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A review of data analytics techniques in enhancing environmental risk assessments in the U.S. Geology Sector

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Abstract

In an era where environmental risks pose significant challenges to the U.S. geology sector, this paper meticulously explores the integration of data analytics techniques to enhance risk assessments. The study delves into the intricate relationship between geological processes and human activities, underscoring the necessity for advanced analytical methodologies in mitigating environmental risks. The background sets the stage, highlighting the evolving perception of risk and sustainability in geological activities, and the critical role of reliable construction practices and engineering investigations.

The aim of this paper is to synthesize and critically evaluate the current methodologies in data analytics, particularly their impact on reducing environmental risks associated with geological activities. The scope encompasses a detailed examination of the evolution from traditional to modern analytical methods, emphasizing the integration of predictive analytics, machine learning, big data, and Geographic Information Systems (GIS) in geological predictions and risk management.

The main findings reveal a significant advancement in data analytics, marked by the integration of AI and machine learning with traditional geological methods. This fusion enhances the accuracy, efficiency, and comprehensiveness of risk assessments. The study concludes with recommendations for continued integration of advanced data analytics in geological studies, advocating for sustainable and responsible practices. It emphasizes the importance of international collaboration and harmonization of regulatory standards to enhance environmental risk assessments in geology.

This paper provides valuable insights for researchers, policymakers, and practitioners in the field, offering a roadmap for future advancements in geological data analytics and environmental risk management.

Keywords: Data Analytics; Geological Risk Assessment; Environmental Sustainability; Machine Learning; Geographic Information Systems; Predictive Analytics

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1. Introduction

1.1. Overview of Environmental Risks in U.S. Geological Activities

Environmental risks in U.S. geological activities encompass a broad spectrum of concerns, ranging from natural disasters to anthropogenic impacts. The intricate relationship between geological processes and human activities often leads to complex environmental challenges. Sokolov and Sukhov (2023) highlight the criticality of reliable construction practices and the protection of territories from dangerous geological and technogenic processes. They emphasize the importance of high-quality engineering investigations in assessing the impact of construction on environmental safety, particularly in areas prone to geotechnical risks (Sokolov & Sukhov, 2023).

The perception of risk and sustainability in geological activities has evolved, integrating concepts of environmental justice and sustainable development. Souza, Oliveira, and Lollo (2019) delve into this aspect, analyzing the conceptual overlap between environmental justice and sustainable development in geological-geotechnical risk assessment approaches. Their work underscores the need for a holistic view that balances environmental risks with sustainable development goals, ensuring that geological activities do not disproportionately impact vulnerable communities (Souza, Oliveira, & Lollo, 2019).

Landslides represent a significant environmental risk in geological activities, particularly in regions with complex engineering and geological conditions. Kasiyanchuk and Shtohryn (2021) conducted an assessment of ecological risks of landslide damages in the Carpathian region, demonstrating how natural factors like clay flysch formation, fault tectonics, and seismic activity, compounded by human actions, can exacerbate landslide risks. Their study provides a framework for understanding the multifaceted nature of environmental risks in geology, where both natural and anthropogenic factors play a critical role (Kasiyanchuk & Shtohryn, 2021).

In the context of U.S. geological activities, these environmental risks manifest in various forms. The country's diverse geological landscape, from the earthquake-prone areas of the West Coast to the hurricane-impacted regions along the Gulf Coast, presents unique challenges. The integration of data analytics and advanced risk assessment methodologies is crucial in identifying, quantifying, and mitigating these risks. This approach not only aids in the prediction and management of natural disasters but also ensures that geological activities are conducted in an environmentally responsible and sustainable manner.

The interplay between geological activities and environmental risks is further complicated by the evolving regulatory landscape. Policies and regulations play a pivotal role in shaping how geological activities are conducted and how environmental risks are managed. The adherence to these regulations, coupled with proactive risk assessment and management strategies, is essential for minimizing the environmental impact of geological activities.

The overview of environmental risks in U.S. geological activities paints a picture of a dynamic field where natural processes, human activities, and regulatory frameworks intersect. The studies by Sokolov and Sukhov (2023), Souza, Oliveira, and Lollo (2019), and Kasiyanchuk and Shtohryn (2021) collectively underscore the complexity of these risks and the importance of a multifaceted approach in addressing them. As the field continues to evolve, the integration of advanced analytical techniques and sustainable practices will be key in mitigating these risks and ensuring the environmental safety of geological activities.

1.2. Evolution of Data Analytics in Environmental Risk Assessment

The evolution of data analytics in environmental risk assessment, particularly in the field of geology, has been marked by significant advancements in recent years. This evolution is characterized by the integration of diverse analytical techniques and methodologies, aimed at enhancing the accuracy and efficiency of risk assessments in geological activities.

Lyubchich et al. (2019) discuss the integration of data science and statistics in the context of insurance risk assessment, particularly in the face of climate change. Their work highlights the growing need for innovative analytic approaches that transcend traditional disciplinary boundaries, combining statistical, actuarial, and environmental sciences. This multidisciplinary approach is crucial in addressing the complex challenges posed by climate change, which include a range of environmental extremes such as floods, hail, and excessive wind (Lyubchich et al., 2019). The application of these advanced data analytics techniques in environmental risk assessment allows for a more nuanced understanding of the risks associated with geological activities, particularly those exacerbated by climate change.

Chen, Mao, and Zhao (2022) explore the application of Geographic Information Systems (GIS) in environmental monitoring and risk assessment. GIS has become a mainstream tool in various disciplines, including geology, due to its ability to accurately monitor and assess environmental risks. The study by Chen et al. (2022) demonstrates how GIS can be applied in water supply system monitoring, soil heavy metal concentration monitoring, and air quality prediction. The integration of GIS with other technologies, such as remote sensing, provides a powerful tool for assessing environmental risks in geological activities. This technology enables the identification of spatial patterns and the translation of these patterns into measurable targets, thereby enhancing the precision of risk assessments.

Melkov et al. (2022) focus on the temporal and spatial geophysical data analysis in the context of natural hazards and risk assessment. Their study, conducted in North Ossetia, Russia, illustrates the importance of a detailed probabilistic assessment of risks of various natures. The research highlights the dynamic balance between natural processes such as mountain building and denudation, and how geodynamic and climatic factors influence these processes. The study by Melkov et al. (2022) underscores the significance of considering both temporal and spatial data in environmental risk assessments, particularly in geological studies where the risks are often multifaceted and complex.

The evolution of data analytics in environmental risk assessment has been driven by the need to address the increasing complexity of environmental risks associated with geological activities. The integration of multidisciplinary approaches, as exemplified in the works of Lyubchich et al. (2019), Chen et al. (2022), and Melkov et al. (2022), reflects a shift towards more comprehensive and nuanced risk assessments. These approaches leverage the strengths of various analytical techniques, from statistical modeling to GIS and remote sensing, to provide a more holistic understanding of environmental risks.

The evolution of data analytics in environmental risk assessment in the field of geology is characterized by a move towards more integrated, multidisciplinary approaches. These approaches not only enhance the accuracy and efficiency of risk assessments but also contribute to a deeper understanding of the complex interplay between geological processes and environmental risks. As the field continues to evolve, the adoption of advanced data analytics techniques will be crucial in mitigating the environmental impacts of geological activities and ensuring sustainable practices in the sector.

1.3. Significance of Data-Driven Approaches in Geology

The significance of data-driven approaches in geology, particularly in the context of environmental risk assessments, has become increasingly evident in recent years. These approaches, leveraging the power of big data, machine learning, and advanced analytics, have transformed the way geological risks are identified, analyzed, and mitigated.

Searcy and Boehm (2022) illustrate the application of data-driven methods in environmental science through their study on beach water quality forecasting. They developed a framework that utilizes historical data sets and machine learning techniques to forecast bacterial standard exceedances at marine beaches. This approach represents a significant advancement in environmental monitoring, allowing for proactive management of public health risks associated with beach water quality. The study demonstrates the potential of data-driven models to provide enhanced information beyond past observations, enabling better decision-making in environmental risk management (Searcy & Boehm, 2022).

Grillone (2021) explores data-driven methodologies in the context of energy efficiency in buildings, highlighting their applicability in various sectors, including geology. His doctoral thesis emphasizes the role of big data and analytics in improving energy efficiency, which is directly relevant to geological studies, especially in areas such as resource management and environmental impact assessments. Grillone's work underscores the versatility of data-driven approaches, showing how they can be adapted to different applications to yield valuable insights for decision-makers (Grillone, 2021).

Gaikwad et al. (2021) discuss the use of data-driven humanitarian mapping in public policy and resilience planning. Their research focuses on developing novel data science methodologies that harness human-machine intelligence for high-stakes decision-making. This approach is particularly relevant in geology, where data-driven methods can be used to map and assess geological hazards, such as landslides, earthquakes, and volcanic activity. The integration of human expertise with machine learning algorithms offers a powerful tool for enhancing the accuracy and effectiveness of geological risk assessments (Gaikwad et al., 2021).

The application of data-driven approaches in geology has several key benefits. Firstly, it allows for the processing and analysis of large volumes of data, which is essential in a field where datasets are often vast and complex. Secondly, these approaches enable more accurate predictions and assessments of geological risks, leading to better-informed decision-making. Thirdly, the integration of various data sources, including remote sensing data, geological surveys, and historical records, provides a more comprehensive understanding of geological phenomena.

Moreover, data-driven approaches facilitate the development of dynamic models that can adapt to changing conditions and new data inputs. This adaptability is crucial in geology, where environmental conditions and risk factors can change rapidly. Additionally, these approaches support the development of interactive tools and visualizations that aid in the communication of complex geological information to a wide range of stakeholders, including policymakers, scientists, and the general public.

1.4. Evaluating Traditional and Contemporary Analytical Methods in Geological Studies

The field of geology has witnessed a significant transformation in its analytical methods over the years. This evolution from traditional to contemporary techniques has been pivotal in enhancing the accuracy and efficiency of geological studies. A comparative analysis of these methodologies reveals the advancements and the impact they have had on the field.

Li et al. (2021) discuss the advancements in metal isotope analytical chemistry, particularly in geological and environmental samples. Traditional methods, while foundational, often faced limitations in terms of precision and ability to handle complex samples. The advent of modern inorganic mass spectrometry techniques, such as TIMS, MC-ICP-MS, SIMS, and LA-ICP-MS/MC-ICP-MS, has revolutionized the field. These techniques offer higher precision, minimal sample preparation, and the ability to conduct in situ isotopic analysis and dating of minerals. This advancement has significantly contributed to the development of geoscience and environmental science, providing deeper insights into geological processes (Li et al., 2021).

Badawy et al. (2022) provide a comprehensive review of modern solid-phase extraction techniques in chromatographic analysis, highlighting their applications in various fields, including geology. Traditional sample preparation methods like liquid-liquid extraction were often laborious and lacked selectivity. In contrast, modern techniques such as solid-phase extraction and microextraction offer several advantages, including minimal use of solvents, automation, higher sample throughput, and enhanced selectivity. These improvements have not only streamlined the analytical process but also increased the reliability and environmental friendliness of geological studies (Badawy et al., 2022).

Al-Ruzouq et al. (2023) present a comparative analysis of machine learning and analytical hierarchy analysis in the development of artificial groundwater recharge maps. This study exemplifies the shift from traditional analytical hierarchy methods to more advanced machine learning techniques. Machine learning offers a more robust and nuanced analysis of complex geological data, leading to more accurate predictions and assessments. This transition to data-driven, algorithmic approaches in geology represents a significant leap in the field's capability to address complex environmental challenges (Al-Ruzouq et al., 2023).

The transition from traditional to modern analytical methods in geology has several implications. Firstly, it has led to a significant improvement in the accuracy and precision of geological assessments. Modern techniques can handle larger datasets and more complex sample matrices, providing a more comprehensive understanding of geological phenomena. Secondly, these advancements have enabled geologists to conduct more detailed and nuanced studies, leading to better-informed decisions in areas such as resource management, environmental protection, and hazard assessment.

Moreover, the integration of advanced technologies like machine learning and mass spectrometry has opened new avenues for research and exploration in geology. These technologies allow for the exploration of previously inaccessible or unexplored aspects of the Earth's crust, providing valuable insights into its composition, history, and processes. Additionally, the use of environmentally friendly techniques aligns with the growing emphasis on sustainable practices in scientific research.

1.5. Regulatory Framework Guiding Environmental Risk Assessments In Geology

The regulatory framework for environmental risk assessments in geology plays a crucial role in ensuring the safety and sustainability of geological activities. This framework encompasses various policies, legislation, and guidelines that guide the assessment and management of environmental risks associated with geological processes and activities.

Sokolov and Sukhov (2023) discuss the importance of regulatory frameworks in the context of engineering and geological research, particularly in relation to construction safety and environmental protection. They emphasize that the reliability of construction and the protection of territories from dangerous geological and technogenic processes must be based on high-quality engineering investigations that comply with state regulations. The absence of a system ensuring the mandatory implementation of these regulations can have detrimental effects on the quality of research materials and, consequently, on environmental safety. This highlights the need for robust regulatory frameworks that can effectively guide and govern engineering and geological investigations (Sokolov & Sukhov, 2023).

Sun (2020) provides an insight into the regulatory approaches for managing soil contamination, a significant aspect of environmental risk in geology. The study focuses on China's strategic plans and legislation for soil contamination management, comparing them with approaches used in other countries like the UK. The differences in risk-based approaches to derive soil screening or guideline values for contaminants between China and the UK are analyzed. This comparative analysis underscores the importance of having a science-based, comprehensive regulatory framework that can adapt to the specific environmental and geological conditions of a region. Such frameworks are essential for effective management and mitigation of soil contamination risks (Sun, 2020).

Popova et al. (2017) discuss the development of regulatory and methodological frameworks aimed at maintaining sanitary and epidemiological welfare, which is closely related to environmental risk assessments in geology. The study highlights the need for revising health legislation to include definitions of fundamental health risk concepts, such as acceptable risk limits and safe conditions. This approach is crucial for applying risk management technologies and methods more effectively in legislative regulation, which can lead to improved safety and quality of life. The paradigm shift towards risk assessment and management methods in regulatory frameworks is essential for addressing the hazards related to environmental factors, including geological activities (Popova et al., 2017).

The regulatory framework for environmental risk assessments in geology is a dynamic and evolving entity. It must continuously adapt to new scientific findings, technological advancements, and societal needs. The integration of comprehensive risk assessment methodologies, public participation, and transparent decision-making processes is vital for the development of effective and robust regulatory frameworks. These frameworks play a pivotal role in guiding the responsible and sustainable exploitation of geological resources while protecting the environment and public health.

Moreover, international collaboration and harmonization of regulatory standards can enhance the effectiveness of environmental risk assessments in geology. Sharing best practices, methodologies, and experiences across borders can lead to the development of more unified and effective regulatory frameworks. This global approach is particularly important in addressing transboundary environmental issues and promoting sustainable development.

The regulatory framework guiding environmental risk assessments in geology is fundamental to the safe and sustainable management of geological activities. As the field of geology continues to advance, the development and refinement of regulatory frameworks will remain crucial in balancing economic development with environmental protection and public health.

1.6. Integration of Interdisciplinary Methods in Geological Studies

The integration of interdisciplinary methods in geological studies is pivotal for addressing the multifaceted nature of environmental risks. This approach combines diverse perspectives and methodologies, enriching the understanding and management of geological phenomena.

Kinnebrew et al. (2020) emphasize the importance of mixed methods research in land-change science and environmental management. Their study categorizes various approaches to mixed methods research, identifying types such as simple nested, informed nested, simple parallel, unidirectional synthesis, and bidirectional synthesis. This typology underscores the need for integrating qualitative and quantitative methods to address different research questions within a project. The authors argue that such integration enhances the epistemological depth of research, enabling a more comprehensive understanding of land-change dynamics and environmental management issues (Kinnebrew et al., 2020).

Tashtamirov (2023) explores interdisciplinary approaches to environmental problems in urbanized and industrial areas, focusing on issues like air and water pollution, urban sprawl, and loss of biodiversity. The research methodology integrates a systematic literature review, statistical analysis, and critical analysis from various fields, including ecology, urban studies, and geography. This interdisciplinary approach is crucial for effectively addressing complex environmental problems in urban and industrial contexts. The study highlights the need for sustainable solutions and advocates for fostering interdisciplinary collaboration and innovative thinking in environmental management (Tashtamirov, 2023).

Svabo (2022) discusses research methods for environmental studies from a social science perspective. The author draws on experience in interdisciplinary research teams to highlight environmental research problems explored in disciplinary collaboration. The book provides a comprehensive overview of quantitative and qualitative research methods, including ethnography, spatial analysis, GIS, and approaches to data collection such as sampling, interviewing, and surveying. This work illustrates the importance of integrating social science methods in environmental studies, particularly in understanding the human dimensions of environmental issues (Svabo, 2022).

The integration of interdisciplinary methods in geological studies offers several advantages. It allows for a more nuanced understanding of complex environmental issues, considering both natural and human factors. This approach also facilitates the development of more effective and sustainable management strategies, as it encompasses a broader range of perspectives and expertise. Additionally, interdisciplinary research can bridge the gap between scientific inquiry and policy-making, ensuring that research findings are relevant and applicable to real-world challenges.

Moreover, interdisciplinary methods promote collaboration among scientists from different fields, fostering innovation and creativity in research. This collaboration is essential in tackling the increasingly complex and interconnected environmental challenges faced in geological studies. It also enhances the capacity for knowledge creation through the exchange of information between distinct methodologies.

The integration of interdisciplinary methods in geological studies is essential for advancing our understanding and management of environmental risks. As the field of geology continues to evolve, embracing interdisciplinary methods will be crucial in addressing the multifaceted nature of environmental challenges and in developing effective and sustainable solutions.

1.7. Challenges and Limitations in Current Risk Assessment Practices

The field of geology, particularly in the context of environmental risk assessments, faces several challenges and limitations. These issues stem from the complexity of geological processes, the variability of natural systems, and the evolving nature of risk assessment methodologies.

Frantzova (2023) addresses the methodology of comprehensive risk assessment for natural disasters, focusing on geological hazards like landslides, earthquakes, and tsunamis. The study highlights the complexity involved in obtaining a comprehensive risk level for various geophysical and geological risks, particularly in northeast Bulgaria. The challenge lies in accurately identifying the various dangers, their impacts, elements at risk, exposure, and vulnerability, as well as analyzing secondary events. This research underscores the difficulty in applying a thorough risk assessment approach that incorporates the concept of risk perception, demonstrating the intricate nature of geological risk assessments (Frantzova, 2023).

Chen (2023) presents a method of potential landslide risk assessment in Dorset, Southern England, emphasizing the challenges in assessing geological hazards. The study utilizes remote sensing techniques to determine the probability of landslide occurrence and provides a quantitative model for risk assessment. However, the research identifies significant limitations, such as the insensitivity of the probability potential risk calculation and challenges related to the temporal resolution of precipitation information. This case study illustrates the difficulties in accurately predicting geological hazards and the limitations of current methodologies in capturing the dynamic nature of these risks (Chen, 2023).

Lee et al. (2022) discuss the challenges in evaluating environmental impacts for aggregate producers through a case study in Western Sweden. The study identifies several methodological and systemic challenges in applying Life Cycle Assessment (LCA) to the aggregate industry. These challenges include the difficulty in standardizing a tool for a nonstandardized industry, the complexity of conducting site-specific LCAs, and the risk of double work when LCA is used for Environmental Product Declarations. The research highlights the need for a best-practice framework to incorporate LCA into current environmental management techniques, while also acknowledging the necessity for further research to efficiently allocate resources in conducting LCA studies (Lee et al., 2022).

The challenges and limitations in current risk assessment practices in geology are multifaceted. They range from methodological issues, such as the need for more accurate and sensitive models, to systemic challenges, like the integration of risk assessment tools into industry practices. These challenges are compounded by the inherent uncertainty and variability of geological processes, making risk assessments complex and often uncertain.

Moreover, the evolving nature of geological risks, driven by factors such as climate change and human activities, adds another layer of complexity to risk assessments. This dynamic environment requires continuous adaptation and improvement of risk assessment methodologies to remain relevant and effective.

Addressing the challenges and limitations in current risk assessment practices in geology is crucial for the effective management and mitigation of environmental risks. As geological studies advance, overcoming these challenges will be key to enhancing our understanding and management of environmental risks associated with geological activities.

Aim and Objectives

The primary aim of this review is to synthesize and evaluate the current methodologies in data analytics as applied to environmental risk assessments in the U.S. geology sector. This comprehensive review seeks to understand how modern data-driven approaches are enhancing the accuracy and effectiveness of environmental risk assessments, particularly in geological activities. The focus is on summarizing the evolution of these methodologies, their impact on reducing environmental risks, and the integration of interdisciplinary methods in geological studies.

The first objective is to analyze the evolution and current state of data analytics techniques in environmental risk assessments within U.S. geology. This involves a detailed examination of the transition from traditional to modern analytical methods, highlighting how advancements in technology and data processing have contributed to more precise and comprehensive risk assessments. The analysis will cover various aspects, including predictive analytics, machine learning, big data, and Geographic Information Systems (GIS), and their roles in enhancing geological predictions and risk management.

The second objective is to explore the integration of interdisciplinary methods in geological studies, focusing on how different scientific disciplines converge to address complex environmental challenges. This objective will assess the effectiveness of combining various methodologies, such as qualitative and quantitative research, remote sensing techniques, and life cycle assessments, in providing a more holistic understanding of environmental risks. The review will also consider the challenges and limitations inherent in current risk assessment practices, offering insights into potential areas for improvement and future research directions.

Through these objectives, the review aims to provide a comprehensive understanding of the current landscape of data analytics in environmental risk assessments in geology, offering valuable insights for researchers, policymakers, and practitioners in the field.

2. Methods

2.1. Criteria for Selecting Data Analytics Techniques in Geology

The selection of data analytics techniques in geology for qualitative analysis is guided by specific criteria that align with the nature of geological data and the environmental risks being assessed. These criteria include the capacity for spatial analysis, the ability to integrate diverse data types, and the suitability for addressing complex environmental issues.

Chen, Mao, and Zhao (2022) highlight the application of Geographic Information Systems (GIS) in environmental monitoring and risk assessment. GIS is chosen for its ability to handle spatial data effectively, making it a crucial tool in geological studies where the analysis of spatial patterns and relationships is fundamental. GIS's capacity to integrate various data types, including remote sensing data, and its real-time geographic location information transmission capabilities, make it an ideal choice for qualitative analysis in geological risk assessments (Chen, Mao, & Zhao, 2022).

Belloula, Dridi and Kalla (2020) discuss the use of the Analytic Hierarchy Process (AHP) in assessing geological hazards. AHP is selected for its effectiveness in decomposing complex decision-making processes into simpler, more manageable sub-problems. This method is particularly useful in geological studies where multiple factors, such as stratigraphic lithology and slope gradient, must be considered. AHP facilitates the qualitative analysis of these factors, enabling a comprehensive assessment of geological risks (Belloula, Dridi & Kalla, 2020).

2.2. Methodological Approaches for Evaluating Environmental Risks

The methodological approaches for evaluating environmental risks in geology involve qualitative analyses tailored to address specific aspects of geological data and environmental risks. These approaches focus on understanding the underlying patterns, relationships, and processes within geological data.

Ulytsky et al. (2019) demonstrate a methodology for assessing the environmental risk of groundwater quality deterioration. Their approach includes the development of a groundwater vulnerability map and a simulated model of anthropogenic pressure magnitude distribution. This qualitative methodology allows for a comprehensive evaluation of groundwater risks by considering the impact of pollution sources and the vulnerability of the groundwater system (Ulytsky et al., 2019).

Orlova (2020) discusses environmental risk management, emphasizing the practical application of various qualitative methods at different levels of the economy. The study highlights the importance of integrating risk management in environmental studies, using methods like content analysis and system analysis. This approach underscores the need for a holistic view of environmental risk management, encompassing macro, meso, and micro levels (Orlova, 2020).

Kinnebrew et al. (2020) and Tashtamirov (2023) further reinforce the importance of interdisciplinary approaches in environmental risk assessment. Kinnebrew et al. (2020) focus on mixed methods research in land-change science, combining qualitative and quantitative methods to enhance the depth of research. Tashtamirov (2023) explores interdisciplinary methods in addressing environmental problems in urbanized and industrial areas, integrating perspectives from ecology, urban studies, and geography.

The selection of data analytics techniques and methodological approaches in geological studies for qualitative analysis is guided by the nature of the data, the specific environmental risks, and the objectives of the study. The integration of GIS, AHP, vulnerability mapping, and interdisciplinary methods provides a robust framework for evaluating environmental risks in geology. These approaches enable a comprehensive understanding of the risks and facilitate the development of effective management strategies.

3. Results of the Study

3.1. Effectiveness of Predictive Analytics in Risk Identification

The effectiveness of predictive analytics in risk identification within the U.S. geological sector is increasingly recognized, particularly in addressing complex environmental challenges. This section explores how predictive analytics is being utilized to enhance risk identification and management in geological activities.

Palma, Martí, and Sánchez (2021) discuss the application of a multitask learning approach in predicting mining industry accidents. Their study demonstrates how predictive analytics can effectively forecast the likelihood of accidents in mining worksites, a critical aspect of geological activities. By fusing different data sources and applying a multi-task learning approach, the model overcomes the constraints of limited data availability, significantly improving the accuracy of risk predictions. This approach exemplifies the potential of predictive analytics in enhancing safety and risk management in the mining sector, a key component of U.S. geology (Palma, Martí, & Sánchez Pi, 2021).

Řezník, Konečný, and Charvát (2019) highlight innovative geospatial and cartographic approaches in identifying and analyzing land degradation, a significant environmental risk in geological studies. Their research emphasizes the role of predictive analytics in visualizing and assessing land degradation risks. By integrating geospatial data with predictive models, the study provides valuable insights into the spatial patterns and potential risks of land degradation. This approach underscores the effectiveness of predictive analytics in not only identifying risks but also in visualizing and communicating these risks to stakeholders (Řezník, Konečný, & Charvát, 2019).

Mehdaoui et al. (2023) explore the contribution of geomatics and remote sensing in environmental studies, particularly in the Cretaceous Basin of Errachidia-Boudenib, Morocco. While not directly focused on the U.S. geology sector, this study offers insights into the broader application of predictive analytics in geological studies. The integration of remote sensing data with predictive models enables the identification of areas vulnerable to environmental risks such as water erosion. This methodology highlights the potential of predictive analytics in environmental risk assessment, providing a framework that can be adapted to various geological contexts, including those in the U.S. (Mehdaoui et al., 2023).

The effectiveness of predictive analytics in risk identification in U.S. geological activities is evident in its ability to forecast potential hazards, analyze spatial data, and visualize environmental risks. As the field continues to evolve, the integration of advanced predictive analytics will play a crucial role in mitigating environmental risks and ensuring the safety and sustainability of geological practices.

3.2. Role of Machine Learning in Enhancing Geological Predictions

The integration of machine learning (ML) in geological predictions has significantly enhanced the ability to assess and manage environmental risks in the U.S. geology sector. This section explores the impact of ML techniques in improving the accuracy and efficiency of geological predictions.

Azarafza et al. (2021) demonstrate the application of deep learning, specifically a deep convolutional neural network (CNN-DNN), in landslide susceptibility mapping. Their study, conducted in the Isfahan province of Iran, showcases how ML can be used to predict geological hazards with high accuracy. The CNN-DNN model outperformed several benchmark machine learning techniques, highlighting the potential of deep learning in geological predictions. This approach is particularly relevant to the U.S. geology sector, where similar geological hazards exist and require advanced predictive techniques (Azarafza et al., 2021).

Guo et al. (2020) discuss the use of a hybrid intelligent method based on random forest and cluster algorithms for spatial prediction of landslides in the Wanzhou District, China. This method combines the strengths of random forest in calculating landslide occurrence probability with cluster algorithms for landslide susceptibility zonation. The study's findings indicate a higher prediction performance compared to traditional models, underscoring the effectiveness of ML in geological risk assessment. The methodology presented in this study can be adapted to the U.S. geological context, providing a robust tool for predicting and managing landslide risks (Guo et al., 2020).

Sarkar et al. (2023) explore the prediction of elevated groundwater fluoride levels across India using a multi-model approach that incorporates geological and environmental factors. The study highlights the role of ML in understanding and predicting the distribution of groundwater contaminants, a critical aspect of environmental risk management in geology. The insights gained from this research are applicable to the U.S. geology sector, where groundwater contamination poses significant environmental risks. The use of ML in this context allows for more accurate predictions and effective management strategies (Sarkar et al., 2023).

The role of machine learning in enhancing geological predictions is evident through its application in various aspects of geological risk assessment. As the U.S. geology sector continues to face complex environmental challenges, the integration of advanced ML techniques will be crucial in enhancing risk assessment and management practices.

3.3. Impact of Big Data on Environmental Risk Management

The advent of big data technology has revolutionized various sectors, including environmental risk management in geology. The ability to collect, store, analyze, and apply large volumes of data has significantly enhanced the efficiency and accuracy of risk assessments and decision-making processes in this field. This section explores the impact of big data on environmental risk management in geology, drawing insights from recent studies.

Zhao et al. (2022) emphasize the transformative role of big data in environmental governance. Their research on the development of an intelligent optimization decision support platform for solid waste environmental risk event disposal underlines the potential of big data in enhancing environmental management. The study demonstrates how the integration of data storage, mining, analysis, and application can lead to more informed and effective decision-making in managing environmental risks. The utilization of multi-source data, including unstructured data such as remote sensing, is crucial in comprehensively understanding and addressing environmental challenges in geology (Zhao et al., 2022).

In the context of agricultural disaster risk management, Wang et al. (2022) highlight the significance of big data analytics in assessing and mitigating risks. Their research provides a technical metric analysis to evaluate the body of research on agriculture disaster management, emphasizing the role of big data in understanding and managing natural catastrophes like flooding and wildfires. This approach is particularly relevant to geology, where similar environmental risks are prevalent. The study illustrates how the flux of raw and analytical data from comprehensive datasets can significantly impact the final performance of forecasting, thereby enhancing the management of environmental risks in geological settings (Wang et al., 2022).

El Khatib et al. (2023) explore the mediation of organizational risk management through big data and analytics. Their comparative case study analysis among companies utilizing big data in risk management, including Apple Inc., Amazon Inc., and Google, provides valuable insights into the roles of big data technology in risk assessment and management. This research underscores the importance of leveraging modern technology to unlock hidden data, which is crucial in the field of geology for identifying, assessing, mitigating, monitoring, and reporting risks. The adoption of big data analytical technology redefines the processes of risk management, making it more efficient and effective (El Khatib et al., 2023).

The integration of big data in environmental risk management in geology offers several advantages. Firstly, it enables the handling of large and complex datasets, which is essential in a field characterized by diverse and voluminous data. Secondly, big data analytics enhance the precision and accuracy of risk assessments, allowing for more reliable predictions and decision-making. Thirdly, the ability to integrate various data types, including remote sensing and geospatial data, provides a more comprehensive understanding of geological phenomena and associated risks.

Furthermore, the application of big data technology in environmental risk management facilitates the development of intelligent decision support systems. These systems can optimize emergency responses and risk event disposal strategies, making them more effective and timely. Additionally, the use of big data analytics in forecasting and predicting environmental risks, such as landslides, floods, and other natural disasters, is crucial for proactive risk management in geology.

The impact of big data on environmental risk management in geology is profound. The ability to harness and analyze vast amounts of data has opened new avenues for understanding and managing environmental risks, leading to more informed, efficient, and effective decision-making processes. As the field of geology continues to evolve, the integration of big data technology will play an increasingly vital role in enhancing environmental risk assessments and management strategies.

3.4. Geographic Information Systems (GIS) in Risk Mapping and Analysis

Geographic Information Systems (GIS) have become an indispensable tool in geology, particularly in the domain of risk mapping and analysis. The integration of GIS with remote sensing (RS) technologies has significantly enhanced the ability to visualize, analyze, and manage environmental risks associated with geological hazards. This section explores the application and impact of GIS in risk mapping and analysis in geology, drawing on insights from recent studies.

Yang et al. (2023) provide a comprehensive overview of the application of GIS and RS in researching rainfall-induced landslide hazards. Their extensive analysis of literature over the past 27 years reveals a steady increase in the use of these technologies for landslide detection, monitoring, prediction models, sensitivity mapping, and risk assessment. The study underscores the importance of GIS in understanding the spatial distribution of landslide events and in developing predictive models for landslide susceptibility. The integration of GIS with RS technologies allows for the effective visualization and analysis of landslide hazards, contributing significantly to decision-making processes in landslide prevention and control (Yang et al., 2023).

Chen et al. (2022) explore the application of GIS in environmental monitoring and risk assessment across various domains, including water, soil, and atmospheric studies. Their research demonstrates the versatility of GIS in monitoring environmental risks, such as soil heavy metal concentration and water supply system vulnerabilities. By utilizing advanced GIS software and combining it with other technologies like wireless sensor networks and microcontrollers, GIS provides a powerful platform for real-time monitoring and risk assessment. This capability is particularly relevant in geology, where the assessment of environmental risks requires the integration of diverse spatial data and the ability to translate these data into actionable insights (Chen et al., 2022).

Shastrakar et al. (2023) highlight the use of GIS in flood risk mapping in the Mumbai District of India. Their study focuses on identifying flood-prone locations using criteria such as population, land use, terrain, and other environmental variables. The integration of GIS with hydrological and geospatial data enables the creation of reliable flood risk maps, which are essential for developing effective flood mitigation policies. This GIS-based multi-criteria method offers several benefits, including low monetary and time investment, making it an increasingly popular approach for flood risk assessment in urban areas. The application of GIS in flood risk mapping is a testament to its potential in geological risk assessment, particularly in areas prone to flooding and other water-related hazards (Shastrakar et al., 2023).

The application of GIS in geological risk mapping and analysis offers several advantages. Firstly, it enables the effective integration and analysis of diverse environmental data, which is crucial in understanding the spatial dynamics of geological hazards. Secondly, GIS provides powerful visualization tools that aid in the communication of complex geological information to stakeholders, including policymakers, scientists, and the general public. Thirdly, the ability of GIS to combine with other technologies, such as RS and wireless sensor networks, enhances its capability in real-time monitoring and predictive analysis of environmental risks.

GIS plays a critical role in risk mapping and analysis in geology. Its ability to handle spatial data, integrate various data types, and provide advanced analytical and visualization tools makes it an essential component in environmental risk management. As geological studies continue to evolve, the integration of GIS will remain pivotal in enhancing the understanding, prediction, and management of environmental risks associated with geological activities.

3.5. Case Studies: Successful Applications of Data Analytics in Geology

The application of data analytics in geology has led to significant advancements in environmental risk assessment and management. This section explores various case studies that demonstrate the successful application of data analytics in geology, highlighting the diverse ways in which these technologies are being utilized to address complex geological challenges.

Siew and Farouk (2023) discuss the implementation of big data analytics in a Malaysian commercial bank, providing insights into the challenges and solutions associated with data analytics in a large-scale organizational context. While this case study is centered around the banking sector, it offers valuable lessons for the geology sector, particularly in terms of managing and analyzing large, complex data sets to discover patterns and insights. The study emphasizes the importance of addressing data quality issues and security risks, which are also pertinent concerns in geological data analytics (Siew & Farouk, 2023).

Tallón-Ballesteros (2021) present a case study on data analytics-based risk management for student performance in an engineering college. This study illustrates the use of historical data and data analytics in improving academic performance, placement, and entrepreneurship. The process and framework developed in this case study can be adapted to geological studies, where data analytics can be employed to manage risks associated with student performance in geology-related educational programs. The strategic initiatives derived from this study can also be beneficial for research and outreach activities in the field of geology (Tallón-Ballesteros, 2021).

Zong et al. (2023) conducted an ecological risk assessment of geological disasters in Fujian, China, based on the "probability-loss" framework. This study utilized a random forest (RF) model for hazard assessment by integrating multiple factors and adopted landscape indices to analyze vulnerability. The use of ecosystem services and spatial population data to characterize potential damage demonstrates the effectiveness of data analytics in geological disaster risk assessment. The findings of this study are crucial for ecological planning and disaster mitigation in geology, providing a model for assessing ecological risks posed by geological disasters (Zong et al., 2023).

Findik and Aras (2022) applied metal pollution indices on surface waters to assess environmental risk in the Damsa reservoir in Cappadocia, Türkiye. This case study highlights the application of data analytics in evaluating the impact of metal pollution on environmental risk. The study's approach to assessing water quality and its implications for environmental risk in geological settings showcases the potential of data analytics in environmental monitoring and risk assessment in geology (Findik & Aras, 2022).

These case studies collectively illustrate the diverse applications and benefits of data analytics in geology. From managing large data sets and addressing security concerns to assessing ecological risks and evaluating environmental impacts, data analytics plays a crucial role in enhancing the understanding and management of geological challenges. As the field of geology continues to evolve, the integration of data analytics will remain pivotal in advancing environmental risk assessments and management strategies.

3.6. Comparative Analysis of Different Analytical Techniques

The field of geology has seen a significant evolution in analytical techniques, especially in the context of environmental risk assessments. This section provides a comparative analysis of different analytical techniques used in geological studies, highlighting their strengths, limitations, and applications.

Knight's study (2022) offers a comparative analysis of portable X-ray fluorescence (pXRF) and laboratory Inductively Coupled Plasma Emission Spectroscopy/Mass Spectrometry (ICP-ES/MS) methods for mineral resource assessment in the Northwest Territories. Their research demonstrates that while pXRF data do not exactly replicate the precision and accuracy of laboratory 4-acid and fusion data, the relationship between the datasets is systematic. This finding is significant as it indicates that pXRF can be a viable tool for illustrating regional geochemical trends and identifying significant geochemical anomalies in surficial samples, despite its limitations in precision and accuracy compared to more traditional laboratory methods (Knight, 2022).

Al-Ruzouq et al. (2023) conducted a comparative analysis of machine learning and analytical hierarchy analysis for developing artificial groundwater recharge maps. Their study highlights the robustness and nuanced analysis provided by machine learning techniques in handling complex geological data, leading to more accurate predictions and assessments. This comparison underscores the transition from traditional analytical hierarchy methods to advanced machine learning techniques, representing a significant advancement in the field's capability to address complex environmental challenges (Al-Ruzouq et al., 2023).

Abdolkhaninezhad et al. (2022) present a comparative analytical study using the bowtie method, Analytic Network Process (ANP), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for environmental risk assessment of urban landfills. Their study identifies the environmental sector as the highest risk in the construction and operation phases of landfills. The comparative analysis of these methods provides insights into the effectiveness of different analytical techniques in identifying and managing environmental risks associated with urban landfills. The study demonstrates the importance of selecting appropriate analytical methods based on the specific requirements and complexities of the geological study (Abdolkhaninezhad et al., 2022).

These comparative analyses reveal that the choice of analytical technique in geological studies depends on various factors, including the nature of the data, the specific environmental risks, and the objectives of the study. While traditional methods like ICP-ES/MS provide high precision and accuracy, newer techniques like pXRF and machine learning offer systematic relationships between datasets and the ability to handle larger and more complex data sets. The integration of various analytical techniques, from statistical modeling to advanced machine learning and GIS, contributes to a more comprehensive understanding of environmental risks in geology. As the field continues to evolve, the adoption of a combination of traditional and advanced analytical techniques will be crucial in enhancing the accuracy and efficiency of environmental risk assessments in geological studies.

4. Discussion of the Results

4.1. Interpreting the Efficacy of Data Analytics in Risk Reduction

The efficacy of data analytics in reducing environmental risks in geology is a subject of increasing importance, given the escalating challenges posed by natural hazards and environmental degradation. This section interprets the effectiveness of data analytics in mitigating risks in geology, drawing on insights from recent studies.

Avalon-Cullen et al. (2023) explore the application of big data and earth observations in improving flood and landslide risk assessment in Jamaica. Their study underscores the potential of big data in enhancing the understanding and management of hydrological-meteorological and geological risks. The integration of earth observation data with big data analytics provides actionable insights for disaster risk reduction (DRR) planning and response. This approach is particularly effective in small island developing states, where the frequency, intensity, and duration of extreme weather events are increasing due to climate change. The study demonstrates that big data analytics can significantly contribute to national preparedness and response strategies, thereby reducing environmental risks in geology (Avalon-Cullen et al., 2023).

Ruzgas et al. (2023) discuss the use of analytics in reducing tax fraud in Lithuania, a rapidly developing East European country. While the study focuses on tax fraud, the methods and findings are relevant to geological risk reduction. The application of data mining techniques in detecting tax evasion parallels the use of similar methods in identifying and mitigating geological risks. The study illustrates how data analytics can extract hidden knowledge and patterns, which is crucial in environmental risk assessment in geology. The ability of data analytics to effectively predict and manage risks can be adapted to geological settings, where it can help in reducing revenue losses and improving decision-making processes (Ruzgas et al., 2023).

Wang and Su (2023) examine the economic loss and financial risk assessment of the ecological environment caused by environmental pollution using big data. Their study highlights the role of big data in assessing the economic impact of environmental degradation, which is directly relevant to geological risk assessment. The improved analytic hierarchy process (AHP) proposed in their study provides a framework for accurately analyzing environmental protection for sustained economic growth and understanding financial risks. This approach is beneficial in geological studies, where assessing the economic impact of environmental risks is crucial for effective risk management and policy formulation (Wang & Su, 2023).

The integration of big data with earth observation, data mining techniques, and improved analytical methods provides a comprehensive approach to risk assessment and management. As the field of geology continues to face complex environmental challenges, the adoption of advanced data analytics will be crucial in mitigating risks and ensuring sustainable practices in the sector.

4.2. Implications of Findings for Future Geological Practices

The findings from recent studies in geology have significant implications for future practices in the field, particularly in the context of environmental risk assessment and management. These implications are crucial for guiding the development of more effective, sustainable, and responsible geological practices.

Milton-Thompson (2019) discusses the development of a risk assessment model using fuzzy logic to assess groundwater contamination from hydraulic fracturing. This study highlights the importance of incorporating advanced analytical techniques, such as fuzzy logic, in geological risk assessments. The application of such techniques allows for more nuanced and accurate assessments, especially in situations with complex data and uncertain conditions. This approach can be instrumental in future geological practices, particularly in areas like hydraulic fracturing, where the potential for environmental impact is significant (Milton-Thompson, 2019).

Allard et al. (2023) present an innovative integrated methodology to address the challenges of permafrost thaw in Nunavik communities. Their approach, which includes producing maps of permafrost conditions and assessing risks of geohazards at the community-scale level, underscores the need for interdisciplinary and collaborative efforts in geological studies. The study demonstrates the value of combining geological knowledge with community engagement and stakeholder consultation. This integrated approach is essential for future geological practices, especially in the context of climate change and its impact on permafrost regions (Allard et al., 2023).

Afzal, Tahir, and Al-Ghamdi (2022) critically review the environmental implications of artificial island developments in the Gulf region. Their study provides recommendations and strategies to mitigate the environmental impact of such developments. This research emphasizes the need for strict compliance with international and national legislation, research and baseline data collection, and strengthening of environmental assessments. The findings from this study have significant implications for future geological practices, particularly in the planning and execution of large-scale projects like artificial island development. The study advocates for a balanced approach that considers economic, social, and environmental aspects in decision-making processes (Afzal, Tahir, & Al-Ghamdi, 2022).

4.3. Integrating Data Analytics with Traditional Geological Methods

The integration of data analytics with traditional geological methods is reshaping the landscape of environmental risk assessment in geology. This fusion of modern and conventional approaches is enhancing the accuracy, efficiency, and scope of geological studies. This section explores how the integration of these methodologies is being implemented and its implications for the future of geological practices.

Chen, Mao, and Zhao (2022) discuss the application of Geographic Information Systems (GIS) in environmental monitoring and risk assessment. Their study exemplifies the integration of data analytics with traditional geological methods. GIS, a data-driven technology, is used in conjunction with traditional field methods for monitoring water supply systems and assessing soil heavy metal concentration. This integration allows for more precise and comprehensive environmental assessments, demonstrating how data analytics can enhance traditional geological practices (Chen, Mao, & Zhao, 2022).

Rawson, Sabeur, and Brito (2022) present a study on intelligent geospatial maritime risk analytics using the Discrete Global Grid System (DGGS). This research integrates advanced data analytics techniques with traditional maritime risk assessment methods. The use of a Random Forest algorithm to predict the frequency and spatial distribution of ship groundings is a prime example of how machine learning can complement traditional risk assessment methods. The study shows that data analytics can provide deeper insights and more accurate predictions than traditional methods alone (Rawson, Sabeur, & Brito, 2022).

Çömert et al. (2023) explore the use of 3D data integration for geo-located cave mapping based on unmanned aerial vehicle (UAV) and terrestrial laser scanner (TLS) data. This study represents a significant advancement in geological mapping, combining traditional cave mapping techniques with modern UAV and TLS technologies. The integration of these methods provides a more detailed and accurate representation of the cave's geometry and potential risks, showcasing the potential of combining traditional geological methods with advanced data analytics (Çömert et al., 2023).

4.4. Future Trends and Innovations in Geological Data Analytics

The field of geological data analytics is rapidly evolving, driven by advancements in technology and the increasing complexity of environmental challenges. This section explores the future trends and innovations in geological data analytics, drawing insights from recent studies.

Rylnikova et al. (2022) discuss the application of artificial intelligence (AI) and big data analytics in the mining industry. Their study highlights the emergence of "digital advisers" that leverage information from various mining operations to optimize processes. This trend indicates a shift towards more intelligent and automated systems in geological data analytics, where AI and machine learning algorithms play a crucial role in predictive analytics and decision-making. The integration of AI with big data analytics is expected to revolutionize the mining industry by enhancing efficiency, safety, and environmental sustainability (Rylnikova et al., 2022).

Akindote et al. (2023) provide a comparative review of big data analytics and Geographic Information Systems (GIS) in healthcare decision-making. While focused on healthcare, the insights from this study are applicable to geology. The integration of big data analytics with GIS is a trend that is likely to gain traction in geological studies. This combination allows for the incorporation of spatial context in data analysis, enhancing the ability to understand and predict geological phenomena. The study also points towards future integrations with AI, real-time analytics, and wearable technology, which could significantly impact geological data analytics (Akindote et al., 2023).

Mahmood et al. (2020) discuss recent advances in big data, emphasizing the importance of understanding its features, classification, analytics, research challenges, and future trends. The study suggests that big data analytics in geology will continue to evolve, with a focus on addressing challenges related to data storage, processing, indexing, integration, and governance. The future trends in geological data analytics are expected to include more sophisticated data manipulation techniques, improved information retrieval, and decision-making processes. The study underscores the need for a deeper understanding of big data analytics to harness its potential effectively in geological studies (Mahmood et al., 2020).

5. Conclusion

This in-depth analysis has successfully navigated the complex landscape of data analytics in the realm of U.S. geological environmental risk assessments. The primary aim was to amalgamate and critically assess the progression and current status of data analytics within geological practices, focusing on their influence in mitigating environmental risks and the incorporation of multidisciplinary approaches.

Employing a diverse methodological framework, the study meticulously scrutinized recent scholarly articles and case studies, ensuring a robust and comprehensive exploration of the topic. This methodical approach facilitated a nuanced understanding, aligning with the study's objectives. The exploration spanned various dimensions of geological risk assessments, including the roles of predictive analytics, machine learning, big data, and Geographic Information Systems (GIS) in refining geological predictions and risk management strategies.

The pivotal outcomes of this research highlight the remarkable strides made in data analytics, marking a paradigm shift in geological studies. The amalgamation of cutting-edge analytical techniques, such as AI and machine learning, with established geological methods has emerged as a key development. This synergy not only elevates the precision and effectiveness of risk assessments but also deepens the comprehension of the intricate relationship between geological processes and environmental risks. The research further illuminated the critical role of comprehensive regulatory frameworks and the integration of diverse data sources in executing thorough risk assessments.

In summation, the research advocates for an ongoing and enhanced integration of sophisticated data analytics in geological studies. It emphasizes the importance of harnessing both traditional and contemporary analytical methods to tackle the multifaceted nature of environmental risks. Future geological practices should pivot towards adopting sustainable and conscientious methodologies, ensuring environmentally responsible and sustainable geological activities. Moreover, the research calls for international collaboration and standardization of regulatory norms to bolster the efficacy of environmental risk assessments in geology.

Offering valuable insights for researchers, policymakers, and industry practitioners, this review paves the way for future innovations in geological data analytics and environmental risk management.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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