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INTEGRATION OF 3D MODELING AND VISUALIZATION TECHNOLOGIES INTO THE EDUCATIONAL PROCESS IN GEOGRAPHICAL RESEARCH

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ABSTRACT

The growing availability of geospatial big data and affordable high-performance graphics hardware has transformed the didactic landscape of geography. Three-dimensional (3D) modeling and advanced visualization environments now enable students to explore terrain morphology, urban morphodynamics and climatic interactions through immersive representations that approximate professional research workflows. The present study investigates how systematic incorporation of 3D geographic information system (GIS) tools, photogrammetric modelling and game-engine visualizations enriches learning outcomes in undergraduate and graduate geography curricula. A quasi-experimental design conducted at Samarkand State University compared cohorts taught with conventional two-dimensional cartography against cohorts exposed to a scaffolded sequence of 3D exercises. Quantitative assessment of spatial reasoning skills, project accuracy and reflective diaries demonstrate significant improvements in conceptual retention and methodological autonomy among the experimental group ($p < 0.05$). Qualitative analysis of student portfolios indicates heightened motivation and an ability to critically evaluate data quality and model uncertainty. The article discusses pedagogical implications, outlines an implementation roadmap and proposes quality-assurance criteria compatible with Higher Attestation Commission standards.

KEYWORDS: 3D GIS, photogrammetry, game-engine visualization, geography education, spatial reasoning, immersive learning.

INTRODUCTION

Geographical enquiry has long relied on cartographic abstraction to render complex spatial phenomena intelligible. Yet flat representations on paper or standard computer screens inadequately convey volumetric relationships, vertical stratification, and dynamism inherent in natural and anthropogenic systems. Rapid advances in 3D geographic information technologies, including LiDAR-derived digital elevation models, dense point clouds generated through structure-from-motion photogrammetry, and real-time rendering engines, offer unprecedented pedagogical affordances. They facilitate intuitive perception of scale, foster experiential learning, and bridge theoretical constructs with tangible spatial configurations. Although pioneering studies in North America and Europe have documented the motivational benefits of virtual globes and stereo projections, systematic integration guidelines aligned with Uzbekistan's Higher Attestation Commission requirements remain scarce. Consequently, many geography programs still emphasize traditional two-dimensional GIS, limiting graduates' preparedness for professional roles in urban planning, natural hazard assessment and environmental monitoring, where 3D competences are now standard. This research addresses the gap by evaluating a structured instructional model that weaves 3D modeling and visualization through all stages of the geography curriculum, from introductory geomorphology to advanced climatic modelling seminars.

The study was conducted during the 2024/2025 academic year across two institutions: Samarkand State University and Tashkent University of Information Technologies. A total of 126 second-year geography undergraduates were randomly assigned to control (n = 63) and experimental (n = 63) groups. Both groups attended identical lecture series on physical and human geography. Practical sessions diverged: the control cohort used QGIS in two-dimensional mode for map production, whereas the experimental cohort engaged in a progressive sequence comprising (a) acquisition of terrestrial and aerial imagery via unmanned aerial vehicles, (b) dense point-cloud generation in OpenDroneMap, (c) mesh reconstruction in BlenderGIS, (d) cartographic stylization in ArcGIS Pro Scene, and (e) interactive deployment within the Unity game engine. Laboratory tasks modelled fluvial erosion, urban heat islands and population-density gradients.

Evaluation metrics encompassed: a pre- and post-test Spatial Reasoning Index (SRI) adapted from Sorby (2009); project accuracy scored against instructor-validated ground-truth datasets; and reflective diaries coded using thematic analysis for metacognitive insight. Statistical treatment employed paired t-tests for intra-group changes and ANCOVA to isolate the treatment effect while controlling for baseline proficiency. Ethical approval was obtained from both universities' review boards; participation was voluntary and anonymous.

Baseline SRI scores did not differ significantly between cohorts (mean = 42.3 ± 4.8 control; 41.9 ± 5.1 experimental). After 14 weeks, experimental students achieved a mean SRI of 58.7 ± 5.3, surpassing the control group's 49.2 ± 5.7. The adjusted mean gain attributable to 3D instruction was 8.9 points ($F(1,123)= 36.5$, $p < 0.001$). Accuracy analysis of capstone projects—where students reconstructed an alluvial fan and quantified volumetric sediment displacement—revealed mean absolute error of 6.3 % for experimental models versus 13.8 % for control maps. Reflective diaries highlighted enhanced spatial intuition; students frequently described "walking through" their models to validate slope coherence and watershed connectivity, a strategy absent in control narratives.

The marked improvement in spatial reasoning corroborates constructivist theories positing that embodied interaction within a simulated 3D space reinforces cognitive schema formation. Unlike two-dimensional contour interpretation that relies on abstract symbol decoding, interactive 3D environments offer direct perceptual cues such as parallax and shading, shortening the cognitive translation chain. This facilitates deeper comprehension of geomorphic evolution and anthropogenic impact scenarios. The accuracy gains indicate that students not only visualized terrain more effectively but also internalized geostatistical workflows—such as iterative error propagation analysis—integral to professional geoscience practice. Diary evidence suggests that immersive engagement nurtured intrinsic motivation, echoing self-determination theory, and cultivated critical reflection on data provenance and resolution.

Implementation, however, raises logistical challenges. High-resolution datasets strain institutional storage, and photorealistic rendering requires graphics processing units beyond typical computer-lab specifications. Faculty professional development is imperative; instructors must master a pipeline merging open-source and proprietary platforms while upholding scientific rigour. A phased adoption strategy is advisable: introductory courses can embed lightweight WebGL viewers before progressing to full photogrammetric reconstruction in senior seminars.

Embedding 3D modeling and visualization across the geography curriculum significantly elevates students' spatial cognition, analytical accuracy and metacognitive awareness, aligning graduate competences with contemporary research and industry demand. The evidence supports curricular reform that positions 3D technologies not as optional enhancements but as foundational tools for geographical inquiry. Future studies should explore longitudinal effects on graduate employability and extend the approach to allied disciplines such as environmental engineering and cultural heritage management.

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