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Serious Game-Based Flood Visualization System for Disaster Mitigation Capacity Building

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Abstract

Flood-prone urban areas continue to face challenges in disaster preparedness due to limited public understanding of flood dynamics and appropriate mitigation responses. Conventional educational approaches often rely on static information that is insufficient to represent rapidly changing flood conditions. This study aims to design and evaluate a serious game–based flood visualization system that serves as an interactive educational medium for disaster mitigation capacity building. The research adopts a structured development approach based on the Game Development Life Cycle, encompassing needs analysis, virtual environment and scenario design, system implementation, and functional and user-based testing. Flood risk conditions are classified using multi-criteria environmental parameters and translated into real-time visual representations within a three-dimensional simulation environment. The results demonstrate that the developed system effectively supports users in recognizing flood behavior, understanding contributing factors, and identifying appropriate mitigation actions. User testing indicates high levels of clarity, engagement, and perceived educational value, suggesting that interactive visualization enhances experiential learning in disaster contexts. This study contributes to disaster education and information systems research by providing a replicable design model that integrates decision-support mechanisms with immersive visualization to strengthen community-level flood mitigation awareness and preparedness.

Keywords: Flood Visualization; Serious Game; Disaster Mitigation; Virtual Environment; Interactive Simulation

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Introduction

Flooding remains one of the most disruptive natural hazards affecting urban regions worldwide, with significant consequences for economic stability, social activities, and environmental sustainability. Rapid urbanization, land-use change, climate variability, and insufficient drainage infrastructure have intensified flood frequency and severity, particularly in coastal and low-lying cities (Cea & Costabile, 2022; Glago, 2021; Tingsanchali, 2012). In Indonesia, several metropolitan areas continue to experience recurrent flood events, where extreme rainfall combined with dense settlement patterns amplifies disaster impacts (Bennett et al., 2023; Gaborit, 2022). Makassar, as a fast-growing coastal city, has repeatedly reported inundation in residential zones, with water depths reaching levels that disrupt daily activities and force temporary evacuations (Ishak & Chowdhury, 2024; Yahya et al., 2025). These conditions underscore the urgency of strengthening community-level disaster preparedness through effective educational and information-based interventions.

Despite the availability of flood hazard information, public understanding of flood dynamics and appropriate mitigation measures remains uneven. Many disaster education initiatives still rely on textual explanations or static visual materials that inadequately represent the dynamic and spatial characteristics of flood events. Previous studies indicate that such approaches limit users' ability to develop situational awareness and translate knowledge into effective response actions during emergencies (Meechang et al., 2020). As a result, there is a growing demand for educational media that can present flood scenarios in a more intuitive, engaging, and context-sensitive manner.

Interactive simulation technologies have gained increasing attention as tools for disaster education and training. Virtual environments enable users to observe, explore, and interact with simulated hazard conditions, supporting experiential learning processes that are difficult to achieve through conventional instruction (Garcia Ulerio et al., 2025; Khanal et

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al., 2022; N. Li et al., 2022). Digital games, particularly serious games designed for educational purposes, further enhance this potential by combining simulation with goal-oriented interaction and feedback mechanisms (Q. Li, 2010). Empirical evidence suggests that game-based learning environments can improve conceptual understanding, motivation, and cognitive engagement in risk-related contexts (Z. Feng et al., 2018; Mao et al., 2022). However, many existing disaster education applications remain limited in visual immersion or fail to integrate analytical decision-support mechanisms that reflect real-world environmental conditions.

To structure the development of interactive educational systems, several studies have adopted formal game development frameworks. The Game Development Life Cycle provides an iterative process that supports systematic design, prototyping, testing, and refinement of serious games (Aleem et al., 2016; Ramadan & Widyani, 2013; Zhu & Wang, 2019). Prior research demonstrates that the application of this model can yield educational games with high feasibility and usability when aligned with learning objectives (Ben Amara et al., 2024; Kobewka et al., 2014). In parallel, decision-support methods such as the Technique for Order Preference by Similarity to Ideal Solution have been widely used in flood risk assessment to process multi-criteria environmental data and generate hazard classifications (Esmaili & Karipour, 2024; Levy, 2005; H. Li et al., 2022). Nevertheless, the integration of such analytical models within immersive three-dimensional educational simulations remains relatively limited.

Previous visualization-based flood studies have primarily focused on technical modeling or professional training, often without explicit consideration of public education and community engagement (Massaâbi et al., 2018; Wang et al., 2019). While these studies demonstrate the value of three-dimensional visualization for understanding flood processes, they frequently lack interactive gameplay elements that support sustained user engagement and contextual learning. Consequently, a gap persists between analytical flood modeling, visualization technology, and accessible educational media designed for non-expert users in disaster-prone communities.

Responding to this gap, the present study proposes the design and evaluation of a serious game–based flood visualization system that integrates a three-dimensional virtual environment with multi-criteria flood classification. Environmental parameters such as rainfall intensity, water level, drainage quality, temperature, and wind speed are processed using a decision-support approach to determine flood risk status, which is then translated into dynamic visual cues within the simulation (Kadir et al., 2024). By embedding these mechanisms within an interactive game framework, the system is intended to support experiential learning and enhance users' understanding of flood behavior and mitigation strategies in a realistic yet accessible manner.

The objective of this research is to develop and assess a serious game–based flood visualization system as an educational medium for disaster mitigation capacity building, with a specific focus on flood-prone residential areas in Makassar. The study seeks to contribute to information systems and disaster education research by demonstrating how immersive visualization and decision-support integration can improve risk communication, learning effectiveness, and community preparedness in urban flood contexts.

Method

This research applies the Game Development Life Cycle as the primary methodological framework to guide the design, development, and evaluation of a serious game-based flood visualization system. The selection of this framework is based on its structured and iterative nature, which has been widely adopted in the development of educational and serious game applications due to its capacity to ensure systematic design, testing, and refinement processes (Aleem et al., 2016; Ramadan & Widyani, 2013; Roedavan et al., 2021). The method was chosen to support both technical robustness and educational effectiveness, enabling the resulting system to be evaluated not only as a functional application but also as a learning medium for disaster mitigation. The findings of this phase serve as the basis for the subsequent design and implementation stages.

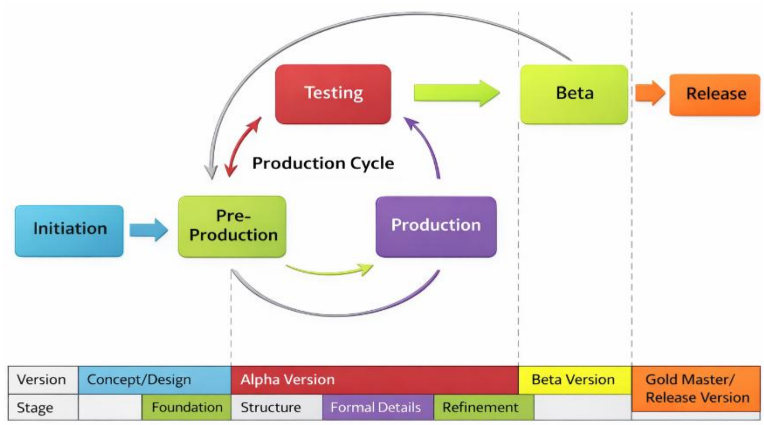

Figure 1. Game Development Life Cycle (GDLC) Model

The research process begins with an initiation stage focused on problem identification and contextual analysis. At this stage, information regarding flood characteristics in Makassar is examined based on recent flood studies and reports that describe rainfall intensity, inundation depth, drainage conditions, and settlement vulnerability in the area (Hendra et al., 2024; Ishak & Chowdhury, 2024; Yahya et al., 2025) This analysis is used to define system requirements, learning objectives, and target user characteristics, ensuring that the simulation scenarios reflect real conditions encountered by communities in flood-prone residential zones.

Following requirement identification, the pre-production stage translates conceptual needs into detailed system designs. Interaction flows and system behavior are modeled using Unified Modeling Language diagrams to describe user actions, system responses, and data processing sequences in a structured manner (Booch et al., 1996; Da-Silva & Paton, 2000). Interface layouts and navigation structures are designed using digital prototyping tools to support clarity and ease of interaction. Environmental parameters relevant to flood risk assessment, including rainfall intensity, water level, drainage quality, temperature, and wind speed, are defined based on multi-criteria flood hazard frameworks reported in previous studies (Esmaili & Karipour, 2024; Franci et al., 2016). Three-dimensional assets representing residential environments and flood-affected areas are then created to provide a realistic spatial context for the simulation, following established practices in disaster visualization development (Massaâbi et al., 2018; Wang et al., 2019).

The production stage involves implementing all design components within an interactive game engine. The virtual environment, three-dimensional visual assets, and user interface elements are integrated into a functional simulation environment consistent with the GDLC workflow (Roedavan et al., 2021). Flood risk classification is performed using the Technique for Order Preference by Similarity to Ideal Solution, which processes the defined environmental parameters to generate a relative flood risk score (Levy, 2005; H. Li et al., 2022). The resulting classification is dynamically linked to the visual simulation, allowing changes in risk level to be represented through water-level animation, environmental color changes, and alert indicators in near real time. This integration enables users to directly observe the relationship between environmental conditions and flood severity within the simulated environment.

System evaluation is conducted through functional testing and user-based assessment. Functional validation follows black-box testing principles to verify that system features operate according to predefined specifications without examining internal code structures (Firdhayanti et al., 2023; Supriyadi, 2020). Usability and educational value are evaluated through structured user testing involving a limited group of residents from selected flood-prone areas in Makassar. Participants interact with the simulation and provide feedback on interface clarity, visual realism, ease of interaction, system responsiveness, and perceived learning support, in line with recommended evaluation practices for serious games and interactive simulations (Cadiz et al., 2023; Mao et al., 2022). Feedback obtained during this stage is used to refine system interaction, improve visual representation, and enhance overall learning experience prior to final release.

The final stage of the method involves consolidating revisions derived from testing and documenting the full development and evaluation process. This documentation is intended to ensure transparency and replicability, allowing future researchers to adapt the methodological approach, extend the system to other geographical contexts, or integrate additional data sources for enhanced disaster mitigation applications. By following an iterative and reproducible methodological framework, this research aligns with contemporary principles of serious game development and applied information systems research (Maxim & Arnedo-Moreno, 2025).

Results and Discussion

Result

The development of the serious game–based flood visualization system was completed following the stages defined in the Game Development Life Cycle framework. The final system integrates an interactive three-dimensional virtual environment, a flood risk classification module based on multi-criteria environmental parameters, and an educational scenario component that provides contextual mitigation guidance. These components operate cohesively to simulate flood conditions that evolve dynamically in response to changing environmental inputs. The main interface of the developed serious game, which serves as the primary interaction point for users, is presented in Figure 2.

Figure 2. Main Interface of the Flood Visualization Serious Game

Functional testing confirmed that all core system features operated according to their intended specifications. Environmental parameters entered into the system were successfully processed by the flood classification module, and the resulting risk levels were generated consistently across different testing scenarios. Several combinations of rainfall intensity, water level, and drainage quality were examined during the system test to evaluate the robustness of the classification mechanism. The sample output of flood risk classification produced by the system is summarized in Table 2.

Table 2. Sample Flood Risk Classification Output

No	Rainfall (mm/h)	Water Level (cm)	Drainage Quality (%)	TOPSIS Score	Classification
1	12	15	80	0.22	Safe
2	35	40	60	0.48	Alert
3	60	75	45	0.72	Standby
4	85	110	30	0.91	Danger

The classification results demonstrate a clear progression from low-risk to high-risk flood conditions as environmental parameter values increase. These analytical results are directly linked to the visualization engine, which automatically converts flood risk levels into dynamic visual representations within the simulation environment. Variations in water elevation, environmental color saturation, and alert indicators allow users to visually interpret the severity of flood conditions. An example of a high-risk flood scenario rendered by the system is shown in Figure 3.

Figure 3. Visualization of a High Risk Flood

In addition to functional validation, user-based testing was conducted to assess usability and perceived learning effectiveness. Participants interacted with the simulation and evaluated the system based on interface clarity, visual realism, ease of interaction, system responsiveness, and educational value. The results of the usability evaluation indicate positive user perceptions across all assessed indicators. A summary of the usability assessment results is presented in Table 3.

Table 3. Usability Evaluation Results

No	Indicator	Mean Score	Category
1	Interface Clarity	4.4	Very Good
2	Visual Realism	4.2	Very Good
3	Ease of Interaction	4.1	Good
4	Educational Value	4.5	Very Good
5	System Responsiveness	4.3	Very Good

Overall, the results confirm that the developed serious game–based system meets its functional requirements and provides an interactive simulation experience that supports disaster mitigation learning.

Discussion

The findings of this study demonstrate that the integration of three-dimensional visualization, serious game mechanics, and multi-criteria flood classification enhances users' understanding of flood dynamics and mitigation strategies. Consistent with the assumptions outlined in the introduction, the results indicate that experiential learning environments offer clear advantages over conventional text-based or static visual materials. By enabling users to observe and interact with evolving flood scenarios, the system supports the development of situational awareness that is essential for effective disaster preparedness.

The successful application of the Technique for Order Preference by Similarity to Ideal Solution within the simulation confirms its suitability for processing multiple environmental indicators in a disaster education context. The close correspondence between analytical classification outputs and visual representations allows users to intuitively understand the relationship between environmental conditions and flood severity. This outcome supports prior studies emphasizing the value of integrating analytical models with visualization to improve risk communication and decision-making (Ding et al., 2014; Esmaili & Karipour, 2024; Levy, 2005). In contrast to visualization-focused studies that primarily address technical users, the present system prioritizes accessibility and interpretability for non-expert audiences in flood-prone communities.

The usability evaluation results are consistent with earlier findings showing that interactive simulations and game-based learning environments can increase engagement, motivation, and perceived learning effectiveness (J. Feng et al., 2018; Mao et al., 2022). High ratings for interface clarity and educational value indicate that the system successfully balances technical complexity with user-friendly interaction, a critical requirement for community-oriented disaster education. Despite these strengths, several limitations should be acknowledged. The current implementation relies on predefined environmental parameters rather than live data streams, which limits its applicability for real-time early warning purposes. In addition, the visual simulation does not yet incorporate detailed hydrodynamic processes such as flow velocity variation or terrain-driven water movement. These limitations highlight opportunities for future research, including the integration of real-time sensor data, expansion to broader geographical contexts, and refinement of visual realism.

Overall, the findings confirm that the developed serious game–based flood visualization system effectively addresses the research objective by providing an engaging and informative medium for disaster mitigation capacity building. The integration of decision-support analysis and immersive visualization advances the role of information systems and interactive technologies in strengthening community-based disaster education and preparedness.

Conclusions and Suggestions

Conclusions

This study demonstrates that the integration of three-dimensional visualization, serious game mechanics, and multi-criteria flood analysis provides a meaningful contribution to disaster mitigation education in flood-prone urban environments. By transforming complex environmental data into interactive visual scenarios, the developed system enables users to better understand how flood conditions evolve and how appropriate mitigation actions can be selected across different risk levels. This approach effectively bridges the gap between abstract flood information and practical decision-making, particularly for non-expert users in community-based learning contexts.

The findings confirm that embedding a decision-support mechanism within an immersive simulation environment strengthens risk communication and enhances situational awareness. The use of the Technique for Order Preference by Similarity to Ideal Solution allows multiple environmental indicators to be processed and translated into intuitive visual cues, supporting users' ability to interpret flood severity and respond accordingly. In combination with a structured game development framework, this integration results in a system that is both technically functional and educationally effective.

From an information systems perspective, this research contributes a replicable design model for serious game–based disaster education that aligns analytical classification with experiential learning principles. The system demonstrates how interactive technologies can be applied to improve disaster mitigation capacity beyond traditional instructional approaches, offering a scalable alternative for community training and awareness programs. Overall, the study highlights the potential of immersive visualization and decision-support integration as strategic tools for strengthening disaster preparedness and advancing applied research in disaster education and information systems.

Suggestions

Based on the findings of this study, several directions for future development and research can be proposed to enhance the applicability and impact of the serious game–based flood visualization system. One important extension involves the integration of real-time environmental data sourced from rainfall gauges, water-level sensors, or official hydrometeorological agencies. Incorporating live data streams would improve the accuracy and responsiveness of the simulation, allowing the system to function not only as an educational tool but also as a complementary medium for early warning awareness and preparedness training.

Further research may also focus on expanding the three-dimensional virtual environment to represent broader geographical areas or multiple flood-prone zones with varying physical characteristics. Such expansion would enable users to explore diverse flood scenarios and support the adaptation of the system for different regional contexts. Enhancing the hydrodynamic representation within the simulation, including more detailed modeling of water flow, terrain elevation, and inundation patterns, would further increase realism and strengthen the system's value for experiential learning.

From an educational perspective, future studies could investigate the incorporation of adaptive learning mechanisms that respond to user behavior and performance during gameplay. Personalizing scenarios and feedback based on user interaction patterns may provide deeper insights into learning outcomes and behavioral readiness in disaster situations. Additionally, longitudinal evaluation involving schools, community organizations, and disaster management agencies is recommended to assess the long-term effectiveness of the system in improving disaster mitigation literacy and preparedness. These directions offer opportunities to extend the current research while reinforcing the role of serious games and immersive information systems in disaster education and community resilience building.

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Contribution

Nur Idil Fitri Idris: conceptualization, system design, data analysis, implementation, and manuscript drafting.
Yuliana: methodology development, software support, data acquisition, and manuscript review.
Markani: validation, educational framework alignment, critical revision of the manuscript, and supervision.
Rosmini: usability evaluation, data interpretation, editing, and final approval of the manuscript.

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