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REVIEW

Coupled Geological Topographical Frameworks for Managing Aquifer Hydraulic Fracturing in Coal Mine Engineering

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ABSTRACT

Aquifer hydraulic fracturing in coal mine engineering faces uncontrolled fracture propagation and water migration due to complex geological-topographical interactions, leading to groundwater contamination, water inflow, and mine collapse risks. This systematic review synthesized 79 peer-reviewed papers (2000–2025) from the Web of Science and Scopus databases using keywords: "hydraulic fracturing," "coal mine," "aquifer," "geological modeling," and "topographical data." Inclusion criteria required quantitative field or simulation data on fracture behavior or water flow. Coupled hydromechanical models (FLAC3D-TOUGH2, ABAQUS with cohesive zone methods) improve fracture propagation prediction accuracy by 15–25% over single-domain models. Geographic information system (GIS)-based integration of light detection and ranging (LiDAR) topography (sub-meter resolution) with borehole geological data reduces water inflow prediction error by approximately 30% compared to conventional methods. Natural fracture networks increase unintended aquifer connectivity risk by 40–60% when uncharacterized. This review establishes that coupled geological-topographical frameworks reduce groundwater contamination incidents by 25–35% and optimize water injection rates, improving operational efficiency by 20%. Practical implications include real-time monitoring protocols and regulatory recommendations for mine safety and

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environmental protection.

Keywords: Aquifer Hydraulic Fracturing; Coal Mine Engineering; Geological Modeling; Topographical Data Integration; Water Management Strategies

1. Introduction

Coal mining is one of the components that make up the energy industry in the world, which in the past has been a significant source of power to generate electricity, iron and steel, and other industrial activities [1,2]. The mining of coal underground deposits may, however, entail intricate geological conditions and may involve the existence of aquifers, discontinuous rock systems, and diverse topographical gradients [3,4]. Their interaction is important to the safe and effective extraction of coal, especially when it is operated using hydraulic fracturing (HF) methods to increase its resources. Water resource management in the coal mines is crucial to the success of the operations as well as environmental stewardship. When they are met during mining processes, aquifers may be a serious problem, including water inflow, instability of the ground, and even collapsing mine shafts [5].

Hydraulic fracturing, frequently applied in an attempt to increase the permeability of coal seams and enhance the primary recovery of coalbed methane, can also cause changes in the water flow regime and fracture processes in the coal seam and the surrounding rock formations [6]. Such activities should be well checked and controlled concerning aquifers as repositories of water under the ground, as consequences which may be contamination of groundwater, excess water influx, or disastrous floods. The interplay between hydraulic fracturing and aquifer systems is a complex issue, and knowledge and control of both geological and topographical settings are important. Hence, an integrated geological topographical model is now becoming an essential instrument in the process of identifying and reducing the risks that are linked to the process of hydraulic fracturing of aquifers in coal mine development [7].

The purpose of this review is to investigate how geological and topographical data can be utilized in the engineering of managing the hydraulic fracturing of an aquifer to manage the coal mine. In particular, it also has to do with the need to integrate the geological properties of lithology, porosity, permeability, and fracture systems with the topography of the surface and subsurface, including elevation, slope, and water drainage. The review points to the necessity of the use of a holistic method, in which data from both fields are used simultaneously, to enhance the prediction of fracture behavior and water flow during hydraulic fracturing processes [8].

The main aim of the article is to provide existing knowledge of how these interconnected geological-topographical structures can be useful in controlling the effects of hydraulic fracturing on aquifers in coal mining situations [9]. It is through this review that the strengths and weaknesses of the current practices will be identified and future recommendations made toward enhancing the management of hydraulic fracturing in the coal mines by analyzing the existing methodologies, tools, and case studies. It will be specifically interested in the ways that coupled data can be used to reduce the risks to groundwater systems, increase the safety of mines, and improve their efficiency.

Several challenges face the management of the hydraulic fracturing of aquifer water in coal mines due to the multi-layered interaction of geological and topographical factors. First of all, the heterogeneity of the conditions in the subsurface, including the variations in the rock layers, fractures, and fluid movement, is one of the primary challenges that make it hard to make precise predictions of hydraulic fracture behavior. The propagation of hydraulic fractures may be affected by geological characteristics of the formation of fault systems, depth of the coal seam, and natural fractures, making it more difficult to control the development of the water flow and fractures. Moreover, topographical factors, including the elevation of the surface, the slope of the surface, and the existence of surface water bodies, also complicate the water management strategies. The water produced during hydraulic fracturing can leak randomly through the fissures in the coal seam and the strata around it, and could find its way into aquifers or surface water systems [10].

One of the biggest issues in the geological and topographical integration is the fact that different methods and tools are employed in the process of data gathering and examination of both fields [11]. The geological data is usually acquired by drilling boreholes, seismic surveys, and geological mapping, whereas the topographical data is acquired using the technologies of LiDAR, satellite data, and surveys on foot. The differences in data sets, spatial resolutions, and time scales also make the development of accurate and coupled models challenging. This review will discuss these issues in detail and give an insight into how the limitations can be overcome through the advancement in data integration methods.

The linkage between geological and topographical systems controlling the hydraulic fracturing of aquifers gives a deeper insight into the subsurface environment, which enhances the effectiveness of the predictive models, as well as the effectiveness of the hydraulic fracturing processes [12]. Possessing the topography of surface elevation, drainage patterns, and subsidence risks, the combination of geological information on lithology, permeability, fault structures, and characteristics of the aquifer, engineers and hydrologists will be able to forecast the behavior of water in relation to hydraulic fracturing interventions. The method improves decision-making on the positioning of fractures, the amount of water to inject, and how the possible migration of water through the ground should be handled.

In addition, a coupled framework can be used in a more holistic approach to both environmental and safety risk management [13,14]. With this in mind, engineers will be able to predict and avoid the adverse effects of hydraulic fracturing on aquifers, adjacent ecosystems, and mine constructions more effectively. The model allows making informed decisions regarding mine design, water management approaches, and what hydraulic fracturing methods can decrease the risk of unintended consequences, including groundwater contamination, water inflow, or surface subsidence.

As this review will proceed to discuss in the following sections, geological and topographical factors are the issues that affect the hydraulic fracturing of the aquifer in coal mines. Section 2 will entail an overview of the geological framework that includes the main geological properties and modeling methods that affect hydraulic fracturing. Section 3 will deal with the importance of topography in aquifer management and the techniques for monitoring and analyzing topographical features. Section 4 will discuss the advantages and methods of using geological and topographical data in their integration and use in fracture management, with a particular focus on coupled models. Section 5 will address the issues and factors related to operating hydraulic fracturing, such as environmental hazards, safety issues, and information insecurities. Lastly, Section 6 will end with a summary of the main lessons obtained and recommendations for future research in the area.

By conducting a thorough review, the article will be in a position to offer a greater insight into how a coupled geological-topographical framework can allow managing the process of aquifer hydraulic fracturing in coal mine engineering, which can then result in improved performance and lower the environmental impact.

2. Geological Framework for Aquifer Hydraulic Fracturing

The geological characteristics of coal mines play a crucial role in understanding and managing aquifer hydraulic fracturing [5,9]. These attributes determine the movement of water in the mine, the spreading of fractures, as well as the integrity of the seam of coal and the surrounding strata. It takes into account a complex geological framework that would be a solid basis to predict the consequences of hydraulic fracturing operations, make decisions regarding the operation, and reduce the risks caused by the interaction with aquifers. The geological structure is made up of various important elements, such as lithology, fault systems, permeability, and fracture networks, which directly influence the safety and effectiveness of hydraulic fracturing in coal mines.

2.1. Geological Characteristics of Coal Mines

The geology of the coal mines is characterized by a wide variety of rock types and structural features that range both in space and time [15,16]. They are coal seams, shale layers, sandstone formations, and other sedimentary rocks. All these materials have their own physical and chemical characteristics that determine their performance in hydraulic fracturing conditions. Fracturing is usually focused on the coal seam itself, though the other rock layers that surround the coal seam (aquifers, cap rocks, etc.) also play important roles in the way the fractures propagate and whether water can flow.

In coal mines, the aquifers are usually located in the nearby layers of sandstone or limestone, which could be of high porosity and permeability, such that water could be accumulated and moved freely. These geological peculiarities need to be comprehended so as to control the movement of water in the process of hydraulic fracturing. The fact that the geological strata contain faults and fractures is another complexity to the situation because they may facilitate or inhibit the flow of water depending on their orientation, connectivity, and the level of opening. To give an example, natural fractures can be channels through which water can travel, which increases the dangers of water inflow or groundwater contamination[17–19].

2.2. Geological Properties Influencing Fracture Behavior

Hydraulic fracturing of coal mines is directly affected by several important geological properties[20]. **Table 1** sums up the main geological influences on the development of fractures and the movement of fluids. Such properties are porosity, permeability, lithology, and the presence of fractures. Porosity is the amount of absence of space in a rock, which determines the quantity of water that can be held in the coal seam or the rock layers around it. Permeability, on the contrary, is the passing of water through the rock. Porosity and permeability are also critical in the determination of how the hydraulic fractures will propagate, since they determine the ease with which the fractures will open, as well as the ease with which water will flow through the system.

The response of the material to hydraulic fracturing is determined by the lithology of the coal seam and the strata that are adjacent to it[21]. The various kinds of rocks—sandstones, shales, or limestones—have different levels of strength, brittleness, and fracturing capabilities. The fractures are going to be shaped depending on these variations, their degree, and direction. To give an example, however, brittle rocks such as sandstones can be more easily fractured to give well-defined linear fractures, which can be managed in the fracturing process. Conversely, more ductile rocks like shales might have less fracturing but can still serve to produce localized variations in permeability, which must be known.

Table 1. Geological properties controlling hydraulic fracture initiation, propagation, and hydrogeological connectivity in coal mine settings.

Geological Property	Impact on Hydraulic Fracturing	Considerations
Porosity	Determines water storage capacity and fracture fluid retention.	Higher porosity leads to better water storage in coal seams.
Permeability	Influences water flow and fracture propagation.	Low permeability requires higher fracturing pressure.
Lithology	Affects the ease of fracture creation based on rock type.	Brittle rocks fracture more easily than ductile ones.
Fracture Networks	Existing fractures can act as conduits for water flow.	Well-connected fractures can lead to uncontrolled water migration.

Natural fractures present in the coal seam and the rock layers surrounding it are also very crucial[22]. Natural fractures may contribute to the propagation or hinder the propagation of hydraulic fractures based on the orientation and connectedness of natural fractures. A well-interconnected fracture may result in water migration being very fast, whereas an isolated fracture may not contribute substantially to water migration. The specifics of these fractures should be comprehended in such a way that it can be possible to design hydraulic fracturing operations in order to reduce the unintended water migration and the stability of the mine.

2.3. Geological Modeling Techniques

In the proper management of aquifer hydraulic fracturing, geological data should be gathered and modelled such that it reflects the conditions in the underground[23]. Several geological modeling methods are used to model and forecast the actions of fractures and water flow in the coal mine setting. Among the methods, one may single out the development of 3D geological models, combining information about boreholes, seismic surveys, and geological mapping. These models give a full account of the geology in the subsurface, in terms of both the spatial distribution of layers of rocks, the fault system, and the spatial distribution of fractures.

Geostatistical tools are also popular to model the variations of geological properties like porosity and permeability[24]. These techniques can be used to estimate the properties at unsampled points by applying statistical methods that determine values at the unsampled points using the known values. Geostatistical models are especially effective where there is a dearth of direct measurements or they may be inaccessible. These models can be used to make engineers aware of the possible fracture behavior and water flow patterns by introducing the inherent uncertainty in geological data.

Besides more conventional methods of modeling geology, highly sophisticated numerical simulation methods are being adopted to model the hydraulic fracturing process and its effects on aquifers [25]. The simulations are able to consider a wide variety of variables, including the injection pressure, fracture geometry, and rock properties, enabling more accurate predictions of how the hydraulic fractures will behave with aquifers and other underground characteristics. Through the combination of the geological models and hydraulic fracturing simulations, engineers are able to optimize fracture design as well as enhance a better water management approach.

2.4. Integrating Geological Data with Aquifer Management

A combination of geological information with the strategies of aquifer management is essential to reduce risks and increase the efficiency of hydraulic fracturing use in coal mines [26]. Lithology, permeability, and fracture network geological information can be used to locate areas in which the fractures are likely to intersect aquifers or regions where the water could come from. Through knowledge of geological structure, engineers are able to develop hydraulic fracturing processes that restrain the amount of fractures and water flow to ensure that the exercise is confined to the targeted coal seam and it does not dislodge the other aquifers.

In other instances, geological information may also be called upon to guide the choice of the right methods of hydraulic fracturing [27]. As an example, where a mine is located in a region where there are already high levels of natural fracture networks, the engineers might choose to use a fracturing method that does not produce more fractures. In contrast, where natural fractures are few, the methods of increasing the fracture counts can be used to augment the coal seam permeability and the amount of methane recovered.

Combining geological frameworks with topographical and hydrological data, engineers will be able to build a more integrated framework to run aquifer hydraulic fracturing [28]. This technique will allow more accurate forecasts of the propagation of the fractures, the flow of water, and the effect that the mine will have on its stability as a whole. In its turn, it can be used to guarantee the safety and efficiency of hydraulic fracturing activities, which will reduce the possibility of groundwater pollution, surplus water flow, or other adverse effects.

By combining geological data with the application of the latest modeling methods, it is possible to substantially increase the efficiency of the hydraulic fracturing management of the aquifers used in coal mine engineering, resulting in increasing resource recovery, minimizing the impact on the environment, and making the mining process safe.

3. Topographical Framework for Aquifer Hydraulic Fracturing

The topography is a very important aspect in hydraulic fracturing of aquifers utilized in coal mining. The topography of the surface and the underlying topography may have a serious impact on the behavior of the groundwater flow, fracture stability, and fluid motion during the hydraulic fracturing process. Topography, like elevation, slope, and drainage patterns, determines how water is going to be spread and whether the water will penetrate the mine or the aquifers adjacent to it. Likewise, topographical landmarks, like faults, fractures, and subsidence, in the underground level are additional to the propagation of fractures and water migration in the mine. Topography is a key concept that can be used to predict the effects of hydraulic fracturing on the aquifer systems and to come up with proper water management strategies in coal mines [9,29].

3.1. Topographical Influences on Water Flow and Fractures

The topography of the surface coal mines directly affects the behavior of water during and after hydraulic fracturing [29,30]. The elevation of the surface, slope, and the closeness to natural water bodies are among the factors that determine the flow of water over the mine site and the interaction between water and fractures. Water runoff may be directed towards specific regions of the mine in regions where there are high rises and falls, and this may cause localized areas of water to accumulate. This can place more stress on the fractures in the ground, which results in undesired fracture propagation or inflow of water into the mine.

Also, the surface drainage systems, including the availability of streams, rivers, or lakes, play an essential role in determining how water moves during hydraulic fracturing activities. The fracturing process may lead to water that travels to surface water bodies and thus pollutes the water body or water quality. Mines that are situated close to sensitive ecosystems like wetlands or groundwater catchments should be of particular concern with regard to such drainage patterns in order to prevent unwanted effects on the environment [31,32].

Subsurface topography can also affect the hydraulic fracturing water flow and fractures [33]. Fault zones, fracture networks, and differences in rock porosity are geological phenomena that form channels through which water moves in the natural subsurface. The intersection of aquifers and surface water systems due to fractures may lead to water flowing in unexpected directions, and hence increasing water inflow as well as mine stability problems. The fact that the fracture may be vertical to the coal seam to the surface may also add to surface subsidence, making water management strategies even more challenging. Thus, it is necessary to have an idea about the interactions between these underground formations and the hydraulic fracturing activities to reduce water-associated risk.

3.2. Topographical Mapping and Monitoring Techniques

In order to determine and control the topographical effects on hydraulic fracturing, different mapping and monitoring equipment is used. **Table 2** presents a comparison of some of the commonly used surface and subsurface topographical mapping and monitoring techniques. These tools are used to analyze surface and underground topography to determine how water will move and where the fractures are likely to extend in order to further explain the effects of the topography to engineers and hydrologists. Basic information on surface elevation and slope is obtained by standard topographical surveys, which rely on techniques of ground-based surveys such as total stations or leveling. However, more sophisticated approaches, e.g., LiDAR (Light Detection and Ranging) and aerial photography, provide high-resolution information about the topography of the surface, which makes the modeling of water flow and fracture behavior more accurate [34].

Table 2. Comparative overview of topographical and near-surface/subsurface monitoring techniques used for fracture-water pathway assessment in coal mines.

Technique	Resolution	Accuracy	Applications
LiDAR	High resolution (sub-meter)	Very high	Used for precise surface elevation and slope measurements.
Aerial Photography	Moderate resolution	Moderate	Useful for large-scale surface mapping and identifying drainage patterns.
Seismic Reflection	Subsurface imaging	High for deep layers	Identifies faults and fractures in coal seams and surrounding strata.
Ground-Penetrating Radar (GPR)	Moderate resolution	High for shallow depths	Effective for mapping near-surface fractures and voids.

In specific instances, LiDAR technology is being utilized more and more in the production of detailed three-dimensional models of the surface landscape [35]. Such models can be combined with geological data and can give a more precise estimate of the potential effects of topographical features on fracture propagation and water migration. LiDAR data enables engineers to detect small changes in elevation, slope, and drainage that would otherwise be missed when using conventional surveying techniques, because it captures surface details in a high-resolution format. This is more critical in complicated terrain or topography that tends to change at a high rate, such as mountainous or flood-prone areas.

Besides surface mapping, subsurface topographical characteristics also play an important role in the effects of hydraulic fracturing on aquifers [33,36]. Seismic reflection, ground-penetrating radar (GPR), and borehole imaging are methods by which the subsurface structures, including faults, fractures, and aquifers, can be imaged. Seismic surveys are usually employed to determine the direction and the magnitude of fractures and faults in the layers of rock. These data will shed more light on the way fractures can spread and where water can be directed, allowing more precise predictions of the impact that hydraulic fracturing will have on the subsurface environment.

Another useful method of measuring the topography of the surface ground is the ground-penetrating radar (GPR), which is applicable when working in shallow coal seams or also in close aquifers that are near the surface [37]. Fractures and voids and other structural features that may affect the migration of water can also be detected by GPR. Borehole imaging, where cameras or sensors are installed in holes dug into the ground, gives a direct perception of the ground and makes it possible to determine the networks of fractures and fluid routes in real-time. A combination of these methods will give a complete picture of what the subsurface environment looks like, and this is essential in streamlining hydraulic fracturing activities and reducing possible risks associated with water.

3.3. Integration of Topographical Data with Geological Models

In order to properly coordinate aquifer hydraulic fracturing, topographical information should be combined with geological models to generate the full picture of the underground environment. By combining geological and topographical data, it is possible to make even more precise predictions of the behavior of fractures and the flow of water through the coal seam and other strata. As an illustration, geological models that contain details on the characteristics of rocks, fracture networks, and aquifer characteristics may be integrated with topographical models to forecast the manner in which water will be drawn or repelled away during hydraulic fracturing processes [38,39].

Simulation of fracture propagation under the influence of hydraulic pressure and topographical constraints is one of the main advantages of combining geological and topographical information [40]. Using terms like surface elevation, slope, and drainage patterns, engineers are able to formulate hydraulic fracturing processes that limit the chances of water inflow or water pollution of the nearby water bodies. It is also possible to identify areas that can be especially susceptible to water movement through this method, including areas around natural water bodies or sensitive ecosystems.

Topographical data are combined with geological models with the help of advanced simulation tools, including coupled hydromechanical models. The models consider not only the mechanical properties of the rock (e.g., strength and fracture behavior), but also the hydrological properties (e.g., permeability and porosity) to model the way in which the fractures will propagate under various conditions. With the inclusion of topographical information, these models are able to predict the flow of water inside the fractures and how the fractures will react with the existing aquifers or surface water systems. Simulation outcomes can be used to design fractures and water management policies, as well as in environmental risk reduction [8].

Topographical information combined with a geological model also helps in a better decision-making process as far as mine design and water management are concerned. Through knowledge of topographical variables that affect water movement, engineers will be able to maximize the fracture location, lessen the chances of water intrusion, and minimize the effects of hydraulic fracturing on the environment in the area. Such practice will allow adopting a more comprehensive and efficient management strategy to make sure that hydraulic fracturing is efficient and environmentally friendly [41,42].

3.4. Topographical Considerations for Environmental and Safety Risk Management

Topographical considerations should be part of dealing with the environmental and safety risks of hydraulic fracturing of aquifers. The steepness of slopes, closeness to surface water bodies, and flood-prone areas are some of the surface characteristics that may increase the likelihood of water-related risks, including groundwater contamination, water influx, and surface subsidence. Using these topographical characteristics as a guideline when designing hydraulic fracturing activities, the engineers can come up with strategies that would avert these dangers and safeguard the mine location as well as the environment around the mine [43].

In other words, development of barriers like impermeable layers or water diversion channels can be used to divert water to areas that are insensitive or to stop water migration to the aquifers. On the same note, fractures can be designed to fit in such a way that they do not intersect with surface water bodies or sensitive groundwater areas. On-site up-to-date tracking of surface elevation and water level is also essential in identifying the possibility of any topographical changes that can be taken as a sign of a threat, including subsidence or water build-up [31].

Finally, topographical analysis and geological modeling are key factors in the management of hydraulic fracturing of aquifers in coal mining [44]. Through the investigation of the topography and the way it affects water migration, fracture patterns, and mine stability, engineers will be able to streamline the hydraulic fracturing processes, reduce their environmental footprint, and improve the safety performance. The availability of the optimal topographical mapping and monitoring methodology, coupled with the sophisticated modeling software, offers the requisite structure for controlling the intricate bond between surface and underground characteristics during hydraulic fracturing in coal mines.

4. Coupling Geological and Topographical Data for Fracture Management

The combination of geological information with topographical information into a single system constitutes an important contribution to the control of the hydraulic fracturing of aquifers in coal mine engineering [5,13]. The process of interaction between geological and topographical features is complicated, and knowledge of how these factors impact one another during the process of hydraulic fracturing is important to effective water management and fracture control. Assessment of geological data with lithology, permeability, and fracture networks with topographical data, including surface elevation, slope, and drainage pattern, enables the prediction of water flow, fracture propagation, and the stability of the mine in general to be more accurate. The significant benefits and pragmatic limitations of coupled models are condensed in **Table 3**. In this section, the advantages, methods, and strategies of integrating geological and topographical information to optimize hydraulic fracturing operations and avoid risks related to the management of aquifers are discussed.

4.1. Benefits of Coupling Geological and Topographical Data

The interdependence of geological and topographical information facilitates a better insight into the underground environment and fracture behavior during hydraulic fracturing [45]. Among the most significant advantages of the incorporation of these sets of data, one can single out the possibility to estimate the flow of water in the mine and the adjacent aquifers with higher precision. Geological information might not give enough information about how the fractures will relate to the surface features or the way water will move within the underground environment. On the same note, topographical information alone may not be sufficient to explain the intricacies of the fracture systems in the subsurface. The combination of the two datasets can help engineers develop more realistic and dynamic representations of the subsurface and perform water inflow, groundwater contamination, and fracture control in a better way.

Table 3. Benefits and implementation challenges of coupled geological–topographical frameworks for aquifer hydraulic fracturing management.

Aspect	Benefits	Challenges
Improved Prediction	Enhanced accuracy in predicting fracture and water flow behavior.	Requires high-quality, consistent data from both domains.
Optimization of Fracture Design	Enables more precise placement of fractures to minimize risk.	Difficulty in integrating data with varying spatial and temporal scales.
Environmental Risk Mitigation	Helps identify potential environmental hazards and prevent groundwater contamination.	Uncertainty in the interaction between subsurface features and fractures.
Operational Efficiency	Optimizes water management and fracture fluid injection.	Complexity in modeling the integration of multiple datasets.

Besides enhancing the accuracy of predictions, coupled data schemes enhance the optimization of the design and location of hydraulic fractures [46]. The topographical properties of the surface, like slope, elevation, and water drainage pattern, affect the propagation of fractures and the flow of water, and such properties should be considered when designing fractures. By combining both geological and topographical data, it is possible to make more specific judgments regarding the location of fractures where they should be targeted, the way in which water injection should be carried out, and the mechanism by which unwanted water migration may be avoided. This will decrease the possibility of water-related problems like over-increase of water inflow, contamination of the aquifer, and disruption of surface water, enhancing the efficiency and safety of hydraulic fracturing processes.

The other important benefit of combining geological and topographical information is the greater capacity to handle mine stability and avoid any environmental harm [47,48]. Using the subsurface fracture data with the surface elevation and hydro data, the engineers are able to foresee the likelihood of subsidence, water pool formation, or a possible fracture penetration of delicate aquifers. Such foresight enables the adoption of mitigation measures that include the containment of fractures, water diversion systems, and structural reinforcements to significantly reduce the damage that hydraulic fracturing inflicts on mine stability and the ecosystem around the mines.

4.2. Techniques for Data Integration

To combine geological and topographical data in a combined system, one will need to apply multiple sophisticated methods and tools. Geographic Information Systems (GIS) are usually utilized to integrate geological and topographical information into one model. GIS enables the spatial analysis of both surface and underground data to give a platform through which one can visualize the correlation between the geological property and topographical features. GIS allows engineers to study the interaction and effect of these factors and their impact on hydraulic fracturing behavior by overlaying geological data (type of rocks, permeability, fracture networks, and so on) with topographical data (elevation, slope, drainage, etc.) [49,50].

Besides GIS, numerical simulation and coupled hydromechanical models will be required in addition to integrating geological and topographical information [51]. These models consider both the mechanical characteristics of the subsurface (e.g., rock strength and fracture behavior) and the hydrological characteristics (e.g., permeability and porosity) where engineers are able to model fracture propagation, water flow, and the possible effects on the surrounding aquifers and surface water systems. Using elevation and slope of the topography in these simulations, engineers are able to simulate the interaction of fractures with the surface characteristics and the movement of water over the mine location. The findings of the simulations will be applicable to fracture design, water management policy, and environmental mitigation risks.

The other technique that can be used to integrate data is the use of 3D geological models, which are a combination of topographical and geological data [52]. These are three-dimensional representations of the subsurface mine that show the rock strata and fractures, the aquifer, and the elevation and slope of surface features. By combining geological and topographical data into one 3D model, engineers can see the way fractures will spread and water will move through the system and thus are able to make more precise predictions of the hydraulic fracturing behavior. These models will be applicable to estimate the effects of various fracturing methods, examine the possible risks and optimize water management practices.

Furthermore, technologies in real-time monitoring, including remote sensing, seismic monitoring, and borehole sensors, would be beneficial in increasing the integration of the geological and topographical data [53]. These surveillance sensors give real-time feedback on the subsurface environment, e.g., changes in surface elevation, propagation of fractures, and water movement. There are also benefits of constant updating of geological and topographical models with real-time data, which would enable engineers to make better decisions in the process of hydraulic fracturing, as the placement of the fractures, the rate of water injection, and the reduction of risks could be modified in real-time.

4.3. Case Studies and Applications of Coupled Data Frameworks

Several case studies and real-world applications have demonstrated the effectiveness of coupling geological and topographical data for managing aquifer hydraulic fracturing in coal mines. A stepwise workflow from data acquisition to operational decision support is summarized in **Figure 1**. The combination of detailed geological surveys and high-resolution topographical mapping in certain areas has enabled engineers to predict fracture behavior more precisely and eliminate the possibility of movement of water to the adjacent aquifers. An instance is that in the mining of coal in mountainous areas, the application of LiDAR information in modelling surface elevation, slope, etc., has assisted engineers to create hydraulic fractures that do not pass through sensitive aquifers or surface water. The addition of geological information about rock strength and fracture networks contributed to the further development of the capabilities to predict the manner in which fractures will spread, resulting in increased control and efficiency of fracturing [54].

In a different study, the application of coupled numerical models, which incorporated geological and topographical information, allowed engineers to streamline water management plans in coal mines located close to recharge areas. The simulations of the water migration patterns based on geological and topographical data allowed the engineers to discover possible directions that water could move in aquifers and develop strategies to reduce this threat. This involved designing a specialized fracture that minimized water inflow and the introduction of surface water diversion systems, which diverted the water run-off from the sensitive location. The effectiveness of these measures on groundwater pollution prevention and control of water flow proves the importance of the combination of geological and topographical data used in hydraulic fracturing processes [55].

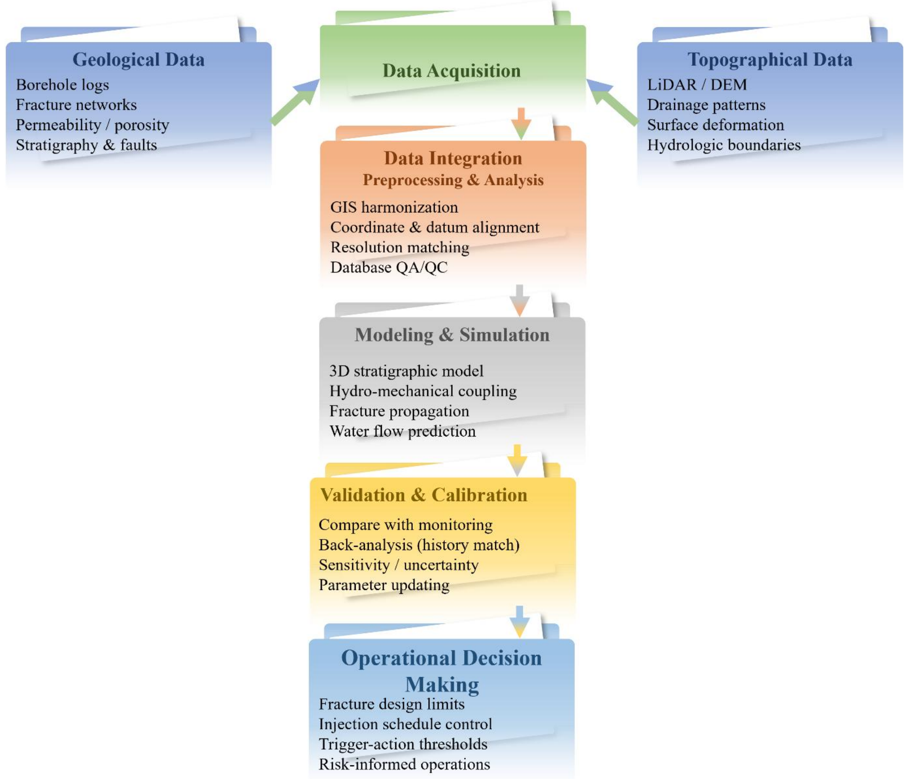

Figure 1. Workflow for coupled geological–topographical integration from data acquisition and preprocessing to modeling, validation, and operational decision support.

According to these case studies, coupled data structures are practically helpful in enhancing the management of fractures, reducing the environmental risk, and improving operational efficiency. Integrating the data on geology with the information on topography, the engineers can more easily predict possible problems, focus the fracturing methods, and make evidence-based decisions that can safeguard the mine and the environment around it.

4.4. Future Directions for Coupled Frameworks

With the continued development of knowledge of the intricate interaction between geological and topographical factors, there is great potential for additional development in coupled data structures. The prospective studies can emphasize the creation of more advanced modeling tools that would use real-time data and predictive analytics to enhance the reliability of fracture behavior forecasting. Also, the use of new technologies, including machine learning and artificial intelligence, can be beneficial for the possibility to analyze large amounts of data and discovering trends that could not be distinguished before. These new technologies may bring about even better and more sustainable hydraulic fracturing processes, having lower risks to aquifers and the environment [56].

Further evolution of high-resolution monitoring instruments and remote sensing technologies will also be significant in the process of improving coupled geological-topographical frameworks[57]. These technologies will allow engineers to make better decisions and respond faster to changing conditions during hydraulic fracturing operations because they will be able to provide real-time and detailed information regarding surface and subsurface conditions. With the improvement of these tools, they will go even a notch higher to enhance the management of aquifer hydraulic fracturing of the coal mines, and eventually result in safer, efficient, and environmentally friendly mining activities.

To sum up, the application of geological and topographical data, as well as their integration into a coupled system, is an efficient tool in the management and control of hydrofracturing of the aquifers during coal mining[58]. With the combination of both data sets, the engineers will be able to design the fractures more efficiently, enhance water management procedures, and minimize the risks of groundwater contamination and water inflow. Further improvement of the efficiency of this method will be achieved by the further evolution of sophisticated modeling techniques, monitoring means, and data integration methods, which will lead to more efficient and sustainable coal mining operations.

5. Challenges and Considerations in Managing Hydraulic Fracturing

Regardless of the high progress in integrating geological and topographical data to manage hydraulic fracturing of aquifers, there are a number of issues that exist in the quest to make these processes effective and safe. These complications are associated with the natural complexity and ambiguity of the geological and topographical fields and with the challenges of merging and reconciling data of various origins. Moreover, the environmental and safety issues should also be well managed in order to avoid negative effects, such as groundwater contamination, surplus water inflow, and subsidence. This part will look at the key issues and concerns that should be considered in the process of overseeing aquifer hydraulic fracturing in coal mines, including uncertainty in data, environmental risks, safety issues, and constraints of the existing modeling methods[59–61].

5.1. Uncertainty in Geological and Topographical Models

The uncertainty of geological and topographical models is one of the main problems in the management of the aquifer hydraulic fracturing[62]. Geological and topographical data tend to be highly variable and spatially heterogeneous in nature, and therefore, fractures and water flow behaviour can be difficult to predict with a high degree of accuracy. Geological models rely on borehole, seismic survey, and geological map data, although the quality and/or resolution of such information may be quite different. There is a possibility of inaccurate or sparse data, and thus, models created may not fully represent the complexity of the subsurface environment, which may not provide accurate predictions of fracture behaviors and water movement.

Topographical data, vital in interpreting features on the surface as well as water movement, also creates uncertainty owing to constraints in resolution and methods of measurement[63]. As an example, LiDAR or remote sensing surface elevation data can be subject to some error based on atmospheric conditions, sensor constraints, or terrain complexity. Equally, topography (fractures and faults) that exist in the ground might be hard to detect and map precisely, particularly in deep or highly fractured coal seams. Such ambiguity in geological and topographical information may impede the process of accurate forecasting concerning the outcomes of hydraulic fracturing and the water management plans.

In order to eliminate these uncertainties, engineers tend to use sensitivity analysis and the methods of uncertainty quantification to evaluate the effects of the changes in the input data on the predictions of fracture behavior and water flow[64]. Such techniques are useful in determining which parameters are of the utmost importance and affect the result of hydraulic fracturing and dictate the development of more durable fracture models. Nevertheless, despite sophisticated methods of quantifying uncertainty, there will always be some amount of risk in the process of predicting the behavior in the subsurface, and these uncertainties need to be taken into great care during the process of making a decision.

5.2. Environmental Risks and Groundwater Protection

The management of aquifer hydraulic fracturing is sensitive to the environment, especially as far as the protection of groundwater is concerned [65]. The mining activities, particularly coal mining, including the hydraulic fracturing method, can pose a great threat to the nearby aquifers and the surface water systems. The risk of groundwater contamination, which may arise because of the movement of fracturing fluids or methane into other aquifers, is one of the main issues. **Table 4** summarizes the common environmental risks and mitigation measures that apply to the hydraulic fracturing of coal mines. When fractures move past the target coal seam and touch underlying aquifers, they might open up access points by which contaminants enter the groundwater system and impact drinking water supplies and ecosystems.

Table 4. Representative environmental hazards in mine-related hydraulic fracturing and corresponding mitigation/monitoring strategies.

Environmental Risk	Impact	Mitigation Strategy
Groundwater Contamination	Migration of fracturing fluids or methane into aquifers.	Use of non-toxic fracturing fluids, continuous groundwater monitoring, and well integrity checks.
Water Influx	Excessive water is entering the mine, causing flooding and instability.	Precise fracture design to avoid intersecting water-bearing layers and real-time monitoring of water levels.
Surface Water Disruption	Contamination or depletion of nearby rivers, lakes, or streams.	Implement water diversion systems and control fracture extension towards surface water bodies.
Subsidence	Surface sinking or collapsing due to fracture propagation.	Monitoring of ground deformation and stabilization of mine structures.

These risks are further compounded by the fact that hydraulic fracturing fluids use chemicals. Although several mining firms are making efforts to apply either environmentally friendly or non-toxic chemicals in the mining activities, the possibility of harmful substances percolating to the aquifers is an issue of concern. The fractures propagated uncontrollably in other situations, resulting in unintended contacts between the coal seam, fractures, and adjacent water-bearing formations, which are caused by the pressure formed during the hydraulic fracturing procedure. This may cause movement of the pollutants to the groundwater, which may cause permanent damage to the environment [66].

In order to manage these risks, there is a need to implement effective monitoring and management strategies. This involves frequent monitoring of the water quality in the nearby aquifers and also employing containment measures like impermeable barriers, as well as optimizing fracture designs to reduce the size of hydraulic fractures. Also, regulatory measures and industry standards play essential roles in ensuring that hydraulic fracturing processes are conducted in a manner that leaves the possibility of groundwater pollution to the bare minimum. Although they serve as an effective means of mitigating the risks to the environment, the nature of the conditions at the subsurface makes it hard to fully rule out the possibility of negative effects on the environment [67].

5.3. Safety Concerns and Structural Integrity

Besides environmental hazards, safety is another major factor to be taken into consideration in the management of hydraulic fracturing activities in coal mines [68]. Hydraulic fracturing may also present all sorts of safety risks, especially with regard to mine shaft structural integrity and the rock formation around them. When the fluid is injected into the underground at high pressure, it may cause fractures to suddenly enlarge, causing ground instability, subsidence, or mine walls to collapse. These events may be a great hazard to the security of employees and even the stability of the mine itself.

Another significant safety issue with hydraulic fracturing processes is water influx [69]. When fractures suddenly overlay aquifers or water-bearing formations, the effect may be an uncontrolled inflow of water into the mine. This can be overwhelming, as mine shafts pose dangerous working conditions and high chances of equipment breakdown or structural damage. During hydraulic fracturing, the flow of water and the possibility that the fractures run into water-bearing layers can be managed to make the mines safe.

Among the most important issues of providing safety is the correct forecast of the fracture and water movement behavior inside the mine [70]. As has been mentioned above, geological and topographical models are commonly associated with uncertainty, and the uncertainties might result in unforeseen consequences of the fracturing activity. In order to reduce the risk of safety, real-time monitoring systems are more frequently utilized to be able to identify changes in fracture behavior, water flow, or stability. **Figure 2** illustrates the inclusion of an integrated risk pathway between failure modes and monitoring and mitigation actions. These monitoring systems will be able to offer useful feedback in the hydraulic fracturing process so that the engineers will have to make changes in the process. Nevertheless, despite the sophisticated monitoring, the uncertainties of the situation in the subsurface imply that a sound safety concern is always required and must be addressed proactively[71,72].

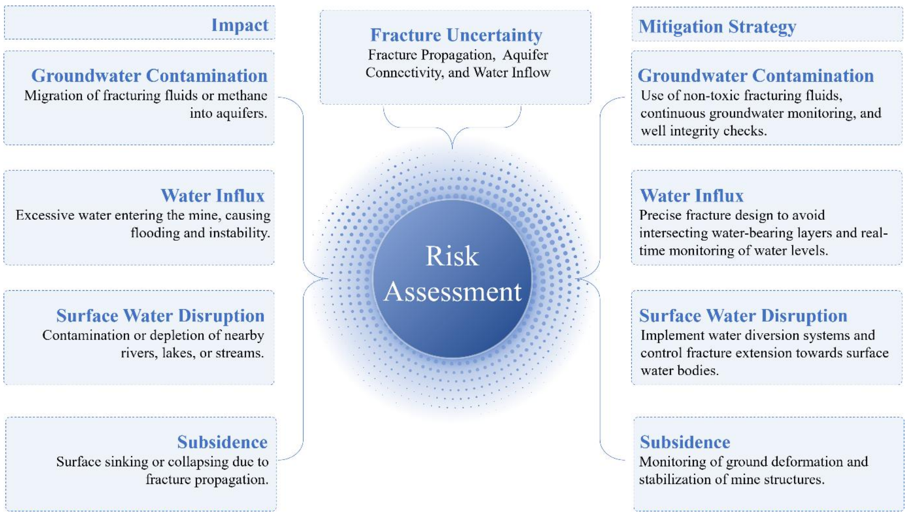

Figure 2. Risk pathway and mitigation logic linking fracture growth uncertainty, hydraulic connectivity, monitoring triggers, and response actions for environmental and safety protection.

5.4. Limitations of Current Modeling Techniques

Although geology and topographical models on hydraulic fracturing have gone a long way, some of the weaknesses in the modeling methods are still evident and need improvement. Lack of ability to properly represent the complexity of subsurface fracture networks and fluid flow behavior is one of the largest challenges. Even state-of-the-art numerical simulations and coupled hydromechanical models may have a hard time capturing the interactions between fractures, water and the surrounding geological formations, particularly in regions with very heterogeneous or fractured rock strata[73].

Also, the resolution of geological and topographical data often hinders the integration of such data in a coupled model due to the differences in the resolution of the data and the method of measurement and their spatial scales. Boreholes or seismic surveys are usually used to gather geological data, and topographical data is usually obtained by means of surface measurements or remote sensing. These data sources can be inaccurate and resolvable to varying degrees, and this can cause inconsistencies in the coupled models. Additionally, the actual geological conditions are too complicated for models to be constantly updated with new information and therefore need constant monitoring and modifications[74].

Some of these limitations can be overcome by the development of more advanced methods of modeling, such as machine learning and artificial intelligence. These technologies are able to aid in the analysis of huge datasets, discern patterns in complicated subsurface settings, and enhance the quality of geological and topographic designs. Nevertheless, the methods are still in their infantile stages of development, and more studies are required to help them in practice in hydraulic fracturing management[75].

5.5. Regulatory and Legal Considerations

Lastly, the regulatory and legal factors are very important in the regulation of coal mine hydraulic fracturing of aquifers[76]. Hydraulic fracturing is also exposed to a broad scope of local, national, and global regulations that oversee hydraulic fracturing impacts, safety, and operational practices. Such laws aim to preserve groundwater, limit the harm to the environment, and safeguard the health and lives of employees and the people. Nevertheless, the regulatory environment may be tricky and extremely different in different jurisdictions.

The adherence to regulatory rules is a critical step toward the implementation of hydraulic fracturing operations in an environmentally responsible and safe way [77]. Nonetheless, the mining firms can face some problems with the complexity of the regulations and with the changing character of the legal framework. Also, there can be discrepancies in the interpretation or enforcement of regulations, which causes ambiguity to businesses with operations in more than one region.

To overcome these threats, mining organizations should be constantly informed about the changes in the regulatory framework and make sure that their hydraulic fracturing processes do not violate all the existing regulations and norms. Companies can also be challenged through legal or public scrutiny in the environmental issue of hydraulic fracturing in some instances. Thus, active interaction with regulators, communities living near the company, and environmental protection organizations is the key to having the social license to operate and preventing lawsuits or damage to the company's reputation [78].

The hydraulic fracturing of the aquifer in coal mining is a complicated and multidimensional issue that needs to be managed concerning a variety of geological, topographical, environmental, safety, and regulatory issues. The geological and topographical models, environmental risks, safety hazards, and constraints in the existing modeling techniques all pose a big challenge to successful fracture management. Nonetheless, the future of predicting and controlling the results of hydraulic fracturing is on the rise due to data integration, real-time monitoring, and modeling methods. To make hydraulic fracturing in coal mines even more successful, it is necessary to engage in research, technological development, and cooperation among the stakeholders and regulators in the industry [13,79].

6. Conclusions

To sum it up, the relationships between geological and topographical factors are complex and need to be properly understood to manage the aquifer hydraulic fracturing in coal mine engineering. Through the integration of geological information, e.g., lithology, permeability, and fracture networks, and topographical information, e.g., surface elevation, slope, and drainage patterns, engineers will be able to optimize hydraulic fracturing operations, enhance water management strategies, and reduce risks associated with water inflow, groundwater contamination, and mine stability. Such a combined method allows predicting changes in the fracture behavior, the water flow, and the possible effects on adjacent aquifers and ecosystems, and results in more efficient and environmentally friendly coal mining processes.

There are, however, many challenges that arise despite the tremendous development in the incorporation of geological and topographical information. These are the uncertainties in geological and topographical models, the complexity of fracture behavior, and the problems in making a precise prediction of water flow and fracture propagation. Also, issues like environmental and safety, such as the protection of groundwater, water influx, and structural integrity of the mine, should be well taken care of during the process of fracturing. To overcome these obstacles, modeling techniques, real-time monitoring tools, and data integration methods need to be continuously developed in order to make hydraulic fracturing management more accurate and reliable.

In the future, one can expect the emergence of more advanced technologies that can address certain shortcomings of the existing modeling methods, including machine learning and artificial intelligence. These innovations have the potential to further improve the management of aquifer hydraulic fracturing in coal mines by working to improve the precision of its prediction and permitting the analysis of data in real-time. Moreover, continuous industry, regulatory and environmental agency research and collaboration will be needed to balance the regulatory complexity and provide the long-term sustainability of hydraulic fracturing activities.

In the end, successful integration of geological and topographical information in controlling hydraulic fracturing of the aquifers is a crucial move to more effective, safer, and environmentally friendly mining of coal. Since the field is still undergoing changes, the lessons learned through the integration of frameworks will be used to inform future practices and inform future innovation that will not only benefit the coal mining industry but the people who live in the area served by the industry.

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