

# Application and Analysis of GIS Technology in Geological Hazard Assessment

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**Abstract:** This paper systematically examines the theoretical significance, technical methodologies and practical applications of Geographic Information Systems (GIS) in geological hazard assessment, with particular emphasis on their role in evaluating typical hazards such as landslides, earthquakes and debris flows. Through spatial data collection, modelling, and analysis, GIS integrates multi-source data including remote sensing imagery, geological surveys, and sensor monitoring to construct hazard susceptibility zoning and risk prediction models, significantly enhancing evaluation precision and operational feasibility. Research indicates that GIS techniques—spatial overlay analysis, proximity analysis, and three-dimensional visualisation—effectively reveal spatial distribution patterns and evolutionary processes of disasters, providing scientific foundations for disaster prevention and mitigation. Nevertheless, GIS applications continue to face challenges including inconsistent data quality, conflicts between model complexity and computational efficiency, and insufficient real-time capabilities. Moving forward, through integration with artificial intelligence, big data, and cloud computing, GIS will demonstrate greater potential in dynamic early warning systems, intelligent modelling, and interdisciplinary collaboration, delivering precise and efficient solutions for geological hazard prevention and control.

**Keywords:** Geographic Information System (GIS); Geological Hazard Assessment; Hazard Susceptibility Zoning; Multi-Source Data Integration

## 1. Introduction

Geological hazard assessment, as a critical component of disaster prevention and mitigation, holds profound theoretical significance in

identifying, evaluating, and forecasting potential risks through rigorous scientific methodologies, thereby furnishing society with robust protective strategies. Geological hazards—encompassing phenomena such as landslides, debris flows, and rockfalls—are typically triggered by a confluence of factors, including tectonic movements, rainfall erosion, and anthropogenic activities, resulting in intricate causal mechanisms. These events not only imperil human lives and property but also exert enduring repercussions on ecosystems and socioeconomic development. Globally, geological hazards pose a significant challenge worldwide. According to United Nations reports, over 7,000 major natural disasters were documented worldwide between 2000 and 2019, with geological hazards comprising a substantial proportion; Asia, in particular, bore the brunt, recording 3,068 incidents, while China, as one of the most severely affected nations, ranked first in disaster incidence [1]. These statistics underscore the acute vulnerability of China's mountainous regions to geological hazards; for instance, in the southwest, earthquake-induced landslides and debris flows are recurrent, leading to annual fatalities in the hundreds and widespread infrastructural damage [2]. During the 1970s and 1980s, researchers primarily relied on geological mapping, geomorphological observations, and rudimentary statistical techniques to delineate hazard-prone zones, which proved efficacious under resource-constrained conditions. Nevertheless, as understanding of disaster causation deepened, traditional qualitative analyses—predominantly reliant on expert judgment—lacked standardized criteria, yielding results that were often incomparable [3]. Similarly, simplistic statistical approaches, while capable of quantifying select indicators, struggled to elucidate the coupled interactions among spatial variables. For example, landslide occurrence is frequently influenced concurrently by terrain slope, lithological properties, rainfall intensity, and

vegetation cover; without accounting for their spatial interdependencies, such methods fail to comprehensively delineate the underlying patterns of hazard genesis [4].

The advent of information technology and remote sensing has elevated Geographic Information Systems (GIS) to a pivotal role in geological hazard research. At its core, GIS leverages spatial analysis paradigms, including spatial autocorrelation and data integration via overlay operations, to synthesize heterogeneous datasets from geological, meteorological, and remote sensing sources into multidimensional evaluative frameworks. For instance, through spatial interpolation and buffer analysis, GIS can quantify the spatial distribution of hazard-triggering factors, enabling precise zonation of susceptibility [5]. In contrast to conventional methods, GIS excels in dynamic modeling and visualization: the latter are inherently static and fragmented, whereas GIS facilitates real-time simulations of hazard evolution, such as susceptibility forecasting via the information value model, which integrates factors like slope, lithology, and precipitation to generate probabilistic predictions, thereby enhancing evaluative objectivity and practicality. In practice, GIS has been extensively applied in regional risk assessments; a study in Huayingshi, for example, employed GIS-based spatial analysis to incorporate eight factors—including slope and faults—into an information value model, achieving stratified delineation of hazard-prone areas. Moreover, GIS's theoretical potential is amplified through integration with machine learning algorithms, as exemplified by the Certainty Factor-Logistic Regression (CF-Logistic) model in susceptibility evaluations, which adeptly handles nonlinear relationships to bolster predictive fidelity [6]. The origins of GIS trace back to the 1960s, initially for land resource management, but its application swiftly expanded to natural disasters. By the 1970s, GIS was instrumental in seismic and landslide risk mapping for susceptibility zoning. Advancements in computing during the 1980s introduced commercial software precursors to ArcGIS, such as ArcInfo, which incorporated spatial analysis modules for hazard factor overlays. The 1990s witnessed the fusion of GIS with remote sensing, engendering integrated monitoring systems for real-time tracking of geological dynamics, including floods and collapses. Entering the 21st century,

the incorporation of cloud computing and big data has empowered GIS to process voluminous geological datasets, such as disseminating risk maps via Web GIS platforms to foster inter-agency collaboration. In geological hazard assessment, GIS evolution underscores a shift from static evaluations to dynamic simulations, exemplified by spatiotemporal models for forecasting landslide trajectories [7].

That said, the integration of GIS technology does not obviate all challenges in hazard assessment. Practical implementation is often hampered by difficulties in data acquisition, untimely updates, and suboptimal resolution. Constructing GIS models necessitates interdisciplinary synthesis from geology, meteorology, hydrology, and beyond; absent such integration, outcomes risk superficiality. While GIS demonstrably outperforms in visualization and spatial analytics, its explanatory power regarding hazard mechanisms and prospective trends remains contingent on augmentation with geophysical modeling and machine learning. In essence, GIS proffers a novel lens for geological hazard evaluation, yet optimizing its utility and mitigating its constraints warrants sustained scholarly inquiry.

Accordingly, this article systematically reviews and examines the theoretical import and applicative architecture of GIS in geological hazard assessment. It emphasizes GIS's strengths in multisource data fusion, spatial relational articulation, and dynamic modeling, while critically appraising its limitations vis-à-vis data quality, model adaptability, and interdisciplinary convergence. Through this exposition, the paper seeks to furnish targeted insights for future investigations and theoretical underpinnings for disaster mitigation and risk governance practices.

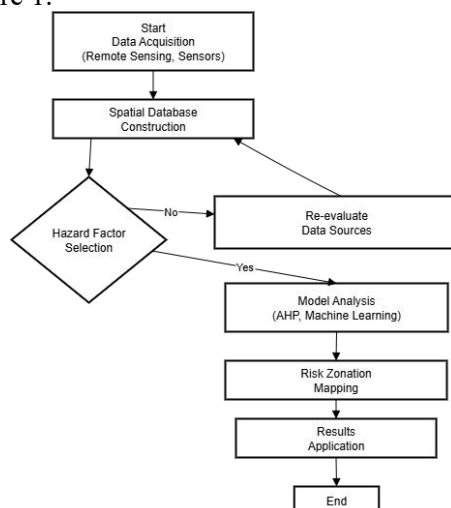
## 2. Overview of GIS Technology

Geographic Information Systems (GIS) constitute a robust framework for spatial data processing and analysis, grounded in the principles of geographic information science (GIScience), which prioritizes the acquisition, storage, analysis, and visualization of spatial data to uncover relational patterns and dynamic processes in geographic phenomena. At the heart of geological hazard assessment lies the identification of triggering factors, susceptibility evaluation, and risk forecasting, wherein GIS's

theoretical application manifests through the articulation of spatial relationships and the construction of analytical models. GIS furnishes a platform for data integration, leveraging spatial analysis models to quantify hazard-inducing factors, thereby facilitating risk prediction and zonation. This section commences with an exposition of GIS's foundational principles, exploring their theoretical integration with geological hazard assessment, the formulation of evaluative indicator systems, and the deployment of prevalent software tools.[8,9]

## 2.1 Technical Principles and Methodological Foundations

The cornerstone principles of GIS technology revolve around the acquisition, modeling, and analysis of spatial data. Data acquisition forms the bedrock of the evaluative framework, drawing from diverse modalities: remote sensing imagery and unmanned aerial vehicle (UAV) photogrammetry enable expeditious procurement of high-resolution terrain data across expansive regions, while geological surveys and sensor networks yield primary data on fault activity, rock-soil mechanical properties, and meteorological dynamics. Harmonizing data from heterogeneous sources demands rigorous coordinate standardization and precision calibration to ensure the integrity of spatial overlays and ensuing analyses, as illustrated in Figure 1.



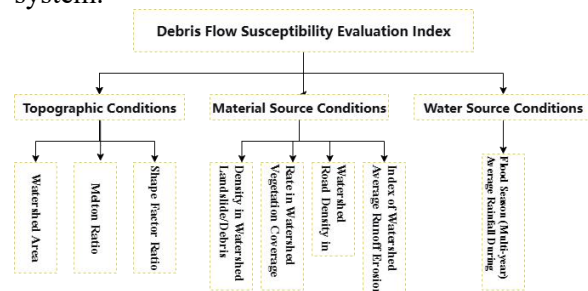
**Figure 1. GIS technology in the Evaluation of Geological Disasters**

On the analytical front, GIS proffers an array of spatial modeling instruments. Spatial overlay analysis serves to discern the coupled effects of multiple factors in hazard-prone zones; for

instance, layering datasets on slope, lithology, and precipitation with assigned weights yields susceptibility zonation maps for landslides. Proximity and buffer analyses simulate the influence extents of linear features, such as roadways and waterways, on hazard distributions. Spatial statistical techniques—including Moran's I index and spatial autocorrelation—illuminate clustering patterns in hazard occurrences and their correlations with environmental covariates, thereby underpinning quantitative inquiries. Furthermore, three-dimensional modeling and visualization capabilities permit intuitive simulations of landslide volumes, deposition extents, and prospective impact zones, deepening insights into underlying hazard mechanisms.

## 2.2 Construction of Evaluative Indicator Systems

In geological hazard assessment, the rigorous assembly of indicator systems is prerequisite to risk quantification and spatial partitioning. GIS's prowess in this domain stems from its capacity to amalgamate disparate data categories via hierarchical modeling, engendering computable indicator architectures. Archetypal indicator systems bifurcate into natural and anthropogenic domains: natural factors encompass geomorphological attributes (slope, aspect, relief), geological attributes (lithology, fault density, soil typology), meteorological attributes (rainfall intensity, cumulative precipitation), and hydrological attributes (riverine distributions, groundwater levels); anthropogenic factors, by contrast, pertain to infrastructural developments, mining operations, and land-use alterations. Figure 2 depicts a regional debris flow susceptibility evaluation predicated on such a system.



**Figure 2. Debris Flow Susceptibility Evaluation Index**

GIS operationalizes weighting schemes—such as weighted overlay, Analytic Hierarchy Process

(AHP), and machine learning paradigms (e.g., random forests, logistic regression)—to apportion indicator weights and execute holistic computations. Evaluative outputs typically manifest as susceptibility zonation maps, which not only delineate risk gradations across locales with perspicuity but also furnish quantitative substantiation for policymakers devising mitigation strategies. This confluence of indicator systems and spatial modeling surmounts the insularity and incommensurability of traditional approaches, rendering hazard assessments more holistic and actionable.

### 2.3 Software Platforms and Tool Applications

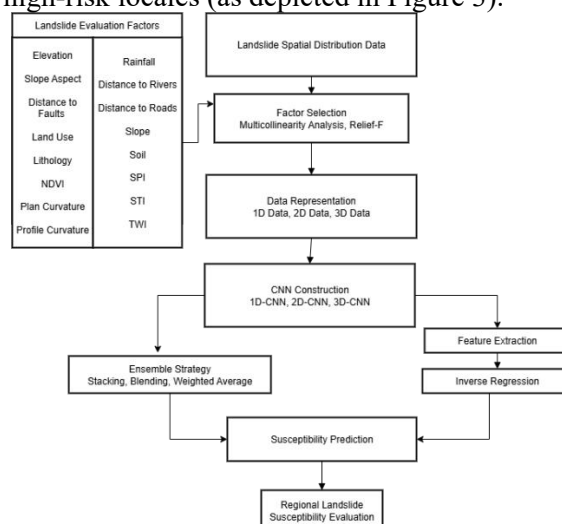
From an implementational standpoint, GIS's maturation owes much to the proliferation of versatile software platforms. Commercial suites like ArcGIS boast sophisticated spatial statistics, three-dimensional modeling, and geoprocessing toolsets, furnishing formidable analytical and visualization faculties for hazard evaluations. Its spatial analyst module and ModelBuilder interface expedite the automation of intricate workflows, augmenting research throughput. Open-source alternatives, such as QGIS, distinguish themselves through extensible plugin architectures, which, when combined with plugins such as GRASS GIS and SAGA GIS, the platform provides customized analytical tools suitable for specific research needs.

Moreover, spatial database technologies occupy an indispensable niche in hazard assessment. PostGIS, as a paradigmatic spatial extension, facilitates efficacious management and querying of voluminous raster and vector datasets, while accommodating dynamic updates to multitemporal and multidimensional inputs. For example, in the wake of seismic events, it enables prompt revisions to fault distributions and surface disruption inventories, thereby enabling real-time risk appraisals. The ubiquity of scripting languages like Python and R within GIS ecosystems empowers researchers to bespoke model development, elevating the precision and intelligence of hazard evaluations.

## 3. Application Scenarios of GIS in Geological Hazard Assessment

### 3.1 GIS Applications in Landslide Hazard Assessment

Landslides arise from the synergistic interplay of multiple factors, including terrain slope, lithological conditions, precipitation volume, and vegetation cover, exhibiting pronounced spatial heterogeneity and clustering. In landslide hazard assessment, GIS furnishes a platform for multilayer data overlay and weighted computation, effectively unmasking latent high-risk locales (as depicted in Figure 3).



**Figure 3. GIS Applications in Landslide Hazard Assessment**

Consider a mountainous region in Yunnan Province as a case in point, where complex topography and recurrent rainfall elevate landslide probabilities. GIS harnessed remote sensing imagery and unmanned aerial vehicle (UAV) photogrammetry to procure high-resolution terrain data, which was amalgamated with lithological and fault distribution data derived from geological surveys to construct a comprehensive spatial database. Spatial overlay analysis then weighted and integrated factors such as slope, rainfall intensity, and soil moisture, yielding a landslide susceptibility zonation map that delineated high-, medium-, and low-risk zones with precision. Buffer analysis complemented this by gauging the influence extents of proximate rivers and roadways on landslide distributions, thereby illuminating the amplifying role of linear infrastructure in hazard proneness. Spatial statistical tools, including Moran's I index, further scrutinized clustering patterns in landslide occurrences, corroborating the robust correlation between precipitation and landslide initiation. In investigations of landslide susceptibility within the Wenchuan earthquake epicentral zone, researchers fused

high-resolution digital elevation models (DEMs), geological structure maps, soil distribution datasets, and precipitation records; weights for individual factors were ascertained via the Analytic Hierarchy Process (AHP), with raster computations executed in ArcGIS to produce susceptibility distribution maps. Through spatial autocorrelation analysis, GIS discerned clustering signatures in landslide points, extrapolating discrete incident loci into areal representations of prospective risk zones—a methodological advance that mitigates the parochialism and limited generalizability of conventional point-based surveys.

By expeditiously integrating multisource data and conducting multifactor analyses, GIS-generated susceptibility zonation maps afford local authorities perspicuous guidance for refining disaster preparedness plans. Concurrently, three-dimensional visualization techniques simulate prospective landslide deposition extents, augmenting prognostic capabilities for hazard ramifications.

### 3.2 GIS Applications in Seismic Hazard Assessment

Earthquakes frequently precipitate intricate secondary hazards, such as surface ruptures, landslides, barrier lakes, and debris flows, whose spatial distributions evince considerable stochasticity. In evaluating seismic secondary hazards, GIS's prowess in multisource data synthesis and dynamic updating emerges

saliently [10].

The 2008 Wenchuan earthquake exemplifies this, wherein the proliferation of barrier lakes post-event imperiled downstream populations and infrastructure. Researchers leveraged remote sensing satellites for swift acquisition of epicentral imagery, employing image classification to delineate landslide deposition zones and river blockages; these were conjoined with DEM data in GIS to reconstruct impoundment models, simulating prospective breach extents for barrier lakes. GIS integrated fault distributions, surface deformation metrics, and historical seismicity archives to erect a dynamic spatial database. As a spatial database extension, PostGIS efficaciously stewarded voluminous vector and raster datasets, accommodating real-time infusions of postseismic surface disruption intelligence. The spatial analysis module, via proximity analysis, appraised risk exposures of settlements and infrastructure proximate to faults, engendering buffer maps that circumscribed high-risk perimeters. The Analytic Hierarchy Process (AHP) operationalized weight assignments for seismic hazard indicators, amalgamating natural covariates—such as magnitude, fault density, and surficial loose material thickness—with anthropogenic ones, including population density and building seismic resilience ratings, to forge comprehensive risk zonation maps (as showed in Table 1).

**Table 1. Classification of Geological Disaster Risk Levels**

Danger level \ Severity Risk Level	Extreme	High	Medium	Low
Extreme	Extreme	Extreme	High	Medium
High	Extreme	High	Medium	Medium
Medium	High	High	Medium	Low
Low	High	Medium	Low	Low

During emergency responses, GIS's spatial database undergirded the expeditious coalescence of disparate information streams. Data on fault activity, aftershock distributions, roadway impairments, and demographic patterns underwent unified projection and normalization, crystallizing into an integrated disaster informatics platform. Anchored therein, relief agencies could promptly generate evacuation routing schematics, prioritizing secure conduits and refugia. Relative to traditional manual cartography, GIS methodologies not only accelerated information throughput but also refined postdisaster decision-making through

scientization and granulation, appreciably curtailing response latencies and attenuating secondary hazard tolls.

### 3.3 GIS Applications in Debris Flow Hazard Assessment

Debris flows represent abrupt, highly destructive geological hazards, mechanistically governed by rainfall intensity, hillslope material accumulation, and hydrological confluence dynamics. Given the temporal ephemerality and nonlinear trajectories of debris flow genesis, GIS applications in this arena predominantly emphasize dynamic modeling and real-time

alerting [11].

In prototypical montane debris flow inquiries in Yunnan Province, researchers extracted basin topography and vegetation cover from remote sensing imagery, fusing these with historical debris flow inventories to formulate geomorphic models predicated on basin confluence analyses. Turning to a debris flow-prone montane locale in Gansu Province—characterized by concentrated precipitation and pronounced valley morphologies—GIS drew upon remote sensing and geological survey data to isolate pivotal factors, including slope, valley density, and vegetation coverage, while spatial database technologies assimilated multitemporal precipitation records. Spatial overlay analysis, augmented by random forest modeling, holistically appraised rainfall intensity, soil typology, and geomorphic attributes, culminating in debris flow susceptibility zonation maps that pinpointed high-risk gullies with exactitude. Proximity analysis extended this by simulating prospective debris flow incursions into downstream hamlets and thoroughfares, informing evacuation protocols and fortification schematics. GIS's three-dimensional modeling faculties rendered intuitive depictions of plausible flow trajectories and deposition perimeters, furnishing referential scaffolds for engineering designs.

Central to this enterprise, GIS's hydrological analysis modules computed basin flow directions, confluence areas, and slope gradients to emulate rainfall-driven accretion processes, thence inferring latent debris flow conduits and deposition precincts. Building thereon, researchers overlaid precipitation forecasts to erect real-time debris flow risk surveillance and alerting apparatuses. Upon rainfall thresholds being breached, the system dispatches hazard alert cartography predicated on GIS-derived peril zones. Contra conventional experiential thresholding, this paradigm markedly elevates alerting timeliness and spatial fidelity, conferring substantial dividends for montane evacuations and governmental exigency orchestration.

#### **4. Advantages and Limitations of GIS Technology in Geological Hazard Assessment**

Notwithstanding the substantive strides achieved through GIS applications in geological hazard assessment, its maturation confronts manifold impediments, encompassing the

intricacies of data procurement and manipulation, deficiencies in model rigor and adaptability, and disjunctions between interdisciplinary collaboration and pragmatic deployment. Concurrently, the burgeoning of remote sensing, big data, artificial intelligence, and cloud computing heralds expansive vistas for GIS in prospective geological hazard inquiry and mitigation.

##### **4.1 Challenges**

While GIS excels in data amalgamation and analytical prowess for geological hazard assessment, its practical invocation grapples with persistent conundrums. Foremost among these is the caliber and uniformity of data, which profoundly impinge upon analytical fidelity. Evaluations hinge on heterogeneous inputs—remote sensing imagery, geological surveys, and sensor telemetry—yet disparities in spatial resolution, temporal continuity, and georeferencing schemas abound. In landslide assessments within Yunnan's montane precincts, for instance, cloud occlusion may engender lacunae in remote sensing coverage, while sparse sampling densities in geological fieldwork fail to encompass labyrinthine terrains, thereby vitiating the veracity of susceptibility zonation maps. Combining these datasets requires careful coordinate alignment and accuracy adjustments, which is further complicated across regions by the lack of standardized protocols and quality control procedures.

A secondary hurdle resides in arbitrating model intricacy against computational thrift. Hazard appraisals for landslides, earthquakes, and debris flows invariably demand multifactor syntheses—via spatial overlays, random forests, or the Analytic Hierarchy Process (AHP)—which, though augmenting precision, exact a toll on processing overheads. Exemplifying this, dynamic impoundment modeling for barrier lakes in the Wenchuan earthquake aftermath necessitates fusing high-resolution digital elevation models (DEMs), real-time precipitation, and surface deformation metrics, imposing stringent exactions on hardware and algorithmic refinement. Moreover, the opacity of esoteric models—particularly in machine learning—obscures weight derivations, impeding lucid causal elucidations for policymakers.

Finally, strictures on real-time acuity and

iterative refurbishment circumscribe GIS's efficacy in exigency rejoinders. In Gansu montane debris flow alerting exemplars, GIS's conjugation with precipitation prognostications yields risk advisories, yet the alacrity of multitemporal data ingress and elaboration remains fettered by bandwidth latencies and database refresh cadences. In sequestered uplands, attenuated sensor deployments and frail telecommunications further beleaguer instantaneous telemetry, eroding alerting dispatch. Compounding this, the ergonomic deficits of extant GIS suites persist: while open-source bastions like QGIS wield formidable functionalities, their steep proficiency gradients deter nonexpert uptake, constraining grassroots disaster prophylaxis.

## 4.2 Prospects

The trajectory of GIS in geological hazard assessment augurs multidimensional convergence and intelligent augmentation. Futurity endeavors ought to prioritize sundry facets: Most importantly, interdisciplinary collaboration should be strengthened, integrating geophysical, climatological, and socioeconomic data to develop more comprehensive risk assessment frameworks. Secondly, real-time surveillance and ambulatory renewal shall burgeon as leitmotifs, wherein edge computing and Internet of Things (IoT) sensorial nexuses empower GIS platforms for instantaneous hazard discernment and augury. Thirdly, intelligent decision-aiding apparatuses shall refine apace, as infusions of machine learning and graph neural networks promise heightened prognostic acuity and spatial heterogeneity rendition. At the same time, promoting public engagement and interactive visualization can transform GIS from a specialist tool into a widely accessible platform for clear and participatory risk communication. In sum, GIS's evolution portends a metamorphosis from insular spatial analytic instrumentalities to amalgamated, perspicacious, and communally stewarded platforms for comprehensive geological hazard governance.

## 5. Conclusion

This article systematically delineates the applicative merits and constraints of GIS technology in geological hazard assessment. Findings affirm that GIS, through its adeptness in spatial data amalgamation, visualization, and

multisource information synthesis, markedly enhances the rigor of hazard risk identification and prognostication. Nonetheless, extant GIS implementations evince lacunae in data integrity, model pliancy, and the dissemination of resultant outputs. Prospective trajectories ought to converge upon interdisciplinary data coalescence, intelligent algorithm propulsion, and participatory visualization interfaces, thereby catalyzing GIS's evolution from ancillary analytic adjunct to perspicacious decision-support apparatus in geological hazard prophylaxis. This inquiry not only furnishes referential scaffolding for theoretical refinements in GIS-mediated hazard evaluations but also proffers conceptual moorings for praxis-oriented deployments and policy articulation.

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