

Development of research competencies in geomorphology education through the integration of digital technologies and modeling

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Abstract: In the context of the ongoing digitalisation of education and the growing importance of research-oriented learning, developing students' research competencies through interdisciplinary approaches has become a key priority in higher education. This study examines the integration of geomorphology with physics and digital technologies as a framework for enhancing research skills and scientific thinking, combining physical modelling with digital tools to deepen students' understanding of landform development processes while fostering analytical, critical, and systems thinking.

The study analyses the educational potential of physical models for demonstrating geomorphological processes - erosion, tectonic movements, and hydrological phenomena - enabling students to observe and interpret the dynamics of natural systems. It also explores the use of Geographic Information Systems (GIS), digital mapping, terrain simulation, and Big Data analysis for collecting, processing, visualising, and modelling geomorphological information, supporting the interpretation of experimental results and the development of digital literacy.

A step-by-step methodology for developing research competence is proposed, encompassing problem-based learning, physical experimentation, digital data analysis, and project-based interpretation of results. Students progress from observing natural phenomena to constructing models, analysing data, formulating hypotheses, identifying causal relationships, and presenting findings in digital formats, thereby developing independent inquiry, collaborative learning, and evidence-based reasoning.

Findings from a pedagogical study involving 30 students indicate that combining practical experiments with digital technologies is associated with increased research competencies, critical thinking, analytical ability, and problem-solving skills, as well as greater motivation to engage in scientific research. The proposed approach offers a practical model for training specialists capable of applying digital methods in geoscience education, relevant to the demands of the digital economy.

Keywords: geomorphology; interdisciplinary approach; physical models; digital technologies; GIS; data analysis; research competencies; research activity; student training; digital literacy.

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1. Introduction

The relevance of integrating geomorphology with physics and digital technologies stems from modern requirements for training and teaching aimed at developing learners' research and digital competencies. As the science of landforms and their formation processes, geomorphology requires an understanding of the physical laws underlying natural phenomena such as tectonic movements, erosion, and hydrological processes. Furthermore, modern digital technologies - geographic information systems (GIS), digital mapping, terrain simulators, and big data analysis - not only allow for the visualisation and modelling of complex processes but also enable the development of learners' skills in analysing, interpreting, and processing information.

The integration of these subjects provides an interdisciplinary approach to education that promotes a deeper understanding of natural processes, develops critical thinking, and prepares learners for research and professional practice in the digital economy (Jia et al., 2025). Such an approach increases interest in the study of geomorphology, develops independent research and analytical skills, and makes the educational process applied and relevant.

The role of an interdisciplinary approach is to integrate knowledge, methods, and tools from various disciplines in order to develop a comprehensive understanding of the phenomena under study and to enhance learners' practical and research competencies. It ensures continuity of knowledge, links theory with practice, and develops skills in critical thinking, data analysis, and systematic problem-solving (Wu et al., 2024). Combining geomorphology with physics and digital technologies, for example, allows for the simultaneous study of natural processes, their physical laws, and modelling methods using modern analytical and visualisation tools, thereby fostering research independence, project-based thinking, and digital literacy.

The problem lies in the insufficient development of learners' research competencies. Despite possessing theoretical knowledge, most learners face difficulties in applying it in practice - formulating scientific hypotheses, analysing data, and interpreting results. Traditional teaching methods, which focus on memorising information and solving standard tasks, do not always foster independent research, critical thinking, or the use of quantitative tools (Aidoo, 2024). This is particularly important from a geomorphological perspective, since a full understanding of landform development processes requires the ability to analyse real data, construct models, and test hypotheses using modern technologies.

The aim of this article is to systematise the integration of interdisciplinary approaches in teaching geomorphology, using physical models and digital technologies to effectively develop students' research competencies. The article presents a step-by-step methodology for developing research skills - from observation and problem identification, through physical experiments and digital data analysis, to interpreting results and presenting them as academic projects.

The scientific novelty of this work lies in systematising and developing a methodology for a comprehensive, interdisciplinary approach to building independent research skills, encompassing physical experiments, digital data analysis, and project-based activities. Its practical significance lies in its potential application in schools and universities to improve the quality of student learning and to develop analytical thinking, research independence, and digital literacy. The use of physical and digital models makes the study of geomorphology visual, interactive, and motivating, strengthens the link between theory and practice, and increases students' interest in the subject.

Theoretical foundations of the interdisciplinary approach and a literature review

Interdisciplinary links in education involve integrating knowledge, methods, and approaches from various subjects to develop learners' holistic competencies. The interdisciplinary approach ensures continuity of knowledge, enables the integration of theoretical knowledge with practical skills, and fosters the ability to analyse, synthesise, and apply information across contexts. In educational practice, interdisciplinary links are realised through project-based activities, research tasks, the use of physical and digital models, and the application of data analysis tools, simulators, and GIS (Abdimanapov et al., 2025). This approach promotes critical thinking, systems analysis, and complex problem-solving skills, and enhances learners' motivation for independent research.

Interdisciplinary links are particularly relevant in the earth sciences, such as geomorphology, where combining physics, informatics, and digital technologies allows not only for the study of natural processes but also for their modelling, data visualisation, and the drawing of sound conclusions - thereby developing learners' research and digital literacy. Geomorphology studies landforms and their formation processes, which are governed by physical laws such as erosion, tectonic movements, and hydrological and geodynamic phenomena (Viles, 2016). Understanding these laws requires the ability to explain processes in physical terms, making the integration of physics and geomorphology a logical and necessary step in educational practice.

GIS, digital mapping, terrain modelling, and other modern digital technologies enable the management, analysis, and visualisation of large datasets. Integrating these tools with physical and geomorphological knowledge supports an interdisciplinary approach that develops learners' skills in independent research, analytical thinking, critical analysis, and digital literacy. The choice to integrate geomorphology, physics, and digital technologies is grounded in educational needs and the demands of the current scientific and professional context (Farooq et al., 2024). This approach combines theoretical knowledge, practical experiments, and digital data analysis, making the learning process visual, interactive, and motivating, while increasing students' interest in natural processes and developing competencies in demand in research and professional practice.

Modern research in geomorphology and geography education pedagogy demonstrates the growing importance of physical and digital methods for developing learners' research, analytical, and digital competencies. Physical terrain modelling remains a fundamental tool in this field, including scale models, hydraulic tables, sand and water simulators, laboratory terraces, and other devices that demonstrate erosion processes, tectonic movements, sediment accumulation, and hydrological changes. Such experimental facilities allow learners to observe the dynamics of landform-building processes, analyse cause-and-effect relationships, formulate hypotheses, and test them through controlled experiments (Franceschi et al., 2025; Panjaitan et al., 2023). This develops critical thinking, systematic analysis, and the ability to conduct experimental work and draw conclusions from empirical data.

In addition to physical models, modern teaching practices actively employ geographic information systems. GIS technologies enable the integration of spatial data from various sources - satellite imagery, elevation models, maps, and field measurements - and their visualisation on digital maps, supporting the analysis of spatial relationships and landform dynamics. The use of GIS in educational tasks contributes to the development of spatial thinking, the ability to work with cartographic information, and the analysis of large spatial datasets. Gladskoy et al. (2020) demonstrate the use of GIS technologies and digital relief models for studying geological structures, while a later study by Pavlova & Telyatnikov (2022) shows that GIS and digital terrain models in teaching geomorphology and ecology enable students to monitor environmental change, analyse deformation processes, and model spatial landscape transformations.

3D modelling and virtual environments are another integral part of the digital approach: using software such as Blender, Unity, and specialised GIS platforms, virtual models of terrain and natural processes can be created that closely resemble reality. These models allow learners to visualise complex geomorphological structures, undertake virtual "expeditions" to modelled landscapes, and simulate erosion or tectonic shifts within a simulator. Sang et al. (2020) show that creating 3D libraries of geological objects - for example, through photo-modelling - opens up stable, interactive educational opportunities, particularly for geostructures where field access is limited. Bondarenko et al. (2020) similarly highlight the didactic potential of virtual information learning environments, noting that such environments increase student engagement, develop geographical and digital literacy, and foster independent research, allowing learners to conduct experiments, model natural processes, and analyse data without leaving the virtual laboratory. The application of Big Data analysis in geomorphological education is also significant: research into large spatial and remote-sensing datasets (satellite imagery, LIDAR, DEM) shows that learners can develop skills in processing, filtering, aggregating, and visualising data, as well as identifying patterns and trends in

landform development (Samsul et al., 2023). This analytical approach contributes to the development of statistical processing, forecasting, and landscape-transformation modelling skills.

The literature review confirms that combining physical and digital methods is particularly effective in developing an interdisciplinary educational approach. It integrates practical experiments with digital analytical work, contributing to the holistic development of learners' independent research, critical thinking, project-based thinking, and digital and spatial literacy, while enhancing motivation through interactivity, experimentation, and visualisation. Overall, the literature suggests that physical terrain modelling methods together with digital tools (GIS, 3D modelling, simulators, Big Data) constitute a modern, well-established, and effective strategy for teaching geomorphology, helping to prepare learners for the demands of modern scientific and professional life.

2. Materials and Methods

A method for integrating physical models and quantitative tools in the teaching of geomorphology. The study of geomorphology requires an understanding of the dynamics of landform-forming processes, their physical laws, and methods of data analysis. An effective approach is to integrate physical models with quantitative tools, which supports interdisciplinary education and develops learners' research skills, analytical and critical thinking, and numeracy.

Figure 1 presents a diagram of the physical models used to study landform development, including terrain models, sand tables, hydraulic simulators, and various experimental setups that allow natural processes to be visualised, controlled, and analysed. The diagram illustrates the primary applications of these models - the study of erosion, tectonic processes, hydrology and flows, and their combinations - showing the formation of river channels, gullies, folds and faults, as well as the development of river valleys and alluvial plains, thereby providing a comprehensive understanding of the mechanisms of landform change.

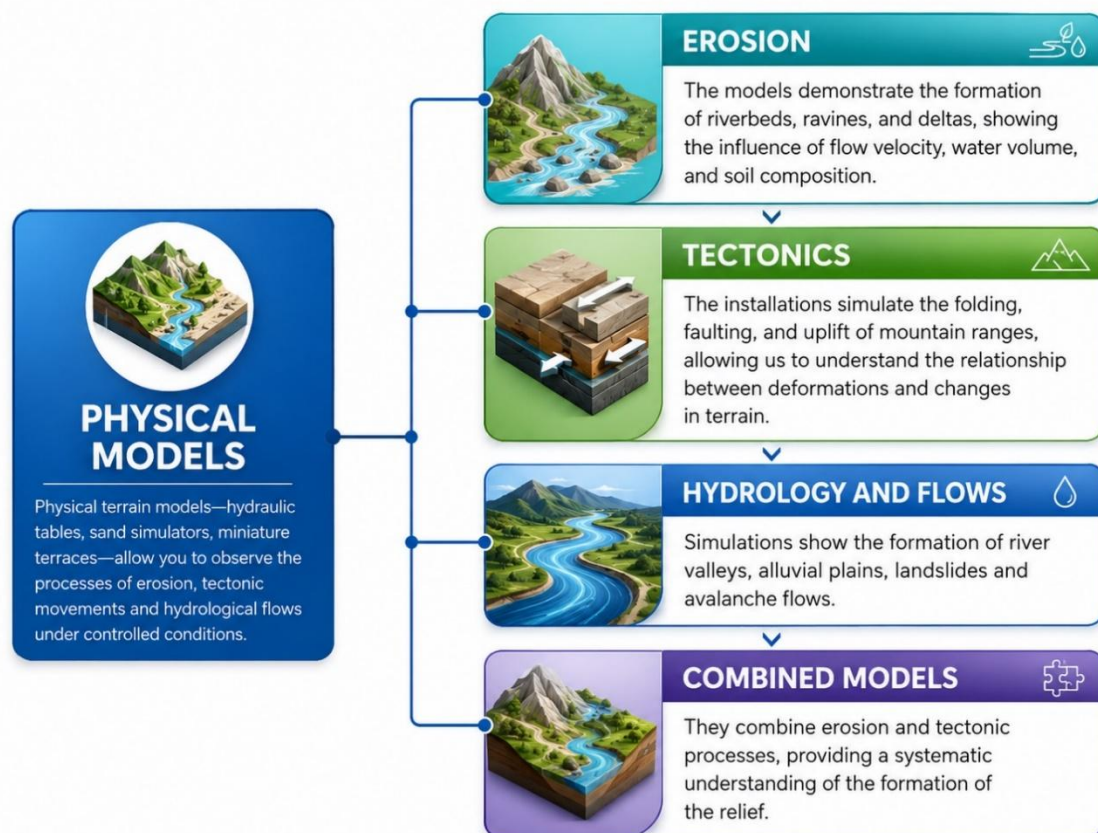


Figure 1. Types of physical models

Figure 2 shows how combining digital tools with physical experiments allows for hypothesis testing, process modelling, and the development of complex research projects. Integrating physical models with digital tools supports an interdisciplinary approach to studying geomorphology by linking hands-on observation with data analysis and visualisation (Xiong et al., 2022). This develops learners' research independence, critical and analytical thinking, project-based skills, and numeracy, increases motivation for the subject, and prepares students for scientific, professional, and interdisciplinary work in the context of contemporary science and the digital economy.

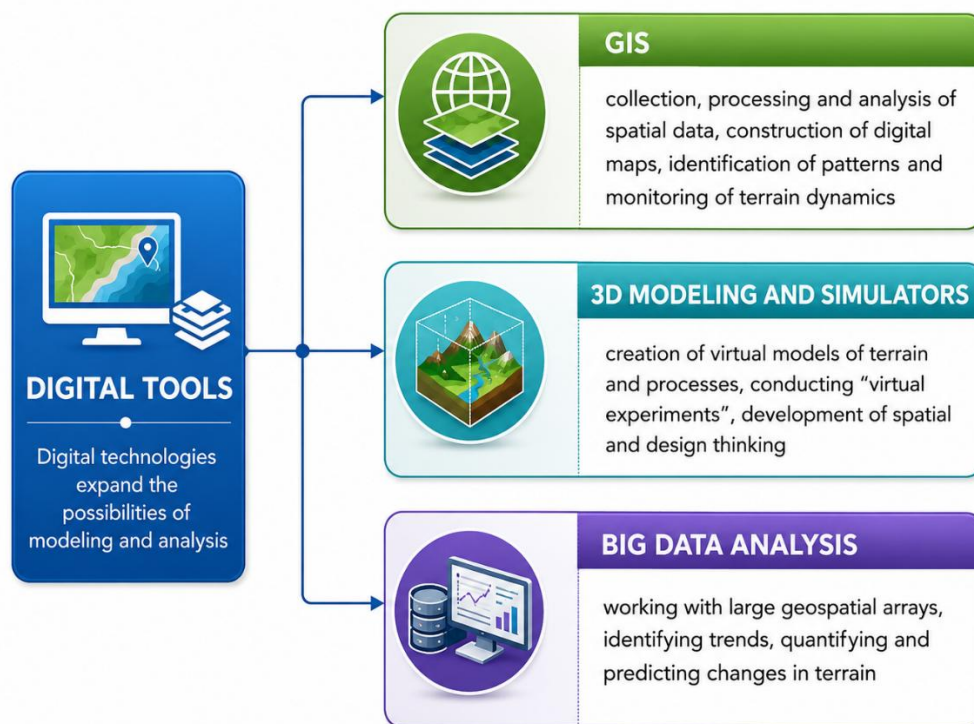


Figure 2. Types of digital tools

The use of digital technologies in teaching geomorphology. In modern geomorphological education, digital technologies play an important role in simulating complex natural processes (Luppichini et al., 2025), enabling their analysis and visualisation, and integrating data from various sources for the comprehensive study of landform processes. The main tools include:

- Geographic Information Systems (GIS): support the collection, processing, and spatial analysis of data on topography, hydrology, soils, and geological structures (Leeonis et al., 2024). Using GIS, researchers can create quantitative maps of erosion processes, monitor tectonic deformation dynamics, and identify patterns in the distribution of natural phenomena;
- Digital maps and satellite data (Big Data): enable work with large datasets such as digital elevation models (DEMs), remote sensing data, and LIDAR, supporting the quantitative analysis of landform changes, the assessment of large-scale processes, and the creation of predictive models;
- Digital laboratories and simulators of landform processes: allow virtual experiments with water currents, landslides, erosion, and tectonic movements, enabling learners to observe the results of changing parameters and model the consequences of natural phenomena;
- Virtual and Augmented Reality (VR/AR) environments: create interactive 3D models of terrain and dynamic processes, helping to develop learners' spatial reasoning, visualisation skills, and project-based approaches.

Using these tools enables students to:

1. Analyse complex data by integrating multiple information sources to identify patterns and dynamics in natural processes;
2. Conduct virtual investigations by modelling processes, monitoring the impact of individual factors, and testing hypotheses without requiring constant access to field sites;
3. Develop digital and research competencies by processing large datasets, visualising results, predicting landform changes, and drawing accurate conclusions;
4. Develop project-based skills and interdisciplinary thinking by integrating knowledge of geomorphology, physics, and information technology to comprehensively study natural processes.

The integration of digital technologies into geomorphology education creates a learning platform for developing learners' research independence, analytical and critical thinking, geospatial data skills, and digital literacy. Combining GIS, 3D modelling, simulators, and big data analysis within an interdisciplinary approach addresses the modern demands of science, engineering, and the digital economy (Horowitz & Schultz, 2014), ensuring a comprehensive understanding of landform development processes and developing competencies in demand for scientific, project-based, and professional activities.

Methods for developing students' research competence. Developing research competence is a key focus of modern education, preparing learners to independently seek, analyse, and interpret information, and to solve practical and scientific problems. The methodology for developing these competencies supports the development of analytical thinking, creativity, the ability to work with data, and independent research.

Principles for developing research competence:

- Scientific integrity and accuracy. Teaching is grounded in up-to-date scientific data, developing learners' understanding of scientific methodology and the criteria for scientific validity;
- Problem-based learning. The research process begins with a problem question or hypothesis that prompts the search for solutions and the analysis of information;
- A practical focus. Tasks are related to real-world processes and phenomena (natural, social, technical), increasing motivation and promoting the application of knowledge;
- Individuality and variety. Students may choose their own topics, methods, tools, and presentation formats;
- Integration of technologies. The use of physical models, digital tools, GIS, simulators, laboratories, and big data supports the development of research skills at a modern level (Yu & Zin, 2023).

Key components of learners' research competencies. Developing research competencies is a key objective of modern education, aimed at fostering learners' ability to independently acquire new knowledge, analyse information, and apply research findings to practical and theoretical problems (Tapullima-Mori et al., 2025). These competencies comprise several interrelated components that constitute individual aspects of research activity.

Figure 3 presents an infographic, "Methodology for Developing Students' Research Competence," outlining a step-by-step model for organising research activity in an interdisciplinary learning context using physical models and digital technologies. Each stage describes learners' activities, the tools used, and the expected learning outcomes, reflecting the logic of skill development - from identifying a problem to reflecting critically on one's own actions. The use of physical models, GIS, digital maps, Big Data technologies, 3D modelling, and data visualisation fosters analytical and critical thinking, independence, and a scientific approach in learners (Ki, 2019). The infographic illustrates the integration of traditional and digital teaching tools within a methodology aimed at developing systems thinking, communication skills, and reflective ability, and can be used as a visual tool for organizing research and project-based learning activities at various educational levels (Hickman, 2023). Because the development of research competencies is closely linked to modern digital tools that allow learners to work with real geospatial data, draw evidence-based conclusions, and design research solutions, acquiring these competencies fosters independent, critical, and project-

oriented thinking - essential for successful professional development in the context of the digital transformation of education and science.

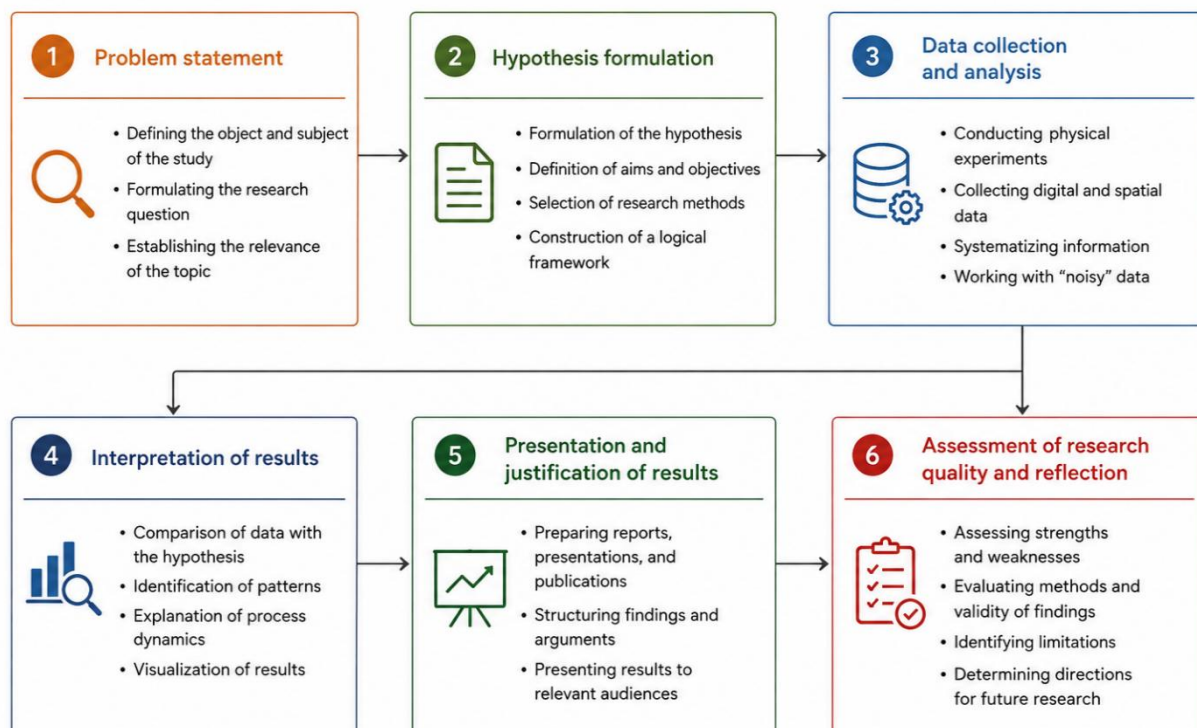


Figure 3. Methodology for developing learners' research competencies

A methodology for developing learners' research competence

The proposed methodology is organised as a sequential research process encompassing problem formulation, hypothesis development, data collection and analysis, interpretation of results, presentation and justification of findings, and assessment of research quality and reflection. These interconnected components reflect the logic of scientific inquiry and are aimed at the systematic development of students' research competencies. The principal learning objectives, activities, tools, and expected outcomes are summarised in Table 1.

Table 1. Developing research competencies

Objective	Activity	Tools	Outcome
Formulating the problem	Situation analysis and problem formulation	Cases, texts, graphics	Identifying the problem
Formulating a hypothesis	Formulating and planning a hypothesis	Discussions, diagrams, tables	Formulating a hypothesis
Data collection	Information seeking, experiments, observations	Databases, reference sources	Data collection skills
Data processing	Systematisation and preliminary processing	Databases, reference sources	Data processing skills
Interpreting results	Evaluating data, drawing conclusions	Tables, charts, graphs	Ability to draw conclusions

The proposed methodology can be applied in a variety of educational contexts, including research-based lessons, project- and research-oriented activities, and specialised educational programmes at colleges and universities. It can also be integrated into extracurricular learning environments, such as academic clubs, STEM laboratories, and digital workshops. This flexibility enables the methodology to support the systematic development of learners' research competencies across both formal and non-formal educational settings.

The proposed methodology provides a coherent and structured framework for developing learners' research competencies (Paucar-Curasma et al., 2025). Its components encourage conscious engagement in scientific inquiry and facilitate an understanding of the internal logic of the research process (Alipina & Kitapbaeva, 2023). A particular strength of the methodology is its practice-oriented nature, integrating problem-based and project-based activities, empirical data collection, physical modelling, and modern digital tools. Through these activities, learners develop the ability to formulate hypotheses, select appropriate research methods, analyse and interpret data, and critically evaluate research outcomes. Overall, the methodology promotes analytical thinking, cognitive independence, scientific reasoning, and the application of research skills to complex academic and practical problems in contemporary interdisciplinary educational contexts.

Stages of Learning for the Development of Research Competencies

1. Motivational stage. This stage creates the conditions for learners to engage actively in research. Project-based tasks, problem-based questions, real-world situations, and scenarios involving uncertainty are used to stimulate interest, strengthen motivation, and define the direction of subsequent inquiry.

2. Practical stage. This stage focuses on empirical investigation and data collection. Learners conduct physical experiments, make observations, or undertake fieldwork. The collected data are systematically recorded and transferred to digital environments, including GIS, spreadsheets, and digital simulators, for subsequent processing and analysis.

3. Analytical stage. This stage involves processing, analysing, and interpreting the collected data using statistical methods, numerical modelling, and graphical and spatial visualisation techniques. Learners construct graphs, maps, and models, identify relevant patterns and relationships, and assess the accuracy and reliability of the obtained results.

4. Presentation and reflective stage. The final stage focuses on communicating and evaluating research outcomes. Learners prepare a final product, such as a report, presentation, model, or research paper, present and interpret their findings, compare the results with the initial hypothesis, justify their conclusions, and reflect on the validity and scientific significance of their work.

3. Empirical research and results

The empirical component of the study was designed to evaluate changes in students' research competencies following the implementation of the proposed interdisciplinary methodology. The pedagogical study involved 30 students enrolled in the *6B01511 Geography-History* educational programme at the Kazakh National Girls' Pedagogical University. Participation was voluntary, and the group included students with different levels of prior preparation in geography and informatics. The pedagogical intervention was conducted over a 15-week period during the fall semester of the 2025–2026 academic year. The pedagogical study was structured into four sequential and interconnected instructional stages: motivational, practical, analytical, and presentation-reflective. This heterogeneity provided an opportunity to examine the applicability of the methodology among learners with varying levels of subject-specific and digital competence. Given the relatively small sample size and the absence of a control group, the empirical findings should be interpreted as evidence of changes observed within the participating group rather than as results that can be generalised to a broader student population.

The overall structure of the instructional implementation and evaluation of the proposed methodology is presented in Figure 4.

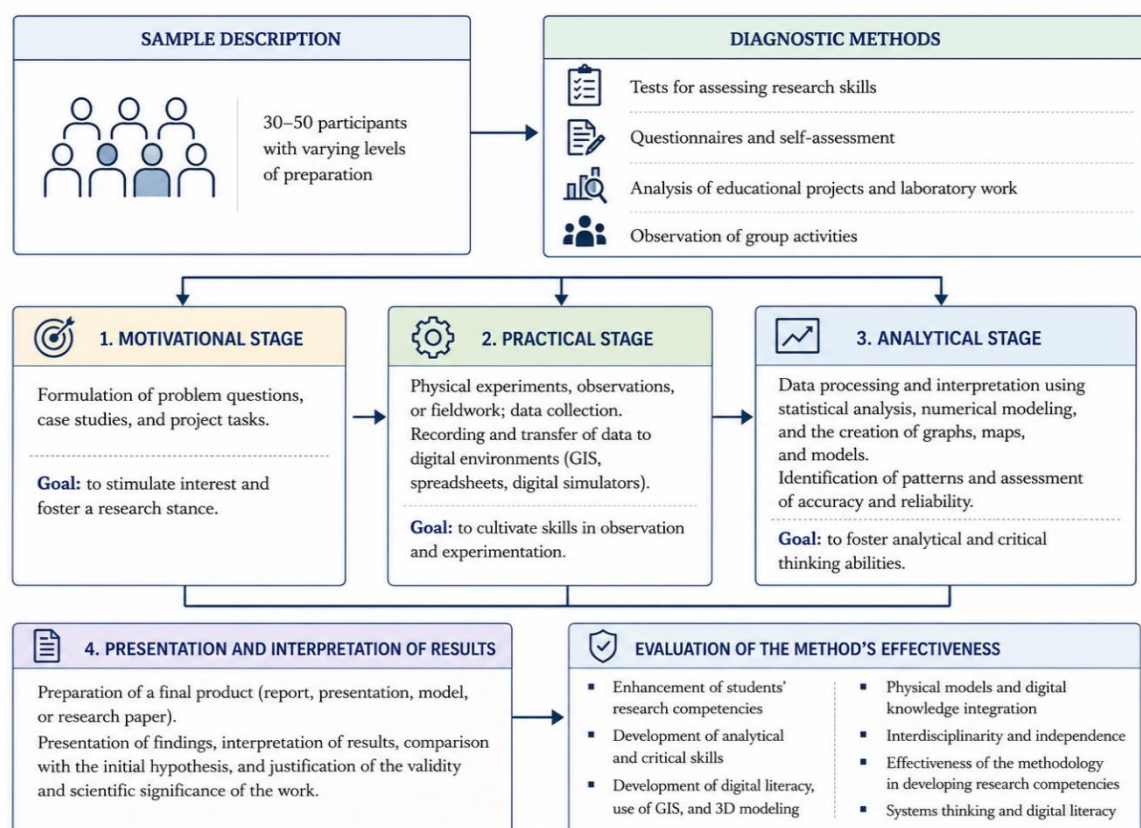


Figure 4. Stages of instructional implementation and evaluation of the proposed methodology

The pedagogical intervention followed four interconnected stages: motivational, practical, analytical, and presentation-reflective. During the motivational stage, students worked with problem-based tasks and analytical cases designed to stimulate interest in geomorphological inquiry and support the formulation of research questions and hypotheses. The practical stage involved experiments with physical terrain models, including hydraulic tables and sand-based terrain models, together with the application of GIS, 3D modelling, and digital simulation tools (Caldwell, 2001; Markov et al., 2022). During the analytical stage, students processed and interpreted the collected data, constructed graphs and visualisations, identified relationships and patterns, and formulated evidence-based conclusions. The presentation-reflective stage involved presenting mini-projects, discussing findings, evaluating initial hypotheses, and reflecting on the research process.

Assessment of Research Competencies

Changes in students' research competencies were assessed using multiple complementary methods. Structured testing was used to evaluate the ability to formulate research problems and hypotheses and to select appropriate research methods. Surveys and self-assessment instruments were used to examine students' confidence in working with physical models and digital technologies. In addition, students' mini-projects, reports, graphs, maps, and visualisations were analysed as evidence of their ability to apply research procedures in practice. Observation of group activities focused on participation, interaction, discussion of hypotheses, interpretation of evidence, and communication of research findings (Ilyashenko, 2019).

Diagnostics were conducted before and after the pedagogical intervention, allowing changes in the main components of students' research activity to be examined (Granberg et al., 2023). The combination of testing, coursework and project analysis, observation, and self-assessment was intended to provide a multidimensional evaluation rather than relying on a single assessment instrument. For each indicator, students' performance was evaluated using predefined assessment criteria corresponding to the research skills assessed. The scores obtained for each indicator were converted into percentages of the maximum achievable score. This procedure enabled direct

comparison of competency levels before and after the pedagogical intervention. The same assessment criteria and scoring procedure were applied at both measurement stages to ensure consistency and comparability of the results. Five indicators were considered: overall research competencies, skills in working with physical models, skills in working with digital tools, analytical and critical skills, and motivation and engagement. The results are presented as percentages of the maximum achievable level (Table 2).

Table 2. Evaluation of research competencies before and after the pedagogical intervention

Indicator	Before (%)	After (%)	Change (percentage points)
Research competencies	50	85	+35
Skills in working with physical models	40	80	+40
Skills in working with digital tools	45	78	+33
Analytical and critical skills	55	88	+33
Motivation and engagement	60	90	+30

Analysis of the Results

The descriptive results indicate positive changes across all five assessed indicators following the implementation of the methodology. Across the five indicators, the mean percentage score increased from 50.0% before the intervention to 84.2% after the intervention. This represents an absolute increase of 34.2 percentage points and a relative increase of 68.4%.

The largest change was observed in skills in working with physical models, which increased from 40% to 80% (+40 percentage points). Overall research competencies increased from 50% to 85% (+35 percentage points), while skills in working with digital tools and analytical and critical skills increased by 33 percentage points each. Motivation and engagement increased from 60% to 90% (+30 percentage points). Thus, improvement was observed across practical, digital, analytical, and motivational dimensions rather than being confined to a single component of research activity.

The changes in the assessed indicators before and after the pedagogical intervention are illustrated in Figure 5.

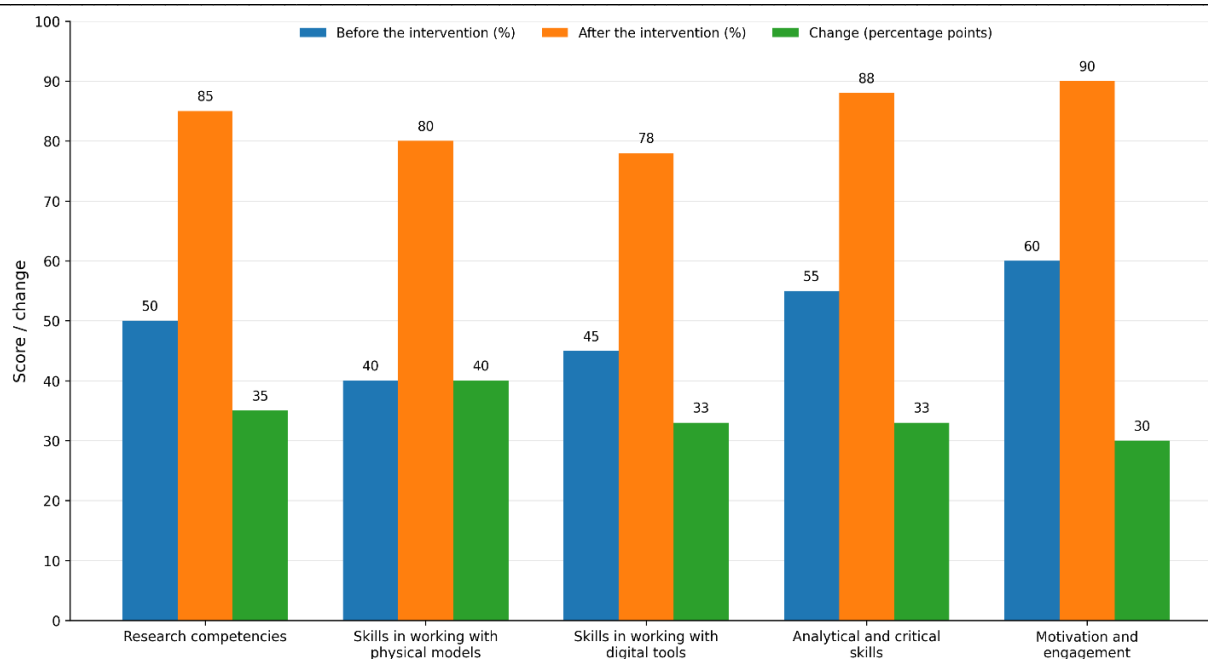


Figure 5. Changes in research competency indicators before and after the pedagogical intervention

The pattern shown in Figure 5 suggests that the most pronounced improvement occurred in students' ability to work with physical models. This finding is particularly relevant to the proposed methodology because physical experimentation constitutes an important link between theoretical explanations of geomorphological processes and their subsequent digital representation and analysis. Improvements in digital, analytical, and critical skills further suggest that combining hands-on experimentation with GIS, modelling, and data visualisation can provide a productive environment for research-oriented learning.

Because the available results are aggregated at the indicator level, they are interpreted descriptively in the present study. Claims of statistical significance are therefore avoided in the absence of individual-level pre- and post-intervention scores required for an appropriate inferential statistical test. Future applications of the methodology should incorporate individual-level measurements and, where possible, a comparison or control group to enable more robust statistical evaluation of intervention effects.

4. Discussion

The findings provide preliminary empirical support for the educational value of integrating physical modelling and digital technologies within a structured approach to geomorphology education. The observed improvements across the five competency indicators suggest that the methodology can support several interconnected dimensions of research-oriented learning, including empirical investigation, digital data processing, analytical reasoning, and learner engagement. However, given the single-group pre-post design, these changes should be interpreted as associations observed during the intervention rather than as evidence of a definitive causal effect.

The findings are broadly consistent with research emphasising the role of digital technologies in geographical education. GIS and related digital tools have been associated with the development of spatial thinking, analytical reasoning, and problem-solving skills (Bondarenko, 2025). Research on the digital transformation of geographical education has similarly highlighted the potential of technology-supported learning to increase student engagement and facilitate the understanding of complex geographical processes (Satymova, 2025). The present study extends this perspective by integrating digital technologies with physical terrain modelling rather than treating digital tools as an independent instructional component.

This combination constitutes an important feature of the proposed approach. Previous studies have demonstrated the educational potential of GIS, digital elevation models, 3D mapping, virtual environments, and physical representations of terrain for visualising and analysing geomorphological phenomena (Carbonell-Carrera & Hess-Medler, 2019; Polidori & El Hage, 2020; Vidal de Souza et al., 2025). In the present methodology, however, physical and digital modelling are incorporated into a single instructional sequence that progresses from problem formulation and empirical observation to data analysis, interpretation, presentation, and reflection. The specific contribution of the study therefore lies in connecting hands-on modelling with digital spatial analysis within a structured research-oriented framework and examining changes in students' competencies before and after its implementation.

The largest improvement in skills related to physical models is noteworthy in this context. Physical terrain models allow geomorphological processes to be observed and manipulated in a tangible form, whereas digital tools enable the resulting spatial patterns and relationships to be processed, visualised, and interpreted at a more analytical level. Their combined use may therefore facilitate a transition from the descriptive study of landforms towards process-oriented analysis, which is fundamental to contemporary geomorphology. Working with empirical observations and geospatial data also encourages students to formulate hypotheses, examine evidence, identify relationships, and justify conclusions rather than merely reproduce theoretical information.

At the same time, the effectiveness of technology-supported instruction depends on appropriate pedagogical and technical conditions. The integration of GIS, 3D modelling, and simulation environments requires adequate digital infrastructure and sufficient teacher competence. Limited access to specialised software or equipment and insufficient teacher preparation may constrain the implementation of the methodology. Consequently, its wider application should be accompanied by appropriate methodological support, teacher professional development, and adaptation to the technological resources available in individual educational institutions.

Several limitations should be considered when interpreting the findings. First, the study involved only 30 students from a single educational programme at one university, which limits the generalisability of the results. Second, the absence of a control group prevents direct comparison with conventional teaching approaches and does not allow the observed changes to be attributed exclusively to the intervention. Third, the available results are based on aggregated competency indicators; therefore, inferential statistical testing of individual pre-post differences could not be performed. Future research should involve larger and more diverse samples, individual-level assessment data, control or comparison groups, and appropriate inferential statistical procedures to evaluate the magnitude and statistical reliability of observed changes.

Despite these limitations, the study demonstrates the practical potential of combining physical terrain models with GIS, 3D modelling, simulation, and data-analysis tools in research-oriented geomorphology education. The proposed methodology creates a coherent connection between observation, experimentation, spatial analysis, interpretation, and scientific communication. Such integration may contribute to the development of research competencies, spatial and critical thinking, digital literacy, and students' ability to address complex geographical problems using multiple forms of evidence.

5. Conclusion

This study developed and evaluated an interdisciplinary methodology for fostering research competencies in geomorphology education through the integrated use of physical models and digital technologies. The proposed approach combines hands-on investigation of geomorphological processes with GIS, 3D modelling, digital simulation, and spatial data analysis within a structured research-oriented learning framework. This integration enables students to progress from problem formulation and hypothesis development to empirical observation, data analysis, interpretation, and scientific communication.

The pedagogical intervention showed positive changes across all assessed competency indicators. The mean score across the five indicators increased from 50.0% before the intervention to 84.2% after its implementation. The largest improvement was observed in skills related to physical models (+40 percentage points), followed by overall research competencies (+35 percentage points). Skills in working with digital tools and analytical and critical skills each increased by 33 percentage points, while motivation and engagement increased by 30 percentage points. These findings suggest that combining physical experimentation with digital analysis can support the development of research-oriented, analytical, and digital competencies in geomorphology education.

The specific contribution of the proposed methodology lies in integrating physical terrain modelling and digital technologies within a single instructional framework rather than treating them as separate educational tools. Physical models provide opportunities for direct observation and experimentation with erosion, tectonic, and hydrological processes, whereas digital technologies extend these activities through spatial analysis, modelling, visualisation, and interpretation. Their combined application supports a transition from the descriptive study of landforms towards a more process-oriented and evidence-based understanding of geomorphological phenomena.

From a practical perspective, the methodology can be incorporated into geography and geomorphology courses in higher education and, with appropriate adaptation, in colleges and other educational settings. It can support research-based and project-based learning, laboratory and field activities, student projects, and interdisciplinary modules combining geography, geoinformatics, and digital modelling. The framework may also contribute to curriculum development aimed at strengthening research skills, spatial thinking, digital literacy, and students' capacity for independent scientific inquiry.

The findings should nevertheless be interpreted in light of the study limitations. The pedagogical intervention involved a relatively small sample of 30 students from a single educational programme and did not include a control group. In addition, the available results were analysed at the aggregated indicator level, which did not permit inferential statistical testing of individual pre–post changes. Consequently, the observed improvements should be regarded as preliminary evidence supporting the potential of the methodology rather than as definitive proof of its causal effectiveness.

Future research should evaluate the methodology using larger and more diverse samples, control or comparison groups, individual-level pre–post measurements, and appropriate inferential statistical procedures. Longitudinal studies could further determine whether the observed competencies are retained and transferred to subsequent academic and professional activities. Additional research may also explore the integration of virtual laboratories, interactive 3D terrain environments, big geospatial data, and machine-learning applications. Such developments could extend the proposed framework and further strengthen the role of research-oriented, interdisciplinary, and digitally supported learning in contemporary geomorphology education.

6. Supplementary Materials: No supplementary materials.

7. Author Contributions:

Conceptualization – Ye.N.; methodology – Ye.N.; software – Ye.N.; investigation – Ye.N., Ye.T.; resources – Ye.N., Ye.T.; methodology development, provision of research materials, and supervision – Ye.T.; writing – original draft preparation, review, editing, and formal analysis – Ye.N.

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12. References

1. Abdimanapov, B., Kumarbekuly, S., & Gaisin, I. (2025). Technology for achieving learning objectives through a system-activity approach and the development of critical thinking in geography studies. *Journal of Ecohumanism*, 3(8), 11989–12004. <https://doi.org/10.62754/joe.v3i8.5797>
2. Aidoo, B. (2024). A reflective study on adopting inquiry-based science teaching methods. *Disciplinary and Interdisciplinary Science Education Research*, 6, 29. <https://doi.org/10.1186/s43031-024-00119-3>
3. Alipina, K. B., & Kitapbaeva, A. A. (2023). Formation of research competencies of students (Bilim alushylyardyn gylimi-zertteu quzyrettiligin qalyptastyru in Kazakh). *Iasau universitetinin habarshysy*, (4)130, 344–360. <https://doi.org/10.47526/2023-4/2664-0686.28>
4. Bondarenko, O. V. (2025). Teaching geography with GIS: a systematic review, 2010–2024. *Science Education Quarterly*, 2(1), 24–40. <https://doi.org/10.55056/seq.903>
5. Bondarenko, O., Pakhomova, O., & Lewoniewski, W. (2020). The didactic potential of virtual information educational environment as a tool of geography students training. *arXiv*. <https://arxiv.org/abs/2002.07473>
6. Caldwell, D. R. (2001). Physical terrain modeling for geographic visualization. *Cartographic Perspectives*, 38, 66–72. <https://doi.org/10.14714/CP38.795>
7. Carbonell-Carrera, C., & Hess-Medler, S. (2019). 3D landform modeling to enhance geospatial thinking. *ISPRS International Journal of Geo-Information*, 8(2), 65. <https://doi.org/10.3390/ijgi8020065>
8. D’Este, P., & Robinson-García, N. (2023). Interdisciplinary research and the societal visibility of science: the advantages of spanning multiple and distant scientific fields. *Research Policy*, 52, 104609. <https://doi.org/10.1016/j.respol.2022.104609>
9. Farooq, E., Zaidi, E., & Shah, M. M. A. (2024). The future classroom: Analyzing the integration and impact of digital technologies in science education. *Jurnal Penelitian dan Pengkajian Ilmu Pendidikan: E-Saintika*, 8(2), 280–318. <https://doi.org/10.36312/esaintika.v8i2.1957>
10. Franceschi, L., Bosino, A., La Licata, M., & De Amicis, M. (2025). Geomorphological mapping and social sciences: a qualitative review. *Geosciences*, 15(7), 271. <https://doi.org/10.3390/geosciences15070271>
11. Gladskoy, I. B., Pavlova, A. V., & Telyatnikov, I. S. (2020). Use of GIS technologies and a digital relief model to study processes in the geological structures of the region. *Ecological Bulletin of the Scientific Centres of the Black Sea Economic Cooperation*, 17(2), 29–35. <https://doi.org/10.31429/vestnik-17-2-29-35>
12. Granberg, C., Palm, T., & Palmberg, B. (2021). A case study of a formative assessment practice and the effects on students’ self-regulated learning. *Studies in Educational Evaluation*, 68, 100955. <https://doi.org/10.1016/j.stueduc.2020.100955>
13. Hickman, J. (2023). Spatial thinking and GIS: developing and assessing student competencies. *International Research in Geographical and Environmental Education*, 32(2), 140–158. <https://doi.org/10.1080/10382046.2022.2138172>
14. Horowitz, S. S., & Schultz, P. H. (2014). Printing space: using 3D printing of digital terrain models in geosciences education and research. *Journal of Geoscience Education*, 62(1), 138–145. <https://doi.org/10.5408/13-031.1>

15. Ilyashenko, L. K. (2019). Determining the level of students' research skills and designing a model of influencing factors on research skills. *Humanities & Social Sciences Reviews*, 7(3), 581–584. <https://doi.org/10.18510/hssr.2019.7386>
16. Jia, W., Pan, L., Neary, S., & Moore, N. (2025). Interdisciplinary knowledge flow in international higher education research: characteristics and mechanisms. *Education Sciences*, 15(2), 221. <https://doi.org/10.3390/educsci15020221>
17. Katoh, S., Aalbers, R., & Sengoku, S. (2021). Effects and interactions of researcher's motivation and personality in promoting interdisciplinary and transdisciplinary research. *Sustainability*, 13(22), 12502. <https://doi.org/10.3390/su132212502>
18. Ki, J. (2019). GIS and big data visualization. In *Geographic information systems and science*. IntechOpen. <https://doi.org/10.5772/intechopen.82052>
19. Leonis, A. N., Ahmed, M. F., Mokhtar, M. B., Lim, C. K., & Halder, B. (2024). Challenges of using a Geographic Information System (GIS) in managing flash floods in Shah Alam, Malaysia. *Sustainability*, 16(17), 7528. <https://doi.org/10.3390/su16177528>
20. Luppichini, M., Capolongo, D., Scardino, G., Scicchitano, G., & Bini, M. (2025). Artificial intelligence in geomorphology: a bibliometric analysis of trends, techniques, and global research patterns. *Geosciences*, 15(9), 331. <https://doi.org/10.3390/geosciences15090331>
21. Markov, D. S., Ginko, V. I., & Malygin, A. D. (2022). Development of geoinformation competencies among students majoring in History and Geography (44.03.05 Pedagogical Education). *Samara Journal of Science*, 11(1), 307–313. <https://doi.org/10.55355/snv2022111308>
22. Muhamad Dah, N., Mat Noor, M. S. A., Kamarudin, M. Z., & Syed Abdul Azziz, S. S. (2024). The impacts of open inquiry on students' learning in science: a systematic literature review. *Educational Research Review*, 43, 100601. <https://doi.org/10.1016/j.edurev.2024.100601>
23. Panjaitan, B. R., Ningrum, E., & Waluya, B. (2023). Digital learning tools in geography education: A systematic literature review. *The Eurasia Proceedings of Educational and Social Sciences*, 33, 135–143. <https://doi.org/10.55549/epess.1413355>
24. Paucar-Curasma, R., Unsihuay-Tovar, R. F., Acra-Despradel, C., & Villalba-Condori, K. O. (2025). Integration of technological resources and problem-solving method for the development of research competencies in engineering and nursing students from two public universities in Peru. *Education Sciences*, 15(9), 1250. <https://doi.org/10.3390/educsci15091250>
25. Pavlova, A. V., & Telyatnikov, I. S. (2022). Use of GIS technologies and a digital terrain model to study spatial processes. *Ecological Bulletin of the Scientific Centres of the Black Sea Economic Cooperation*, 19(1), 35–41. <https://doi.org/10.31429/vestnik-19-1-35-41>
26. Polidori, L., & El Hage, M. (2020). Digital elevation model quality assessment methods: a critical review. *Remote Sensing*, 12(21), 3522. <https://doi.org/10.3390/rs12213522>
27. Samsul, S. A., Yahaya, N., & Abuhassna, H. (2023). Education big data and learning analytics: A bibliometric analysis. *Humanities and Social Sciences Communications*, 10, 709. <https://doi.org/10.1057/s41599-023-02176-x>
28. Sang, X., Xue, L., Leng, X., Li, X., & Zhou, J. (2020). Using photo modeling based 3DGRSL to promote the sustainability of geo-education: a case study from China. *arXiv*. <https://arxiv.org/abs/2004.05535>
29. Satymova, Z. (2025). Interdisciplinary research methodologies in teaching geography under digital transformation. *Eurasian Science Review: An International Peer-Reviewed Multidisciplinary Journal*, 3(7), 152–159. <https://doi.org/10.63034/esr-573>
30. Tapullima-Mori, C., Pizzan Tomanguillo, S., Pizzan Tomanguillo, N., Vásquez Sánchez, M., & Soria Quijaite, J. (2025). Charting the path to excellence: a review of research competencies in university students. *Journal of Technology and Science Education*, 15(2), 364–379. <https://doi.org/10.3926/jotse.2729>

31. Vidal de Souza, A. S., Maia, R. P., Rocha, H., Araújo, M. B. de, & Moura, P. E. de F. (2025). Technologies applied to geomorphology teaching - virtual reality and digital models. *Revista Brasileira de Geomorfologia*, 26(3). <https://doi.org/10.20502/rbg.v26i3.2639>
32. Viles, H. (2016). Technology and geomorphology: are improvements in data collection techniques transforming geomorphic science? *Geomorphology*, 270, 121–133. <https://doi.org/10.1016/j.geomorph.2016.07.011>
33. Wu, S., Lin, M., Ji, M., & Wang, T. (2024). Exploring core knowledge in interdisciplinary research: Insights from topic modeling analysis. *Applied Sciences*, 14(21), 10054. <https://doi.org/10.3390/app142110054>
34. Xiong, L., Li, S., Tang, G., & Strobl, J. (2022). Geomorphometry and terrain analysis: data, methods, platforms and applications. *Earth-Science Reviews*, 233, 104191. <https://doi.org/10.1016/j.earscirev.2022.104191>
35. Yu, L., & Zin, Z. M. (2023). The critical thinking-oriented adaptations of problem-based learning models: a systematic review. *Frontiers in Education*, 8, 1139987. <https://doi.org/10.3389/educ.2023.1139987>

Цифрлық технологиялар мен модельдеуді интеграциялау арқылы геоморфологияны оқытуда зерттеу құзыреттіліктерін дамыту

Ерлан Нуркеев, Ердаулет Тулегенов

Аңдатпа: Білім беруді цифрландыру үдерісінің жалғасуы және зерттеуге бағытталған оқытудың маңыздылығының артуы жағдайында пәнаралық тәсілдер арқылы студенттердің зерттеу құзыреттіліктерін дамыту жоғары білім берудің негізгі басымдықтарының біріне айналды. Бұл зерттеуде зерттеу дағдылары мен ғылыми ойлауды жетілдірудің негізі ретінде геоморфологияны физика және цифрлық технологиялармен интеграциялау қарастырылады. Физикалық модельдеу мен цифрлық құралдарды ұштастыру студенттердің жер бедерінің қалыптасу үдерістерін терең түсінуіне, сондай-ақ аналитикалық, сыни және жүйелік ойлау қабілеттерін дамытуға бағытталған.

Зерттеуде эрозия, тектоникалық қозғалыстар және гидрологиялық құбылыстар сияқты геоморфологиялық үдерістерді көрсету үшін физикалық модельдердің білім беру әлеуеті талданды. Бұл модельдер студенттерге табиғи жүйелердің динамикасын бақылауға және түсіндіруге мүмкіндік береді. Сонымен қатар геоморфологиялық ақпаратты жинау, өңдеу, визуализациялау және модельдеу үшін географиялық ақпараттық жүйелерді (GIS), цифрлық картографиялауды, жер бедерін модельдеуді және үлкен деректерді (Big Data) талдауды қолдану қарастырылды.

Аталған технологиялар эксперимент нәтижелерін түсіндіруге және цифрлық сауаттылықты дамытуға ықпал етеді. Зерттеу құзыреттіліктерін дамытуға арналған кезеңдік әдістеме ұсынылды. Ол проблемалық оқытуды, физикалық эксперимент жүргізуді, цифрлық деректерді талдауды және нәтижелерді жобалық негізде түсіндіруді қамтиды. Студенттер табиғи құбылыстарды бақылаудан бастап модельдер құруға, деректерді талдауға, гипотезалар ұсынуға, себеп-салдарлық байланыстарды анықтауға және зерттеу нәтижелерін цифрлық форматта ұсынуға дейінгі кезеңдерден өтеді. Бұл үдеріс өз бетінше зерттеу жүргізу, бірлесіп оқу және дәлелдерге негізделген ғылыми пайымдау дағдыларын дамытуға мүмкіндік береді.

30 студенттің қатысуымен жүргізілген педагогикалық зерттеу нәтижелері практикалық эксперименттерді цифрлық технологиялармен ұштастыру зерттеу құзыреттіліктерінің, сыни ойлаудың, аналитикалық қабілеттердің және проблемаларды шешу дағдыларының артуымен, сондай-ақ ғылыми зерттеулерге қатысу уәжінің жоғарылауымен байланысты екенін көрсетті. Ұсынылған тәсіл цифрлық экономика талаптарына сәйкес келетін және геоғылымдарды

оқытуда цифрлық әдістерді қолдана алатын мамандарды даярлаудың практикалық моделін ұсынады.

Түйін сөздер: геоморфология; пәнаралық тәсіл; физикалық модельдер; цифрлық технологиялар; GIS; деректерді талдау; зерттеу құзыреттіліктері; зерттеу қызметі; студенттерді даярлау; цифрлық сауаттылық.

Развитие исследовательских компетенций при обучении геоморфологии посредством интеграции цифровых технологий и моделирования

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Аннотация: В условиях продолжающейся цифровизации образования и возрастания значимости исследовательски-ориентированного обучения развитие исследовательских компетенций студентов посредством междисциплинарных подходов становится одним из ключевых приоритетов высшего образования. В данном исследовании рассматривается интеграция геоморфологии, физики и цифровых технологий как основа для развития исследовательских навыков и научного мышления.

Сочетание физического моделирования и цифровых инструментов направлено на углубление понимания студентами процессов формирования рельефа, а также на развитие аналитического, критического и системного мышления. В исследовании анализируется образовательный потенциал физических моделей для демонстрации геоморфологических процессов - эрозии, тектонических движений и гидрологических явлений, позволяющих студентам наблюдать и интерпретировать динамику природных систем. Также рассматривается применение географических информационных систем (GIS), цифрового картографирования, моделирования рельефа и анализа больших данных (Big Data) для сбора, обработки, визуализации и моделирования геоморфологической информации.

Использование данных технологий способствует интерпретации результатов экспериментов и развитию цифровой грамотности. Предложена поэтапная методика развития исследовательских компетенций, включающая проблемно-ориентированное обучение, проведение физических экспериментов, анализ цифровых данных и проектную интерпретацию полученных результатов. Студенты последовательно переходят от наблюдения природных явлений к построению моделей, анализу данных, формулированию гипотез, выявлению причинно-следственных связей и представлению результатов в цифровом формате. Такой подход способствует развитию самостоятельной исследовательской деятельности, совместного обучения и научного мышления, основанного на доказательствах.

Результаты педагогического исследования с участием 30 студентов показывают, что сочетание практических экспериментов и цифровых технологий связано с повышением уровня исследовательских компетенций, критического мышления, аналитических способностей и навыков решения проблем, а также с усилением мотивации к участию в научно-исследовательской деятельности. Предлагаемый подход представляет собой практическую модель подготовки специалистов, способных применять цифровые методы в геонаучном образовании, и соответствует современным требованиям цифровой экономики.

Ключевые слова: геоморфология; междисциплинарный подход; физические модели; цифровые технологии; GIS; анализ данных; исследовательские компетенции; исследовательская деятельность; подготовка студентов; цифровая грамотность.