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Hydrogeological risk assessment of tunnel excavation using a hybrid AHP-AI model: a case study

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ABSTRACT

This study investigates the hydrogeological impacts of the Bazideraz water transfer tunnel on the spring discharge of the Sarab Garm Spring in western Iran, a critical local water resource. A hybrid methodology is developed, integrating the Analytic Hierarchy Process (AHP) with Artificial Intelligence (AI) techniques, which are employed to refine the weights assigned to critical parameters. Fourteen key factors—including karst development, rock permeability, and fault influences—are assessed to quantify the risk of reduced spring discharge due to tunnel excavation. The AHP facilitates structured pairwise comparisons, while AI methods enhance the validation of these weights. The calculated risk index ® for Sarab Garm Spring is found to be 257, categorizing it within the moderate-to-high risk range and indicating a significant likelihood of flow reduction if no mitigation measures are implemented. Sensitivity analysis reveals that karst potential and rock mass permeability are the most influential factors affecting risk. These findings underscore the importance of geological structures, karst features, and aquifer-tunnel interactions in assessing spring vulnerability. This research provides a robust, data-driven tool for proactive pre-construction risk assessment. It supports sustainable tunnel design by informing targeted mitigation strategies to ensure water security and environmental protection in complex hydrogeological settings.

KEYWORDS

Tunnel excavation, spring discharge, hydrogeological risk, AHP, artificial intelligence, Bazideraz, Karst, Zagros

I. INTRODUCTION

This study addresses challenges related to potential groundwater loss due to tunneling activities, specifically the lack of integrated models for assessing hydrogeological risks in the context of complex geological formations. Sustainable groundwater management is critical in mountainous and semi-arid regions where springs serve as primary water sources for domestic, agricultural, and ecological needs. The construction of large-scale hydraulic infrastructure, such as water transfer tunnels, poses significant risks to these vital resources by disrupting natural hydrogeological regimes. This disruption can lead to altered groundwater flow paths, reduced discharge rates, and potential depletion of nearby springs.

The Bazideraz water transfer tunnel, a key component of the Garmsiri water transfer scheme in western Iran, is designed to divert water from the Sirvan River basin to agricultural plains experiencing water scarcity. Spanning approximately 8,390 meters in length and 5.5 meters in diameter, the tunnel traverses geologically complex terrain, including multiple stratigraphic units such as the Gurpi, Pabdeh, Asmari, and Gachsaran formations. Each of these formations presents unique permeability characteristics, karstification potential, and tectonic deformations, necessitating a thorough assessment of the tunnel's hydrological impacts.

Previous studies have documented risks associated with tunneling activities, including aquifer drawdown, spring depletion, and structural instabilities resulting from changes in hydraulic gradients. However, there remains a gap in integrated methodologies that effectively quantify these risks in relation to specific geological and hydrological contexts.

This study focuses on the potential impacts of the Bazideraz tunnel on regional springs, with particular emphasis on the Sarab Garm Spring, a significant water source in the area. A hybrid analytical approach, combining the Analytic Hierarchy Process (AHP) with Artificial Intelligence (AI) techniques, is employed to evaluate the risks associated with tunneling. Specifically, this research employs Artificial Neural Networks (ANN) optimized by Particle Swarm Optimization (PSO) in conjunction with AHP due to their effectiveness in handling complex, multi-criteria decision-making scenarios. The AHP facilitates structured pairwise comparisons to derive the relative weights of various

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factors, while ANN-PSO optimizes these weights and enhances the model's predictive capabilities. This integrated framework allows for a more nuanced understanding of the interrelated factors influencing groundwater vulnerability during tunnel excavation.
The specific objectives of this study are to:

1. Characterize the geological and hydrogeological settings along the tunnel alignment.
2. Evaluate the vulnerability of confined springs, particularly Sarab Garm, to excavation activities.
3. Implement a risk-based decision model to quantify the impacts of tunneling on spring discharge.
4. Provide mitigation strategies aimed at ensuring water security and environmental protection.

The novelty of this research lies in its application of a hybrid AHP-AI framework to assess the hydrological risks associated with tunneling in the context of the Iranian Geology. This methodology not only enriches existing studies by incorporating expert-derived weights for various risk factors but also employs AI techniques for dynamic risk assessments, enabling real-time monitoring and adjustments based on field data.

By leveraging this multi-criteria decision-making framework, this research aims to offer a practical and scientifically robust method for pre-construction risk assessment, supporting sustainable tunnel design and contributing to effective groundwater management in complex hydrogeological environments.

II. Literature Review

The excavation of tunnels in hydrogeologically sensitive regions carries inherent risks related to groundwater inflow, potentially disrupting aquifer systems, reducing spring discharge, and affecting water quality (Yoo, 2016; Jiang et al., 2018; Zhang et al., 2019). The magnitude of these impacts depends on several factors, including tunnel depth, excavation methods, and the permeability of the surrounding rock mass.

Building on early studies focused on empirical observations and analytical solutions (Katibeh & Aalianvari, 2012; Farhadian, Aalianvari, & Katibeh, 2012), recent research has increasingly emphasized numerical modeling and advanced risk assessment techniques. Numerical simulations allow for a more detailed understanding of groundwater flow patterns and drawdown effects (Niu et al., 2017; Liu et al., 2020), while risk assessment frameworks help identify vulnerable areas and prioritize mitigation measures (DeMatteis & Fissore, 2001).

Farhadian has made significant contributions to the field of groundwater inflow prediction and mitigation in tunneling projects. His work has focused on optimizing analytical equations for estimating groundwater seepage into tunnels (Farhadian, Aalianvari, & Katibeh, 2012), with a particular emphasis on case studies from Iranian tunnel projects. In a recent publication, Farhadian (2025) explores the strategic placement of minor drainage tunnels to reduce inflow into main tunnels, providing valuable insights for tunnel design and construction practices.

Aalianvari et al (2024) employed sophisticated numerical models to simulate groundwater flow patterns around tunnels, considering the heterogeneity of geological formations. Farhadian et al (2025) explored the use of machine learning algorithms to predict groundwater level changes based on historical data and geological parameters.

Samiei and Aalianvari (2025) developed a hybrid AHP-AI framework that combines multi-criteria decision-making with artificial intelligence algorithms. Their methodology enables the selection, weighting, and integration of critical factors, such as karst potential, host rock permeability, joint aperture, and crushed zone width, into a quantitative risk index ®. The risk level is then categorized into six classes ranging from very low to critical, facilitating preemptive mitigation planning.

However, despite these advancements, several gaps remain in the existing literature. Many studies rely on simplified geological models that do not fully capture the complexity of karst systems and fractured rock masses. Furthermore, few studies have integrated geomorphological factors, such as surface slope and basin area, into their risk assessments, which can significantly influence groundwater recharge and flow patterns.

Moreover, the application of hybrid AHP-AI frameworks to water transfer tunnels in folded and faulted sedimentary zones, particularly in regions like the Zagros Mountains, is limited. While Samiei and Aalianvari (2025) demonstrated the potential of this approach, their study did not specifically address the unique challenges posed by the geological conditions of the Bazideraz Tunnel.
This study aims to address these gaps by:

- Integrating geomorphological parameters into the risk assessment framework.
- Applying a hybrid AHP-AI model tailored to the specific geological and hydrogeological conditions of the Bazideraz Tunnel and the Sarab Garm Spring.
- Providing a practical and scientifically robust method for pre-construction risk assessment and sustainable tunnel design in complex hydrogeological environments.

This review highlights the need for hybrid models that blend theoretical insights, expert knowledge, and field data to produce reliable and practical assessments for groundwater risk management in tunneling projects, particularly in data-scarce environments.

III. Study Area Description

The Bazideraz Tunnel is located in the western part of Iran within the structurally complex Zagros Fold-Thrust Belt, a region known for its diverse geological units and high groundwater potential. This tunnel forms a critical segment of the Garmsiri Water Transfer Project, aimed at diverting water from the Sirvan River basin to downstream agricultural plains with water deficits. The summary of engineering geological parameters of tunnel route and tunnel specification are shown in table 1.

The tunnel alignment traverses several stratigraphic units of the Zagros sedimentary sequence, including:

- Gurpi Formation: Dominated by marl and shale with low permeability.
- Pabdeh Formation: Alternating marl and limestone layers; moderate potential for karstification.
- Asmari Formation: Thick-bedded carbonate rocks with high secondary permeability, known for hosting confined aquifers and springs.
- Gachsaran Formation: Evaporitic layers (gypsum, anhydrite) with low permeability; often problematic for tunnel stability.
- Aghajari Formation: Sandy-clayey units; generally less permeable.

These formations are disrupted by folding, faulting, and jointing, with clear evidence of tectonic stresses such as thrust faults and crushed/fractured zones, especially near anticline hinges. This structural complexity creates favorable conditions for confined flow and spring emergence, particularly at lithological boundaries (Fig.s 1 & 2).

Table 1. The summary of the engineering geological parameters of the tunnel route and the tunnel specification

	Length	Diameter	Entrance elevation	Exit elevation	
	8,390 meters	5.5 meters	1,547 m.a.s.l	1,540 m.a.s.l	
Lithology	Aqajari Formation	Gachsaran Formation	Asmari Formation	PAbdeh Formation	Gurpi Formation
RQD (AVG)	50	82	87	92	43
RMR (Avg)	65	50	70	55	55

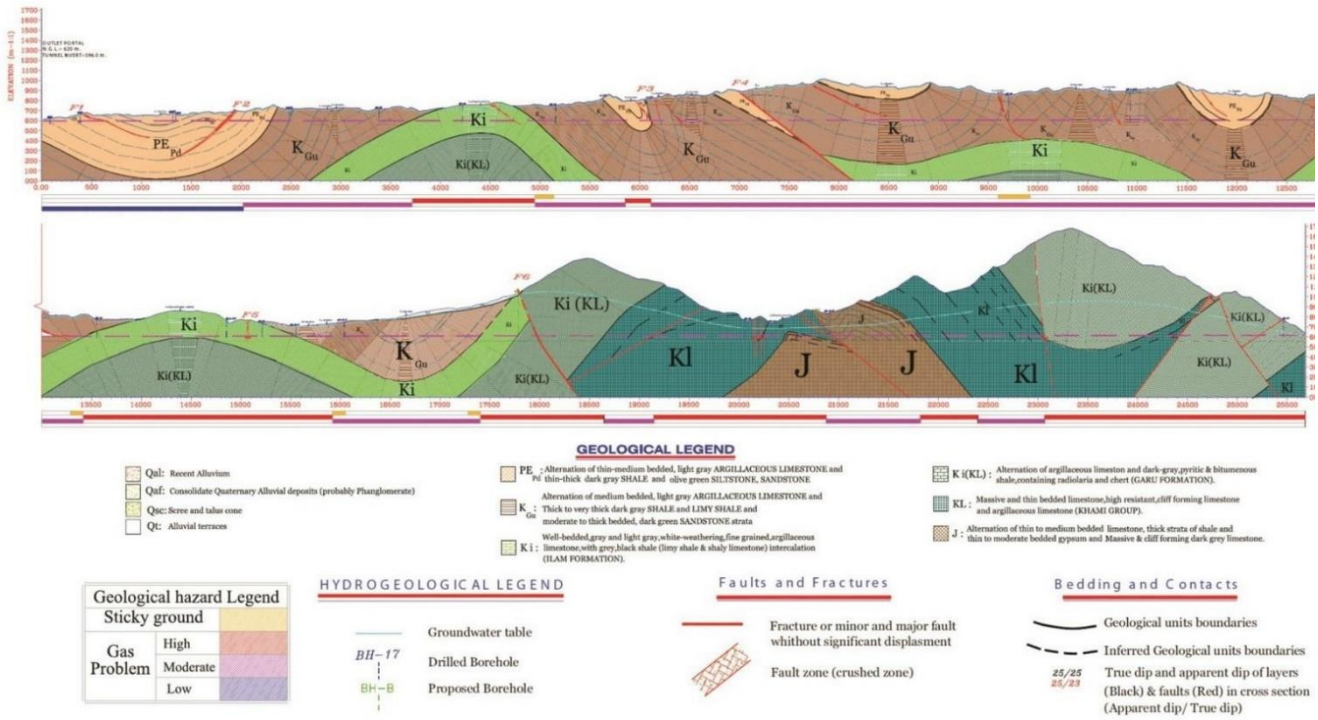

Fig. 1. Longitudinal geological profiles of tunnels in the Zagros Fold–Thrust Belt, comparable to the Bazideraz Tunnel site (Salimi et al., 2019)

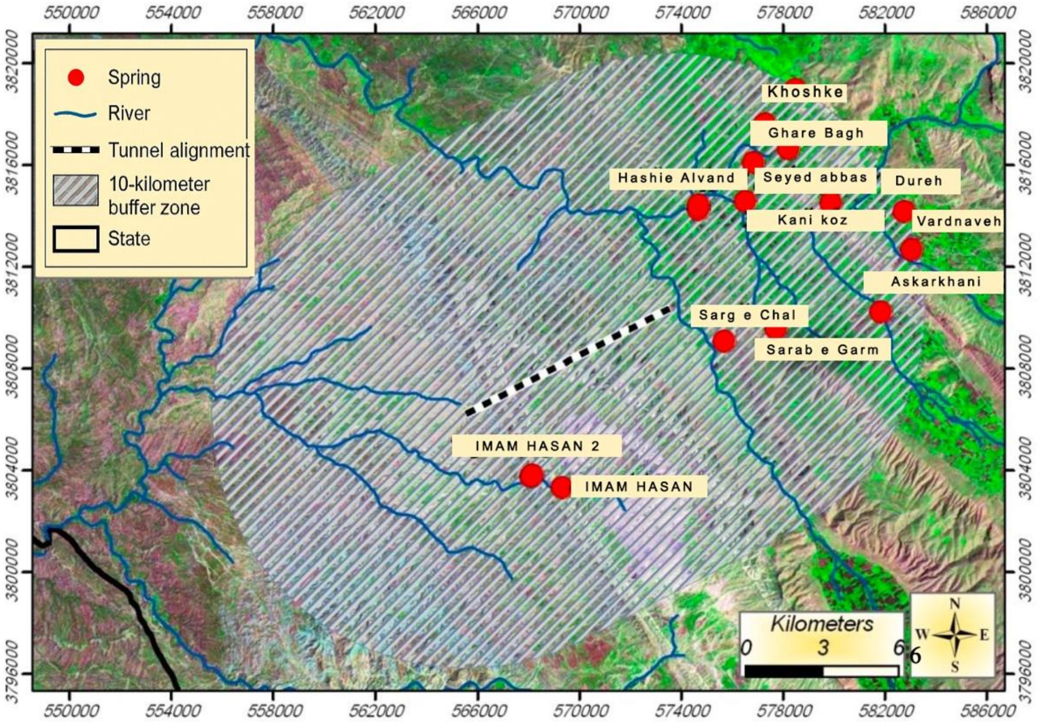

Fig. 2. Spatial relationship between springs and Bazideraz Tunnel (Prepared by authors based on project data, 2014).

A. Hydrogeological Conditions

The region is hydrogeologically active, with several springs—most notably the Sarab Garm Spring—located near or above the tunnel path. This spring shows characteristics of a confined karstic source, fed by deep flow systems under pressure.

Key hydrogeological features include:

- High variability in permeability across formations.
- Presence of fault-fracture systems connecting deep aquifers to surface discharge zones.
- Groundwater level gradients aligned with regional topography and structural dips.
- Observed seasonal and long-term variability in spring discharge, potentially linked to geological disturbances or upstream water abstraction.

B. Potential Vulnerability

Given the presence of highly permeable karst units (e.g., Asmari), fractured rock masses, and tectonic features near the tunnel route, there is significant risk of groundwater inflow into the tunnel and drawdown in connected springs. The Sarab Garm Spring, due to its elevation and hydraulic connection with deeper confined units, is especially vulnerable to tunnel-induced depressurization.

In subsequent sections, these geological and hydrogeological parameters are integrated into a quantitative risk model to assess the potential impact of tunnel excavation on spring discharge, using a hybrid AHP–AI framework.

IV. METHODOLOGY

This study adopts a hybrid decision-making framework that integrates the Analytic Hierarchy Process (AHP) with Artificial Intelligence (AI)-based optimization to assess and quantify the hydrogeological risks of tunnel excavation, specifically the potential impact on Sarab Garm Spring and surrounding groundwater systems along the Bazideraz Tunnel alignment.

The Drawdown Hazard Index (DHI) is introduced to quantify the risk of spring flow reduction or depletion resulting from tunnel-induced depressurization. It is calculated based on geological and hydrological parameters such as karst development, rock permeability, and fault zones, reflecting the vulnerability of a spring to reduced discharge due to tunneling activities

A. Framework Overview

The methodology involves four main steps:

1. Parameter Identification and Classification
2. Expert-Based Weighting via AHP
3. Risk Index Calculation
4. Risk Classification and Mapping

B. Parameter Identification and Classification

Based on literature review, geological field investigations, and previous studies on tunnel-induced groundwater disturbances, 14 critical parameters were selected for evaluation. These parameters include both intrinsic geological-hydrogeological characteristics and tunnel-related design factors (see Table 2):

Table 2. Selected parameters and their risk influence domains

Category	Parameter
Karst Features	Karst Development, Rock Type
Hydraulic Factors	Host Rock Permeability, Groundwater Level, Rock Mass Permeability
Structural Features	Crushed Zone Width, Fault Type, Fracture Intersected by Fault
Discontinuity Data	Joint Frequency, Aperture, Gouge Material
Geomorphology	Surface Slope, Basin Area
Weathering	Rock Weathering Degree

Geomorphological parameters such as surface slope and basin area are critical as they influence surface runoff and groundwater recharge dynamics, significantly affecting hydrogeological risk assessments.

C. *Weight Assignment Using AHP*

An AHP-based pairwise comparison matrix was constructed using expert evaluations gathered via a structured questionnaire distributed to 100 specialists (35% PhDs, 65% MScs) in hydrogeology, geotechnics, and tunnel engineering.
Steps:

- Pairwise comparison matrix constructed based on the relative importance of parameters.
- Normalization of each column and derivation of final weights via row averages.
- Consistency check performed using the Consistency Ratio (CR), where $CR < 0.1$ indicates acceptable reliability.

Table 2. Final Parameter Weights

Parameter	Weight (%)
Karst Potential	30
Host Rock Permeability	14
Aperture	12
Rock Type	8
Rock Mass Permeability	8
Crushed Zone Width	6
Fracture–Fault Intersection	4
Joint Frequency	3
Fault Gouge	3
Geomorphology	3
Groundwater Level	3
Basin Area	3
Fault Type	2
Weathering Degree	1

D. *Risk Index Calculation*

Each parameter was assigned a score (P_i) from 1 to 5 based on its measured or observed value, following classification schemes (e.g., permeability classes, aperture size, karst development level).

The final risk index (R) for any point along the tunnel route is calculated as:

$$R = \sum_{i=1}^{14} w_i . P_i \qquad (1)$$

Where, w_i is the weight of parameter i (from AHP), and P_i is the score of parameter i.

E. *Risk Classification*

Based on the calculated R values, six risk categories are defined (Table 4):

Table 4. Calculated risk value

Risk Level	R Range	Interpretation
Very Low	120–180	No mitigation required
Low	180–240	Routine monitoring recommended
Moderate	240–300	Optimization of excavation methods advised
High	300–360	Preventive measures necessary
Very High	360–420	Immediate mitigation required
Critical	420–480	Potential project redesign or local suspension

F. *Integration with AI*

To enhance predictive accuracy and reduce subjectivity:

- AI algorithms (e.g., Neural Networks, PSO) may be applied for:
  - Optimizing weight adjustments,
  - Sensitivity analysis,
  - Pattern recognition in spatial data.

These tools enable future incorporation of real-time field monitoring data for dynamic risk updates during excavation.

The Artificial Neural Network (ANN) model utilized in this study follows a multi-layer perceptron architecture with one hidden layer containing 10 nodes, using a sigmoid activation function. The network was trained using the Levenberg-Marquardt algorithm. A coefficient of determination (R^2) of 0.85 was achieved for the training set, indicating a high level of prediction accuracy. The network was optimized using Particle Swarm Optimization (PSO) to fine-tune the model parameters."

V. Results and Risk Assessment

A. *Risk Index Calculation for Sarab Garm Spring*

Based on the AHP scoring system and field investigations, the Sarab Garm Spring scored a total risk index (R) of 257, placing it in the "Moderate-to-High Risk" category of the classification scale. The breakdown of parameter scores is as follows (Table 5).

This risk index reflects the combination of high karst development, elevated groundwater levels, and significant fracture systems within a permeable limestone host rock.

Karst Development received a score of 3 due to significant evidence of karst features in the vicinity, including visible sinkholes and rapid drainage observed during site assessments.

Table 5. Calculated Score for springs:

Parameter	Weight (%)	Score (P_i)	Weighted Score
Karst Development	30	3	90
Host Rock Permeability	14	3	42
Aperture	12	2	24
Rock Type	8	3	24
Rock Mass Permeability	8	3	24
Crushed Zone Width	6	2	12
Fracture Intersected by Fault	4	2	8
Joint Frequency	3	2	6
Fault Gouge	3	1	3
Geomorphology	3	2	6
Groundwater Level	3	3	9
Basin Area	3	2	6
Fault Type	2	1	2
Weathering Degree	1	1	1
Total R	—	—	257

B. *Interpretation and implications*

The moderate-to-high risk level suggests that Sarab Garm Spring is likely to experience flow reduction, or in extreme cases, partial drying, if excavation of the Bazideraz Tunnel proceeds without mitigation measures.

Key contributing factors to the high R-value include:

- Well-developed karst systems are characterized by rapid subsurface flow connectivity.
- High rock mass permeability facilitates water loss toward tunnel voids.
- Fracture-fault intersections, forming vertical preferential pathways.
- Proximity to tunnel axis, enhancing pressure gradient interactions.

In parallel, the Drawdown Hazard Index (DHI) value for Sarab Garm Spring is 0.7, which corresponds to the “very high hazard” class. This further confirms the vulnerability of the spring to tunnel-induced depressurization.

C. *Comparative risk among springs*

A summary of risk indices (R) for nearby springs is shown below (Table 6):

Table 6. Summary of risk indices (R) for nearby springs

Spring Name	R Index	Risk Level
Sarab Garm	257	Moderate–High
Emam Hasan	231	Moderate
Sarg-e Chal	103	Very Low
Askarkhani	119	Low
Vardnaveh	100	Very Low
Dureh	114	Low

Sarab Garm Spring emerges as the most vulnerable water source along the tunnel route and warrants protective hydrogeological interventions.

VI. Discussion

The assessment of tunneling impacts using the AHP-AI framework reveals significant hydrogeological risks, particularly for Sarab Garm Spring, due to the tunnel’s proximity to highly permeable and karstified rock formations.

A. *Interpretation of risk profile*

The risk index of 257 places Sarab Garm Spring in the moderate-to-high category, indicating a non-negligible threat to spring discharge continuity. The following factors appear to be the most influential:

- Karst Development (Weight: 30%): The presence of mature karst features in the Asmari Formation suggests extensive conduit flow paths susceptible to drainage toward the tunnel void.
- Host Rock and Rock Mass Permeability (Total Weight: 22%): Field permeability measurements indicate values >10^{-4} m/s, which favors rapid groundwater migration and makes flow interception by the tunnel highly probable.
- Fracture Systems and Crushed Zones: Tectonic structures, including faults intersecting the spring recharge zone, intensify hydraulic connectivity between aquifers and the tunnel path.
- Topography and Groundwater Level: A relatively high potentiometric surface above tunnel grade induces a positive hydraulic gradient, driving water toward the excavated void.

B. *Spatial risk gradient along tunnel*

Risk distribution analysis shows a gradient increase in hydrogeological vulnerability as the tunnel crosses the Asmari–Gachsaran transition zone, where both fractured limestones and plastic evaporitic layers are present. Springs located in this segment (like Sarab Garm and Emam Hasan) exhibit the highest drawdown sensitivity.

C. *Implications for tunnel design and operation*

These findings underline the need for proactive groundwater management before and during tunnel construction:

- Hydraulic Isolation: Pre-grouting or double-lining systems in karstic zones can help prevent inflow.
- Drainage Control: Installing secondary drainage galleries may alleviate pressure build-up and reduce concentrated inflow.

- Real-Time Monitoring: A piezometric network should be established across the spring's recharge zone to detect early signs of drawdown.
- Adaptive Excavation Planning: Tunnel boring should proceed with phased hydrogeological verification, particularly in risk-prone sections.

D. Methodological contribution

This study demonstrates the practical effectiveness of the AHP-AI hybrid model in quantifying the impact of tunneling on groundwater systems:

- The AHP structure enables expert-driven prioritization of factors, accounting for local geological expertise.
- Quantitative scoring and consistency analysis ensure reproducibility and reliability.
- Integration with field data and geological maps yields a risk model tailored to the site's specific conditions.

VII. CONCLUSION

This study assessed the hydrogeological impacts of the Bazideraz Tunnel excavation on nearby springs—particularly Sarab Garm Spring—using a novel hybrid AHP–AI framework. By integrating geological, hydrogeological, and structural data with expert judgment and multi-criteria decision-making, a quantitative risk index (R) was developed to rank vulnerability levels.

Key findings include:

- Sarab Garm Spring was identified as the most vulnerable, with a risk index of 257, placing it in the *moderate-to-high* category.
- The most influential risk factors were karst potential, rock and rock mass permeability, and crushed zone width.
- Springs with strong karst connections and proximity to high-gradient faults were found to be at greater risk of drawdown or flow reduction due to tunnel drainage effects.
- The AHP-AI framework proved effective in synthesizing diverse data sources and supporting risk-informed decision-making for tunneling in sensitive hydrogeological settings.

This work demonstrates that even in data-limited environments, systematic integration of expert insights and field data enables reliable groundwater impact assessment.

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