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Review Article

Hydrogeological Characteristics of the Namdock Coal Mine Area and an Evaluation Method for Water Inflow Prediction Using the Entropy Weight Method and ANFIS (Adaptive Neuro-Fuzzy Inference System)

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Abstract

Water inrush is a critical geological hazard restricting safe and efficient mining operations in the Namdock Coal Mine, which is situated in a complex hydrogeological setting with developed faults, fractured aquifers, and variable lithological compositions. This study systematically characterizes the hydrogeological features of the mine area and proposes a novel water inflow prediction method integrating the Entropy Weight Method (EWM) and Adaptive Neuro-Fuzzy Inference System (ANFIS). First, field discharge observations and drilling surveys were conducted to clarify the mine's hydrogeological structure, including water-bearing strata distribution, fault-conductive pathways, and seasonal water inflow variability. Then, the EWM was applied to quantify discharge risk levels for different mining drifts, identifying high-risk zones with entropy weight values exceeding 0.2221. On this basis, an ANFIS model was established using six key influencing factors (mining depth, coal seam thickness, dip angle, hanging wall failure degree, geological structure, and season) as inputs and measured water inflow as output. The model was trained with 25 groups of field data and validated with 5 groups of test data, achieving a low-test error of 1.0158%—significantly outperforming the traditional BP neural network (8.56% test error). Field application in the mine's 9-Pit area demonstrated that the integrated method could accurately predict water inflow in high-risk drifts and guide the optimization of mining sequences. This research provides a scientific and efficient technical tool for water inrush prevention in anthracite coal mines with complex hydrogeological conditions.

Keywords: Namdock Coal Mine, Hydrogeological Characteristics, Water Inflow Prediction, Entropy Weight Method, ANFIS

1. Introduction

1.1 Research Background and Significance

Coal is one of the most important energy sources globally, and its safe mining is crucial to ensuring energy security and social economic development. However, geological hazards such as water inrush frequently occur during underground coal mining, causing serious casualties, property losses, and environmental damage [9]. Coal remains a core energy source supporting regional economic development in the DPR Korea, while water inrush poses one of the most destructive geological hazards in underground coal mining. Water inrush is closely related to the hydrogeological characteristics of the mining area, including lithological composition, structural features, aquifer distribution, and groundwater dynamics [11]. Therefore, a systematic study of the hydrogeological characteristics of the mining area is the premise and foundation for accurately predicting mine water inflow and preventing water inrush hazards. Water inrush events can lead to production suspension, equipment damage, and severe casualties, especially with the increase of mining depth and the complexity of hydrogeological conditions [1-3]. The Namdock Coal Mine, located in the Pukchang coalfield, is characterized by steeply inclined coal seams, developed fault structures, and strong hydrogeological connectivity between roof/floor aquifers and mining spaces. During the rainy season, surface water infiltrates into the mine through fractures, causing frequent water inrush accidents in key drifts and restricting the mining of over 420,000 tons of coal reserves in the Uihe Hemisphere area [4].

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Figure 1: Location and Tunnel Skeleton Structure of the Study Area

Traditional water inrush prediction methods, such as geological radar and transient electromagnetic methods, are limited by low accuracy in complex strata and high equipment costs [4,5]. In contrast, machine learning models combined with weight evaluation methods have shown advantages in handling nonlinear relationships between multi-factor and water inflow. In recent years, scholars at home and abroad have conducted extensive research on mine hydrogeological characteristics and water inflow prediction methods. Common water inflow prediction methods include hydrogeological analogy method, analytical method, numerical simulation method, and machine learning-based methods [12,13]. The hydrogeological analogy method is simple and easy to operate but has high requirements for the similarity of hydrogeological conditions between the analogy area and the target area [10]. The analytical method is widely used due to its clear principle, but it is difficult to accurately determine boundary conditions and calculation parameters in complex hydrogeological environments [14]. The numerical simulation method can effectively handle complex boundary conditions and has high prediction accuracy, but it relies heavily on the accuracy of hydrogeological parameter calibration [11]. With the development of artificial intelligence technology, machine learning methods such as deep belief network (DBN), long short-term memory (LSTM), and support vector regression (SVR) have been gradually applied to mine water inflow prediction, showing excellent performance in handling nonlinear and non-stationary data [5,9]. Therefore, this study aims to clarify the hydrogeological characteristics of the Namdock Coal Mine and establish a high-precision water inflow prediction model based on EWM and ANFIS, providing technical support for safe mining.

1.2. Research Status

Global research on coal mine water inrush prediction has focused on geological characterization, hydrogeological modeling, and machine learning applications. Li et al. identified faults and fractures as primary water-inrush pathways in North China coal mines, emphasizing the role of structural connectivity [6]. Wang et al. used the entropy weight method to assess water inrush risks for thick coal seams under reservoirs [7]. In terms of machine learning, Zhang et al. applied support vector regression (SVR) to predict drilling speed for water-inrush detection, achieving an R^2 of 0.968 [5]. However, few studies have integrated entropy weight risk zoning with ANFIS for water inflow prediction, especially for anthracite coal mines with steeply inclined seams and seasonal water inflow variability.

1.3. Research Objectives and Technical Route

The core objectives of this study are

- Systematically characterize the hydrogeological characteristics of the Namdock Coal Mine, including water-bearing structures, discharge variation rules, and high-risk zone distribution.
- Establish a discharge risk evaluation system using the Entropy Weight Method to identify key risk drifts.
- Develop an ANFIS-based water inflow prediction model and validate its accuracy through field data.
- Apply the integrated method to optimize mining sequences and verify its engineering effectiveness.

The technical route includes four steps.

- Field hydrogeological survey and discharge observation
- EWM-based risk zoning
- ANFIS model construction and training
- Field application and effect verification

1.4. Hydrogeological Characteristics of the Namdock Coal Mine Area

1.4.1. Regional Tectonic and Lithological Setting

The Namdock Coal Mine is located in the Nangrim Massif, a major tectonic block of the Korean Peninsula, and belongs to the Pyeongan Supergroup coal-bearing basin. The coal-bearing strata are Permian–Triassic clastic rocks, including sandstone, shale, and limestone lenses [5]. The mine's structural framework is dominated by northeast–southwest trending folds and normal faults, with fault zones serving as primary water-conductive pathways. The coal seams dip at 15°–30°, with an average thickness of 1.5–2.0 m, and are overlain by sandstone and shale roofs with varying stability [5]. The groundwater dynamics in the Namdock Coal Mine area are mainly affected by climate, tectonic movement, lithological characteristics, and human activities. The variation of groundwater level in the study area shows obvious seasonal characteristics: the groundwater level rises gradually from spring to summer with the increase of rainfall, reaching the highest level in autumn; the groundwater level decreases gradually from winter to the next spring due to the decrease of rainfall and the increase of evaporation, reaching the lowest level in spring. The annual variation amplitude of groundwater level is 2–5 m for the Quaternary loose rock phreatic aquifer, 1–3 m for the sandstone confined aquifer, and 0.5–2.0 m for the carbonate rock confined aquifer. The variation amplitude of groundwater level in the carbonate rock confined aquifer is small due to the large water storage capacity and stable recharge conditions.

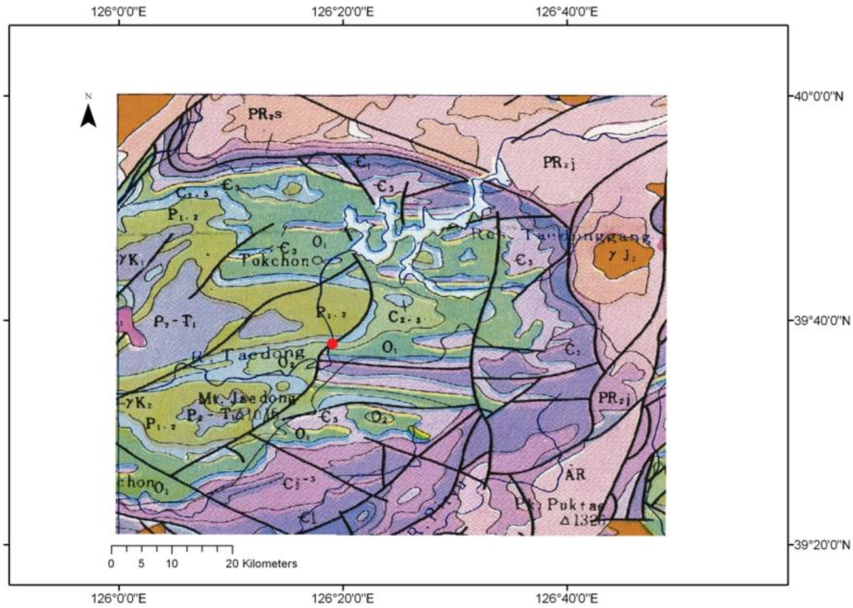

Figure 2: Geological Map of the Study Area

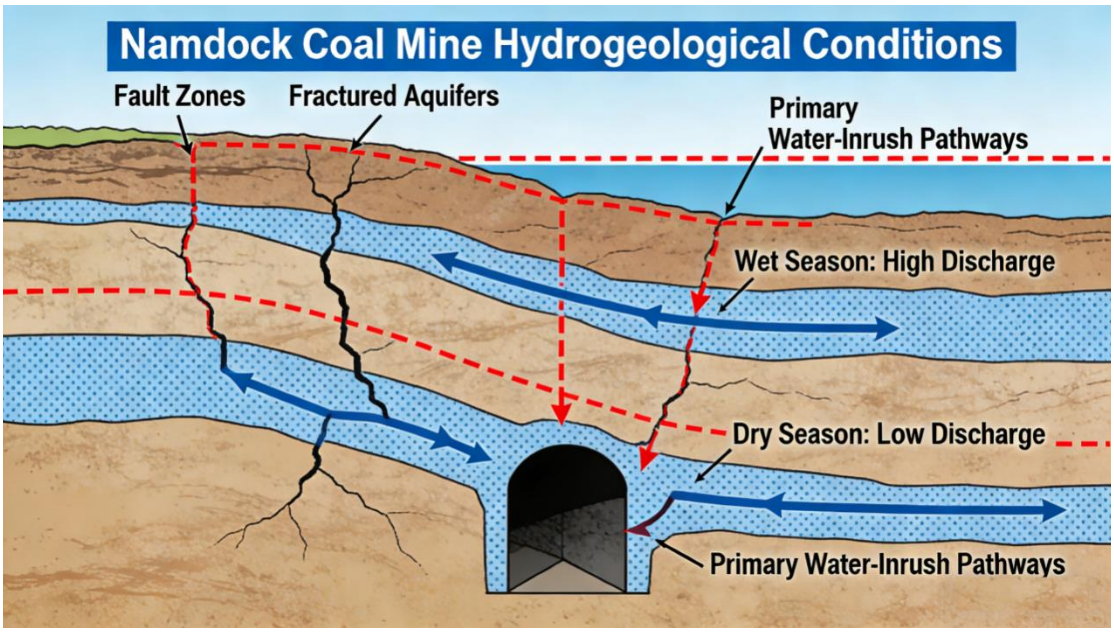

Figure 3: Hydrogeological Conditions of the Namdock Coal Mine

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The groundwater flow direction in the study area is mainly controlled by the terrain and tectonic features. The groundwater in the Quaternary loose rock phreatic aquifer flows from the piedmont to the valley, consistent with the surface water flow direction. The groundwater in the sandstone confined aquifer and carbonate rock confined aquifer flows from the high groundwater level area to the low groundwater level area, and the flow direction is roughly north-south, affected by the regional tectonic movement. The groundwater flow velocity is 0.01–0.1 m/d for the Quaternary aquifer, 0.001–0.01 m/d for the sandstone aquifer, and 0.01–0.05 m/d for the carbonate rock aquifer [5]. The groundwater recharge in the Namdock Coal Mine area mainly comes from three aspects: atmospheric precipitation recharge, surface water recharge, and lateral runoff recharge. Atmospheric precipitation is the most important recharge source, accounting for about 60–70% of the total recharge. The rainfall seeps into the groundwater system through the surface soil and rock fractures, recharging each aquifer. Surface water recharge mainly occurs in the valley area, where the surface water seeps into the Quaternary aquifer through the riverbed, and then recharges the deep aquifers through vertical seepage. Lateral runoff recharge comes from the regional groundwater system, and the groundwater from the surrounding areas flows into the study area through the aquifers, recharging the local groundwater system.

1.5. Water-Bearing Structures and Inflow Sources

The main water-bearing structures in the mine area include.

- Fractured aquifers in coal-bearing strata: The Sadong Formation sandstone and shale have porosities of 8.5–15.2% and 4.2–8.7%, respectively, forming fractured aquifers with moderate water storage capacity [5].
- Fault-conductive aquifers: Northeast–southwest trending faults (e.g., F1 fault) connect shallow and deep aquifers, leading to sudden water inrush when drilling through fault zones.
- Surface water infiltration: During the rainy season, surface water enters the mine through fractures in the upper wall, causing a significant increase in discharge in drifts 3, 6, and 9.

1.6. Seasonal Variation of Mine Discharge

Field discharge observations were conducted on 6 drifts using ditch, vessel, and pump-based measurement methods. The results show that.

- Drift 3 has the highest average discharge (1035.27 m^3/d), with significant seasonal fluctuations (634.2–1621 m^3/d).
- Drifts 5 and 8 have low and stable discharge (28.94–35.57 m^3/d), indicating weak hydrogeological connectivity.
- Discharge in most drifts' peaks during the rainy season (June–August), which is closely related to surface rainfall infiltration.

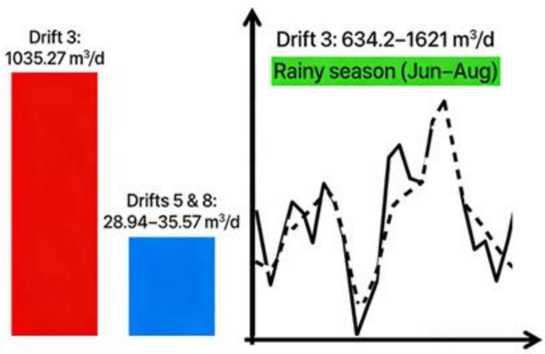

Figure 4: Seasonal Variation of Mine Discharge at the Namdock Coal Mine.

1.7. Discharge Risk Evaluation Based on the Entropy Weight Method

1.7.1. Principle of the Entropy Weight Method

The Entropy Weight Method is an objective weighting method that quantifies the importance of indices based on their information entropy. For mine discharge risk evaluation, the entropy weight of each drift reflects the degree of discharge variation and risk level. The calculation steps are as follows [7].

- Data standardization: Normalize the discharge data of each drift to eliminate dimensional differences.
- Entropy calculation: Let m = number of evaluated drifts in the water impact zone, and n = number of discharge observations per drift over a measurement period. For each drift, measured discharge during the period is expressed as: (Eq. 1).

$$X = \{x_{ij}\} \quad (i = \overline{1,m} : j = \overline{1,n}) \tag{1}$$

Based on traditional entropy theory, the entropy value of discharge change characteristics for each drift is.

$$H_j = \frac{-\sum_{i=1}^{n} f_{ij} \ln f_{ij}}{\ln n} \tag{2}$$

In Eq. 2,

$$f_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}} \tag{3}$$

- Entropy Weight Calculation.

The entropy weight (quantitative estimate of discharge risk) for each drift's discharge change characteristics is calculated as

$$w_j = \frac{1 - H_j}{m - \sum_{j=1}^{m} H_j} \quad (4)$$

The process of quantifying the discharge risk per lead mine in the nine mine areas, the water impact zone of the study area coal mine, and selecting the discharge risk zone is as follows.

1.8. Risk Zoning Results

Based on 5 days of discharge observation data for 6 drifts, the entropy weight values were calculated. The results show that.

• Drifts 3, 6, and 9 have entropy weight values exceeding 0.2221, which are 33.23% higher than the average value (0.1667), identifying them as high-risk drifts.

• Drifts 2.5, 5, and 8 have entropy weight values below 0.1285, belonging to low-risk drifts.

The high-risk status of drifts 3, 6, and 9 is attributed to their developed fractures, strong connection with surface water, and significant seasonal discharge fluctuations.

1.9. Water Inflow Prediction Model Based on ANFIS

1.10. Principle of ANFIS

The Adaptive Neuro-Fuzzy Inference System integrates the self-learning ability of neural networks and the fuzzy reasoning ability of fuzzy systems. It automatically extracts fuzzy rules from input-output data and achieves high-precision prediction of nonlinear systems [8]. The ANFIS model structure used in this study includes five layers: input layer, fuzzification layer, rule layer, defuzzification layer, and output layer.

1.11. Selection of Input and Output Variables

Six key factors influencing water inflow were selected as input variables.

• Mining depth (m): Quantitative index reflecting the hydrostatic pressure of aquifers.

• Coal seam thickness (m): Affecting the contact area between coal seams and aquifers.

• Coal seam dip angle (°): Influencing the development of mining-induced fractures.

• Hanging wall failure degree: Qualitative index converted to quantitative values (0.1–0.9) according to failure severity.

• Geological structure influence: Qualitative index converted to quantitative values (0.1–0.9) based on fault and fold development.

• Season: Represented by month, reflecting seasonal rainfall impacts.

The output variable is the measured water inflow (L/s) of coal faces.

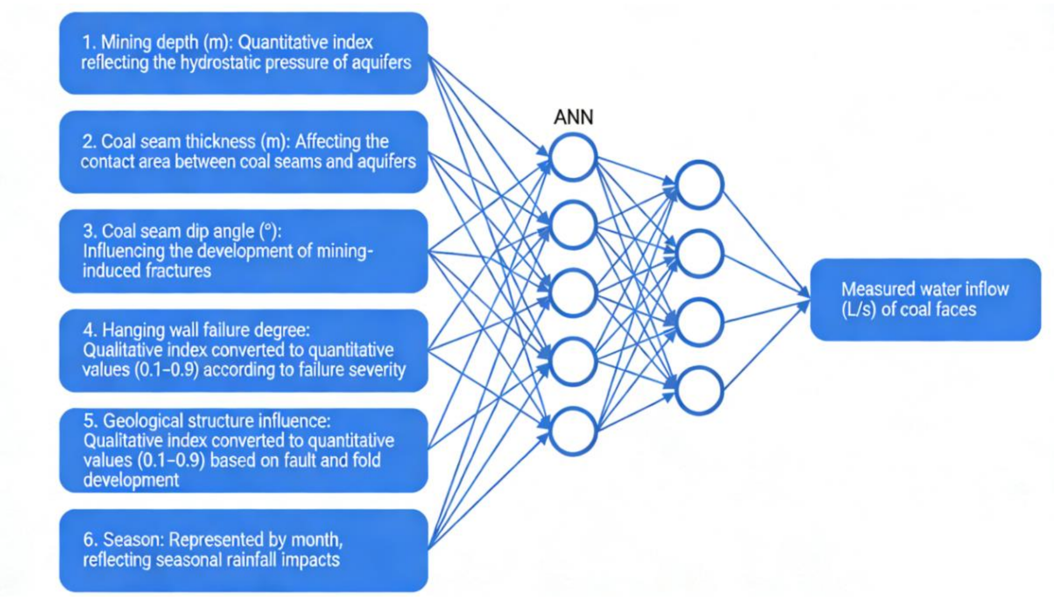

Figure 5: Structure of the ANFIS Model

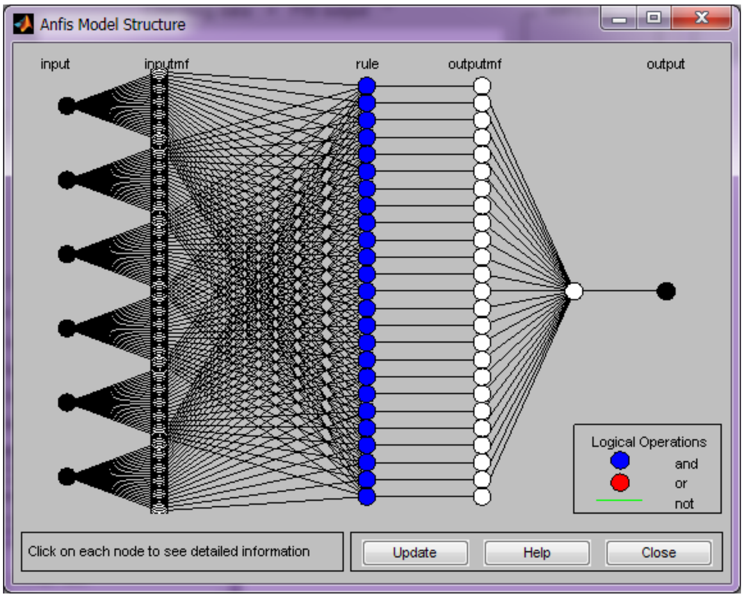

Figure 6: Architecture of the Adaptive Neuro-Fuzzy Inference System for Coal Mine Water Inflow Prediction

1.12. Model Training and Validation

A total of 30 groups of field data were collected, with 25 groups as training data and 5 groups as test data. The model parameters were set as follows.

- Membership functions: Gaussian functions for mining depth, hanging wall failure degree, and geological structure; trapezoidal functions for coal seam thickness and dip angle; triangular function for season.
- Training parameters: Hybrid learning algorithm, 1250 training epochs, error tolerance of 0.

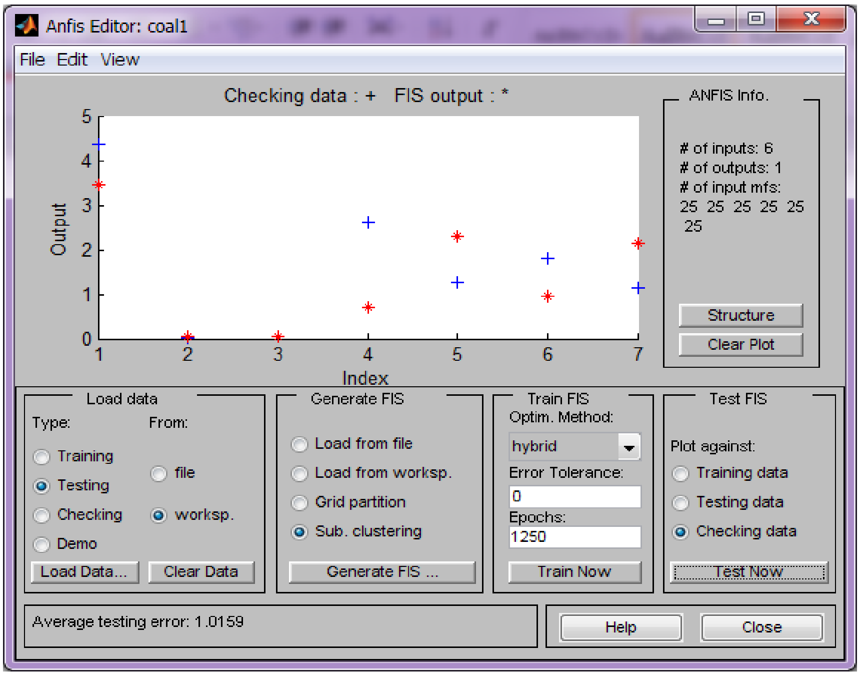

Figure 7: ANFIS Testing Results (Dots = Actual Values; Crosses = Predicted Values)

The validation results show that the ANFIS model achieves a test error of 1.0158%, and the predicted values are highly consistent with the measured values. In contrast, the traditional BP neural network has a test error of 8.56%, verifying the superiority of the ANFIS model.

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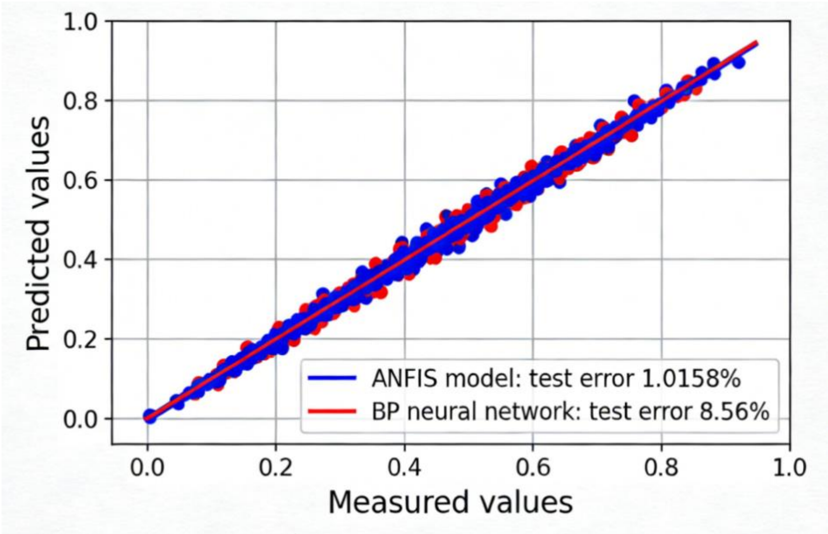

Figure 8: Comparison of ANFIS and BP Neural Network Testing Results

1.13. Field Application and Effect Verification

1.14. Application in the 9-Pit Area

The integrated EWM-ANFIS method was applied to the 9-Pit area of the Namdock Coal Mine. First, high-risk drifts (3, 6, 9) and low-risk drifts (2.5, 5, 8) were identified using EWM. Then, the ANFIS model was used to predict water inflow in the upper and lower 0-drift and 1-drift areas, which were previously halted due to water inrush risks.

The prediction results show that.

• The 1-drift area has a predicted water inflow of 3.01–3.04 L/s during the rainy season, indicating high risk.

• The 0-drift area has a lower predicted water inflow (0.66–1.26 L/s) due to its smaller coal seam thickness and lower hanging wall failure degree.

Two potential repeated mining areas (upper/lower 0-drift and upper/lower 1-drift) were evaluated. The predicted discharge values are shown in Figure 9.

1.15. Engineering Effect

Based on the prediction results, the mine prioritized mining in the 0-drift area after pre-dewatering measures. From July 5, 2024, the 0-drift area achieved a coal output of 2570 tons with a yield rate of 36% and a monthly yield of 1750 tons, without water inrush accidents. For the high-risk 1-drift area, additional dewatering wells were drilled, reducing water inflow to a safe range for mining.

2. Conclusions

• The Namdock Coal Mine is characterized by complex hydrogeological conditions, with fault zones and fractured aquifers as primary water-inrush pathways, and discharge shows significant seasonal fluctuations.

• The Entropy Weight Method can effectively quantify discharge risk levels, identifying drifts 3, 6, and 9 as high-risk zones in the 9-Pit area.

• The ANFIS-based water inflow prediction model has high accuracy (test error 1.0158%) and outperforms traditional BP neural networks, providing reliable support for mining sequence optimization.

• Field application verifies that the integrated EWM-ANFIS method can guide safe mining in water-affected areas, achieving both economic and safety benefits.

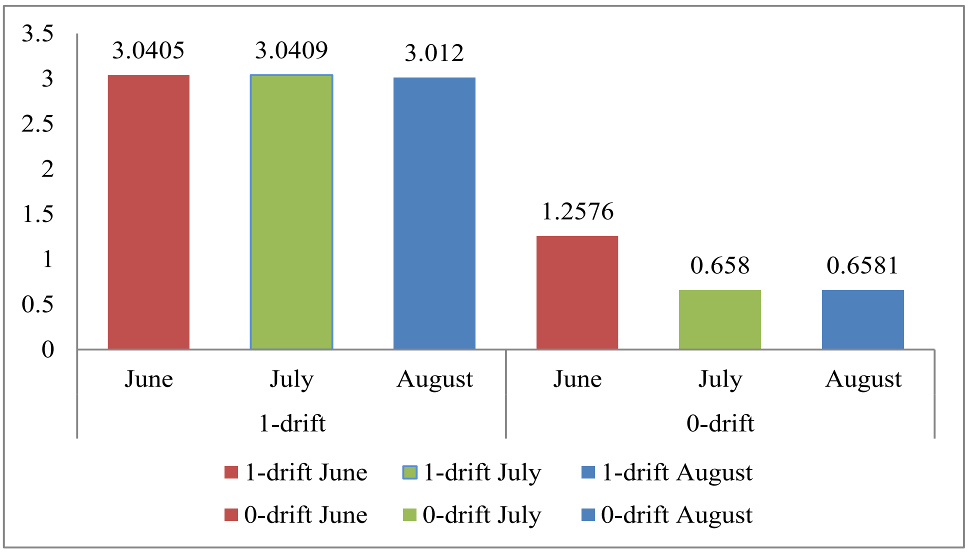

Figure 9: Predicted Discharge for the Rainy Season (June–August)

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Figure 10: On-Site Mine Drilling with a Full-Hydraulic Mine Drilling Rig

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