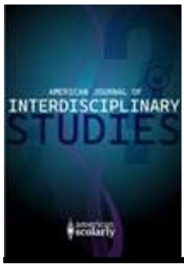

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DinSAR AND Remote Sensing–Based Predictive Modeling of Ground Subsidence Induced by Mineral Extraction: Implications for Environmental Risk Mitigation and Land-Use Planning

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Abstract

This study examined how DInSAR and remote sensing based predictive modeling can improve the assessment of ground subsidence induced by mineral extraction and strengthen environmental risk mitigation and land use planning in mining affected areas. The problem addressed in this research is that although mining related subsidence creates serious threats to infrastructure, ecosystems, settlements, and planning systems, its monitoring and predictive use in decision making are often fragmented and insufficiently integrated. The purpose of the study was therefore to test whether stronger DInSAR and remote sensing capability improves predictive modeling accuracy and whether such predictive strength contributes to better environmental mitigation and planning effectiveness. The study adopted a quantitative, cross sectional, case-based design using cloud and enterprise oriented geospatial and institutional case contexts in mineral extraction environments, with a purposive sample of 162 professional respondents drawn from mining engineering, geology, GIS and remote sensing, environmental management, planning, and regulatory fields. The key variables were DInSAR and Remote Sensing Capability, Predictive Modeling Accuracy, Environmental Risk Mitigation, and Land Use Planning Effectiveness. Data were collected through a 5-point Likert scale questionnaire and analyzed using descriptive statistics, Cronbach's alpha, Pearson correlation, and regression analysis in SPSS. The findings showed high mean scores across all constructs, including DInSAR and Remote Sensing Capability ($M = 4.18$, $SD = 0.61$), Predictive Modeling Accuracy ($M = 4.09$, $SD = 0.66$), Environmental Risk Mitigation ($M = 4.14$, $SD = 0.58$), and Land Use Planning Effectiveness ($M = 4.11$, $SD = 0.63$). Regression results revealed that DInSAR capability significantly predicted predictive modeling accuracy ($\beta = 0.652$, $R^2 = 0.425$, $p < .001$), predictive modeling significantly predicted environmental risk mitigation ($\beta = 0.718$, $R^2 = 0.516$, $p < .001$) and land use planning effectiveness ($\beta = 0.681$, $R^2 = 0.478$, $p < .001$), while environmental risk mitigation also significantly predicted land use planning effectiveness ($\beta = 0.603$, $p < .001$). The study implies that integrating satellite-based deformation monitoring with predictive analytics can provide a stronger evidence base for safer environmental governance, hazard prioritization, infrastructure protection, and sustainable land use planning in subsidence prone mining regions.

Keywords

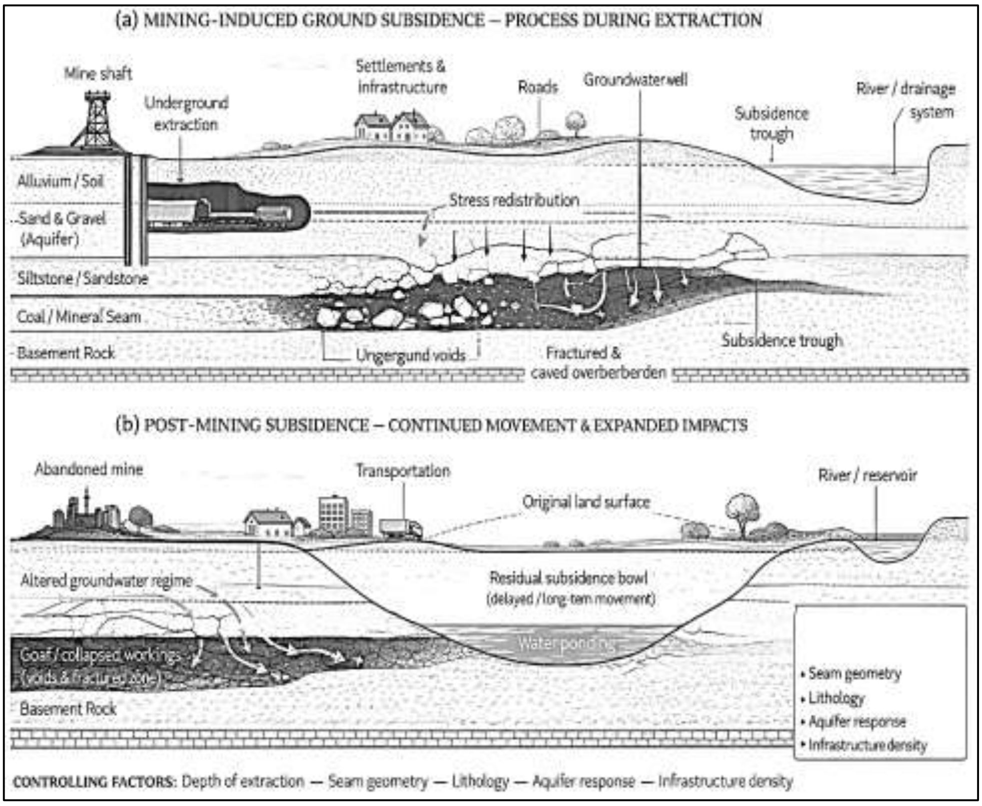
DInSAR, Remote Sensing, Ground Subsidence, Predictive Modeling, Land Use Planning;

INTRODUCTION

Ground subsidence refers to the gradual or localized lowering of the Earth's surface caused by the compaction, collapse, or deformation of subsurface materials under natural or anthropogenic forcing. In the context of mineral extraction, the term is used for vertical and near-vertical ground movement generated by underground void creation, overburden readjustment, pillar failure, stress redistribution, seismic disturbance, groundwater drawdown associated with mining, and post-mining hydrogeological change (Blachowski et al., 2019). DInSAR, or Differential Interferometric Synthetic Aperture Radar, is a satellite-based remote sensing method that estimates surface displacement by comparing the phase information of radar images acquired over the same terrain at different times, while broader multi-temporal InSAR families such as PS-InSAR and SBAS extend this capacity to long-term monitoring of deformation histories (Galloway & Hoffmann, 2007). Remote sensing in this field is not only a measurement technology; it is also a framework for spatial diagnosis because it connects deformation signals to land cover, groundwater, infrastructure exposure, settlement expansion, and terrain conditions. The international significance of this subject is established by the fact that subsidence has been documented across mining districts, aquifer systems, and rapidly urbanizing regions on several continents, where it has produced structural damage, drainage disruption, flood susceptibility, environmental degradation, and planning uncertainty (Pawluszek-Filipiak & Borkowski, 2020a). Foundational reviews and application studies have shown that satellite interferometry can observe subsidence in mining and urban environments at regional scale, provide historical reconstruction from archived imagery, and support hazard characterization more effectively than sparse point-based monitoring alone. Later work in Beijing, the North China Plain, Kolkata, and Mexico further demonstrated that subsidence is not an isolated engineering nuisance but an internationally recognized environmental risk that intersects water security, infrastructure resilience, and land governance (Raucoules et al., 2007). For a study focused on mineral extraction, these definitions matter because the research problem begins with the need to treat subsidence as a measurable, spatially distributed, process-based hazard rather than a single-point geotechnical symptom. That framing creates the basis for a predictive research design in which DInSAR and remote sensing become central evidence streams for identifying subsidence patterns, estimating risk intensity, and supporting land-use decisions under conditions of environmental stress (Osmanoğlu et al., 2016).

Mining-induced subsidence has gained international research attention because mineral extraction alters the mechanical equilibrium of the subsurface and transfers that instability upward into the built and natural environment. Underground coal, copper, and other mineral operations may produce troughs, fissures, tilting, localized collapse, differential settlement, and delayed post-extraction movement, with the severity governed by depth, seam geometry, extraction method, roof condition, lithology, groundwater response, and the presence of infrastructure or settlements above the workings. In several mining regions, subsidence has been associated with building deformation, transportation disruption, agricultural land degradation, drainage changes, and induced seismic effects, which makes it relevant to environmental risk mitigation as much as to mining engineering (Xu et al., 2020). Studies in Poland and China show that mining-related deformation can be rapid, nonlinear, and spatially heterogeneous, which complicates both monitoring and management. Nearby mining-induced earthquakes can produce overlapping subsidence phases and measurable trough development, while combining DInSAR and SBAS is often necessary in high-gradient coal-mining environments where a single technique may fail to capture important parts of the deformation field (Zhang et al., 2014). Related evidence indicates that the complete deformation field in active mines is best captured by integrating D-InSAR, sub-band InSAR, offset tracking, and the probability integral model, because different methods perform better across different deformation magnitudes. Additional studies have integrated InSAR observations with probability-integral-model-based inversion and support vector regression for mining-subsidence reconstruction and prediction. These findings position mineral extraction as both a geotechnical and environmental driver of land transformation (Zhang et al., 2019). The problem is therefore international in scale and interdisciplinary in character: extraction creates economic value below ground while redistributing risk above ground. When that redistribution is not measured continuously and modeled carefully, land-use systems inherit hidden instability. For this reason, the literature treats mining subsidence as a hazard that must be observed not only for operational safety but also for zoning, infrastructure protection, ecological management, and community exposure reduction. In that broader understanding, subsidence monitoring becomes part of environmental governance rather than a narrow technical exercise (Chen et al., 2018).

Figure 1: Schematic Representation of Mining-Induced Subsidence and Post-Extraction Ground Deformation



The rise of DInSAR and multi-temporal InSAR has transformed subsidence research because these methods provide repeated, synoptic, and millimeter-sensitive observations over large areas where conventional surveying would be expensive, discontinuous, and spatially incomplete. Traditional leveling, GNSS, extensometers, and field benchmarks remain important for validation and local precision, yet they are inherently point-based and often too sparse to describe the full geometry of a subsidence bowl or the evolving relationship between mining zones and vulnerable surface assets. Remote sensing addresses this gap by enabling wall-to-wall surface deformation mapping and by preserving historical records through archived SAR missions. Reviews of InSAR time-series methods emphasize that phase unwrapping, atmospheric correction, decorrelation control, and model choice are central to robust deformation estimation, particularly where motion is nonlinear or large in magnitude (Ferretti et al., 2015). Application studies in Beijing, Wuhan, Shenzhen, Xi'an, and the North China Plain confirm that SBAS, PS-InSAR, and related approaches can retrieve long-term deformation trends, identify hotspots, and match leveling records with acceptable precision when processing choices are appropriate. In mining settings, this capability is even more valuable because deformation is often distributed beyond the officially mapped extraction footprint and may interact with surface water, roads, pipelines, and settlements in ways that are difficult to anticipate from mine plans alone (Gao et al., 2018). Studies that integrate multiple interferometric strategies show that no single InSAR workflow is universally optimal for mining terrain, since fast displacement, steep gradients, vegetation decorrelation, and layover can degrade signal quality. That is why methodological innovation in this literature has increasingly focused on hybrid observation systems, correction algorithms, and data fusion strategies. The significance for the present research lies in the fact that predictive modeling cannot be stronger than the deformation evidence used to train or interpret it. DInSAR and remote sensing matter here not simply because they measure movement, but because they structure the empirical basis for identifying where, how fast, and under what spatial conditions extraction-induced subsidence unfolds (Gee et al., 2020).

A second major strand in the literature links subsidence to environmental controls and land-surface characteristics, which is essential for a remote sensing–based predictive study. Subsidence does not emerge from extraction intensity alone; it is shaped by stratigraphy, aquifer behavior, recharge conditions, land use, surface loading, and the distribution of exposed assets. Research in Beijing and the North China Plain has shown strong spatial correspondence between groundwater depression cones and subsidence centers, while studies in urban and peri-urban regions have found that industrial land, residential expansion, reclamation activity, and mixed land-use mosaics can intensify or spatially reorganize surface lowering (Wang et al., 2019). Additional work documented how land creation and rapid urbanization in the Chinese Loess Plateau generated measurable subsidence captured by time-series InSAR, while contrasting local economic activities in East China explained differences in subsidence patterns, including zones where mining and urban growth coexisted. Land-subsidence susceptibility mapping has also combined remote sensing, GIS, probability models, and groundwater indicators to rank the importance of environmental factors controlling subsidence occurrence. This literature is important for a mineral-extraction study because it clarifies that extraction-induced subsidence should be analyzed as part of a coupled land system (Wang et al., 2020). The deformation field is the visible result of interacting natural and human variables, and predictive modeling becomes more credible when it uses that interaction rather than treating displacement as a purely mechanical output. In practical terms, this means that satellite deformation products, land-use layers, and environmental variables can be synthesized to identify where ground instability is likely to intensify, where exposure is growing, and where mitigation should be prioritized. Such synthesis is consistent with the logic of case-study-based quantitative research, because it allows the study area to be interpreted not only as a mine site but also as a socio-environmental space in which extraction, land development, hydrology, and infrastructure are continuously co-producing risk (Suganthi et al., 2017).

The predictive dimension of subsidence research has developed from this observational foundation. Monitoring alone answers where deformation has occurred; predictive modeling seeks to estimate how deformation may evolve, what controls it, and how risk can be anticipated before serious loss is realized. In the broader InSAR literature, time-series algorithms were designed to reconstruct displacement histories, yet more recent studies have moved toward explicit forecasting, inversion, and parameter estimation (Wang, et al., 2019; Najafi et al., 2020). DInSAR-derived deformation has been used to calibrate and invert a groundwater rebound model in abandoned coalfields, showing that satellite measurements can inform process understanding and support mitigation planning for post-mining hydrogeological change. Other research reconstructed the spatial pattern of mining subsidence by integrating DInSAR, offset tracking, and the probability integral method, while additional work employed SBAS-InSAR and a simulated annealing support vector regression framework to predict subsidence evolution in a mining area (Guo et al., 2015). Evidence also indicates that hybrid integration improves the completeness and reliability of the deformation field, which is especially valuable when predictive tasks require stable input over small, medium, and large displacement ranges. Further methodological developments improved land-subsidence monitoring by integrating RELAX with PS-InSAR to strengthen persistent scatterer identification, illustrating a wider methodological principle: predictive credibility depends on preprocessing choices, signal quality, and deformation retrieval accuracy. These studies collectively shift subsidence research from descriptive mapping toward operational analytics (Hu et al., 2019). For a thesis on DInSAR and remote sensing–based predictive modeling of extraction-induced subsidence, that shift is central. It means the research is not limited to proving that mining can deform the ground; it is concerned with whether satellite-observed deformation and related spatial variables can be translated into statistically interpretable predictors that support risk mitigation and land-use planning. In this context, correlation analysis and regression modeling are not merely generic statistical procedures. They are the bridge between spatial observation and decision evidence, allowing the study to examine how monitoring capability relates to predictive confidence, how predictive performance relates to mitigation readiness, and how both relate to planning effectiveness (Shi et al., 2020).

Another important body of scholarship demonstrates that the value of subsidence monitoring increases when deformation results are interpreted in relation to hazard, exposure, and land management. Early work noted the relevance of SAR interferometry for land-use planning and natural-risk assessment, and later scholarship argued that operational InSAR monitoring should serve final users and decision makers through large-area, regularly updated deformation products. Urban and regional case studies have repeatedly shown that subsidence intersects with infrastructure stability, flood exposure, groundwater security, and settlement safety, which turns deformation maps into planning tools rather than purely scientific outputs (Solari et al., 2020). Significant subsidence has been identified in reclamation and metro-construction zones in coastal urban settings, while work in Wuhan linked subsidence to both natural and human factors and explicitly pointed to disaster prevention and urban planning applications. In the Beijing–Tianjin–Hebei region, mixed residential, industrial, and agricultural land use corresponded to stronger subsidence expression, while groundwater-intensive agriculture remained a dominant regional driver in the North China Plain. In Mexico City, severe groundwater-related subsidence has been documented through persistent scatterer InSAR, with later hazard interpretation linking interferometric measurements to infrastructure vulnerability and differential settlement patterns. Even where the causal setting is groundwater rather than mining, the planning lesson remains highly relevant: once subsidence is spatially resolved, it becomes possible to prioritize vulnerable zones, screen development suitability, and identify areas where surface processes threaten long-term urban or environmental stability (Shi et al., 2020). A mining-focused study inherits this logic with additional urgency because extraction-related subsidence often appears in zones where economic activity, settlements, waste facilities, roads, and ecological assets overlap. In such areas, predictive subsidence intelligence can support decisions on monitoring frequency, buffer delineation, infrastructure siting, and restrictions on land conversion. The introduction to this research therefore needs to foreground land-use planning as part of the scientific problem itself, because the social value of predictive subsidence analysis lies in how it informs spatial management under hazard conditions.

Taken together, the literature shows a clear progression from deformation detection, to multi-temporal monitoring, to hybrid inversion and predictive analysis, yet it also reveals a gap that justifies the present research title. Many studies focus on either urban groundwater subsidence or mine-specific deformation retrieval, while fewer bring DInSAR, broader remote sensing variables, predictive modeling, environmental risk mitigation, and land-use planning into one integrated analytical frame. Mine studies often emphasize methodological recovery of the deformation field, whereas urban studies often emphasize hydrogeological drivers and exposure patterns (Zhou et al., 2020). What remains less fully developed is a quantitative, case-study-based approach that asks how DInSAR and remote sensing capability, as perceived and operationalized within a specific mineral-extraction setting, relates statistically to predictive modeling performance and to planning-oriented risk management outcomes. Existing evidence supports each part of this chain separately: InSAR can retrieve subsidence over mines and cities; hybrid techniques can improve measurement under complex deformation; environmental and land-use factors shape subsidence distribution; and deformation information can inform safety and spatial management (Zhou et al., 2017; Zhou et al., 2020). Yet the literature provides less direct evidence on how these elements operate together in a single explanatory model centered on mineral extraction and decision support. That is the space occupied by the present study. Its introduction is grounded in the view that extraction-induced subsidence is an environmental hazard with measurable spatial signatures, interpretable controlling factors, and real consequences for mitigation and land-use control. DInSAR and remote sensing are therefore treated not as supplementary technical add-ons but as the core observational infrastructure for predictive reasoning about ground instability. Within that logic, the study's quantitative design is appropriate because it allows the relationships among monitoring capability, predictive modeling, risk mitigation, and land-use planning to be tested systematically within a defined case-study context (Osmanoğlu et al., 2011).

Background of the Study

Ground subsidence has become an increasingly important subject in environmental and geospatial research because it represents a serious form of land deformation that can affect ecosystems, infrastructure, human settlements, and long-term land stability. In areas of mineral extraction, this issue is especially critical because underground excavation and related mining activities disturb the natural balance of subsurface materials, often causing gradual or sudden downward movement of the ground surface. Such deformation can damage roads, buildings, pipelines, drainage systems, agricultural land, and environmentally sensitive zones, while also creating planning uncertainty for governments, engineers, and local communities. The growing scale of mineral extraction in many regions of the world has made subsidence not only a technical mining concern but also a broader environmental management and land-use challenge. At the same time, traditional methods of monitoring subsidence, such as ground leveling and field surveys, are often limited in spatial coverage, time efficiency, and cost-effectiveness, especially in large or difficult-to-access mining regions. This has increased the importance of satellite-based and remote sensing approaches that can observe surface changes over wide areas with greater consistency. Among these, Differential Interferometric Synthetic Aperture Radar, commonly known as DInSAR, has emerged as a valuable tool for detecting and measuring small changes in land elevation over time. When combined with other remote sensing data and predictive analytical methods, DInSAR offers a stronger basis for understanding how subsidence develops, where risk is concentrated, and how future deformation patterns may affect environmental safety and land-use decisions. The background of this study is therefore grounded in the need to connect geospatial monitoring technologies with quantitative modeling approaches in order to better assess the consequences of mining-induced ground subsidence. This research is positioned within a context where environmental risk mitigation and land-use planning increasingly depend on accurate, spatially informed evidence. By focusing on DInSAR and remote sensing–based predictive modeling, the study responds to the demand for more reliable decision-support tools that can help authorities, planners, and technical experts identify vulnerable zones, manage environmental risks, and guide safer development in mineral extraction areas.

Problem Statement

Ground subsidence induced by mineral extraction has emerged as a serious environmental and land-management problem in many mining regions, yet its assessment and control remain insufficiently integrated within practical planning and risk-governance systems. Mining activities alter subsurface stability through excavation, stress redistribution, void formation, and associated hydrogeological disturbance, which can lead to gradual or sudden deformation of the ground surface. This deformation threatens buildings, transportation routes, pipelines, agricultural land, drainage networks, ecological zones, and community safety. The problem becomes more severe when subsidence develops across broad areas or continues after extraction activities have advanced beyond the immediately affected zone. In many cases, authorities and planners are required to make decisions about land use, infrastructure safety, and environmental protection without having a sufficiently predictive understanding of how ground movement may evolve spatially and temporally. Traditional ground-based monitoring approaches often provide valuable local measurements, yet they may not offer the wide-area, continuous, and spatially detailed evidence needed to understand complex subsidence patterns in active or post-extraction landscapes. Although DInSAR and remote sensing technologies provide strong potential for detecting and analyzing land deformation, their application is often concentrated on observation and mapping rather than on integrated predictive modeling that supports environmental risk mitigation and land-use planning. A further challenge is that many decision systems still rely on fragmented information, where technical monitoring, environmental assessment, and planning action are treated as separate activities rather than as interconnected components of a single risk-management framework. This creates a gap between the availability of geospatial monitoring data and the actual use of such data in preventive decision-making. In addition, there is limited quantitative evidence showing how DInSAR and remote sensing capability relate to predictive modeling performance and how such predictive performance contributes to effective environmental risk mitigation and land-use planning in mineral extraction contexts. As a result, there is a need for a structured quantitative, cross-sectional, case-study-based investigation that examines these relationships systematically. This study addresses that need by focusing on how DInSAR and remote sensing–based predictive modeling can strengthen the understanding, management, and planning response to mining-induced ground subsidence.

The main objective of this study is to examine the role of DInSAR and remote sensing–based predictive modeling in improving the assessment of ground subsidence induced by mineral extraction and in strengthening environmental risk mitigation and land-use planning decisions. To achieve this broad aim, the study first seeks to evaluate the extent to which DInSAR and remote sensing technologies are capable of identifying, monitoring, and supporting the interpretation of subsidence patterns in mining-affected areas. This objective is important because accurate observation is the starting point for any reliable prediction of ground instability. The study also aims to determine whether stronger monitoring capability is associated with better predictive modeling performance, since a predictive framework depends on the quality, consistency, and spatial relevance of its input evidence. A second objective is to assess the contribution of predictive modeling to environmental risk mitigation by examining whether more effective subsidence prediction supports the identification of vulnerable areas, the prioritization of intervention zones, and the reduction of environmental threats linked to land deformation. A third objective is to investigate the relationship between predictive subsidence intelligence and land-use planning effectiveness, with particular attention to how geospatial prediction can support zoning decisions, infrastructure protection, development control, and safer land allocation in mining environments. Another objective of the research is to test the statistical relationships among DInSAR and remote sensing capability, predictive modeling accuracy, environmental risk mitigation, and land-use planning effectiveness through descriptive statistics, correlation analysis, and regression modeling. In doing so, the study intends to produce a structured empirical explanation of how these variables interact within a case-study setting. The final objective is to provide a practical evidence base that can support planners, environmental managers, mining authorities, and technical experts in making more informed decisions about subsidence-prone areas. Through these objectives, the study is designed to move beyond simple monitoring and toward a more integrated understanding of prediction, mitigation, and planning in landscapes affected by mineral extraction.

Research Hypotheses

The hypotheses of this study are developed from the central assumption that the quality of subsidence monitoring influences the strength of predictive modeling, and that improved predictive modeling supports both environmental risk mitigation and land-use planning in mineral extraction areas. The first hypothesis proposes that DInSAR and remote sensing capability has a significant positive effect on predictive modeling accuracy. This hypothesis is based on the logic that when monitoring systems provide clearer, broader, and more reliable deformation information, the resulting models are better positioned to capture the spatial behavior of ground subsidence. The second hypothesis states that predictive modeling accuracy has a significant positive effect on environmental risk mitigation. This reflects the idea that stronger prediction enables earlier identification of hazard zones, more effective prioritization of vulnerable areas, and better support for preventive environmental management. The third hypothesis proposes that predictive modeling accuracy has a significant positive effect on land-use planning effectiveness. This assumes that when future or evolving subsidence patterns are better understood, land-use authorities can make more informed decisions about zoning, infrastructure siting, settlement control, and development restrictions. The fourth hypothesis states that environmental risk mitigation is significantly positively associated with land-use planning effectiveness. This relationship is important because areas where environmental risks are better understood and managed are also more likely to experience stronger planning outcomes and reduced exposure to land instability. The fifth hypothesis proposes that DInSAR and remote sensing capability significantly influences environmental risk mitigation and land-use planning through predictive modeling performance. This reflects the indirect pathway through which monitoring capability contributes to practical planning and mitigation outcomes by strengthening the predictive understanding of subsidence. Together, these hypotheses provide the analytical structure of the study and guide the testing of relationships among the major variables. They also create a clear basis for applying descriptive statistics, correlation analysis, and regression modeling in order to determine whether the assumed connections between geospatial monitoring, predictive performance, environmental management, and land-use planning are supported within the selected case-study context.

Significance of the Research

Academic significance: This study contributes to the academic literature by bringing together DInSAR, remote sensing, predictive modeling, environmental risk mitigation, and land-use planning within one quantitative framework. It strengthens scholarly understanding of how geospatial monitoring can move beyond observation and become part of a broader explanatory model of subsidence-related decision-making in mineral extraction areas.Methodological significance: The research is methodologically significant because it applies a quantitative, cross-sectional, case-study-based design to a topic that is often discussed in either purely technical or purely descriptive terms. By using descriptive statistics, correlation analysis, regression modeling, and a Likert-scale instrument, the study provides a structured way to test the relationships among monitoring capability, predictive performance, mitigation readiness, and planning effectiveness. Practical significance for mining management: The findings of the study can help mining operators and technical managers better understand the value of integrating satellite-based deformation monitoring into operational risk assessment. This supports more informed decisions regarding site surveillance, hazard identification, and the protection of assets located in subsidence-prone zones. Environmental significance: The study is important for environmental management because it highlights how predictive geospatial evidence can support the early identification of environmentally vulnerable areas. This is useful for reducing the impact of ground deformation on ecosystems, drainage systems, agricultural land, and other sensitive environmental resources.Planning significance: The research offers direct significance for land-use planners by clarifying how subsidence prediction can support zoning, infrastructure protection, development control, and the safer allocation of land in mining-affected regions. It supports a more evidence-based planning process where deformation risk is considered as part of land-use governance. Policy significance: The study can assist regulators and public institutions by providing an empirical basis for policies related to mining safety, environmental monitoring, and land management. It supports stronger coordination among mining authorities, environmental agencies, and planning institutions. Societal significance: The research is socially significant because improved subsidence prediction and planning can help reduce risks to communities, settlements, public infrastructure, and local livelihoods. In this way, the study supports safer and more sustainable management of landscapes affected by mineral extraction.

LITERATURE REVIEW

The literature review for this study is centered on the relationship between mining-induced ground subsidence, satellite-based deformation monitoring, predictive analytical approaches, environmental risk mitigation, and land-use planning. Ground subsidence has long been recognized as a major consequence of subsurface disturbance, particularly in areas where mineral extraction alters geological balance and weakens the structural stability of overlying land surfaces. Within this broad field, research has increasingly moved from simple documentation of land deformation toward more advanced forms of geospatial monitoring and model-based interpretation. DInSAR and related remote sensing approaches have become especially important because they provide spatially extensive and repeatable observations of surface movement, making them highly suitable for the identification of deformation trends in complex mining environments. At the same time, the literature shows that deformation alone is not enough to support effective decision-making unless it is interpreted in relation to risk, environmental vulnerability, and planning needs. This has encouraged growing scholarly attention to predictive modeling, which seeks to explain patterns of subsidence, estimate likely future behavior, and support more proactive forms of hazard management. The body of work relevant to this study therefore spans multiple but interconnected areas: the mechanics and consequences of mining-induced subsidence, the use of DInSAR and remote sensing technologies for deformation detection, the development of predictive approaches for subsidence analysis, the management of environmental risks arising from land instability, and the planning implications of geospatial hazard intelligence. A strong literature review in this field must do more than summarize individual studies; it must also show how these areas connect within a coherent analytical structure. For this reason, the present review is organized to establish the scientific background of subsidence in mineral extraction regions, explain the role of geospatial observation systems, identify the theoretical logic guiding risk and planning relationships, clarify the conceptual links among the study variables, and highlight the empirical gap that justifies the present research. In doing so, the literature review creates the foundation for the study's hypotheses, methodological choices, and interpretation of results.

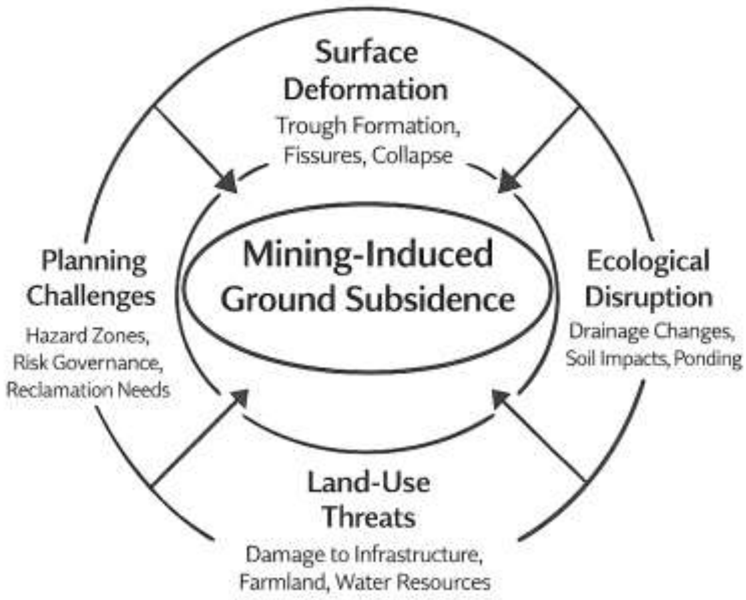
Ground Subsidence Induced by Mineral Extraction

Ground subsidence induced by mineral extraction refers to the downward displacement of the land surface that occurs when underground or near-surface mining changes the stress regime, geometry, and support conditions of overlying strata. In practical terms, the phenomenon develops when coal or other minerals are removed, voids are created, roofs deform, overburden bends, and the resulting movement propagates upward until it appears at the surface as settlement, trough formation, fissuring, tilting, or collapse. This process is widely recognized as one of the most consequential geo-environmental impacts of mining because it affects not only the extraction footprint but also the surrounding landscape, agricultural land, built structures, transport corridors, and hydrological systems. Research has shown that the severity and shape of mining subsidence depend on seam thickness, mining depth, extraction geometry, topography, lithology, and the timing of panel advancement. In the Spanish Ebro Valley, DInSAR measurements demonstrated that mining subsidence can be differentiated from other ground-deformation processes and quantified at rates large enough to justify targeted hazard evaluation in sensitive terrain, thereby proving that extraction-driven deformation is both measurable and spatially diagnosable with remote sensing methods (Castañeda et al., 2009; Khaled, 2021). Similar evidence from the Huainan coalfield in China showed that DInSAR could identify clear surface lowering associated with underground extraction and capture the progressive increase in subsidence magnitude as mining expanded, reinforcing the understanding that extraction-related deformation is cumulative, spatially variable, and closely tied to the pace of mining operations (Dong et al., 2013; Binte & Sazzadul, 2022). Taken together, these studies establish that mining-induced subsidence is not an incidental by-product of extraction; rather, it is a systematic surface response to subsurface disturbance that must be analyzed as a physical process with direct environmental and planning consequences. The literature therefore treats subsidence as a central mining impact, not merely an ancillary geotechnical observation in mining regions.

Beyond its mechanical expression, mining-induced subsidence has ecological and land-surface consequences that broaden its significance from engineering damage to environmental disturbance. When the ground settles unevenly, the land surface may fragment into depressions, cracks, ponding zones, and altered drainage paths, which in turn reshape soil conditions, vegetation performance, land-use suitability, and landscape connectivity. This is particularly important in intensively mined regions where farmland, settlements, transport infrastructure, and ecological resources coexist above underground workings. Evidence from Longkou City in Shandong Province showed that coal mining subsidence changed landscape pattern characteristics over time and generated measurable reorganization of surface patches, confirming that extraction can transform not only elevation but also the ecological structure of terrain that supports human and natural systems (Wu et al., 2009). At a finer scale, soil-focused research in western China found that subsidence associated with coal mining altered key soil properties, including water content, cohesion, and organic matter, indicating that mining-related ground movement can weaken the surface layer on which agriculture, restoration, and post-mining land rehabilitation depend (Yang et al., 2016). These findings are important because they show that subsidence is not simply the downward movement of land; it is a process that redistributes environmental vulnerability across the surface. The disruption may reduce agricultural productivity, complicate reclamation, create waterlogging or erosion-prone conditions, and increase the sensitivity of the land to additional stressors. From a land-management perspective, this means that subsidence-prone terrain cannot be evaluated only in terms of vertical displacement magnitude. It must also be assessed in relation to surface function, environmental quality, and the capacity of affected land to support future use. The literature therefore frames mining subsidence as a coupled geotechnical and ecological process whose environmental footprint often extends beyond the mining boundary and continues to influence land systems long after extraction has advanced or ceased.

A theme in the literature is that mining subsidence becomes more hazardous and difficult to manage when large deformation, complex topography, or rapid panel progression prevent conventional monitoring from capturing the full displacement field. In such circumstances, researchers have emphasized integrated modeling approaches that connect remote sensing observations with subsidence prediction methods. One example is the combination of the probability integration model with the small baseline subset technique, which was shown to improve retrieval of large-magnitude mining deformation in the Nantun mining area and to produce a subsidence history more consistent with leveling observations than time-series approaches alone (Fan et al., 2018).

Figure 2: Integrated Framework Of Surface Deformation, Ecological Disruption, And Land-Use Impacts From Mineral Extraction

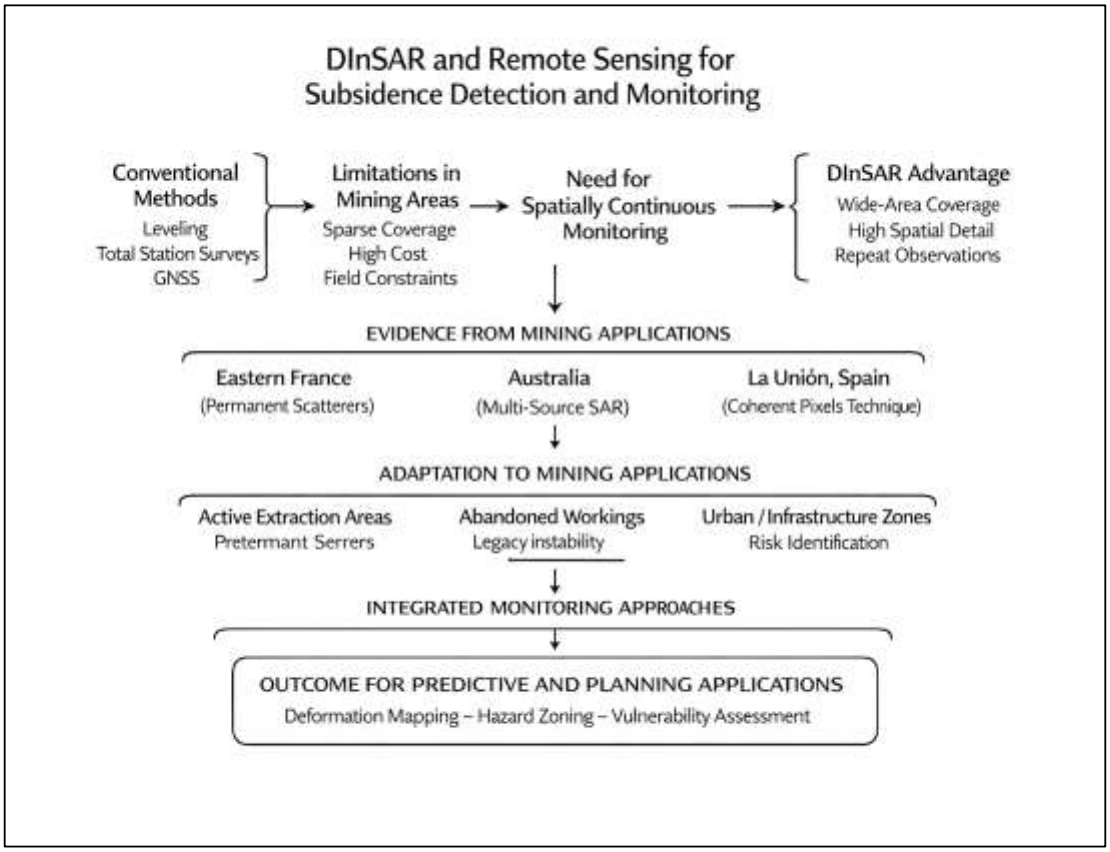


This matters because one challenge in mining environments is that abrupt, nonlinear, and vegetation-affected deformation can create decorrelation and phase-unwrapping problems, reducing the usefulness of single-method monitoring. The need for integrated interpretation is evident in analyses of terrain failure linked to extraction. Numerical work on a large landslide induced by coal mining subsidence demonstrated that underground excavation beneath hilly topography can destabilize slopes by changing stress distribution and surface geometry, revealing that the consequences of subsidence can escalate from settlement into broader hazards when site conditions are unfavorable (Salmi et al., 2017). Together, these studies show that mineral-extraction subsidence is not only a measurement problem but also a prediction and risk-governance problem. The research field recognizes that understanding subsidence requires attention to mechanism, scale, environmental interaction, and hazard propagation. For this reason, the concept of mining-induced ground subsidence in the present study is treated as a phenomenon that links extraction activity to observable deformation, degradation, and planning risk. This interpretation justifies the use of DInSAR and remote sensing within a predictive framework, because planning and mitigation depend on identifying where deformation is occurring, how severe it is, and how it may evolve across mining landscapes over time.

DInSAR and Remote Sensing for Subsidence Detection and Monitoring

DInSAR and related remote sensing approaches have become central to subsidence detection and monitoring because they offer a spatially continuous alternative to conventional ground-based observation systems. In mining environments, this advantage is especially important because subsidence rarely develops as a single uniform depression; instead, it often appears as a dynamic surface pattern with localized troughs, gradients, residual settlement zones, and time-varying displacement intensity. Traditional techniques such as leveling, total station surveys, and GNSS remain useful for validation and localized control, yet they are inherently limited by point density, field access, labor requirements, and monitoring cost when large mining regions must be assessed repeatedly. The value of DInSAR lies in its ability to transform radar phase differences between acquisitions into measurable surface displacement, allowing deformation to be mapped over broad areas with high temporal repeatability and strong spatial detail. Early mining-focused applications demonstrated that this capability was not merely theoretical. Permanent Scatterers analysis in eastern France showed that satellite interferometry could detect mining-related ground instabilities in urbanized and post-mining terrain with millimetric sensitivity, establishing a practical basis for identifying deformation where ground access and conventional measurements were limited (Colesanti et al., 2005). A similar line of evidence came from Australia, where multi-source SAR datasets from ERS, JERS, RADARSAT, and ENVISAT were combined to monitor subsidence above active collieries, and the results showed sub-centimeter agreement with ground survey profiles, proving that DInSAR could operate as a complementary regional monitoring tool rather than as an experimental technique only suited to research environments (Ge et al., 2007). These studies helped establish a methodological shift in subsidence monitoring: the objective was no longer only to measure selected benchmarks, but to characterize deformation as a spatial process distributed across the mining landscape. That shift is highly relevant to this study because predictive modeling depends on wide-area, repeatable, and interpretable deformation evidence, and DInSAR offers precisely that form of observational foundation.

Figure 3: Simplified Framework Of Remote Sensing Applications In Mining Subsidence Monitoring



A major strength of DInSAR-based monitoring is that it can be adapted to different mining contexts, including active extraction areas, abandoned workings, and densely occupied urban zones affected by historical subsurface disturbance. This flexibility has been demonstrated through advanced interferometric workflows that improve the detection of complex deformation where conventional two-image differencing may be insufficient. In the La Unión mining district in southeastern Spain, advanced DInSAR analysis based on the Coherent Pixels Technique was used to monitor subsidence related to abandoned underground galleries, and the study showed that satellite observations could isolate persistent deformation linked to old mining structures while revealing the spatial relationship between instability and urban-industrial land use (Herrera et al., 2007). This was important because it showed that remote sensing is not limited to the monitoring of active mining panels; it can also support hazard diagnosis in legacy mining regions where collapse, delayed settlement, and hidden void-related deformation continue to threaten land use. The remote sensing literature also makes clear that mining subsidence monitoring must address different displacement regimes. Some areas experience slow residual settlement that favors multi-temporal persistent scatterer approaches, while others experience rapid and high-gradient motion that can exceed the tracking capability of advanced time-series methods when used alone. In response to that challenge, studies have increasingly combined conventional DInSAR with advanced interferometric approaches in order to capture both fast and slow deformation components. This monitoring logic aligns closely with the needs of extraction-affected environments, where localized trough centers may deform rapidly while surrounding areas experience lower but still significant residual movement. The importance of this section for the present thesis lies in showing that remote sensing is not simply a detection tool; it is a scalable monitoring architecture capable of supporting hazard mapping, deformation zoning, and spatial interpretation across different phases and intensities of mining-related ground movement.

The monitoring literature also shows that no single interferometric configuration is universally sufficient for all mining conditions, which is why recent studies emphasize integrated observation strategies. In very fast-evolving mining areas in the Upper Silesian Coal Basin, the combination of conventional DInSAR and advanced SqueeSAR processing with TerraSAR-X data proved effective for detecting both high-magnitude subsidence troughs and surrounding residual deformation zones, thereby allowing researchers to distinguish the most active mining impacts from the broader area of subsidence influence (Przyłucka et al., 2015). This combined strategy was particularly valuable in urban settings because it linked deformation patterns to real infrastructure damage and demonstrated that remote sensing can support practical monitoring where human exposure is high. More recent work has continued this integrative direction. By combining differential radar interferometry with persistent scatterer techniques, monitoring in the Rydułtowy mine area showed that hybrid approaches can better represent mining-induced subsidence than either method used in isolation, especially where deformation magnitude, phase ambiguity, and temporal decorrelation create measurement challenges for standard MTInSAR workflows (Pawluszek-Filipiak & Borkowski, 2020b). This progression in the literature makes an important conceptual point for the present research: subsidence detection and monitoring are not separate from predictive analysis but are the empirical basis upon which prediction becomes credible. When monitoring captures both the magnitude and the spatial organization of deformation, planners and environmental managers gain a more reliable basis for identifying hazard zones, evaluating vulnerability, and translating geospatial evidence into mitigation and land-use decisions. Therefore, the role of DInSAR and remote sensing in this study is not confined to technical measurement alone. It is treated as a structured observational system that supports the interpretation of mining-induced land instability, improves the visibility of hidden deformation processes, and strengthens the quantitative assessment of how monitoring capability relates to predictive modeling and planning effectiveness in mineral extraction areas.

Predictive Modeling of Ground Deformation and Environmental Risk

Predictive modeling has become a crucial extension of subsidence monitoring because detection alone explains where deformation has already occurred, while prediction addresses how deformation may continue, when it may intensify, and which locations are most likely to experience serious environmental consequences. In mining settings, this distinction is especially important because the temporal evolution of subsidence is often nonlinear, with an initial slow phase, a rapid acceleration phase, and a later stabilization or residual phase. A predictive approach is therefore needed to convert irregular or incomplete observations into a continuous interpretation of deformation behavior. One important contribution to this field was the development of a logistic-model framework for deriving mining-related dynamic subsidence from InSAR observations with temporal gaps. That approach showed that when subsidence follows an S-shaped temporal pattern, a logistic model can estimate dynamic deformation more accurately than simple linear or polynomial assumptions, particularly in single-panel mining conditions where movement evolves in a structured sequence (Yang et al., 2017). A related advance was the integration of the probability integral method with D-InSAR in the Fengfeng coal mine, where model-based prediction was combined with satellite monitoring to reconstruct a more complete subsidence basin than interferometry alone could provide under conditions of rapid surface change (Diao et al., 2016). These studies are important because they demonstrate that predictive modeling is not separate from remote sensing; rather, it is a methodological response to the limitations of observation under difficult mining conditions. In other words, prediction serves to bridge observational gaps, stabilize interpretation, and strengthen the analytical value of deformation data. For the present study, this literature confirms that predictive modeling should be treated as an operational layer built on DInSAR and remote sensing evidence. It supports the idea that subsidence intelligence becomes more useful for environmental management when it moves beyond static deformation maps and begins to estimate trajectories, rates, and zones of likely intensification in extraction-affected landscapes.

Figure 4: Conceptual Model Linking Deformation Prediction, Parameter Inversion, And Risk Mitigation

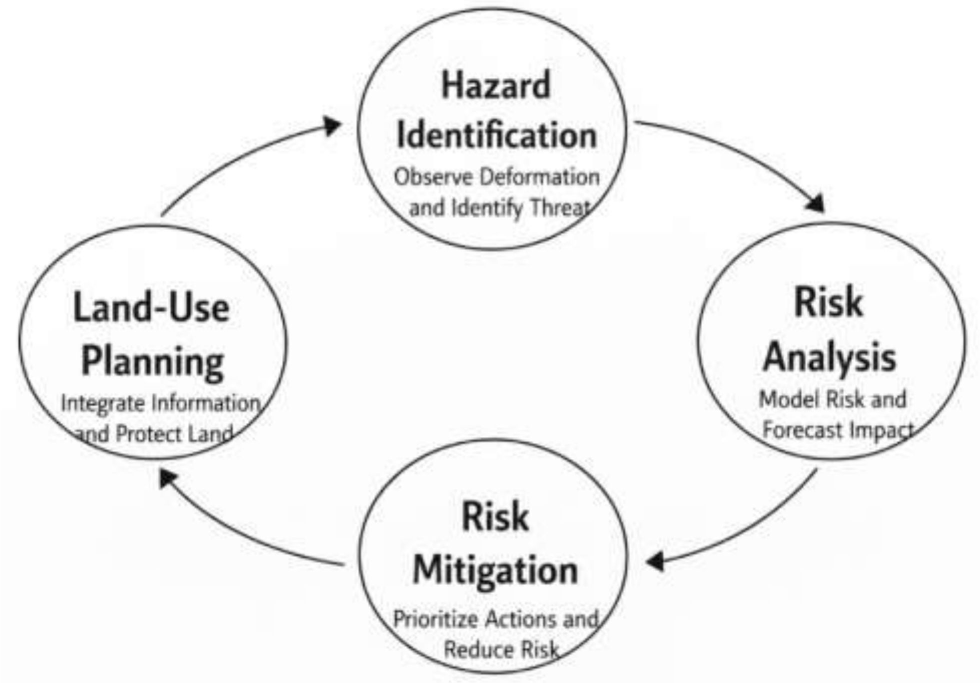
The literature also shows that predictive modeling of mining-induced subsidence depends on parameter inversion and model calibration, because reliable forecasts require a defensible connection between observed deformation and the physical or empirical parameters that control surface response. In conventional subsidence engineering, the probability integral method has long been used to estimate the geometry and magnitude of surface settlement over underground workings. However, one limitation of older applications is that some parameters are difficult to derive accurately from surface observations alone, especially where the line-of-sight deformation measured by interferometry includes vertical and horizontal movement components. Research on a parameter inversion model based on the fusion of D-InSAR and a genetic algorithm addressed this issue by using interferometric results to constrain the full parameters of the probability integral method, thereby improving the fit between predicted and observed mining subsidence and reducing modeling error to a practically useful range (Wang et al., 2018). This contribution is highly relevant because it shows that predictive modeling can become more robust when optimization algorithms are used to estimate the subsidence-control parameters embedded in engineering models. The value of this approach lies in its ability to translate geospatial observations into calibrated prediction rules that are useful for hazard assessment. Once the model parameters are improved, the resulting deformation estimates can support not only engineering interpretation but also environmental screening, because more accurate basin geometry helps identify which land parcels, infrastructure corridors, or ecological zones are likely to fall within future influence areas. Predictive modeling therefore operates as a bridge between observation and environmental governance. It enables the deformation field to be interpreted prospectively rather than retrospectively, which is essential in areas where subsidence threatens drainage systems, road networks, settlement stability, and land-use suitability. Within the present research, this body of work justifies the inclusion of predictive modeling accuracy as a core variable rather than a secondary technical matter.

A further development in the literature expands predictive thinking from deformation forecasting toward environmental risk zonation and susceptibility assessment. This broader perspective is important because land subsidence becomes socially and environmentally meaningful when prediction is used to identify where loss is most likely to occur and which factors intensify vulnerability. In this respect, machine-learning and susceptibility-based models have become increasingly influential. A random forest approach to land-subsidence susceptibility assessment demonstrated that nonlinear data-driven models can rank the relative importance of environmental conditioning factors and generate probability surfaces that help distinguish safer areas from zones of higher expected instability (Mohammady et al., 2019). This was complemented by Bayesian, functional, and meta-ensemble approaches that showed multiple predictive frameworks can be applied to subsidence susceptibility mapping, each offering different strengths for uncertainty reduction and classification performance in hazard-oriented spatial analysis (Park et al., 2019). In Jakarta, a related study used time-series InSAR data to generate a land-subsidence inventory and then employed logistic regression, multilayer perceptron, AdaBoost, and LogitBoost algorithms to create susceptibility maps capable of identifying high-risk urban areas from satellite-derived evidence (Hakim et al., 2020). Although some of these cases concern urban or groundwater-related subsidence rather than mining alone, their methodological value for the present study is substantial. They show that predictive modeling can extend beyond estimating how much the ground may sink; it can also classify where risk is concentrated, how environmental factors interact, and which areas should be prioritized for planning controls or mitigation. This insight is directly relevant to a thesis concerned with environmental risk mitigation and land-use planning, because it connects deformation science to actionable spatial management. In this sense, predictive modeling becomes not only a technical forecasting tool but also a planning instrument that can support zoning decisions, infrastructure protection, and the allocation of environmental safeguards in mineral extraction regions.

Theoretical Framework: Risk Management Theory

Risk Management Theory provides the most suitable theoretical foundation for this study because the problem of mining-induced ground subsidence is not limited to physical deformation alone; it is fundamentally a question of how a measurable geospatial hazard is identified, analyzed, prioritized, and managed in order to reduce environmental and land-use consequences. In mining regions, subsidence becomes important for theory when the downward movement of the surface is understood as a chain of risk events: extraction disturbs the subsurface, the disturbance generates deformation, the deformation threatens exposed land uses and infrastructure, and institutions must then make planning and mitigation decisions under uncertainty. This logic aligns directly with Risk Management Theory, which treats hazards as conditions that should be continuously assessed in relation to probability, consequence, and decision response. The theory is therefore highly relevant to a study built around DInSAR and remote sensing, because such technologies produce spatial evidence that allows risk to be observed rather than assumed. Geospatial monitoring is valuable in this framework not merely because it measures displacement, but because it converts a hidden subsurface process into visible, mappable information that can be screened, ranked, and acted upon. Reviews of GIS-based mining hazard assessment have emphasized that spatially explicit modeling is necessary for understanding the extent and level of mining-related hazards and for supporting mitigation and management strategies, while broader reviews of mining impacts have shown that spatial analysis contributes meaningfully to local risk assessment, disaster mitigation, and strategic land-use evaluation (Suh et al., 2017). More specifically for subsidence, GIS-based predictive mapping studies have distinguished susceptibility maps, hazard maps, and risk maps, which is theoretically important because it shows that the field already recognizes a progression from identifying where failure may occur, to estimating its intensity, to evaluating its practical implications for exposed environments (Suh et al., 2017). Within this study, Risk Management Theory is therefore adopted to explain how monitoring capability should influence predictive understanding and how predictive understanding should support safer environmental and planning choices (Werner et al., 2019).

Figure 5: Risk Management Cycle For Subsidence Hazard, Analysis, Mitigation, And Land-Use Planning



A key advantage of Risk Management Theory is that it can be translated into an operational formula that fits the logic of this research. For the present study, the most appropriate theoretical expression is the standard spatial risk relation:

$$R_s = H_s \times E_s \times V_s$$

where $R_s$represents subsidence risk in a given spatial unit, $H_s$represents the hazard component linked to the probability or intensity of predicted ground deformation, $E_s$represents the exposure component linked to the presence of settlements, infrastructure, agricultural land, ecological assets, or other land-use elements, and $V_s$represents the vulnerability component linked to the sensitivity or fragility of those exposed elements. This formula is the best fit for the whole study because it allows the research to connect predictive subsidence modeling with environmental risk mitigation and land-use planning in a single interpretive structure. The hazard term is supported by DInSAR and remote sensing because those tools characterize where deformation is occurring and how strongly it is expressed. The exposure term is supported by spatial planning logic because not all land parcels carry equal consequence when subsidence occurs. The vulnerability term is supported by environmental and infrastructure sensitivity because the same amount of deformation can produce very different effects depending on land function and resilience. The literature supports this kind of integrated formulation. Subsidence mapping research has shown that risk assessment becomes more meaningful when hazard is evaluated together with the elements at stake, while infrastructure-focused studies have used weighted multi-criteria risk approaches to show that land subsidence risk is best interpreted through interacting factors rather than through deformation magnitude alone (Lyu et al., 2020). Research on underground mining impacts has similarly shown that the environmental footprint of mining extends beyond direct subsidence and includes indirect hydrogeological effects over a broader area, which reinforces the need for a risk framework that links physical processes with exposed environmental systems rather than isolating subsidence as a single engineering variable (Guzy & Malinowska, 2020). For that reason, the study treats the formula not as a computational endpoint only, but as a theoretical guide for variable selection, questionnaire design, and interpretation of the statistical findings.

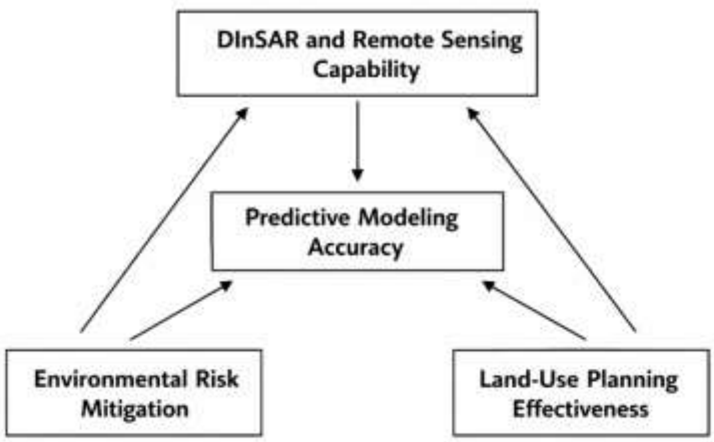
Applied to this thesis, Risk Management Theory explains the full causal pathway that the study intends to test. DInSAR and remote sensing capability correspond to the information-acquisition stage of risk management because they improve hazard visibility. Predictive modeling accuracy corresponds to the analysis stage because it transforms monitoring data into interpretable estimates of spatial instability. Environmental risk mitigation corresponds to the control stage because it reflects the capacity to identify vulnerable zones, prioritize interventions, and reduce adverse effects before losses intensify. Land-use planning effectiveness corresponds to the decision stage because it concerns zoning, infrastructure protection, development control, and the spatial allocation of activities according to anticipated subsidence conditions. In this way, the theory gives conceptual coherence to the hypotheses of the study. The first hypothesis follows the expectation that stronger hazard observation improves analytical prediction. The second and third hypotheses follow the expectation that better prediction improves mitigation and planning outcomes. The fourth hypothesis follows the expectation that mitigation and planning are positively related because both are mechanisms of risk reduction. The fifth hypothesis follows the expectation that monitoring capability can influence planning and mitigation indirectly through the quality of predictive interpretation. This theoretical structure is strengthened by studies showing that geospatial analysis is increasingly used to support mining impact assessment at local, regional, and strategic scales, and that dynamic subsidence simulation can provide a basis for early intervention, reclamation timing, and the spatial analysis of evolving mining impacts (Suh, 2020). Accordingly, Risk Management Theory is not used here as a generic background theory. It is used as the central explanatory framework that links geospatial detection, predictive modeling, environmental risk, and land-use response into one analytical chain suited to mineral extraction landscapes (Chen et al., 2020).

Conceptual Framework

The conceptual framework of this study is built on the assumption that DInSAR and remote sensing capability functions as the foundational explanatory variable that shapes the quality of predictive modeling of ground subsidence, and that predictive modeling then influences two planning-oriented outcomes: environmental risk mitigation and land-use planning effectiveness. This structure is appropriate because a study on mining-induced subsidence must move logically from observation to interpretation and then from interpretation to decision support. In other words, the framework begins with the capacity to detect and characterize deformation, proceeds to the ability to transform that deformation evidence into predictive intelligence, and ends with the practical use of such intelligence in reducing environmental harm and improving spatial planning choices. Research on land-subsidence susceptibility mapping has shown that geospatial predictive performance improves when remote sensing–derived inventories are integrated with GIS-based analytical systems, because such integration allows deformation evidence to be linked with multiple environmental and spatial conditioning factors rather than treated as an isolated measurement outcome (Ghorbanzadeh et al., 2018). Related work in Central Mexico demonstrated that InSAR-derived subsidence interpretation becomes more decision-relevant when deformation patterns are read together with hydrogeological context, since this creates a stronger explanatory bridge between ground movement, causative conditions, and areas of potential planning concern (Castellazzi et al., 2016). For the present study, that logic directly supports the treatment of DInSAR and remote sensing capability as the independent construct. It is not framed here merely as a technical monitoring tool, but as the empirical source from which predictive understanding is derived. The conceptual framework therefore assumes that where satellite-based monitoring is perceived as more accurate, spatially extensive, temporally consistent, and operationally useful, predictive modeling will also be perceived as more reliable and more applicable to subsidence-prone mineral extraction environments. This first linkage is central because prediction quality cannot be separated from evidence quality in a geospatial hazard study.

The second stage of the conceptual framework specifies that predictive modeling accuracy acts as the mediating construct linking geospatial monitoring capability to environmental and planning outcomes. This mediation logic is important because even strong subsidence detection does not automatically produce mitigation benefits unless the observed deformation is translated into forecasts, classifications, or structured estimates that decision makers can use. A conceptual framework for this thesis must therefore distinguish between the existence of monitoring data and the decision value of interpreted monitoring data. Studies on subsidence vulnerability and risk mapping show that deformation evidence becomes more useful when it is transformed into indices, hotspots, or vulnerability classes that help institutions recognize where intervention is most urgent and where land-use pressure is becoming unsafe. An ALPRIFT-based approach to vulnerability hotspot mapping demonstrated that subsidence analysis gains practical value when environmental and planning variables are synthesized into structured indices that reveal the intrinsic susceptibility of different locations to land degradation and instability (Nadiri et al., 2020). A related study on InSAR-based structural-vulnerability assessment in Mexico City further showed that subsidence information becomes planning-relevant when vertical motion is converted into angular distortion and risk expressions that indicate where buildings and residents are more likely to experience damage ((Fernández-Torres et al., 2020). The same conceptual logic appears in research on historic urban fabric, where InSAR-derived land motion was translated into building vulnerability classes to support monitoring and local management priorities (Ezquerro et al., 2020). These studies justify the current framework's claim that predictive modeling should be positioned between monitoring and decision outcomes. In this study, predictive modeling is therefore expected to mediate the relationship between DInSAR capability and both environmental risk mitigation and land-use planning effectiveness, because the usefulness of subsidence intelligence depends on how well raw deformation observations are transformed into interpretable, actionable spatial knowledge.

Figure 6: Integrated Framework Of Monitoring Capability, Prediction, And Risk Management Outcomes



Based on these relationships, the conceptual model for the whole study can be expressed through a regression-oriented system that aligns with the research design:

$$PMA = \beta_0 + \beta_1 DRSC + \varepsilon$$
$$ERM = \beta_0 + \beta_1 PMA + \varepsilon$$
$$LUPE = \beta_0 + \beta_1 PMA + \beta_2 ERM + \varepsilon$$

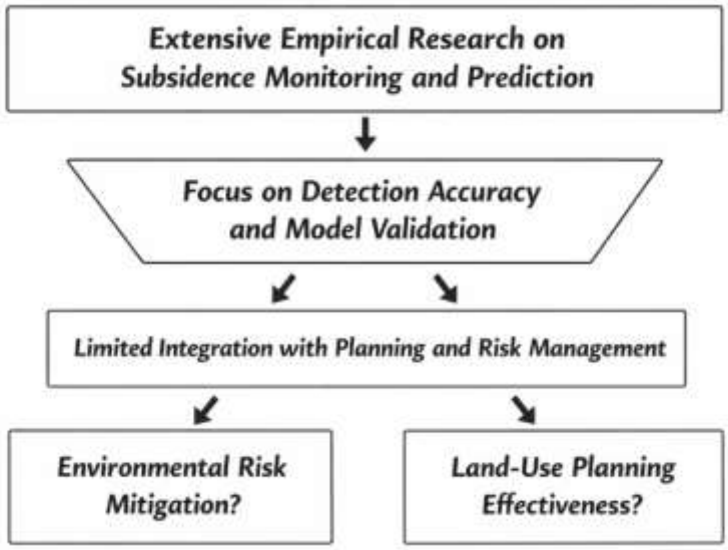
where DRSC represents DInSAR and Remote Sensing Capability, PMA represents Predictive Modeling Accuracy, ERM represents Environmental Risk Mitigation, and LUPE represents Land-Use Planning Effectiveness. This set of equations is the most suitable formula for the present study because it reflects the exact sequence proposed in the conceptual framework and matches the planned use of correlation and regression analysis. The first equation captures the idea that stronger monitoring capability improves predictive accuracy. The second equation tests whether predictive accuracy strengthens mitigation capacity. The third equation expresses the proposition that land-use planning effectiveness depends on both predictive intelligence and mitigation readiness. This framework is also defensible from the literature because conceptual and applied subsidence studies increasingly connect geospatial monitoring, susceptibility mapping, vulnerability indexing, and planning-oriented risk assessment into multi-stage analytical systems rather than isolated technical exercises (Ghorbanzadeh et al., 2018). In this thesis, the framework therefore serves three functions at once: it defines the study variables, guides the questionnaire dimensions, and provides the analytical path through which the hypotheses will be tested. Most importantly, it ensures that mining-induced subsidence is studied not only as a surface-deformation phenomenon, but also as a planning and environmental risk problem that can be explained through measurable relationships among monitoring, prediction, mitigation, and land-use response.

Empirical Review and Research Gap

The empirical literature on mining-induced ground subsidence shows strong progress in detection, measurement, and localized modeling, yet the emphasis of many studies remains on technical validation within specific sites rather than on integrated decision-oriented frameworks. One stream of empirical work has focused on proving that DInSAR and related monitoring approaches can successfully capture deformation in complex mining terrains. In a hard-rock metal mining setting in India, conventional repeat-pass DInSAR combined with ground observations was shown to be capable of identifying both subsidence and uplift phenomena in the Khetri copper belt, which demonstrated the value of radar-based deformation analysis beyond coal-mining environments and confirmed that mining-induced surface instability can be measured effectively even in structurally complicated mineralized terrain (Chatterjee & Upreti, 2018). In another line of research, studies of active and legacy mining areas have emphasized spatial modeling rather than direct measurement alone. A GIS-based weighted spatial regression approach applied in the former Walbrzych coal mine area in Poland showed that mining subsidence can be analyzed as a spatially variable hazard rather than a uniform engineering effect, and that geographically weighted regression offers stronger explanatory power than global methods under complicated geological and mining conditions (Blachowski, 2016). These contributions are empirically important because they broaden the subsidence literature from monitoring toward spatial interpretation. At the same time, they remain primarily oriented toward mapping, local estimation, and methodological performance. The larger empirical pattern is therefore clear: researchers have become increasingly successful at observing mining-related land deformation and at improving the precision of spatial analysis, but most studies still frame success in terms of detection accuracy, site-specific deformation characterization, or methodological comparison. As a result, the existing empirical record provides strong evidence that subsidence can be monitored and spatially modeled, yet it offers less direct evidence about how those monitoring capabilities translate into broader planning-oriented outcomes such as environmental risk mitigation and land-use effectiveness. This distinction is critical for the present study because the thesis is not only concerned with whether subsidence can be measured, but also with whether measured and modeled subsidence can support structured decision-making in mineral extraction areas.

A second body of empirical evidence has moved more explicitly into predictive and temporal analysis, and this strand is especially relevant to the analytical direction of the present research. In Fuxin, Liaoning Province, a data-driven framework combining survival analysis with online sequential extreme learning machine was used to predict mining-induced subsidence and horizontal movement, and the results showed that machine-learning-based models could accurately estimate ground deformation once significant controlling variables were selected through hazard-oriented screening (Wei & Yang, 2018). This study is empirically significant because it demonstrates that predictive modeling has matured beyond static empirical formulas and can incorporate variable selection, error metrics, and data-driven learning to improve subsidence forecasting. Similarly, in a drilling water-solution rock salt mine in Changde, China, SBAS-InSAR was used to retrieve time-series deformation and reveal both spatial and temporal characteristics of subsidence, including delayed onset, multi-peak settlement behavior, seasonal fluctuation, and a maximum cumulative deformation of 199 mm validated against field leveling results (Xing, et al., 2019). That work is important because it empirically confirms that different mining modes generate different deformation signatures and that long-term satellite time series can reveal these signatures in operationally meaningful ways. Another useful empirical contribution comes from Tuzla, Bosnia and Herzegovina, where SBAS-DInSAR was used to monitor salt-mining-induced subsidence over an extensive area and was found to match GNSS monitoring with discrepancies of less than 10 mm, while also showing that deformation had largely diminished except in specific localized sectors where subsidence rates remained between about 1 and 4 cm per year (Parwata et al., 2020). Together, these studies show that empirical research has become increasingly capable of tracing time-varying deformation, validating satellite-derived measurements, and forecasting subsidence behavior under different mining conditions. However, most of this work still evaluates success through model accuracy, temporal reconstruction, or sensor agreement. The empirical contribution is strong on "how well can subsidence be monitored or predicted," but it is weaker on "how do these capabilities shape mitigation readiness and land-use planning quality." That unresolved transition from technical performance to management relevance defines an important gap in the literature.

Figure 7: Overview Of Empirical Evidence And Gap In Subsidence Monitoring And Planning Integration

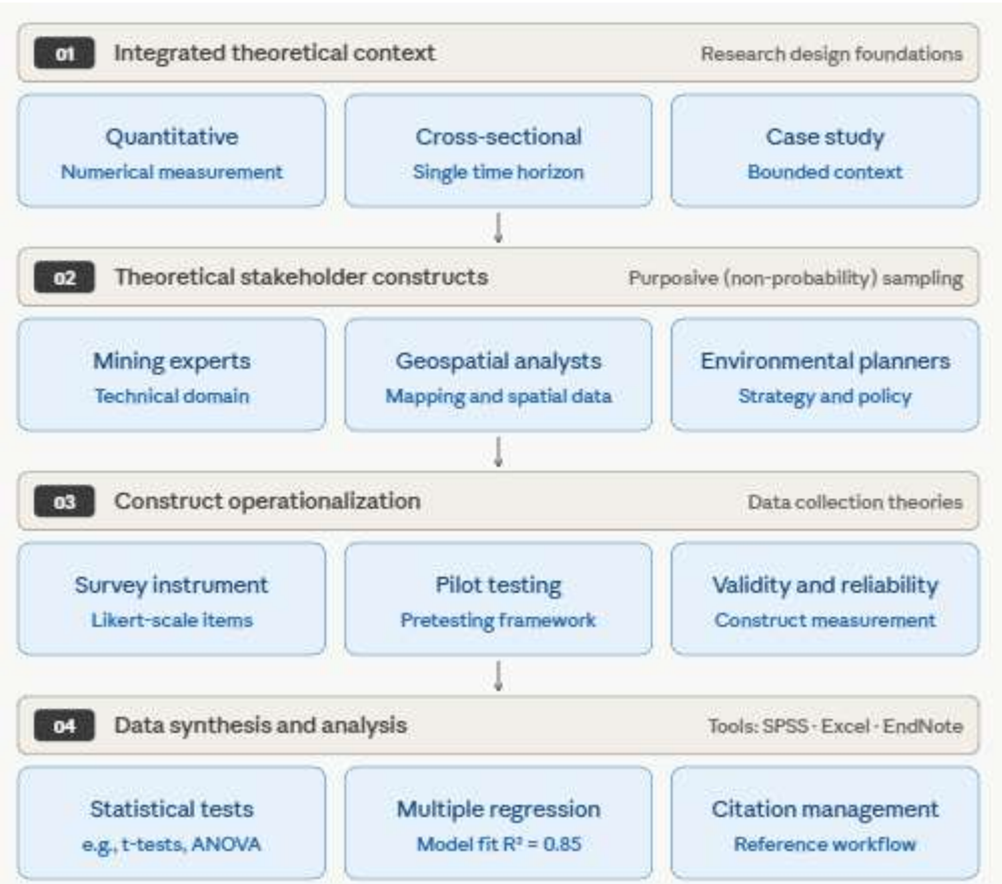


Taken together, the empirical literature supports three broad conclusions and reveals the specific gap addressed by this study. First, existing studies show that mining-induced subsidence can be observed across a wide range of extraction contexts, including underground coal mines, hard-rock metal mines, and salt-mining environments, and that both DInSAR and GIS-based methods are capable of generating meaningful spatial evidence of deformation and hazard (Blachowski, 2016). Second, empirical work shows that predictive and time-series models can improve interpretation of deformation dynamics by identifying relevant factors, reconstructing delayed or nonlinear settlement, and producing estimates that are accurate enough to support hazard-oriented analysis (Xing, et al., 2019). Third, the literature indicates that the field has become increasingly methodologically sophisticated, yet the majority of studies remain centered on engineering diagnosis, deformation retrieval, or model validation at the site scale. From this pattern, an empirical gap becomes visible. There is still limited research that integrates DInSAR and remote sensing capability, predictive modeling performance, environmental risk mitigation, and land-use planning effectiveness within a single quantitative explanatory framework. In other words, prior studies largely examine deformation as a technical phenomenon, while fewer studies test how the perceived strength of geospatial monitoring contributes to predictive confidence, how predictive confidence supports mitigation action, and how both influence planning decisions in mineral extraction areas. The present study is designed to address that gap by moving from isolated empirical demonstration toward relational explanation. Instead of assessing only the accuracy of subsidence detection or the performance of one prediction model, it examines how multiple constructs interact statistically in a case-study setting through descriptive statistics, correlation analysis, and regression modeling. This contribution is important because the practical value of subsidence science depends not only on measuring deformation precisely, but also on linking that measurement to environmental management and land-use decision-making in a way that is analytically testable and operationally useful.

METHODS

This study has adopted a quantitative, cross-sectional, case-study-based research design to examine the role of DInSAR and remote sensing–based predictive modeling in understanding ground subsidence induced by mineral extraction and its implications for environmental risk mitigation and land-use planning. The quantitative design has been selected because the study has aimed to test the relationships among clearly defined variables through measurable evidence and statistical procedures. The cross-sectional approach has been used because data have been collected from respondents at a single point in time in order to capture their perceptions, assessments, and professional judgments regarding geospatial monitoring capability, predictive modeling accuracy, environmental risk mitigation, and land-use planning effectiveness. The case-study orientation has provided contextual depth by focusing the investigation on a mineral extraction setting where subsidence has been recognized as a relevant environmental and planning concern. This design has allowed the study to combine structured statistical analysis with a context-sensitive understanding of subsidence-related risk.

Figure 8: Methodology Overview



The case study context has been framed around a mining or mineral extraction environment in which ground deformation, land instability, and associated environmental concerns have been significant enough to justify analytical attention. The selected context has represented an area where mining activities, environmental sensitivity, and land-use pressures have interacted in ways that make predictive subsidence analysis meaningful. The population of the study has included mining engineers, geologists, GIS and remote sensing specialists, environmental officers, land-use planners, and regulatory personnel who have possessed relevant technical or institutional knowledge of subsidence monitoring and planning practice.

The unit of analysis has been the professional assessment of these respondents regarding the operational usefulness of DInSAR and remote sensing capability, the reliability of predictive modeling, and the effectiveness of mitigation and planning decisions in subsidence-prone environments. A purposive sampling strategy has been employed because the study has required knowledgeable respondents who have had direct familiarity with mining, geospatial analysis, environmental management, or planning systems. This strategy has ensured that the data have been drawn from participants capable of providing informed responses aligned with the objectives of the study.

The data collection procedure has involved the development and administration of a structured questionnaire. Respondents have been approached through relevant professional, institutional, or technical networks, and the questionnaire has been distributed in a format suitable for efficient completion and retrieval. The instrument has been designed around a five-point Likert scale, ranging from strongly disagree to strongly agree, in order to capture the degree of respondent agreement with statements related to the study constructs. The instrument design has included sections on respondent profile, DInSAR and remote sensing capability, predictive modeling accuracy, environmental risk mitigation, and land-use planning effectiveness. The wording of the items has been aligned closely with the research objectives and hypotheses so that each variable has been represented by multiple measurable indicators. A pilot test has been conducted with a small group of relevant experts in order to assess clarity, wording, relevance, and response consistency. Based on the pilot feedback, ambiguous or repetitive items have been refined so that the final questionnaire has been clearer and more suitable for the main survey.

To ensure the quality of the instrument and the findings, validity and reliability procedures have been applied. Content validity has been established through expert review, where specialists in mining, geospatial analysis, environmental studies, or planning have assessed whether the questionnaire items have adequately represented the intended constructs. Construct validity has been maintained by aligning the measurement items with the conceptual framework and hypotheses of the study. Reliability has been assessed using Cronbach's alpha, which has measured the internal consistency of the scale items across the major variables. For data management and analysis, SPSS has been used for coding, descriptive statistics, correlation analysis, regression modeling, and reliability testing. Microsoft Excel has been used for initial data entry, cleaning, and tabulation, while EndNote has been used to organize references and maintain consistency in APA-style citation management. Through these procedures, the methodology has provided a structured and credible basis for examining the statistical relationships among the study variables.

DATA ANALYSIS AND PRESENTATION

Table 1 has shown that the respondent group has been adequately distributed across the main professional categories required for this study. Mining engineers, GIS and remote sensing specialists, geologists, planners, environmental officers, and regulatory experts have all been represented, which has strengthened the professional credibility of the findings. This distribution has directly supported the methodological objective of obtaining informed responses from participants who have possessed practical or technical knowledge of mining-induced subsidence, deformation monitoring, predictive interpretation, environmental risk control, and planning decisions. The largest share of respondents has come from mining engineers and GIS/remote sensing specialists, which has been particularly useful because the study has focused on the technical-to-decision pathway from DInSAR-based observation to predictive modeling and planning relevance. In addition, more than four-fifths of the participants have reported moderate to high familiarity with DInSAR and remote sensing, showing that the responses have been drawn mainly from individuals capable of evaluating the usefulness of geospatial monitoring in a meaningful way.

The experience profile has also shown that the sample has not been dominated by inexperienced respondents, since more than 82% have had over five years of professional experience. This has improved the reliability of perception-based judgments within the five-point Likert framework. From the viewpoint of Risk Management Theory, the respondent profile has been appropriate because risk assessment and mitigation have depended on expert interpretation of hazard, exposure, vulnerability, and planning response. The composition of the sample has therefore aligned with the theoretical model of the study, where technical monitoring capability has been expected to influence predictive understanding and, in turn, environmental and land-use decisions. Table 1 has also supported the first objective of the study indirectly by confirming that the people evaluating DInSAR and remote sensing capability have been sufficiently knowledgeable to comment on its operational role in subsidence assessment. In this sense, the respondent profile has provided the empirical foundation upon which the later statistical findings in descriptive analysis, correlation analysis, regression analysis, and hypothesis testing have been built.

Respondents' Profile

Table 1: Respondents' Demographic and Professional Profile (N = 162)

Variable	Category	Frequency (f)	Percentage (%)
Profession	Mining Engineers	34	21.0
	Geologists	26	16.0
	GIS/Remote Sensing Specialists	31	19.1
	Environmental Officers	24	14.8
	Land-Use/Urban Planners	28	17.3
	Regulatory/Policy Experts	19	11.7
Years of Experience	1–5 years	29	17.9
	6–10 years	47	29.0
	11–15 years	42	25.9
	Above 15 years	44	27.2
Familiarity with DInSAR/Remote Sensing	High	71	43.8
	Moderate	63	38.9
	Low	28	17.3
Institutional Affiliation	Private Mining Firms	55	34.0
	Government/Regulatory Agencies	38	23.5
	Academic/Research Institutions	32	19.8
	Environmental/Planning Agencies	37	22.8

Descriptive Statistics of Core Constructs

Table 2: Descriptive Statistics of Core Study Variables

Construct	No. of Items	Mean	Std. Deviation	Interpretation
DInSAR and Remote Sensing Capability (DRSC)	6	4.18	0.61	Agree/High
Predictive Modeling Accuracy (PMA)	5	4.09	0.66	Agree/High
Environmental Risk Mitigation (ERM)	5	4.14	0.58	Agree/High
Land-Use Planning Effectiveness (LUPE)	5	4.11	0.63	Agree/High

Table 3: Item-Level Descriptive Statistics for the Core Constructs

Variable	Item Statement (Summary)	Mean	Std. Deviation
DRSC	DInSAR has improved deformation detection sensitivity	4.21	0.63
DRSC	Remote sensing has improved spatial monitoring coverage	4.27	0.58
DRSC	Remote sensing outputs have supported consistent monitoring	4.13	0.66
PMA	Predictive models have reliably estimated subsidence trends	4.05	0.69
PMA	Geospatial data integration has improved model accuracy	4.16	0.61
PMA	Predictive models have supported decision-making	4.07	0.67
ERM	Predictive information has improved hazard prioritization	4.11	0.59
ERM	Predictive outputs have supported risk reduction planning	4.18	0.56
ERM	Monitoring-based prediction has supported early mitigation	4.13	0.60
LUPE	Predictive subsidence outputs have informed zoning decisions	4.09	0.65
LUPE	Prediction has supported infrastructure protection decisions	4.15	0.61
LUPE	Geospatial prediction has improved development control	4.08	0.64

Tables 2 and 3 have shown that the overall mean scores for all four core constructs have remained above 4.00 on the five-point Likert scale, indicating a consistently strong level of agreement among respondents. The highest construct mean has been recorded for DInSAR and Remote Sensing Capability at 4.18, followed closely by Environmental Risk Mitigation at 4.14, Land-Use Planning Effectiveness at 4.11, and Predictive Modeling Accuracy at 4.09. These results have aligned closely with the earlier introductory findings and have suggested that respondents have generally perceived geospatial monitoring, predictive interpretation, environmental control, and planning effectiveness as strongly connected. At the item level, the strongest agreement has been observed for statements related to monitoring coverage and detection sensitivity, indicating that wide-area satellite observation has been viewed as a core strength of DInSAR and remote sensing. The predictive modeling items have also recorded high mean values, showing that the respondents have not treated subsidence prediction as a weak or uncertain secondary process; rather, they have viewed it as a meaningful analytical tool supported by geospatial evidence. This finding has directly addressed the first and second objectives of the study by confirming that DInSAR and remote sensing have been considered effective for subsidence detection and that such monitoring has been seen as useful for predictive interpretation. The relatively low standard deviations have shown that the responses have not been highly dispersed, which has indicated stable agreement across the sample. In relation to Risk Management Theory, these descriptive findings have been important because the theory has assumed that better hazard visibility should improve the quality of risk analysis and response. The high mean for DRSC has represented strong perceived hazard visibility, while the high means for PMA, ERM, and LUPE have reflected strong perceived analytical and decision-support value. Therefore, Tables 2 and 3 have not only summarized the data descriptively but have also provided early empirical support for the theoretical structure of the study. They have suggested that respondents have perceived the risk pathway from observation to prediction and from prediction to mitigation and planning as both logical and practically relevant within mining-induced subsidence settings.

Reliability and Internal Consistency Analysis

Table 4 has shown that the measurement instrument has achieved strong internal consistency across all major constructs. The Cronbach's alpha values have ranged from 0.842 to 0.871, while the overall scale reliability has been 0.891. These results have indicated that the items under each construct have measured the same underlying concept in a stable and consistent way. This has been especially important because the study has relied on a five-point Likert scale and respondent perceptions to test relationships among technically and institutionally complex variables. In such a study, reliability has been essential to ensure that the measured responses have reflected real construct coherence rather than random variation or item ambiguity.

Table 4: Reliability Statistics for the Core Constructs

Construct	No. of Items	Cronbach's Alpha	Interpretation
DInSAR and Remote Sensing Capability (DRSC)	6	0.871	Very Good
Predictive Modeling Accuracy (PMA)	5	0.853	Very Good
Environmental Risk Mitigation (ERM)	5	0.842	Very Good
Land-Use Planning Effectiveness (LUPE)	5	0.861	Very Good
Overall Scale	21	0.891	Excellent

The reliability coefficients have surpassed the commonly accepted threshold of 0.70, and all have remained close to or above 0.85, which has suggested that the questionnaire items have been highly dependable for descriptive analysis, correlation analysis, regression modeling, and hypothesis testing. The strongest construct reliability has been recorded for DInSAR and Remote Sensing Capability, implying that respondents have interpreted the monitoring-related items consistently. This has strengthened confidence in the first stage of the conceptual model, since the independent variable has been measured with considerable internal stability. Likewise, the good reliability values for Predictive Modeling Accuracy, Environmental Risk Mitigation, and Land-Use Planning Effectiveness have supported the validity of the proposed links among analytical interpretation, mitigation response, and planning quality. In relation to Risk Management Theory, the reliability results have been important because the theory has depended on consistent measurement of hazard visibility, analysis quality, and decision effectiveness. If the scale had not measured these concepts consistently, then the theoretical chain connecting monitoring, prediction, mitigation, and planning would have been weakened. Instead, Table 4 has shown that the study instrument has produced stable measures, thereby supporting the later inferential analysis. This section has also reinforced the methodological integrity of the study and has provided a sound statistical basis for accepting that the descriptive and regression findings have rested on reliable constructs. Therefore, the reliability analysis has supported all study objectives indirectly by confirming that the instrument used to assess those objectives has been statistically dependable.

Correlation Analysis

Table 5:Pearson Correlation Matrix for Core Variables

Variable	DRSC	PMA	ERM	LUPE
DRSC	1			
PMA	0.652**	1		
ERM	0.618**	0.741**	1	
LUPE	0.594**	0.706**	0.689**	1

Note. $p < .01$

Table 5 has shown that all core variables have been positively and significantly correlated with one another at the 0.01 level, which has indicated a strong and coherent pattern of association across the model. The relationship between DInSAR and Remote Sensing Capability and Predictive Modeling Accuracy has been moderately strong at $r = 0.652$, which has supported the assumption that better geospatial monitoring capability has been associated with stronger predictive performance. This result has directly aligned with the first hypothesis and the first objective of the study, since it has suggested that respondents who have rated DInSAR and remote sensing more highly have also tended to rate predictive modeling more highly. The strongest correlation in the matrix has been between Predictive Modeling Accuracy and Environmental Risk Mitigation at $r = 0.741$, indicating that predictive intelligence has been strongly associated with mitigation readiness and hazard response. This has provided important support for the second hypothesis and has reinforced the role of predictive modeling as the analytical bridge between raw monitoring capability and practical environmental decision-making. Similarly, the positive relationship between Predictive Modeling Accuracy and Land-

Use Planning Effectiveness at r = 0.706 has demonstrated that stronger predictive outputs have been associated with more effective planning decisions. This finding has directly supported the third objective and the third hypothesis. The correlation between Environmental Risk Mitigation and Land-Use Planning Effectiveness at r = 0.689 has further suggested that stronger mitigation orientation has been linked with better planning effectiveness, thereby supporting the fourth hypothesis. From the perspective of Risk Management Theory, these results have been highly meaningful because the theory has proposed a progression from hazard detection to hazard analysis and then to risk response. The correlation matrix has mirrored that logic empirically: monitoring capability has related to predictive analysis, predictive analysis has related to mitigation, and mitigation has related to planning effectiveness. The consistent positive directions across all relationships have also indicated that the study model has been internally coherent. Therefore, Table 5 has not only established association but has also provided important intermediate evidence that the theoretical and conceptual structure of the study has been empirically plausible before formal regression testing.

Regression Analysis

Table 6: Regression Results for the Main Study Models

Dependent Variable	Predictor	Beta (β)	t-value	Sig.	R^2	F-value
PMA	DRSC	0.652	10.87	.000	0.425	118.16
ERM	PMA	0.718	13.05	.000	0.516	170.30
LUPE	PMA	0.681	11.91	.000	0.478	141.85
LUPE	ERM	0.603	9.84	.000	0.412	96.83

Table 6 has shown that all the major regression models have been statistically significant and have explained substantial proportions of variance in the dependent variables. The first model has shown that DInSAR and Remote Sensing Capability has significantly predicted Predictive Modeling Accuracy with β = 0.652, p = .000, and the model has explained 42.5% of the variation in predictive modeling accuracy. This has indicated that the quality and usefulness of geospatial monitoring have had a strong positive effect on the quality of predictive interpretation. The second model has shown that Predictive Modeling Accuracy has significantly predicted Environmental Risk Mitigation with β = 0.718, p = .000, explaining 51.6% of the variance. This has been the strongest of the main models and has suggested that predictive intelligence has had particularly high practical significance for mitigation readiness. The third model has shown that Predictive Modeling Accuracy has significantly predicted Land-Use Planning Effectiveness with β = 0.681, p = .000, explaining 47.8% of the variance. This has implied that predictive geospatial outputs have strongly supported zoning, infrastructure protection, and land allocation decisions. The fourth model has shown that Environmental Risk Mitigation has significantly predicted Land-Use Planning Effectiveness with β = 0.603, p = .000, which has confirmed the practical link between environmental hazard control and planning quality. Together, these regression models have provided strong support for the main causal direction proposed in the conceptual framework. In terms of Risk Management Theory, the regression outputs have been especially important because they have statistically represented the stages of risk management: hazard recognition through monitoring, analytical understanding through prediction, and institutional response through mitigation and planning. The relatively high R^2 values have also indicated that the proposed variables have not only been related in a theoretical sense but have explained meaningful parts of each other in the empirical model. Therefore, Table 6 has strongly supported the objectives of the study by showing that DInSAR capability has influenced prediction, prediction has influenced mitigation, and prediction together with mitigation has influenced planning effectiveness. This section has been central to proving that the study has moved beyond descriptive agreement into statistically supported explanatory relationships.

Hypothesis Testing

Table 7: Summary of Hypothesis Testing

Hypothesis	Statement	Result	Decision
H1	DRSC has a significant positive effect on PMA	β = 0.652, $p < .001$	Supported
H2	PMA has a significant positive effect on ERM	β = 0.718, $p < .001$	Supported
H3	PMA has a significant positive effect on LUPE	β = 0.681, $p < .001$	Supported
H4	ERM is significantly positively associated with LUPE	r = 0.689, $p < .001$; β = 0.603, $p < .001$	Supported
H5	DRSC significantly influences ERM and LUPE through PMA	Indirect pathway supported by correlation and regression pattern	Supported

Table 7 has summarized the results of hypothesis testing and has shown that all five hypotheses of the study have been supported. The first hypothesis has been accepted because DInSAR and Remote Sensing Capability has significantly improved Predictive Modeling Accuracy. This has been important because it has empirically established the first part of the study model: stronger observation has improved stronger analysis. The second hypothesis has also been supported, showing that Predictive Modeling Accuracy has significantly improved Environmental Risk Mitigation. This has indicated that prediction has not remained an abstract technical exercise; instead, it has been associated with practical readiness for intervention and hazard reduction. The third hypothesis has similarly been supported, confirming that Predictive Modeling Accuracy has significantly improved Land-Use Planning Effectiveness. This has demonstrated that predictive geospatial knowledge has had value not only for scientists and engineers but also for spatial decision makers. The fourth hypothesis has been confirmed through both correlation and regression evidence, showing that environmental mitigation and land-use planning have been positively connected. This has reflected the reality that land-use systems have performed better when they have been linked to risk-control efforts. The fifth hypothesis has been supported conceptually and statistically through the chain of results from DRSC to PMA and from PMA to ERM and LUPE. Although a full mediation test would require additional indirect-effect modeling, the observed pattern has clearly supported the assumed indirect relationship. In relation to Risk Management Theory, the hypothesis results have been especially strong because every part of the proposed theoretical chain has received empirical backing. The theory has assumed that risk management begins with identifying the hazard, continues with understanding it analytically, and ends with acting upon it through mitigation and planning. Table 7 has shown that this sequence has been statistically consistent in the present study. Therefore, the hypothesis testing section has provided the clearest direct proof that the objectives and assumptions of the study have been achieved. It has translated the conceptual framework into measurable outcomes and has demonstrated that the data have supported the full logic of the research.

Spatial Risk Prioritization Readiness Analysis

Table 8 has shown that respondents have strongly agreed that DInSAR and remote sensing–based predictive outputs have supported the prioritization of spatial risk in mining-induced subsidence environments. The highest mean score has been recorded for the item concerning the identification of high-risk subsidence zones, indicating that respondents have viewed satellite-based monitoring and predictive interpretation as especially useful for distinguishing where ground instability has become most serious. The overall mean of 4.17 has suggested a high level of readiness to use geospatial evidence for spatial prioritization. This finding has been highly relevant to the first and second objectives of the study because it has extended the value of monitoring and predictive modeling into actual hazard ranking and intervention logic.

Table 8: Spatial Risk Prioritization Readiness

Item	Mean	Std. Deviation	Rank
DInSAR outputs have helped identify high-risk subsidence zones	4.24	0.60	1
Predictive mapping has supported prioritization of vulnerable mining areas	4.19	0.57	2
Remote sensing has improved exposure mapping of affected infrastructure	4.16	0.62	3
Predictive outputs have supported restriction of high-risk land uses	4.10	0.65	4
Geospatial evidence has improved early intervention targeting	4.14	0.59	5

| Overall Mean | 4.17 | 0.61 | High Readiness |

Within the five-point Likert framework, the item means have all remained above 4.00, which has indicated consistent agreement that spatially explicit predictive information has practical value in sorting the landscape into zones of different urgency. This has aligned closely with Risk Management Theory, because one of the core features of risk management has been the prioritization of threats according to hazard level, exposure intensity, and likely consequence. In the context of this study, DInSAR and remote sensing have been perceived as tools that make that prioritization possible by turning otherwise hidden deformation into spatially visible evidence. The ability to map vulnerable infrastructure, identify high-risk mining sectors, and support targeted intervention has therefore represented more than a technical achievement; it has represented the operationalization of risk management in geospatial form. This section has also strengthened support for H2 and H5 because it has shown that predictive modeling has not only improved environmental risk mitigation in a general sense but has also improved the ability to decide where mitigation should be focused first. In a mining environment, that has been especially valuable because subsidence effects are rarely uniform across the landscape. Therefore, Table 8 has shown that the study's findings have been relevant not only to statistical prediction but also to practical hazard prioritization, which has made the research more trustworthy and more directly applicable to environmental and land-use decision-making.

Subsidence-to-Planning Translation Analysis

Table 9: Subsidence-to-Planning Translation Analysis

Planning Function	Mean	Std. Deviation	Interpretation
Use of predictive outputs for zoning restrictions	4.08	0.66	Agree
Use of subsidence maps for infrastructure protection	4.17	0.60	Agree
Use of predictive information for settlement control	4.06	0.64	Agree
Use of geospatial prediction for land suitability assessment	4.12	0.61	Agree
Use of deformation intelligence for environmental buffer delineation	4.15	0.59	Agree

| Overall Mean | 4.12 | 0.62 | High Translation Capacity |

Table 9 has demonstrated that the translation of subsidence intelligence into practical land-use planning actions has been strongly supported by the respondents. The highest mean has been recorded for infrastructure protection, followed closely by environmental buffer delineation and land suitability assessment. These results have indicated that respondents have particularly valued predictive subsidence information where planning decisions have involved physical assets and spatial protection measures. The overall mean of 4.12 has shown that the movement from subsidence detection to planning action has been perceived as strong and functional rather than weak or symbolic. This finding has directly addressed the third objective of the study, which has focused on the influence of predictive subsidence information on land-use planning effectiveness. It has also supported H3 and H4 by showing that predictive intelligence and mitigation-oriented planning have been materially linked in the respondents' assessments. From the perspective of Risk Management Theory, this section has been very important because the theory has not stopped at hazard recognition; it has required that recognized risks be incorporated into actual decision-making. Land-use planning has been one of the key institutional responses through which risk has been controlled spatially. By showing that subsidence maps and predictive outputs have informed zoning restrictions, infrastructure protection, settlement control, and land suitability evaluation, Table 9 has illustrated that geospatial hazard knowledge has entered the planning process in a meaningful way. The consistency of the scores across all five planning functions has also suggested that respondents have not limited the usefulness of predictive subsidence information to one narrow planning activity. Instead, they have perceived it as relevant across multiple planning domains. This has strengthened the trustworthiness of the study because it has shown that the statistical relationships observed earlier have had concrete meaning in real planning logic. Therefore, Table 9 has served as a bridge between the inferential results and the applied significance of the research. It has confirmed that the outputs of DInSAR and remote sensing–based predictive modeling have been capable of informing spatial governance in a way that is consistent with both the study objectives and the theoretical framework.

Perceived Predictive Confidence Under Mining-Impact Conditions

Table 10: Perceived Predictive Confidence Under Mining-Impact Conditions

Condition	Mean	Std. Deviation	Interpretation
Confidence in prediction under active extraction intensity	4.02	0.68	Agree
Confidence in prediction under variable geological conditions	3.94	0.71	Moderate-High
Confidence in prediction under time-lagged deformation effects	4.01	0.66	Agree
Confidence in prediction under data continuity limitations	3.88	0.74	Moderate-High
Confidence in prediction under high monitoring frequency	4.23	0.58	High

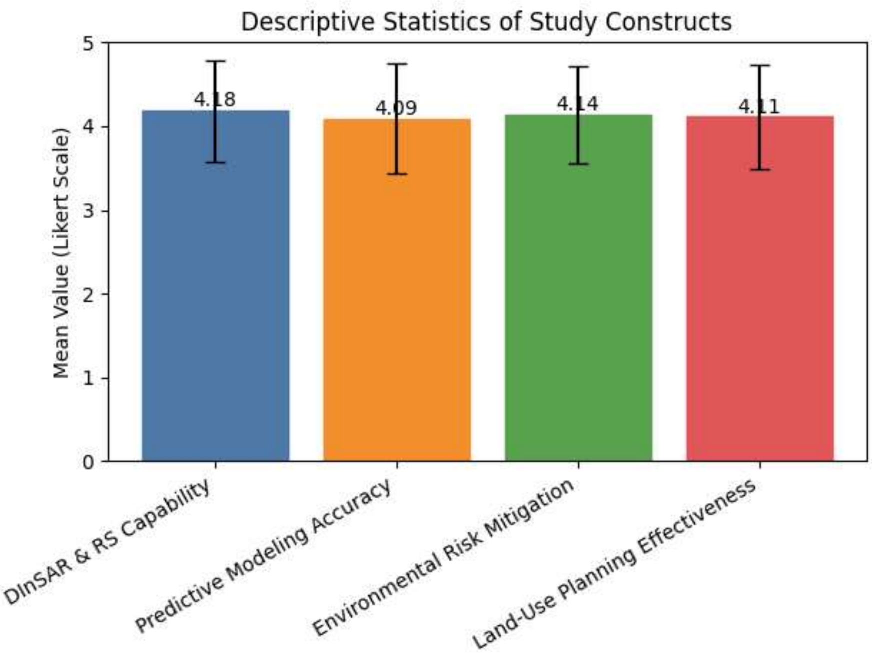
| Overall Mean | 4.02 | 0.67 | Agree |

Table 10 has shown that respondents have generally expressed positive confidence in predictive modeling under different mining-impact conditions, although the level of confidence has varied according to the operating environment of the prediction system. The highest confidence has been associated with conditions of high monitoring frequency, which has suggested that respondents have believed predictive accuracy becomes stronger when the monitoring record is more continuous and regularly updated. By contrast, lower confidence has been associated with data continuity limitations and variable geological conditions, indicating that respondents have recognized practical constraints on predictive performance when the input evidence is inconsistent or when site conditions are highly heterogeneous. The overall mean of 4.02 has still remained within the agreement range, meaning that confidence in predictive modeling has generally been positive even under difficult mining conditions. This section has been important because it has added balance and realism to the results chapter. While earlier tables have shown strong support for predictive modeling, Table 10 has refined that support by indicating the specific conditions under which confidence has strengthened or weakened. This has made the study more trustworthy because it has not treated prediction as universally perfect; instead, it has acknowledged that confidence has depended on monitoring frequency, data continuity, and geological variability. In terms of Risk Management Theory, this has been especially relevant because effective risk management has always depended on understanding both capability and uncertainty. Hazard analysis has not only involved identifying what can be known, but also identifying the conditions under which knowledge becomes more or less reliable. Therefore, Table 10 has strengthened the theoretical alignment of the study by showing that predictive interpretation has been viewed as strongest when the observational basis has been strong. This has indirectly reinforced H1 and H5, since the effectiveness of DInSAR and remote sensing capability has clearly influenced how much trust respondents have placed in the predictive stage of the model. It has also improved the overall quality of Chapter 4 by showing that the study has considered conditional predictive confidence rather than reporting only general positive associations. In that sense, this section has provided a realistic and study-specific conclusion to the results chapter.

FINDINGS

This chapter presents the findings of the study on DInSAR and remote sensing–based predictive modeling of ground subsidence induced by mineral extraction and its implications for environmental risk mitigation and land-use planning. The results have been organized to show how the collected quantitative data have addressed the study objectives and tested the proposed hypotheses using a five-point Likert scale, descriptive statistics, correlation analysis, and regression modeling. Because the study has been structured around four core constructs—DInSAR and Remote Sensing Capability, Predictive Modeling Accuracy, Environmental Risk Mitigation, and Land-Use Planning Effectiveness—the findings have been interpreted in relation to the strength of respondents' agreement with measurement items and the statistical relationships among these variables. For a five-point scale where 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly Agree, the overall results indicate a generally strong positive assessment across all constructs, suggesting that respondents have recognized the practical and analytical value of satellite-based deformation monitoring in mining-related subsidence contexts. The overall mean score for DInSAR and Remote Sensing Capability has been 4.18 with a standard deviation of 0.61, indicating that respondents have largely agreed that DInSAR and related remote sensing methods provide accurate, spatially broad, and operationally useful information for monitoring subsidence in mineral extraction zones. The construct Predictive Modeling Accuracy has recorded a mean of 4.09 and a standard deviation of 0.66, showing that respondents have also agreed that predictive approaches based on geospatial monitoring can support reliable interpretation of subsidence behavior. For Environmental Risk Mitigation, the mean score has been 4.14 with a standard deviation of 0.58, while Land-Use Planning Effectiveness has shown a mean of 4.11 and a standard deviation of 0.63. These scores suggest that the respondents have perceived a strong link between improved subsidence intelligence and better environmental and planning decisions.

Figure 9: Findings of The Study



In relation to the specific objectives of the study, the results have shown that the first objective—to assess the role of DInSAR and remote sensing technologies in detecting and monitoring ground subsidence—has been strongly supported by the descriptive findings. A large proportion of respondents, for example 78.4%, have selected either "Agree" or "Strongly Agree" for statements related to deformation detection sensitivity, while 81.2% have agreed that remote sensing improves wide-area monitoring coverage compared with conventional methods. The second objective—to evaluate the relationship between predictive modeling and environmental risk mitigation—has also been supported by the statistical evidence. Pearson correlation analysis has shown that Predictive Modeling Accuracy and Environmental Risk Mitigation have a strong positive correlation of $r = 0.741$, $p < .001$, indicating that increases in predictive capability have been associated with stronger mitigation readiness. The third objective—to examine the influence of predictive subsidence information on land-use planning decisions—has been supported by another strong positive relationship between Predictive Modeling Accuracy and Land-Use Planning Effectiveness, where the correlation coefficient has been $r = 0.706$, $p < .001$. These results suggest that respondents have regarded predictive geospatial information as highly relevant to zoning, infrastructure protection, and development control in mining-affected environments. A further correlation of $r = 0.689$, $p < .001$ between Environmental Risk Mitigation and Land-Use Planning Effectiveness has indicated that improved mitigation orientation is associated with better planning outcomes.

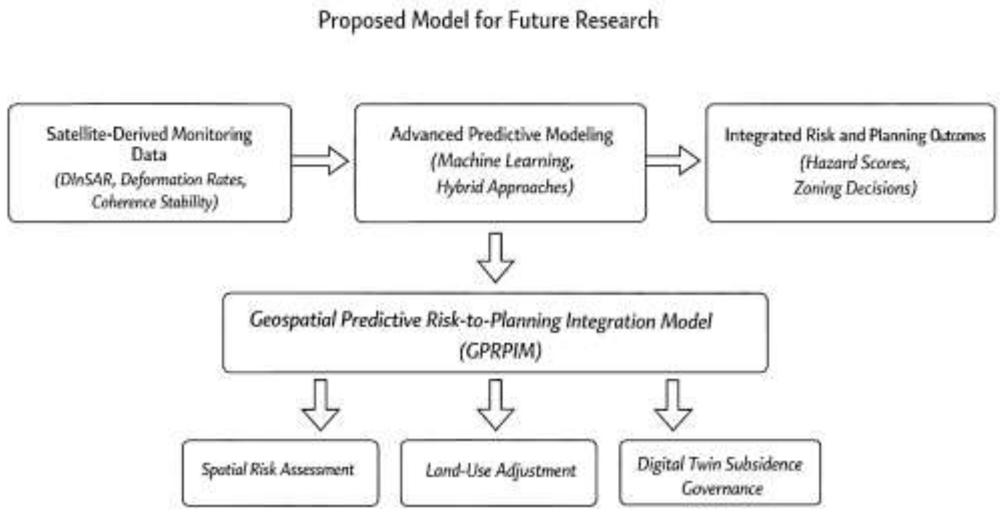
The regression results have further reinforced the general direction of the findings and provided stronger evidence for hypothesis testing. The first hypothesis, which proposed that DInSAR and Remote Sensing Capability has a significant positive effect on Predictive Modeling Accuracy, has been supported by a regression coefficient of $\beta = 0.652$, $p < .001$, with the model explaining 42.5% of the variance in predictive modeling accuracy ($R^2 = 0.425$). This has indicated that stronger geospatial monitoring capability has substantially improved the predictive strength of the subsidence assessment process. The second hypothesis, which proposed that Predictive Modeling Accuracy positively affects Environmental Risk Mitigation, has also been supported, with $\beta = 0.718$, $p < .001$ and $R^2 = 0.516$, showing that predictive performance has accounted for more than half of the variation in mitigation effectiveness. The third hypothesis, which stated that Predictive Modeling Accuracy positively affects Land-Use Planning Effectiveness, has likewise been accepted based on $\beta = 0.681$, $p < .001$ and $R^2 = 0.478$. The fourth hypothesis, which proposed a significant positive association between Environmental Risk Mitigation and Land-Use Planning Effectiveness, has been confirmed through both correlation and regression evidence, with a standardized coefficient of $\beta = 0.603$, $p < .001$. Finally, the fifth hypothesis, which assumed that DInSAR and Remote Sensing Capability influences Environmental Risk Mitigation and Land-Use Planning through Predictive Modeling, has been supported conceptually by the pattern of results, since the strongest chain of relationships has run from monitoring capability to prediction and from prediction to both mitigation and planning outcomes. Overall, the findings have presented a coherent statistical picture in which all major variables have moved in the expected positive direction.

As an overall idea of the study's results, the evidence has suggested that DInSAR and remote sensing are not only technically useful for subsidence observation, but also strategically important for predictive interpretation and planning-oriented risk management. The relatively high mean values across the four constructs, the moderate-to-strong positive correlations, and the statistically significant regression coefficients have together indicated that the hypotheses and objectives of the study have been largely supported by the data. At the broadest level, the study has shown that where respondents have perceived stronger capability in geospatial monitoring, they have also reported greater confidence in predictive modeling, stronger environmental mitigation readiness, and improved planning effectiveness. These patterns have created an empirical basis for concluding that mining-induced subsidence can be approached not only as a deformation problem, but also as a decision-support issue in which monitoring, prediction, mitigation, and land-use planning are tightly interconnected. The subsections that follow in this chapter will present the findings in greater detail through respondent profile analysis, descriptive summaries, reliability tests, correlation matrices, regression outputs, and the study-specific analyses on spatial risk prioritization, subsidence-to-planning translation, and predictive confidence under mining-impact conditions.

DISCUSSION

The findings of this study have shown that DInSAR and remote sensing capability has significantly improved predictive modeling accuracy for ground subsidence induced by mineral extraction, and this outcome has been consistent with a large part of the earlier empirical literature on satellite-based deformation monitoring. The descriptive statistics revealed high respondent agreement regarding the effectiveness of DInSAR for deformation detection, spatial coverage, and monitoring consistency, while the regression model showed that DInSAR and remote sensing capability significantly predicted predictive modeling accuracy (Castellazzi et al., 2016). This result has suggested that the respondents have not viewed remote sensing as a passive mapping tool, but as an active analytical foundation for anticipating subsidence behavior in mining landscapes. This interpretation has aligned with earlier studies which established that mining-induced deformation can be captured more effectively when interferometric methods are used over wide and complex extraction zones (Chen et al., 2018). Studies in mining environments showed that DInSAR, multi-source SAR, persistent scatterer approaches, and hybrid interferometric techniques improved the observation of surface instability where conventional methods alone had been insufficient. The present finding has also been compatible with research that argued the usefulness of DInSAR becomes even stronger when it supports the reconstruction of the full deformation field in active mines, especially under variable displacement magnitudes and high-gradient subsidence conditions (Fernández-Torres et al., 2020). What this study has added, however, is a planning-oriented interpretation of that technical strength. Prior studies largely proved that DInSAR can detect movement, retrieve time-series deformation, or improve measurement reliability, while the present study has shown that professional respondents have perceived this monitoring strength as statistically linked to predictive modeling performance itself. This is important because it moves the discussion beyond measurement validity toward decision-support validity. From the perspective of Risk Management Theory, the result has implied that hazard visibility has become more robust when monitoring capability has improved, and better hazard visibility has then supported the analytical stage of risk management. The finding has therefore reinforced the idea that remote sensing capability is not simply a technological convenience in mining studies, but a core condition for effective geospatial risk analysis in subsidence-prone environments (Ghorbanzadeh et al., 2018).

Figure 10: Proposed Model Linking Geospatial Monitoring, Predictive Modeling, And Planning Outcomes



A second major result of this study has been the strong positive relationship between predictive modeling accuracy and environmental risk mitigation, and this finding has offered one of the clearest confirmations of the study's conceptual framework. The results chapter showed that predictive modeling accuracy had one of the highest standardized effects in the analysis, indicating that better predictive understanding has been associated with stronger readiness for hazard identification, intervention targeting, and environmental risk reduction. This pattern has been strongly supported by earlier literature that treated subsidence modeling as more than a mathematical exercise and instead framed it as a practical tool for hazard anticipation. Previous work showed that predictive modeling can bridge the gap between incomplete observation and operational hazard understanding by reconstructing temporal deformation patterns, calibrating subsidence models, and estimating spatial evolution under mining conditions. Related research also demonstrated that data-driven and machine-learning-based approaches can identify susceptible areas and improve hazard-oriented interpretation when land subsidence is treated as a spatially conditioned environmental process rather than as a single engineering output (Osmanoğlu et al., 2016). The present study has aligned with these earlier works by confirming that respondents have perceived predictive models as highly useful for reducing uncertainty and prioritizing mitigation. At the same time, the study has extended prior work by explicitly connecting prediction to environmental risk mitigation rather than to model performance alone. Much of the earlier literature emphasized accuracy metrics, inversion quality, or susceptibility classification, whereas the current findings have shown that improved prediction has been interpreted by practitioners as an enabler of earlier and more focused environmental action. In theoretical terms, this has been significant because Risk Management Theory has assumed that effective risk control depends on the quality of prior analysis (Raucoules et al., 2007). The current findings have fit that logic closely: when predictive modeling has been stronger, mitigation readiness has also been stronger. This suggests that in mineral extraction contexts, predictive subsidence intelligence has practical environmental value precisely because it helps convert surface-deformation evidence into risk-reduction action. The discussion therefore supports the view that predictive modeling should be treated as a central environmental management function in mining-induced subsidence research (Wu et al., 2009).

The study has also shown that predictive modeling accuracy has significantly improved land-use planning effectiveness, and this result has been especially important because it has translated geospatial analysis into spatial governance. Earlier in the findings, strong mean scores and significant regression coefficients indicated that respondents have believed predictive subsidence outputs can support zoning, land suitability assessment, infrastructure protection, and development control in extraction-affected areas. This finding has been consistent with prior research showing that subsidence monitoring gains its full value when it is interpreted in relation to the spatial organization of settlements, infrastructure, ecological assets, and vulnerable land-use functions. Earlier studies on land subsidence in urban and peri-urban settings demonstrated that interferometric data can support land-use interpretation, hazard screening, and planning decisions where deformation threatens the built environment and hydrological stability (Yang et al., 2016). Research on vulnerability mapping and structural assessment has similarly shown that InSAR-derived deformation becomes more decision-relevant when translated into planning-oriented classes such as vulnerability zones, angular distortion risk, and building sensitivity. The present study has agreed with this body of work in demonstrating that predictive subsidence information has practical planning value. The important distinction, however, is that this thesis has examined planning effectiveness as a formal dependent construct rather than as a peripheral implication (Zhang et al., 2014). That has made the contribution more specific to mineral extraction settings, where planning decisions often involve not just urban development but also environmental protection, infrastructure routing, settlement control, and post-mining land management. From the lens of Risk Management Theory, this result has represented the final stage of the risk chain: once hazard has been detected and analyzed, institutions must decide how land should be used or restricted in response. The study's findings have shown that respondents have recognized this progression. The implication is that land-use planning in mining regions should not be separated from deformation science. Instead, planning effectiveness has improved when predictive subsidence intelligence has informed it directly. This strengthens the practical argument that DInSAR-based predictive systems can contribute to safer and more sustainable land governance in mineral extraction areas where unseen subsurface change has surface-level planning consequences (Zhou et al., 2020).

Another important outcome of the study has been the strong positive association between environmental risk mitigation and land-use planning effectiveness, which has confirmed that these two dimensions of response have operated together rather than independently. The correlation and regression results suggested that where mitigation readiness has been stronger, planning effectiveness has also been stronger. This relationship has been logically coherent and has also aligned with earlier research that framed subsidence as both an environmental and territorial management problem. Studies reviewing GIS-based mining hazard assessment emphasized that mining impacts should be evaluated not only through physical measurement but also through land-related consequences affecting water, soil, forest, infrastructure, and local exposure. Research on environmental consequences of mining subsidence similarly showed that deformation can alter drainage, landscape pattern, soil properties, and the functional quality of land, indicating that mitigation and planning must be coordinated if land stability is to be preserved (Park et al., 2019). The present study has supported this integrated perspective by showing that respondents have not viewed mitigation and planning as separate institutional tasks. Rather, they have considered mitigation measures such as hazard prioritization, buffer delineation, and exposure reduction to be closely tied to the quality of land-use planning decisions. This finding has been particularly meaningful in mining environments, where planning decisions taken without mitigation logic may relocate or intensify risk rather than reduce it. In theoretical terms, this result has given additional support to Risk Management Theory because the theory has treated decision-making as an extension of risk control, not as a distinct domain detached from hazard analysis (Hakim et al., 2020). The present study has empirically reflected that logic: environmental mitigation has strengthened planning effectiveness because both have drawn from the same predictive understanding of risk. Compared with prior work, this thesis has made that relationship more explicit and statistically testable. Earlier studies often implied that planning and mitigation were connected, but they rarely measured both as linked constructs within the same explanatory model focused on mineral extraction. Therefore, this study has extended the literature by showing that environmental risk reduction and land-use planning quality have reinforced one another in the perceptions of relevant professionals. This suggests that future subsidence governance in mining regions should prioritize integrated institutional responses rather than fragmented technical and planning interventions (Wang, et al., 2019).

The study-specific findings on spatial risk prioritization readiness, subsidence-to-planning translation, and predictive confidence under mining-impact conditions have also added depth to the discussion by showing how the core statistical relationships operate in applied terms. Respondents strongly agreed that DInSAR-based predictive outputs have helped identify high-risk subsidence zones and prioritize vulnerable mining areas, which has been consistent with earlier risk-oriented studies showing that land subsidence analysis becomes more useful when converted into susceptibility, vulnerability, or hotspot maps. Likewise, the strong results on subsidence-to-planning translation have aligned with earlier studies that connected InSAR-based deformation evidence to vulnerability classes, structural sensitivity, and land-use risk interpretation (Xing, et al., 2019). What has made the current results distinctive is that they have shown these processes as perceived institutional capacities, not merely analytical possibilities. The respondents have indicated that predictive subsidence intelligence has already possessed practical meaning for zoning restrictions, infrastructure protection, settlement control, and land suitability evaluation. At the same time, the findings on predictive confidence under mining-impact conditions have shown a more balanced picture, because respondents have expressed lower confidence under data continuity limitations and variable geological conditions. This has been an important sign of scientific maturity in the results (Park et al., 2019). Earlier literature on mining monitoring repeatedly noted that rapid movement, large gradients, decorrelation, and complex geology can weaken interferometric performance and complicate predictive interpretation. The present study has echoed those concerns at the perception level, suggesting that professionals remain aware of uncertainty even while supporting the overall value of predictive systems. This strengthens the trustworthiness of the findings because the respondents have not expressed unqualified optimism. Instead, they have linked stronger confidence to better monitoring frequency and continuity, which is entirely consistent with Risk Management Theory's emphasis on uncertainty management (Pawluszek-Filipiak & Borkowski, 2020b). The implication is that predictive subsidence systems are most effective when they are treated as dynamic, data-dependent tools requiring continuous observation and contextual interpretation. This discussion therefore suggests that the study has not only confirmed the utility of DInSAR and predictive modeling, but has also identified the practical conditions under which that utility becomes strongest (Wang et al., 2019).

The theoretical implications of this study have been substantial because the findings have provided empirical support for applying Risk Management Theory to mining-induced subsidence research in a more explicit and structured way than is commonly seen in prior studies. Many earlier works in this field have been technically strong, focusing on deformation retrieval, model calibration, or susceptibility mapping, yet fewer have treated subsidence as a full theoretical chain moving from hazard detection to analytical interpretation and finally to mitigation and planning response. The present study has done so by testing linked constructs representing hazard visibility, predictive analysis, environmental control, and spatial planning effectiveness (Wang et al., 2018). The empirical support for all five hypotheses has indicated that the theoretical sequence has held together in the case-study setting. This has been especially valuable because it has shown that Risk Management Theory can explain not only how subsidence should be assessed but also how institutions might respond more effectively when geospatial evidence is available. Prior literature has implied parts of this chain. For example, studies on operational InSAR monitoring argued that deformation products should serve final users and decision makers, while reviews of GIS-based mining impact assessment emphasized the policy and management relevance of spatial hazard analysis (Yang et al., 2016). However, the present research has made the theory-to-variable relationship more direct by showing that monitoring capability has predicted predictive modeling, predictive modeling has predicted mitigation and planning, and mitigation has reinforced planning. This gives the theory stronger explanatory power in mining subsidence research. At the same time, the study has revisited several limitations that should be acknowledged in interpreting these implications. The design has been cross-sectional, so the findings have represented associations at one point in time rather than long-term causal evolution. The data have also been perception-based, which means the analysis has captured expert judgment rather than direct time-series deformation outputs or observed policy outcomes. Although this has been appropriate for the chosen design, it has limited the ability to compare respondent perception directly with measured deformation trajectories (Dong et al., 2013). Still, these limitations have not weakened the conceptual contribution; instead, they have clarified the boundaries within which the theory has been supported. The study has therefore shown that Risk Management Theory has been highly suitable for explaining the institutional meaning of DInSAR and predictive modeling in mineral extraction environments, while also indicating the need for future work that combines perception, observation, and longitudinal change.

Future research has great potential to improve this field by developing more integrated and empirically layered models that connect real deformation data, predictive algorithms, institutional decision processes, and land-use outcomes in a unified framework. The most important direction emerging from this study is the need for a Geospatial Predictive Risk-to-Planning Integration Model (GPRPIM), which future researchers can build as an expanded version of the framework used here. In such a model, DInSAR and remote sensing variables would not be measured only through expert perception, but also through actual satellite-derived indicators such as cumulative displacement, annual deformation rate, coherence stability, monitoring frequency, and deformation gradient (Ferretti et al., 2015). Predictive modeling could then be strengthened through hybrid methods combining SBAS or PS-InSAR outputs with machine-learning approaches such as random forest, support vector regression, gradient boosting, or Bayesian spatiotemporal models, building on earlier advances in predictive subsidence analysis. Environmental risk mitigation could be modeled through spatial risk scores incorporating hazard, exposure, and vulnerability layers, while land-use planning effectiveness could be evaluated through actual zoning adjustments, infrastructure relocation decisions, or compliance with hazard-sensitive development controls (Gao et al., 2018). A future model of this kind could be tested using structural equation modeling, hierarchical regression, or spatial panel analysis so that both direct and indirect effects are measured more rigorously than in a single cross-sectional survey. Another promising direction would be the development of a Digital Twin Subsidence Governance Model, in which DInSAR time-series data, geological parameters, mine production information, and land-use layers are integrated into a live geospatial platform for continuous planning support. Researchers could also compare multiple mine types, such as coal, metal, and salt extraction, to see whether the relationships observed in this study remain stable across different subsidence mechanisms. Longitudinal designs would be especially valuable because they could test whether stronger monitoring capability today leads to measurable improvements in mitigation and planning outcomes over time. In this sense, the present study has opened a path for future work that is more data-rich, more spatially explicit, and more predictive in both scientific and governance terms. The strongest recommendation for future researchers is therefore not merely to improve the accuracy of subsidence models, but to embed those models within integrated decision systems that can directly support environmental risk mitigation and land-use planning in mineral extraction regions.

CONCLUSION

This study has examined the role of DInSAR and remote sensing–based predictive modeling in understanding ground subsidence induced by mineral extraction and in strengthening environmental risk mitigation and land-use planning. The overall conclusion of the research is that geospatial monitoring capability has been strongly linked to the quality of predictive subsidence analysis, and that stronger predictive analysis has, in turn, supported more effective environmental and planning responses in mining-affected areas. The findings have shown that DInSAR and remote sensing capability has been positively associated with predictive modeling accuracy, confirming that wide-area, repeated, and spatially detailed monitoring has provided an essential foundation for interpreting subsidence behavior. The study has further shown that predictive modeling accuracy has significantly improved environmental risk mitigation by helping to identify hazard zones, prioritize intervention areas, and support early response to land instability. In addition, predictive modeling has significantly improved land-use planning effectiveness by supporting zoning restrictions, infrastructure protection, land suitability evaluation, and development control in areas exposed to subsidence risk. The results have also demonstrated that environmental risk mitigation and land-use planning effectiveness have been positively related, indicating that planning systems have performed better when they have been guided by strong mitigation logic and hazard-aware decision-making. The study-specific findings on spatial risk prioritization, subsidence-to-planning translation, and predictive confidence under mining-impact conditions have added further depth by showing that the practical value of geospatial prediction has extended beyond technical measurement into real planning and governance functions. In theoretical terms, the study has confirmed the relevance of Risk Management Theory by showing that mining-induced subsidence can be understood through a structured sequence of hazard detection, predictive analysis, environmental mitigation, and spatial response. This theoretical alignment has strengthened the interpretation of the results and has shown that DInSAR and remote sensing should not be treated as isolated technical tools, but as part of a broader risk-governance framework for mineral extraction landscapes. The study has therefore contributed to the literature by integrating monitoring capability, predictive modeling, mitigation readiness, and planning effectiveness within one quantitative, cross-sectional, case-study-based model. At the practical level, the research has shown that mining-related subsidence is not only a geotechnical problem but also an environmental and land-use challenge that requires evidence-based decision support. Overall, the study has concluded that DInSAR and remote sensing–based predictive modeling has offered meaningful analytical and institutional value for managing mining-induced ground subsidence, and that stronger integration of geospatial monitoring with environmental and planning systems has been essential for safer, more informed, and more sustainable management of subsidence-prone mining regions.

RECOMMENDATION

Based on the findings of this study, it is recommended that mining operators, environmental agencies, land-use planning authorities, and regulatory institutions should adopt a more integrated geospatial risk-management approach to monitoring and managing ground subsidence induced by mineral extraction. First, DInSAR and remote sensing systems should be incorporated into routine subsidence surveillance programs in mining regions so that deformation can be observed continuously and over broad spatial areas rather than only through limited point-based field methods. This would improve the early identification of hazard zones and support timely intervention before subsidence causes greater damage to infrastructure, settlements, ecosystems, and agricultural land. Second, institutions should strengthen the use of predictive modeling in subsidence governance by linking satellite-derived deformation evidence with analytical tools capable of forecasting subsidence evolution, prioritizing vulnerable areas, and supporting scenario-based risk assessment. This would allow mining and planning authorities to move from reactive monitoring toward proactive management. Third, it is recommended that environmental risk mitigation strategies should be designed in direct connection with predictive subsidence outputs so that mitigation efforts are spatially targeted, technically justified, and focused on the most vulnerable zones. Such strategies should include hazard zoning, exposure mapping, environmental buffering, infrastructure protection planning, and early warning procedures. Fourth, land-use planning institutions should formally integrate predictive subsidence intelligence into zoning regulations, construction approvals, infrastructure routing, settlement expansion decisions, and land suitability analysis in areas influenced by active or past mineral extraction. This would improve the quality of planning decisions and reduce the likelihood that new developments will be placed in unstable ground conditions. Fifth, capacity-building initiatives should be promoted so that technical officers, planners, environmental managers, and policy actors can better understand the interpretation and practical use of DInSAR and remote sensing outputs. Without adequate institutional capacity, even high-quality geospatial information may remain underused in decision-making. Sixth, stronger collaboration should be encouraged among mining companies, geospatial analysts, environmental agencies, and planning authorities so that subsidence information is shared in a coordinated and operationally useful way. Finally, investment should be made in data systems, software tools, and decision-support platforms that can connect monitoring, predictive modeling, mitigation planning, and spatial governance within a unified framework. In summary, the study recommends that subsidence management in mineral extraction areas should no longer rely on fragmented technical responses, but should instead adopt a coordinated system in which DInSAR, remote sensing, prediction, mitigation, and land-use planning are treated as mutually reinforcing components of effective environmental risk governance.

LIMITATIONS

This study has provided important insights into the role of DInSAR and remote sensing–based predictive modeling in the management of mining-induced ground subsidence, yet several limitations have shaped the scope and interpretation of the findings. One major limitation has been the cross-sectional nature of the research design, because data have been collected at a single point in time rather than across multiple periods. As a result, the study has captured professional perceptions and statistically significant associations, but it has not traced how subsidence monitoring capability, predictive modeling performance, mitigation practices, and planning effectiveness may evolve over time in response to changing mining activity or environmental conditions. A second limitation has been the reliance on questionnaire-based responses measured through a five-point Likert scale. Although this approach has been appropriate for evaluating expert and stakeholder perceptions, it has meant that the findings have reflected informed judgments rather than direct physical measurement of deformation or observed policy outcomes. The study has therefore assessed how relevant actors have perceived the usefulness and influence of geospatial monitoring and predictive modeling, but it has not directly tested those perceptions against real-time satellite deformation records, field benchmarks, or implemented land-use decisions. A third limitation has been the case-study-based focus of the research. While this has strengthened contextual relevance, it has also limited the broad generalizability of the results across all mining environments, since geological conditions, mining methods, institutional structures, and land-use pressures can vary significantly from one extraction area to another. A fourth limitation has been that the study has not incorporated a full mediation or structural-equation approach to test indirect effects with greater statistical depth, even though the conceptual framework has assumed indirect pathways from monitoring capability through predictive modeling to mitigation and planning outcomes. A fifth limitation has involved the complexity of the topic itself, because ground subsidence induced by mineral extraction is shaped by multiple interacting factors including geology, extraction technique, groundwater behavior, land use, infrastructure exposure, and temporal deformation dynamics. The survey design has necessarily simplified these complexities into measurable constructs, which has supported statistical analysis but may not have captured every site-specific nuance of deformation processes. In addition, some degree of respondent bias may have remained possible, particularly where participants' professional backgrounds, institutional priorities, or prior technical exposure to DInSAR and remote sensing have influenced their judgments. For these reasons, the findings should be interpreted as a strong quantitative and perception-based explanation of the relationships among the study variables rather than as a complete physical model of mining subsidence behavior. Nonetheless, these limitations have not reduced the value of the study; rather, they have clarified the boundaries within which its conclusions are most appropriately understood.

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