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Prediction of Mine Water Inflow Based on Growth Curve Model

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Abstract: During the construction and operation of a coal mine, water inrush incidents frequently occur. Minor water-related accidents can cause delays in mining operations, while major incidents can result in significant losses and casualties. This paper takes a coal mine in Shanxi as a case study, employing growth curve models and optimal weighted coefficient models to predict the mine's water inflow over the next five years. The predicted water inflow for the No. 4 coal seam, when mining in a single area, is 534.07 m^3/h, with a maximum inflow of approximately 694.29 m^3/h. Using the analytical method's prediction results as a reference, future scenarios are forecasted through the growth curve model approach. Analysis of the prediction accuracy reveals that the optimal coefficient combination model, established using three growth curve models, has the highest accuracy at 91.52%. The findings of this study provide valuable insights for future water management in coal mining operations.

Keywords: Mine Water Inflow; Growth Curve Model; Optimal Weights.

1. Introduction

During normal coal mining operations, inrush water can pose threats not only to the safety of the mining site and workers but also to the surrounding environment, leading to severe and irreversible ecological damage[1],[2]. Therefore, accurately predicting the water inflow in a coal mine during future extraction activities is crucial for providing a scientific basis to protect water resources and quality in mining areas[3].

The principle of the growth curve model method relies on certain mathematical growth curves. It begins by analyzing the data and general trends of water inflow, followed by the identification of an appropriate curve model. By substituting known data into the model to solve for parameters, the equation can be determined, and predictions can be made for the desired time frame. This method is particularly accurate for predicting future water inflow in mines that have been operational for many years. Previous studies, such as those by Peng Erlei[4], have successfully utilized this method, combining it with a composite model to predict water inflow in the Zhongtai Coal Mine.

In this paper, the growth curve models, including the Logistic model, Gompertz model, and modified exponential model, are applied to predict the water inflow in the mining area. A comparison of the prediction accuracies of the four models is conducted, establishing a weighted coefficient model based on the three growth curves.

2. Hydrogeological Overview of the Mine

2.1. Hydrogeological Conditions

Based on the analysis of mine data, the underground water system in the mining area can be divided into three distinct groundwater systems: the Cambrian-Ordovician carbonate rock karst fracture aquifer, the Carboniferous-Permian clastic rock fracture aquifer, and the Neogene loose clastic sediment pore aquifer. The primary source of groundwater replenishment in this mining area is precipitation. Rainwater moves to the subterranean layer through various conduits, forming groundwater, which typically flows from west to east. The distribution of the underground aquifers is summarized in Table 1.

Table 1. Statistics of Aquifer Distribution in the Mining Area

Main Aquifer Layer	Main Lithology	Water Yield	Thickness (m)	Water Level Elevation (m)
Middle-Lower Ordovician	Dolomitic Limestone	Weak-Strong	0.60–16.50	1042.01–1065
Upper Carboniferous Taiyuan Group	Fine to Medium-grained Sandstone	Weak	13.52–47.61	1052.02–1065.14
Lower Permian Shanxi Group	Fine to Coarse Sandstone and Gravel	Weak	15.18–41.18	1014.12–1068.23
Neogene Lower-Middle	Fine to Medium-grained Sandstone	Weak-Medium	20.3–242.7	1072.93–1212.74
Neogene Upper	Sand, Gravel, and Clay	Weak-Medium	36.3–153.7	1065.2–1189.52

The main aquitards in the mining area are the clastic aquitard of the Middle Carboniferous and the clastic aquitard of the Middle and Lower Permian. The main lithology and thickness of the aquitards are shown in Table 2.

Table 2. Statistics of Aquitards in the Mining Area

The main aquiclude	main rocks	water-resisting property	Thickness (m)
Middle Carboniferous clastic rock aquiclude	Mudstone, sandstone	moderation	23.68~44.27
Clastic rock aquiclude in the middle and lower part of Permian	mudstone	good	0~414.88

2.2. Mine water filling factors

The primary source of direct water inflow into the coal mine is the fractured water from the sandstone of the Shanxi Group. The secondary source of replenishment is the karst fractured water from the carbonate rocks of the Middle Ordovician. Additionally, due to the unique lithology of the roof strata of the No. 4 coal seam, loose aquifers may also serve as an indirect source of water inflow into the coal seam. The fractured sandstone aquifer of the Taiyuan Group typically exhibits underdeveloped fracture systems and does not represent a major source of inflow.

2.3. Characteristics of mine water inflow

Real-time monitoring of the mine's water inflow has been conducted through a flow automatic observation station. The dynamic curve of the mine water inflow from 2016 to 2024 is illustrated in Figure 1.

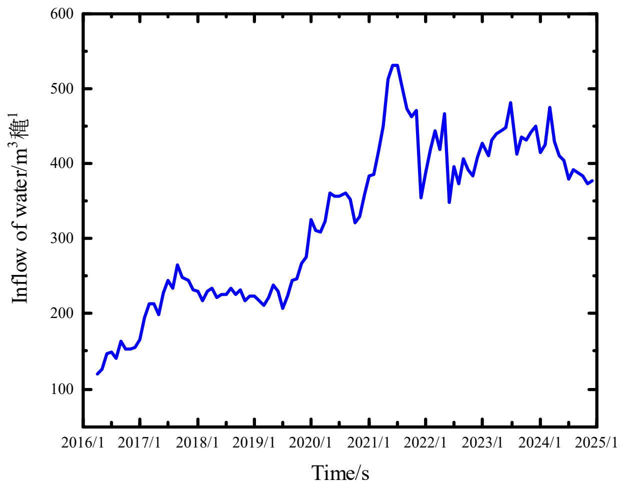

Figure 1. Mine water inflow dynamic curve

It can be seen from Fig.1 that with the increase of time, the mine water inflow increases year by year, and it has been increasing steadily from 2016 to 2021, reaching the maximum water inflow in 2021, and then gradually tends to be stable.

3. Hydrogeological Overview of the Mine

3.1. Prediction of mine water inflow

Based on the hydrogeological conditions of the coal mine, the direct water recharge aquifer of the No. 4 coal seam in the mining area can be generalized as homogeneous. Analysis of inrush data and conditions from the past few years indicates that under normal circumstances, the water consumption in the mining area remains relatively stable. The large well method is employed to transform the originally irregular and complex boundary into a "large well" for easier calculation.

The prediction formula for water inflow from the overlying aquifer is as follows:

$$Q_r = 0.05692K \frac{(2H-M)\ M-h^2}{\lg R_0 - \lg r_0} \qquad (1)$$

Where: Q_r is the normal water inflow of the expected mine roof aquifer ; K is the permeability coefficient ; H is the height of water column ; m is the thickness of aquifer ; r_0 is the reference radius ; R_0 is the reference influence radius ; h is the distance from the water level to the bottom ;

among them :

$$\begin{aligned} R_0 &= R + r_0 \\ R &= 10.2062H\sqrt{K} \\ r_0 &= 1000\sqrt{F/\pi} \end{aligned} \qquad (2)$$

Where: R is to calculate the influence radius ; F is the area taken.

The prediction formula of water inflow in floor aquifer is as follows :

$$Q_f = 0.11375KMH / (\log R_0 - \log r_0) \qquad (3)$$

Q_f represents the expected normal water inflow rate from the mine's floor aquifer.

Under the current mining conditions, the height of the "three zones" for the No. 4 coal seam and the depth of disturbance to the floor involves both the Upper and Lower Shihezi Group sandstone aquifers. Based on the water withdrawal test results and monitoring data from hydrogeological boreholes that expose the relevant aquifers, the overlying aquifer of the No. 4 coal seam corresponds to the Upper and Lower Shihezi Group aquifers. Data from the No. 2 intake shaft shows a permeability coefficient of 0.0014 m/d and a water level elevation of 1254.99 m. The floor aquifer of the No. 4 coal seam corresponds to the Shanxi Group aquifer, with data from boreholes 3407 and 27158 indicating a permeability coefficient of 0.0733 m/d and a water level elevation of 1068.02 m. The elevation of the bottom of the No. 4 coal seam is 684.80 m.

Based on the borehole data from the water withdrawal tests, the thickness of the overlying aquifer for the No. 4 coal seam is found to range from 22.70 m to 162.56 m, while the thickness of the floor aquifer ranges from 1.45 m to 24.24 m.

By substituting all the relevant data into the formula, the water inflow can be calculated, and the results are presented in Table 3.

Table 3. Calculation of Water Inflow for No. 4 Coal Seam

Mining Area	Roof and Floor Strata	K	H	M	F	r_0	R	R_0	Q	Total
Area 1	Roof Strata	0.0014	570.19	122.32	15.09	2191.64	217.74	2409.38	241.24	500.87
	Floor Strata	0.0733	383.22	13.91			1058.92	3250.56	259.63	
Area 2	Roof Strata	0.0014	570.19	70.80	10.17	1799.22	217.74	2016.96	121.63	365.49
	Floor Strata	0.0733	383.22	15.34			1058.92	2858.14	243.86	
Area 3	Roof Strata	0.0014	570.19	60.32	12.28	1977.08	217.74	2194.82	114.42	263.65
	Floor Strata	0.0733	383.22	8.70			1058.92	3036.00	149.23	
Area 4	Roof Strata	0.0014	570.19	59.19	16.71	2306.28	217.74	2524.02	130.16	406.26
	Floor Strata	0.0733	383.22	14.18			1058.92	3365.20	276.10	
Area 5	Roof Strata	0.0014	570.19	98.53	15.43	2216.19	217.74	2433.93	200.98	416.30
	Floor Strata	0.0733	383.22	11.43			1058.92	3275.11	215.32	
Area 6	Roof Strata	0.0014	570.19	64.10	15.26	2203.95	217.74	2421.69	134.36	470.40
	Floor Strata	0.0733	383.22	17.46			1058.92	3262.87	336.04	
Area 7	Roof Strata	0.0014	570.19	62.64	13.01	2034.99	217.74	2252.73	121.86	475.55
	Floor Strata	0.0733	383.22	20.14			1058.92	3093.91	353.69	
Average Value										414.07

The calculation results indicate that during the mining of Coal Seam 4, the water inflow in the mining area ranges from 263.65 to 500.87 m^3/h, with an average inflow of 414.07 m^3/h. If the water inflow in the roadway is calculated to be 120 m^3/h, then the total water inflow for Coal Seam 4, when mining is conducted in only one mining area, would amount to 534.07 m^3/h. Based on empirical data, the maximum water inflow is generally 1.3 times the normal inflow. Therefore, the maximum water inflow for Coal Seam 4 is approximately 694.29 m^3/h.

3.2. Prediction of Mine Water Inflow Using Different Curve Models

3.2.1. Different Growth Curve Models

(1) Logistic Growth Curve Model

The Logistic growth curve model, also known as the self-limiting equation, was introduced in the 19th century primarily to address issues related to population growth in ecology. This model is also applicable for predicting water inflow in mines. The prediction formula is as follows:

$$dQ/dt = \alpha Q - \beta Q^2, \alpha > 0, \beta > 0 \tag{4}$$

Variable Substitution:

$$-Q^{-2} dQ/dt + \alpha/\beta = \beta \tag{5}$$

$$dQ^{-1}/dt + \alpha/\beta = \beta \tag{6}$$

To find the general solution to the non-homogeneous linear equation.

$$Q^{-1} = Ce^{-\int \alpha dt} + e^{-\int \alpha dt}\int \beta e^{\int \alpha dt} dt = Ce^{-\alpha t} + \beta e^{-\alpha t}\int e^{\alpha t} dt = Ce^{-\alpha t} + \beta e^{-\alpha t}\frac{1}{\alpha}e^{\alpha t} \tag{7}$$

We need to determine C. Setting $Q=Q_0$, $t=t_0$, we can derive the expression for C.

$$Q_0^{-1} = Ce^{-\alpha t_0} + \beta e^{-\alpha t_0}\frac{1}{\alpha}e^{\alpha t_0} \tag{8}$$

$$C = \frac{\alpha - Q_0\beta}{\alpha Q_0}e^{\alpha t_0} \tag{9}$$

Substituting the expression for C yields the following result:

$$\frac{1}{Q} = \frac{(\alpha - Q_0\beta)\, e^{\alpha t_0 - \alpha t} + \beta Q_0}{\alpha Q0} \tag{10}$$

Thus,

$$Q = \frac{\alpha/\beta}{(\alpha/\beta Q_0 - 1)e^{\alpha t_0 - \alpha t} + 1} = \alpha/\beta\left[1 + (\alpha/\beta Q_0 - 1)\, e^{-\alpha(t-t0)}\right]^{-1} \tag{11}$$

Let $K_1 = \alpha/\beta$, $A_1 = \alpha$, $B_1 = (\alpha/\beta Q_0 - 1)\, e^{\alpha t_0}$ then the above equation can be expressed as:

$$Q = \frac{K_1}{1 + B_1 e^{-A_1 t}} \tag{12}$$

Equation (12) represents the water inflow growth curve model derived using the Logistic growth curve model, where K_1 denotes the maximum value of the water inflow Q.

(2) Modified Exponential Curve Model

The modified exponential curve model, also known as the simple extrapolation method, involves fitting a curve based on exponential functions to the past measured data of the object being predicted. This establishes a model that can describe the development of the object and allows for predictions by substituting in new states. The condition for fitting the modified exponential curve model is that the development process of the target to be calculated approximately follows an exponential function curve and does not exhibit sudden changes. This model can clearly be used for predicting water inflow in mines.

Letting $Q_1 = 1/Q$, $M = 1/M_1$, $A = B_1 / K$, $B = e^{-A_1}$ in Equation (12) be represented as follows:

$$\frac{1}{Q_1} = \frac{1}{K}\left[1 + \frac{A}{K}B^t\right]^{-1} \tag{13}$$

$$Q_1 = K + AB^t \tag{14}$$

Equation (14) provides the model for mine water inflow Q_1 concerning tt derived from the modified exponential curve model theory.

(3) Gompertz Curve Model

By letting $Q = e^Y$, $K_2 = e^K$, $A_2 = \mathrm{e}^A$, $B_2 = B$ in Equation (14), we can derive the formula:

$$Q_3 = K_2 A_2^{B_2^t} \tag{15}$$

This represents the mine water inflow Q_3 concerning time tt obtained using the Gompertz curve model theory. Using the known data on mine water inflow, we can solve the aforementioned three curve models and predict mine water inflow based on their respective solutions.

3.2.2. Curve Model Calculation

(1) Solution of the Modified Exponential Curve Model

The mine water inflow Q changes with time t. Let the water inflow sequence be Q_t, $t=t_1$, t_2、t_3....t_n. To solve for parameters A, B, and K, we can use the three-segment method, yielding K=487.8, A=−451.19, and B=0.79. This leads to the modified exponential curve equation:

$$Q_1 = 487.8 - 451.19 \times 0.79^t \tag{16}$$

The solution process for the Logistic growth curve model is similar to that of the modified exponential model, where we solve for parameters K_1, A_1, and B_1. We find K_1=492.31, A_1=0.36, and B_1=3.11. By substituting the observed water inflow data from recent years into the above equation, we obtain:

$$Q_2 = \frac{492.31}{1 + 3.11e^{-0.36t}} \tag{17}$$

The solution process for the Gompertz growth curve model follows the same method as that of the modified exponential model. We solve for parameters K_2, A_2, and B_2, finding K_2=491.7, A_2=0.2033, and B_2=0.7533. Substituting the observed water inflow data from recent years into the above equation yields:

$$Q_3 = 491.7 \times 0.2033^{0.7533^t} \tag{18}$$

Using the modified exponential model for prediction and analyzing the results, the results are shown in Table 4.

Table 4. Analysis of Predicted Values using Modified Exponential Model

Model	Particular year	Actual value ($m^3 \cdot h^{-1}$)	Predicted value ($m^3 \cdot h^{-1}$)	Absolute error ($m^3 \cdot h^{-1}$)	Relative error (%)	Precision (%)
Modified Exponential Model	2016	145.11	131.36	13.75	0.094755703	0.905244297
	2017	223.58	206.21	17.37	0.077690312	0.922309688
	2018	226.30	265.35	39.05	0.172558551	0.852835877
	2019	233.99	312.06	78.07	0.333646737	0.749823752
	2020	338.98	348.97	9.99	0.029470765	0.971372897
	2021	455.92	378.12	77.8	0.170643973	0.829356027
	2022	403.67	401.15	2.52	0.006242723	0.993757277
	2023	437.67	419.34	18.33	0.041880869	0.958119131
	2024	404.58	433.72	29.14	0.07202531	0.932813797
Logistic Growth Model	2016	145.11	155.31	10.2	0.070291503	0.934324899
	2017	223.58	195.84	27.74	0.124071921	0.875928079
	2018	226.30	239.43	13.13	0.058020327	0.945161425
	2019	233.99	283.45	49.46	0.211376555	0.825507144
	2020	338.98	325.15	13.83	0.040798867	0.959201133
	2021	455.92	362.35	93.57	0.205233374	0.794766626
	2022	403.67	393.78	9.89	0.024500211	0.975499789
	2023	437.67	419.14	18.53	0.042337834	0.957662166
	2024	404.58	438.86	34.28	0.084729843	0.921888529
Gompertz Growth Model	2016	145.11	148.09	2.98	0.020536145	0.979877102
	2017	223.58	199.11	24.47	0.109446283	0.890553717
	2018	226.30	248.86	22.56	0.099690676	0.909346621
	2019	233.99	294.38	60.39	0.258087952	0.794856988
	2020	338.98	334.11	4.87	0.014366629	0.985633371
	2021	455.92	367.52	88.4	0.193893666	0.806106334
	2022	403.67	394.88	8.79	0.021775212	0.978224788
	2023	437.67	416.83	20.84	0.047615784	0.952384216
	2024	404.58	434.17	29.59	0.073137575	0.931846972

Model predicts the normal water inflow and the maximum water inflow (calculated as 1.3 times the normal inflow) for the coal mine over the next five years, as presented in Table 5.

Table 5. Prediction Results of Modified Exponential Model for 2025-2029

Model	Particular year	Normal water inflow ($m^3 \cdot h^{-1}$)	Maximum water inflow ($m^3 \cdot h^{-1}$)
Modified Exponential Model	2025	445.08	578.604
	2026	454.05	590.265
	2027	461.14	599.482
	2028	466.74	606.762
	2029	471.16	612.508
Logistic Growth Model	2025	453.75	589.875
	2026	464.76	604.188
	2027	472.76	614.588
	2028	478.50	622.05
	2029	482.60	627.38
Gompertz Growth Model	2025	447.71	582.023
	2026	458.18	595.634
	2027	466.23	606.099
	2028	472.39	614.107
	2029	477.08	620.204

3.3. Optimal Weighted Coefficient Model

In the previous sections, three different curve models were used to predict the water inflow of the coal mine, each yielding different results. There are noticeable discrepancies when compared to actual data. To minimize these errors, methods can be employed to reduce discrepancies. Given the existence of three models, the optimal weighted coefficient method from economics can be utilized to construct a combination model. This involves assigning a weight to each model and combining the three models into a new model, expressed as: $Q=mQ_1+nQ_2+pQ_3$, where m,n,p are all less than 1 and satisfy the equation $m+n+p=1$.

Next, we can use this approach to construct a new water inflow model that minimizes errors and yields more accurate predictions.

Let:

$$F_t = K_1F_{1t} + K_2F_{2t} + \cdots + K_iF_{it} = \sum_{i=1}^{n} K_iF_{it} \quad (19)$$

The prediction error can be expressed as:

$$E_t = Y_t - F_t = Y_t - \sum_{i=1}^{n} K_iF_{it} = \sum_{i=1}^{n} K_iE_{it} \quad (20)$$

The sum of squared prediction errors can be expressed as:

$$X = \sum_{t=1}^{N} E_t^{\,2} = \sum_{t=1}^{N} (\sum_{i=1}^{n} K_iE_{it})^2 \quad (21)$$

$$Z = \begin{bmatrix} \sum_{t=1}^{N} E_{1t}E_{1t} & \cdots & \sum_{t=1}^{N} E_{1t}E_{nt} \\ \cdots & \cdots & \cdots \\ \sum_{t=1}^{N} E_{nt}E_{1t} & \cdots & \sum_{t=1}^{N} E_{nt}E_{nt} \end{bmatrix} \quad (22)$$

Thus:

$$X = \sum_{t=1}^{N} E_t^2 = \sum_{t=1}^{N} (\sum_{i=1}^{n} K_iE_{it})^2 = \begin{pmatrix} K_1 \\ \cdot \\ \cdot \\ \cdot \\ K_i \end{pmatrix} \begin{bmatrix} \sum_{t=1}^{N} E_{1t}E_{1t} & \cdots & \sum_{t=1}^{N} E_{1t}E_{nt} \\ \cdots & \cdots & \cdots \\ \sum_{t=1}^{N} E_{nt}E_{1t} & \cdots & \sum_{t=1}^{N} E_{nt}E_{nt} \end{bmatrix} (K_1 \cdots K_i) = K^TZK \quad (23)$$

Let $R = [1,1\cdots1]^T$. Since the sum of the weighting coefficients must equal 1, we have R=1.

Typically, the matrix Z is invertible, so the optimal weighted coefficient vector exists and is unique. Thus:

$$K_i = \frac{Z^{-1}R}{R^TZ^{-1}R} \quad (24)$$

Using knowledge from linear algebra, this can be substituted to show that:

$$K_i = \frac{Z^*R}{R^TZ^*R} \quad (25)$$

Since $J < \min\{J_i\}$ holds, it can be understood that the sum of squared prediction errors of the new combined model is less than that of any individual model.

Where: Y_t: Actual mine water inflow; F_{it}: Predicted water inflow of the i-th model at time t;F_t: Predicted water inflow of the combined model;E_{it}: Error of the i-th model at time t;E_t: Predicted error of the combined model;K_i: Weight coefficient of the i-th model; Let $t=1,2......N$; $i=1,2......n$; $\sum_{i=1}^{n} K_i = 1$.

The calculation method is as follows:

(1) Calculate the adjoint matrix Z^*:

$$Z^* = (z_{ij}^*)_{n\times n} \tag{26}$$

Where z_{ij}^* is the cofactor of z_{ij}.

Calculate:

$$D_i = \sum_{i=1}^{n} m_{ij}^* \tag{27}$$

Solve:

$$D = D_1 + D_2 + \cdots D_i = \sum_{i=1}^{n} D_i \tag{28}$$

Solve:

$$K_i = \frac{d_i}{d} \tag{29}$$

By substituting the predicted results from the three models, we can obtain the most suitable weight coefficients, ensuring that the resulting error is less than that of any individual model.

$$Z = \begin{bmatrix} 15455 & 13778 & 14254 \\ 13778 & 14055 & 13819 \\ 14254 & 13819 & 13989 \end{bmatrix}$$

Calculate the adjoint matrix Z^* of the invertible matrix Z:

$$Z^* = \begin{bmatrix} 5228984 & 4648924 & 9941788 \\ 4648924 & 12559829 & 17181033 \\ 9941788 & 17181033 & 27386741 \end{bmatrix}$$

Thus, we have:

$$D_1 = 5228984 + 4648924 + 9941788 = 19819696$$

$$D_2 = 4648924 + 12559829 + 17181033 = 34389786$$

$$D_3 = 9941788 + 17181033 + 27386741 = 54509562$$

$$D = 19819696 + 34389786 + 54509562 = 108719044$$

$$\frac{D_1}{D} = 0.18, \quad \frac{D_2}{D} = 0.32, \quad \frac{D3}{D} = 0.5$$

Then, we can establish the new model equation as:

$$Q_t = 0.18Q_1 + 0.32Q_2 + 0.5Q_3 \tag{30}$$

According to formula (30), the results can be obtained as shown in Table 6:

Table 6. Analysis of Predicted Values using the Combined Model

Particular year	Actual value ($m^3 \cdot h^{-1}$)	Predicted value ($m^3 \cdot h^{-1}$)	Absolute error ($m^3 \cdot h^{-1}$)	Relative error (%)	Precision (%)
2016	145.11	147.39	2.280	0.015712218	0.984530837
2017	223.58	199.34	24.24	0.108417569	0.891582431
2018	226.30	248.81	22.51	0.099469730	0.909529360
2019	233.99	294.06	60.07	0.256720373	0.795721962
2020	338.98	333.92	5.060	0.014927134	0.985072866
2021	455.92	367.78	88.14	0.193323390	0.806676610
2022	403.67	395.66	8.010	0.019842941	0.980157059
2023	437.67	418.02	19.65	0.04489684	0.955103160
2024	404.58	435.59	31.01	0.076647387	0.928809201

Using this model, we predict the normal water inflow and maximum water inflow (calculated as 1.3 times the normal inflow) for the coal mine for the years 2025, 2026, 2027, 2028, and 2029, as presented in Table 7.

Table 7. Prediction Results of Combined Model for Mine Water Inflow for 2025-2029

Particular year	Normal water inflow ($m^3 \cdot h^{-1}$)	Maximum water inflow （$m^3 \cdot h^{-1}$）
2025	449.17	583.921
2026	459.54	597.402
2027	467.40	607.620
2028	473.33	615.329
2029	477.78	621.114

4. Model Comparison

Four different models were used to calculate the normal water inflow for the coal mine in the years 2025, 2026, 2027, 2028, and 2029. The prediction results from these four models will be compared and analyzed. The process is summarized in

Table 8.

Table 8. Comparison of Results from Four Models

Model	Absolute Error Sum ($m^6 \cdot h^{-2}$)	Relative Error Sum (%)	Standard Deviation ($m^3 \cdot h^{-1}$)	Relative Standard Deviation (%)	Average Relative Error (%)	Average Accuracy (%)
Modified Exponential Model	15454.7528	0.1931	41.44	0.15	0.111	90.17
Logistic Growth Model	14055.1413	0.1217	39.52	0.12	0.0957	91.00
Gompertz Growth Model	13988.9817	0.1348	39.43	0.12	0.0932	91.43
Optimal Weighted Coefficient Model	13914.0469	0.1337	39.32	0.12	0.0922	91.52

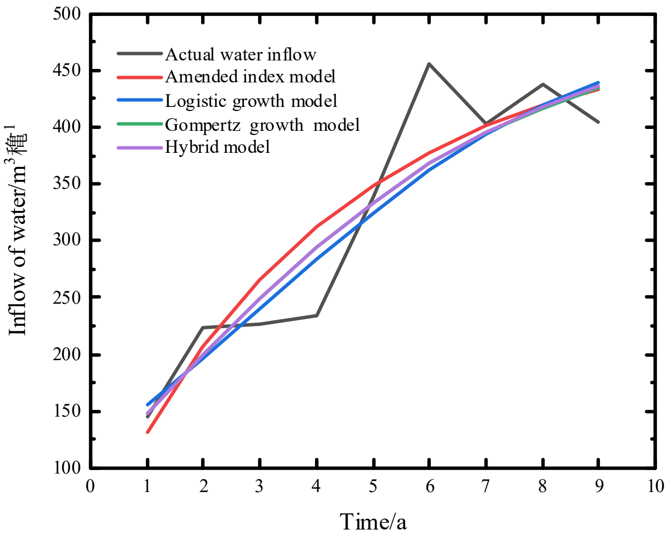

Figure 2. Trend Graph of Predictions from the Four Models

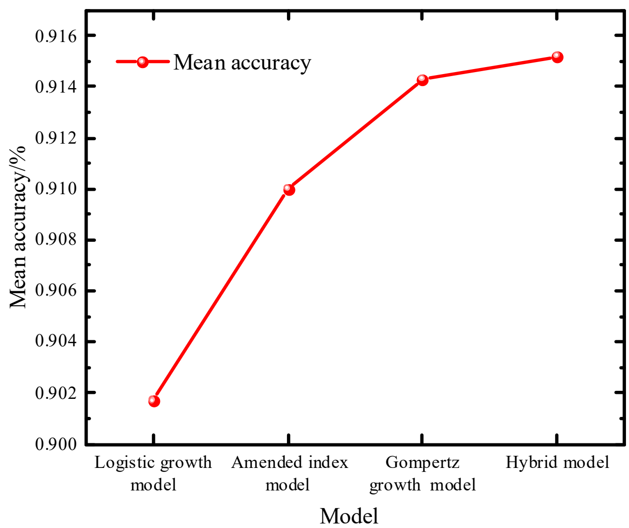

Figure 3. Comparison of Prediction Accuracy Among the Four Models

By analyzing the various indicators of the prediction results from the four models, it is observed that the optimal weighted coefficient model has a higher average accuracy than the other three models, achieving an average accuracy of 91.52%. Among them, the modified exponential model has the lowest accuracy at 90.17%. Additionally, the trends of the prediction results from the four models, as shown in Figure 2, indicate that the combined model yields the best prediction results, significantly reducing errors and improving prediction accuracy.

From the calculation results of the aforementioned methods, the analytical method predicts the normal water inflow at 534.07 m^3/h and the maximum value at 694.29 m^3/h. Based on nine years of measured data, the highest water inflow during this period was 531 m^3/h in June and July of 2021. The predictions from the other methods also appear slightly higher, possibly due to the lack of information regarding the mining face area for the next five years when applying the analytical method. This could lead to an overestimation of water inflow. Nevertheless, the primary purpose of the analytical method is to verify whether the errors in other prediction methods are excessively large.

The results from the other methods differ significantly, as each method simulates the actual hydrogeological conditions to varying degrees, resulting in different parameter estimates. As shown in Figure 3, the Gompertz model within the conventional three growth curve models has the highest prediction accuracy at 91.43%. The combined model, i.e., the optimal coefficient method, has higher prediction accuracy than the Gompertz model while being simpler to calculate. Therefore, the optimal weighted coefficient model is selected as the final prediction result, with the predicted water inflow from 2025 to 2029 being 449.17 m^3/h, 459.54 m^3/h, 467.40 m^3/h, 473.33 m^3/h, and 477.78 m^3/h, respectively.

5. Conclusions

This study focuses on a coal mine in Shanxi, using monthly water inflow data from 2016 to 2024 along with other information to explore the hydrogeological conditions of the coal mine in depth. The average water inflow of the coal at No. 4 was taken as a reference for using the analytical method. Additionally, the gray system prediction method and growth curve model methods were employed to scientifically predict the future water inflow of the mining area. The prediction accuracies of both the gray system prediction method and growth curve model methods were computed, and the growth curve model method with the highest accuracy was ultimately selected as the final prediction result. The main conclusions are as follows:

(1) The large well method predicted the average water inflow of the No. 4 coal seam during normal mining at 417.07 m^3/h and estimated that the water inflow in the coal mine would reach 534.07 m^3/h when only one mining area is in operation, with a maximum water inflow of about 694.29 m^3/h.

(2) The water inflow predictions were made using the modified exponential model, Logistic model, Gompertz model, and a combined model with higher accuracy. The prediction accuracy of the modified exponential model was 90.17%, while the Logistic model achieved an accuracy of 91%. The Gompertz model had a prediction accuracy of 91.43%, and the combined model (optimal coefficient method) reached 91.52%. Thus, the combined model is determined to be the most accurate for this coal mine.

(3) According to the predictions from the combined model, the water inflow from 2025 to 2029 will be 449.17 m^3/h, 459.54 m^3/h, 467.40 m^3/h, 473.33 m^3/h, and 477.78 m^3/h, respectively.

(4) The results of this study provide a reasonable and effective water inflow calculation method for the mine and hold certain reference value for predicting water inflow in similar mines.

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