HARNESSING VIRTUAL REALITY FOR GEOSCIENCE EDUCATION: UNVEILING THE PEDAGOGICAL POTENTIAL OF IJEN CRATER'S VOLCANIC LANDSCAPE

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Abstract: Virtual Reality systems in geography education are generally limited to 3DoF, allowing only rotational movement without translation. This study aims to develop an innovative 6DoF VR learning media using Unity to simulate volcanic processes, ecosystems, and disaster mitigation in the Ijen Crater. The "KawahIjen" VR is designed to provide an immersive and interactive learning experience, overcoming the limitations of conventional media. The research employs a Research and Development (R&D) method, adapting the Hannafin and Peck model, which includes needs analysis, design, development, and implementation stages. Results show the VR has a high usability level, with a System Usability Scale (SUS) score of 81. The 6DoF feature allows users to interact with and explore the virtual environment freely, offering deeper learning experiences. Additionally, it serves as a potential educational tool for disaster mitigation, especially for remote communities with limited access to Ijen. This study contributes to innovative and effective geoscience learning media development.

Kata kunci: VR 6DOF, Unity, Ijen Crater, Geoscience

Abstrak: *Sistem VirtualReality dalam pendidikan geografi umumnya masih berbasis 3DoF, yang hanya memungkinkan rotasi tanpa translasi. Penelitian ini bertujuan mengembangkan media pembelajaran VR 6DoF inovatif menggunakan Unity untuk mensimulasikan proses vulkanik, ekosistem, dan mitigasi bencana di Kawah Ijen. VR "Kawah Ijen" dirancang agar imersif dan interaktif, serta mengatasi keterbatasan media konvensional. Metode yang digunakan adalah Research and Development (R&D), mengadaptasi model Hannafin dan Peck dengan tahapan analisis kebutuhan, desain, pengembangan, dan implementasi. Hasil penelitian menunjukkan media ini memiliki tingkat keterpakaian sangat baik dengan skor SUS 81. Fitur 6DoF memungkinkan pengguna berinteraksi dan mengeksplorasi lingkungan virtual secara bebas, sehingga pengalaman belajar menjadi lebih mendalam. Selain itu, VR ini berfungsi sebagai alat edukasi mitigasi bencana yang potensial, khususnya bagi masyarakat di daerah terpencil yang sulit mengakses Kawah Ijen. Penelitian ini berkontribusi pada pengembangan media pembelajaran geosains yang inovatif dan efektif*

Keywords: *VR 6DOF, Unity, KawahIjen, Geosains*

INTRODUCTION

Virtual Reality has transformed the educational paradigm by offering immersive and interactive learning experiences (Kamiñska et al., 2019), Especially in the field of geosciences, this technology enables students to access and explore complex and hazardous natural phenomena, such as volcanic activity, which are not always physically accessible due to disaster risks or geographical limitations. (Huang et al., 2019). The implementation of VR in geoscience education has been proven to enhance student engagement and conceptual understanding, although several challenges still need to be addressed.

VR systems commonly used in geography education are still largely based on 3DoF (3 Degrees of Freedom), which only allow rotational movement without translational motion. This limitation results in a significant lack of realism and interactivity in exploration, as users are unable to move freely within the virtual environment (Viola et al., 2022). Moreover, previous studies have shown that the use of 3DoF often limits the immersive experience and is less effective in supporting the exploration of complex virtual environments, thereby reducing knowledge retention related to dynamic geological processes (Barbot et al., 2023; Chandrasekera et al., 2019). Therefore, a new approach that is more interactive and realistic is needed to simulate geoscientific phenomena.

To address this limitation, 6DoF (6 Degrees of Freedom) technology offers more comprehensive freedom of movement by allowing users not only to change their viewpoint but also to move translationally within the virtual space. This enables direct interaction with objects and the simulated environment, providing a deeper and more authentic learning experience (Atsikpasi & Fokides, 2022). This technology has been identified as an ideal candidate for geoscience education, particularly in understanding phenomena involving spatial scale and complex dynamics (Jost et al., 2019). However, the adoption of 6DoF systems remains limited due to various barriers, including technical complexity, the need for more advanced hardware, and relatively high development costsi(Ikbal et al., 2021; Nagta et al., 2022).

Ijen Crater in Indonesia is one of the most fascinating and unique volcanic geosites in the world, featuring rare natural phenomena such as blue fire, a highly acidic lake with an extreme pH (0-1), and traditional sulfur mining activities (Aliya Fatimah, 2021; Scher et al., 2013). This area presents an extraordinary opportunity for multidisciplinary learning, encompassing geochemistry, disaster mitigation, and environmental conservation (Pratama et al., 2018; Sanjaya et al., 2019; Wildani et al., 2023). However, direct access to Ijen Crater is highly restricted due to the risk of exposure to toxic gases and the extreme terrain (Susetyo et al., 2024), which hinders field learning processes. Until now, students generally rely on two-dimensional representations (images or videos), which fail to capture the three-dimensional dynamics and the actual scale of the volcanic phenomena (Taher et al., 2023). This study not only develops innovative learning media but also has the potential to serve as a disaster mitigation educational tool that can be accessed by remote communities, reducing the risks associated with physical exploration of Ijen Crater.

Previous studies examining the application of VR in geosciences have generally focused on general volcano simulations (Asgary et al., 2020) or geospatial data visualization (Zhao et al., 2019). The study by Asgary et al. (2020) used HoloLens for general volcano simulation, but did not include 6DoF interaction or multidisciplinary ecosystem simulation like that of Ijen Crater. To date, no research has integrated 6DoF systems with the Unity Engine to simulate complex volcanic ecosystems such as Ijen Crater. The use of Unity is considered ideal due to its flexibility in building dynamic environments with features such as real-time lighting, weather simulation, and physics interaction (Andaru et al., 2019; Ustun et al., 2018). Additionally, this platform is compatible with relatively affordable VR devices, such as the Oculus Quest, which further expands its potential for educational applications (Prasetya et al., 2023). However, challenges in optimizing system performance to avoid lag still need to be addressed (Nusrat et al., 2021).

"Based on the various weaknesses identified in previous studies, this research aims to develop a VR 6DoF learning media using Unity that can simulate volcanic processes, ecosystems, and disaster mitigation at Ijen Crater in a more realistic and immersive manner. This study also aims to assess the effectiveness of the 6DoF system in enhancing students' understanding of geology, geochemistry, and volcanic disaster mitigation strategies (Occhipinti, 2025). Thus, this research is expected to provide a theoretical contribution in the form of an optimized 6DoF VR development framework for geosciences, combining principles of interactive pedagogy (Checa& Bustillo, 2020) and disaster risk analysis. Furthermore, this study also seeks to provide a practical application in the form of an immersive geography learning solution for schools in remote areas, as well as a disaster mitigation educational tool for communities around Ijen Crater. This contribution is expected to address the need for more inclusive and interactive geoscience education access, while contributing to global literacy on the use of 6DoF VR technology in disaster education and environmental conservation. Therefore, further research could explore various approaches in VR project development, such as educational games, to create more effective and meaningful learning experiences for users.

METODE

This study is located in the Ijen Crater area, which is situated in the Banyuwangi and Bondowoso regencies, East Java Province, Indonesia.This study uses the Research and Development (R&D) method by adapting the Hannafin and Peck development model (Guna et al., 2019; Hannafin, M. J., Peck, 1998). This method was chosen for its ability to produce valid, practical, and effective products through a structured and iterative development process. The Hannafin and Peck model consists of three main phases: (1) Needs Assessment, (2) Design, and (3) Develop/ Implement. Each phase is carried out through revision and evaluation at each stage, as shown in Figure 1. below, which illustrates the three main stages in the development of 6DoF VR for geoscience learning.

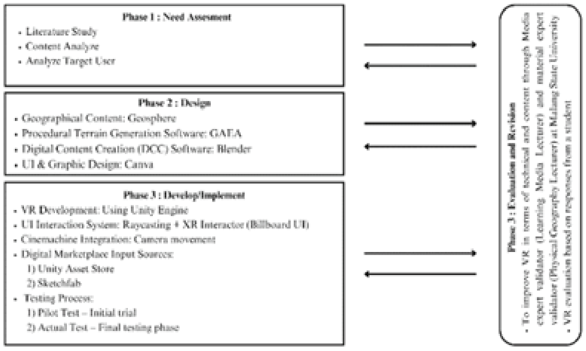


Figure 1. Research Method Flowchart: Development of Virtual Reality (VR) Media Using Unity

a. Needs Assessment Stage

In this stage, a needs analysis is conducted to identify the limitations of 3DoF VR in terms of immersion and limited interaction, which hinder environmental exploration in geography learning (Radianti et al., 2020). Due to these issues, the development of 6DoF VR is seen as a solution. Interviews were conducted with 2 teachers and 30 students using open-ended questionnaires to identify UI/UX design preferences and priority learning materials.

b. Design Stage

The design phase of this 6DoF VR project focuses on creating a realistic, interactive, and immersive experience. This process includes designing exploration scenarios that allow users to explore various geosites, namely Ijen Crater, Kalipait, BulanSabit Crater, PintuAngin Crater, ApetLepet Hill, Curah Penai, Mount Papak, MountRante , and Galuh Park. The exploration points are arranged in a sequence designed to ensure that the learning experience feels natural and progressive (Slater & Sanchez-Vives, 2016) .

The user interface is developed with Human-Computer Interaction (HCI) principles in mind to ensure intuitive navigation and ease of use. Usability testing was conducted from the early stages to refine the UI elements, ensuring they remain minimalist yet informative without diminishing the user's immersion.

The virtual environment is created with a realistic approach, as shown in Figure 2. which illustrates the VR development framework using the Unity Engine along with other supporting applications such as Gaea, Blender, and Canva. Additionally, this image highlights the key elements of VR development, such as the XR Plugin, VR camera system, raycasting-based interactive controls, and user support systems.

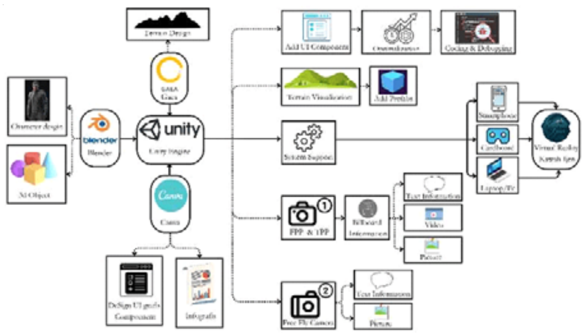


Figure 2. Framework for Developing Virtual Reality Using Unity Engine

a. Development and Implementation Stage

In this stage, product implementation is carried out through an iterative testing and refinement process. This process includes:

- Expert Validation: Media experts are evaluated based on usability criteria (scale 1-5), while subject matter experts assess the accuracy of the geography content.
- User Testing: Conducted at SMA Katolik Yos Sudarso Batu with the involvement of ten students and two geography teachers. Data collection is performed using questionnaires.
- Data Analysis: Quantitative data areanalyzed using descriptive statistics to determine the effectiveness of the product. Meanwhile, qualitative data are analyzed through data reduction, data presentation, and conclusion drawing.
- Usability Evaluation: The usability evaluation aims to measure the ease of use and comfort of users when interacting with the VR system. The measurement is conducted using the System Usability Scale (SUS) method, which consists of 10 statements with a Likert scale of 1–5 (Brooke, 1996; Vlachogianni& Tselios, 2022).

Figure 3. shows the virtual environment of Ijen Crater and its surroundings, developed using Unity. The use of realistic 3D modeling techniques, real-time lighting, and optimized rendering aims to create an immersive geoscience exploration experience.

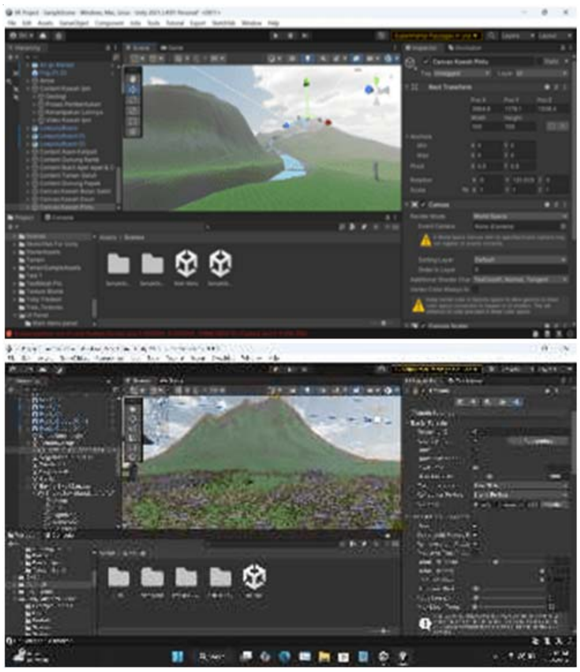


Figure 3. Development of the Ijen Crater Environment Area and its Surroundings

The development of VR in Unity uses various optimization techniques to maintain the application's performance stability. Additionally, optimizations are made to minimize latency and increase frame rate, ensuring a comfortable user experience. The techniques used include:

- Foveated Rendering: Optimizing rendering only in the area viewed by the user to reduce the GPU load (Matthews et al., 2020).
- Occlusion Culling: Ignoring objects that are not visible to speed up the rendering process (Gross &Gumhold, 2021).
- Level of Detail (LOD): Adjusting the level of detail of objects based on the user's distance (Keil et al., 2021; Wate et al., 2013).

The development of Virtual Reality using Unity requires several key elements to ensure an optimal and immersive experience. (1) XR Plugin and SDKs, such as OpenXR, are used to support the VR devices being used. (2) The camera system (VR Camera Rig) allows real-time head movement and user viewpoint. (3) Controls and interactions are supported by raycasting for navigation and object selection. (4) The VR environment is built with optimized 3D models, using lightweight shaders and lighting to maintain stable performance. (5) Physics systems, such as Rigidbody for characters, are applied to create more responsive interactions. (6) Performance optimization, such as Foveated Rendering, Occlusion Culling, and maintaining a stable frame rate (90Hz - 120Hz), is essential to ensure user comfort. With these elements, the resulting VR experience can be more realistic, comfortable, and responsive for users(Tytarenko, 2023).

In the development of the coding system in Unity, C# is used as the main language with a Component-Based Architecture approach, as shown in Figure 4. which allows scripts to be attached to GameObjects to control behaviors in the game (Yang et al., 2020). Scripting in Unity utilizes Mono Behaviour with key functions such as Start(), Update(), and Fixed Update(). The principles of Object-Oriented Programming (OOP) are applied with design patterns such as Singleton and State Pattern to maintain modularity and code readability. In terms of physics and interactions, Unity uses Rigidbody for physics simulation and handles collisions with methods like OnTrigger Enter() and On Collision Enter(). The Input System is used to handle inputs from the keyboard, mouse, or controller, while Raycasting enables interactions with objects in the game world, including in VR (Wan et al., 2024). To maintain performance, techniques such as Object Pooling are used to reduce repeated instantiation, and Coroutines and async/await are employed to run processes efficiently without burdening the frame rate. Scene management uses Scene Manager, while data storage can be done via Player Prefs, JSON, or Scriptable Object. Debugging and performance analysis are also essential in Unity coding, utilizing Debug.Log (), Profiler, and Frame Debugger to ensure optimal performance. With this structured approach, Unity coding can result in a more effective, flexible, and easily expandable system

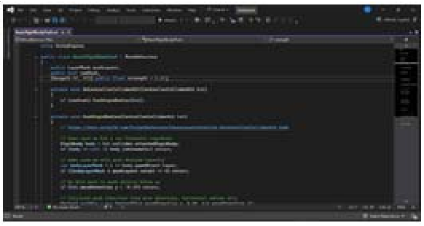


Figure 4. Coding and Debugging VR with C# in Unity

Although this research has been designed with a systematic approach, there are several limitations that need to be considered. The trial conducted only involved students from SMAKatolikYosSudarsoBatu, so the results obtained may not fully represent a broader population. Additionally, factors such as prior experience with VR and individual preferences could influence the evaluation outcomes. Therefore, the generalization of these findings should be done with caution, and further research with a more diverse sample is needed to strengthen the validity of the results.

RESULTS AND DISCUSSION

This Virtual Reality-based learning media is named ‘KawahIjen’, and it is packaged as an application (.apk). The VR application was developed for geosphere-related content and can be easily operated on all types of Android, iOS, and Windows devices. The application can be accessed anytime and anywhere, with internet connectivity only required during the initial download.

The main advantage of VR compared to other learning methods such as 2D videos and desktop simulations lies in its immersiveness and interactivity. Unlike 2D videos, which are passive, or desktop simulations, which are limited to screen-based exploration, VR allows users to directly interact with the virtual environment (Zhao et al., 2020). To enhance the immersive learning experience, the application is equipped with several key features, including an intuitive user interface (UI), dynamic lighting, flexible camera perspective switching (first person and third person), and realistic 3D audio.

In addition, VR provides an exploratory experience through a real-time dynamic lighting system and spatial audio effects that adjust according to the user's position. Information billboards within the VR environment also serve as important learning elements, allowing students to access geosphere materials in the form of photos, infographics, and interactive videos. With these features, geosphere concepts can be understood more clearly and intuitively, making VR more effective than conventional learning methods.

a. User Interface Components

The user interface (UI) components in this VR application consist of: (1) Main Menu, which serves as the initial display and includes options such as Start, Help, and Quit; (2) the Pause Menu, which appears when the game is temporarily halted and contains options such as Resume, Restart, Reference, and Return to Main Menu; and (3) the Game Interface, which is the in-game UI displayed during the gameplay experience. The selection of user interface components is carefully designed to minimize user confusion and to support a smooth transition into the geography learning experience for students.

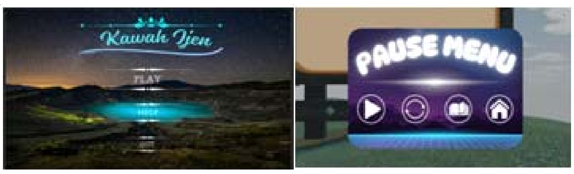


Figure 5. Main Menu and Pause Menu of KawahIjen Virtual Reality

b. Dynamic Lighting System

To create a more realistic VR environment, a dynamic sky system is provided, featuring real-time lighting, weather effects, and atmospheric changes that dynamically adjust according to time and environmental conditions, with a setting of 1 minute in Unity equating to 1 hour in real life. Lighting and shading are also configured so that illumination adapts in real time to the user's position, allowing gradual and natural transitions in lighting, sun position, sky colors, and weather conditions such as rain, fog, or the shift between day and night. This creates a more natural lighting effect. It enables users to experience environmental dynamics that accurately reflect the geography of Ijen Crater, allowing students to better understand the impact of these changes on volcanic ecosystems in a more direct and engaging way.

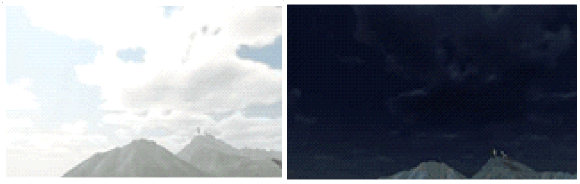
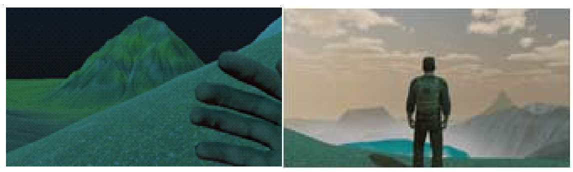


Figure 6. Lighting Flexibility in the Daily Cycle

In addition, the lighting and shading system is designed to adjust the intensity and direction of lighting based on the user's position within the VR world (Scorpio et al., 2020). This allows for more accurate shadow and lighting effects, enhancing visual depth and user immersion. With this implementation, any changes in the volcanic area such as Ijen Crater-particularly in light intensity and shadow-can visually reflect the transformations occurring in the terrain, rock formations, and geosystems surrounding the crater. This facilitates a better understanding of how natural lighting influences the geological and geographical study of an area.

c. Flexible Camera Transition

For movement transitions, the Cinemachine feature in Unity is used to enable seamless switching between First Person and Third Person perspectives. Each camera must be configured to ensure smooth transitions and provide a comfortable experience for users. A Cinemachine Virtual Camera is placed at the character's head with zero damping to ensure responsive and real-time movement (Park & Kim, 2022). In addition, Cinemachine POV is used to control camera rotation based on player input, while a Field of View (FOV) of approximately 60–90 degrees is applied to provide a more realistic perspective that mirrors the real-world view, allowing students to better understand the topography of Ijen Crater.



Gambar 7. First Person and Third Prespective

Meanwhile, an additional camera feature, the Free Fly Camera, allows free movement within the 3D space without being locked to the character, and does not use Cinemachine. This camera is directly controlled through a script that manages user input for manual camera translation and rotation. This mode is often used for debugging purposes or for unrestricted exploration within the virtual environment.

d. AudioSpatializer

On the audio side, Spatial Sound is utilized by employing an Audio Spatializer to create dynamic 3D sound effects that adjust according to the user's position, helping students to experience the natural sounds ofIjen Crater and its surroundings. Unity supports this technology through Resonance Audio or the Oculus Audio SDK, allowing sounds to be perceived more realistically depending on the direction and distance of the sound source (Popp & Murphy, 2022). This aspect enriches sensory-based learning in geography by enabling students to experience the landscape not only visually but also through auditory perception. It supports a multi-sensory approach in geography education, which has been shown to enhance conceptual understanding of physical environments and natural dynamics.

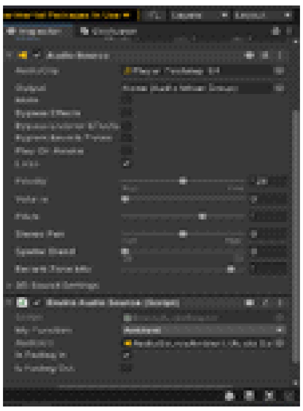


Figure 8. Audio Spatializer

e. Information Billboards

The information billboards within the KawahIjen Virtual Reality experience are designed to present geosphere materials in a modular format to reduce users' cognitive load, in accordance with Cognitive Load Theory (CLT). Information is structured progressively and segmented, allowing students to grasp concepts more easily without being overwhelmed with information at once (Modular Information Presentation) (Haryana et al., 2022; Sweller, 1988).

In addition, each information board is equipped with interactive elements, such as quick quizzes or light simulations, enabling users to immediately test their understanding. Augmented Feedback is applied through instant feedback on the users' answers, allowing them to recognize their results and correct mistakes in real time (Udeozor et al., 2023) .

The geosphere materials are integrated with geospatial content tailored to learning needs, through user target analysis, technology identification, and content analysis. The materials are presented in various media formats, including photos, infographics, and videos sourced from platforms like YouTube, making the information boards serve as educational resources within the VR environment and supporting students' competencies.

Figure 9. Information Billboard

The Raycast system is used to detect interactions between users and objects within the VR environment, enabling users to intuitively and responsively select geographic features, press buttons, or interact with objects in the virtual environment (Waschk&Krüger, 2022).

Usability Evaluation Results (SUS)

Usability evaluation was conducted by involving 10 students and 2 teachers who tested the VR application. After the session, participants completed a System Usability Scale (SUS) questionnaire to assess the ease of use and user comfort of the application. The table below presents a breakdown of the SUS statement responses:

Table 1. SUS Results

NO	SUS Statement	Average Score
1	I found the system to be easy to use.	4.4
2	I found the system to be complex to use.	1.6
3	I felt comfortable using the system.	4.5
4	I felt that I needed technical support to use the system.	1.5
5	The features of the system work well.	4.3
6	The system has a lot of inconsistencies.	1.7
7	I felt confident using the system.	4.6
8	I needed to learn a lot of new things to use the system.	1.8
9	I felt the system was efficient to use..	4.5
10	I would recommend the system to others.	4.6
	Total SUS Score	**32.4**
	Mean SUS	**81.0**

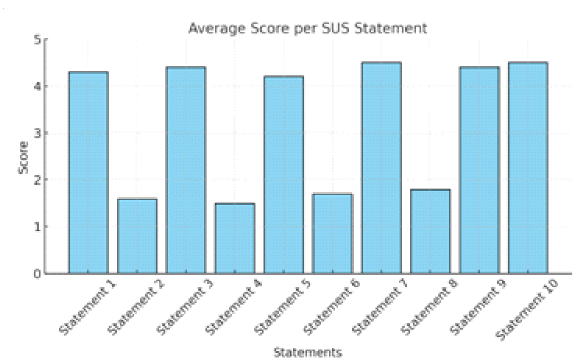


Figure 10. Chart Sus Results

Based on the results of the usability evaluation, it can be concluded that the KawahIjen VR application has a good level of usability, with a SUS score of 81.0. The table and graph of the SUS results show that the highest-rated items were the statements "I felt confident using this media" and "I found the system easy to use." These findings indicate that the interface and interactivity aspects of the VR are already aligned with usability heuristics principles, particularly in the aspects of "match between system and the real world" and "user control and freedom" (Hidayat&Yuhana, 2023; Nielsen, 1995). The VR experience remains comfortable for users; however, to further enhance comfort, some improvements could be made, such as adjusting the camera movement speed and adding a Comfort Mode feature.

Case Study

This research was conducted with a limited trial at YosSudarso High School to test the effectiveness of using Virtual Reality "KawahIjen" as a learning medium. Figure 11. Show The participants in this trial consisted of 10 students per group from grades X and XI and 2 Tecahers.

Figure 11. Implementation Trial of the KawahIjen VR Educational Media with Student and Teacher Participants

Table 2. Classification of the Geosphere and Characteristics (Stahler, 1992)

Characteristic	Category	Sub-Characteristic
Physical	Lithosphere	Geology and geomorphology
	Hydrosphere	Water
	Atmosphere	Weather and climate
	Pedosphere	Soil
Social	Anthroposphere	Humans, animals, and plants
	Biosphere	Social, economic, and cultural

Participant selection was based on previously studied materials: Chapter 5: The Hydrological Cycle and Its Role in the Ecosystem for Grade X, and Chapter 7: Disaster Mitigation and Adaptation for Grade XI. The use of VR in learning provides an interactive and exploratory experience, helping students gain a deeper understanding of concepts through realistic simulations, as illustrated in Table 2. In addition, the list of Educational Spots in the KawahIjen VR environment, along with corresponding media sources and student learning outcomes, is presented in Table 3.

Table 3. Geosphere Components and Related Topics of VR KawahIjen Material

Cate gory	Charac teristic	Sub-Charac teristic	Subject Topic
Phy sical	Litosphere	Geology, geomor phology	Formation processes, geology, and geomorphology
	Hidrosphere	Air	Water quality
	Atmosphere	Weather, climate, atmospheric phenomena	Air temperature, air pressure, humidity
	Pedosphere	Soil types, soil fertility	Soil and land
Social	Antropo sphere	Humans, animals, plants	Human, animal, and plant life
	Biosphere	Social, economic, cultural	Social interaction and norms

Table 4. List of Educational Spots in VR KawahIjen

Spot light	Infor mation Board	Media Source (Photo/ Video/ Infographic)	Learning Outcomes
Geo sitelien	3	Media Source (Photo/Video/ Infographic) Geological & geomor phological infographics, drone video	Learning Outcomes Understand volcanic processes and their environmental impacts
Social Life of IjenG eosite	1	Documentary video of community activities	Recognize the social and economic life of communities around Ijen
Kalipait	3	Acid river photos, water content infographics	Explain the characteristics of acid rivers and their impact on the ecosystem
BulanS abit Crater	1	Crater formation infographic	Analyze geological phenomena of craters and sulfur formation
Pintu Angin Crater	1	Crater infographic	Understand the process of volcanic gas emission and its danger to humans
Daun Crater	1	Conservation area photo, ecological infographic	Identify conservation areas and the importance of environmental preservation
Mount Papak	1	Geological history infographic	Understand the formation history of mountains in the Ijen area
Mount Rante	1	Mountain infographic	Learn about ecosystem-based mountain formation
Curah Penai	1	Surrounding ecosystem infographic	Learn about the formation of mountainous regions
Apet Lepet Hill	1	Erosion and formation infographic	Explain erosion processes and hill formation
Galuh Park		Vegetation photos, biodiversity infographic	Understand biodiversity and the importance of conservation

The KawahIjen VR, developed using Unity, is supported by 6 Degrees of Freedom (6DoF) movement, allowing users to move and interact freely within the virtual world, thereby providing a more immersive learning experience. Based on a usability evaluation using the System Usability Scale (SUS), the KawahIjen VR achieved a score of 81, categorized as excellent (Brooke, 1996). This indicates that users felt comfortable and found the system easy to use when exploring the virtual environment.

Each location within the Ijen complex holds significant scientific and educational value that is dynamic and plays an important role in maintaining environmental balance (Abdurrachman, 2023). However, not everyone has the opportunity to explore it directly, making VR a primary alternative (Pan & Hamilton, 2018). This technology offers a deeper learning experience, in line with the Immersive Learning Framework, which emphasizes that learning becomes more effective when learners can experience and directly interact with learning objects in an immersive digital environment (Mulders et al., 2020). Furthermore, this concept aligns with the Geospatial Thinking Framework, which highlights that spatial and geographic understanding can be enhanced through technologies that enable space-based exploration (M. Bagher et al., 2023). Students are able to access various sources of information, including the geographical characteristics of the IjenGeosites, allowing KawahIjen VR to facilitate an interactive learning process for students.

In addition to enhancing geospatial understanding, the KawahIjen VR also has the potential to serve as a more concrete and contextual model for disaster mitigation education, particularly for students in volcanic hazard-prone areas. The Geospatial Data Visualization in VR, as shown in Figure 12. demonstrates how complex geographic data (such as elevation and location data) can be transformed into 3D visual representations. In VR, similar data can be imported and rendered within an immersive virtual environment. VR users can explore the landscape from various perspectives, fly over it, or even "walk" across its surface, offering a much more intuitive understanding compared to traditional 2D maps.

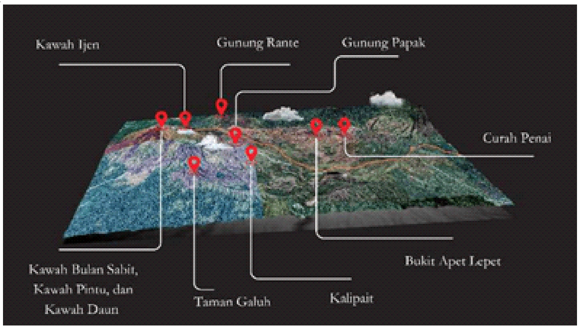


Figure 12. Plotting Spotlight of Virtual Reality KawahIjen

1. Geositeijen(Coordinates: 8°03'31" S - 114°14'34" E)

The formation of the Ijen Crater was caused by an explosive eruption that subsequently created a crater filled with rainwater (Zaennudin et al., 2012). A permanent solfatara exists at the edge of the lake, continuously producing pure sulfur(B. S. Putra, 2014). In addition to its stunning geological phenomena, Ijen Crater also holds a rich ecosystem that deserves appreciation(Widowati et al., 2023). Around the mountainous and forested areas of Ijen, there is a wide variety of endemic flora and fauna. Certain characteristic plant species, such as the Javanese edelweiss (Anaphalisjavanica), can be found on the mountain slopes(Syahbudin, 2019). This biodiversity highlights the importance of preserving the KawahIjen environment to maintain it as a balanced natural habitat.

The use of VR technology in geography education enables students not only to visualize the geosites of KawahIjen but also to spatially experience their scale through immersive interaction(Masruroh et al., 2023). Within this virtual site, students can explore the crater's morphology, directly observe solfatara activity, and interactively recognize endemic flora such as the edelweiss. This approach makes concepts such as volcanism, biodiversity conservation, and ecosystem functions more tangible and easier to understand.

2. Kalipait(Coordinates: 8°07'48" S - 114°09'41" E)

The Kalipait River has an extremely high level of acidity (low pH) due to its abundant sulfur content (Sari et al., 2023). The acidity of Kalipait water can reach a pH of 0 to 1, making it one of the most extremely acidic river flows. Its water appears yellowish to greenish and emits a strong sulfur odor. These conditions make it difficult for most freshwater organisms to survive, although some extremophile microbes are capable of adapting (Yuliani et al., 2023).

As part of the Ijen Watershed (DAS Ijen), Kalipait holds significant ecological and geological importance. The chemical conditions of Kalipait's water are often the focus of studies in environmental geochemistry, disaster mitigation, and water quality monitoring. Volcanic activities at Ijen Crater, such as the release of toxic gases, can affect Kalipait's water quality and pose risks to the communities living along the river. In the development of virtual technologies, the modeling of the Kalipait River flow has been adapted into VR simulations.

This aims to support education related to environmental conservation around Ijen Crater. Through these simulations, learners are not only able to visualize the acidic river but also understand the chemical dynamics of the water, pollution processes caused by volcanic gases, and their impacts on ecosystems and nearby communities. Students can explore how high sulfur concentrations affect aquatic biota or how acidic flows move from the crater to the river. This approach helps make complex concepts, such as geosystem interactions and the geological impacts on social environments, more contextually and practically understandable.

3. Bulan Sabit Crater, PintuAngin Crater, Daun Crater (Coordinates: 8°03'44" S - 114°14'46" E)

CraterBulanSabit gets its name from its crescent moon-like shape when viewed from above. Meanwhile, PintuAngin Crater is named after the strong wind phenomena frequently occurring around it, caused by natural gaps or corridors that amplify gusts of wind and produce a distinctive rumbling sound due to differences in air pressure inside and outside the crater.Daun Crater features lush mountain vegetation resulting from mineral-rich volcanic activity, with wild plants growing in the surrounding area. The hiking trails leading to these craters are filled with vegetation such as wild berries, and are characterized by dry, steep paths covered with bushes, fallen trees, and landslide-prone terrain. These three craters are located side by side and are part of a conservation area.

The crescent shape of BulanSabit Crater is visualized through a topographic view from above, allowing students to understand the relationship between crater formation and volcanic processes. At PintuAngin Crater, the VR simulation adds sound effects and particle movement to simulate strong gusts of wind, enriching the multisensory experience and helping students grasp concepts of air pressure and wind gap morphology. Meanwhile, the visualization of vegetation around DaunCrater offers students the opportunity to observe how volcanic soil conditions influence the growth of mountain flora. The hiking trails visualized within the VR terrain also introduce learners to geographical risks such as landslides and steep terrain, thereby strengthening awareness of conservation efforts and risk management in volcanic areas.

4. Mount Papak (Coordinates: 8°03'15" S - 114°13'37" E)

The name "Papak" in Javanese means flat or even, reflecting the relatively flat summit of this mountain compared to other peaks in the Ijen complex (Virgiawan, 2020). This topography makes it visually distinctive and a characteristic feature of Mount Papak. Although not as famous as the Ijen Crater, Mount Papak hosts a unique montane forest ecosystem (Supriyanto et al., 2020). The vegetation around this mountain is rich in endemic Javanese flora and serves as a habitat for various types of wildlife, including several species of endemic birds (Abdillah, 2021). Mount Papak does not have an official hiking trail frequently used by tourists. However, for researchers, nature enthusiasts, or experienced hikers exploring the entire Ijen complex, Mount Papak offers a unique perspective on the volcanic landscape of the region.

Through VR, Mount Papak is introduced as part of the mountain ecosystem within the

Ijen complex that is often overlooked in conventional learning. The visualization of its uniquely flat summit helps students understand variations in volcanic mountain morphology and how these variations affect the types of vegetation and distribution of fauna in the surrounding area.

5. Mount Rante (Coordinates: 8°03’46" S - 114°14’43" E)

Mount Rante is part of the Ijen volcanic complex, which was formed from volcanic activity that occurred thousands of years ago. Mount Rante, standing at an elevation of 2,600 meters above sea level, offers stunning views, including a sunrise that appears above the clouds. The hiking trail is narrow and sandy, with a route length of approximately 3.5 km, featuring steep topography composed of sandy footpaths (Farid PrasetyoManggala Putra et al., 2020).

In the Mount Rante area, VR is utilized as an interactive medium to introduce volcanic mountain topography and the complexities of hiking trail dynamics. Through VR, students can experience the challenges of steep terrain immersively while also understanding how elevation and rock types influence the structure and difficulty of hiking trails.

6. ApetLepet Hill dan Curah Penai (Coordinates: 8°05’45" S - 114°13’45" E)

The soil structure of ApetLepet Hill and Curah Penai is dominated by volcanic rocks and sandy soils, which are fertile and support the growth of vegetation such as grasslands. The layered landscape of the hills indicates ongoing erosion and sedimentation processes over thousands of years. The difference between the two is that Curah Penai features expansive agricultural lands cultivated by local residents around the crater area, surrounded by small, pointed hills that resemble a painting when viewed from ApetLepet Hill.

The visualization of soil textures, vegetation patterns, and agricultural land distribution helps students analyze how natural and social factors interact to shape cultural landscapes. Additionally, interactive features in VR, such as geospatial annotations and contour maps, enhance the understanding of concepts like erosion, sedimentation, and land use zoning (Habibiyah et al., 2023). This aligns with the perspective that immersive digital learning media can strengthen students’ spatial abilities in the digital era (A. K. Putra et al., 2023). Through this approach, geography learning moves beyond simple observation, promoting direct and profound spatial interpretation and ecological awareness.

7. Galuh park (Coordinates: 7°57’00" S - 113°48’00" E)

Colorful flower fields dominate the vegetation in this area, creating the impression of a vast and lush garden. Covering approximately 2.5 hectares, Taman Galuh is often referred to as a “fairyland” due to its vibrant flower displays and the scenic green hills that delight visitors. This place offers a refreshing atmosphere, ideal for tourists seeking an escape from the hustle and bustle of city life. Taman Galuh not only features beautiful flower gardens but also grasslands, savannas, and cultivated fields of crops such as corn, strawberries, and cabbages managed by local residents.

Taman Galuh is presented as an interactive environment to help students understand the relationship between the beauty of natural landscapes and the socio-economic activities of surrounding communities. Students can explore this area immersively to observe vegetation distribution, land use patterns, and the forms of human interaction with nature. Additionally, it serves to introduce key geographical concepts such as nature-based tourism. Through this experience, students are encouraged to think critically about sustainability, the impact of human activities on the environment, and the importance of preserving buffer zones like Taman Galuh.

In its implementation, there are several limitations, such as the requirement for high device specifications. 6DoF VR demands significant graphic performance, so on lower-spec devices, potential lag and reduced frame rates may diminish realism and user comfort. Nevertheless, VR still holds great potential for enhancing students’ geospatial understanding of the Ijen Crater phenomenon, and its development needs to be continually refined to become more inclusive and effective.

CONCLUSION AND SUGGESTIONS

Virtual Reality has transformed the educational paradigm by offering immersive and interactive learning experiences. The application of VR in geoscience education has been proven to enhance student engagement and conceptual understanding, although various challenges still need to be addressed. The 3DoF system is limited to view rotation, whereas 6DoF provides full freedom of movement, enhancing realism and interactivity. 6DoF VR, utilizing Unity, is capable of simulating volcanic processes, ecosystems, and disaster mitigation, particularly in the geosciences field. This study also aims to test the effectiveness of the 6DoF system in improving students' understanding of the exploration of the Ijen Crater through VR.

The VR development for the Ijen Crater using Unity Engine was based on literature studies, content analysis, and user target analysis. The research results show that the developed VR media, named "Kawah Ijen," successfully presents a realistic virtual environment. Features such as an intuitive user interface (UI), dynamic lighting system, flexible camera movement, 3D audio, and interactive information boards are used to present geosphere material integrated with geospatial elements in the form of photos, infographics, and videos.

Future development steps may also explore other approaches such as VR-based educational games to further increase student engagement. Expanding accessibility to various types of devices and operating systems is also an important factor to ensure this media can be widely used across different educational institutions.

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