered design, including the perception layer, network layer, content layer, and application layer:

Perception Layer (Hardware Layer): Consists of VR/AR devices, tracking systems, and data acquisition sensors. Students interact with the virtual environment through head-mounted displays, data gloves, and other devices to obtain real-time immersive experiences. Sensors deployed in the field (such as water level gauges and rain gauges) can also upload real-time data, which are incorporated into the virtual scene to achieve digital twin synchronization.

Network Layer (Software Support Layer): Provides the network communication and computational services required for virtual–real interaction. High-bandwidth and low-latency network technologies (such as 5G) are used to ensure synchronous interaction among multiple users online. Cloud servers operate three-dimensional rendering engines and physical computing modules to simulate complex hydrological processes, such as real-time rainfall–runoff–confluence processes. Blockchain technology can be applied to record students' experimental behaviors and manage digital resources, ensuring data security and trustworthiness.

Content Layer (Resource and Scenario Layer): Stores and manages various digital teaching contents, including high-precision 3D terrain models, virtual hydrological instrument models, experimental scripts, and task scenarios. Virtual experimental environments are built based on real watersheds, such as river models and flood process models, enabling students to conduct training in settings close to reality [6]. This layer also includes AI-driven virtual tutors and virtual peers, presented in the form of digital humans, who provide guidance, demonstrations, and interactions.

Application Layer (Teaching Function Layer): Directly oriented toward teachers and students, offering modules for course configuration, experimental practice, interactive communication, and performance evaluation. Teachers can publish virtual experimental projects on the platform and set parameters (such as simulating specific rainfall scenarios), while students enter the scenes with virtual identities to perform experimental operations and collaborative learning. The platform records students' operational data, provides real-time feedback, and generates learning reports for evaluation.

4.2 Key Module Examples

The platform features several distinctive modules.

Virtual Field Practice Module: Employs a digital twin watershed environment that allows students to explore virtual field settings and practice surveying, water sampling, and related tasks.

Virtual Laboratory Module: Provides simulated setups for hydrological experiments (such as seepage tests and velocity measurements), enabling students to repeatedly operate virtual instruments independently.

Collaborative Practice Module: Supports multiple students synchronously entering the same virtual scene as avatars to complete group exercises or projects, fostering teamwork.

Intelligent Tutor Module: AI-driven virtual tutors monitor students' operations in real time, offering personalized guidance and Q&A support, thereby enhancing teaching interactivity.

Together, these modules constitute the core functions of the hydrology virtual simulation training platform, providing students with comprehensive practice training experiences.

Previous studies have already developed prototype Metaverse-based educational platforms. For example, Jovanović and Milosavljević (2022) designed the "VoRtex" Metaverse learning platform, which realized gamified collaborative learning scenarios and provided a reference for our platform's construction [7]. The proposed platform architecture integrates advanced technologies with hydrology-specific teaching content, aiming to reproduce the entire real teaching process in a virtual environment. In doing so, it compensates for the limitations of real-world conditions while also expanding new models of teaching.

5. Application Prospects and Challenges

5.1 Application Prospects

The Metaverse-based hydrology training platform holds broad prospects in education and teaching. Through this platform, it is possible to.

Enhance the effectiveness of practical teaching: Students engage in hands-on practice within immersive virtual environments, which strengthens their understanding of abstract hydrological concepts and stimulates learning interest [6]. For example, virtual flood drills enable students to participate in flood-control decision-making, thereby improving their ability to cope with complex situations.

Break the constraints of time and space: Teachers and students can enter virtual experimental scenarios anytime and anywhere, no longer restricted by geographical location or weather conditions. This provides opportunities for institutions in remote areas or those lacking practice bases to share high-quality practical teaching resources.

Achieve personalized learning: The Metaverse environment supports dynamic adjustment of task difficulty according to students' levels, and provides targeted guidance through intelligent tutors, meeting the diverse learning paces and needs of students. Each student can repeatedly practice weaker areas in the virtual space, thereby consolidating knowledge and improving skills.

Promote collaboration and innovation: The platform supports multi-user online interaction, allowing students to form teams for project-based training, cultivating teamwork. At the same time, the virtual environment encourages bold trial-and-error and innovative experimental designs, motivating students to explore new approaches to hydrological problems.

The study by Grosser et al. has already verified the value of virtual training in improving student interest and learning effectiveness [6]. As technology matures, the Metaverse will gradually integrate into hydraulic engineering education, becoming an important supplement to practical teaching [4]. Furthermore, the Metaverse is expected to be applied in professional training within the water conservancy industry and in science popularization, thereby building an immersive lifelong learning ecosystem.

5.2 Challenges

Despite the promising prospects, there are still many challenges to be overcome in implementing a Metaverse-based hydrology virtual simulation training platform [1].

Technology and facilities: Achieving high-fidelity simulation requires strong computational power and network support. Current limitations in bandwidth and latency may affect the real-time multi-user interaction experience. Professional-grade VR equipment is costly, and large-scale deployment in schools faces financial constraints. In addition, the lack of unified standards across software and hardware platforms leads to insufficient content compatibility and interoperability.

Content and accuracy: Constructing authentic and reliable hydrological virtual environments requires large amounts of precise measured data and models. If the parameters of the digital twin watershed are inaccurate, the simulation results will deviate from reality, undermining teaching credibility. Developing high-quality teaching content and virtual experiment scripts also demands professional expertise and significant initial resource investment.

Teacher and student adaptability: Teachers need to possess a certain level of technical literacy to effectively design teaching activities using the platform. At present, most hydrology teachers have limited knowledge of Metaverse technologies, and faculty training needs to be strengthened. For students, entering immersive virtual environments for the first time may cause motion sickness and discomfort, requiring an adaptation period [3]. Students lacking self-discipline may even become overly immersed in the virtual world, negatively affecting their regular learning [8].

Management and ethics: In virtual teaching spaces, how to effectively manage student behavior, prevent academic misconduct, and avoid inappropriate interactions is a new challenge. In addition, issues concerning student data collection and usage must consider privacy protection, while intellectual property rights in virtual environments also need to be clearly defined [4]. Educational authorities and schools must establish corresponding policies and standards when introducing Metaverse teaching, in order to ensure teaching order and quality.

Some scholars, through bibliometric analysis, have pointed out that empirical research on Metaverse education remains scarce, and long-term evaluations of its effectiveness are insufficient [1,8]. Before large-scale application, these challenges must be carefully addressed and gradually resolved.

6. Conclusion

Metaverse technologies have brought new opportunities for practical teaching in hydrology. A Metaverse-based virtual simulation training platform can overcome the traditional constraints of time, space, and safety in teaching, meet the urgent need for immersive practice in hydrology education, and enhance students' practical abilities and learning motivation. This paper provides a condensed introduction to the main contents of the original study, including the conceptual framework of the platform, key technical elements, and expected teaching outcomes. Overall, the Metaverse hydrology training platform has the potential to become an important supplement to higher education in water resources, supporting the cultivation of innovative hydrology talents.

However, it is also necessary to recognize the technical bottlenecks and application challenges that remain. To fully realize the potential of the Metaverse in education, joint efforts from educators, technology developers, and administrators are essential. On the one hand, more investment should be made in research and development to improve virtual simulation models and interaction technologies, as well as to promote the formulation of industry standards for Metaverse education. On the other hand, more empirical research should be carried out to evaluate the teaching effects and impacts of virtual training, providing a basis for the improvement of instructional design [9]. As emphasized by Dwivedi et al. (2022), only through continuous testing and optimization in practice can Metaverse education move beyond hype and achieve sustainable development.

Looking ahead, with the evolution of technology and the renewal of teaching concepts, the Metaverse will play a greater role in engineering education such as hydrology, bringing new momentum to educational innovation and the transformation of talent cultivation models.

Funding

The 2022 Educational Reform Research Project of Sichuan Water Conservancy Vocational College "Research on Virtual Simulation Training Platform Based on Metaverse" (Project number: JG2022-23)

References

[1] Onu P, Pradhan A, Mbohwa C, 2024, Potential to use metaverse for future teaching and learning. Education and Information Technologies, 29: 8893–8924. http://doi.org/10.1007/s10639-023-12167-9

[2] Hwang GJ, Chien SY, 2022, Definition, roles, and potential research issues of the metaverse in education: an artificial intelligence perspective. Computers & Education: Artificial Intelligence, 3: 100082. http://doi.org/10.1016/j.caeai.2022.100082

[3] Park SM, Kim YG, 2022, A metaverse: taxonomy, components, applications, and open challenges. IEEE Access, 10: 4209–4251. http://doi.org/10.1109/ACCESS.2021.3140175

[4] Dwivedi YK, Hughes L, Baabdullah AM, et al., 2022, Metaverse beyond the hype: multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. International Journal of Information Management, 66: 102542. http://doi.org/10.1016/j.ijinfomgt.2022.102542

[5] Wang L, Chen HZ, Cai W, 2023, Education in the metaverse: current situation and future innovations. Journal of East China Normal University (Educational Sciences), 41(11): 38–51. http://doi.org/10.16382/j.cnki.1000-5560.2023.11.004

[6] Grosser PF, Xia Z, Alt J, Rüppel U, Schmalz B, 2023, Virtual field trips in hydrological field laboratories: the potential of virtual reality for conveying hydrological engineering content. Education and Information Technologies, 28: 6977–7003. http://doi.org/10.1007/s10639-022-11434-5

[7] Jovanović A, Milosavljević A, 2022, VoRtex metaverse platform for gamified collaborative learning. Electronics, 11(3): 317. http://doi.org/10.3390/electronics11030317

[8] Tlili A, Huang R, Shehata B, et al., 2022, Is metaverse in education a blessing or a curse: a combined content and bibliometric analysis. Smart Learning Environments, 9: 1–31. http://doi.org/10.1186/s40561-022-00205-x

[9] Pradana M, Elisa HP, 2023, Metaverse in education: a systematic literature review. Cogent Social Sciences, 9(2): 2252656. http://doi.org/10.1080/23311886.2023.2252656