Sinkron : Jurnal dan Penelitian Teknik Informatika
Volume 10, Number 3, July 2026
DOI : https://doi.org/10.33395/sinkron.v10i3.16164
e-ISSN : 2541-2019
p-ISSN : 2541-044X

A WebGIS-Based Location Analysis System for Disaster Mitigation in Bitung City Using Ray Casting and Haversine Formula

Romeo Fernando Mikhael Dendeng[1)], **Kristofel Santa**[2)*], **Sondy C. Kumajas**[3)]
[1,2,3)] Universitas Negeri Manado, Indonesia
[1)]22210040@unima.ac.id, [2)]kristofelsanta@unima.ac.id, [3)]sondykumajas@unima.ac.id

Submitted :May 1, 2026 | **Accepted** : June 8, 2026 | **Published** : July 5, 2026

Abstract: Indonesia is highly vulnerable to multi-hazard natural disasters, and Kota Bitung specifically faces high risks due to its geographical contours. Currently, the dissemination of disaster information by the Regional Disaster Management Agency (BPBD) relies heavily on conventional static maps. Most existing disaster WebGIS platforms focus merely on static visualization and lack an integrated system capable of instantly analyzing a user's coordinate status against multi-hazard spatial polygons while simultaneously providing location-based evacuation routing. To address this gap, this research aims to design and develop a responsive WebGIS that allows users to independently detect their risk status and logically find the nearest evacuation route. The system development utilizes the Rapid Application Development (RAD) method. The core engine integrates the Ray Casting algorithm to solve the Point-in-Polygon problem against disaster zone boundaries, and the Haversine Formula to calculate the nearest available evacuation point. Based on comprehensive evaluations, including accuracy testing, spatial distance validation, and 11 distinct black-box testing scenarios, the system successfully processed GPS-based coordinate inputs, handled polygon boundary edge-cases, and generated evacuation routes using the OpenSource Routing Machine (OSRM). Ultimately, the proposed system provides a functional prototype for location-based disaster risk analysis and evacuation point recommendation, serving as a foundational interactive instrument to support emergency preparedness in Kota Bitung.

Keywords: WebGIS, Disaster Management, Ray Casting Algorithm, Haversine Formula, Evacuation Routing.

INTRODUCTION

Indonesia is an archipelagic country with a very high vulnerability to various natural disaster threats. Geographically, Indonesia's location along the Asia-Pacific Ring of Fire, characterized by high tectonic activity, causes the country to constantly face real natural disaster risks (Pirmansyah & Tri Wahyudi, 2023). The high frequency of disaster events demands optimal preparedness from various government and community elements to minimize the resulting impacts. Unfortunately, in practical field operations, disaster management agencies are often confronted with operational constraints, such as delays in delivering disaster report information and the lack of accurate and up-to-date mapping systems, which ultimately lead to unpreparedness in disaster handling and mitigation processes (Aini, Susanto, & Yunita, 2024). Therefore, the combination of unavoidable geographical vulnerability and persistent operational challenges in the field creates an urgent need for an efficient and integrated geospatial decision support system for disaster management (Majid, Muhayat, & Norgina, 2026). Through the adoption of a targeted disaster management information system, it is expected that the delivery of disaster data, location mapping, and mitigation measures can be managed more quickly, accurately, and systematically to maximally minimize disaster-related losses.

Although emergency area mapping is crucial, disaster mitigation efforts in Bitung City, North Sulawesi, still face challenges regarding visual communication and information delivery. Currently, the Regional Disaster Management Agency (BPBD) of Bitung City relies on static maps that are difficult for the general public to quickly comprehend during sudden natural disasters. The reliance on non-interactive and hard-to-access data frequently delays public response and acts as a major barrier to effective evacuation decision-making on the ground (Tarigan, 2025). Furthermore, while previous WebGIS platforms have been widely utilized for disaster visualization, they

*Kristofel Santa

e-ISSN : 2541-2019
p-ISSN : 2541-044X

predominantly focus on static hazard mapping without integrating direct user-position analysis (Daud, Ugliotti, & Osello, 2024). Studies utilizing the Haversine formula for location-based evacuation systems often lack a robust polygon risk detection mechanism (Vitri, 2025). This indicates a significant research gap: the absence of an integrated system capable of instantly analyzing a user's coordinate status against multi-hazard spatial polygons while simultaneously providing location-based evacuation routing.

To address these issues, this study proposes the design of a Web-Based Geographic Information System (WebGIS) application that integrates the Ray Casting algorithm and the Haversine Formula. To ensure system reliability and adaptability to rapid requirement changes, the development process employs the Rapid Application Development (RAD) method. Ultimately, this WebGIS is designed to serve as an interactive location-based spatial analysis instrument, thereby enhancing the adaptive capacity and mitigation preparedness of the Regional Disaster Management Agency (BPBD) and the local community in facing multi-hazard disaster threats. Specifically, the main contributions of this research are threefold: first, developing a WebGIS for user position analysis against disaster zones based on the Ray Casting algorithm; second, integrating the Haversine Formula for nearest evacuation point recommendations; and third, testing the system functions through black-box scenarios based on location input, risk zone detection, and evacuation routing.

LITERATURE REVIEW

The application of Geographic Information Systems (GIS) and WebGIS has now become the primary foundation for designing modern disaster mitigation architectures. The principal advantage of WebGIS lies in its ability to dynamically provide and analyze spatial data to monitor various hazard threats, as proven effective in hotspot distribution monitoring systems for forest and land fire mitigation (Sukojo & Lisakiyanto, 2021). Furthermore, the continuous evolution of geospatial technologies has proven that interactive spatial visualization significantly enhances user awareness and experience, a principle successfully adapted in various sectors including e-tourism (Manggopa, Komansilan, Kumajas, & Batmetan, 2022). However, despite this technological shift, a major limitation of previous disaster WebGIS approaches is their continued reliance on static maps. They predominantly visualize disaster zones but fail to provide interactive, location-based evacuation recommendations (Aini et al., 2024). This limitation makes conventional static mapping insufficient for active emergency response, as it lacks personalized routing guidance for affected populations (Kenap, Raranta, & Maramis, 2026).

To address the limitations of static mapping, geofencing technology has emerged to precisely monitor whether a user's geo-positional coordinates are within a disaster-affected boundary (Sutedi, Julianto, & Fitriani, 2024). In this context, the Ray Casting algorithm is a highly reliable method for resolving the Point-in-Polygon computational problem (Basid & Nugroho, 2022). By projecting an imaginary straight line from the user's position point outward across the polygon boundary to logically calculate line intersections, this algorithm balances high detection accuracy with computational efficiency, making it ideal for spatial reporting architectures (Lawonn et al., 2023).

Once a user is detected within a hazard zone, determining the nearest safe location becomes critical. The Haversine Formula is widely recognized as a standard algorithm for accurately calculating spherical distances between two coordinates (Sudiatmika, Dewi, & Jayaningsih, 2021). Previous research has utilized Haversine to detect nearest healthcare facilities or clinics during emergencies (Tiwi, Santa, & Rorimpandey, 2024). Nevertheless, studies utilizing only distance-based algorithms often lack integration with polygon risk detection, meaning the system recommends nearest locations without logically confirming if the user's exact origin point is actually inside an intersecting danger zone (Vitri, 2025).

Based on the review of previous studies, WebGIS has been widely used for disaster risk visualization, while the Haversine formula is commonly applied for nearest location recommendations. However, most existing systems have not yet integrated direct user risk status detection via point-in-polygon analysis and evacuation point recommendations within a single location-based disaster analysis module. Therefore, this study fills this critical gap by integrating the Ray Casting and Haversine algorithms into a cohesive disaster WebGIS architecture.

METHOD

The software development process in this research applied the Rapid Application Development (RAD) model. This methodology was selected due to its highly iterative approach, which facilitates accelerated development and rapid prototyping, making it highly effective for building responsive and dynamic spatial mapping systems (Nilawati & Martin, 2023). The implementation of the RAD method has also been proven effective in accelerating the development cycle through iterative prototyping and active user involvement (Runtu, Maramis, & Hasibuan, 2025). In disaster mitigation, system requirements often change rapidly based on user feedback. Therefore, the RAD method is more suitable than traditional sequential models because it allows for direct user involvement and quick adaptations. The development process in this study consists of four main phases:

*Kristofel Santa

e-ISSN : 2541-2019
p-ISSN : 2541-044X

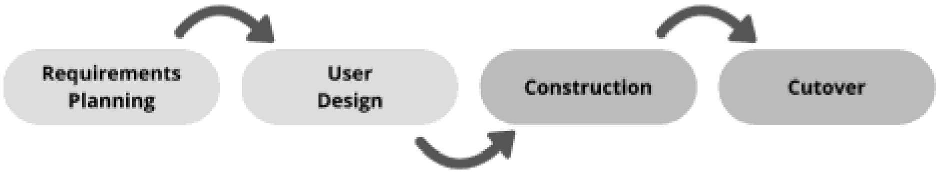

Fig. 1 Rapid Application Development Method

The first phase is requirements planning where the focus was on gathering the necessary spatial data and identifying the functional requirements of the system based on the needs of the BPBD Kota Bitung. The study collected three different types of data sources including vector polygon files used to map the administrative boundaries of Bitung City, comprising 69 *Kelurahan* (village) polygons. For disaster risk information, spatial data was extracted from the official InaRISK Web Map Service covering five specific hazards: floods, tsunamis, droughts, extreme waves and abrasions, and earthquakes. These layers were processed using QGIS to generate targeted GeoTIFF raster files exclusively for the Bitung City area with a spatial resolution of 0.00027 decimal degrees, approximately equivalent to 30x30 meters per pixel. Furthermore, it is important to note that the current system prototype utilizes dummy coordinates to act as temporary safe points for evacuation routing validation. Official evacuation data from BPBD will be required for future operational deployment.

The second phase is user design where the gathered requirements were translated into a system blueprint and a working prototype. A major part of this step was planning the mathematical logic for the location features. The Ray Casting algorithm was designed to run a Point-in-Polygon check to calculate which specific Kelurahan polygon contains the user's coordinates. Subsequently, the system extracts the pixel values from the customized InaRISK GeoTIFF layer to identify the disaster risk level. To perform this pixel extraction dynamically within the browser without server-side processing, the system converts the user's geographical coordinates (latitude and longitude) into the raster's matrix indices using the following equations:

$$x = \left\lfloor \frac{lng - x_{min}}{pixelWidth} \right\rfloor \quad (1)$$

$$y = \left\lfloor \frac{y_{max} - lat}{pixelHeight} \right\rfloor \quad (2)$$

Based on these indices, the system reads the multi-band (RGB) or single-band values. A value greater than zero or matching specific hue thresholds categorizes the area as "Affected" (triggering an evacuation prompt), while null or zero values (NoData) categorize it as "Safe". The Haversine Formula was also incorporated to compute the spherical distance to the closest evacuation point. The prototype interface was continuously evaluated and iteratively refined to ensure high usability for the general public during panic situations.

The third phase is construction where the approved designs and algorithms were coded into a fully functional WebGIS application. The back-end logic was programmed to handle location inputs dynamically. The front-end was developed to smoothly render the interactive digital map, visually overlaying the Kelurahan vector boundaries alongside the disaster risk raster layers extracted from the processed GeoTIFF files. To prevent browser memory overload, the system applies visual rendering optimization at a display resolution of 64 pixels per block, while the background algorithm maintains the original 30-meter resolution for precise analytical accuracy. Feedback loops were maintained throughout this coding process to refine any visual rendering issues immediately and ensure that the integration of Ray Casting and Haversine logic functioned seamlessly within the web environment.

The final phase is cutover which involved transitioning the application from development to deployment. To evaluate the system's scientific reliability and address limitations in standard functional testing, a robust evaluation methodology was established. First, Accuracy Testing was designed for the Ray Casting algorithm by plotting numerous test coordinates inside, outside, and exactly on the boundaries (vertices) of the 69 polygons. Second, Distance Validation was formulated to compare the spherical straight-line distance calculated by the Haversine formula against the actual road network travel distance provided by the OpenSource Routing Machine (OSRM). Third, Performance Testing was included to measure the system's response time in milliseconds. Finally, an extended Black-box testing framework was executed encompassing 11 distinct scenarios, including: valid coordinates in safe/affected zones, coordinates outside Bitung City, empty inputs, incorrect formats, disabled GPS, boundary edge cases, unreadable raster data, unavailable evacuation points, OSRM routing failures, and straight-line fallback functionality.

*Kristofel Santa

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Furthermore, to quantitatively evaluate the system's performance and computational efficiency, a built-in performance monitoring module was implemented within the WebGIS prototype. This module utilizes the high-resolution performance.now() method to strictly measure the algorithmic execution time (CPU time) in milliseconds. By isolating the computational runtime of the Ray Casting and GeoTIFF pixel extraction algorithms from external network latency or internet connection speed, the system generates highly objective metrics for the location analysis response time and raster loading performance. Additionally, this module automatically computes the spatial distance differences by comparing the spherical straight-line calculation (Haversine) against the actual road network travel distance (OSRM), providing the precise error distance metric required for evaluation.

RESULT

The development of the WebGIS application resulted in an interactive platform capable of performing on-demand spatial analysis. The system successfully integrates administrative boundary shapefiles with static raster-based hazard maps (GeoTIFF) into a unified interface (Figure 2). To determine individual safety status, users can input their coordinates manually or via GPS (Figure 3), prompting the Ray Casting and Haversine algorithms to execute. The system then returns a comprehensive risk status alongside the visual evacuation route (Figure 4).

Fig. 2 Disaster Map Page

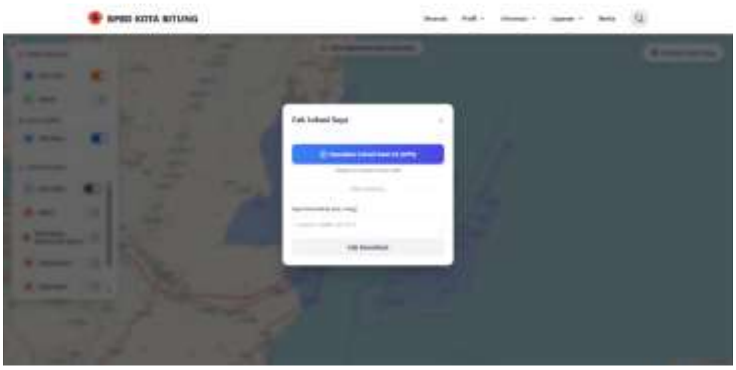

Fig. 3 Check My Location Feature

Fig. 4 Risk Analysis Result

*Kristofel Santa

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To scientifically verify the system's reliability beyond visual interface confirmation, an extended evaluation methodology was executed. This included comprehensive Black-box testing across 11 edge-case scenarios, algorithmic accuracy testing, and spatial distance validation. The results of these quantitative and functional evaluations are detailed in the subsequent tables.

Table 1 Blackbox Testing Results

Test Scenario	Expected Result	Actual Result	Status
Valid coordinates in a safe zone	System identifies location outside hazard layers and displays "Aman" status.	Popup displays "Aman" with a green badge; no evacuation route is drawn.	Valid
Valid coordinates in an affected zone	System detects high pixel values, displays "Terdampak", and generates route to nearest safe point.	Popup displays "Terdampak" (Red); draws OSRM road route and straight-line Haversine.	Valid
Coordinates outside Bitung City administrative boundary	System returns undefined or warns user that location is out of bounds.	Ray Casting fails to find matching polygon; system alerts " Luar Wilayah Jangkauan".	Valid
Empty coordinate input	Form submission is blocked; prompts for input.	Browser HTML5 validation prevents submission; shows "Wajib Diisi!".	Valid
Incorrect coordinate format (e.g., using letters)	System rejects input and asks for proper Lat, Lng format.	throws an alert: " Format Salah! (Lat, Long) ".	Valid
Device GPS is disabled or permission denied	The system will request the user to enable GPS; if denied, no coordinate points will appear and no action will be taken.	The system requested GPS permission; upon denial, no coordinates were displayed and the map remained unchanged.	Valid
Location exactly on the polygon boundary (edge/vertex)	The system will correctly select the chosen point and identify which Kelurahan polygon the coordinates fall into.	The system accurately selected the point and successfully identified the correct Kelurahan polygon without error.	Valid
GeoTIFF raster data is unreadable or fails to load	If the layer data is unreadable, no hazard layer will appear on the map even if the layer toggle is activated.	No layer was displayed on the map despite the hazard layer being toggled on.	Valid
Evacuation point database is empty/unavailable	System detects "Terdampak" but handles missing destination securely.	Alerts " Tidak ditemukan titik evakuasi. "; no route drawn.	Valid
OSRM server fails to provide a road route	OSRM fetch fails; system catches the network error.	Console logs routing error; system skips drawing the road network polyline.	Valid
Fallback to straight-line distance when OSRM fails	System relies on Haversine coordinate-to-coordinate line.	Successfully draws a straight dashed line to the evacuation point using Haversine.	Valid

*Kristofel Santa

e-ISSN : 2541-2019
p-ISSN : 2541-044X

Table 2 Ray Casting Accuracy and System Performance Metrics

Evaluation Metric	Measured Value	Unit/Status
Total Coordinate Points Tested	20	Points
Correct Zone Detections	20	Points
Zone Detection Accuracy	100	%
Average Location Analysis Response Time	15.77	ms (milliseconds)
GeoTIFF Layer Loading Performance	90.2	ms (milliseconds)

Table 3 Distance Calculation Comparison: Haversine vs OSRM

Test Case	Origin Coordinates	Destination (Evacuation Point)	Haversine Distance (Straight-Line)	OSRM Distance (Road Network)	Error Distance (Difference)
Case 1	1.44153, 125.16136	1.44909, 125.16402	0.89 km	1.49 km	0.60 km
Case 2	1.44311, 125.17204	1.44877, 125.17121	0.64 km	0.92 km	0.28 km
Case 3	1.44429, 125.18553	1.44945, 125.18428	0.59 km	1.58 km	0.99 km

DISCUSSIONS

The implementation of the WebGIS application demonstrates a significant advancement in spatial disaster analysis through the successful integration of the Ray Casting algorithm and the Haversine formula. The results indicate that the Ray Casting algorithm effectively performs point-in-polygon evaluations to accurately determine whether a user's current coordinate falls within a designated disaster-prone zone. This finding aligns with existing research which highlights that crossing-number algorithms and smart-geofencing techniques provide high computational accuracy for spatial boundary detection in regional mapping (Basid & Nugroho, 2022). By seamlessly segmenting affected areas based on geo-positional features, the system allows authorities to identify and isolate at-risk locations efficiently (Sutedi et al., 2024). However, while Ray Casting is highly effective for standard polygon boundaries, it requires careful computational handling of boundary cases. Our evaluation demonstrated that the algorithm successfully resolves instances where a user's location falls exactly on the boundary line or vertex of a polygon, ensuring no analytical errors occur during edge-case scenarios.

Furthermore, the system utilizes the Haversine formula to calculate the shortest spherical distance between the user's current location and the nearest available evacuation point. Previous studies have extensively validated the reliability of the Haversine method in various location-based services, such as determining the nearest healthcare facilities or public transportation stops (Candra, Rachmawati, & Faradillah, 2021). Nevertheless, it is critical to logically distinguish between "nearest by spherical distance" and "nearest by road network travel distance." The Haversine formula calculates the straight-line distance across the Earth's surface, which may not reflect the actual travel route. Therefore, our system employs Haversine primarily to identify the nearest evacuation point geographically, and subsequently integrates the OpenSource Routing Machine (OSRM) to generate the actual navigable road network route. This methodological relationship ensures that users receive immediate location-based early warnings and evacuation guidance using open-source map integration (Rahman, Alam, & Chowdhury, 2012), while acknowledging that the closest point geographically might not always be the fastest route to traverse.

Overall, the combination of these algorithms within a Web-Based Geographic Information System significantly enhances disaster management and mitigation efforts. As highlighted by recent developments in geological data management and real-time spatial platforms, WebGIS serves as a vital tool for dynamic data distribution and community preparedness (Tarigan, 2025). For practical implementation by the Regional Disaster Management Agency (BPBD), this technology transitions traditional static hazard maps into interactive emergency decision-support systems. However, to fully operationalize this prototype, critical practical steps must be taken. The system strictly requires the integration of official evacuation data from BPBD, continuous dynamic risk updates, rigorous field validation, and integration with local early warning systems to ensure community safety.

However, this study has several limitations that must be acknowledged as potential threats to its validity. First, the generation of evacuation routes relies heavily on data from the OpenSource Routing Machine (OSRM), which may not fully cover all local roads, small streets, or newly constructed roads in the city of Bitung. Second, the accuracy of the system's GPS tracking capability depends heavily on the GPS hardware capabilities of user devices and signal stability, which can be disrupted during extreme weather conditions. Finally, the current hazard analysis

*Kristofel Santa

e-ISSN : 2541-2019
p-ISSN : 2541-044X

uses static GeoTIFF raster data extracted from InaRISK. Therefore, continuous dynamic shifts in disaster zone boundaries will require manual updates to spatial data to maintain accuracy.

CONCLUSION

In conclusion, this study successfully developed a WebGIS prototype for disaster analysis in Kota Bitung, demonstrating that the integration of the Ray Casting and Haversine algorithms serves as a robust foundational scientific approach for location-based risk analysis. The Ray Casting algorithm effectively resolves point-in-polygon evaluations to determine user risk status, while the Haversine formula logically identifies the nearest evacuation point for subsequent OSRM routing. Comprehensive evaluation, including 11 distinct black-box scenarios, accuracy testing, and spatial distance validation, confirmed that the core spatial analysis and routing functionalities operate successfully.

However, several critical limitations must be acknowledged. First, the system currently utilizes dummy coordinates for evacuation points. Second, the hazard analysis relies on static raster layers. Third, the system lacks usability testing with end-users. Fourth, there is an absence of real-time performance testing under heavy server loads. Finally, the system has not yet undergone field validation using official BPBD data. Future work must address these limitations by focusing on the integration of real-time disaster data APIs, conducting extensive field validation with official BPBD datasets, and performing comprehensive usability evaluations to ensure operational readiness during actual emergencies.

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*Kristofel Santa