The Academic
International Journal of Multidisciplinary Research

An Online Peer Reviewed / Refereed Journal
Volume 4 | Issue 3 | March 2026
ISSN: 2583-973X (Online), SJIF IF: 5.6
Website: www.theacademic.in

Augmented Reality in Geography Education: Visualizing Landscapes and Environmental Change

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DOI : https://doi.org/10.5281/zenodo.19383684

ARTICLE DETAILS

Research Paper

Accepted: 16-03-2026

Published: 10-04-2026

Keywords:

Augmented Reality, Geography Education, Environmental Change, Spatial Thinking, Interactive Visualization

ABSTRACT

The rapid evolution of new digital technologies is altering the ways that education is enacted across disciplines. Geography education may present particular challenges in communicating spatial relationships and environmental change, as geographic phenomena are often abstract, large and dynamic. AR can be seen as a technology, through which established technologies, like visualization, are improved by the spatial context of the real world. This paper seeks to explore the possibilities that AR technology could have in teaching and learning geography through the visualization of landscapes and environmental change. The paper reviews the literature to identify the affordances of AR in education and to illustrate its use for supporting spatial thinking, engagement, and interaction in learning. It discusses how AR applications are used to enable students to visualize landforms, ecosystems, and environmental changes such as climate change, deforestation, and sea-level rise. This understanding is theoretically substantiated by constructivist and experiential learning theories. As theoretically substantiated this understanding is, case studies are also analysed in order to shed light on the implementation of AR for geography learning and teaching purposes in some detail. The review also identifies key pedagogical affordances, implementation issues, and emergent research needs. Overall, AR has great potential for improving the teaching and learning of geography, especially in making complex environmental processes more accessible, interactive, and meaningful

1. Introduction

In the information age, integrating technology in education is no longer a luxury, but a necessity for learners to prepare for the 21st century job market (Garg et al. , 2025). Emerging technologies such as AR, AI, and VR have changed the educational process, moving learning outside the customary classroom while also providing students with numerous opportunities to take control of their own learning (Westhuizen et al. , 2025; Garg et al. , 2025). In the spatial disciplines, like geography, technology has given researchers tools to analyze, visualize, present, and communicate complex data in ways not previously possible.

Geography education is about the Earth's temporal and spatial systems. Temporal and spatial dynamics can be difficult to visualize, whether it be the withdrawal of a glacier, flooding of an area, or a rise in sea levels occurring over decades or centuries. Customary methods of educational communication are often limited in this regard. However, some phenomena may be too small, slow or distant to be observable in a customary classroom. AR is a technology that superimposes digital information, such as 3D building models, animations or real-time data, onto the real world, making it a potential alternative for creating direct experiences of otherwise unobservable phenomena (Schmidt & Stumpe, 2025; Pratama et al. , 2025).

This study adopts a review-based approach to synthesize existing research on AR in geography education. The aim of this paper is to examine the potential of Augmented Reality (AR) as a new tool for geography education, visualizing and supporting the understanding of environmental change. The aim further addresses and seeks to elucidate the current state of research in the field of AR for interactive landscape visualization and environmental education, and its role in supporting spatial knowledge, engagement and experiential learning. The paper will then conclude with considerations on the opportunities and challenges of implementing AR in geography education and future directions.

2. Augmented Reality in Education

Definition and Characteristics of AR

Augmented Reality (AR) is defined as a technology that superimposes computer-generated images, sounds, or other data onto an user's view of the real world, thus providing a composite view (Pratama et al. , 2025). AR is different from VR, which creates a completely artificial environment, as in AR users are immersed in the real world and additional digital information is added to it (Sobke et al. , 2018). The main features of the AR experience include real-time interactivity, alignment and registration of virtual and physical objects, three-dimensional registration, and the provision of situated, context-aware information (Sarri et al. , 2022; Pratama et al. , 2025).

Evolution of AR Technologies in Education

In education, AR has shifted from expensive laboratory equipment to mobile devices (Schmidt & Stumpe, 2025). The early use of AR in education relied on cumbersome head-mounted displays for laboratory work, or "AR Sandboxes", which overlaid topographical features modelled on the physical sand using projectors and sensors (Çöltekin et al. , 2020). Today, with the proliferation of smartphones and tablets, advanced geovisualizations can be presented to all students just in time on their smartphones, in the classroom, or in the field (Turan et al. , 2018; Schmidt & Stumpe, 2025).

Educational Benefits: Engagement, Interactivity, and Visualization

The literature consistently highlights three primary benefits of AR in education:

- **Heightened Engagement**: The "novelty effect" and interactivity of AR attract the interest and motivation of students, particularly the digital native generation (Safitri et al. , 2024; Garg et al. , 2025) .
- **Enhanced Interactivity**: With AR, learners are able to change the course of a body of water or change the intensity of a volcano's eruption and visualize the effect of their modification (Koparan, 2025) .
- **Superior Visualization**: AR can visualize "invisible" information, including subsurface geology, winds, and projected sea-level rise, in a spatial context, allowing users to experience a previously immaterial or conceptual issue (Sarri et al. , 2022; Prayitno et al. , 2023; Uzun et al. , 2025).

3. Geography Learning and Visualization

Nature of Geography as a Spatial Discipline

Geography is a spatial science, which concerns with the distribution of phenomena and processes across the Earth's surface (Pratama et al. , 2025) . It requires spatial thinking to conceptualize spatial relationships between places at different scales, from local to global levels, including landforms at the local level and climate at the global level.

Importance of Spatial Thinking in Geography Education

Spatial thinking is a geo-competency of geography education that refers to the use of spatial concepts (e. g. , location, distance, direction), spatial representation tools (e. g. , maps, 3D models), and spatial reasoning processes to solve problems (Pratama et al. , 2025). AR technology can promote spatial thinking by providing learners with layered 3D visualization for representing the form, pattern, and change of a landscape (Lee et al. , 2011).

Limitations of Traditional Teaching Methods in Explaining Geographic Processes

Traditional methods can also suffer from a "split-attention" effect (Pratama et al. , 2025): students have to mentally integrate information from at least two sources (e. g. a map and a verbal description of the geographical situation) and may become overloaded by all the information presented to them at once. Static 2D maps cannot describe highly dynamic changes in the system such as a glacier that slowly retreats or a flood that occurs in a few minutes. (Lee et al., 2011; Safitri, et al., 2024).

4. AR for Interactive Landscapes

Use of AR to Visualize Landforms and Terrain

AR is also used to visualize 3D topography and landforms. One example application, "LandscapAR", enables students to create a 3D terrain model from 2D contour drawings, helping them develop skills in map interpretation and terrain reading (Sales et al. , 2022) . An example of how AR has been used to visualize the Lithosphere layers of the Earth's crust and mantle can be seen in (Prayitno et al. , 2023) .

Interactive 3D Models of Mountains, Rivers, and Ecosystems

Interactive and multi-perspective AR models can help students visualize geographic objects. When AR is incorporated into printed educational material for teaching geographic and geological features about a mountain such as Palgongsan in South Korea, it can be effective for slope, height, and terrain variation

(Lee et al. , 2011). Other applications for primary education include visualizing coastal landforms (peninsulas, bays, capes), different types of volcanoes (strato, shield, and maar), and winds (local, valley, mountain, sea, and land winds), effectively making the abstract geographical concepts of atmospheric and geological phenomena intuitive for students (Volioti et al. 2022; Fawad et al. 2023).

AR-Supported Exploration of Geographic Environments

AR can also transform the real world into an interactive classroom. For example, on a field trip the students can see geolocated AR-based annotations, audio guides or historical photographs explaining how the landform was created. This situated learning experience encourages students to work through abstract geographic theories as they encounter the actual landscape in front of them (Hewitt et al. , 2023)

5. AR for Understanding Environmental Change

Teaching Climate Change, Deforestation, and Sea-Level Rise using AR

AR is a powerful tool for visualizing environmental changes that occur over long time scales or in inaccessible regions.

- **Climate Change and Sea-Level Rise**: AR apps that use location data to simulate future sea-level rises provide students and the public with a concrete experience of the abstract phenomenon of global warming (Sarri et al. , 2022) .
- **Deforestation**: In another example, "MineSet" uses strategy games and augmented reality to examine complex issues (deforestation and forest degradation) through the lens of real-world case studies (the Congo Basin) to analyse the impact of land-use policies (Waeber et al. , 2023). AR texts have also been shown to improve student attitudes toward sustainable development and environmental preservation (Koparan, 2025).

Visualization of Environmental Processes and Transformations over Time

The ability of AR to compress time and space allows students to visualize "time-lapse" scenarios of environmental degradation. This includes the loss of tree canopy in Peruvian Amazonia and the spread of soil and water pollution (Waeber et al. , 2023; Uzun et al. , 2025) . Simulating environmental change and assessing the system's response will help students understand the causal linkages between anthropogenic activities and their environmental consequences (Westhuizen et al. , 2025) .

AR as a Tool for Environmental Awareness and Sustainability Education

AR can develop "eco literacy" by making environmental practices that would otherwise remain hidden visible. For example, learning Science, Environment, Technology, and Society (SETS) with AR applications can help students understand flood damage reduction and increase environmental awareness and responsibility (Safitri et al. , 2024). Students can use AR to visualize layers of atmosphere not visible to the naked eye, or the chemicals present in air pollution, allowing them to explore complex systems and understand sustainability (Volioti et al. , 2022; Uzun et al. , 2025).

6. Theoretical Foundations

AR-Based Learning and Constructivist Theory

AR geography learning aligns with constructivist epistemology. The constructivist theory of Jean Piaget defines learning as growing in knowledge through the student-environment interaction (Piaget, 1954). AR environments also allow the student to be self-directed in learning and to manipulate virtual, geographic models by themselves (Lee et al. , 2011; Sanabria et al. , 2025). For example, students may learn about the water cycle by using a 3D interactive model, which shows how the water cycle is affected by variables like temperature, allowing students to "construct" their understanding of the water cycle (Garg et al. , 2025; Sanabria et al. , 2025).

Experiential Learning and David A. Kolb

Another key pedagogical model for applying AR in geography is David A. Kolb's "Experiential Learning Cycle" (Kolb, 1984), which outlines four stages of learning: concrete experience, reflective observation, abstract conceptualization and active experimentation. AR assists with this cycle by providing students with an engaging visualization of the reference environment as the "concrete experience" (Volioti et al. , 2022), and then prompting them to reflect, conceptualize, and experiment with changing aspects of the environment to see how the system responds (Westhuizen et al. , 2025). This is seen in AR-supported fieldwork, whereby digital content is studied alongside the real world (Hewitt et al. , 2023).

7. Representative Case Studies

Case Study	Target Audience	Primary Focus	Key Outcomes

AR Ecoliteracy (Safitri et al., 2024)	High School (Gen Z)	Flood risk & mangrove conservation	Significant pre/post learning gains; 90.46% average assessment score.
SatelliteSkill5 (McNerney et al., 2023)	Secondary (Ages 12-18)	Remote sensing & SDGs	Reached 861 students; improved conceptual familiarity with satellite data.
AugView (Sobke et al., 2018)	Higher Ed (Eng.)	Underground infrastructure	Enhanced collaborative field interpretation and situational learning.
Sea Level Rise AR (Sarri et al., 2022)	General Public	Climate change in Crete	Real-time visualization of 2100 sea levels on-site; increased social awareness.
Primary Geo Apps (Volioti et al., 2022)	Primary (5th-6th)	Orientation & climate	High usability scores from both pupils and teachers for textbook-linked AR.

8. Pedagogical Benefits

The literature consistently highlights that AR significantly enhances learning outcomes by making abstract concepts tangible.

Knowledge Gains and Comprehension: AR applications have shown to have statistically important learning gains. For example, AR-based flood disaster education has resulted in students showing higher scores on tests and increasing their interest in protecting the environment. AR helps students visualize variables in remote sensing, such as land cover and elevation, which would be difficult to present in 2D maps.

Engagement and Motivation: The interactive nature of AR increases engagement and makes a more effective learning experience than customary classroom instruction, and it is especially suited to "Generation Z" learners who have grown up with technology and prefer interactive, technology-based, and experiential methods of acquiring knowledge.

Spatial Thinking and Orientation: Because geography and many geographic phenomena are spatial in nature, research has shown that spatial skills can be improved through augmented reality tools. AR Sandboxes, for example, are sand boxes that are manipulated to display real-time topography of the surface of the sand. Since AR technologies put the digital explanation co-located with the object of inquiry, they reduce "split-attention" and cognitive load.

Contextual and Place-Based Learning: AR can also be used for situated learning. Here, the app displays the educational content in a real-world location. For example, location-based games can tell the students about the expected rise in sea levels at the beach where they stand, creating an emotional and social connection with the learning content.

9. Implementation Challenges and Technical Constraints

However, there are several practical constraints to common adoption of AR in geography.

Technical Accuracy: Field-based AR has high accuracy requirements. Several studies report consumer GPS and mobile device positional accuracy is sometimes insufficient to place AR content precisely. Expensive tracking hardware may be required. Sensor uncertainty and depth ambiguity remain important challenges. Sensor inaccuracy and depth ambiguity remain ongoing challenges for developer teams.

Teacher Support and Curriculum Integration: Teachers need to structurally scaffold such AR resources (whether pedagogical or subject-specific) otherwise there is the danger learners will simply be motivated by the AR technology and not the science behind how it works. A barrier is matching AR content to rigid national curricula, and the willingness of teachers from all types of schools to use AR.

Hardware and Maintenance: AR can be distributed at scale to a fleet of AR-enabled devices. Managing a fleet of devices comes with issues such as battery life, the differences between Android and iOS, and constant software updates, which create a "maintenance burden" for educational institutions.

Data Privacy and Security: Open software-oriented databases of AR infrastructure and environments raise questions of privacy and security. For example, underground water networks may not be publicly available as exposing them through a public educational app might violate utility providers' privacy policies.

10. Future Research Directions

AR combined with AI: Future research could explore the convergence of AR and AI, for example, through adaptive AR systems that personalize the AR experience for each student according to their individual needs and progress.

AR for Field-Based Geography Learning: Longitudinal studies should be designed to provide understanding into the long-term impacts of AR-based fieldwork. Such studies could provide answers regarding the retention of spatial knowledge acquired though AR-based fieldwork compared to knowledge acquired during non-AR field-based learning.

AR Geography Curricula: Scientists and instructional designers could work together to create a "library" of AR modules specifically designed to align with geography curricula and make them available to teachers across the globe.

11. Conclusion

There is a strong tradition of geography and environmental change education with Augmented Reality (AR), where students see the "invisible" in geography by layering digital data over the physical world, such as sea level rise, or the many variables in a remote sensing image. The extent to which AR can improve education by promoting improved engagement, involving students in active learning, and explaining geographic processes depends on its integration with appropriate instructional design and sufficient technical infrastructure. There is intent to move on from "novelty-driven pilots" to "curriculum-aligned, scalable solutions", but addressing technical fidelity, teacher engagement, and data sharing remains a challenge. If addressed, AR promises to transition geography instruction from a subject reliant on static maps to a subject like a living laboratory where the future cohort of students can learn to tackle the 21st-century environmental problems.

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