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Visualization Technologies in Geomorphology Education: The Role of 3D Models, GIS, Maps, and VR/AR in Supporting Learning Effectiveness

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ABSTRACT: Visualization technologies have become increasingly important in geomorphology education because they enable learners to explore complex landforms, spatial relationships, and relief-forming processes through more interactive and practice-oriented learning experiences. This study examines the educational role of three-dimensional (3D) models, digital and traditional maps, geographic information systems (GIS), and virtual and augmented reality (VR/AR) in supporting the learning of geomorphological concepts. A quasi-experimental approach was used to compare visualization-enhanced instruction with traditional teaching methods among university students studying geography. The assessment combined pre- and post-instruction testing, questionnaires, observation of the learning process, and evaluation of practical and project-based activities, while teachers' perceptions of visualization technologies were also considered. The experimental group, which used 3D models, GIS, and VR/AR tools, showed an increase in the average learning score from 62.4 to 84.7, corresponding to a 35.7% improvement. In comparison, the control group taught primarily through traditional methods improved from 61.8 to 70.2, representing a 13.6% increase. In addition, 87% of surveyed teachers positively evaluated the use of innovative visualization technologies. The findings suggest that visualization-enhanced instruction can support students' understanding of geomorphological processes, spatial and critical thinking, engagement, and independent research skills. At the same time, successful implementation depends on adequate digital infrastructure, teacher preparation, and students' digital competence. The study highlights the value of integrating visualization technologies with theoretical instruction and practical activities to support more interactive, analytical, and research-oriented geomorphology education.

Keywords: Geomorphology, Visualization technologies, Geographic information systems (GIS), Virtual and augmented reality (VR/AR), Spatial thinking.

I. INTRODUCTION

Geomorphology, which examines the processes shaping and transforming the Earth's surface, holds a significant position within the school geography curriculum. Through the study of geomorphological processes, students gain insight into the origins and evolution of landforms, the interaction between internal and external forces of the Earth, and the ways these processes influence ecosystems and human activities. In the context of climate change, the increasing frequency of natural hazards, and intensified human pressure on the environment, it becomes especially important to equip students with the skills to analyze landscape processes, anticipate their possible development, and adopt environmentally responsible attitudes.

Learning geomorphology goes beyond the acquisition of factual knowledge. It actively supports the development of critical and analytical thinking, as well as the ability to make well-reasoned decisions related to environmental protection and spatial planning. An understanding of geomorphological processes enables students to recognize the close links between natural systems and society, appreciate the principles of sustainable development, and better understand the challenges associated with managing natural risks. These include hazards such as floods, landslides, earthquakes, and soil erosion, which have direct social, economic, and environmental consequences [1].

Geomorphological processes are a combination of natural and anthropogenic factors that shape the Earth's relief. Endogenous processes (tectonic movements, volcanism, earthquakes) create large landforms, such as mountain systems, Earth faults, and volcanic formations. Exogenous processes (weathering, erosion, the activity of rivers, glaciers, wind, and the sea) shape and destroy the Earth's surface, forming valleys, canyons, dunes, and terraces. Anthropogenic processes (construction, mining, urbanization) create artificial landforms and amplify natural changes. Studying them using modern technologies (geographic information systems (GIS), 3D modeling, aerial photography) allows us to analyze the dynamics of changes and predict the consequences of natural and anthropogenic impacts [2]. Of particular importance in the study of geomorphology is the development of spatial thinking, i.e., the ability to perceive and analyze objects and processes in three-dimensional space. It helps to work with maps and models and to predict changes in the relief and their consequences. The use of visualization, digital maps, and GIS makes learning more visual and practice-oriented. Furthermore, it develops students' research skills and critical thinking, which is especially relevant in the context of the digital transformation of education [3].

The use of visual tools transforms learning from static to dynamic: animations allow you to demonstrate the movement of tectonic plates or volcanic eruptions, and interactive 3D models allow you to explore terrain, change perspective, and identify patterns. Working with digital maps and real geodata develops the ability to analyze information and draw conclusions. All this creates an effective learning environment where knowledge is formed through experience and independent research, increasing motivation and the quality of learning.

Cognitive visualization enhances understanding and memorization of information through clarity. Dual coding theory (A. Paivio) explains that combining text and images increases the effectiveness of perception, while the constructivist approach (J. Piaget, L. Vygotsky) emphasizes active interaction between students and the material, and cognitive load theory (J. Sweller) shows that visualization facilitates the understanding of complex processes [4–6]. In the context of geography, this is achieved through maps, 3D models, and GIS, which contribute to the development of spatial and critical thinking, as well as the skills to apply knowledge to solve practical problems (from predicting natural risks to assessing human impact on the environment). Thus, the relevance of this study is determined by the need to analyze the role of visualization in teaching geomorphology and to evaluate the effectiveness of various digital and visual technologies in improving the quality of students' learning.

Unlike many previous studies that investigate visualization tools in geography education separately, this study focuses on a comparative analysis of traditional maps, digital cartography, and geographic information systems (GIS) within the context of school-level geomorphology education. The main novelty of the study lies in integrating these approaches into a unified educational framework and examining their relative effectiveness in supporting students' spatial understanding and analysis of geomorphological processes. In contrast to existing research, which is mainly concentrated on individual technologies or higher education settings, this study emphasizes practical application at the school level and the development of students' spatial thinking through hands-on learning activities.

To address the identified gap in geography education research, this study is framed around the problem of insufficient integration and comparative evaluation of different visualization approaches in teaching school-level geomorphology. Although digital technologies such as GIS, 3D modeling, and VR/AR are widely recognized as effective educational tools, there is still a need to better understand how these approaches differ in supporting students' spatial thinking and conceptual understanding of geomorphological processes within school contexts. Therefore, the main objective of this study is to examine the pedagogical role of different visualization methods in geomorphology education and to clarify their contribution to students' learning development. The study is guided by research questions focused on how various visualization tools influence students' understanding of geomorphological processes, the development of critical and spatial thinking skills, and the effectiveness of traditional versus digital approaches. By addressing these questions, the study contributes to a more structured understanding of how visualization technologies can be meaningfully integrated into school geography education, moving beyond general claims about educational technology effectiveness toward a more context-specific and comparative analysis.

II. RESEARCH GAP AND CONTRIBUTIONS

Despite numerous reviews on the use of visualization in geography education, most prior studies have focused on descriptive or theoretical analysis without systematically measuring learning outcomes. The research gap lies in the lack of controlled empirical studies that quantitatively compare the effectiveness of visual learning tools in geomorphology education. Existing literature highlights the potential benefits of digital maps, GIS, and 3D modeling, but the actual impact on students' learning performance remains largely unverified.

This study addresses this gap by implementing a controlled experiment with experimental and control groups, allowing for a direct comparison of traditional versus visualization-enhanced teaching methods. The findings demonstrate significant learning gains in the experimental group (+35.7%) compared to the control group (+13.6%), providing concrete evidence of the effectiveness of visual tools in enhancing understanding of geomorphological processes.

Contributions of this study include:

- Empirical validation of visualization techniques in geomorphology education.
- Quantitative evidence of improved learning outcomes through interactive digital maps, GIS, and 3D models.
- Practical insights for educators seeking to integrate visualization tools into geography curricula to foster spatial thinking, critical analysis, and applied problem-solving skills.
- By explicitly quantifying learning improvements, this research moves beyond prior literature reviews, offering a measurable and pedagogically actionable contribution to the field.

III. LITERATURE REVIEW

Visualization occupies a central place in contemporary geography education, particularly in the teaching of geomorphology, where students are required to comprehend complex spatial structures and continuously evolving processes. Educational psychology provides a strong theoretical foundation for this approach. For instance, A. Paivio's dual coding theory [4] suggests that information is learned more effectively when verbal explanations are supported by visual representations. Similarly, the constructivist perspectives of J. Piaget and L. S. Vygotsky highlight the importance of students' active engagement with models, diagrams, and visual materials, enabling them to construct knowledge through meaningful interaction. [6] From the standpoint of J. Sweller's cognitive load theory, visual representations help reduce mental overload when studying complex phenomena, thereby making learning clearer and more accessible [5].

In recent years, rapid advances in digital visualization have significantly expanded the possibilities of geography education. Technologies such as geographic information systems (GIS), three-dimensional modeling, and virtual and augmented reality (VR/AR) are increasingly being integrated into the learning process. Studies indicate that 3D terrain models, often created using digital elevation models (DEM), substantially enhance students' spatial reasoning and support a clearer understanding of the interaction between internal and external geomorphological processes [3]. GIS tools allow learners to work with authentic spatial data, fostering analytical thinking and encouraging independent research [7]. VR and AR technologies offer immersive learning experiences by enabling the visualization of landforms in motion and the simulation of hazardous events such as volcanic eruptions, landslides, and floods, which increases students' research interest and motivation [8].

A growing body of empirical evidence confirms the educational value of visualization in geography instruction. Research by Czimre et al. [9] demonstrates that interactive maps and 3D models significantly enhance student engagement and deepen understanding of relief formation processes. Similarly, the implementation of AR applications in school settings has been shown to boost learning motivation and improve spatial analysis skills [10]. Overall, visualization not only supports more effective learning, but also promotes critical thinking, predictive abilities, and independent inquiry skills that are essential for understanding the impacts of climate change and increasing human influence on the natural environment.

Visualization in teaching geomorphology is an innovative and effective tool that helps develop students' spatial thinking, analytical skills, and research skills. Modern technologies (GIS, 3D models, VR/AR) not only make learning more visual and interactive, but also encourage schoolchildren and students to apply their geographical knowledge to solve real-world problems, from predicting natural hazards to sustainable land-use planning [11]. Moreover, the use of such technologies contributes to the development of critical thinking, the ability to work with large data sets, interdisciplinary analysis, and independent research, which increases students' preparedness for professional and scientific activities in the modern digital society.

However, most previous studies have examined these visualization tools individually and have primarily focused on higher education contexts. Fewer studies have conducted a comparative evaluation of different visualization approaches in school-level geomorphology education.

IV. MATERIALS AND METHODS

1. ETHICAL CONSIDERATIONS

All participants provided informed consent prior to taking part in the study, and participation was entirely voluntary. Test data were anonymized to protect students' privacy, and all information was stored securely with access limited to the research team. These measures ensured that the study adhered to ethical standards for educational research and safeguarded the rights and confidentiality of all participants. For project and practical task scoring, inter-rater reliability was assessed where applicable. Each assignment was independently evaluated by two raters, and agreement was quantified using appropriate metrics such as Cohen's kappa or intraclass correlation. High levels of inter-rater reliability ensured that scoring was consistent and minimized potential bias from individual evaluators.

Traditional methods of teaching geomorphology, based on verbal explanations, texts, and traditional paper maps, often prove insufficient for conveying complex concepts and processes. Abstract descriptions of geomorphological phenomena such as tectonic movements, volcanism, or erosion processes can be difficult to understand without visual examples. This creates a need for modern visual tools such as 3D models, digital maps, geographic information systems, and animations, which help students better understand the dynamics of geographic processes. Visualization not only promotes clarity, but also actively engages students in the learning process, improving their ability to perceive and analyze information [4–6].

The study was conducted with school students who were organized into groups based on different instructional approaches, including traditional map-based teaching, digital cartography, and GIS-supported learning activities. Grouping was determined according to the existing educational setting and instructional conditions. To ensure the validity of comparisons, baseline characteristics of the groups were checked prior to the instructional intervention. These checks focused on students' prior knowledge and academic performance in geography, and confirmed that the groups were comparable at the beginning of the study.

The reliability and validity of the research instruments were ensured through several procedures. The assessment tools, including tests and practical tasks, were developed in alignment with the study objectives and curriculum content in geomorphology. Content validity was established through expert review by geography educators, ensuring that the tasks accurately reflected the key concepts and skills being assessed.

Reliability was supported by the use of consistent evaluation criteria and standardized scoring rubrics applied across all groups. In addition, inter-rater reliability was considered in the evaluation of practical assignments, contributing to the consistency and objectivity of the assessment process.

2. CARTOGRAPHIC METHODS

2.1 Traditional and Digital Maps

Maps remain the fundamental means of representing geographic features and processes in a visual form. Although traditional paper maps offer limited interactivity, they continue to play an essential role in helping students grasp core geographic concepts, including scale, landforms, water systems, climate zones, and political or natural boundaries. Working with printed maps supports the development of spatial awareness, map-reading skills, an understanding of geographic coordinates, and the ability to orient oneself in real space. At the same time, technological progress has led to the widespread adoption of digital maps in educational practice. Unlike static paper maps, digital maps provide interactive and flexible ways of exploring geographic information: students can zoom in and out, switch between different layers, apply various cartographic projections, and actively engage with spatial data [12]. These tools enhance the accuracy and clarity of information, make learning more adaptable, and allow for the timely updating of data, for example in relation to natural hazards or ongoing climate change.

Geographic information systems (GIS) further expand the educational potential of cartography. GIS are advanced platforms designed for the collection, storage, analysis, and visualization of spatial data. In educational settings, they are used to illustrate complex spatial patterns and to support the analysis of geomorphological processes. Through working with GIS, students can explore how natural phenomena such as erosion, volcanic activity, or climate variability shape landscapes and influence environmental conditions [13]. This hands-on engagement with real geospatial data not only deepens conceptual understanding but also strengthens analytical thinking and research skills, preparing learners for more advanced studies and practical applications in geography and related fields. The main capabilities of GIS for the educational process are:

- Analysis of terrain changes: GIS allows you to track the dynamics of landscape changes over time, for example, to analyze the consequences of earthquakes or erosion processes.
- Creation of thematic maps: With GIS, students can create maps that reflect various aspects of geomorphological processes, such as flood risk areas or regions with high seismic activity [14].
- Working with spatial data: Students learn to work with coordinates, geographic layers, and to integrate data from different sources, which develops their skills in working with big data and mapping platforms.

Using GIS helps improve students' analytical and critical thinking skills by allowing them to work with real geographic data, explore hypotheses, and draw conclusions based on analysis.

2.2 Analysis of Topographic Maps and Aerial Photographs

Topographic maps are the primary tool for detailed representation of relief, natural and man-made objects, as well as for determining the spatial relationships between various elements of the landscape. Such maps clearly show relief contours, elevations, water bodies, roads, cities, and other features, helping students understand how geographic factors influence the formation of relief features and their changes [3,12].

The analysis of aerial photographs and satellite images adds another important element to the study of geomorphology. These visual resources provide insight into real changes in the Earth's surface, such as damage from earthquakes, changes in erosion, deforestation, urbanization, and more. Aerial photographs, especially in the context of new image processing technologies, can be used to create detailed relief maps that show not only natural features but also anthropogenic changes. Aerial photographs and satellite images allow students to conduct spatial analysis by comparing changes in images with data on geographical processes, which helps develop critical thinking skills, analytical abilities, and an understanding of the impact of various factors on relief changes.

The combination of traditional and digital maps, as well as the use of GIS and aerial photographs, provides a multifaceted approach to the study of geomorphological processes and gives students a deep understanding of the dynamics of changes in the Earth's surface. This approach allows for the integration of different types of data and representations of geographical phenomena, which contributes to a comprehensive understanding of geomorphology. On the one hand, traditional maps, with their clear and understandable projections, help to form basic ideas about relief and spatial relationships. On the other hand, digital maps and GIS make it possible to work with up-to-date data, identify trends, and predict changes in real time [15].

The use of aerial photographs and satellite images allows us to observe changes in landscapes from above and over longer periods of time, which is especially important for analyzing processes such as erosion, deforestation, or the consequences of natural disasters. This helps students see in practice how geomorphological processes change the Earth's surface, which greatly deepens their understanding of these processes and their connection to human activity. Furthermore, this approach encourages students to participate in research activities and motivates them to work independently with cartographic and geospatial data, which develops their critical thinking and analytical skills [16]. As a result, students not only acquire knowledge about geomorphology, but also gain the practical skills necessary to work with modern digital technologies and solve complex problems in the fields of geography and ecology.

3. 3D TERRAIN MODELS

3D modeling and visualization of relief play an important role in modern geography education. Thanks to 3D technologies, it is possible to more accurately and clearly represent geomorphological processes, which are an important part of the school curriculum [17]. These technologies cover both physical relief models and digital 3D modeling, which improve perception and deepen understanding of relief-forming processes.

4. PHYSICAL RELIEF MODELS

Physical relief models are three-dimensional physical representations of the Earth's surface that can be used to demonstrate geomorphological processes. Such models can be made from various materials, such as plaster, plastic, or metal. They are often used in educational institutions to demonstrate the processes of weathering, erosion, the formation of valleys, mountain ranges, and other natural phenomena [17].

5. MATERIAL-BASED RELIEF MODELS

For example, plaster models can be used to demonstrate changes in relief under the influence of erosion or volcanic activity with the help of water or sand. These physical models help students see how various natural processes interact in real time [17].

6. DIGITAL 3D MODELING

Unlike physical models, digital 3D terrain models can be constructed using computer programs and technologies. Data obtained from GIS (geographic information systems), satellite images, and digital elevation models (DEM) are used to create such models. An example is the creation of three-dimensional terrain models from elevation data, such as DEM files, which can be used to display the characteristics of the Earth's surface in detail. These models have high resolution and allow for the visualization of complex geographical objects and processes, such as mountain ranges, river basins, glacial features, etc [17].

7. VIRTUAL AND AUGMENTED REALITY IN THE STUDY OF TERRAIN

7.1 Virtual Reality (VR) in Geography Education

Virtual reality offers unique opportunities to create immersive educational scenarios in which students can "travel" across the terrain and observe geomorphological processes in real time. Virtual reality allows students to explore the planet's relief from different angles, for example, moving through mountains, descending into volcanic craters, or passing through river valleys [8,9].

A. Software for Creating Virtual Terrain Models

There are platforms and programs, such as Unity and Unreal Engine, that are used to create virtual worlds. With their help, you can create interactive 3D landscapes where students can study the dynamics of natural processes, such as tectonic movements, volcanism, or climate change. For example, some schools already use specialized VR software and apps in which students wear headsets and walk through virtual 3D models of real geographical objects. This not only improves their understanding of theoretical aspects, but also develops their spatial thinking [8,9].

Augmented reality (AR) is a technology that puts virtual objects into the real world. In the context of geography education, it can be used to superimpose 3D models of terrain onto real maps or landscapes [18].

B. Using AR to Visualize Geomorphology

The use of AR in school geography courses allows, for example, the relief of a region to be displayed on a map in 3D format or to see how geomorphological processes such as erosion or changes in the shape of rivers change in real time. Students can interact with these models in real time, making learning more engaging and visual [18].

C. AR Software and Apps

Computer and mobile apps with AR, such as Google Earth, can integrate 3D terrain models into real geographical maps. For example, you can superimpose layers with detailed information about landforms or current geomorphological changes such as avalanches, earthquakes, and volcanic eruptions [18].

7.2 Creating Interactive Geomorphological Models

Interactive geomorphological models not only encourage students to actively participate in the learning process, but also develop their analytical skills and ability to predict outcomes. By allowing them to change terrain parameters such as elevation, slope, water flow, or soil type, students can observe in practice how these changes affect the formation and development of various geographical features. This practical research helps students understand the relationships between natural processes such as erosion, weathering, tectonic movements, and their consequences for the environment and human activity. Importantly, such models help not only to explain but also to predict possible changes in the future, which develops students' critical thinking skills and their ability to solve environmental and social issues [19].

The use of interactive models allows for the integration of interdisciplinary connections into teaching, for example, with ecology, biology, or climatology, broadening students' horizons and providing a holistic view of the processes taking place on the planet. Creating 3D terrain models with Python opens up a wide range of possibilities for visualizing geomorphological processes and helps students understand complex geographical phenomena more effectively. The Matplotlib library with the mpl_toolkits. mplot3d module provides an easy way to build basic 3D graphs, allowing you to create static relief visualizations. However, for more complex and interactive visualizations that may include model manipulation, viewing angle changes, and scaling, Plotly or PyVista should be used. These libraries provide more flexible options for creating dynamic and customizable 3D terrain models that support user interaction.

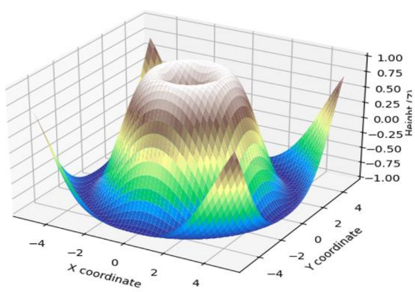

FIGURE 1. Interactive 3D terrain model.

- Plotly allows you to build interactive charts that can include both terrain and additional data layers, such as temperature, humidity, or seismic activity. This makes it possible to create rich multimedia models that can be used for deeper analysis of geomorphological processes.

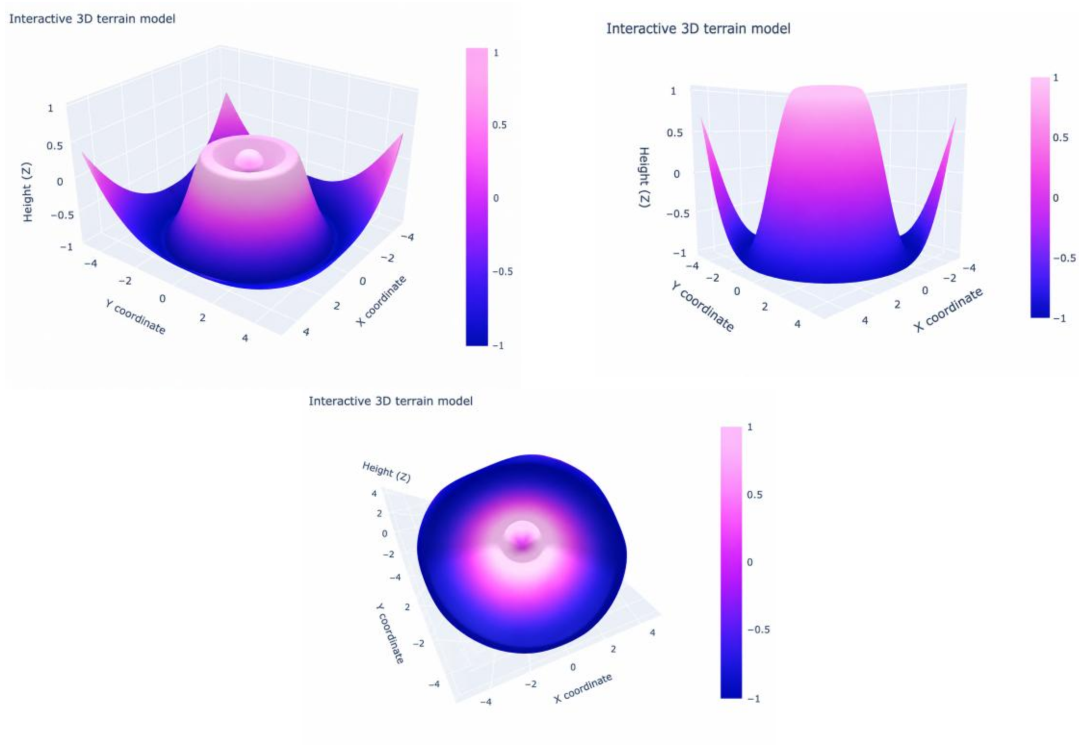

FIGURE 2. Interactive 3D terrain model.

- PyVista offers more advanced tools for processing 3D data, especially using terrain data obtained from digital elevation models. This library provides functions for creating complex 3D meshes, visualizing geographic objects with high detail, and visualizing various geophysical characteristics.

Using Python and similar libraries lets you make dynamic educational tools that make learning more interactive and engaging, and give students the chance to not only observe but also actively interact with geomorphological models. It helps students to understand and absorb the material better.

7.3 Interactive Models Using GIS and 3D Technologies

A. GIS (Geographic Information Systems)

GIS plays an important role in creating interactive maps and terrain models. With GIS, you can create multi-layered maps that display terrain, data on climate, ecosystems, and land use [7,20]. Software such as QGIS allows students to analyze terrain by overlaying different layers, such as satellite imagery, contour lines, and digital elevation models [7].

B. 3D models for analyzing terrain changes

Using 3D software such as Blender, SketchUp, or ArcScene allows you to create detailed terrain models that can be explored and modified. These models help students understand how various geomorphological processes (for example, erosion, soil settlement, glacial action) affect terrain over time [17,19].

C. *Interactive apps*

For a deeper dive into the topic, you can create interactive mobile apps and websites that allow users to change terrain parameters, such as slope, soil type, or climatic conditions, and observe the results of these changes. The use of 3D terrain models and modern technologies such as virtual and augmented reality, as well as interactive apps and GIS, greatly improves the perception of geographical processes. These innovative approaches allow students not only to understand but also to actively explore the dynamics of relief changes, which contributes to the development of their critical thinking and analytical skills [20].

To ensure methodological rigor, the study clearly defines the composition of experimental and control groups and describes the procedures used for group assignment. Participants were allocated using controlled methods to enhance comparability, and baseline equivalence was assessed to confirm that both groups started from similar levels of knowledge and skills. These measures provide a robust foundation for interpreting the observed effects of visualization-enhanced instruction, minimizing potential biases and strengthening the validity of the findings. All statistical analyses were performed using standard procedures. Pre–post differences within and between groups were assessed using appropriate tests (e.g., t-tests or non-parametric equivalents), after verifying assumptions such as normality and homogeneity of variances. Corrections for multiple comparisons were applied where necessary to control the family-wise error rate, ensuring the robustness and reliability of the results.

The study quantified the "dose" of technology exposure by recording the number of hours each student engaged with GIS, 3D models, and other visualization tools per week. Dose–response relationships were then examined to assess whether increased time spent using these tools was associated with greater learning gains, providing a more nuanced understanding of the impact of visualization-enhanced instruction.

V. EMPIRICAL STUDY OF THE EFFECTIVENESS OF THE APPROACH

An empirical study was conducted to evaluate the effectiveness of visualization technologies (3D models, maps, GIS, and VR/AR) [21,22] in teaching geomorphology and their impact on the development of students' critical and spatial thinking. The study involved students of a pedagogical university studying geography, as well as teachers using both traditional and innovative teaching methods. The methodology included systematic observation of the learning process, analysis of the completion of project and practical tasks, as well as a survey of participants to identify their perception of the usefulness of digital tools. The results of the study made it possible to determine the impact of visualization technologies on the assimilation of educational material, the formation of research skills and competencies, and confirmed the potential of integrating such tools to modernize pedagogical practice and improve the quality of education in the field of geography.

1. *ASSESSMENT METHODS*

- Testing was used to identify the level of knowledge on key topics in geomorphology before and after the use of visualization technologies.
- Questionnaires were used to assess students' subjective perception of innovative teaching tools, their level of engagement and motivation.
- Observation of the learning process made it possible to identify changes in the dynamics of academic performance and activity in class.
- A comparative analysis of the results of the control and experimental groups allowed us to establish differences in the effectiveness of traditional and innovative approaches.

The research methodology was based on a combination of quantitative and qualitative methods, which provided a comprehensive assessment. Quantitative data (test results and questionnaires) were statistically processed, while qualitative data (observations, interviews with teachers) were analyzed in terms of their content. Thus, the empirical study made it possible to evaluate the effectiveness of using visualization in teaching geomorphology both in terms of improving academic performance and in terms of motivating students and developing their spatial thinking.

Table 1. Dynamics of material assimilation and student motivation levels.

Group	Average score before application of the approach (out of 100)	Average score after application of the approach (out of 100)	Increase (%)	Level of motivation
Experimental group (using 3D models, GIS, and VR/AR)	**62.4**	**84.7**	**+35.7%**	High
Control group (traditional methods)	**61.8**	**70.2**	**+13.6%**	Average
Teachers (performance evaluation, % of positive reviews)	–	–	–	**87%**

The table shows data on the academic performance of students in educational programs 6B01511 "Geography–History" and 6B01510 "Geography" at the Kazakh National Women's Teacher Training University. The experimental group consisted of students majoring in 6B01511 "Geography–History", whose training actively used innovative visualization technologies: 3D modeling, geographic information systems (GIS), and VR/AR elements.

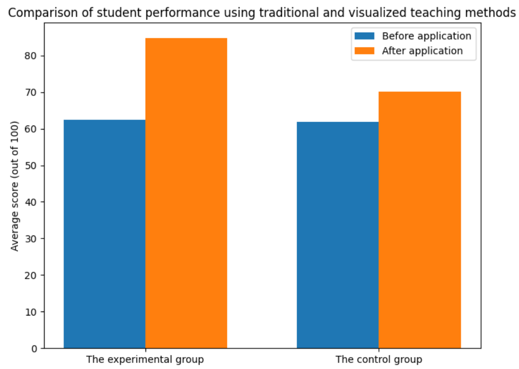

FIGURE 3. Comparison of student performance using traditional and visualized teaching methods.

The control group consisted of students majoring in 6B01510 "Geography", whose training was based primarily on traditional teaching methods. A comparative analysis shows that the experimental group's average score increased from 62.4 to 84.7, which corresponds to an increase of +35.7%, and was accompanied by a rise in the level of academic motivation to high. The control group showed more modest dynamics: the average score increased from 61.8 to 70.2, which corresponds to an increase of +13.6%, while the level of motivation remained at an average level.

The data obtained indicate that the use of visualization and modeling technologies significantly increases the effectiveness of the educational process and contributes to a deeper understanding of the educational material compared to traditional teaching methods. An additional survey of teachers showed that 87% of respondents positively assessed the effectiveness of introducing innovative educational technologies. This confirms not only their potential to improve the quality of learning, but also the willingness of teachers to integrate them into the educational process. Thus, the results of the study demonstrate that the use of 3D models, GIS, and VR/AR in teaching geomorphology is a more productive approach compared to traditional methods.

This diagram clearly demonstrates a comparison of the learning outcomes of students in two groups, experimental and control, before and after the application of different teaching methods. Experimental group (using 3D models, GIS, and VR/AR): the average score increased from 62.4 to 84.7, reflecting a significant increase in performance (about +35.7%). Control group (traditional teaching methods): the average score increased from 61.8 to 70.2, which corresponds to a more moderate increase (+13.6%).

The diagram shows that the use of innovative visualization technologies is significantly more effective in improving learning outcomes and student motivation than traditional methods. This indicates that traditional methods, although they provide certain positive results, are inferior in effectiveness to modern tools focused on visualization, interactivity, and practical involvement of students. The use of 3D models, GIS, and VR/AR contributes to a deeper understanding of the processes and phenomena being studied, as students can not only perceive information theoretically, but also observe its implementation in a visual or interactive form [23]. Furthermore, such technologies have a positive effect on cognitive activity, critical thinking, and independence in learning. Thus, visualization tools can be considered not just as an auxiliary tool, but as a key factor in improving the quality of the educational process and its compliance with modern requirements.

VI. RESEARCH RESULTS

Examining geomorphological changes within the learning process plays an important role in developing students' critical thinking skills. By analyzing landscape transformations, learners begin to recognize clear cause-and-effect relationships between natural processes and human activities. Working with maps, three-dimensional models, and GIS-based data enables students not only to observe and document changes in relief, but also to thoughtfully evaluate their implications for ecosystems and human life. Such learning activities encourage students to compare evidence, develop and test hypotheses, anticipate possible outcomes, and suggest alternative solutions. These processes directly support the formation of critical thinking while simultaneously strengthening analytical and research skills, spatial reasoning, and digital literacy. As a result, students become better prepared to apply their knowledge in interdisciplinary and practice-oriented contexts, enhancing their professional readiness and independence when addressing complex real-world problems [24].

The integration of digital tools further expands these educational opportunities by enabling multi-variant analysis and modeling. Through simulation and data-driven exploration, students gain a more comprehensive understanding of geomorphological processes and their dynamics. This experience supports the development of independent research skills and helps learners transfer theoretical knowledge into practical applications. At the same time, it reinforces interdisciplinary connections between geography, ecology, history, and the social sciences [25]. Ultimately, the use of advanced digital technologies promotes systematic and critical thinking, the ability to work with large and complex datasets, and informed decision-making in natural, anthropogenic, and socio-economic contexts. These competencies significantly enhance students' academic and professional potential, as well as their preparedness for scientific inquiry and problem-solving in a rapidly changing world [26].

Comparative analysis of the results of students using traditional and analytical teaching methods. The comparison results showed that students in the experimental group, where analytical methods were used (visualization of geomorphological processes using GIS, 3D models, and VR/AR), demonstrated a greater increase in academic performance and motivation compared to the control group, which was taught using traditional methods. The average score in the experimental group increased by 35.7%, while in the control group it increased by only 13.6%. An increase in interest in the subject and readiness for independent research was also noted among students in the experimental group. These results confirm the effectiveness of integrating modern visualization technologies into the educational process, contributing to the development of critical and analytical thinking, digital data skills, and the formation of a research culture necessary for solving complex problems in professional and scientific activities.

These results indicate that the introduction of modern visualization technologies not only improves the quality of knowledge acquisition but also creates conditions for a deeper understanding of interdisciplinary connections. Students learn to integrate knowledge from different fields, which contributes to the formation of systematic thinking. Furthermore, the use of analytical tools shifts the focus from the reproductive assimilation of information to research and project activities, during which students independently formulate hypotheses, justify conclusions, and propose practical solutions.

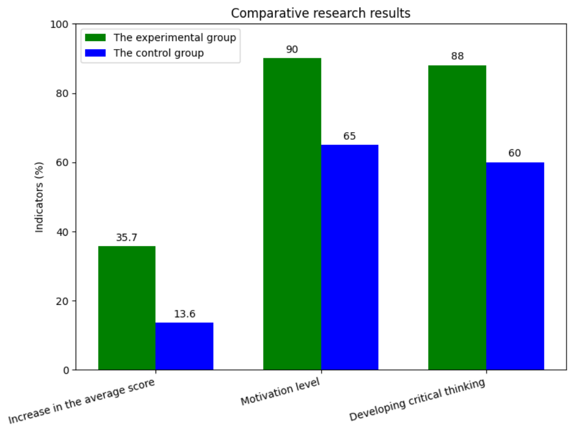

FIGURE 4. Comparative research results.

In the current context of the digitalization of education, the use of innovative educational technologies is seen as one of the key factors in improving the quality of training for specialists. These methods stimulate active learning, develop critical and spatial thinking, and form the research and analytical skills that are in demand in professional activities.

To further validate the findings, the learning gains observed in the experimental group were examined across core subtopics of geomorphology, including tectonics, erosion, and fluvial processes. This robustness analysis demonstrates that the benefits of visualization-enhanced instruction are consistent across different content areas, rather than being limited to a specific topic. By confirming that positive effects persist across multiple types of geomorphological phenomena, this approach strengthens the generalizability of the results and supports the broader applicability of interactive visualization and GIS tools in geography education. To further ensure the consistency of the results across different analytical perspectives, the findings from overall performance comparisons and subtopic-level analysis were examined jointly. Both levels of analysis demonstrate a stable pattern, indicating that the advantages of visualization-based instruction remain consistent regardless of whether geomorphological processes are considered in general or within specific thematic areas. This alignment between overall and subtopic results supports the internal coherence of the study findings and strengthens the reliability of the observed educational effects.

VII. DISCUSSION

An explicit error analysis was conducted to account for potential sources of bias and confounding factors. Testing effects were considered, recognizing that repeated exposure to assessment tasks could influence learning gains independently of the intervention. Instructor bias was mitigated by applying standardized teaching procedures across all groups. Additionally, the novelty of visualization technologies, including interactive 3D models and GIS tools, was acknowledged as a possible contributor to increased engagement and performance. Addressing these factors provides a more nuanced interpretation of the observed results and reinforces the reliability of the study's conclusions.

An analysis of participant subgroups based on prior digital competence indicates that learning gains from visualization-enhanced instruction were generally consistent across different levels of technology experience. However, students with higher digital skills tended to engage more efficiently with GIS and 3D tools, suggesting that prior familiarity with technology may amplify the benefits of visualization. These findings highlight the importance of considering digital competence when designing interventions and support tailored approaches to maximize learning outcomes across diverse student populations. The use of visualization technologies (3D models, GIS, VR/AR) in teaching geomorphology has proven to be highly effective in improving student performance and motivation. The advantages of this approach are:

Table 2. Advantages and limitations of visualization technologies in teaching geomorphology.

Advantages	Limitations
Clear representation of complex geomorphological processes	Requires significant technical and financial resources (equipment, software)
Improved student performance and motivation	Requires special training and professional development for teachers
Development of critical thinking and research skills	Differences in students' digital literacy levels can cause imbalance
Encouraging independent and project-based activities	Risk of fragmented knowledge acquisition with insufficient theoretical support
The ability to model dynamic natural phenomena (e.g., erosion, tectonic processes)	Limited methods for objectively assessing the effectiveness of technologies
Development of interdisciplinary connections (geography + ecology + ICT + engineering)	Dependence on infrastructure stability (Internet, technical support)

At the same time, certain limitations have been identified. First, the introduction of such technologies requires significant resources, both technical (equipment, software, license packages) and human (teacher training, methodological preparation). Second, there are differences in the level of digital literacy among students, which can create an imbalance in learning outcomes and require the introduction of compensatory ICT modules into the curriculum. Moreover, excessive visualization without sufficient theoretical support can lead to fragmented knowledge acquisition and the formation of superficial ideas. It is worth noting that the sustainable introduction of visualization technologies requires the development of standardized methods for assessing their effectiveness in order to minimize subjective factors and ensure the comparability of results in different educational institutions [13,27].

The integration of visualization technologies (3D modeling, GIS, VR/AR) into the educational process has significant potential for higher education institutions in different countries, but its scale and format largely depend on the level of development of the digital infrastructure and educational policy of the state [27]. In countries with a high level of digitalization (the USA, EU countries, South Korea, Japan), these methods can form the basis for comprehensive educational programs that include virtual laboratories, interdisciplinary courses, the use of digital copies of natural objects, and integration with international research projects. Here, systematic support from the state and universities is possible, ensuring the long-term sustainability of such initiatives. In countries with limited resources, it seems more realistic to introduce simplified versions of software (for example, QGIS as an alternative to commercial products) and use cloud services for modeling and analyzing geodata. This approach minimizes technical support costs and allows the methodology to be adapted to local conditions while maintaining its educational value [28].

International cooperation is particularly important, as it opens up opportunities for the creation of global educational platforms, including shared geodata bases and joint research projects. This helps students develop intercultural research skills, learn how to deal with global challenges (climate change, natural disasters, urbanization), and broaden their horizons beyond the local context. Visualization in the teaching of geomorphology improves the quality of education, develops critical and spatial thinking, research and analytical skills, and prepares specialists for interdisciplinary work and international scientific cooperation in a global digital environment [27,28].

Table 3. Comparative characteristics of the integration of visualization methods into the educational process of universities in different countries.

Aspect	Developed countries (USA, EU, Japan, South Korea)	Developing countries (Central Asia, Africa, Latin America)
Digital infrastructure	High-speed Internet, powerful server capacity, wide availability of VR/AR equipment.	Limited Internet access, lack of modern equipment, weak technical base.
Software	Use of commercial and advanced solutions (ArcGIS, Autodesk, ESRI CityEngine).	Use of simplified or free platforms (QGIS, Google Earth, cloud services).
Support from the government and universities	Systematic implementation of digital laboratories, integration into educational standards.	Individual projects dependent on external grants and teacher initiatives.
Forms of training	Virtual laboratories, interdisciplinary courses, use of digital copies of territories.	Local projects, educational case studies, use of basic visualizations (online maps, simple 3D models).
International cooperation	Participation in global educational networks and research consortia.	Participation through exchange programs and grants, access to international platforms in a limited format.
Human resources	High digital literacy of teachers, regular professional development courses.	Insufficient staff training, limited opportunities for professional growth in the field of digital technologies.
Impact on students	Development of global research competencies, big data and modeling skills.	Development of basic analytical and research skills, adaptation of knowledge to local conditions.

Prospects for future research are related to refining the pedagogical effectiveness of the proposed approaches. Long-term experiments are needed to identify the impact of visualization technologies on the quality of knowledge, professional training, and critical thinking of students. Another important area is the development of methodological materials and digital tools aimed at integrating GIS and 3D modeling into other disciplines, such as ecology, geoinformatics, and urban studies [29].

Particular attention should be paid to issues of inclusiveness and accessibility. The creation of adaptive platforms that take into account the characteristics of students with different levels of training and technical equipment will make the educational process more equitable and effective [27,29]. Further research may also focus on:

- assessing the cognitive effects of VR/AR use (development of spatial thinking, analytical skills, and the ability to predict outcomes);
- studying the influence of cultural and regional factors on the perception of digital teaching methods;
- developing integrated courses where visualization is combined with project and research activities;
- creating universal international standards and open educational resources that will allow universities in different countries to exchange experience and data.

The potential for further scientific work extends beyond the boundaries of a single discipline and is aimed at creating a new educational environment where visualization is a key tool for developing students' interdisciplinary and research competencies. The integration of digital technologies into the learning process contributes not only to the acquisition of knowledge in geomorphology, but also to the formation of critical and systematic thinking skills, the ability to analyze complex natural and anthropogenic processes, develop sound solutions, and work with a large amount of data [30]. The result is an educational model focused on the practical application of knowledge, stimulating independent research, interdisciplinary interaction, and the training of specialists capable of responding effectively to global environmental and socio-economic challenges.

The findings of this study may have broader applicability beyond the immediate sample. Visualization-enhanced instruction and GIS tools could be adapted for secondary school students, supporting the development of spatial thinking at an earlier stage. Similarly, students from non-geography majors may benefit from these methods, although differences in prior digital skills and familiarity with spatial tools should be considered when designing interventions. This discussion highlights the potential for extending the use of visualization technologies across diverse educational contexts while acknowledging factors that may influence effectiveness. Future studies should include longitudinal follow-up testing to evaluate retention of geomorphological knowledge over time. Assessing learning outcomes several weeks or months after the intervention would provide insights into the durability of visualization-enhanced instruction and help determine whether observed gains persist beyond the immediate post-test.

VIII. CONCLUSION

The findings of this study demonstrate that integrating contemporary visualization technologies such as geographic information systems (GIS), three-dimensional (3D) modeling, and virtual and augmented reality (VR/AR) into the teaching of geomorphology significantly enhances learning outcomes and supports the development of students' critical thinking. Engagement with digital models and spatial datasets requires learners to analyze, compare, and interpret information, thereby fostering independent problem-solving skills, systematic reasoning, and the ability to construct scientifically grounded arguments. When geomorphological analysis is carried out using these tools, it becomes a powerful means of cultivating a research-oriented mindset among future specialists, enabling them to understand the complex interactions between endogenous, exogenous, and human-induced processes and to evaluate their environmental and socio-economic implications. The use of visualization technologies also helps students develop a well-informed and responsible perspective on major global challenges, including climate change, natural hazards, and urban development. Critical thinking is reflected in their ability to approach issues holistically, consider the interplay between natural and anthropogenic factors, and anticipate the long-term consequences of decisions. In this way, digital visualization contributes to the formation of professional competencies and an environmentally conscious worldview grounded in scientific reasoning and a commitment to sustainable development.

Looking ahead, future research should focus on longitudinal studies that examine the long-term effects of digital technologies on students' cognitive development and professional growth. Promising directions include the development of international digital databases and virtual laboratories for collaborative geomorphological research, the creation of adaptive learning platforms tailored to individual needs, and further evaluation of interdisciplinary teaching models. Overall, the integration of visualization technologies in geomorphology education offers substantial potential to improve learning quality, stimulate research activity and critical thinking, promote international academic collaboration, and prepare specialists capable of making informed decisions in response to complex natural and global challenges. It should be noted that the findings of this study should be interpreted with consideration of methodological limitations. Given the quasi-experimental design, the results indicate associations between the use of visualization tools and students' learning outcomes rather than strict causal relationships. In addition, potential influencing factors such as teacher effect, novelty effect, and testing effect may have impacted the observed results despite efforts to maintain consistency in instruction and assessment. Therefore, while the study provides meaningful evidence of the pedagogical value of visualization-based approaches in geomorphology education, the generalizability of the findings may depend on contextual factors such as educational settings, available resources, and students' prior digital competencies.

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