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Immersive VR Geovisualization for Landscape Restoration: From Meshes to Meaning

Marzia Gabriele

Politecnico di Milano, Dept. of Architecture, Built environment and Construction engineering (ABClab-GICARUS), Via Ponzio, 31, 20133, Milan, Italy – (marzia.gabriele@polimi.it)

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Abstract

Landscape restoration in semi-arid environments demands not only effective interventions but also communicative approaches that make complexity legible and foster ecological literacy. Immersive technologies such as Virtual Reality (VR) transform geospatial data into navigable environments, making processes tangible and transferable experiences. This study translates a remote restoration site in the Murcia region of Spain, characterized by limited accessibility and harsh conditions, into an immersive Virtual Reality geovisualization. A UAV structure-from-motion survey produced a high-resolution textured model that was geospatially situated with BlenderGIS (ESRI imagery over a 30 m digital elevation model) and then reconstructed in Twinmotion under a calibrated HDRI skydome. The scene is engineered for room-scale use with teleport-only locomotion and a uniform down-scale that enables hand-scale inspection of swales, ponds, ground cover, tree rows, and micro-topography. Three access points organize short narrated sequences that guide users from landscape overview to near-field readings, converting mesh into meaning. A pilot on Meta Quest 3 yielded encouraging signals: high presence and perceived realism, low discomfort, positive self-reported competence, and intent to re-engage. The pilot also surfaced technical priorities, including tighter blending between the VR layers, and bias-aware context. The contribution is a reproducible workflow that combines geospatial context and proxemic design to support spatial reasoning, knowledge transfer, and public communication. Strategically, the module offers a path toward a participatory, education-ready XR tool for regenerative practice, and a future platform for stakeholders, to support cognitive spatial reasoning and field-digital decision-making.

1. Introduction

Amid accelerating transformations in hybrid human–terrestrial systems, immersive media are increasingly mobilized as strategic instruments for education, knowledge exchange, and engagement. Location-based augmented-reality deployments demonstrate that playful spatial interaction can measurably reshape mobility patterns across diverse user groups (Althoff et al., 2016). In parallel, serious-games approaches appropriate core game mechanics—goal setting, feedback loops, and situated challenges—to catalyse environmental learning and pro-ecological behaviours beyond entertainment. In landscape and geography education, immersive 3D geovisualization has been shown to enhance spatial reasoning, ecological literacy, and collaborative problem-solving; even low-cost, desktop virtual environments developed in standard game engines increase representational realism and user motivation to interrogate site-specific processes (Carbonell-Carrera et al., 2021). Hybrid field–digital excursions further indicate that coupling interactivity with observation supports self-paced exploration, peer dialogue, and critical reflection (Koegst et al., 2022). At the same time, a recent systematic review consolidates evidence that VR/AR/MR can deliver measurable learning benefits across higher-education contexts while flagging implementation and evaluation shortfalls that require rigorous study designs (Balalle, 2025). Importantly, restorative and affective responses to virtual landscapes are not uniform: a mixed-design VR experiment shows that perceived restoration depends on the composition of landscape elements and varies across occupational cohorts, indicating that "green" alone is insufficient without attention to content and audience (Chen & Takatori, 2025). These practices and findings foreground the need for evaluation frameworks that align technological innovation with pedagogical intent and geographic fidelity (Papadimitriou, 2022), while recognizing that narrative and aesthetic framings condition how digital landscapes are perceived and remembered (Kühne, 2020). Advances in human-centred interaction design extend these opportunities to geospatial realism with adaptive content and personalized interaction (Wang et al., 2025). Extended Reality (XR) (Figure 1) spans the full "reality–virtuality" continuum, from Augmented Reality (AR) at the real-world end (digital overlays on physical scenes), through Mixed Reality (MR)—including Augmented Virtuality (AV), where virtual content predominates but co-exists with the physical—to Virtual Reality (VR) at the computer-generated end (fully synthetic environments). XR thus brackets the AR→MR/AV→VR range, parameterized by immersion, presence, and bidirectional interaction (Milgram & Kishino, 1994; Maas & Hughes, 2020; Andalib & Monsur, 2024). Recent participatory studies caution that VR appraisals of cultural ecosystem services (aesthetics, sense of place) can be systematically positively biased when situational context (e.g., anthropogenic noise, signs of neglect, "messy complexity") is under-modeled—an issue with implications for co-design and expectation management (Krauss et al., 2025).

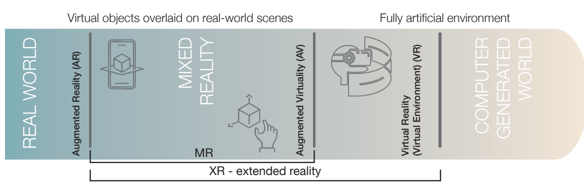

Figure 1. The reality–virtuality spectrum, adapted from Milgram & Kishino, 1994 and Andalib & Monsur, 2024.

Within this framework, the application presented here occupies the high-immersion VR end of the spectrum: a virtual, navigable reconstruction of Camp Altiplano (Murcia, Spain), a semi-arid landscape marked by soil degradation and hydrological stress.

Photogrammetry-derived, textured 3D landscape models (UAV–SfM) are integrated with BlenderGIS terrain context and deployed in Twinmotion with High Dynamic Range Imaging (HDRI) skydome, first-person locomotion/teleport, and micro-interactions. This configuration enables controlled exposure to otherwise inaccessible site conditions and embeds chronological interpretive pathways— "from mesh to meaning"—that explicate swales, ponds, ground cover, tree rows, and micro-topography as interlocking components of regenerative practice. Despite rapid growth of XR in design education, the supplementary role of XR-based immersion in learning remains comparatively under-evaluated, as underscored by mixed-methods studies of co-created VR modules in landscape architecture (Andalib & Monsur, 2024) and by higher-education syntheses calling for stronger assessment designs (Balalle, 2025). Longitudinal bibliometrics likewise reveal a theory–application imbalance in XR education, with high theoretical attention and fewer applied/evaluative studies (Xing et al., 2021). In parallel, evidence from VR assessments of green stormwater infrastructure shows that presence without careful modeling of situational context and multisensory cues may overstate perceived benefits, reinforcing the need for bias-aware design and evaluation in educational and participatory deployments (Krauss et al., 2025; Chen & Takatori, 2025). Accordingly, the VR module is configured for real-world evaluation: after use, participants complete a brief post-test and provide short, open-ended feedback. A separate outreach build supports public dissemination, allowing non-expert audiences to explore the experience. By positioning a geospatially precise, narrativized VR environment at the virtual end of the reality–virtuality spectrum, the study addresses the reported gaps in XR evaluation and establishes a replicable pathway for education and communication in landscape/geo-education (Table 1).

Mode	Representative studies examined	Key gaps highlighted
AR	Location-based AR & serious games shaping mobility/learning (Althoff et al., 2016); hybrid field–digital excursions (Koegst et al., 2022); evaluation needs in geo-education (Papadimitriou, 2022); synthesis of AR/VR/MR deployment and pedagogy in higher education (Balalle, 2025).	Sparse longitudinal learning metrics; outdoor tracking/fidelity constraints and teacher capacity issues (Papadimitriou, 2022; Balalle, 2025).
AV	Limited landscape-education exemplars; general XR pilots and trend analyses (Xing et al., 2021); higher-ed review noting few AV/MR evaluations (Balalle, 2025).	Very small evidence base; few comparative trials; pipeline scalability and replicability concerns (Xing et al., 2021; Balalle, 2025).
VR	Immersive geovisualisation improving spatial reasoning and motivation (Carbonell-Carrera et al., 2021); landscape communication/interpretation (Lange, 2001; Portman et al., 2015; Prisille & Ellerbrake, 2020); co-created VR modules showing positive learning signals (Andalib & Monsur, 2024); affective/cognitive effects in restorative-scene VR (Chen & Takatori, 2025); VR for participatory assessment of cultural ecosystem services in green stormwater infrastructure, with evidence of positive bias when situational context is under-modeled (Krauss, Rippy & Blumenauer, 2025).	Application trails theory; need for mixed-methods learning assessment and geospatial accuracy checks (Xing et al., 2021; Papadimitriou, 2022); bias-aware design for participatory VR (context, soundscape, "cues to care") to avoid over-promising services (Krauss et al., 2025).
	Position of this research	
VR	Placed at the high-immersion end of the spectrum. Deploys a UAV–SfM → BlenderGIS → Twinmotion pipeline for a geospatially faithful, narrated restoration site (Camp Altiplano), with HDRI skydomes, first-person locomotion/teleport, and micro-interactions. Designed for room-scale user tests (Meta Quest) and public dissemination. Addresses the theory–application gap (Xing et al., 2021) and evaluation calls (Papadimitriou, 2022; Andalib & Monsur, 2024), while incorporating bias-aware practices highlighted by participatory VR research (Krauss et al., 2025).	

Table 1. XR modes analyzed in landscape/geo-education and the position of the present research.

2. Methods

This section outlines the methodology leading to the development of the final Extended Reality (VR) environment in Twinmotion. The workflow progressed from a UAV-based aerial survey to structure-from-motion (SfM) photogrammetric reconstruction, followed by 3D textured-mesh optimization and geospatial contextualization.

The UAV campaign produced high-resolution nadir and oblique imagery that, when processed in Agisoft Metashape, yielded an orthophoto and DEM for the site together with a triangulated mesh and 8k texture atlas. Geospatial context was then assembled with the BlenderGIS add-on by combining ESRI satellite basemaps with the OpenTopography SRTM 30 m Digital Elevation Model, recreating the surrounding terrain at regional scale. The SfM-derived textured model and the BlenderGIS scene were subsequently imported into Twinmotion, where the Murcian Altiplano setting was reconstructed through HDRI skydome, calibrated materials, vegetation assets, light ambient animations, and annotated hotspots to ensure spatial coherence and didactic legibility. To accommodate the real-world test scale boundary, the Twinmotion scene adopts a proxemic micro-world strategy with a uniform down-scaling, teleport, short-narrated access points, camera-height offset, collision constraints, and shallow depth-of-field. The resulting VR-ready scene was deployed to Meta Quest 3 via the Meta Quest app/Air Link for in-lab evaluation and public dissemination (Figure 2, Table 2).

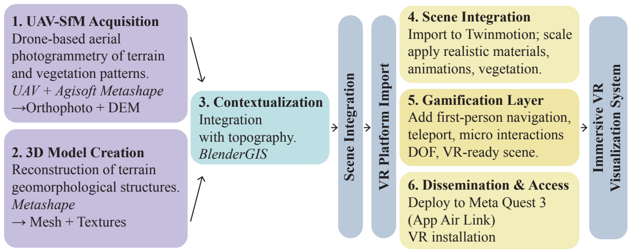

Figure 2. End-to-end workflow for the Camp Altiplano VR.

Step	Method	Tool / Output
1. UAV–SfM Acquisition	Drone-based aerial photogrammetry of terrain and vegetation patterns.	DJI UAV + Agisoft Metashape → Orthophoto + DEM
2. 3D Model Creation	Reconstruction of the terrain geomorphological structures.	Metashape → Mesh + Textures
3. Contextualization	Integration with topography.	BlenderGIS
4. Scene Integration	Import to Twinmotion; scale; apply materials, animations and vegetation assets.	Twinmotion
5. Gamification Layer	Add first-person navigation, teleport, Depth of Field (DOF) and micro-interactions.	Twinmotion → VR-ready scene
6. Dissemination & Access	Deploy to Meta Quest 3.	Meta Quest App Air Link VR installation

Table 2. Implementation steps, methods, and tool/outputs.

2.1 UAV–SfM Survey and Processing for Immersive Models

The UAV–SfM photogrammetric workflow was adapted to ecologically fragile and logistically challenging conditions, with the goal of generating a high-resolution 3D model optimized for VR integration. Recent research in UAV–SfM methods applied to landscapes, emphasizes that high-relief or morphologically complex environments demand enhanced image acquisition strategies to preserve 3D fidelity (Genzano, 2024). In such contexts, the integration of oblique imagery has proven critical for reducing data voids, maintaining vertical detail, and capturing topographic intricacies across all spatial dimensions (x, y, z) (Figure 3). The aerial survey was conducted using a DJI Mini 2 drone equipped with a 1/2.3" CMOS sensor (FC7303 camera), acquiring 4000 × 2250-pixel images at 8.12 mm/pixel ground sampling distance (GSD) from a flight altitude of 26 m Above Ground Level (AGL). Over 5,300 images were captured with ca. 80% frontal and ca. 70% side overlap, combining nadir and ~45° oblique views to enhance vertical surface visibility and model accuracy across swales, berms, and dead-soil areas (Table 3).

The acquisition strategy also aligns with best practices for ensuring photogrammetric completeness in non-planar terrain with slope discontinuities and geomorphological complexity (Nesbit and Hugenholtz, 2019).

2.1.1 VR-Ready Landscape Model: Optimization and Export

The UAV–SfM workflow produced a single, site-wide, high-resolution textured 3D model of the Camp Altiplano restoration area optimised for immersive deployment. Processing choices were tuned to maximise internal geometric coherence and visual fidelity while keeping the asset navigable in VR—i.e., balancing survey-grade detail with a polycount compatible with real-time rendering (cf. the need for spatial interrogation in landscape learning; Kühne, 2022). Depth-map generation and dense-cloud filtering were set to Low/Mild, yielding a dense cloud of 26,558,638 points with RGB (3-band, uint8) colours. Meshing produced 5,311,727 faces and 2,659,445 vertices with per-vertex RGB (3-band, uint8) and an 8,192 × 8,192 texture atlas (Table 4). The image network combined nadir and oblique views to capture multi-scalar landforms—slope breaks, swale geometry, berms and retention ditches, agroforestry rows, erosion channels, and early vegetative cover—mitigating "dead-ground" occlusions. Morphology was verified in the orthometric strips (Figure 3, bottom). The final asset was exported as textured OBJ.

Parameter	Specification
Drone platform	DJI Mini 2
Camera sensor	1/2.3" CMOS (FC7303)
Image resolution	4000 × 2250 pixels
Ground Sampling Distance	8.12 mm/pixel
Flight altitude	26 m AGL
Number of images acquired	ca. 5,300
Frontal overlap	ca. 80%
Side overlap	ca. 70%
Image acquisition angles	Nadir and ~45° oblique

Table 3. UAV Photogrammetric Survey Parameters.

Processing Stage	Parameter	Value
Depth Maps Generation	Quality	Low
	Filtering mode	Mild
Dense Point Cloud	Number of points	26,558,638
	Point colors	3 bands, uint8
	Depth maps quality	Low
	Filtering mode	Mild
3D Model	Faces	5,311,727
	Vertices	2,659,445
	Vertex colors	3 bands, uint8
	Texture	8,192 × 8,192

Table 4. SfM Processing Parameters

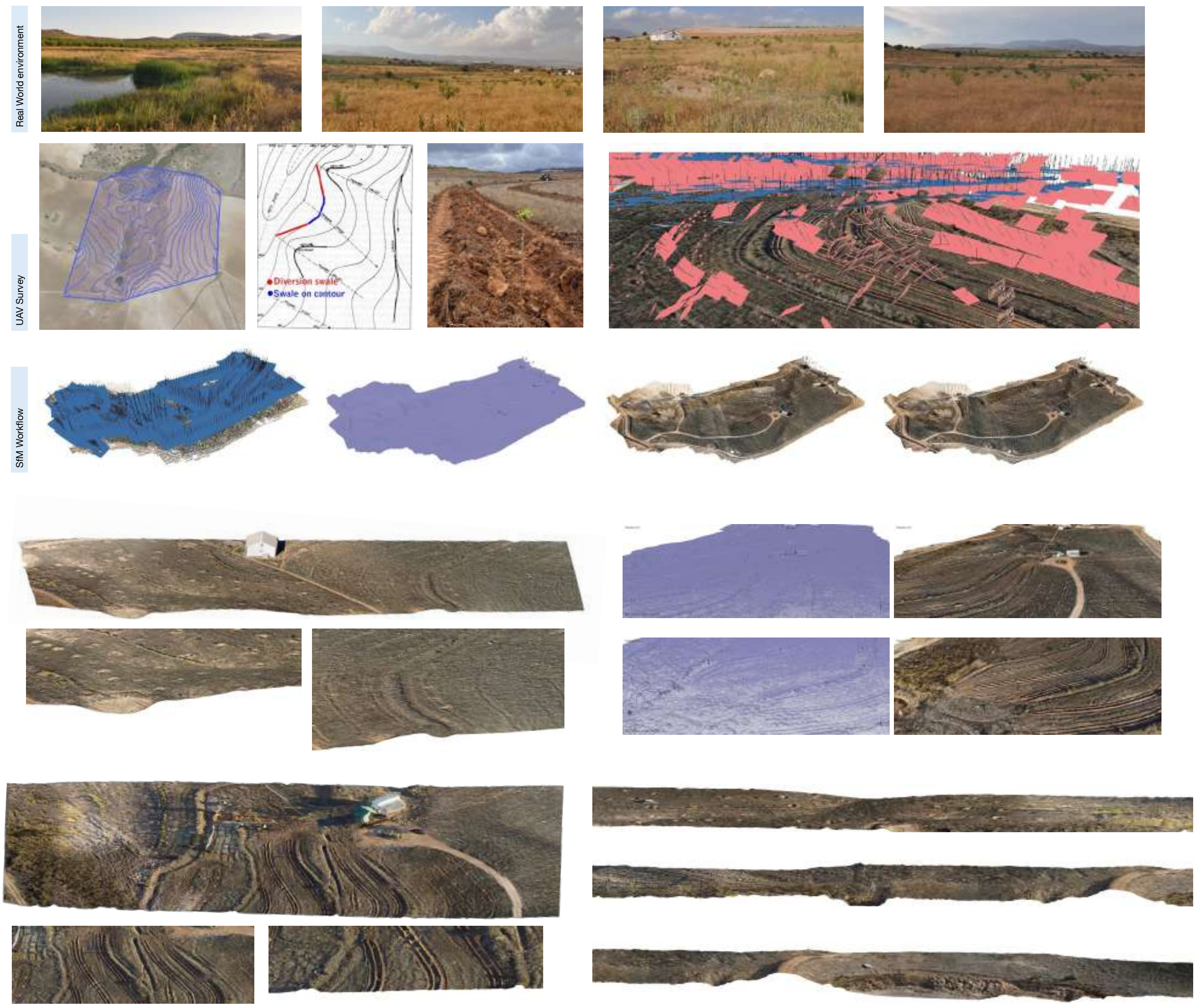

Figure 3. Top: real world site overview; contours/boundary, field photos, and SfM tie-point coverage showing flight overlap. Middle: SfM Workflow: point cloud, untextured mesh, and textured 3D reconstructions capturing swales, berms/terraces, roads, and micro-topography. Bottom: orthometric transects that document regenerative earthworks.

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2.2 Geospatial Base Layer Construction for VR

To situate the UAV–SfM reconstruction within its wider geomorphological setting, a geospatial context was built in Blender using the BlenderGIS add-on. A 1-arc-second (~30 m) Shuttle Radar Topography Mission (SRTM) Version 3.0 Digital Elevation Model (DEM) was retrieved via OpenTopography. SRTM v3.0 (NASA MEaSUREs) is the void-filled release that blends elevation from ASTER GDEM2, USGS GMTED2010, and the USGS National Elevation Dataset, improving completeness and consistency. The DEM was draped with ESRI World Imagery to produce a textured terrain of the Murcian Altiplano that preserves both topographic accuracy and visual realism. The terrain was then aligned and scaled to the high-resolution SfM mesh of the core survey area to ensure continuous elevations and seamless textures across datasets. For VR deployment in Twinmotion, the DEM terrain geometry was exported as OBJ (for robust mesh fidelity) and the BlenderGIS scene textures were exported as glTF to retain UV mapping. Inside Twinmotion, the glTF texture was reapplied to the OBJ terrain, yielding a fully textured, spatially coherent base landscape that frames the immersive experience (Figure 4).

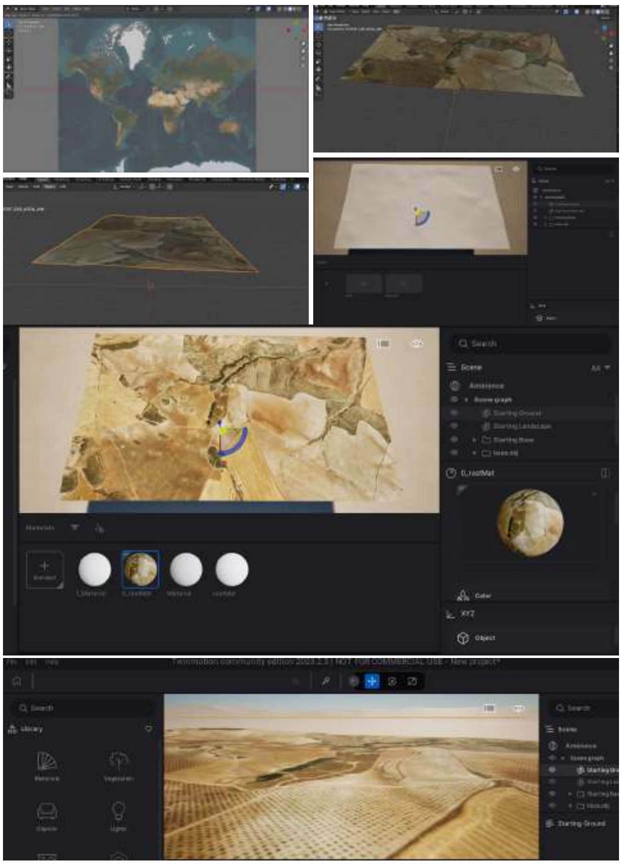

Figure 4. Workflow for geospatial context reconstruction and VR integration. (A) ESRI satellite basemap fetched in BlenderGIS; (B) SRTM v3.0 (30 m) DEM meshed and shaded in Blender; (C) textured DEM aligned with the SfM core model; (D) OBJ/glTF export and terrain import into Twinmotion for VR staging.

2.3 Proxemic Micro-World Design in Twinmotion (VR)

The VR implementation in Twinmotion operationalizes a metrically faithful transfer of the SfM- and BlenderGIS-derived environment—preserving native scale relations and spatial topology—into an XR “micro-world” that maintains usability, perceptual coherence, and proxemic validity. Proxemic and distance judgments are interrogated under immersion to evaluate how perceived scale, orientation, and spatial relations adapt when an extensive outdoor landscape is experienced under bounded physical affordances (estimated range of real-world test scale boundary: 5 m × 2 m and 4 m × 3 m). Preliminary trials on Meta Quest 3 (real-time spatial scanning, reconstruction, and tracking) informed scene parametrization for first-person exploration. To anchor human scale perception, a young regenerative almond tree is designated as the primary scaling referent; under a uniform 1:15 down-scale. At this scale, a 2.5 m young almond tree (Prunus dulcis) renders at ≈0.167 m (16.7 cm), enabling hand-scale inspection without compromising inter-element proportions (plots, berms, swales, ponds). Locomotion is teleport-only to minimize cybersickness. The camera height offset is set to 0.10–0.15 m to approximate eye level under 1:15. Inter-layer collisions are enabled (terrain/vegetation/walkable surfaces) to maintain physical plausibility, and moderate DOF (≈ f/2.4–f/3.2) reinforces miniature cues while preserving spatial legibility. Because the full ≈ 8 ha site becomes visually extensive at 1:15 (28.0 × 13.33 m), navigation is organized via teleport hotspots and narrated access viewpoints.

2.3.1 Skydome Configuration and Lighting

The immersive “Micro-World” scene is deployed inside a hemispherical skydome textured with a single 2:1 equirectangular (lat–long) HDRI, providing 360° azimuth and 180° zenith–nadir coverage; the horizon is leveled and the texture seam (U = 0) rotated out of view. The dome uses an unlit/emissive material (cast/receive shadows off) and a radius ≫ scene scale (≈10–50×) to suppress parallax. Illumination is implemented as a background-only skydome with procedural sun/sky, with solar azimuth/elevation matched to site geolocation, date, and a precise time of the day. HDRI assets are authored at 4096 px on-device (mipmapped, ASTC-compressed; EXR retained only for desktop look-dev), ensuring stable performance while preserving sky fidelity.

3. Results

This section reports the outcomes and applications of the methodological pipeline and summarizes initial user-test feedback. First, the instantiation of the UAV–SfM and BlenderGIS assets in Twinmotion is documented, yielding an immersive, narrativized micro-world of Camp Altiplano. Next, the role of proxemic and skydome configurations in supporting cross-scale spatial reasoning is demonstrated, together with preconfigured teleport “access” scenes that serve as user entry points. Finally, early Meta Quest 3 user-test indicators—presence, navigability, and comprehension of hydrological and agroforestry interventions—are presented, from which design implications for future development and iteration are derived.

3.1 From Mesh to Meaning: Landscape Restoration Process

The immersive scene fuses the UAV–SfM textured mesh of Camp Altiplano with a BlenderGIS geospatial base layer—ESRI World Imagery draped on a 30 m SRTM DEM—and calibrated HDRI skydome in Twinmotion, yielding a spatially coherent, photorealistic representation of the Noroeste Murciano (Figure 5). Oblique image acquisition increased redundancy and vertical coverage, improving reconstruction of geomorphological structure and reducing “dead-ground” occlusions; the model resolves horizontal and vertical variability—erosion channels, relief breaks, swale geometry, soil surface textures, and tree-planting patterns—and supports 360° interrogation from

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landscape overview to feature-level inspection (e.g., from the Agroforestry plot to the single young almond tree; Figure 6). Such multiscale interaction is associated with gains in spatial reasoning, memory, and the interpretation of complex landscape systems (Carbonell-Carrera et al., 2021; Prisille & Ellerbrake, 2020; Lange, 2001; Portman et al., 2015; Chen & Takatori, 2025). Within the HDRI skydome, the experience is explicitly scaffolded by five narrative layers that orient users prior to narration: the Base/Terrain (the 8-ha restoration surface with recognizable topography, paths, and land-use blocks), the Land Units (textures and micro-features such as soil colour, vegetation patches, and restoration plots), the Tree-in-the-Hand proxemic anchor (the portal connecting user and landscape), the Explorative Layer (teleport navigation across the micro-world), and the Atmosphere (volumetric light and a 360° dynamic sky) (Table 5). The Twinmotion scene preserves SfM-derived relief, swale morphology, and slope gradients while adding vegetation, hydrological infrastructure, and terrain refinements to communicate the restoration sequence; contour-aligned swales that intercept runoff and animated pond surfaces that convey retention and biodiversity functions express the hydrological logic (Figure 7). Seasonal and diurnal plausibility is maintained by matching solar azimuth/elevation and sky luminance to site geolocation, date, and time, reinforcing environmental realism.

Figure 5. The 360° immersive reconstruction of the Camp Altiplano restoration site in Twinmotion. The georeferenced SfM is embedded in BlenderGIS base layers beneath a calibrated HDRI skydome.

Figure 6. Agroforestry planting rows with the integration of young almond trees from the Twinmotion library, anchoring elements that connect user and landscape.

Figure 7. Nature-based ponds represented with animated water elements from the Twinmotion library and terrain textures from the 3D model.

The Base / Terrain	The 8-ha area of restoration terrain. Recognizable topography, pathways, and main land use blocks.
The Land Units	Show textures and micro-features — soil color, vegetation patches, restoration plots.
The Tree in the Hand	The anchor element; the "portal" that connects user and landscape.
The Explorative Layer	VR navigation area over the terrain; user teleports across the micro-world areas.
The Atmosphere	Volumetric light, 360° HDRI dynamic sky.

Table 5. VR micro-world layers and functions.

3.2 Multi-scale Narrative Sequences

Three teleport nodes are identified as the VR access points that structure the experience—Artificial Pond, Agroforestry System, and Swales—implemented as trigger colliders on a navigation-only surface and cross-linked so users can move in either direction while the default traversal follows the restoration chronology (Figure 8). A global 1:15 down-scale is applied; a young almond tree of ~2.5 m is rendered at ~0.167 m and serves as the primary scaling anchor, allowing hand-scale interrogation of adjacent features (plots, berms, swales, ponds) without distorting their relative proportions. Locomotion is teleport-only and confined to a real-world space boundary (5 m × 2 m). Camera pose is constrained to low-altitude, proxemic viewpoints (offset ≈0.10–0.15 m), with depth-of-field and per-layer collisions (terrain–vegetation–walkable). Exposure is tuned to preserve edge definition on fine relief while avoiding miniature artefacts. Lighting is driven by a background-only HDRI skydome with a procedural sun/sky aligned to the site's geolocation and date–time. The build runs on Meta Quest 3. The Agroforestry access exemplifies the multi-scale narration (Figure 9) (VR scale: 7.80 × 5.67 m): an elevated panorama first resolves row curvature and spacing relative to slope and catchment boundaries; subsequent mid-range viewpoints register ground-cover bands as the initial biotic stratum—delivering soil protection, nitrogen enrichment, and enhanced infiltration—thereby cueing progression to near-field inspection.

Figure 8. Overview of the three teleport access points that structure the narration in VR.

Figure 9. Multi-scale sequence for the Agroforestry VR access, frames illustrate the controlled progression.

Figure 10. Proximity navigation within the Agroforestry access (teleport reticle and controller visible)

Collectively, the configuration enables a deliberate within–field of view approach: participants progress from row-scale panoramas to hand-scale inspection of individual trees using first-person, teleport-only locomotion with a single controller, preserving proxemic consistency and visual continuity throughout the scene (Figure 10).

3.3 VR Pilot Test Evaluation (Meta Quest 3)

A first Camp Altiplano VR public demo was run under voluntary, anonymous participation with informed consent. Questionnaire eligibility was limited to individuals ≥13 years (children aged 7–12 were observed qualitatively only). Across the session, 50 people engaged with the VR build (28 children 7–12; 12 youth 13–25; 8 adults 26–60; 2 >60) (Figure 11). Of the 22 eligible participants, 7 completed the survey (ages: 13–25 = 4; 26–60 = 2; >60 = 1). The instrument captured presence/usability (Likert 1–7), discomfort/comfort (1–5), perceived competence pre/post on desertification/soil-health and EU Soil Mission topics (European Commission, 2024) (1–7), behavioural intentions (1–7), and overall appraisal (1–10).

Figure 11. Room-scale pilot sessions (Researchers Night in Milan, 26 September 2025): representative photos of participants interacting with the Twinmotion VR scene on Meta Quest 3.

Figure 12 summarizes the pilot test metrics: presence/usability indices were high: "sense of being there" = 5.6/7, realism = 5.1/7, ease of use = 5.9/7, controller/interaction clarity = 5.7/7. Discomfort remained low (nausea = 1.7/5; vertigo = 1.9/5; visual strain = 2.6/5). Self-rated competence increased across all topics, with the largest pre–post gains for community-led regeneration (+2.1), soil-regeneration practices (+1.8), and landscape-scale nature-based solutions (+1.7). Reported intentions were positive (seek more information = 5.7/7; discuss with others = 5.6/7;

change personal practices = 5.2/7; volunteer/participate = 5.0/7). Overall appraisal averaged 8.3/10 and likelihood-to-recommend 8.5/10. Most-cited strengths were scene detail/3D fidelity (5/7 selections), clarity of the restoration process (5/7), and teleport-only locomotion (4/7). The most frequent issues were tether/cable disconnections (3/7), transient controller-tracking loss (3/7), and "immersion too intense" for two participants (2/7). Children's sessions were short and highly engaged (median ≈ 3.8 min), with rapid mastery of teleport, frequent crouch/lean inspections, repeated play requests, no observed nausea, occasional headset removal due to intensity, and minor operational hiccups attributable to cable snagging.

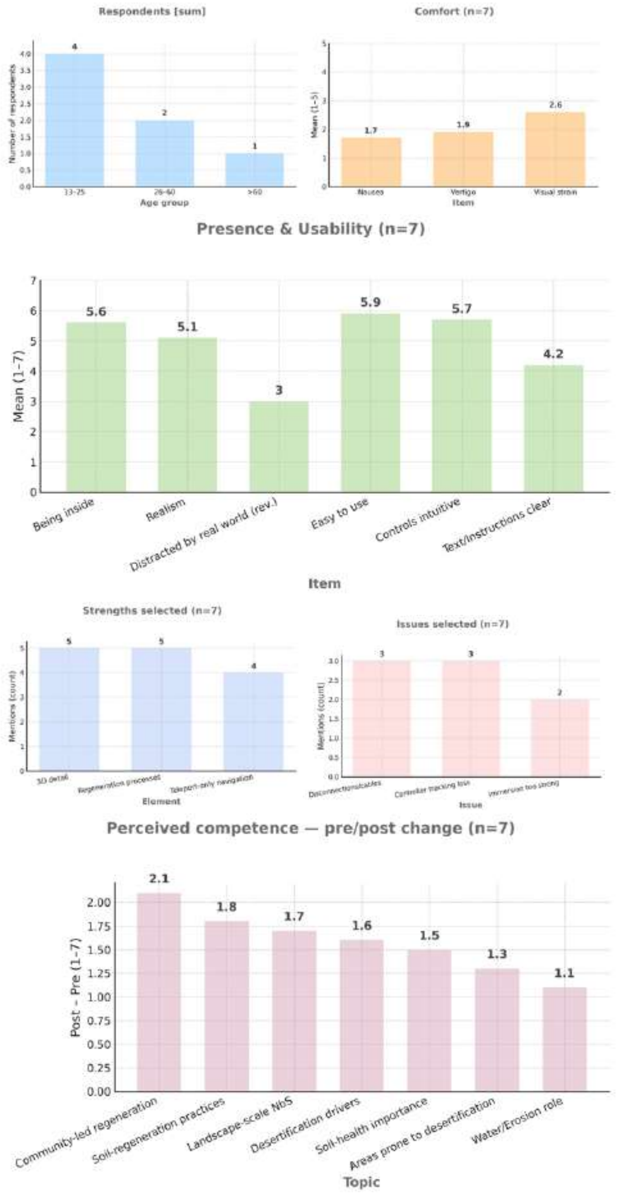

Figure 12. Summary metrics for the pilot (n = 7): presence/usability (1–7), discomfort (1–5), pre–post competence deltas on restoration/soil topics, behavioral-intention scores (1–7), and overall appraisal (1–10).

4. Discussion

This section discusses and interprets the technical and educational outcomes of the VR deployment, focusing on usability, spatial-reasoning, and narrative comprehension.

The proxemic micro-world met its primary design goals: users reported strong presence with low discomfort; teleport-only locomotion and the 1:15 global scale supported deliberate, hand-scale inspection; and the three narrated access points efficiently oriented participants to hydrological and agroforestry interventions. Questionnaire results corroborate these signals—mean presence/usability scores were high (e.g., "being inside" ≈5.6/7; ease of use ≈5.9/7) with low discomfort (nausea ≈1.7/5; vertigo ≈1.9/5), and self-reported competence increased across soil/regeneration topics (largest gains ≈+1.7–+2.1), indicating educational value (Figure 12). When users remained within the high-resolution SfM core, the combination of geometric fidelity, matched solar azimuth/elevation, and the HDRI yielded coherent depth cues and clear readings of swales, ponds, and tree-pit details—consistent with the intended learning outcomes. Beyond usability, overall effectiveness depended on how well three assets blended across scales: (i) the UAV–SfM high-resolution core mesh, (ii) the BlenderGIS base layer (ESRI imagery on a 30 m SRTM DEM), and (iii) the HDRI skydome. The strength of this triad is complementary function—the DEM/HDRI pair provides rapid, site-wide orientation, while the SfM mesh enables near-field interpretation. However, several participants teleported toward the BlenderGIS terrain because its extent invited exploration; being static, coarse (~30 m), and low-texture-resolution, it offered limited near-field detail and occasionally pulled attention away from the information-rich SfM zone. This exposed a multi-scale mismatch. Hand-off between layers also showed colour/illumination discontinuities and minor spatial seams at the SfM–DEM boundary, reducing immersion. Taken together, these results indicate a viable, engaging pipeline for landscape/geo-education; tightening multi-scale layer integration, and validating with controlled studies will convert the promising usability signals into robust, transferable evidence.

5. Future developments

To preserve the documented educational gains while strengthening technical coherence, future work will: (1) constrain the navigation mesh to the SfM footprint with soft boundary prompts and jump links between access points; (2) improve cross-scale blending by tone mapping and white balancing both layers to the HDRI skydome, feather-stitching the SfM edge into the DEM, and baking ambient occlusion for consistent shading; (3) raise base-layer fidelity by replacing the SRTM 30 m DEM/imagery with higher-resolution sources and by extending SfM coverage where feasible; and (4) continue UAV campaigns to update the Camp Altiplano terrain and vegetation so the core model remains current. In parallel, soundscapes and explicit "cues to care" will be added to reduce positive appraisal bias. Educationally, clearer seams, matched lighting, and appropriately constrained exploration should reduce distraction, keep users in information-dense areas, and tighten alignment between scientific content and perception—without sacrificing the observed strengths (high presence, easy onboarding, strong intent to re-engage and recommend). These steps position the system as a participatory, education-ready XR tool for regenerative practice and as a multi-stakeholder platform for wider deployment to support spatial reasoning and field–digital decision-making (Brumana et al., 2024; Gabriele et al., 2023), thereby aligning with the EU Soil Mission objectives (European Commission, 2024).

Conclusions

The study delivers a practical, scalable pipeline that translates survey-grade landscapes into proxemic, room-scale VR geovisualizations supporting hand-scale ecological reasoning.

Beyond visualisation, the system functions as a geo-educational instrument: narrated access points align attention with the causal structure of regenerative hydrological and agroforestry interventions, enabling knowledge transfer. Methodologically, it contributes a reproducible pattern—high-fidelity SfM core, geospatially coherent context, and controlled locomotion/scale—adaptable to other landscape settings. The results foreground design obligations for credible XR: cross-scale coherence, bias mitigation, and performance-aware asset management. Educational promise is evident but requires controlled evaluations linking presence/workload to learning and retention. Strategically, the approach can mature into a participatory XR tool, coupling field digital excursions with stakeholder co-interpretation to support cognitively active decision-making.

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