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Immersive geospatial learning for flood disaster education: Integrating GIS, augmented reality, spatial literacy, and ecopedagogy

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Abstract

Flood disasters remain a recurring challenge in many regions and underscore the importance of educational approaches that help students understand environmental risks and develop preparedness capacities. Although Geographic Information Systems (GIS), Augmented Reality (AR), spatial literacy, and environmental learning have gained increasing attention in disaster education, these elements are often implemented independently, limiting opportunities for more integrated learning experiences. This research designed and evaluated immersive geospatial learning for flood disaster education by bringing together GIS, AR, spatial literacy, higher-order thinking skills, and ecopedagogical perspectives within a single instructional framework. The study adopted an Educational Design Research approach consisting of needs analysis, learning material development, expert validation, classroom implementation, and educational evaluation. Learning activities were supported by GIS-based flood hazard maps, AR visualizations, inquiry-based investigations, and environmental reflection grounded in local flood issues. Expert assessment confirmed the feasibility of the learning materials, with average scores of 4.72 for content, 4.56 for media, and 4.76 for language, resulting in an overall score of 4.68. The effectiveness evaluation involved 107 senior high school students through a quasi-experimental design. Students who participated in immersive geospatial learning achieved significantly higher gains in spatial literacy and flood preparedness than those receiving conventional instruction ($p < .05$), with a large effect size (Cohen's $d = 1.02$). These results suggest that combining geospatial technologies with inquiry and environmental reflection can create meaningful learning experiences that strengthen both spatial understanding and disaster preparedness in geography education.

Keywords: Augmented reality, Flood disaster education, Geographic information systems, Immersive geospatial learning, Spatial literacy.

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Institutional Review Board Statement: The study involved minimal risk and followed ethical guidelines for social science fieldwork. Formal approval from an Institutional Review Board was not required under the policies of the Institute for Research Ethics Committee of the [Universitas Negeri Gorontalo, Indonesia]. Informed verbal consent was obtained from all participants, and all data were anonymized to protect participant confidentiality.

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Contents

Contribution of this paper to the literature

This study contributes to the existing literature by introducing an integrated immersive geospatial learning framework that combines GIS, Augmented Reality, spatial literacy, higher-order thinking skills, and ecopedagogy for strengthening students' capacity in flood disaster education.

1. Introduction

Floods are among the most frequent and destructive hydrometeorological hazards worldwide, causing extensive human suffering and substantial economic, social, and environmental losses. The increasing frequency and severity of flood events have been linked to climate variability, rapid urbanization, land-use transformation, watershed degradation, and declining ecosystem resilience (Andreadis et al., 2022; Laeni, van den Brink, & Arts, 2021; Yang et al., 2023). These challenges are particularly evident in developing countries where population growth, environmental degradation, and limited adaptive capacity intensify vulnerability to flood hazards. Beyond physical damage, recurrent flooding disrupts educational processes, weakens community resilience, exacerbates social inequalities, and hinders sustainable development efforts (Fahrudin et al., 2024; Rahat, Pradhananga, & ElZomor, 2024). Consequently, strengthening disaster risk reduction (DRR) through education has become an important priority for enhancing societal resilience in the face of escalating environmental challenges.

Education plays a critical role in disaster preparedness by enabling learners to understand hazard processes, recognize environmental vulnerabilities, evaluate risk factors, and develop mitigation and adaptation strategies before disasters occur (Hoffmann & Blecha, 2020; Pal, Raj, Pal, & Sukwanchai, 2021). Contemporary disaster education extends beyond hazard knowledge and increasingly emphasizes resilience, environmental responsibility, critical thinking, and informed decision-making (Hawa et al., 2023; Partini & Hidayaht, 2024). Nevertheless, disaster-related instruction in many schools continues to rely on teacher-centered approaches that prioritize factual knowledge rather than contextual inquiry and problem-solving. Such practices often limit students' ability to connect disaster concepts with environmental conditions encountered in their daily lives (Kamil, Utaya, Sumarmi, & Utomo, 2020; Zhang & Wang, 2022).

Indonesia represents one of the countries most exposed to hydrometeorological hazards in Southeast Asia. Flood events occur regularly across both urban and rural areas, generating significant economic and social consequences. Gorontalo Province has experienced recurrent flooding associated with watershed degradation, land-use conversion, inadequate drainage systems, and unsustainable environmental management. Recent flood events affected thousands of households and displaced large numbers of residents, underscoring the need for educational interventions that strengthen preparedness and environmental awareness from an early age (Arsyad, 2024; Gorontalo City Central Statistics Agency, 2024). Existing learning resources, however, frequently present flood hazards as generalized phenomena detached from local environmental contexts. Limited opportunities are therefore available for students to investigate local vulnerability patterns, interpret spatial risk distributions, and evaluate mitigation alternatives relevant to their communities.

Addressing these challenges requires educational approaches capable of fostering spatial understanding and environmental reasoning. Spatial literacy has been recognized as a fundamental competency in geography and disaster education because it enables learners to interpret spatial relationships, recognize geographic patterns, understand environmental processes, and utilize spatial information for decision-making (Kerski, 2015; Oberle, Araya, & Alvarez, 2024). Within disaster contexts, spatial literacy supports the interpretation of hazard maps, identification of vulnerable locations, and evaluation of disaster mitigation strategies (Ridha et al., 2021; Safitri, Juhadi, & Aji, 2024). The growing availability of geospatial technologies has created new opportunities for strengthening these competencies through more authentic and contextual learning experiences.

Geographic Information Systems (GIS) have become increasingly important in geography education due to their capacity to visualize, analyze, and communicate spatial information. GIS-based learning enables students to engage with authentic geographic data and investigate real-world environmental problems through spatial analysis (Li & Liu, 2022; Vojtek, 2023). At the same time, Augmented Reality (AR) offers opportunities to visualize environmental processes that are often difficult to observe directly, thereby transforming abstract concepts into interactive learning experiences (Li et al., 2022; Safitri et al., 2024). Previous studies have demonstrated that immersive technologies can enhance conceptual understanding, learner engagement, and environmental reasoning (Romualdi, Sudrajat, & Aman, 2023; Tyas, Pujianto, & Suyanta, 2021). Despite these advances, GIS, AR, spatial literacy, higher-order thinking skills (HOTS), and ecopedagogy are frequently examined as separate educational components rather than integrated elements within a unified disaster education framework.

Several important gaps remain evident in the literature. First, many studies emphasize technological development or media feasibility while providing limited evidence regarding pedagogical integration. Second, research involving GIS and AR often focuses on technological functionality rather than examining how these technologies support spatial reasoning, environmental understanding, and preparedness-oriented learning. Third, limited attention has been given to integrating geospatial technologies, spatial literacy, HOTS, and ecopedagogical perspectives within a single instructional framework for disaster education. Consequently, there remains insufficient understanding of how immersive learning resources can simultaneously promote spatial competence, environmental awareness, critical inquiry, and disaster preparedness in authentic educational settings.

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This study addresses these gaps through the development and evaluation of immersive geospatial learning materials for flood disaster education that integrate Geographic Information Systems (GIS), Augmented Reality (AR), spatial literacy, higher-order thinking skills, and ecopedagogical principles. The developed materials combine GIS-based flood hazard mapping, AR-enhanced visualization, inquiry-oriented learning activities, and environmental reflection centered on local flood issues. By integrating these components within a contextual learning framework, the study contributes empirical evidence regarding the feasibility and educational potential of immersive geospatial learning for strengthening disaster preparedness, environmental understanding, and spatial competencies among secondary school students.

2. Literature Review

2.1. Disaster Education and Spatial Literacy

Disaster education has evolved from a knowledge-transmission approach toward a broader educational framework that emphasizes preparedness, resilience, environmental awareness, and adaptive capacity. Within disaster risk reduction (DRR), schools are increasingly recognized as strategic institutions for developing disaster knowledge and preparedness among younger generations (Hoffmann & Blecha, 2020; Pal et al., 2021). Effective disaster education not only improves understanding of hazard processes but also strengthens learners' abilities to assess risks, make informed decisions, and respond appropriately to environmental challenges (Hawa et al., 2023; Partini & Hidayaht, 2024).

A fundamental competency supporting these outcomes is spatial literacy. Spatial literacy refers to the capacity to understand spatial relationships, interpret geographic information, recognize patterns across space, and utilize spatial reasoning for problem-solving and decision-making (Kerski, 2015; Oberle et al., 2024). In disaster contexts, spatial literacy enables learners to identify hazard-prone locations, interpret risk maps, analyze environmental interactions, and evaluate mitigation alternatives (Ridha & Kamil, 2021; Safitri et al., 2024). Individuals with strong spatial literacy are generally better equipped to understand the geographic dimensions of environmental risks and to make informed decisions regarding disaster preparedness and adaptation.

Research has consistently shown that spatial literacy contributes to improved geographic reasoning and environmental understanding. Learners who develop strong spatial competencies demonstrate greater ability to interpret spatial data, analyze environmental processes, and evaluate alternative solutions to geographical problems (Jo & Bednarz, 2009; Kerski, 2015). Such competencies are particularly important in flood disaster education because flood vulnerability is inherently spatial, resulting from interactions among topography, land use, hydrological conditions, and human activities.

Despite its importance, spatial literacy remains insufficiently integrated within many disaster education programs. Learning activities often emphasize hazard knowledge while providing limited opportunities for spatial investigation, environmental analysis, and geographic reasoning (Ridha & Kamil, 2021). Consequently, students may understand disaster concepts theoretically but experience difficulties in applying this knowledge to real environmental situations. This limitation highlights the need for educational approaches capable of connecting disaster learning with authentic spatial experiences and contextual environmental problems.

2.2. Geographic Information Systems and Augmented Reality in Geography Education

Technological advances have expanded opportunities for developing spatial literacy through geospatial learning environments. Geographic Information Systems (GIS) have become one of the most widely adopted technologies in geography education because they enable visualization, analysis, and communication of spatial information in meaningful ways (Li et al., 2022; Vojtek, 2023). GIS allows learners to investigate authentic geographic data, identify spatial patterns, and analyze environmental processes through evidence-based inquiry.

Previous studies have reported positive effects of GIS-supported learning on spatial thinking, geographic reasoning, environmental awareness, and student engagement (Favier & van der Schee, 2014; Li & Liu, 2022). The use of GIS enables students to move beyond passive learning by interacting directly with spatial datasets and exploring relationships among environmental variables. Such experiences are particularly valuable in disaster education because hazard vulnerability is often determined by spatial interactions among natural and human systems.

Alongside GIS, Augmented Reality (AR) has emerged as a promising educational technology capable of enhancing learner engagement and conceptual understanding. AR overlays digital information onto real-world environments, allowing users to interact with virtual representations while maintaining awareness of their physical surroundings (Li et al., 2022). Educational applications of AR have demonstrated benefits in visualization, motivation, conceptual learning, and experiential engagement (Romualdi et al., 2023; Tyas et al., 2021).

Within disaster education, AR offers unique advantages because many environmental processes are difficult to observe directly. Flood dynamics, hazard propagation, and vulnerability patterns often occur at scales that are challenging to visualize through traditional instructional media. AR-based learning environments can address these limitations by presenting interactive simulations that allow learners to explore environmental phenomena from multiple perspectives. Such immersive experiences have been shown to improve understanding of environmental processes and strengthen engagement with disaster-related learning tasks (Li et al., 2022; Romualdi et al., 2023).Although GIS and AR have independently demonstrated educational benefits, research integrating these technologies within a unified learning framework remains limited. Existing studies frequently examine GIS-based learning or AR-supported learning separately, resulting in insufficient understanding of how the combined use of these technologies can support disaster preparedness, spatial reasoning, and environmental understanding simultaneously.

2.3. Higher-Order Thinking Skills and Ecopedagogical Learning

Flood disasters represent complex socio-ecological challenges shaped by interactions among environmental, social, economic, and political factors. Understanding such complexity requires learners to engage in higher-order thinking processes involving analysis, evaluation, interpretation, and problem-solving. Higher-order thinking skills

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(HOTS) have therefore become a central objective within geography education because they enable students to examine complex environmental issues and formulate evidence-based solutions (Abdimanapov, Kumarbekuly, & Gaisin, 2025; Zohar & Dori, 2003).

HOTS-oriented learning encourages learners to investigate environmental evidence, assess competing perspectives, evaluate mitigation alternatives, and justify decisions using logical reasoning. Previous research has demonstrated that inquiry-based and problem-based learning approaches can significantly strengthen critical thinking and analytical reasoning in geography education (Hawa et al., 2023). These competencies are essential within disaster education because preparedness requires more than factual knowledge; it demands the ability to interpret environmental information and make adaptive decisions under uncertain conditions.

Ecopedagogy complements HOTS by emphasizing environmental responsibility, sustainability, and critical reflection on human-environment relationships. Originating from critical environmental education, ecopedagogy views environmental problems as socio-ecological issues shaped by human actions, cultural practices, economic systems, and development choices (Kinyota, 2021; Misiaszek, 2016, 2025). This perspective encourages learners to examine environmental degradation, resource exploitation, and ecological vulnerability from ethical and sustainability-oriented viewpoints.

Within flood disaster education, ecopedagogical approaches help learners understand that disaster vulnerability is not solely determined by natural processes. Human activities such as deforestation, watershed degradation, uncontrolled urban expansion, and unsustainable land-use practices often contribute significantly to increasing flood risks (Fauzi, Fitriasari, & Muthaqin, 2022; Wardhani et al., 2022). Reflection on these relationships encourages students to develop environmental responsibility alongside disaster preparedness competencies.

The integration of HOTS and ecopedagogy therefore provides opportunities for learners to engage with disaster issues cognitively and ethically. Such integration supports the development of critical, reflective, and environmentally responsible citizens capable of responding to contemporary environmental challenges.

2.4. Research Gap and Conceptual Framework

A review of existing literature reveals several unresolved issues. First, many studies emphasize technological innovation, media development, or usability evaluation while providing limited attention to pedagogical integration and educational outcomes) (Li & Liu, 2022; Romualdi et al., 2023). Second, GIS and AR are frequently investigated as independent technologies rather than complementary tools capable of supporting integrated disaster learning experiences. Third, limited research has simultaneously incorporated spatial literacy, HOTS, and ecopedagogical perspectives within technology-supported disaster education environments.

As a consequence, insufficient empirical evidence exists regarding how immersive learning resources can integrate geospatial technologies, spatial reasoning, environmental awareness, and preparedness-oriented learning within a coherent educational framework. Addressing this gap is particularly important given the increasing demand for innovative educational approaches capable of preparing learners for complex environmental challenges and disaster risks.

The present study responds to these limitations through the development and evaluation of immersive geospatial learning materials for flood disaster education that integrate Geographic Information Systems (GIS), Augmented Reality (AR), spatial literacy, higher-order thinking skills (HOTS), and ecopedagogical principles. The conceptual framework assumes that the integration of geospatial technologies, inquiry-oriented learning, environmental reflection, and spatial reasoning can create meaningful learning experiences that strengthen preparedness, environmental understanding, and spatial competencies among secondary school students.

3. Research Method

3.1. Research Design

This study employed Educational Design Research (EDR) to develop and evaluate immersive geospatial learning materials for flood disaster education. EDR is particularly appropriate for addressing complex educational problems because it combines the systematic design of educational interventions with empirical investigation conducted in authentic learning environments (McKenney & Reeves, 2018; Plomp, 2013). The approach facilitates iterative refinement while simultaneously generating practical solutions and theoretical insights.

The research was conducted through five interconnected phases: (1) needs analysis, (2) development, (3) validation, (4) implementation, and (5) educational evaluation. Findings obtained at each phase informed subsequent revisions, enabling continuous improvement of the developed learning materials. Geographic Information Systems (GIS), Augmented Reality (AR), spatial literacy, higher-order thinking skills (HOTS), and ecopedagogical perspectives were integrated throughout the development process to support contextual and preparedness-oriented learning.

The study was guided by the following research questions: (1) How can immersive geospatial learning materials integrating GIS, AR, spatial literacy, HOTS, and ecopedagogy be developed for flood disaster education? (2) To what extent are the developed learning materials feasible for classroom implementation? (3) How do the developed learning materials contribute to students' spatial literacy and flood preparedness?

3.2. Development Framework of GIS and AR-Supported Immersive Learning Materials

Development of the learning materials was informed by geospatial learning principles, constructivist learning theory, higher-order thinking skills, and ecopedagogical perspectives. The framework was designed to support contextual exploration of flood hazards through the integration of spatial literacy, geospatial technologies, inquiry-based learning, and environmental reflection.

Five interrelated components formed the foundation of the framework. Spatial literacy activities emphasized hazard interpretation, spatial reasoning, geographic analysis, and decision-making. GIS provided flood hazard maps and geospatial datasets that enabled investigation of environmental conditions and vulnerability patterns. AR enhanced learning through interactive visualization of flood processes and mitigation scenarios. HOTS-oriented activities encouraged analysis, evaluation, and problem solving, while ecopedagogical learning promoted

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environmental responsibility and sustainability-oriented reflection. Learning activities were structured through five stages: exploration, investigation, analysis, reflection, and preparedness planning. The sequence was designed to connect geospatial investigation with environmental understanding and disaster preparedness.

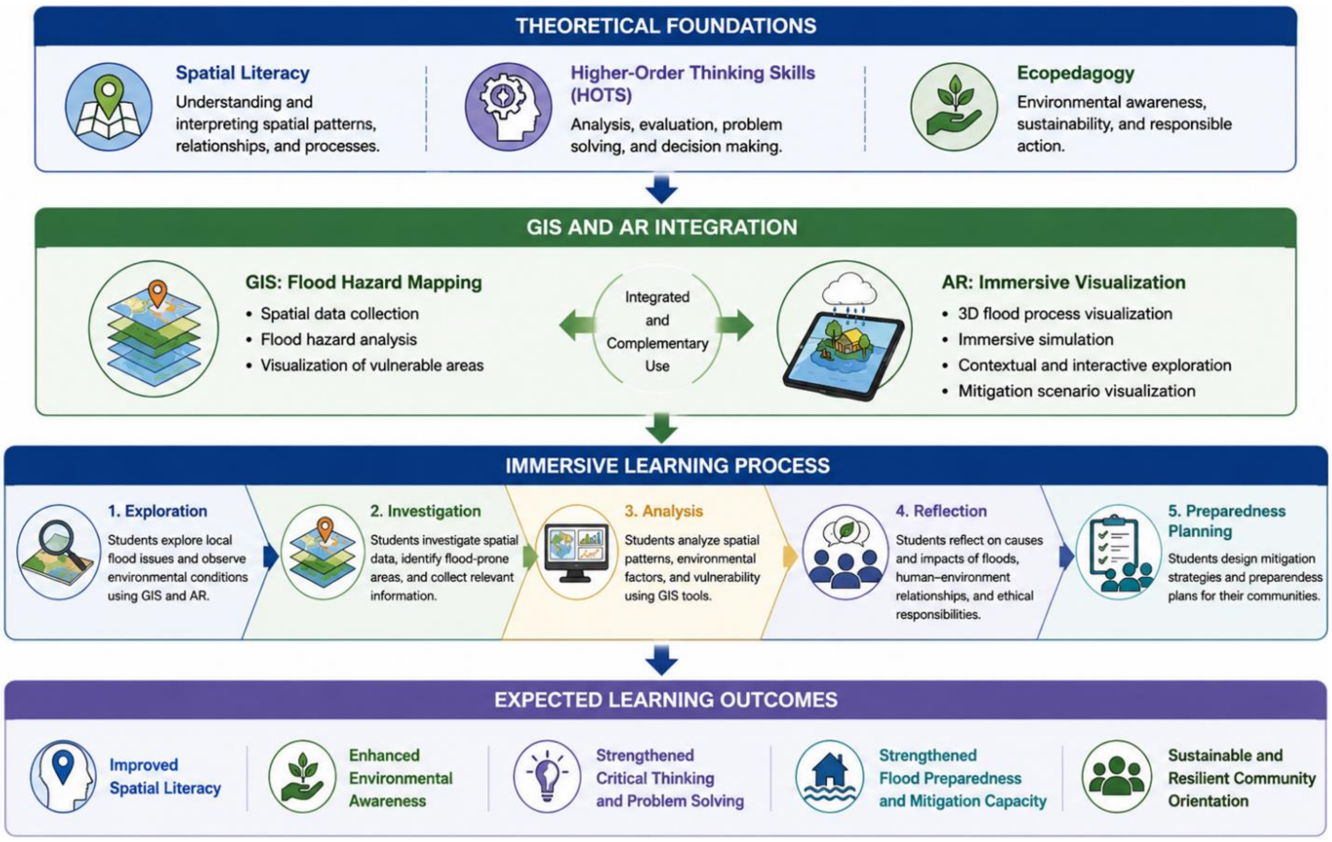

Figure 1. Framework of GIS and AR-Supported Immersive Learning Materials for Flood Disaster Education.

3.3. Research Context and Participants

The study was conducted in Gorontalo City, Indonesia, an area frequently affected by flood disasters associated with watershed degradation, land-use transformation, rapid urban expansion, and drainage limitations. The recurrent occurrence of flooding provided an authentic context for the development and implementation of disaster education materials. Participants were selected according to the objectives of each research phase. Table 1 presents the participants involved in each phase of the Educational Design Research and their respective roles in the study

Table 1. Research Participants.

Research Phase	Participants	Purpose
Needs Analysis	Geography teachers and Grade XI students	Identification of learning needs and instructional challenges
Expert Validation	Geography education expert, educational technology expert, and language expert	Evaluation of content, media, and language quality
Implementation and Evaluation	107 Grade XI students from six senior high schools	Examination of educational feasibility and learning outcomes

Purposive sampling was employed during the implementation phase because EDR prioritizes contextual relevance and meaningful educational application rather than population representativeness (Creswell & Poth, 2017; McKenney & Reeves, 2018).

3.4. Instruments

Multiple instruments were employed to support the analysis, development, validation, and evaluation phases of the study. Instrument development was guided by disaster education competencies, spatial literacy frameworks, HOTS indicators, and ecopedagogical learning outcomes identified in previous studies (Kerski, 2015; Ridha et al., 2021).

3.4.1. Needs Analysis Questionnaire

The questionnaire examined instructional needs related to disaster education, spatial literacy, and technology integration. Table 2 presents the dimensions and indicators included in the needs analysis questionnaire.

Table 2. Needs Analysis Instrument.

Dimension	Indicators
Disaster Education	Flood causes, impacts, mitigation, adaptation, preparedness
Spatial Literacy	Hazard map interpretation, spatial reasoning, geographic analysis
Technology Readiness	Digital literacy, GIS familiarity, AR accessibility

3.4.2. Expert Validation Instrument

Expert validation was conducted using structured evaluation sheets covering content quality, media quality, and language quality. Table 3 presents the assessment aspects and indicators used by the experts to evaluate the developed learning materials.

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Table 3. Expert Validation Indicators.

Aspect	Indicators
Content	Scientific accuracy, curriculum alignment, disaster relevance, spatial literacy integration, HOTS integration, ecopedagogical relevance
Media	Visual design, navigation, usability, interactivity, accessibility
Language	Clarity, readability, consistency, communicative effectiveness

3.4.3. Learning Outcome Assessment

Learning outcomes were evaluated using structured assessments designed to measure spatial literacy, flood preparedness, higher-order thinking skills, and environmental understanding. Table 4 presents the learning outcome constructs and their corresponding indicators used in the educational evaluation.

Table 4. Learning Outcome Constructs.

Construct	Indicators
Spatial Literacy	Interpretation of flood hazard maps, identification of spatial patterns, analysis of environmental relationships, spatial decision-making
Flood Preparedness	Hazard awareness, mitigation knowledge, preparedness planning, adaptive responses
HOTS	Analysis, evaluation, evidence-based reasoning, problem solving
Ecopedagogical Understanding	Environmental awareness, sustainability reasoning, human environment relationships, environmental responsibility

The assessment framework was developed based on disaster education competencies, spatial literacy indicators, and higher-order cognitive processes proposed in contemporary geography education literature (Kerski, 2015; Ridha & Kamil, 2021).

3.5. Validation and Revision Procedures

Prior to implementation, all research instruments and learning materials underwent expert validation to establish content validity and instructional feasibility. Expert review is an essential procedure in Educational Design Research because it enables systematic evaluation of educational products before field implementation and contributes to the credibility of the development process (Cohen, Manion, & Morrison, 2017; McKenney & Reeves, 2018; Plomp, 2013).

Content validity was established through expert judgment using Aiken's V coefficient. Experts assessed the relevance, representativeness, clarity, and appropriateness of each instrument item using a five-point rating scale. Aiken's V is widely used to quantify agreement among experts regarding item relevance and is particularly appropriate for educational measurement studies involving a limited number of validators (Aiken, 1985; Penfield & Giacobbi, 2004).

The coefficient was calculated using.

$$V = \frac{\sum s}{n(c-1)} \quad (1)$$

Where s represents the adjusted rating score, n represents the number of experts, and c represents the number of response categories. Following established recommendations, coefficients exceeding 0.80 indicate strong content validity, whereas lower values suggest the need for item revision (Cohen et al., 2017).

Instrument reliability was evaluated using Cronbach's alpha coefficient to determine internal consistency. Reliability values greater than 0.70 were considered acceptable, values greater than 0.80 indicated good reliability, and values exceeding 0.90 indicated excellent reliability (Taber, 2018; Tavakol & Dennick, 2011).

In addition to quantitative validation results, qualitative feedback from experts was analyzed and incorporated into the revision of learning materials, GIS-based hazard maps, AR components, assessment instruments, and instructional procedures. This iterative revision process ensured that the final version of the immersive learning materials met pedagogical, technical, and content-related quality standards.

3.6. Data Collection Procedures

Data collection was conducted throughout all phases of Educational Design Research. During the needs analysis phase, questionnaire responses, interviews, and curriculum documents were collected to identify instructional needs and contextual learning challenges. During the development phase, design artifacts, expert reviews, and prototype evaluations were gathered to support iterative refinement.

The implementation phase involved classroom implementation of the developed immersive learning materials. Data collected during this phase included achievement test scores, classroom observation records, and student responses regarding learning experiences. Learning activities incorporated GIS-supported hazard mapping, AR-assisted visualization, collaborative inquiry, contextual problem solving, and ecopedagogical reflection activities designed to strengthen disaster preparedness and spatial literacy competencies (Kyaw & Tun, 2023; Purnomo, Widiyanto, Novyanto, & Pratiwi, 2023).

3.7. Data Analysis

Both qualitative and quantitative analytical procedures were employed. Qualitative data obtained from interviews, observations, and expert comments were analyzed using the interactive model consisting of data condensation, data display, and conclusion drawing. This approach facilitates systematic interpretation of complex educational phenomena and supports iterative refinement of educational designs (Miles & Huberman, 2014).

Quantitative data were analyzed using descriptive and inferential statistics. Descriptive statistics were used to summarize needs analysis findings, expert validation scores, and student responses. Quantitative data were analyzed using descriptive and inferential statistics.

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Descriptive statistics were used to summarize needs analysis findings, expert validation results, implementation outcomes, and student responses. Learning outcome data obtained during classroom implementation were analyzed using normalized gain (N-Gain), independent-sample t-tests, and Cohen's d effect size analysis to examine educational outcomes associated with the use of the developed immersive learning materials. N-Gain was used to measure learning improvement, while independent-sample t-tests were employed to identify differences between learning groups.

Cohen's d was calculated to determine the practical significance of the intervention beyond statistical significance. The combined use of significance testing and effect size analysis is widely recommended in educational research because it provides a more comprehensive interpretation of intervention effectiveness (Cohen et al., 2017; Field, 2013; Pallant, 2020).

3.8. Ethical Considerations

Participation was voluntary and based on informed consent obtained from participating schools, teachers, and students. All information collected during the study was treated confidentially and used exclusively for academic purposes. Participant anonymity was maintained throughout data analysis and reporting in accordance with ethical standards for educational research.

4. Results and Discussion

4.1. Needs Analysis of Flood Disaster Learning

The needs analysis was conducted through questionnaires, interviews, and curriculum review involving geography teachers and Grade XI students in Gorontalo City. The findings revealed that existing flood disaster learning materials were predominantly textbook-oriented and provided limited opportunities for students to explore local flood issues. Teachers reported difficulties in contextualizing disaster concepts using local environmental conditions, while students experienced challenges in interpreting spatial information and understanding the relationships between environmental factors and flood occurrence.

The analysis further indicated limited integration of spatial literacy, higher-order thinking skills (HOTS), and environmental reflection within existing learning resources. Most learning activities focused on conceptual knowledge acquisition rather than spatial investigation, problem solving, and disaster preparedness. Both teachers and students expressed strong preferences for interactive learning resources incorporating maps, visual media, simulations, and digital technologies capable of representing local flood conditions.

Technology readiness assessment demonstrated that students were familiar with digital learning environments and showed positive attitudes toward the use of geospatial technologies in geography learning. GIS-based visualization and Augmented Reality (AR) were perceived as potentially useful tools for improving understanding of flood hazards and mitigation strategies.

These findings confirmed the need for immersive geospatial learning materials capable of integrating spatial literacy, environmental awareness, and preparedness-oriented learning within a contextual flood disaster education framework. To summarize the findings obtained from the questionnaires, interviews, and curriculum review, Table 5 presents the major instructional needs identified during the needs analysis phase.

Table 5. Summary of Needs Analysis Findings.

Dimension	Major Findings
Disaster education	Learning materials insufficiently contextualized to local flood conditions
Spatial literacy	Difficulties in map interpretation and spatial reasoning
HOTS	Limited opportunities for analytical and problem-solving activities
Technology integration	Strong preference for GIS, AR, and interactive learning media
Environmental awareness	Need for stronger integration of sustainability and disaster preparedness

4.2. Development of GIS and AR-Supported Immersive Learning Materials

Results from the needs analysis informed the development of immersive geospatial learning materials integrating Geographic Information Systems (GIS), Augmented Reality (AR), spatial literacy, HOTS, and ecopedagogical principles. The development process followed the framework presented in Figure 1, which illustrates the integration of geospatial technologies, pedagogical components, and disaster preparedness learning outcomes.

The framework positioned spatial literacy as the foundation for understanding environmental risks, while GIS and AR functioned as technological tools supporting exploration and visualization. HOTS-oriented inquiry activities enabled students to investigate environmental evidence and evaluate disaster mitigation alternatives, whereas ecopedagogical reflection encouraged examination of human–environment relationships and environmental responsibility.

GIS resources were developed using local flood hazard information to ensure contextual relevance. Spatial data layers representing environmental characteristics were integrated to generate learning resources capable of illustrating flood vulnerability patterns across Gorontalo City.

Figure 2 illustrates the spatial distribution of flood hazard levels in Gorontalo City and serves as the primary geospatial resource for identifying vulnerable areas and supporting spatial analysis during learning activities.

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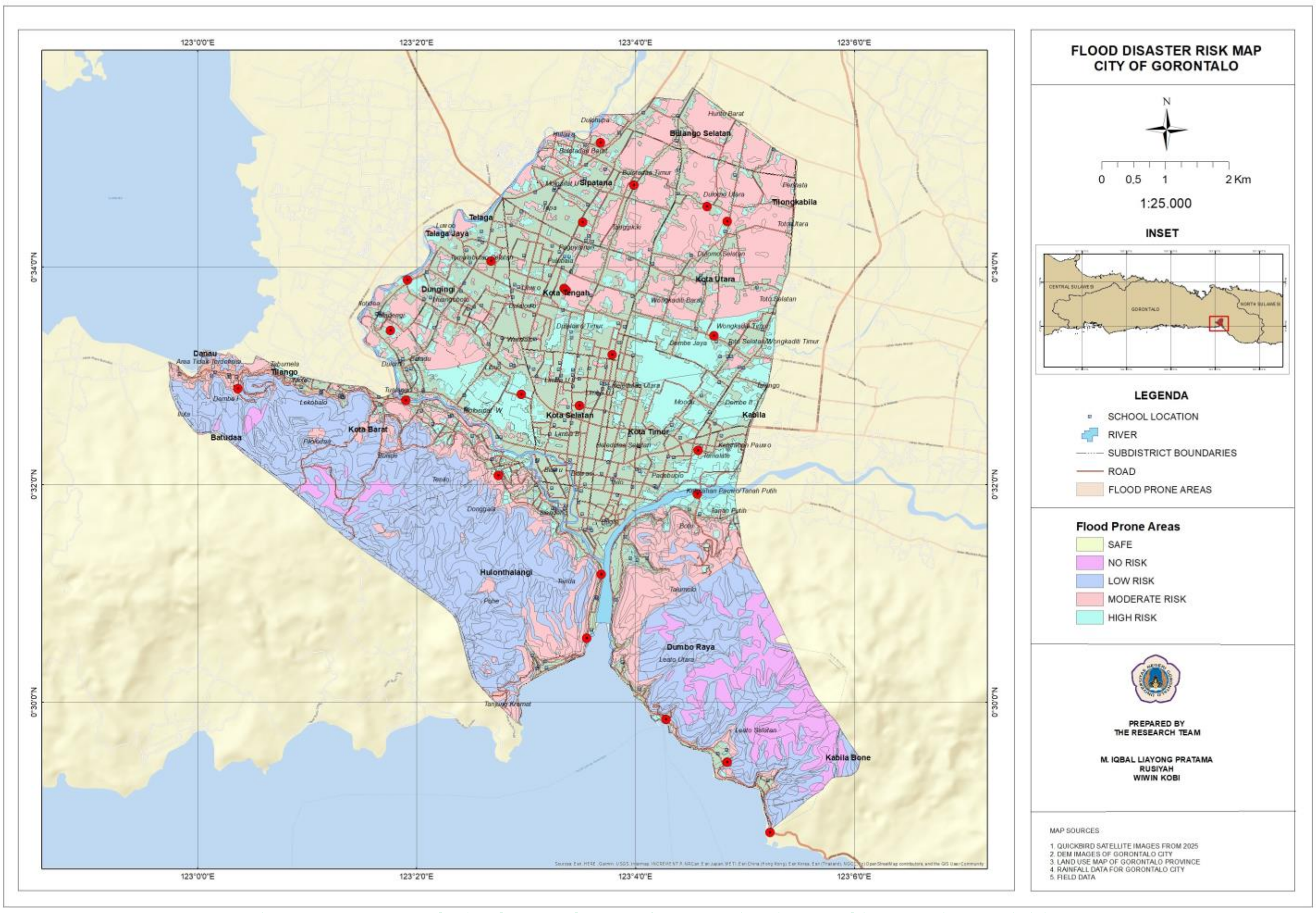

Figure 2. GIS-Based Flood Hazard Map of Gorontalo City Used in Learning Activities.

The flood hazard map served as a primary geospatial resource for identifying vulnerable locations, interpreting spatial patterns, and supporting environmental analysis. Integration of authentic geospatial information enabled students to examine local flood conditions and evaluate relationships among environmental variables influencing flood risk.

To enhance visualization and learner engagement, AR components were developed to represent flood processes and mitigation scenarios through interactive mobile-based environments. AR visualization enabled learners to explore environmental conditions from multiple perspectives and observe flood impacts that are difficult to demonstrate through conventional instructional media. Figure 3 illustrates the Augmented Reality interface used to visualize flood distribution and mitigation scenarios, enabling students to interact with geospatial information through immersive learning experiences.

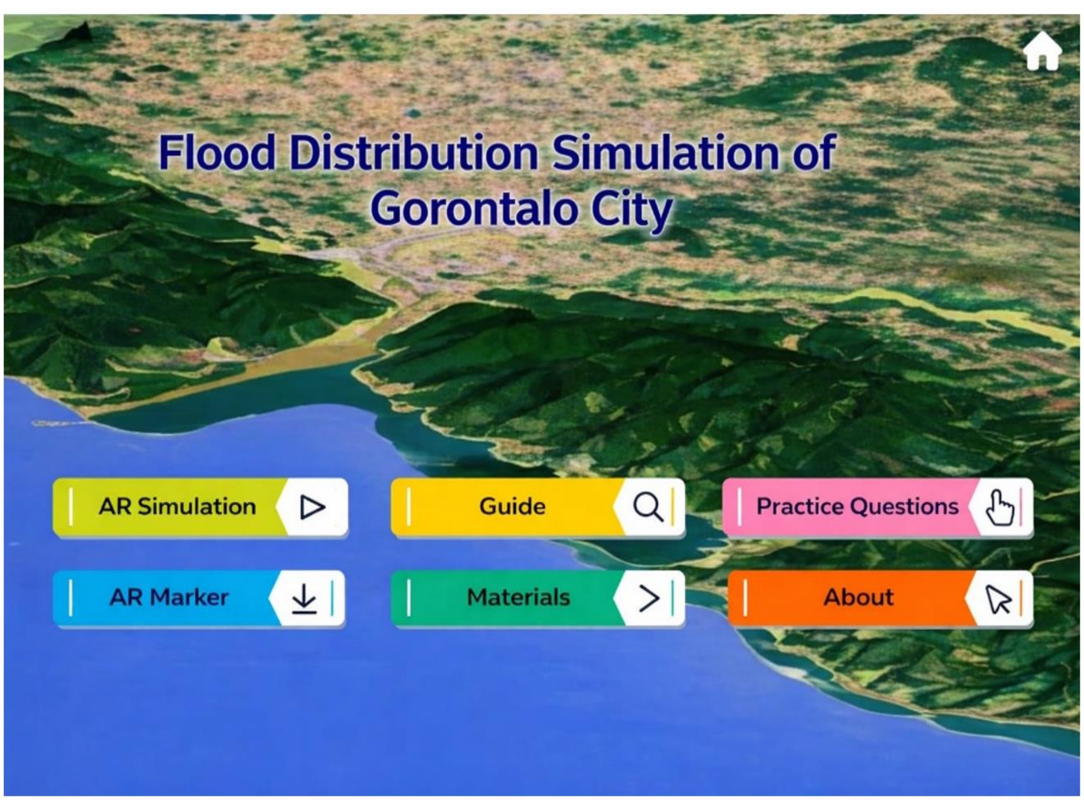

Figure 3. AR interface for flood distribution visualization.

The combination of GIS and AR transformed abstract disaster concepts into contextual and observable learning experiences, supporting both cognitive and affective engagement with environmental issues.

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4.3. Expert Validation and Revision Outcomes

Prior to classroom implementation, the developed learning materials underwent expert validation involving specialists in geography education, educational technology, and language. Validation focused on content quality, media design, usability, and language appropriateness. The materials were structured to support analytical and evaluative thinking through HOTS-oriented tasks, including scenario-based questions and problem-solving exercises (Asari, Fadjarajani, Badriah, Nurjamilah, & Shaari, 2025; Kamil et al., 2020).

Initial evaluation identified several aspects requiring improvement, including enhancement of visual presentation, refinement of instructional organization, strengthening of HOTS-oriented activities, and improvement of language clarity. Expert recommendations were incorporated through iterative revision cycles, resulting in substantial improvements across all assessed dimensions. Table 6 presents the results of the expert validation conducted to evaluate the feasibility of the developed immersive geospatial learning materials across the content, media, and language aspects.

Expert validation was conducted through five iterative validation rounds. Following each round, the learning materials were revised based on qualitative feedback provided by the experts before being re-evaluated in the subsequent round. Therefore, the scores presented in Validation Rounds 1–5 reflect the progressive improvement of the learning materials throughout the iterative refinement process. The Final Score represents the score obtained in the fifth (final) validation round after all recommended revisions had been incorporated.

Table 6. Results of Iterative Expert Validation of the Developed Learning Materials.

No.	Aspect	Validation					Final Score	Category
		Round 1	Round 2	Round 3	Round 4	Round 5		
1	Media Aspect	3.16	3.84	4.2	4.36	4.56	4,56	Highly feasible
2	Material Aspect	3.44	3.76	3.88	4.24	4.72	4,72	Highly feasible
3	Language Aspect	3.12	3.68	4.08	4.36	4.76	4,76	Highly feasible
Average							4.68	Highly feasible

As shown in Table 6, the validation scores consistently increased across the five validation rounds, indicating continuous improvement in the quality of the learning materials. The Final Score is identical to the score obtained in Validation Round 5 because the fifth round represented the final expert evaluation, after which no further revisions were required prior to classroom implementation.

Qualitative feedback resulted in several revisions involving improvements to GIS visualization, refinement of AR navigation, enhancement of inquiry activities, and clarification of instructional guidance. These revisions strengthened the pedagogical coherence and usability of the learning materials prior to implementation (Aryani, Pramudita, Sinangkling, & Tama, 2023; Widiharto, Fajriyah, & Kiswoyo, 2021).

4.4. Implementation of Immersive Geospatial Learning Materials

Implementation was conducted in senior high schools within Gorontalo City using the validated learning materials. Classroom activities incorporated GIS-supported hazard mapping, AR visualization, collaborative inquiry, environmental analysis, and preparedness planning tasks. Figure 4 illustrates the classroom implementation of the immersive geospatial learning materials, demonstrating students' engagement with GIS-based activities, collaborative inquiry, teacher facilitation, and AR-supported spatial visualization.

Figure 4. Real-world implementation of GIS- and AR-supported immersive learning in geography education: (1) Collaborative learning activities; (2) Use of interactive digital materials; (3) Teacher-guided instruction; and (4) AR-based spatial visualization.

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Students engaged in the interpretation of flood hazard maps, identification of vulnerable locations, analysis of environmental conditions, and evaluation of mitigation alternatives. AR simulations enabled visualization of flood distribution patterns and facilitated exploration of flood impacts under different environmental scenarios. Throughout the implementation process, students demonstrated active participation and engagement in geospatial investigation and contextual disaster learning activities.

Classroom observations indicated that the combination of GIS and AR enhanced students' ability to connect abstract disaster concepts with local environmental realities. The immersive learning environment encouraged collaborative discussion, spatial reasoning, and evidence-based decision-making related to flood preparedness.

The results support existing literature that highlights the role of interactive and context-based materials in disaster education (Romualdi et al., 2023; Yuniarti, Setiawan, & Hariyanto, 2020). The results also reaffirm the importance of expert validation and iterative refinement in ensuring instructional quality (Widiharto et al., 2021). The integration of local hazard data further aligns with recommendations for contextualized curricula in flood-prone regions (Kitagawa, 2023; Wardhani et al., 2022).

4.5. Educational Evaluation

Educational evaluation was conducted following classroom implementation to examine learning outcomes associated with the use of GIS and AR-supported immersive learning materials. The evaluation involved 107 Grade XI students from six senior high schools in Gorontalo City and focused on spatial literacy, flood preparedness, higher-order thinking skills, and environmental understanding.

Pretest results indicated relatively similar baseline competencies between groups prior to implementation. Students in the experimental group achieved a mean score of 54.7 (SD = 8.1), while students in the control group obtained a mean score of 53.8 (SD = 7.9). The similarity of these scores suggests that both groups entered the learning process with comparable levels of understanding regarding flood hazards, spatial interpretation, and preparedness-related concepts. Initial observations further revealed that many students experienced difficulties in interpreting hazard maps, identifying spatial relationships among environmental variables, and applying disaster mitigation concepts to authentic local situations. Table 7 presents the baseline learning outcomes of the experimental and control groups before the implementation of the immersive geospatial learning materials.

Table 7. Baseline learning outcomes prior to implementation.

Group	n	Mean	SD
Experimental	54	54.3	8.1
Control	53	53.8	7.9

Following implementation, notable differences emerged between students who engaged with immersive geospatial learning materials and those who received conventional instruction. The experimental group achieved a mean posttest score of 84.7 (SD = 6.4), whereas the control group obtained a mean score of 71.6 (SD = 7.2). These results indicate substantially higher learning outcomes among students exposed to GIS-based hazard mapping, AR-supported visualization, inquiry-oriented investigation, and preparedness planning activities. Table 8 presents the post-implementation learning outcomes of the experimental and control groups following the learning intervention.

Table 8. Post-implementation learning outcomes.

Group	n	Mean	SD
Experimental	54	84.7	6.4
Control	53	71.6	7.2

Statistical analysis revealed a significant difference between groups ($p < 0.05$), indicating that the observed improvement was unlikely to occur by chance. Beyond statistical significance, effect size analysis produced a Cohen's d value of 1.02, representing a large practical effect. These findings demonstrate that the educational benefits associated with immersive geospatial learning materials extend beyond measurable score gains and reflect meaningful improvements in students' ability to interpret spatial information, analyze flood-related environmental conditions, and formulate preparedness-oriented responses. Table 9 presents a summary of the educational evaluation results, including statistical significance, effect size, and improvements observed in students' learning outcomes.

Table 9. Summary of educational evaluation results.

Indicator	Result
Statistical significance	$p < 0.05$
Effect size	Cohen's $d = 1.02$
Spatial literacy	Improved
Flood preparedness	Improved
Hazard analysis	Improved
Contextual reasoning	Improved
Mitigation planning	Improved

Educational improvements were particularly evident in tasks requiring interpretation of flood hazard maps, identification of vulnerable areas, analysis of environmental relationships, and evaluation of mitigation alternatives. GIS-based learning activities enabled students to investigate the spatial dimensions of flood risk through authentic geospatial data, while AR visualization transformed abstract hazard information into observable environmental scenarios. The combination of these technologies encouraged learners to connect theoretical concepts with local environmental realities, thereby strengthening contextual understanding and preparedness-oriented reasoning.

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The evaluation results also suggest that learning gains were not solely attributable to technological novelty. Improvement emerged from the interaction among spatial literacy activities, HOTS-oriented inquiry, ecopedagogical reflection, and immersive visualization embedded within the instructional framework. Students were required to investigate environmental evidence, evaluate disaster mitigation strategies, and reflect on human-environment relationships, thereby engaging multiple cognitive and affective dimensions of disaster learning simultaneously. This multidimensional learning experience contributed to stronger preparedness competencies and more meaningful understanding of flood-related challenges within the local context of Gorontalo City.

The findings indicate that immersive geospatial learning materials provide an effective approach for connecting geospatial technologies, spatial reasoning, environmental awareness, and disaster preparedness within a unified educational framework. Results from the needs analysis revealed that existing flood disaster learning resources were insufficiently contextualized and provided limited opportunities for students to investigate local environmental conditions. Such findings reinforce concerns raised in previous studies that disaster education often emphasizes conceptual knowledge while offering relatively few opportunities for learners to engage in authentic environmental inquiry and preparedness-oriented learning (Hoffmann & Blecha, 2020). The development of immersive learning materials was therefore directed toward addressing these limitations through the integration of Geographic Information Systems (GIS), Augmented Reality (AR), spatial literacy, higher-order thinking skills (HOTS), and ecopedagogical perspectives.

The integration of GIS and AR emerged as a central component supporting contextual disaster learning. GIS-based flood hazard maps enabled learners to investigate local vulnerability patterns, interpret spatial distributions of flood risk, and examine relationships among environmental variables influencing flood occurrence. Access to authentic geospatial information encouraged students to move beyond descriptive understanding and engage in geographic reasoning grounded in real environmental conditions. Similar observations have been reported in geography education research, which highlights the capacity of GIS to support spatial inquiry, environmental analysis, and evidence-based learning through interaction with real-world geographic (Li & Liu, 2022; Vojtek, 2023). AR complemented these capabilities by transforming static geospatial information into interactive visual experiences. Visualization of flood processes and mitigation scenarios enabled learners to observe environmental interactions that are often difficult to comprehend through conventional instructional media. The combination of GIS and AR therefore expanded learning opportunities by linking spatial analysis with immersive visualization, creating a more meaningful and engaging learning environment (Li et al., 2022; Romualdi et al., 2023).

Another important finding concerns the role of immersive learning in supporting spatial literacy development. Interaction with hazard maps, environmental datasets, and contextual flood scenarios encouraged learners to identify spatial patterns, interpret geographic relationships, and evaluate environmental risks. Spatial literacy is increasingly recognized as a critical competency in geography and disaster education because it enables individuals to understand how environmental processes and human activities interact across space (Kerski, 2015; Oberle et al., 2024). The learning experiences developed in this study provided opportunities for students to engage directly with geospatial representations rather than relying solely on textual descriptions. Such experiences are important because spatial reasoning develops through active interaction with spatial information and contextual problem-solving activities rather than through memorization of geographic concepts alone (Ridha & Kamil, 2021; Safitri et al., 2024).

The findings further suggest that preparedness-oriented learning can be strengthened when disaster education is closely connected to local environmental realities. Learners were encouraged to investigate flood-prone areas, examine environmental causes of flooding, and evaluate alternative mitigation strategies relevant to their communities. This approach reflects the principles of place-based disaster education, which emphasize the importance of connecting learning activities with local contexts and lived experiences (Hoffmann & Blecha, 2020; Pal et al., 2021). Engagement with local flood issues increases the relevance of learning because students perceive environmental risks not as abstract concepts but as challenges that directly affect their surroundings. Such contextualization contributes to stronger environmental awareness and preparedness-oriented reasoning, both of which are essential components of disaster risk reduction.

The contribution of HOTS and ecopedagogical learning was also evident throughout the development and implementation process. Flood disasters represent complex socio-ecological phenomena shaped by interactions among environmental, economic, social, and political factors. Understanding these complexities requires learners to analyze environmental evidence, evaluate competing explanations, and formulate context-sensitive responses. Inquiry-oriented learning activities incorporated within the materials encouraged analytical reasoning, problem solving, and evidence-based decision making, all of which are central elements of HOTS development (Abdimanapov et al., 2025; Zohar & Dori, 2003). At the same time, ecopedagogical reflection encouraged students to examine the consequences of human activities for environmental sustainability and disaster vulnerability. Flood risk was explored not only as a natural phenomenon but also as a consequence of land-use change, watershed degradation, and environmental management practices. Such perspectives align with ecopedagogical principles that emphasize critical awareness, environmental responsibility, and sustainable relationships between society and nature (Kinyota, 2021; Misiaszek, 2016, 2025).

Taken together, the findings demonstrate that educational effectiveness was generated not by technological innovation alone but by the interaction among technological, cognitive, spatial, and environmental dimensions embedded within the learning framework. GIS provided opportunities for spatial investigation, AR enhanced visualization and engagement, HOTS-oriented inquiry strengthened analytical reasoning, and ecopedagogical reflection fostered environmental responsibility. The integration of these components created a multidimensional learning environment capable of supporting meaningful engagement with flood-related challenges. This finding extends previous research that has often examined GIS, AR, spatial literacy, HOTS, or ecopedagogy as separate domains of inquiry. The present study demonstrates that greater educational value can be achieved when these elements are systematically integrated within a coherent pedagogical design.

The study contributes to disaster education and geography education literature by proposing an immersive geospatial learning framework that connects geospatial technologies with contextual inquiry, environmental reflection, and preparedness-oriented learning. From a practical perspective, the developed materials offer

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educators a feasible approach for contextualizing disaster education through local environmental issues and authentic geospatial information. The integration of GIS-based hazard mapping and AR visualization provides opportunities to transform disaster learning into a more interactive, relevant, and meaningful educational experience. Such approaches may strengthen school-based disaster risk reduction initiatives and support broader efforts to develop environmentally aware and disaster-resilient communities in flood-prone regions.

5. Conclusion

This study developed and evaluated immersive geospatial learning materials for flood disaster education through the integration of Geographic Information Systems (GIS), Augmented Reality (AR), spatial literacy, higher-order thinking skills (HOTS), and ecopedagogical perspectives within a contextual learning framework. The findings indicate that the developed materials are pedagogically feasible and capable of supporting meaningful engagement with local flood-related issues through geospatial investigation, immersive visualization, inquiry-based learning, and environmental reflection.

The integration of GIS-based flood hazard mapping and AR-assisted visualization expanded opportunities for students to explore authentic environmental conditions, interpret spatial patterns, and examine relationships between human activities and disaster vulnerability. Learning activities designed around inquiry, analysis, reflection, and preparedness planning further supported the development of spatial reasoning, environmental awareness, and preparedness-oriented thinking. These results demonstrate that geospatial technologies can contribute more effectively to disaster education when embedded within a coherent pedagogical framework rather than functioning solely as visualization tools.

A major contribution of this study lies in demonstrating how GIS, AR, spatial literacy, HOTS, and ecopedagogy can be systematically integrated within a single instructional resource for disaster education. This integration extends existing approaches to technology-enhanced geography learning by connecting technological, cognitive, spatial, and environmental dimensions in ways that support both educational and disaster risk reduction objectives. The developed framework provides a practical reference for educators seeking to contextualize disaster education through local environmental issues and authentic geospatial information.

Several limitations should be acknowledged. Implementation was conducted within senior high schools in a single regional context, which may limit broader generalization. Future studies are encouraged to examine the applicability of the learning materials across different educational levels, geographical settings, and hazard types. Longitudinal investigations may also provide deeper insights into the sustained influence of immersive geospatial learning on environmental behavior, community resilience, and disaster preparedness.

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