When the Map Becomes a Place: Immersive Virtual Reality Terrain Exploration with GeoVR

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Abstract. *GeoVR is a Virtual Reality application for geographical and geomorphological education, built as a Learning Space within the fuelsME ecosystem. Users explore Digital-Elevation-Model-based terrain, switching between an immersive ground-level view and a scalable sandbox overview, supported by an analytical toolset (height indicator, compass, profiler, ruler) and a terrain layer configurable for any region without code changes. Guided by scale fluidity, analytical concreteness, and collaborative inquiry, we argue that dual-mode navigation supports scale-fluid geomorphological reasoning, and that layered VR architectures let domain-specific applications focus on differentiating affordances rather than generic infrastructure. We report deployment observations and a planned evaluation agenda.*

Keywords. Virtual Reality, Geography, Geomorphology, Educational Applications, Terrain Exploration, fuelsME, Field Trip Simulation, Multi-User VR

1 Introduction

Geography and the geosciences share a foundational pedagogical challenge: the phenomena students need to understand are written into landscapes distributed across the entire surface of the earth. Glacial cirques, river deltas, fault scarps, and volcanic calderas are the primary sources for a discipline whose core concepts are spatial, scalar, and temporal. Physical field trips are regarded as an important element in promoting geographical learning processes (Fuller et al., 2000, 2006).

However, even during physical field trips, it is often difficult to select key landscape features from the wealth of impressions and to grasp their spatial location. A major challenge is the identification of forms and their temporal and spatial changes, which in turn allow conclusions to be drawn about the dynamics of processes, such as the reconstruction of former valley floors and river courses, which are of fundamental importance for understanding geomorphodynamic systems such as the development of runoff regimes and flood development (Tillmann and Wunderlich, 2023). The varying scales and timeframes involved in observing these phenomena, as well as the translation of conventional two-dimensional representations, very quickly exceed learners' visual-spatial imagination (Kastens and Manduca, 2012). Photographs flatten depth, topographic maps demand cartographic literacy, and desktop GIS software places learners outside the data they are trying to understand.

Virtual Reality (VR) offers a fundamentally different relationship: the learner stands inside a three-dimensional landscape that responds to their movement and invites exploration. Recent evidence shows that well-designed VR learning environments match traditional instruction on academic outcomes while substantially raising engagement and motivation (Allcoat and von Mühlenen, 2018; Wright et al., 2023). More importantly, VR enables experiences fieldwork cannot: continuous scale change from satellite altitude to ground level within seconds, or direct superposition of terrain states from different geological periods.

This paper presents GeoVR, a VR application for geographical education that realises these possibilities through Digital Elevation Model (DEM)-based terrain rendering, dual-mode spatial navigation, and an interactive analytical toolset. GeoVR is one Learning Space within a larger VR ecosystem built under the fuelsME:Create framework (Mascher et al., 2024), which provides shared multi-user infrastructure and a collaborative co-

design process for technology and didactics. This paper treats that framework as given and focuses on what GeoVR contributes on top of it.

1.1 Contributions

This paper makes three contributions:

1. A design case study of GeoVR, documenting the pedagogical rationale, terrain pipeline, and dual-mode navigation design (micro/macro) of a VR learning environment for geomorphology.

2. An architectural argument for layered, reusable VR infrastructure in education: by inheriting shared multi-user capabilities rather than rebuilding them, domain-specific applications can direct most of their development effort toward the pedagogical affordances that differentiate the learning experience.

3. A preliminary deployment report and an evaluation plan intended for pre-registration, drawing on informal observations from early seminar use to surface emerging interaction patterns and to specify the controlled studies that will test GeoVR's learning claims.

GeoVR is presented here as a single instance of how a domain-specific VR learning environment can be built on shared infrastructure. Whether the same approach transfers to adjacent disciplines such as geology, environmental science, or urban planning is an open question that this paper does not attempt to settle.

2 The fuelsME:Create Context

GeoVR is one of several Learning Spaces (*fuelsME:Lernräume*) within the fuelsME:App, a VR application developed under the fuelsME:Create collaborative framework (Mascher et al., 2024) by a research consortium of several higher-education institutions.

The fuelsME:Create framework is relevant to this paper in two ways. First, it provides the organisational process within which GeoVR was designed: an interdisciplinary agile methodology in which educators act as Product Owners responsible for backlog prioritisation, ensuring that pedagogical requirements drive technical decisions rather than the reverse (Sabah et al., 2025). Second, it provides the shared technical infrastructure, fuelsME:Core, on which GeoVR is built.

2.1 fuelsME:Core as a Shared Infrastructure Layer

fuelsME:Core is a Unity-based multi-user VR runtime that provides the foundational capabilities required by any Learning Space in the fuelsME ecosystem: real-time network synchronisation across connected Head-Mounted Displays (HMDs), a configurable avatar system, reusable interaction primitives, and a token-based session isolation mechanism that allows multiple concurrent research groups to share server infrastructure without interfering with one another (Mascher et al., 2024).

The architectural consequence for GeoVR is significant: the application does not implement any of these capabilities. It inherits them. Concretely, the GeoVR codebase contains no networking, avatar, or session-management code; its implementation effort was spent almost entirely on the four domain-specific capabilities that differentiate geographical education (the terrain pipeline, the two view modes, the analytical toolset, and terrain-scale navigation). In the consortium's product backlog, all GeoVR-specific items addressed these pedagogical features; infrastructure items were handled once, at the fuelsME:Core level, and benefited every Learning Space simultaneously. The reuse also runs in the other direction: components developed for GeoVR, in particular the DEM-based heightmap import pipeline and the terrain-scaled teleportation, are candidates for adoption by other spatially oriented Learning Spaces in the ecosystem. Table 1 makes this division explicit.

Table 1. Division of responsibility between fuelsME:Core and GeoVR

Capability	fuelsME:Core (foundation)	GeoVR extension
Multi-user networking	Provided (built-in)	Inherited / no changes needed
Avatar system	Provided (built-in)	Inherited / no changes needed
Session isolation	Token-based rooms	Inherited / no changes needed
Terrain rendering	Not provided	DEM-based 3D terrain pipeline
View modes	Not provided	Micro (immersive) / Macro (sandbox)
Analytical tools	Not provided	Height indicator, compass, elevation profiler, height ruler
Spatial navigation	Basic locomotion	Teleportation tuned for terrain scale

2.2 The Learning Space

Within the fuelsME:Create framework, a distinction is drawn between a Learning Space (the technical and visual environment, authored once) and a Scenario (a specific deployment of that space for a defined course, group, and set of learning objectives)(Mascher et al., 2024). GeoVR is a Learning Space. It has been deployed in several distinct Scenarios: one focusing on glacial landform identification for a physical geography seminar, another centred on river morphology comparison for an environmental studies module (Sabah et al., 2025).

This distinction matters for the interpretation of the design decisions described in Section 3. Every design choice in GeoVR was made at the Learning Space level: it must serve the full range of scenarios for which the space will be used, not just the first one. This has pushed the design toward generality and configurability: terrain can be swapped by loading different DEM data, and tasks can be changed by reconfiguring scenario-level prompts, rather than toward narrow optimisation for a single course.

3 GeoVR: Design and Implementation

3.1 Pedagogical Design Principles

The design of GeoVR was governed by three pedagogical principles, developed iteratively through the interdisciplinary process described in fuelsME:Create (Mascher et al., 2024; Sabah et al., 2025) and informed by the geoscience education literature. Immersive virtual reality can enhance experiential understanding but may impose additional cognitive load if not carefully designed (Parong and Mayer, 2018; Mayer, 2002), and the three principles described below reflect deliberate choices made by the design team to manage this trade-off between immersion and cognitive demand.

The first principle is *scale fluidity*. Geomorphological reasoning requires the ability to move between spatial scales: from the regional overview that reveals drainage patterns to the local detail that reveals erosion mechanisms. A fixed perspective, whether map, photograph, or conventional three-dimensional model, privileges one scale at the expense of others. GeoVR's design makes scale switching a primary interaction rather than an afterthought (Lawson and Mayer, 2025).

The second principle is *analytical concreteness*. Students often struggle to connect the abstract conventions of topographic maps (contour lines, colour-coded elevation bands, gradient arrows) to felt spatial experience. GeoVR's toolset is designed to bridge this gap by overlaying quantitative data (elevation values, bearing angles, profile curves) directly onto the immersive terrain, so that students can read a number and simultaneously see and feel what it means.

The third principle is *collaborative inquiry*. Geography is fundamentally a discipline of shared observation and contested interpretation. GeoVR's multi-user design is not a convenience feature: it is a deliberate response to the evidence that shared spatial attention in VR supports richer discussion and deeper conceptual development than solo exploration (van der Meer et al., 2023). This principle is realised in GeoVR through three concrete mechanisms. First, the co-present avatars inherited from fuelsME:Core make each learner's position, orientation, and pointing gestures visible within the terrain, so that attention can be directed deictically ("this ridge here") rather than only verbally. Second, the two view modes support shared attention in complementary ways: in macro view, learners stand around the sandbox model as they would around a physical relief model and can jointly inspect the same feature from different angles, while in micro view, co-located exploration lets learners experience the same landform from within, at their own vantage points. Third, the analytical tools produce quantitative readings that give learners a shared vocabulary for coordinating attention across distance: a learner can announce their elevation from the height indicator and thereby anchor a joint reference point in the terrain. Section 4 reports an emergent instance of this last mechanism observed in early seminar use.

3.2 Terrain Pipeline

The technical foundation of GeoVR is a terrain pipeline that converts publicly available Digital Elevation Model (DEM) data into interactive Unity Terrain objects. The pipeline proceeds in three stages.

3.2.1 Data Acquisition and Preprocessing

GeoVR supports DEM sources that provide raster-format elevation data at sufficient resolution for educational use, including the Shuttle Radar Topography Mission (SRTM) dataset (approximately 30-metre horizontal resolution globally) and the Copernicus Digital Elevation Model (approximately 10-metre resolution for Europe). Raw DEM files are preprocessed using standard GIS tooling to clip the region of interest, fill data voids, and resample to the resolution appropriate for the target Unity Terrain size.

The choice of source dataset involves a trade-off between global coverage, resolution, and licence

compatibility. SRTM data is in the public domain and covers most of the earth's land surface, making it the default choice for curriculum flexibility. Copernicus DEM data offers significantly higher resolution for European locations, which is relevant for scenarios focused on Alpine glaciology or river morphology in densely studied European catchments.

3.2.2 Terrain Generation in Unity

Processed DEM data is imported into Unity as a heightmap and applied to a Unity Terrain object. The Terrain object's resolution parameters (heightmap resolution, detail resolution, and base map resolution) are tuned to balance visual fidelity against performance on the Meta Quest 2's mobile GPU. In practice, a heightmap resolution of 513×513 with detail and base map resolutions of 1024×1024 provides adequate detail for educational use without exceeding the Quest 2's memory budget.

Texturing is applied procedurally using Unity's Terrain layer system, with texture weights computed from elevation and slope at each surface point. This produces naturalistic colouration (green valley floors shading to grey rockfaces and white snowfields at altitude) without requiring manual authoring per terrain tile and without depending on satellite imagery that may be cloud-covered or unavailable for a given region.

3.2.3 Terrain Reuse and Configuration

Because terrain generation is separated from scenario configuration, the same GeoVR Learning Space can be used with any DEM dataset without code changes. Switching to a new geographic location requires only loading a different heightmap asset and adjusting the scale parameters that convert raw elevation units to Unity world-space metres. This configurability is the mechanism that makes GeoVR viable for the full range of scenarios in the curriculum rather than just the scenario it was first built for.

3.3 Dual-Mode Spatial Navigation

GeoVR offers two complementary view modes that give users fundamentally different analytical relationships to the terrain. The design of these modes is the central pedagogical affordance of the application and the aspect of the design that most directly required coordination between the educational geographers and the software engineers in the fuelsME:Create process (Sabah et al., 2025).

3.3.1 Micro View: Immersive Field Mode

In micro view, the user is scaled to human height and placed within the terrain. Navigation is achieved through short-distance teleportation: the user points a controller at a target location on the terrain surface and triggers a near-instantaneous transition, avoiding the nausea that continuous locomotion can induce on mobile VR hardware. The teleportation arc is visually rendered as a parabolic cursor that snaps to the terrain surface, giving users precise control over their destination (Fig. 1).

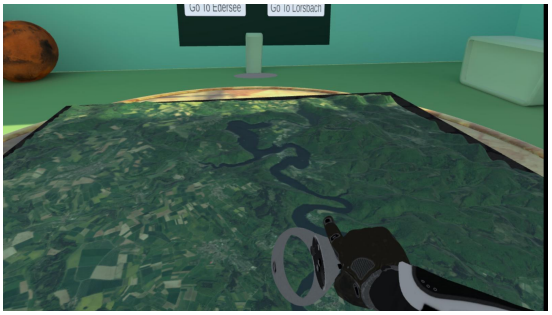


Figure 1. Micro view: the user is scaled to human height and placed inside the terrain. Navigation uses short-distance teleportation, visualised here as a parabolic cursor snapping to the terrain surface.

Micro view is designed for tasks that require felt spatial experience: identifying the cross-sectional shape of a glacial valley, appreciating the gradient of a river's long profile, or observing the relative heights of a terrace sequence from within the floodplain. These are tasks that no map or diagram can support in the same way, because they depend on the learner's proprioceptive sense of their own position within a three-dimensional space.

3.3.2 Macro View: Sandbox Mode

In macro view, the terrain is rendered at a reduced scale as a physical model on a horizontal surface at approximately waist height, analogous to a sandbox relief model in a geography classroom (Fig. 2). The user can walk around the model, lean over it, and view it from any angle. This mode supports tasks that require a synoptic perspective: identifying drainage divides, tracing the paths of major rivers from source to mouth, or comparing the morphology of adjacent valleys.

The distinction between micro and macro view is not merely cosmetic. In micro view, the user is inside the data; in macro view, the user is outside it looking in. Both perspectives are necessary for complete geomorphological understanding, and the ability to switch between them within a single session, without leaving the virtual environment,

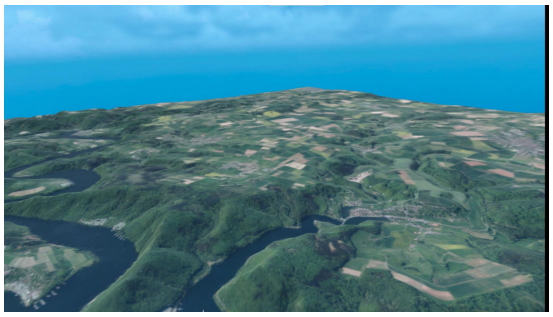


Figure 2. Macro view: the terrain is rendered at reduced scale as a physical model at waist height, analogous to a sandbox relief model. The user can walk around the model and view it from any angle.

is a capability that has no analogue in traditional fieldwork or GIS software.

3.4 Interactive Analytical Toolset

GeoVR provides a suite of interactive tools that extend the scope of analysis available within the virtual terrain. All tools are accessed via the Meta Quest 2 controller buttons and mapped to the interaction framework provided by fuelsME:Core, ensuring consistency with the other Learning Spaces in the fuelsME:App (Fig. 3).

- **Height indicator:** Displays the absolute elevation of the user's current position in real time. In micro view, this grounds the user's felt experience in quantitative data; in macro view, it allows point-to-point elevation comparison. The indicator updates continuously as the user moves, supporting the development of intuition about elevation gradients.
- **Compass:** Displays magnetic bearing as an overlay, supporting orientation exercises that require students to connect cardinal directions to terrain features. The compass is particularly useful in scenarios where students must read a topographic map alongside the VR environment and locate specific features by bearing.
- **Elevation profiler:** Allows the user to draw a transect line across the terrain surface using the controller trigger. The application computes the elevation profile along the transect and renders it as a two-dimensional graph overlaid on the terrain. This tool directly bridges the gap between immersive experience and cartographic representation: students can select two points they have physically visited in micro view and immediately see the quantitative cross-section connecting them (Sabah et al., 2025).
- **Height ruler:** A measuring tool that reports the real-world height of a selected terrain feature, expressed in actual metres above sea level rather than in-VR units. Whereas the height indicator reports the user's own elevation, the height ruler lets students measure features they observe, such as the relief of a valley wall, the prominence of a peak, or the depth of a gorge, and develop accurate intuitions about the real-world scale of what they are seeing.

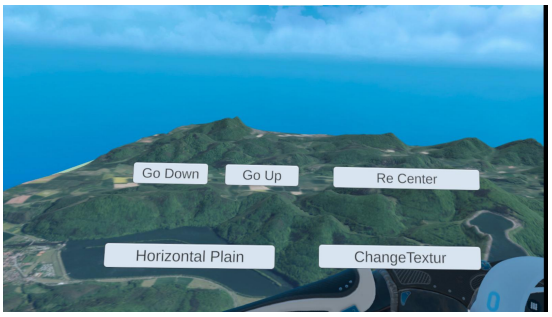


Figure 3. A subset of GeoVR's interactive tools, accessed through a menu attached to the user's virtual arm, keeping controls within easy reach during exploration.

4 Pedagogical Deployment and Early Experience

4.1 Multi-User Session Management

GeoVR is deployed as part of the fuelsME:App on Meta Quest 2 HMDs managed through Meta's App Lab distribution platform, which the fuelsME:Create framework uses to maintain separate release channels for development, educator, and public demo use (Mascher et al., 2024). This infrastructure is fully shared with the other Learning Spaces in the fuelsME ecosystem and requires no GeoVR-specific configuration.

Session isolation, the mechanism that prevents two concurrent seminar groups from sharing the same virtual room, is handled by the token system described in fuelsME:Create (Mascher et al., 2024). When a geography course session is registered, a unique token is generated and distributed to the enrolled students. Only HMDs presenting the same token join the same GeoVR session. This ensures that two courses using GeoVR simultaneously on the same server infrastructure cannot observe or disturb each other, which is essential for both the pedagogical experience and the integrity of any concurrent research data collection.

4.2 Observed Interaction Patterns

Early seminar deployments of GeoVR at *Anonymized for review* have allowed informal observation of how students interact with the application in practice. The first cohort consisted of twelve first-year geography students with high self-reported computer skills (M=4.25, SD=0.97 on a 5-point scale) and mixed prior VR familiarity (M=3.42, SD=1.51), with three students reporting little or no prior VR experience and six reporting high familiarity. We emphasise the methodological status of what follows: these are anecdotal impressions gathered by the attending educators during regular seminar sessions, without a systematic observation protocol, coding scheme, or formal analysis procedure. Given the small cohort and the informal setting, the patterns reported below should be read as formative feedback that motivates the evaluation programme in Section 5, not as empirical findings. With that caveat, several patterns are noteworthy.

Students in this cohort used the scale-switching affordance more than anticipated. Rather than spending extended periods in one mode before switching, they tended to alternate between micro and macro view as they tested ideas, forming an interpretation in macro view about the shape of a valley, descending into micro view to check it from the inside, and returning to macro to revise. This iterative pattern resembles the kind of inference cycle characteristic of geomorphological fieldwork. Whether it in fact reflects authentic disciplinary reasoning, rather than, for example, novelty-driven exploration of the mode-switching mechanic itself, cannot be determined from informal observation. We therefore treat it as a hypothesis: the planned evaluation (Section 5) will test it by correlating logged view-mode transitions with think-aloud data.

The collaborative dimension of GeoVR generated spontaneous interactions that the educators had not planned for. In one session, students began using the height indicator not as an individual measurement tool but as a way of coordinating joint attention: "I'm at 1,847 metres, can you see me from there?" This single episode is consistent with the form of collaborative sense-making that the literature on multi-user VR identifies as a distinctive affordance of shared virtual environments (van der Meer et al., 2023), and it illustrates the third design principle (Section 3) in use; whether such tool-mediated joint attention occurs systematically is a question for the planned evaluation.

The elevation profiler was the tool with the steepest learning curve in this cohort. Students required explicit instruction in how to interpret the profile graph, which is expected: the tool makes demands of cartographic literacy that not all first-year students possess. This observation has informed the design of the accompanying scenario materials, which now include a guided introduction to cross-section interpretation before students encounter the profiler in open exploration.

4.3 Limitations Encountered

Several practical limitations have emerged from early deployments. The Meta Quest 2's processing constraints impose a cap on terrain resolution that is occasionally visible as faceted geometry on steep slopes. This artefact does not impair the educational function of the application for most scenarios, but it reduces the credibility of the representation for students who are familiar with the actual terrain being modelled. Higher-resolution rendering on more capable hardware is a priority for future development.

The token distribution process, though straightforward from a technical standpoint, adds an administrative step for educators that is unfamiliar and has caused confusion in several sessions. A self-service booking interface that automates token generation and distributes it via the university's learning management system is under development.

Finally, GeoVR currently supports only static terrain: the temporal change tool described in the original feature specification has not yet been implemented. Dynamic comparison of terrain states across geological time periods remains a high-priority item in the product backlog and is expected to be completed in the next development cycle.

5 Research Agenda for Empirical Evaluation

GeoVR has been evaluated informally through observation and educator feedback, but a rigorous empirical evaluation programme has not yet been conducted. This section outlines the research questions that the consortium intends to pursue and the methodological approaches planned for each. The studies described here have not yet been pre-registered; the consortium intends to pre-register the study designs, hypotheses, and analysis plans on a public registry before data collection begins.

The primary research question concerns learning outcomes: does GeoVR-mediated terrain exploration produce measurably superior spatial cognition and geomorphological reasoning relative to traditional map-and-photograph instruction? Addressing this question requires a controlled study design comparing GeoVR and non-VR conditions on pre- and post-tests of spatial reasoning and dis-

ciplinary knowledge. (Gielstra et al., 2024) provide a useful methodological precedent for this kind of evaluation in a VR geoscience context.

A secondary research question concerns the specific contribution of the collaborative, multi-user design: does joint exploration of virtual terrain produce different learning outcomes than solo exploration? The literature on collaborative VR (van der Meer et al., 2023) suggests it should, but empirical evidence from geoscience contexts is sparse. GeoVR's architecture, which allows the multi-user feature to be selectively enabled or disabled at the scenario level, makes it unusually well-suited for an experiment that isolates this variable. A third research question concerns long-term retention: are spatial understanding gains from VR-based learning maintained over weeks and months, or do they decay at the same rate as gains from conventional instruction? (Allcoat and von Mühlenen, 2018) note that most VR learning studies measure immediate post-test outcomes; retention data is a gap in the literature that GeoVR evaluations will be designed to address.

Methodologically, the evaluations will combine quantitative outcome measures with qualitative data from think-aloud protocols during GeoVR sessions, post-session interviews, and analysis of in-session interaction logs. The log data, which records each user's position, tool activations, and view-mode transitions throughout a session, is a distinctive advantage of VR over traditional fieldwork: it provides a continuous, objective record of how students engaged with the terrain, which can be analysed for patterns that correlate with learning outcomes. This log analysis will also test the hypothesis raised by the informal observations in Section 4: if rapid alternation between micro and macro view reflects disciplinary inference rather than novelty-driven exploration, mode transitions should co-occur with interpretive talk in the think-aloud data and should persist beyond students' initial familiarisation with the application.

6 Conclusion

This paper has presented GeoVR as a design case study of a pedagogically grounded VR Learning Space built on the fuelsME:Create framework (Mascher et al., 2024). The framework provided both the organisational process for co-designing technology and didactics and the shared fuelsME:Core infrastructure for multi-user VR. Within that scaffolding, GeoVR's development could be directed at affordances specific to geographical education rather than at the generic infrastructure any multi-user VR application requires.

What this paper demonstrates are GeoVR's specific contributions: a DEM-based terrain pipeline that supports any geographic region without code changes, a dual-mode spatial navigation design that pairs immersive field experience with synoptic overview, and an interactive toolset that bridges immersive observation and cartographic representation. Its effects on learning outcomes, long-term retention, and collaborative learning remain open questions. The informal seminar observations are consistent with authentic geomorphological reasoning and have already shaped the accompanying scaffolding materials, but establishing these effects requires controlled studies. The next step is therefore a pre-registered evaluation combining outcome measures, think-aloud protocols, and in-session interaction logs.

The broader implication of this work is architectural as much as pedagogical. Building GeoVR on shared infrastructure rather than from scratch allowed development effort to remain focused on the discipline-specific affordances that differentiate the learning experience. Whether this layered approach scales to other domains and other institutions remains an open question, and one that will be tested as fuelsME:Core moves toward public release as an open foundation for use beyond the original consortium.

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