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Geospatial Analytics Platforms and Hazard Assessment in Urban Drainage Systems

Natsuki Takahashi*
Department of Computer Science, School of Computing, Institute of Science Tokyo, Tokyo, Japan

Corresponding author: natsuki.takahashi@isct.ac.jp

Abstract

Urban drainage systems are increasingly stressed by rapid urbanization and extreme weather events induced by global climate change. To manage the resulting pluvial flooding hazards, municipal authorities and engineering practitioners rely on geospatial analytics platforms that integrate geographic information systems with dynamic hydraulic models. However, while the technical capabilities of these systems have advanced significantly, the human factors governing their operational utility and decision-making efficacy remain understudied. This paper presents a comprehensive survey-based assessment of geospatial analytics platforms in urban drainage hazard assessment, gathering empirical evidence from a diverse cohort of municipal planners, design engineers, and academic researchers. The analysis evaluates user perceptions regarding model accuracy, interface usability, and decision-making confidence across various platform architectures. The findings indicate that while platforms excel at high-resolution static hazard mapping, significant usability bottlenecks persist regarding system latency, interface clutter, and dynamic simulation visualization. These challenges increase cognitive load and can delay critical emergency and design interventions. Based on the survey insights, we outline policy and technical recommendations aimed at standardizing spatial data frameworks, implementing role-based adaptive user interfaces, and establishing robust practitioner training protocols to maximize the disaster risk reduction potential of these analytical tools.

Keywords: Urban Drainage; Geospatial Analytics; Hazard Assessment; Survey Analysis; Software Engineering

1. Introduction

1.1 Urbanization and Drainage Challenges

Modern cities are expanding at an unprecedented rate, resulting in substantial transformations of land cover, soil permeability, and local hydrological regimes. The conversion of natural landscapes, such as forests, wetlands, and grasslands, into impervious urban surfaces like asphalt roads, concrete pavements, and dense building footprints radically reduces the natural infiltration capacity of watersheds [1]. During intense precipitation events, this lack of infiltration leads to rapid surface runoff accumulation, accelerated peak discharge times, and increased total runoff volumes. Consequently, municipal drainage infrastructures, many of which were designed decades ago under historical hydrological assumptions, are frequently overwhelmed.

The challenges of rapid land-use change are compounded by the growing frequency and severity of extreme weather events associated with global climate change [2]. Stationary design storm assumptions, historically used by civil engineers to size storm sewers, detention basins, and open channels, are no longer sufficient. Extreme rainfall events that were once expected to occur once in fifty or a hundred years are now occurring multiple times within a single decade. This shift results in frequent pluvial flooding, which inundates urban transportation networks, causes extensive damage to residential and commercial properties, disrupts critical infrastructure, and poses immediate threats to public safety and public health.

To address these vulnerabilities, municipal engineers and urban planners must move beyond reactive maintenance and adopt proactive flood risk management strategies. This requires a deep understanding of how water moves through both overland surfaces and subsurface pipe networks during extreme rain events.

Analyzing these complex physical interactions is essential for identifying localized drainage bottlenecks, evaluating the performance of proposed infrastructure upgrades, and preparing effective emergency evacuation and response plans.

1.2 Role of Geospatial Analytics Platforms

To analyze and visualize these complex hydrological and hydraulic processes, the field of water resources engineering has increasingly integrated geographic information systems (GIS) with computational hydraulic models. This integration has led to the development of geospatial analytics platforms, which serve as specialized spatial decision support systems for urban drainage design and hazard assessment [3]. These platforms allow users to import high-resolution digital elevation models, define detailed pipe network geometries, input spatially distributed rainfall datasets, and simulate surface-subsurface water interactions.

Modern geospatial platforms have transitioned from isolated desktop applications, which required manual data conversions and specialized coding, to integrated, web-based environments. These web-based geospatial platforms can render complex spatial datasets in real-time, overlaying inundation depths and velocity vectors directly onto municipal basemaps, aerial imagery, and utility networks. This visual capability has democratized access to hydraulic modeling outputs, allowing not only specialized hydraulic engineers but also municipal administrators, emergency responders, and urban planners to engage with flood risk data.

Despite these technological advancements, the practical success of these platforms depends heavily on the human-machine interface. A highly accurate hydraulic model is of limited value if the platform displaying its outputs is too complex to navigate during an emergency or if its visualizations are easily misinterpreted by decision-makers. The effectiveness of a geospatial platform in reducing urban flood risk is determined by how well it supports the cognitive tasks of its users, who must rapidly process visual information, assess hazards, and make decisions under time-sensitive and high-consequence conditions.

1.3 Objectives and Scope of the Study

This study evaluates the operational utility of geospatial analytics platforms in urban drainage hazard assessment by analyzing empirical evidence collected from active practitioners. While existing literature extensively covers the mathematical algorithms, grid resolutions, and computational speeds of hydraulic models, there is a lack of empirical research focusing on user interaction, perceived accuracy, and decision-making workflows within these spatial interfaces.

By conducting a structured survey of urban drainage practitioners, including municipal planners, private consulting engineers, and academic researchers, this study addresses three key research objectives. First, it identifies how different user cohorts perceive the technical accuracy and spatial reliability of geospatial hazard representations. Second, it evaluates the primary usability bottlenecks, such as system latency and interface clutter, that hinder effective platform operation. Third, it examines how interface usability impacts decision-making confidence during infrastructure planning and emergency management.

The scope of this paper encompasses a detailed review of spatial decision-support literature, a comprehensive description of the survey methodology, an architectural analysis of modern drainage analytics platforms, and a statistical discussion of the survey findings. Ultimately, the empirical evidence gathered here is used to formulate actionable design and policy recommendations for platform developers and municipal authorities, ensuring that future geospatial tools are better optimized for urban resilience workflows.

2. Literature Review and Theoretical Framework

2.1 Evolution of Hazard Assessment Methodologies

The methodologies used to assess urban drainage hazards have evolved significantly over the past century, driven by advancements in hydrology, computational mechanics, and geospatial technologies. Early urban flood assessment relied on simplified, empirical formulas like the Rational Method to estimate peak discharges [4]. These static calculations assumed uniform rainfall intensities and uniform catchment characteristics, ignoring the temporal variations of storms and the complex routing behaviors of urban sewer networks.

With the development of digital computers in the mid-twentieth century, dynamic modeling became possible. The introduction of the Storm Water Management Model by the United States Environmental Protection Agency represented a major milestone, enabling the continuous simulation of rainfall-runoff processes and dynamic wave routing through sewer conduits. However, early iterations of these hydraulic models were strictly one-dimensional, conceptualizing the urban surface as a series of simplified catchments draining into a network of one-dimensional pipes.

The emergence of two-dimensional overland flow modeling, coupled with one-dimensional pipe network simulations, revolutionized hazard assessment [5]. This coupled modeling approach simulates how water surcharges from overwhelmed manholes, flows along streets, pools in topographic depressions, and re-enters the drainage network. This level of detail is critical for urban areas, where flow paths are highly constrained by buildings, curbs, and roadways. Modern hazard assessments rely on these coupled simulations to produce detailed maps showing flood boundaries, depths, velocities, and hazard ratings across complex urban landscapes.

2.2 Geospatial Tools in Urban Water Management

The utility of advanced hydraulic models was initially limited by the labor-intensive processes required to prepare input data and interpret output files. The integration of GIS into hydraulic engineering workflows addressed these limitations by providing a spatial framework for data management and visualization [6]. GIS platforms allowed engineers to automate the delineation of sub-catchments, calculate average slope and imperviousness from digital elevation models and land-use layers, and visually map simulated flood extents.

The transition from desktop-based GIS to web-based geospatial platforms has further expanded the role of spatial tools in urban water management. Cloud-enabled geospatial platforms allow massive datasets, including high-density LiDAR terrain models, to be stored, processed, and visualized in web browsers without requiring local high-performance hardware [7]. This shift has enabled real-time modeling, where live rainfall telemetry from rain gauges and weather radar is fed directly into online hydraulic models, generating real-time flood inundation forecasts.

These modern platforms also facilitate collaborative workflows, allowing multiple municipal departments to access a single, shared representation of urban drainage hazards. For instance, public works departments can track pipe maintenance needs, urban planners can evaluate the zoning impacts of floodplains, and emergency managers can plan evacuation routes, all within the same spatial interface. This shared situational awareness is essential for coordinated municipal planning and disaster response.

2.3 User Perception and Human Factors in Spatial Decision Support Systems

Despite the computational power of modern geospatial platforms, their ultimate effectiveness is governed by user interaction. Human factors and usability principles, often studied in the context of human-computer interaction, are critical to the success of spatial decision support systems [8]. The Technology Acceptance Model and the Unified Theory of Acceptance and Use of Technology suggest that a user's intention to adopt and utilize a technology is primarily determined by its perceived usefulness and perceived ease of use.

In urban drainage hazard assessment, perceived usefulness is closely tied to the user's trust in the platform's visual outputs. If practitioners believe that simulated flood boundaries are inaccurate or that the underlying elevation data is unreliable, they are unlikely to use the platform for high-stakes decision-making. Perceived ease of use is determined by the design of the user interface, including navigation intuitive, visual hierarchy, and the cognitive load required to interpret complex spatial layers.

Information overload is a common challenge in geospatial interfaces. When platforms present users with multiple overlapping layers, such as flow direction arrows, velocity vectors, water depth colors, pipe dimensions, and base map details, the cognitive capacity of the user can be overwhelmed. This cognitive overload can lead to errors in hazard interpretation and delays in critical decision-making. Therefore, understanding user perception and usability barriers is essential for designing geospatial interfaces that effectively support urban drainage hazard assessment.

3. Methodology and Survey Design

3.1 Target Population and Sampling Strategy

This study used a quantitative survey methodology to gather empirical evidence on how practitioners interact with geospatial analytics platforms in urban drainage workflows. The target population comprised professionals directly involved in urban drainage design, stormwater management, flood risk mitigation, and spatial urban planning. This included civil engineers, municipal GIS analysts, emergency managers, and academic researchers.

To ensure a representative sample across different operational contexts, a stratified random sampling strategy was used. Participants were recruited from municipal government departments, private engineering consultancies, and academic research institutions across various regions. This stratification was designed to capture a wide range of perspectives, from those who focus on daily operational tasks and regulatory compliance to those engaged in advanced academic research and model development [9].

The survey was distributed digitally through professional associations, international water management networks, and academic research groups. To ensure data quality, screening questions were included at the beginning of the survey to verify that respondents had active experience using geospatial platforms for urban drainage or hazard assessment within the past two years.

3.2 Survey Instrument and Variable Selection

The survey instrument was developed based on established technology evaluation frameworks and was refined through a pilot testing process with five domain experts. The final questionnaire was divided into four distinct modules, each designed to capture specific aspects of the user's experience and background.

The first module gathered demographic and platform-usage data, including the respondent's primary professional role, years of experience, and the specific type of geospatial platform they use most frequently. The second module assessed perceived accuracy, asking respondents to rate how well the platform's simulated flood boundaries, depths, and velocities align with historical observation data [10].

The third module focused on usability and cognitive load, utilizing items adapted from the System Usability Scale. Respondents evaluated elements such as platform navigation, visual clarity, system response times, and the effort required to switch between different scenario views. The fourth module measured decision-making confidence, exploring how effectively the platform's outputs support actions like zoning adjustments, infrastructure sizing, and emergency routing [11]. Responses for the rating-based questions were recorded using a five-point Likert scale, ranging from strongly disagree to strongly agree.

3.3 Analytical Techniques and Verification Processes

Following the data collection phase, the raw survey responses were cleaned and prepared for statistical analysis. Incomplete submissions and responses that failed the initial screening criteria were removed. The final dataset was analyzed using both descriptive and inferential statistical techniques to identify key trends and correlations.

To validate the reliability of the survey constructs, Cronbach's alpha coefficients were calculated for each module, confirming that the questions within each category consistently measured the intended latent variables. Exploratory factor analysis was also conducted to verify the structural independence of the usability, perceived accuracy, and decision-making confidence constructs.

Hypothesis testing was performed using analysis of variance to determine if there were statistically significant differences in platform perceptions across different professional roles and experience levels. Additionally, multiple linear regression models were constructed to evaluate which platform characteristics, such as real-time simulation capability or scenario-comparison interfaces, were the strongest predictors of overall decision-making confidence. This statistical analysis provided a rigorous framework for interpreting the empirical survey evidence.

4. Architectural Framework of Geospatial Analytics for Drainage Networks

4.1 Core Components of Modern Geospatial Platforms

To contextualize the survey findings regarding usability and perceived accuracy, it is helpful to examine the underlying architectural design of modern geospatial analytics platforms. These platforms are complex systems that must integrate diverse spatial datasets, run intensive physical models, and render high-resolution visuals. A typical platform architecture consists of three core components: the data layer, the analytical modeling engine, and the visual presentation layer [12].

The data layer manages both static and dynamic inputs. Static inputs include terrain data, land-use classifications, and sewer network geometries. Dynamic inputs include real-time rainfall data, sensor readings from sewer pipes, and weather forecasts. This layer must support various spatial formats and utilize spatial indexing techniques to query massive geospatial datasets efficiently.

The analytical modeling engine is responsible for executing the mathematical equations that govern water movement. This engine runs hydrological models to estimate surface runoff, hydraulic models to calculate pipe flow, and overland flow models to simulate street flooding. To provide timely results, modern platforms often employ parallel processing, utilizing multi-core CPUs or graphics processing units (GPUs) to run these simulations quickly.

The visual presentation layer is the user interface, which renders the model outputs on interactive maps. This layer uses web map tile services and vector tile technologies to display high-resolution layers smoothly. It must also handle interactive features, allowing users to query individual pipes, view dynamic hydrographs, and compare different flooding scenarios side-by-side.

4.2 Integration of Hydraulic Models with Spatial Interfaces

Historically, the integration of hydraulic models and GIS was a loose coupling, requiring users to manually export data from one system and import it into another. This manual transfer process was slow, prone to errors, and made iterative design workflows difficult. Modern geospatial platforms utilize a tight coupling, where the hydraulic model and the spatial database are integrated into a single system [13].

In a tightly coupled architecture, any changes made to the sewer network or land-use layers in the GIS interface are automatically updated in the hydraulic model's input database. When a simulation is run, the engine computes the hydraulic state variables and writes the results directly back to the spatial database. This allows the visualization layer to render the flooding outputs in real-time or as a continuous animation, with no manual post-processing required.

This seamless integration enables rapid, iterative design workflows. For example, an engineer can add a proposed detention basin directly to the map interface, rerun the simulation, and immediately see how the change reduces downstream surface flooding. This tight coupling is critical for supporting dynamic design and hazard assessment workflows.

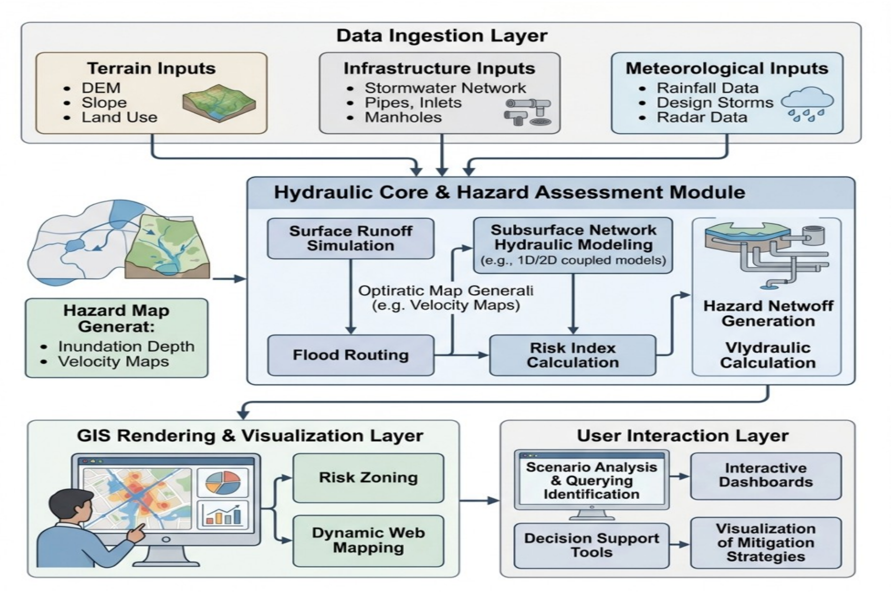

Figure 1: Conceptual Framework of Hazard Assessment Integration in Geospatial Analytics Platforms

4.3 Hazard Visualization and Decision-Making Workflows

The visual design of a geospatial platform directly affects how easily users can interpret hazards and make decisions. Effective hazard visualization requires presenting complex, multi-dimensional data in a clear, actionable format. Platforms achieve this by using dynamic styling, intuitive color palettes, and interactive information displays.

For example, flood depth is typically represented using sequential blue color gradients, with darker shades indicating deeper water. Flow velocities are often visualized using moving particle animations or vector arrow fields, which show both the direction and speed of water movement. Critical infrastructure, such as hospitals, power stations, and primary evacuation routes, can be overlaid on the hazard map, with automatic visual alerts appearing when these assets are threatened by rising water levels.

These visual features are designed to support a structured decision-making workflow. During planning phases, the workflow focuses on identifying system vulnerabilities, evaluating design alternatives, and establishing regulatory flood zones. During emergency situations, the workflow shifts to real-time monitoring, identifying blocked transportation routes, and coordinating emergency resources. The platform must adapt its interface to support these distinct workflows, ensuring that users have access to the right level of detail at each stage of their decision-making process.

5. Statistical Results and Discussion

5.1 Demographic and Platform-Usage Analysis

The survey gathered a total of 312 complete, validated responses from practitioners active in urban drainage and hazard assessment. The cohort represented a balanced mix of professional backgrounds, with 115 respondents working in municipal government planning departments, 138 working as design engineers in private consulting firms, and 59 working as researchers or professors in academic institutions.

Table 1: Participant Demographic and Platform Usage Profile

Metric Category	Response Category	Frequency	Percentage
Professional Role	Municipal Planner	115	36.8
Professional Role	Design Engineer	138	44.2
Professional Role	Research Scientist	59	19.0
Experience Level	Less than 5 Years	68	21.8
Experience Level	5 to 10 Years	142	45.5
Experience Level	More than 10 Years	102	32.7
Primary Platform	Desktop GIS Integrated	154	49.4
Primary Platform	WebGIS Cloud Platform	118	37.8
Primary Platform	Specialized Hydraulic UI	40	12.8

The demographic analysis shown in Table 1 reveals an experienced respondent pool, with over 78 percent of participants having more than five years of professional experience in the field. Regarding platform usage, while traditional desktop-integrated GIS solutions remain the most common, cloud-based WebGIS platforms now represent a substantial share (37.8 percent). This indicates a clear industry transition toward web-based, collaborative tools for managing spatial water data [14].

5.2 Perception of Hazard Assessment Accuracy

Perceived accuracy is a fundamental driver of user trust in geospatial platforms. Respondents rated several dimensions of analytical accuracy on a scale of 1 to 5, where higher scores indicate greater satisfaction with the platform's outputs.

Table 2: Assessment of Analytical Features of Geospatial Platforms

Feature Dimension	Mean Rating	Standard Deviation	Agreement Percentage
Inundation Boundary Accuracy	4.12	0.68	82.4
Temporal Flood Progression	3.56	0.89	58.1
Infrastructure Capacity Alerts	3.89	0.74	72.1
Integration of Green Infrastructure	3.12	1.12	41.5
Scenario Comparison Efficiency	4.24	0.62	86.9

The results in Table 2 show that while respondents generally trust static inundation boundaries (mean 4.12) and find scenario comparison features highly efficient (mean 4.24), they are less satisfied with how platforms represent temporal flood progression (mean 3.56) and green infrastructure performance (mean 3.12). Green infrastructure elements, such as permeable pavements and bioswales, are highly distributed and micro-scale, making them difficult to represent accurately in macro-level geospatial platforms [15].

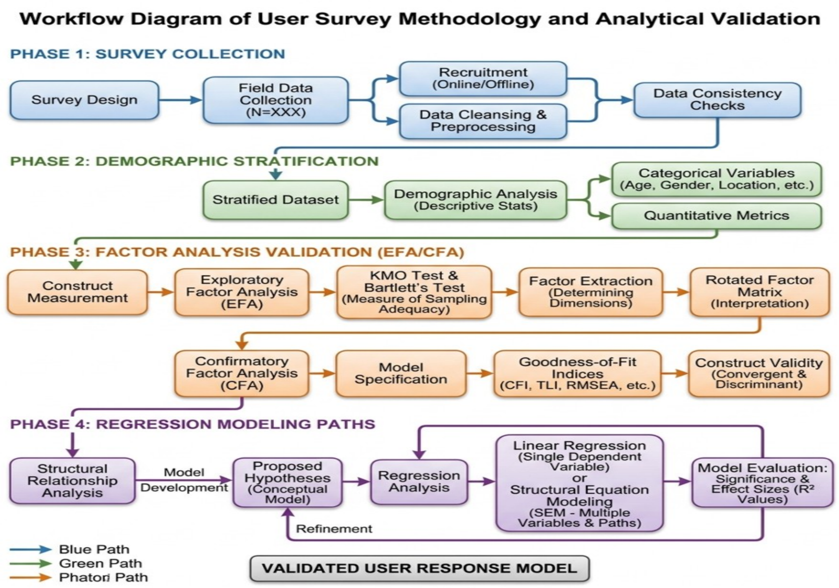

Figure 2: Workflow Diagram of User Survey Methodology and Analytical Validation

The statistical analysis also highlighted significant differences in perceived accuracy between professional groups. An ANOVA test showed that municipal planners rated inundation boundary accuracy significantly higher than design engineers did. Planners typically use hazard maps for macro-level zoning and risk communication, where general boundaries are sufficient. Design engineers, however, require high-precision hydraulic values at specific sewer connections to size physical infrastructure. This difference in application explains why engineers are more critical of spatial approximations and simplification errors [16].

5.3 Usability Challenges and Decision-Making Support

Usability is key to translating computational accuracy into effective real-world action. The survey asked respondents to identify the primary usability barriers they encounter when using geospatial platforms for hazard assessment.

Table 3: Primary Usability Barriers and Reported Frequencies

Barrier Classification	Primary Symptom	Frequency	Percentage
System Latency	Rendering lag during high-resolution layer loading	112	35.9
Interface Clutter	Overwhelming amount of spatial layers shown simultaneously	89	28.5
Data Incompatibility	Difficulties importing standard hydrologic model files	64	20.5
Insufficient Training	Lack of tutorials for advanced analytical functions	47	15.1

As shown in Table 3, system latency is the most common usability barrier, reported by 35.9 percent of respondents. High-resolution spatial datasets, such as LiDAR-derived elevation models, require significant computational resources to render, leading to lag when zooming or panning. Interface clutter is also a major concern (28.5 percent), as users often struggle to find critical tools when the map display is overcrowded with overlapping data layers [17].

Multiple regression analysis was conducted to examine the relationship between usability factors and user decision-making confidence. The regression model showed that interface clutter and system latency were significant negative predictors of decision-making confidence. When platforms suffer from rendering lag or overcrowded displays, users experience higher cognitive load and report lower confidence in their ability to make timely, accurate decisions during high-pressure hazard assessments. This emphasizes the importance of optimizing interface design alongside technical modeling capabilities.

6. Policy Implications and Technical Recommendations

6.1 Enhancing Interface Usability and Training Protocols

To maximize the practical utility of geospatial platforms, developers must shift focus from simply adding features to refining user-experience design. Platforms should implement role-based interface configurations that adapt to different user needs. For example, an emergency responder's view should prioritize clear hazard boundaries and critical road-closure overlays, while hiding complex engineering details like pipe velocity vectors. This targeted presentation reduces cognitive load and helps users make faster decisions during crisis situations.

Additionally, municipal authorities must invest in ongoing training programs for their staff. Simply licensing advanced software is not enough to improve urban resilience [18]. Structured training should focus not just on basic navigation, but on interpreting probabilistic hazard maps and utilizing multi-scenario comparisons. Well-designed training ensures that practitioners can confidently use these tools to support urban planning and disaster risk reduction workflows.

6.2 Technical Integration Standards for Urban Planning

To address data incompatibility issues, national and international regulatory bodies should establish standardized spatial data frameworks for urban water infrastructure. Developing open-source data standards for representing sewer pipes, overland flow paths, and green infrastructure features would simplify data exchange between municipal GIS databases and analytical platforms.

Furthermore, platform developers should leverage cloud architectures to reduce system latency. By offloading resource-intensive hydraulic modeling and geospatial rendering to distributed cloud servers, local agencies can run high-resolution simulations on standard office computers. This democratization of advanced tools is essential for smaller or less-resourced municipalities, enabling them to implement modern flood hazard mitigation strategies.

6.3 Limitations and Directions for Future Research

While this study provides valuable empirical insights, several limitations should be noted. The survey respondents were primarily located in regions with relatively well-developed digital municipal infrastructure. Consequently, the findings may not fully reflect the challenges faced by practitioners in developing nations, where data scarcity and limited technical capacity are primary barriers to adopting geospatial platforms [19].

Future research should focus on conducting long-term studies to track how municipal decision-making and infrastructure resilience improve over time following the adoption of advanced geospatial tools. Additionally, researchers should explore how emerging technologies, such as artificial intelligence and real-time machine learning models, can be integrated into geospatial interfaces to provide faster, predictive hazard assessments during extreme storm events.

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