A Hybrid AHP-AI Framework for Assessing and Mitigating Tunneling Impacts on Confined Spring Discharge

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ABSTRACT

Tunnel excavation poses a significant threat to groundwater systems, particularly impacting confined tunnel springs and jeopardizing hydrological balance and water resource sustainability. This study tackles the challenges of tunnel-induced groundwater changes by introducing a novel hybrid framework. This framework combines expert qualitative insights with advanced quantitative modeling, leveraging the Analytic Hierarchy Process (AHP) and artificial intelligence. Building upon existing research that uses numerical and empirical models to assess tunneling impacts on aquifers and spring discharge, our approach integrates multi-criteria decision-making to identify and prioritize factors driving groundwater loss. We evaluate parameters impacting spring discharge, highlighting the importance of karst cavities, rock mass permeability, fracture aperture, and rock mass type. The proposed model categorizes excavation sites into six impact levels, from harmless to completely hazardous. Key findings underscore the influence of tunnel depth, excavation method, and geological conditions on groundwater drawdown and spring depletion. This framework offers an improved decision model for predicting hydrological consequences, bridging research gaps, and providing practical guidance for mitigating environmental impacts, ensuring sustainable groundwater management, and optimizing tunnel construction.

KEYWORDS

Tunnel Excavation, Confined Tunnel Springs, Groundwater Modeling, Analytic Hierarchy Process, Artificial Intelligence, Environmental Sustainability.

1. Introduction

Tunnel excavation is crucial for modern infrastructure development, supporting transportation networks, utilities, and urban expansion. However, this process poses significant challenges to groundwater systems, particularly impacting the flow and sustainability of springs and other underground water sources. Excavation can induce substantial alterations in the hydrological characteristics of the surrounding environment, potentially leading to water loss, ecological damage, and the depletion of vital groundwater resources. Recognizing and understanding the factors contributing to these impacts is essential for developing strategies to mitigate adverse environmental effects and optimize tunnel construction practices.

Several studies have examined the relationship between tunnel construction and groundwater behavior. For example, research by Yoo. [1] and Jiang et al. [2] has highlighted tunnel-induced groundwater drawdown, illustrating the consequent risks to nearby aquifers through the use of various numerical modeling techniques to predict changes in water flow and identify high-risk areas. Additionally, Zhang et al. [3] explored how tunnel excavation affects spring flow, revealing the critical role of structural characteristics, such as depth and construction methods, in influencing water loss dynamics. While existing research has identified several key factors, a comprehensive model integrating their combined influence remains lacking.

To address this gap, this study proposes a hybrid methodology combining qualitative expert assessments with statistical modeling and multi-criteria decision-making, including the Analytic Hierarchy Process (AHP). A structured survey collected qualitative data from experts, which was then used to quantitatively rank influencing factors, facilitating the development of a robust decision model aimed at understanding and predicting tunnel-induced water loss. This integration allows for a more refined assessment of key parameters, leading to more precise predictions of tunnel-induced water loss.

Earlier methodologies employed various approaches, such as finite element modeling and empirical analysis, to simulate these effects. This study refines these methods by incorporating both qualitative and quantitative insights, thus offering a more holistic understanding of the phenomena involved. Ultimately, the aim is to present a comprehensive model that considers a wide array of factors influencing groundwater behavior during tunnel construction. This model is expected to provide a more accurate and reliable tool for predicting and mitigating groundwater loss during tunnel construction, thereby offering a more reliable framework for environmental assessments and management practices, and significantly contributing to the mitigation of water loss and its ecological consequences, promoting sustainable tunnel excavation practices.

Literature Review

Impact of Tunnel Excavation on Groundwater Systems

The impact of tunnel excavation on groundwater systems, especially with regard to groundwater levels, aquifers, and nearby springs, has been the subject of extensive research. Tunneling activities, particularly in confined or fractured rock environments, can significantly alter groundwater flow, leading to water loss, reduced spring flow, and potential changes in water quality. For instance, Katibeh et al. [4] highlighted that tunneling could create substantial drawdown in surrounding aquifers, thereby affecting the availability of groundwater resources essential for local ecosystems and human consumption. Their study employed numerical modeling to demonstrate how tunnel excavation disrupts groundwater flow, especially in regions characterized by high permeability or fractured rock formations.

Building on this, Farhadian et al. [5] investigated the relationship between tunnel excavation and groundwater behavior, emphasizing that the extent of groundwater loss and aquifer depletion is heavily influenced by factors such as tunnel depth, surrounding geology, and excavation methods. Lee[6] and Wang[7] found that deeper tunnels, or those excavated in permeable strata, result in more pronounced hydrological changes. Similarly, Eftekhari et al. [8] focused on how tunnel excavation can reduce spring flow, underscoring the critical roles of tunnel design and construction techniques, particularly for tunnels traversing fractured rock.

An essential conceptual framework for understanding the risks associated with tunnel excavation is the Drawdown Hazard Impact (DHI), introduced by Dematteis et al. [9] DHI encapsulates the potential hazards arising from decreased groundwater levels due to tunnel construction, particularly affecting nearby aquifers, springs, and wells.

Dematteis et al. developed a framework to evaluate DHI by considering various influencing factors, including tunnel depth, surrounding geology, and the proximity to water-bearing layers. Their findings indicate that DHI is particularly pronounced in areas with highly permeable geological formations, where the tunneling process can lead to significant groundwater drawdown, impacting not only the immediate vicinity of the tunnel but also larger surrounding groundwater systems.

DHI is influenced by several parameters, such as excavation methods, tunnel depth, and the structural characteristics of the surrounding rock mass. Tunneling through fractured or karstic rock formations, for example, is particularly likely to cause substantial groundwater inflow into the tunnel, thereby decreasing the water available to neighboring springs. Dematteis's work emphasizes the need to consider DHI in the planning and design phases of tunnel projects, as its impacts could result in long-term alterations to groundwater flow patterns and the sustainability of local water resources.

Additionally, Aalianvari [10] made notable contributions to the understanding of the hydrogeological impacts of tunnel excavation.

Methods for Assessing Groundwater Inflows into Tunnels

Frenelus et al. [11] explored the impact of tunnel excavation on groundwater systems and reviewed various methods for evaluating groundwater inflows into tunnels. Their study emphasized the importance of accurately predicting groundwater inflows during tunnel construction, particularly in rocky environments, where complexities such as permeability variations and fracture networks can lead to unpredictable water inrushes.

The assessment or prediction of groundwater inflows into tunnels, especially in rocky environments, is one of the key challenges in tunnel design and construction. Accurate evaluation of these inflows is crucial for ensuring the stability of tunnels and mitigating potential environmental and structural impacts. Various methods have been developed for this purpose, each with its own strengths and limitations.

Analytical and Semi-Analytical Methods: Frenelus et al. [11] presented that these approaches are based on simplified assumptions, often modeling the rocky medium as homogeneous and isotropic. While they are computationally efficient, their accuracy is often limited due to the complex and heterogeneous nature of rocky environments.

Numerical Methods: These methods provide a more detailed and precise analysis of groundwater inflows, especially in heterogeneous or anisotropic media. Jahanmirir et al. [12] show that, these methods require extensive geological and hydrogeological data, making them resource-intensive in terms of both time and cost.

Empirical and Semi-Empirical Methods: Niu et al. [13] highlighted that these methods are often derived from field observations and adjusted for specific conditions. While more flexible in certain situations, their predictions are not always accurate across diverse geological contexts.

Machine Learning Methods: With recent advancements, Farhadian et al. [5] investigated machine learning techniques like neural networks, support vector machines, and hybrid models have been applied to predict groundwater inflows. These methods are highly effective when large and diverse datasets are available but require significant computational resources and expertise.

By combining these approaches and adapting them to the specific geological and hydrological conditions of tunnel projects, more accurate predictions can be achieved, leading to better design and safer construction practices.

Hydrogeological Consequences of Tunnel Excavation

The hydrogeological consequences of tunnel excavation, particularly in areas with confined aquifers, have been well.

documented in the literature. Niu et al. [13] used numerical simulations to analyze groundwater flow in response to tunneling activities. Their study highlighted the potential for significant changes in groundwater levels, which can lead to water shortages and changes in the quality of nearby springs. Liu et al. [14] also conducted field studies and experiments to assess the impact of tunnel excavation on surrounding groundwater systems. Their research found that in areas with fractured rock or karst formations, tunneling can result in considerable water inflow into the tunnel, affecting both the immediate groundwater system and the surrounding ecological environment.

Methodology

Parameter Selection and Weighting:

In this study, a questionnaire was prepared by examining all the parameters that can affect the water loss of springs and groundwater due to tunnel excavation. Using this questionnaire and presenting it to experts in this field to qualitatively score the impact of each of these parameters, initial data related to the level of impact and the ranking of the impact of these parameters were obtained. Using statistical methods and multi-criteria decision-making models such as AHP and artificial intelligence, the impact weights of various influential parameters can be determined according to the initial qualitative data and the different parameters can be ranked in different categories according to their importance (Fig.1). This ranking based on the obtained weights can be used to present a specific and efficient relationship that includes all the influential parameters in this process. After reaching a conclusion and classification, the desired relationship can be improved and a more efficient form can be presented for it using machine learning and artificial intelligence.

The weights for the 14 chosen parameters, calculated based on the average responses from 100 carefully structured questionnaires converted from qualitative to quantitative data, are presented in Figure 2. The online questionnaire was distributed to 100 professionals in the field. Among the respondents, 15% were university faculty, while the remainder consisted of practitioners in tunneling and geotechnical engineering. Notably, 35% of the participants held doctoral degrees, while the others had master's degrees. The collected responses were subjected to statistical analysis and reviewed individually.

$$n_{ij} = \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \quad (1)$$

Parameter Selection

In this study, the key parameters influencing the environmental risks of tunnel excavation were identified through a questionnaire distributed among experts and professionals in geotechnical engineering and water resource management. The questionnaire aimed to evaluate the relative importance of each parameter in affecting groundwater systems. After collecting responses, the data were analyzed using multi-criteria decision-making methods to determine the most significant parameters.

Analysis and Weighting:

1.Data Collection:

The questionnaire results were structured into a matrix that represented the relative importance of each parameter as assessed by the experts.

2.Importance Analysis Using AHP:

The Analytic Hierarchy Process (AHP) was employed to analyze the collected data. The steps included:

Constructing a Pairwise Comparison Matrix:

This matrix compared the relative importance of each parameter against others:

$$A = \{a_{ij}\},\ aij = \frac{\text{Importance of Parameter j}}{\text{Importance of Parameter i}}$$

Normalizing the Matrix:

Each element in a column was divided by the sum of its respective column:

Calculating Final Weights:

The final weight of each parameter was computed as the average of the normalized values in its row:

$$w_i = \frac{\sum_{j=1}^{n} n_{ij}}{n} \quad (2)$$

Where n is the number of iteration.

3.Consistency Check: To ensure the accuracy of the analysis, the **Consistency Index (CI)** and **Consistency Ratio (CR)** were calculated:

$$\mathrm{CI} = \frac{\lambda_{\max} - \mathrm{n}}{\mathrm{n}-1}, \ \mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad (3)$$

Where RI is the Random Index for the number of parameters (n). A CR<0.1indicates acceptable consistency. λ_{max} is the largest eigenvalue.

Selection of 14 High-Impact Parameters:

Based on the weight analysis, **14 parameters with the highest weights** were selected for further assessment. These parameters and their final weights are as follows:

Table 1. The Effective Parameters

	Karst Potential	
	Geomorphology	
Geological Parameters	Discontinuity	Joint set Frequency Aperture Roughness Direction Persistency Filling material
	Fault	Fault Type Displacement Crashed Zone Width Slip band Fracture intersected by fault Host rock permeability Gouge
	Formation	Rock Type Weathering Degree
Hydrologic Parameters	Rock Mass Permeability Basin Area Climate Annual Raining Groundwater Level	
Geometric Parameters	Tunnel Radius Tunnel Length Overburden Tunnel level relative to the spring Tunnel Direction Tunnel distance from the spring Tunnel position relative to the spring Spring Type	

After evaluating the introduced parameters and reviewing the opinions, the weight of each parameter was determined, which is shown in Figure 1.

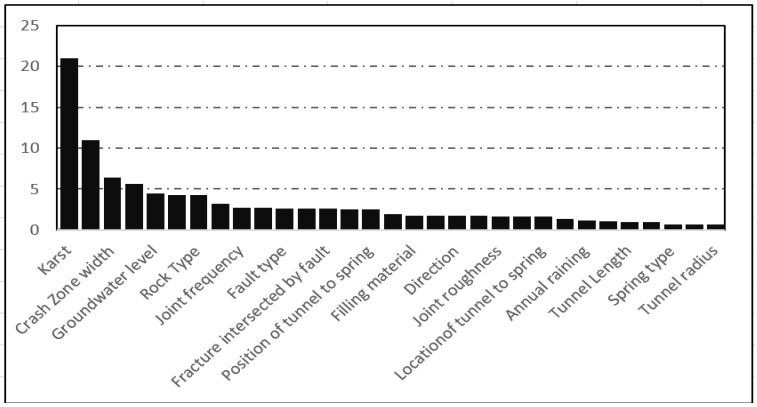


Figure 1. The Weight of Effective Parameters

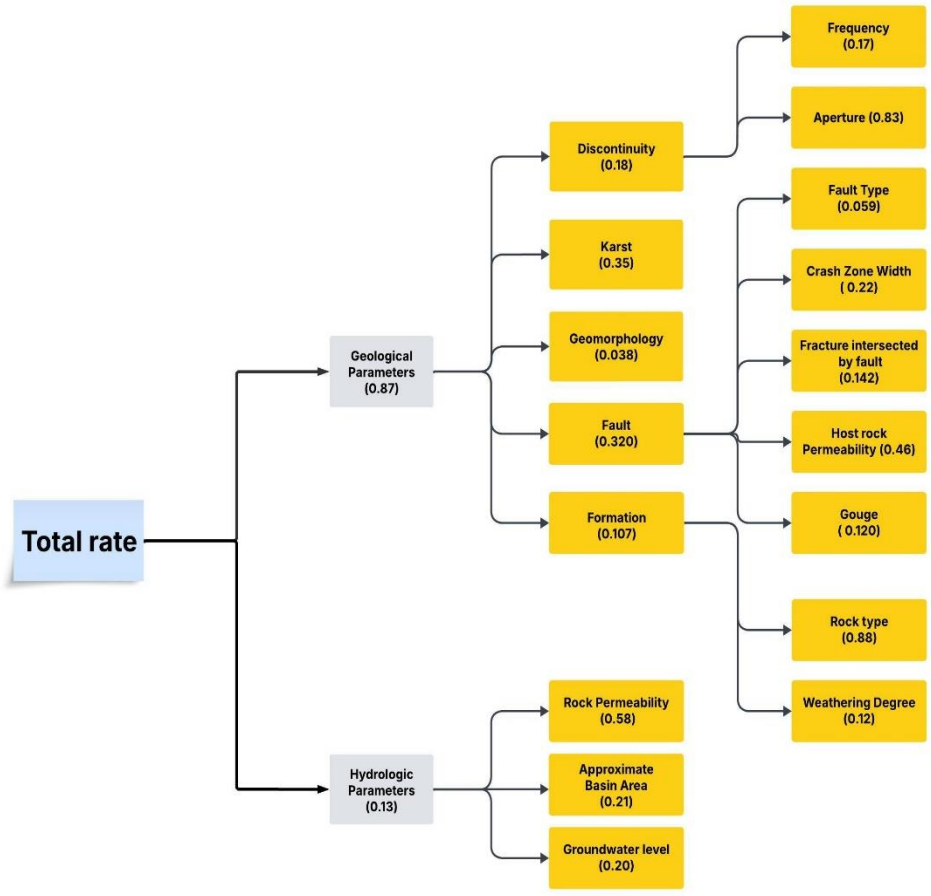


Figure 2. Total weight of all parameters

The selection of the 14 parameters with high weights in this study was based on a detailed and multi-step analytical process, as outlined below:

1.Identification of Key Criteria:

The criteria influencing groundwater behavior during tunnel excavation were identified through expert consultations in geotechnical engineering and water resource management. These criteria encompass

geological, hydrological, and tunnel design factors.

2.Application of Multi-Criteria Decision-Making (AHP):

The Analytic Hierarchy Process (AHP) was employed to evaluate and rank the relative importance of each parameter. This method allowed for pairwise comparisons of criteria, resulting in the calculation of each parameter's final weight based on its relative significance.

3.Normalization and Weight Calculation:

The weights derived for each parameter were normalized to represent their relative contribution within the final model. These weights quantify the influence of each parameter on groundwater systems.

4.Selection of Priority Parameters:

From the identified criteria, the 14 parameters with the highest weights were selected. This selection focused on those parameters most critical in influencing groundwater flow and the environmental impacts of tunnel excavation.

5.Integration of Qualitative and Quantitative Knowledge:

The selection process combined qualitative insights from experts with quantitative analysis, ensuring that the final model is both scientifically robust and practically applicable.

The primary goal of selecting these parameters is to develop a comprehensive and reliable model for predicting and mitigating the environmental and hydrological risks associated with tunnel excavation. This approach enables decision-makers and engineers to focus on key factors and adopt optimal strategies for managing tunnel construction projects effectively (Table.2).

Table 1. Final Weight of Selected Parameters

Parameter	Final Weight (%)
Karst	30
Host Rock Permeability	14
Aperture	12
Rock Type	8
Rock mass permeability (without fault)	8
Crashed Zone Width	6
Fracture intersected by fault	4
Joint Frequency	3
Fault Gouge	3
Geomorphology	3
Ground Water Level	3
Basin Area	3
Fault Type	2
Weathering Degree	1

This structure was selected as it has been found to be effective in groundwater inflow into tunnel. In addition, the rating value can also be easily understood by nongeotechnical specialists. From consideration of the field investigation of different tunnels in various geological conditions [Amirkabir Tunnel (23 km), Azad Dam Divergence Tunnel (3 km), Seymare Dam Divergence Tunnel (3 km), a tunnel in the west of Iran(10 km), and Sangtuda-2 Power Plant Tunnel (2 km) in Tajikistan],

literature review, numerical modeling, sensitivity analysis in each case, and finally, researcher experience in tunneling, it was noted that the parameters would have varying degrees of influence on the groundwater inflow into tunnels. To account for this, each of the parameters was attributed a maximum rating and an associated rating scale, reflecting its importance within the classification system (see Tables. 3).

Integration into the Final Risk Formula:

The selected parameters and their weights were incorporated into the final risk assessment formula:

$$R = \sum_{i=1}^{14} w_i, P_i$$

Where:

- w_i: Weight of parameter i.
- P_i: Score of parameter i based on its range and impact.

This methodology ensures that the most significant factors influencing groundwater risks during tunnel excavation are prioritized, providing a reliable framework for risk assessment.

Parameter Identification:

Fourteen critical parameters influencing groundwater systems were identified:

Table.3. Proposed rate foe relating parameters

Karst Development	Highly Developed 5	Developed 4	Moderate 3	Poorly Developed 2	Absent 1
Host Rock Permeability(m/s)	$>10^{-3}$ 5	10^{-4}–10^{-3} 4	10^{-5}–10^{-4} 3	10^{-6}–10^{-5} 2	$<10^{-6}$ 1
Aperture(mm)	More than 10 5	10-7 4	4-7 3	1-4 2	Less than 1 1
Rock Type	Carbonate 5	Sandstone 4	Combined layers 3	Shale & Slate 2	Igneous 1
Crashed Zone Width(m)	>10m 5	7-10m 4	4-7m 3	1-4m 2	<1m 1
Fracture Count	More than 5 5	30-50 4	10-30 3	5-10 2	Less than 5 1
Joint Frequency(l/m)	>10 5	7-10 4	4-7 3	1-4 2	<1 1
Gouge	Clean 5	Washable 4	Un washable 3	Close 2	
Ground Water Level(m)	>200 5	100-200 4	50-100 3	10-50 2	<10 1
Geomorphology	Steep 5	Moderately Steep 4	Rolling 3	Undulating 2	Flat 1
Fault Type	Normal slip 5	Strike slip 3	Reverse slip 1		
Weathering Degree	Very highly decomposed 5	Highly weathered 4	Moderately weathered 3	Slightly weathered 2	Fresh 1
Basin Area(Km2)	>500 5	500-300 4	300-100 3	100-50 2	<50 1

Steps for Using the Formula:

- **Determining Scores (P_i):** Extract the score for each parameter based on its actual value from relevant tables, such as permeability, distance from springs, or other related parameters
- **Weighting (w_i):** Determine the weights of parameters using evaluation methods like AHP or optimization algorithms (e.g., Genetic Algorithm or Particle Swarm Optimization).
- **Calculating the Final Index (R):** Substitute the scores and weights into the formula to calculate the final index.

Risk Assessment Framework:

Range of Final Index:

Based on the defined weights (w_i)and parameter scores (P_i), the calculated R value will always remain within the range of **120,480**. This is due to the following:

The total weights sum to **100%**, limiting the impact of scores.Even at the lowest (Pi=1) or highest (Pi=5) scores, R will remain within this controlled range. Scores are confined between **1 (minimum)** and **5 (maximum)**, ensuring Rmin=120 and Rmax=480 under practical conditions. Any R value outside this range would indicate errors in weight, scores, or calculation.This ensures a robust framework for risk assessment, aligning parameter impacts with realistic boundaries.

The table 4 categorizes the range of the final risk index into different levels of risk. This classification helps in identifying the necessary actions and level of monitoring required during the project.

Table 4. Risk Level Classification Based on Final Index (R)

Range of R	Risk Level	Description
120≤R<180	**Very Low**	Negligible impact; no specific actions are required.
180≤R<240	**Low**	Limited impact; regular monitoring is recommended.
240≤R<300	**Moderate**	Noticeable impact; optimization of methods or more detailed evaluation suggested.
300≤R<360	**High**	Significant impact; preventive actions or changes in project design are required.
360≤R<420	**Very High**	Major impact; immediate preventive measures are recommended.
420≤R≤480	**Critical**	Severe impact; project suspension or immediate protective measures are necessary.

Explanation of Risk Categories:

1. **Very Low (120 ≤ R < 180):**

Description: The impact is negligible, and the project poses minimal risks to groundwater or the surrounding environment.

Action Required: No specific actions are necessary, but basic monitoring can be maintained.

2. **Low (180 ≤ R < 240):**

Description: The impact is limited, with minor effects on groundwater systems.

Action Required: Regular monitoring is recommended to ensure the risks remain under control.

3. **Moderate (240 ≤ R < 300):**

Description: The impact is noticeable, and groundwater systems may experience measurable changes.

Action Required: Optimization of construction methods or a more detailed evaluation of risks is suggested.

4. **High (300 ≤ R < 360):**

Description: The impact is significant, potentially causing substantial effects on groundwater systems and the environment.

Action Required: Preventive actions or adjustments to the project design are required to mitigate risks.

5. **Very High (360 ≤ R < 420):**

Description: The impact is major, with a high likelihood of severe effects on groundwater systems.
Action Required: Immediate preventive measures should be implemented to reduce risks.

6. **Critical (420 ≤ R ≤ 480):**

Description: The impact is severe, posing critical risks to groundwater and requiring urgent attention.
Action Required: Project suspension or immediate protective measures are necessary to prevent irreversible damage.

Conclusion

This study presents a comprehensive and robust framework for assessing the impact of tunnel excavation on groundwater systems, integrating both qualitative expert insights and quantitative analytical methods. By employing the Analytic Hierarchy Process (AHP), the study identifies and prioritizes 14 key parameters that significantly influence groundwater behavior, with 'Karst' emerging as the most critical factor. The proposed risk assessment formula, which incorporates these parameters and their respective weights, provides a reliable tool for categorizing risk levels into six distinct categories—from Very Low to Critical. This framework not only enhances the ability to predict and mitigate environmental and hydrological risks associated with tunnel construction but also offers flexibility in adapting to specific project requirements. The integration of multi-criteria decision-making and advanced modeling techniques ensures that the model is both scientifically rigorous and practically applicable, making it a valuable resource for engineers, project managers, and environmental planners. Future research could focus on further refining the model by incorporating additional parameters or exploring its application in diverse geological and hydrological contexts. Additionally, the framework can be adapted to various types of projects and domains, making it a versatile tool for addressing the complex challenges of groundwater management in tunnel construction. Ultimately, this study contributes significantly to the advancement of knowledge in the field of groundwater hydrology and tunnel engineering, providing a reliable and practical framework for decision-makers and practitioners to navigate the complexities of tunnel excavation and groundwater management.

Statements and Declarations

The authors declare that they have no conflict of interest.

Competing Interests

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Data Availability

The data presented in this study are available on request from the corresponding author

Consent for Publication

All the authors have read and agreed to the submitted version of the manuscript.

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