MUSUBOU-AR: An Open-Source Geospatial AR Framework for Integrating Public GIS Data, Field Authoring, and Disaster Walking Tours

Daisuke Yoshida [1, 2], Van Thien Nguyen [3], Hirofumi Hayashi [3], Keiko Ishihara [4]

[1] Graduate School of Informatics, Osaka Metropolitan University, Osaka, Japan – daisuke@omu.ac.jp
[2] Center for Spatial Information Science, the University of Tokyo, Chiba, Japan
[3] Applied Technology Co. Ltd., Osaka, Japan – th-nguyen@apptec.co.jp; hayashi@apptec.co.jp
[4] Hiroshima International University, Hiroshima, Japan – k-ishiha@hirokoku-u.ac.jp

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Abstract

Conventional hazard maps, public GIS layers, and disaster education materials are essential resources for community disaster risk reduction, but they do not always support in-situ spatial understanding during field-based training. This paper presents MUSUBOU-AR, a publicly released open-source geospatial augmented reality framework that links public GIS resources, local scenario authoring, mobile AR visualization, and post-activity review for disaster walking tours. The system combines a map mode based on public and custom XYZ tiles, an AR mode for location-based visualization of hazards and disaster-related field resources, a web-based authoring environment for points, routes, and GIS layers, GPX-based field logging and review, and optional LiDAR-enhanced AR visualization for improving environmental alignment and ground-surface-aware rendering. As a representative field deployment, the framework was used in a joint disaster walking tour in the Hiro area of Kure City, Hiroshima Prefecture. In this paper, the case is used primarily to examine the field-deployment workflow of MUSUBOU-AR, including public hazard-map use, route and point authoring, AR scenario configuration, and on-site operation. A previously reported facilitator survey provides supplementary evidence that the activity supported situated geospatial interpretation among university student facilitators. Although the supporting survey evidence was limited by a small sample and no control group, the results suggest that MUSUBOU-AR can support reusable geospatial workflows for field-based disaster risk communication.

1. Introduction

Hazard maps, public GIS layers, and disaster education materials are widely used as basic resources for community disaster risk reduction and risk communication (Hagemeier-Klose and Wagner, 2009; Kellens et al., 2013). They provide essential information on flood inundation, landslide susceptibility, evacuation facilities, and other local hazards. However, these resources are usually represented as two-dimensional maps or web-based layers, and their interpretation in the field is not always straightforward because effective map-based communication depends on cartographic design, user understanding, and the communication context (Fuchs et al., 2009; Snel et al., 2019). During disaster walking tours and community-based training, participants are expected to connect map-based hazard information with the actual terrain, streetscape, buildings, drainage channels, slopes, and evacuation routes around them. This translation from mapped information to situated understanding is particularly difficult for children, first-time visitors, and residents who are not accustomed to interpreting geospatial information.

Augmented reality (AR) has the potential to support such field-based interpretation by overlaying virtual information onto real environments. Previous studies in disaster education and geospatial learning have explored practical drills, ICT-based learning materials, game-based activities, and AR/VR-based disaster experiences, including immersive evacuation training and AR-supported evacuation applications (Feng et al., 2018, 2020; Lovreglio and Kinateder, 2020). These studies have shown the value of immersive or interactive learning environments for improving awareness, engagement, preparedness, and behavioral responses. Nevertheless, many implementations focus primarily on the learning experience or educational outcomes, while the geospatial workflow behind field deployment is often less emphasized. In particular, there remains a need for an open and reusable framework that connects public hazard-map resources, local field knowledge, route and scenario authoring, in-situ AR visualization, and post-activity review.

To address this gap, we developed MUSUBOU-AR, an open-source geospatial augmented reality framework for disaster walking tours, community disaster risk communication, and place-based disaster learning. MUSUBOU-AR is designed not only as a mobile AR application but also as a reusable workflow for transforming public and locally prepared geospatial information into deployable field scenarios. The framework provides a map mode that supports public and custom XYZ tiles, an AR mode that visualizes virtual hazards at location-based positions, a web-based authoring environment for creating points, routes, and GIS layers, GPX-based logging and review functions, and optional LiDAR-enhanced visualization for environmental alignment and ground-surface-aware rendering. The source code is publicly available through a GitHub repository, supporting reuse and reproducibility (Yoshida, 2017).

The system is intended to bridge the gap between map-based hazard information and in-situ spatial interpretation. In a disaster walking tour, organizers can prepare route-based scenarios using public hazard maps, local field inspection, and additional disaster-related geographic information. Participants can then observe simulated hazards such as inundation, fire, landslide, collapse, or liquefaction at relevant locations while also referring to map layers and route information. After the activity, GPX-based logs can be reviewed to support reflection and further analysis. In this way, MUSUBOU-AR integrates open geospatial data, mobile AR visualization, field authoring, and post-activity review into a single practical workflow.

This paper presents the design and field validation of MUSUBOU-AR. The main contributions are fourfold. First, we present an open-source mobile GIS/AR framework for field-based disaster risk communication. Second, we describe an interoperable workflow that integrates public GIS tiles, locally authored route and scenario data, and web-based field authoring. Third, we introduce GPX-based field logging and review functions, together with optional LiDAR-enhanced visualization for improving environmental alignment and ground-surface-aware AR rendering. Fourth, we report a representative field deployment and supplementary evaluation in a disaster walking tour conducted in the Hiro area of Kure City, Hiroshima Prefecture, focusing on whether the framework can support situated interpretation of hazard maps and local risk features by university student facilitators. The remainder of this paper is organized as follows. Section 2 reviews related work. Section 3 describes the MUSUBOU-AR framework. Section 4 presents the field deployment and validation case. Section 5 summarizes supporting evidence from a previously reported facilitator survey. Section 6 discusses the academic contribution, reusability, contribution to the FOSS4G community, practical implications, and limitations. Section 7 concludes the paper.

2. Related Work

2.1 Hazard maps, public GIS, and disaster risk communication

Hazard maps and public GIS layers are fundamental tools for disaster risk communication (Hagemeier-Klose and Wagner, 2009; Kellens et al., 2013). They provide spatially explicit information on flood inundation, landslide susceptibility, evacuation facilities, and other local hazards. Web-based GIS services have further improved public access to such information by allowing users to browse hazard layers together with base maps and aerial imagery (Hagemeier-Klose and Wagner, 2009). However, the availability of map-based information does not necessarily guarantee in-situ understanding, because the effectiveness of hazard maps depends on map design, communication context, and users' prior knowledge (Fuchs et al., 2009; Snel et al., 2019). Users must interpret symbols, legends, scales, and hazard categories, and then relate them to actual terrain, streetscapes, drainage channels, slopes, and evacuation routes. This translation from two-dimensional cartographic information to situated judgment is especially challenging in field-based learning and community disaster walking tours.

For disaster risk communication, therefore, the issue is not only whether hazard information is available, but also whether it can be connected to the places where people make decisions and tailored to diverse users' perspectives (Kellens et al., 2013; Snel et al., 2019). In field activities, participants need to understand why a particular street, waterway, slope, or intersection may become hazardous under specific disaster scenarios. This requires a mediating interface between public geospatial data and local place-based interpretation. MUSUBOU-AR addresses this need by linking hazard-map resources and locally prepared route scenarios with mobile AR visualization in the field.

2.2 AR/VR and serious games for disaster education and training

Immersive technologies have been increasingly explored in disaster education and training. Virtual reality and serious games have been proposed as alternatives or complements to traditional drills, lectures, posters, and videos because they can represent dangerous situations without exposing participants to real hazards (Feng et al., 2018). Building on this line of research, previous studies have also developed and evaluated VR serious games for earthquake preparedness and post-earthquake evacuation training, showing their potential to improve knowledge, self-efficacy, engagement, and behavioral preparedness (Feng et al., 2020).

These studies demonstrate the usefulness of immersive or interactive environments for disaster learning, including AR-based evacuation training and evacuation research (Catal et al., 2020; Lovreglio and Kinateder, 2020). However, many existing systems are designed as stand-alone simulations, building-scale evacuation tools, or experience-oriented training environments. Their focus is often placed on learning outcomes, user engagement, or behavioral responses. In contrast, outdoor disaster walking tours require a different technical workflow: local hazard-map resources must be transformed into route-based scenarios, connected to actual field locations, displayed on mobile devices, and reviewed after the activity. The contribution of MUSUBOU-AR is therefore not limited to providing AR disaster experiences; it lies in integrating these experiences with an open geospatial data and authoring workflow.

2.3 Geovisualization, location-based AR, and open geospatial workflows

Geovisualization and 3D representations have been studied as means of supporting spatial understanding, exploration, knowledge construction, and decision support, especially when users need to interpret complex geographic processes in risk communication contexts (Andrienko et al., 2007; MacEachren et al., 2004; MacEachren and Kraak, 1997).

Location-based AR is particularly relevant to field deployment because it can present digital information at or near the places to which that information refers. This makes it suitable for disaster walking tours, where participants move through real streets while interpreting local hazard features. Nevertheless, many AR/XR systems do not fully address the operational requirements for repeated deployment in different communities. In practice, organizers need to prepare public GIS layers, local routes, hazard points, scenario data, and field logs using reproducible tools. Open-source GIS tools, such as QGIS, can reduce this barrier by supporting data preparation, conversion, and tile generation for local deployment workflows (QGIS Development Team, 2026; Steiniger and Bocher, 2009).

This study positions MUSUBOU-AR in this gap. While previous research has shown the value of hazard maps, immersive disaster training, and geovisualization, fewer studies have examined how public GIS layers, locally authored route scenarios, in-situ AR visualization, and post-activity field logs can be combined into a reusable open-source framework for outdoor disaster walking tours. MUSUBOU-AR contributes to this area by integrating XYZ tile-based public GIS overlays, web-based field authoring, location-based AR hazard visualization, GPX-based review, and optional LiDAR-enhanced AR visualization within a single deployable workflow.

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3. MUSUBOU-AR: Open-Source Geospatial AR Framework

3.1 System overview

MUSUBOU-AR is designed as an open-source mobile GIS/AR framework for disaster walking tours. The framework connects public GIS resources, local field knowledge, route-based scenario data, mobile AR visualization, and post-activity review. It consists of five main components: a mobile application with map and AR modes, public and custom geospatial layers, a web-based authoring environment, GPX-based field logging and review, and optional LiDAR-enhanced AR visualization. Figure 1 illustrates the overall workflow of these components, and Table 1 summarizes their main roles in the deployment process.

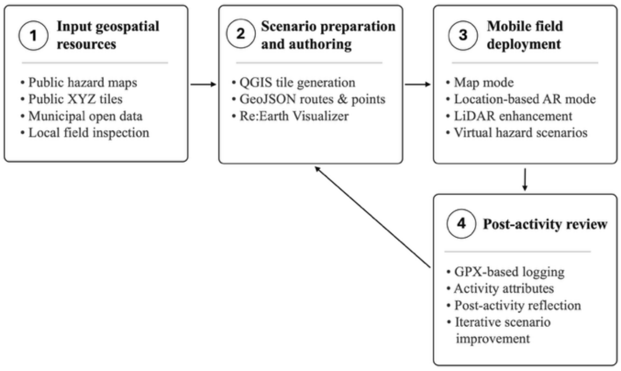

Figure 1. Overview of the MUSUBOU-AR open geospatial workflow, linking geospatial inputs, scenario authoring, mobile field deployment, and post-activity review with an iterative feedback loop.

Component	Role in the deployment workflow
Geospatial inputs and preparation	Public hazard maps, XYZ tiles, municipal open data, field inspection records, QGIS, and GeoJSON are used to prepare routes, AR hazard points, and tiled GIS layers.
Web-based authoring	A customized Re:Earth Visualizer supports editing of walking routes, AR hazard points, GIS layers, and field scenarios.
Mobile map mode	MUSUBOU-AR displays base maps, hazard layers, routes, and point data using public/custom XYZ tiles and GeoJSON.
Mobile AR mode	MUSUBOU-AR visualizes location-based virtual hazards and disaster-related field resources, with optional LiDAR-enhanced AR visualization.
GPX logging and review	GPX logs and GPXreaderWeb support post-activity reflection and iterative improvement of routes and scenarios.

Table 1. Main components of the MUSUBOU-AR open geospatial workflow.

At the implementation level, the mobile application is developed for iOS. The map mode is implemented in Swift using a Mapbox-based map display for base maps, XYZ tile overlays, routes, and GeoJSON point data, while the AR mode is implemented using Unity to render location-based virtual hazards and field-learning resources.

3.2 Public GIS and XYZ tile interoperability

The map mode supports public and custom XYZ tile layers. Public base maps and hazard-related map layers can be overlaid with locally authored route and point data. Local datasets can be prepared using standard GIS workflows, including conversion to GeoJSON for AR points and generation of custom XYZ tiles through QGIS and related tools. This design makes it possible to adapt the same application to different municipalities and field sites without changing the application code. In the Japanese deployment context, the map mode can use publicly distributed XYZ tiles, including Geospatial Information Authority of Japan tiles and hazard-related map layers distributed through national or municipal web map services. Project-specific layers can also be prepared as custom XYZ tiles in QGIS, for example using tile-generation plugins, and deployed on a web server without modifying the mobile application. Figure 2 shows example interfaces of the map mode, including base map display and overlays of flood hazard-map and historical aerial-photo XYZ tile layers.

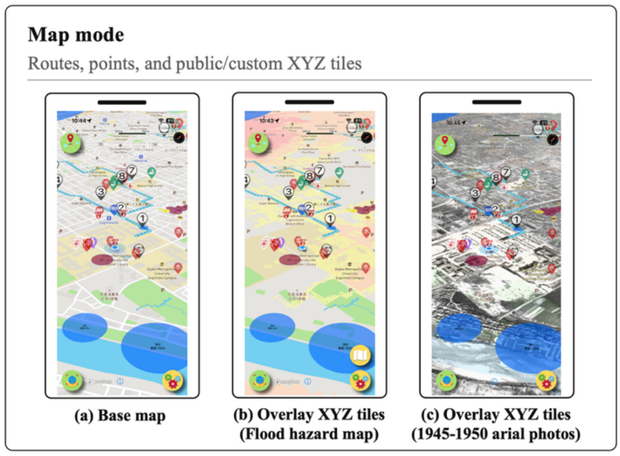

Figure 2. Example interfaces of the map mode in MUSUBOU-AR: (a) base map display, (b) overlay of a flood hazard-map XYZ tile layer, and (c) overlay of a historical aerial-photo XYZ tile layer.

3.3 Web-based field authoring

To reduce the practical barrier to repeated deployment, we developed a web-based authoring environment by customizing Re:Earth Visualizer, an open-source WebGIS platform (Re:Earth Project, 2026). The tool allows organizers to create and edit the core datasets required by MUSUBOU-AR, including walking routes, AR hazard points, and GIS layers. Figure 3 shows the authoring interface using the Hiro area deployment dataset as an example, where routes and points can be edited on a web map and associated with field-specific scenario information. The scenario data can include the hazard type, display location, explanatory information, links to supplementary web or video content such as YouTube videos, and optional temporal parameters. These parameters allow organizers to define time-varying events, such as gradually expanding inundation or spreading fire, as part of the deployment dataset rather than as hard-coded application behavior. The tool can also import existing GeoJSON-based datasets and export the main deployment files used by MUSUBOU-AR, including *data.geojson*, *LinePolygon.geojson*, and *gis_data.json*. This import–edit–export workflow enables organizers to revise AR points, walking routes, GIS layer settings, and related scenario information through a web-based interface. This design separates local scenario preparation from mobile application development: organizers can prepare or modify deployment datasets for each municipality, school district, or event without changing the application code. The authoring tool used in this study is available online at cerdar.reearth.io (12 June 2026). Supplementary user guides for the MUSUBOU-AR application and the data authoring tool are provided on the project website (Osaka Metropolitan University Urban Resilience Research Center, 2026). At present, the documentation is available only in Japanese, and an English version is planned for future release. The authoring workflow therefore functions as a core component for regional redeployment, transforming public geospatial resources and local field knowledge into reusable, deployable AR scenarios for disaster walking tours.

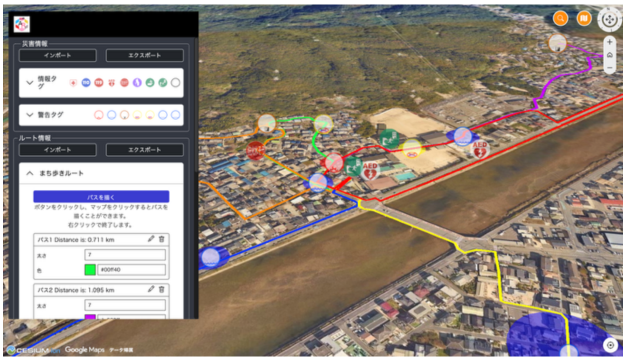

Figure 3. Example interface of the web-based authoring tool for preparing and exporting MUSUBOU-AR deployment datasets, shown here using the Hiro area deployment dataset, including walking routes, AR hazard points, GIS layers, and related scenario information.

The deployment dataset is implemented as a set of external configuration and geospatial data files rather than as hard-coded application content, reflecting the separation between application logic and local deployment data. Table 2 summarizes the main files used in the current implementation. This file-based structure allows local AR points, walking routes, GIS layers, and server-based dataset references to be updated or replaced without modifying the mobile application itself.

In the application workflow, locally stored deployment files on the device are used preferentially when they are available. If the required local files are not available, the application can fall back to built-in default or server-based datasets, with *disaster.json* providing the reference information needed to retrieve the corresponding *data.geojson* through the network.

File	Main role in MUSUBOU-AR deployment
data.geojson	Describes AR point data, including virtual disaster scenarios, disaster-related facilities, and field-learning resources.
LinePolygon.geojson	Stores walking-tour route geometry and related line/polygon information used for route-based field deployment.
gis_data.json	Defines GIS layers overlaid on the background map, including public hazard-map layers and project-specific XYZ tile layers.
disaster.json	Specifies server-based dataset reference information used to retrieve *data.geojson* when local point data are not stored on the device.

Table 2. Main deployment data files used in MUSUBOU-AR.

3.4 GPX-based logging and review

The framework includes GPX-based logging and review functions for post-activity reflection. When used with Apple Watch-based activity logging, walking trajectories and activity-related attributes can be recorded during field activities. Because positional records and biometric or activity-related records may be stored separately and sampled at different intervals, the framework synchronizes these records and converts them into a unified GPX-based dataset. GPXreaderWeb visualizes the resulting records on a web map together with attributes such as walking speed, elevation, and heart rate (Yoshida, 2022), allowing field trajectories and activity conditions to be reviewed after the activity. In this paper, this component is positioned as an infrastructure for post-activity review and future behavioral analysis. By linking field trajectories and activity-related attributes with a web map, the review process closes the deployment loop from scenario preparation and on-site AR use to post-activity reflection and iterative improvement of routes and hazard-point placement.

3.5 AR mode and LiDAR-enhanced visualization

The AR mode renders the disaster scenarios and location-based field resources configured through the authoring workflow, including static and, where applicable, time-varying hazard events. For LiDAR-equipped iPhone Pro and iPad Pro models, MUSUBOU-AR provides LiDAR-enhanced visualization, building on the portable time-of-flight depth-sensing capabilities of recent Apple Pro devices (Tondo et al., 2023). This function improves environmental alignment and enables ground-surface-aware rendering, such as displaying floodwater at a specified height above the recognized ground surface. For non-LiDAR devices, the application preserves backward compatibility by using the conventional AR implementation. Figure 4 shows representative examples of the AR mode, including a field-view example of flood visualization during outdoor use, virtual hazard scenarios such as fire and building collapse, and location-based icons for disaster-related facilities or field-learning resources. In addition to the examples shown in Figure 4, the AR mode also supports other disaster scenarios such as landslide, block-wall collapse, and liquefaction.

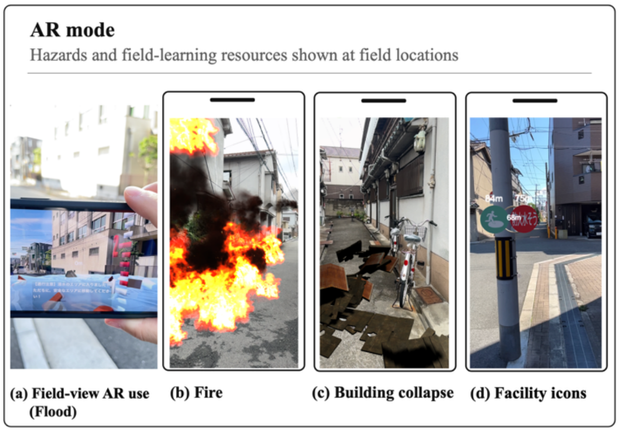

Figure 4. AR mode examples in MUSUBOU-AR: (a) flood visualization, (b) fire, (c) building collapse, and (d) facility/learning-resource icons.

The AR mode is not limited to virtual hazard visualization. It can also display location-based icons for disaster-related facilities and field-learning resources, such as AEDs, evacuation shelters, fire cisterns, and other locally relevant points. These icons can be linked to explanatory text, web pages, or video content, enabling participants to access supplementary learning materials at the corresponding field locations. For example, an organizer can associate an AR icon with a short explanatory video or a YouTube-based quiz, allowing disaster-related information to be delivered as part of the walking-tour scenario rather than as a separate classroom activity.

On LiDAR-equipped iPhone Pro and iPad Pro devices, MUSUBOU-AR uses scene understanding to recognize environmental surfaces such as the ground, walls, and nearby physical structures. This information is used to improve the spatial stability of AR placement and to support ground-surface-aware rendering. In the flood visualization, for example, virtual water can be rendered at a specified height relative to the recognized ground surface, rather than being displayed only as a camera-facing overlay. Figure 5 illustrates an outdoor example of LiDAR-based scene understanding, in which ground and wall surfaces are recognized and used to support stable AR placement, ground-surface-aware rendering, and wall-related hazard visualization. In addition to floodwater rendering relative to the recognized ground surface, the recognized wall geometry can be used as a spatial reference for simulations such as block-wall collapse.

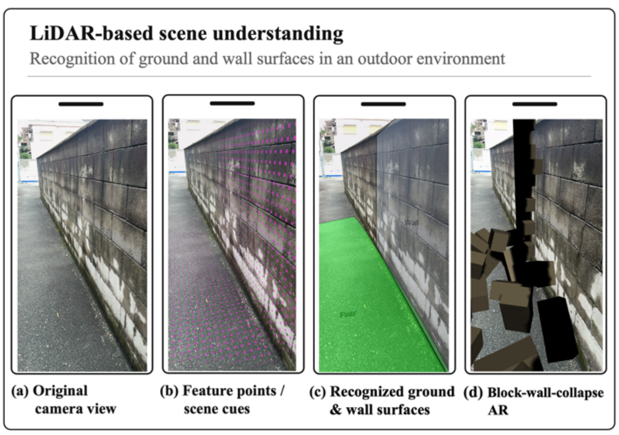

Figure 5. LiDAR-based scene understanding and hazard placement: (a) camera view, (b) feature points, (c) recognized ground/wall surfaces, and (d) wall-collapse AR placement.

3.6 Design principles for reproducible field deployment

The design of MUSUBOU-AR was guided by three principles for reproducible field deployment. The first principle is the separation of application logic from local deployment data. Hazard points, walking routes, explanatory information, temporal scenario parameters, and GIS layers are prepared as external datasets rather than being hard-coded into the mobile application. This separation allows the same application to be reused in different municipalities, school districts, and community events by replacing the deployment datasets.

The second principle is interoperability with standard geospatial data formats and public map services. By using GeoJSON for point and route data and XYZ tiles for base maps, hazard-map overlays, and project-specific raster layers, the framework can be connected to existing GIS workflows and public geospatial resources. This design enables organizers to prepare local datasets using standard tools such as QGIS and to publish custom layers through ordinary web servers without requiring specialized AR development.

The third principle is closure of the field-deployment loop through post-activity review. Field activities do not end with on-site AR visualization. GPX-based logs and GPXreaderWeb allow walking trajectories and activity-related attributes to be reviewed after the activity, supporting reflection, route improvement, and future behavioral analysis. In this way, MUSUBOU-AR connects preparation, field deployment, and review as an iterative geospatial workflow.

These principles distinguish the framework from stand-alone AR disaster-experience applications. The contribution of MUSUBOU-AR lies not only in visualizing virtual hazards in the field, but also in providing a reproducible workflow through which public GIS resources and local field knowledge can be transformed into deployable, reviewable, and reusable disaster walking tour scenarios.

4. Field Deployment and Validation Case

4.1 Deployment overview

MUSUBOU-AR has been deployed in multiple community- and school-based disaster education settings in Japan. These deployments include school-based disaster walking tours, public disaster awareness events, facility-based training, and municipality-supported educational programs. Although the scale and setting differ, the common deployment workflow consists of collecting public hazard information and local field knowledge, designing routes and points, preparing AR scenario data, conducting the field activity, and reviewing participants' observations. In this paper, we draw on these deployments and focus on the Hiro area case in Kure City as a representative field-deployment case because it clearly illustrates the end-to-end geospatial workflow: public hazard-map use, local field inspection, route design, AR hazard placement, mobile field operation, and post-activity review.

4.2 Disaster walking tour in the Hiro area, Kure City

One recent representative field-deployment case was conducted in the Hiro area of Kure City, Hiroshima Prefecture. This community-based disaster walking tour involved pupils from Yokoro Elementary School, which is located in the study area shown in Figure 6, and university student facilitators from Hiroshima International University. The area includes lowland environments along the lower Kurose River and nearby slope environments, making it suitable for field-based interpretation of flood and landslide hazards. Before the activity, university students studied local topography, public hazard maps, municipal materials, and three-dimensional terrain representations. They also conducted field inspections around the school district and recorded potentially hazardous locations with photographs and maps. Figure 6 shows the field-deployment map of the Hiro area case, including the walking routes, AR hazard points, and surrounding base-map context used for risk interpretation.

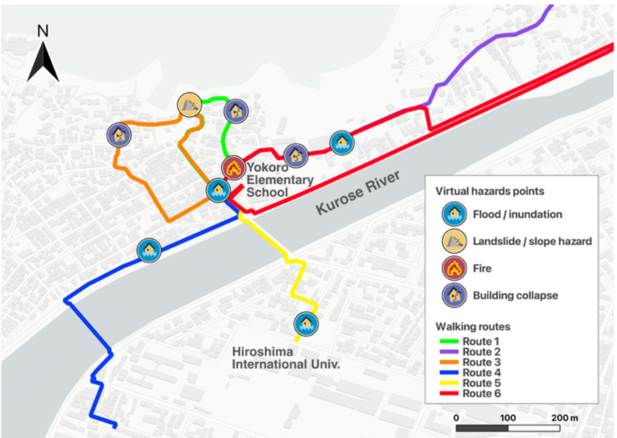

Figure 6. Field-deployment map of the Hiro area case in Kure City, showing the walking routes, AR hazard points, and surrounding base-map context used for disaster risk interpretation. The map illustrates how public GIS resources, local field inspection, and route-based scenario design were integrated into the MUSUBOU-AR deployment workflow.

Route design and hazard placement were based on publicly available flood and landslide hazard maps, fire cistern locations recorded during field inspection, student field reports, and additional on-site verification. The scenarios were designed to reflect both lowland flood risk and slope-related hazards. During the field activity, participants received an introductory lecture on local disaster history, terrain, and hazard maps, walked along assigned routes with MUSUBOU-AR, stopped at configured locations, experienced virtual hazards, and discussed local risk features. Local features such as roadside waterways, narrow roads, low-lying areas, and slope environments were used as discussion points for connecting public hazard-map information with field observations.

Separate pre- and post-activity questionnaire surveys were administered to elementary school pupils and university student facilitators. The educational outcomes of the elementary school pupils are outside the primary scope of this paper and are reported separately. The facilitator survey has also been reported in detail elsewhere (Ishihara et al., 2025). Here, the Hiro area case is used mainly to examine how MUSUBOU-AR can be deployed as an open geospatial workflow for disaster walking tours.
As summarized in Section 5, the previously reported facilitator survey focused on items related to geospatial interpretation, including noticing environmental danger signs, understanding hazard maps and disaster-related signs, identifying dangerous and relatively safe places on maps, and planning evacuation routes while using maps. In this paper, these reported results are used not to make broad causal claims about educational effectiveness, but to support the interpretation that the field deployment helped facilitators connect mapped hazard information with actual local environments.

5. Supporting Evidence from a Previously Reported Facilitator Survey

A separate study analyzed pre- and post-activity questionnaire responses from university student facilitators who participated in the Hiro area disaster walking tour (Ishihara et al., 2025). In this paper, we do not reanalyze the facilitator survey in detail. Instead, we refer to the reported results as supplementary evidence for the field deployment of MUSUBOU-AR.

The reported results suggest that the activity improved several aspects of situated geospatial interpretation among university student facilitators, including recognition of environmental danger signs, understanding of hazard maps and disaster-related signs, identification of dangerous and relatively safe places on maps, and route-planning using maps (Ishihara et al., 2025). The same study also reported a significant overall post-activity shift toward higher response levels in a cumulative logit mixed model, with an odds ratio of 21.7 for moving to a higher response category. In the open-ended responses, facilitators frequently identified roadside ditches, waterways, and narrow roads as hazardous places, mainly in relation to flood or inundation risk. These findings support the interpretation that MUSUBOU-AR can help facilitators connect public hazard-map information with local field features during route-based disaster learning.

Because the survey did not include a control group and involved a limited number of participants, these results should not be interpreted as causal proof of educational effectiveness. Rather, they provide supporting field-based evidence that the MUSUBOU-AR deployment workflow can be meaningfully used in a real disaster walking tour involving public GIS data, local route design, AR scenario configuration, and on-site facilitation.

6. Discussion

6.1 Academic contribution and positioning

From an academic perspective, the framework also provides a case of how open geospatial technologies can be operationalized in situated risk communication. The workflow demonstrates that public hazard maps, locally authored scenarios, mobile AR visualization, and field logs can be treated as connected components of a reproducible geospatial process. This framing is important because the effectiveness of AR in disaster education depends not only on visual immersion, but also on how spatial data are selected, transformed, authored, deployed, and reviewed in relation to local environments.

6.2 Reusability and contribution to open geospatial workflows

The main contribution of MUSUBOU-AR is its reusable open geospatial workflow. The framework does not depend on a single predefined study area or closed data environment. Instead, public GIS layers, locally prepared hazard information, route data, and AR points can be prepared through standard geospatial workflows and deployed through the mobile application. This design allows the same application to be adapted to different municipalities, schools, and community events by replacing the underlying route, point, and tile datasets. From a FOSS4G perspective, the contribution lies not only in the mobile application itself, but also in the integration of open-source tools, public geospatial data, and field-deployable AR into a coherent workflow, building on the broader role of free and open-source GIS in reproducible geospatial practice (Steiniger and Bocher, 2009).

For redeployment in other communities, the essential requirements are not the redevelopment of the mobile application, but the preparation of local deployment datasets and an appropriate field operation plan. Organizers need to identify relevant public hazard-map layers, prepare walking routes and AR points, configure background GIS layers, and test the visibility and positional behavior of AR content at the actual field locations. Because the application can preferentially use locally stored deployment files and can also retrieve server-based datasets, the same framework can support both preconfigured local use and network-based updating. This flexibility is particularly important for community events and school-based activities, where network conditions, device availability, and local facilitation capacity may differ across sites.

From a reproducibility perspective, the reusable elements of the framework are the mobile application source code, the web-based authoring workflow, the deployment-data structure, and the GPX-based review process. In contrast, the actual hazard-map layers, walking routes, AR points, explanatory content, and field-operation plans remain site-specific and can be replaced for each community or educational activity. This separation makes it possible to reproduce the overall workflow while adapting the local content to different geographic and institutional contexts.

6.3 Role of AR in situated geospatial interpretation

The previously reported facilitator survey provides supplementary evidence that MUSUBOU-AR can support situated geospatial interpretation during disaster walking tours (Ishihara et al., 2025). The reported questionnaire results showed improvements in items related to noticing environmental danger signs, understanding hazard maps, identifying dangerous and relatively safe places on maps, and planning evacuation routes. These results indicate that the framework may help facilitators connect public hazard-map information with local field features while guiding route-based activities. This suggests that the AR component functioned not merely as an immersive visual effect, but as a mediating interface between hazard-map knowledge and place-based interpretation in the field, consistent with the view that interactive geovisualization can support knowledge construction and spatial decision support (Andrienko et al., 2007; MacEachren et al., 2004).

6.4 Practical implications for disaster walking tours

The deployment also highlights the importance of authoring and preparation in field-based disaster education. AR content becomes meaningful only when virtual hazards are placed in relation to local topography, public hazard maps, field observations, and route design. The web-based authoring workflow therefore plays an important role in lowering the barrier to repeated deployment. Similarly, GPX-based review can support post-activity reflection and iterative improvement of routes and scenarios.

At the same time, outdoor AR-based disaster walking tours require careful facilitation. Participants should be cautioned against focusing solely on the mobile screen while walking, especially near roads, waterways, slopes, or other hazardous locations. The AR content should therefore be used mainly at planned stopping points or under the guidance of facilitators. In addition, route design should consider walking safety, group size, visibility of the device screen under outdoor lighting conditions, and the availability of network access or locally stored datasets. These operational considerations are important for using AR as a support tool for place-based interpretation rather than as a distraction from the surrounding environment.

6.5 Limitations and future work

This study has several limitations. First, the supporting facilitator survey was based on a relatively small sample and did not include a control group; therefore, the results should be interpreted as supporting field-based evidence rather than causal proof of educational effectiveness. Second, the supporting evidence is based on short-term responses from university student facilitators, and long-term retention was not assessed. The educational outcomes of elementary school pupils are treated outside the main scope of this geospatial framework paper and are reported separately. Third, although the framework includes LiDAR-enhanced visualization and GPX-based logging, this paper does not provide a quantitative benchmark of AR alignment accuracy, LiDAR-assisted placement accuracy, water-height rendering accuracy, relocalization stability, or detailed behavioral patterns. Future work will address these limitations through additional deployments, controlled evaluation designs, technical accuracy assessment, and more detailed analysis of field logs.

7. Conclusions

This paper presented MUSUBOU-AR, an open-source geospatial augmented reality framework for disaster walking tours and community disaster risk communication. The framework addresses the gap between map-based hazard information and in-situ spatial understanding by connecting public GIS resources, locally authored route and scenario data, mobile map and AR visualization, and post-activity review within a single deployable workflow. Rather than treating AR as a stand-alone visual effect, MUSUBOU-AR positions AR visualization as one component of a broader open geospatial process for preparing, deploying, and reviewing place-based disaster learning activities.

The representative deployment in the Hiro area of Kure City demonstrated how the framework can be applied to a route-based disaster walking tour. Public hazard maps, local field inspection, walking routes, AR hazard points, and disaster-related field resources were integrated into a field scenario that could be used on mobile devices. The previously reported facilitator survey provided supplementary evidence that the activity supported situated geospatial interpretation, although the main contribution of this paper is the presentation of the reusable workflow itself rather than a causal evaluation of educational effectiveness.

The broader implication of this study is that disaster walking tours can be designed as reproducible geospatial workflows rather than as one-off local activities. By separating application logic from local deployment data and by using open-source tools, public map services, GeoJSON-based datasets, XYZ tiles, and GPX-based review, MUSUBOU-AR can be adapted to different communities and educational settings. Future work will extend this framework through additional deployments, controlled evaluation designs, technical assessment of AR visualization accuracy, usability evaluation of the authoring workflow, and detailed analysis of field logs to better understand participant behavior during disaster walking tours.

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