Facies-Controlled Geostatistical Porosity Model for Estimation of the Groundwater Potential Area in Hongliu Coalmine, Ordos Basin, China

Liyao Li, Juan Qu,* Jiuchuan Wei, Fei Xia, Jindong Gao, and Chao Liu

ABSTRACT: Accurate and reliable evaluations of potential groundwater areas are of significance in the hydrogeological assessments of coalfields because water inrush disasters may be caused by unclear groundwater potential. A three-dimensional geological model of porosity based on deterministic modeling and a facies-controlled method are used to determine the groundwater potential of the coal measure aquifer. The modeling processes are as follows: based on the interlayer and discontinuity (faults) data extracted from boreholes and geological maps, an integrated sequence framework model is developed. Using the results of sedimentary microfacies identification and the method of deterministic modeling, a sedimentary microfacies model is successfully established. Finally, based on facies-controlled and sequential Gaussian methods, an effective porosity model is established that can predict the groundwater potential. The predicted results show that sandstones sedimented in channel, point bar, and batture environments possess high effective porosity and strong groundwater potential; however, the sandstones sedimented in interdistributary bays, flood plains, and sand sheets possess low effective porosity. Model validation was performed based on the hydrological pumping test data collected from observation boreholes, drainage water inflow data from dewatered boreholes in the tunnel around workface, and the mine water inflow in tunnels and the workfaces. The validation analysis results show that the effective porosity and sedimentary facies were correlated with the actual flux. The predicted results are consistent with the actual flux data, validating the predicted model.

1. INTRODUCTION
Groundwater is a valuable natural resource to facilitate human activities.1 However, groundwater can pose a critical threat to the safety of coal mines due to water inrush disasters, which have been occurring in Chinese coal mines for many years.2 Water inrush disasters have resulted in the second-highest percentage of mine accidents in China and produced considerable economic losses.3–6 The fundamental cause of water inrush disasters is the lack of knowledge regarding the groundwater potential; thus, accurately and reliably evaluating the groundwater yield potential of aquifers is important for the prevention of water inrush disasters in order to improve coalmine safety.7

Considering the significance of the estimation of the groundwater potential, several methodologies have been proposed in recent years. Chen introduced a lithologic structure index based on sedimentology and petrology theories.8 This index represents a combination of the results of geophysical surveys and can be used to evaluate the groundwater-holding capacities of sandstone. An integrated application of several methods to determine aquifer quality was proposed by Neuman.9 According to the results of groundwater detection and pumping testing, Kang researched the distribution rules of the sandstone aquifer and the groundwater yield potential of the Shanxi Formation.10 Based on an investigation of the effective porosity, sedimentary facies, and geophysical characteristics, Tao classified the system structure of aquifers in the Cretaceous Formation of the Ordos Basin, but this classification was only based on a single borehole and section.11 Ma introduced a heterogeneity index, which uses the entropy-weight method to determine the degree of heterogeneity.12 However, the accuracy of the weight value of each factor has not been validated, and it is difficult to obtain suitable weight values. According to the geophysical exploration data, Gao comprehensively applied a three-dimensional (3D) high-density electrical method and a transient electromagnetic method to predict the quality of
sandstone aquifers. However, geophysical prospecting data often have inevitable limitations. For instance, the electrical method is based only on resistivity data, which cannot clearly distinguish water-saturated sandstone and mudstone in engineering practice.

To overcome the limitations noted above, a method that can accurately predict the 3D distribution of a sandstone aquifer is required. In this research, a 3D stochastic visual modeling technique is adopted to establish a geological model of structural characteristics and the 3D distribution of the groundwater yield potential. Additionally, a facies-controlled porosity modeling method is introduced in this paper to predict the distribution of sandstone aquifer characteristics based on sedimentology.

In areas of weak cementation with relatively simple structures, the pore space of sandstone is the most influential factor in determining the groundwater yield potential. The petrophysical properties (porosity and permeability) and the thickness of stratum are the main factors affecting the groundwater potential in these kinds of study areas. A single factor (the thickness of stratum or petrophysical property) is not sufficient to precisely predict the groundwater potential area. A facies-controlled porosity model represents a combination of the models of sedimentary facies (which reflects the thickness of sandstones) and effective porosity. Thus, a facies-controlled porosity modeling method (reflecting the sandstone thickness and effective porosity) is proposed in this paper to predict the groundwater potential area.

2. RESULTS—A CASE STUDY OF THE HONGLIU COALMINE ORDOS BASIN, CHINA

2.1. Geological Setting. The Ordos Basin is one of the most important coal accumulating basins in the midwestern region of China. Coal-bearing strata deposited in the late Paleozoic, Carboniferous-Permian and Mesozoic Triassic have been discovered in many parts of the basin. There are four main coalfields located along the western edge of the Ordos Basin, which is the major coal-producing base in China (Figure 1a,b). The Ningdong coalfield is approximately 20 km southeast of the city of Yinchuan (Figure 1b). The study area is situated in the northern Ningdong coalfield. The ZJM, XJG, Hf7, and Hf8 faults are the main internal faults in the coalfield (Figure 1c). The YYH syncline and MJT anticline are located in the western and eastern parts of the study area, respectively (Figure 1c).

The formations overlying coal seams in the Hongliu coalmine are listed as follows based on the decreasing age: the Cenozoic Quaternary Formation, Anding Formation, and Zhiluo Formation of the Mesozoic Jurassic. The Zhiluo Formation is divided into the following three members by the decreasing age: the lower Zhiluo (J2z1), middle Zhiluo (J2z2), and upper Zhiluo (J2z3) (Figure 2a). Based on previous
research, J2z1, J2z2, and J2z3 represent a braided stream, meandering stream, and delta front depositional environment, respectively. The lower Zhiluo, or "Qilizhen sandstone", has a thickness between 60 and 180 m.

The total dissolved solid (TDS) values of the coalmine groundwater in J2z3 range from 6540 to 87,041 mg L\(^{-1}\), with an average value of 38,652 mg L\(^{-1}\); the TDS values of J2z2 range from 3641 to 60,874 mg L\(^{-1}\), with an average value of 22,589 mg L\(^{-1}\); and the TDS values of J2z1 range from 3657 to 26,530 mg L\(^{-1}\), with an average value of 11,516 mg L\(^{-1}\). The TDS values for J2z3 are higher than those for other members of the Zhiluo Formation. Figure 3 illustrates the results of hydrochemical experiments conducted in the Hongliu coalmine. Most water types are Ca\(^{2+}\)-SO\(_4\) for the member of J2z1, Na\(^{+}\)-Cl, Na\(^{+}\)-HCO\(_3\), Mg\(^{2+}\)-Cl for the member of J2z2, and Na\(^{+}\)-Cl, Mg\(^{2+}\)-Cl, and Na\(^{+}\)-CO\(_3\) for the member of J2z3. Based on the borehole data, hydrochemical experiments, and the previous research results, each member of the Zhiluo Formation is relatively independent with a stable mudstone aquiclude.

According to the previous research results of core observation and thin section analysis, there are only a few fractures in the target area, with most fractures located in the upper Zhiluo Formation. Due to the relatively simple structural conditions and few fractures, the major water storage space in the target area is the pore space. Furthermore, the Zhiluo Formation is the roof aquifer of the No. 2 coal seam, which is the main minable coal seam in the Hongliu coalmine (Figure 2b). Therefore, the sandstone aquifer porosity of the Zhiluo Formation is vital to mine safety.

2. Data Preparation and Quality Assessment.
Assessing the quality of the input data is essential to establish reliable 3D geological models that are in accordance with the structural and sedimentary characteristics of the study area.

Several steps were taken in data preparation and quality assessment:

1. Basic information was collected from 89 boreholes, including the borehole header coordinates and well information.
2. Stratigraphic sequences were partitioned, and aquifers and aquicludes were identified. The individual-layer data of each member of Zhiluo Formation were reorganized based on the stratigraphic layers.
3. The fault parameters were collected from boreholes and actual exposure in each workface.

Figure 2. (a) Stratigraphic chart of the western edge of the Ordos Basin. (b) Lithologic and sedimentary characteristics of the Zhiluo Formation in borehole H1104 (Gr: group; Sr: series; Fr: formation; and Mb: member).
4. Forty-two core samples were tested in the overburden porosity experiment to determine the effective porosity of sandstone samples (specific details of the samples and test are presented in Table 1 of the Supporting Information).

2.3. 3D Sequence Framework Modeling. A 3D sequence framework model was used to represent the regional structure, especially in the areas between specific wells. The fault model and the horizon model are the two main parts of the structural model, which provides a framework for the sedimentary facies model and a model of physical properties.29

The fault model was depicted as a fault plane in 3D space (Figure 4a). The fault parameters, such as the strike, dip direction, and dip angle, were determined through a seismic exploration method in the exploration stage of the coalmine. The cross-surface lines of the faults in the structural map of the top and bottom surfaces, such as the fault line in the Figure 1c, were collected from the coalmine design institute to build the fault model. The fault points, specifically, the intersecting points of faults and the boreholes, were used to verify the actual locations of faults (Figure 4b). Considering these fault parameters and data, fault models of the study area were established (Figure 4). The different colors of slices represent different fault planes in Figure 4; the frame along with the fault slice constitutes the fault skeleton.

The horizontal model, a 3D visualization of the stratigraphic interfaces, was built based on the individual-layer data, which were collected in individual layers in each borehole. Two horizontal surfaces included one geological entity. The Zhiluo Formation includes three members, thus, four sets of individual-layer data were used to build the four horizon surfaces (Figure 5a), which could be used to establish the three geological entities representing three members of the Zhiluo Formation. Data from 356 individual layers (Figure 5b) in the Zhiluo Formation of Hongliu coalmine were used to create the horizontal model. Figure 4c illustrates the horizon model of J2z based on the associated individual-layer data. Ultimately, four horizon models of the target area (Figure 5d) were established and used to construct the sequence framework model.

After the fault and the horizontal surfaces were established, the 3D sequence framework model was established to connect the space between each horizon. The 3D sequence framework model (Figure 5e), which reflects the structural characteristics of the study area, was a geological entity generated in the horizon model (Figure 5e,f). Figure 5f expands on the black box in Figure 5e. A 3D fence diagram is presented in Figure 5g to depict the internal features shown in Figure 5f.

2.4. Sedimentary Microfacies Modeling. 2.4.1. Direction of Source Materials. The direction of source materials influences the distribution of sedimentary microfacies.30 The distribution of the clastic structure and the component maturity reflect the transport direction and distance of clastic sediments. In this case, the compositional maturity and heavy minerals of the Zhiluo Formation decrease from southeast to northwest, which indicates that the source materials in the study area mainly came from the northwestern portion of the basin.22,23

2.4.2. Sedimentary Microfacies Identification. According to previous research,11,22,23 J2z1, J2z2, and J2z3 represent a braided stream, meandering stream, and delta front, respectively. In this research, the sedimentary environment of the Hongliu coalmine is in accordance with that presented in former research based on the lithology, depositional structure, and grain types. The identification of signs of sedimentary facies is the major target of the identification of sedimentary microfacies. A well log analysis was conducted to define different depositional facies, especially without core analysis data. γ ray (GR) curves, which reflect variations in the grain size and
facies rhythm, as well as lithological changes in sedimentary microfacies in the vertical direction, were used to establish the relation between lithology and logging of the study area.

Different types of sedimentary facies exhibit different shapes and amplitudes of logging. For example, flood plain mudstones in middle and lower J\textsubscript{2z} and sand sheets in upper J\textsubscript{2z} are abundant in radioactive minerals that produce high GR values. The electrical curves of the flood plain mudstones and sand sheets are mainly finger-shaped and tooth-shaped. The batture, channel, and estuary sandbar microfacies mainly exhibit box-shaped and bell-shaped curves because of the high thickness of the sand. The main channel exhibits a normal rhythm and the curves of the main channel have high amplitudes at the bottom of the curve and low amplitudes at the top of the curve (Table 1).

The borehole data were combined with logging information to analyze the facies of the regional sedimentary environment. The core descriptions of boreholes, which reflect the depositional structures of sedimentary rocks, were used to identify the sedimentary microfacies in the study area. Taking J\textsubscript{2z} \textsubscript{1} (lower Zhiluo Formation) as an example, the braided stream deposition includes braided river channel, batture, and flood plain microfacies (Figure 6). The differences in microfacies indicate various sedimentary structures. The braided river course and batture deposits usually displayed abundant tabular cross bedding, trough cross bedding, and block bedding, and a mud-pebble structure was generally observed at the bottom of each section of sandstone (Figure 6). Sandstones observed in the main channel always displayed fining upward sequences with a considerable thickness. The flood plain deposits typically exhibited rippled bedding and sand-laminated siltstone bedding, and the sandstone thickness was thinner than that of the batture and braided river course. Thus, the sandstones of the batture and main channel are the major aquifers in the lower Zhiluo Formation; however, the flood plain is a major aquiclude.

2.4.3. Geological Modeling of Sedimentary Microfacies.

The spatial distribution of microfacies can be used to determine the locations of aquifers and aquicludes, especially porous aquifers.\textsuperscript{20,29} However, in 2D microfacies research,
Figure 5. Horizon model of Hongliu coalmine. (a) Zoomed view of the black box in (b). (b) All the well tops that were used to generate horizons. (c) Horizon model of layer J2z. (d) Four horizon models of Hongliu coalmine. (e) 3D regional structural model. (f) Zoomed view of the black box indicating faults and contour changes. (g) 3D fence diagram of (f).
Table 1. Electrofacies Characteristics of the Sedimentary Microfacies in the Zhiluo Formation from the Well Log Data (Fm: Formation; Meb: Member; NR: Normal Rhythm; AR: Antirhythm; and CR: Composite Rhythm)

| strata       | Fm    | meb       | sedimentary environment       | microfacies                        | curve shape       | rhythmicity | GR amplitude                  |
|--------------|-------|-----------|--------------------------------|------------------------------------|-------------------|-------------|--------------------------------|
| Zhiluo       | J2z   | upper     | delta front                    | submerged distribute               | box-shape; bell-shape | NR          | top high; bottom low          |
|              |       |           | channel                        | sand sheet                         | finger-shape       | none        | middle-high                    |
|              |       |           | estuary dam                    | funnel-shape; bell-shape           |                  | AR/CR       | middle-high                    |
|              |       |           | inter-distributary bay         | finger-shape                       |                  | none        | middle-high                    |
|              |       |           | point bar                      | box-shape                          |                  | NR          | low                            |
|              |       |           | flood plain                    | tooth-shape                        |                  | none        | high                           |
|              |       |           | Main channel                   | tooth-shape or bell-shape          |                  | NR          | headpiece high; bottom low    |
|              |       |           | natural levee                  | finger-shape                       |                  | none        | high                           |
| J2z middle   |       | meandering-stream               |                                |                                    |                  | AR          | middle-high                    |
| J2z lower    |       | braided-stream                    |                                |                                    |                  | CR          | middle-high                    |

Figure 6. The planar distribution of microfacies in the lower Zhiluo Formation (the planar graph). Single borehole section descriptions of H204, H401, H406, H303, H1111, and H1104 (the bar chart). The granularity of sandstone is reflected by the width of the borehole section.

only 2D distributions based on planar graphs and bar charts are used, and these distributions do not show the internal changes in a layer.

Considering this aspect, a 3D sedimentary microfacies model was established based on an assigned value simulation method, which is a deterministic modeling method based on the geological information and assessment. All the sedimentary microfacies data were derived from the sedimentary microfacies identification (Figure 7a). Next, the 2D sedimentary microfacies map was established based on the
Figure 7. Geostatistical modeling of sedimentary microfacies. (a) 2D distribution map of facies codes in the lower Zhiluo Formation. (b) 2D sedimentary microfacies distribution map based on facies codes. (c) 3D sedimentary microfacies model based on the 2D distribution map. (d) 3D cross section with $J = 90$. 
results of borehole identification and the direction of source material (Figure 7b). Finally, based on the assigned value method, the 3D microfacies model was depicted according to the 2D microfacies distribution map (Figure 7c). The profile morphological characteristics were depicted based on the field outcrops in the Ordos Basin. The river course profile exhibited an upper flat and lower convex form, while the baffle form was an upper convex and lower flat lens-type (Figure 7d).

2.5. Effective Porosity Modeling. 2.5.1. Calculation Analysis of the Porosity Data. The effective porosity and thickness of the sandstone are the main factors that affect the groundwater yield potential, especially with respect to weakly cemented aquifers.26 Based on the experimental data, the effective porosity values of sandstone in the study area range from 10.24 to 21.54%, with a mean of 15.61%. However, the experimental samples did not cover all the boreholes in the study area; therefore, a regression analysis between the acoustic time (AC) and effective porosity was conducted to develop a regression equation and calculate the effective porosity without core measurements. The following regression equation was obtained: 

\[ y = 0.29x - 2.5175 \]

\[ y = 0.209x - 2.5175 \] (Figure 8). The effective porosity value of each member in Zhiluo Formation, which is an average value of the sandstone layer for each member, was calculated from the AC values in each borehole. The final effective porosity value calculated from each borehole of each member (Table 2 in the Supporting Information) was used to obtain Figure 9.

All the effective porosity data were divided and then grouped into four groups based on the different sedimentary type and sedimentogenesis. The channel sediment was the riverbed clastic lag deposit in the braided stream, meandering stream, and delta front sedimentary system of the Zhiluo Formation, representing the first group (Figure 9a). The average effective porosity values of channel microfacies are higher than those of other microfacies. The point bar, baffle, and estuary dam all belong to the dam deposit, which shows the second highest average effective porosity values among all the microfacies in the study area (Figure 9b). The sand sheet and natural levee sediment were deposited when the clasts carried by water flow rushed out of the riverbed, these two sedimentary microfacies exhibit the second lowest average effective porosity values among all the microfacies in the Zhiluo Formation (Figure 9d). The interdistributary bay sedimented in a weak hydrodynamic force condition, and mud is the predominant deposit in this environment; the flood plain sediment was deposited during flooding, and mud is also the predominant deposit in the flood plain. The interdistributary bay and flood plain microfacies show the lowest effective porosities in the Zhiluo sediment (Figure 9c).

The original effective porosity data of each sedimentary facies were processed through input, output, and normal transforms to ensure that the data exhibited a normal distribution (Figure 10). The effective porosity data were standardized in this process to range from −2 to 2, as shown in Figure 10.

2.5.2. Facies-Controlled Porosity Modeling. Facies-controlled modeling was used to decrease the variability in porosity in different sedimentary facies.30,31 The azimuth controls the direction of the material source and the flow. The major range represents the influence sphere on the major source material direction, and this parameter was affected by the form of sedimentary facies distribution. The minor range direction is orthogonal with the major range, and it also refers to the influence sphere. For instance, the proportion of the extended distance in the major and minor directions is 3:1–2.1 in the baffle deposit and the range proportion on the major and minor directions is near 2.4:1 (Table 2). The vertical range is affected by the sandstone thicknesses, so the parameters of the flood plain deposit are smaller than those of the channel deposit. The final parameters of the azimuth and range were obtained according to the search cone and actual semivariance data, and the search cone was used to fit the spherical variogram by manual operation, when the fitting variogram is consistent with the actual semivariance data, it means that the variogram is credible (Figure 11). Cross section and fence diagrams were drawn to illustrate the internal characteristics and effective porosity of sedimentary facies (Figure 12).

3. DISCUSSION AND VALIDATION

Statistically, simulated results become less reliable with increasing distance from the data points (boreholes). To some extent, stochastic modeling can be defined as a process of valid “guessing”,15,20 in which known information is used to generate a probabilistic model based on mathematical techniques. However, pure mathematical methods often fail to accurately reflect the actual geological conditions. Thus, facies-controlled porosity modeling, which is rational and practically significant, can be used to reflect the groundwater yield potential in sandstone aquifers.

The thickness of the aquifer (sandstone) in Figure 13a is a key parameter to depict the 2D distribution map of sedimentary facies (Figure 13b). Thus, the 2D facies distribution was used to develop the sedimentary microfacies model. According to the original effective porosity data (Figure 9), the braided river course (channel) and baffle deposit in area B shown in Figure 13c include relatively high effective porosity values, and the flood plain deposits in the areas A in the same figure have low porosities, as reflected by the facies-controlled porosity model (Figure 13c). However, Figure 13d is a model established using the sequential Gaussian method without a facies-controlled and the results are not consistent with the original effective porosity data shown in Figure 9.
A statistical analysis was carried out for the facies-controlled porosity model. The range of effective porosity in channel deposits of the porosity model in Figure 13c is 18.2−24.4%, and the thickness of sandstones is comparatively thick. The range of effective porosity in flood plain deposit of the porosity model in Figure 13c is 13.07−20.9%, and the thickness of sandstones is comparatively thin. Generally, the effective porosity is high in areas with sediments deposited in channels, point bars, and battures, and the facies-controlled

Figure 9. Effective porosity histograms for microfacies of the Zhiluo Formation. (a) Channel. (b) Point bar, batture, and estuary dam. (c) Interdistributary bay and flood plain. (d) Sand sheet and natural levee.

Figure 10. Data processing for the original effective porosity to ensure a normal distribution. (a) Original input data of effective porosity in the upper Zhiluo dam deposit (left) and the final data after output (right). (b) Original data of effective porosity in the lower Zhiluo channel deposit (left) and the final data after output (right).
porosity model results are consistent with the actual effective porosity data for each depositional facies shown in Figure 9. Furthermore, a zonal quantitative analysis of the effective porosity model was carried out using the "volume calculation" feature in the modeling software. The thickness of sandstone and the effective porosity were the key parameters. The effective porosity volumes of the area B in Figure 13c was $6529.27 \times 10^6$ m$^3$, while that of the area A in Figure 13c was $2080.75 \times 10^6$ m$^3$, these two areas have different values of sandstone thicknesses and effective porosity. Thus, the groundwater potential area will not be located in floodplain deposit areas, where there is relatively thinner sandstone and lower effective porosity.

Validation was performed based on the results of a hydrological pumping test in boreholes, the drainage water inflow from dewatered boreholes in the tunnel around the workface, and the mine water inflow in tunnels and the workface area. Figure 1c shows the locations of hydrological boreholes and workfaces in the study area. The actual flux ($Q$), which is shown in Table 3, is an important factor that reflects the groundwater potential in coalmine. The data collected in Table 3 exhibit a rule: the sandstone-dominated sedimentary microfacies, such as channel and dam deposits, possess relatively higher effective porosity than do the mud-dominated microfacies, and the actual flux was also high; the mud-dominated sedimentary microfacies, such as flood plain and interdistributary bay, possess relatively low effective porosity, and the actual flux was low.

The groundwater potential law of the mining area was obtained based on the method of facies-controlled geostatistics. According to this law, the sandstone-dominated areas may be at a higher risk of water inrush disasters. Second, the groundwater potential law in a coalmine is of significance to adjust and optimize the mining layout of the coalmine. As a high productivity mining method, long coal mining workfaces can be adopted in the mud-dominated sedimentary area. However, in the areas of the sandstone-dominated sedimentary microfacies, small mining workfaces should be adopted for the drainage layout. Finally, the groundwater potential law provides geological guarantee for mine drainage and pressure reduction engineering. For example, in mud-dominated areas, a small amount of drilling and drainage construction can be carried out, and the pumping pump power can be small; however, the drainage construction in the sandstone-dominated areas corresponds to opposite characteristics.

| subfacies    | microfacies         | variogram |
|--------------|---------------------|-----------|
|              | horizontal range    |           |
|              | max.    | min.    | range | azimuth (deg) |     |
| delta front  | submerged channel   | 1115.5   | 745.4 | 5.5           | 325 |
|              | sand sheet          | 1524.7   | 945.4 | 3.4           | 327 |
| meandering   | estuary sandbar     | 1102.4   | 845.7 | 4.5           | 330 |
| stream       | point bar           | 1278.4   | 975.4 | 7.3           | 332 |
|              | flood plain          | 1287.4   | 356.3 | 3.1           | 328 |
|              | main channel        | 1224.5   | 312.4 | 5             | 325 |
| braided      | batture             | 1234.4   | 514.2 | 7             | 324 |
| stream       | flood plain          | 1324.4   | 304.1 | 3.1           | 330 |
|              | main channel        | 1824.4   | 423.7 | 6.4           | 328 |

Figure 11. Search cone (a,c,e) and variograms (b,d,f) for the major direction for each sedimentary facies. The black squares of (b,d,f): actual semivariance data. The blue curves of (b,d,f): fitting variograms. (a) Major direction search cone of the braided river course. (b) Varioograms fitting curve of the braided river course. (c) Major direction search cone of batture. (d) Varioograms fitting curve of batture. (e) Major direction search cone of flood plain. (f) Varioograms fitting curve of flood plain.
In general, the areas sedimented in channel, point bar, and batture environments exhibit high effective porosity, and the actual flux was high in these areas. However, certain boreholes and workfaces do not exhibit this trend (Table 3), including the Z7 and Z6 boreholes and workface 030201/(1), which are located near the XJG, ZJM, and Hf7 faults, respectively (Figure 1). These faults are normal faults (extension faults) that conduct and store groundwater because of the fracture and fault plane space; thus, the actual flux data do not follow this general trend.

Figure 12. (a,b) Fence diagrams of sedimentary facies and effective porosity, respectively. (c,d) Magnified cross sections of sedimentary facies and effective porosity at I = 120. These figures show that the point bar, batture, and main channel deposit facies tend to have the highest porosities.
4. CONCLUSIONS

The main objectives of this research were to establish a model of 3D sandstone aquifers and determine the groundwater yield potential of the Zhiluo Formation. The research results discussed above support the following conclusions:

1. A 3D structural model that includes faults, horizons, and zones was established for 2D and 3D analyses of the study area. Data of 356 individual-layers in the Zhiluo Formation of the Hongliu coalmine were used. Ultimately, four horizon models of the target area were established to construct the geological model.

2. Based on previous research, core observations, and well-logging data analysis, the Zhiluo Formation of the Hongliu coalmine developed delta front, meandering stream, and braided stream microfacies labeled J2z3, J2z2, and J2z1, respectively. The microfacies, which reflect the thickness and quality of sandstone, were identified. An assigned value simulation method was used to establish a sedimentary model with obvious sedimentary boundaries.

3. A regression analysis between the AC and experimentally derived effective porosity was conducted to calculate the effective porosity based on fitting functions without core or experimental data. The groundwater yield potential of the Zhiluo Formation was determined.
yield potential and heterogeneity, which are reflected by various microfacies and porosities, were determined via facies-controlled modeling and the sequential Gaussian simulation method. Generally, the areas of sediments deposited in channels, point bars, and battures exhibited high effective porosities and strong ground water potential, and the facies-controlled modeling results matched the actual effective porosity data from each depositional facies.

(4) The porosity and sedimentary facies that were predicted and identified during the modeling process reflected the actual flux based on the pumping test and borehole dewatering data. Overall, the areas of sediments deposited in channels, point bars, and battures exhibited high porosity, and the actual flux was high in these areas.

5. EXPERIMENTAL SECTION AND COMPUTATIONAL METHODS

5.1. Sedimentological and Deterministic Modeling. A sedimentological analysis method was used to distinguish and divide the sedimentary subfacies and determine the 3D spatial distribution of aquifers.30 In this study, the core records from 89 boreholes in the Hongliu coalmine were collected. Sedimentary studies were performed using all the borehole data, which included information regarding color, variations in facies-controlled modeling and the sequential Gaussian simulation method. This software is a set of 3D visualization modeling software based on the Windows platform, which integrates structural modeling, lithofacies modeling, reservoir attribute modeling, and virtual reality. Petrel provides a shared information platform for geologists, geophysicists, rock physicists, and hydrogeologists. The sequential Gaussian simulation method and the automatic surface fitting (ASF) method were implemented in Petrel software to establish the final model.

Before modeling, the data (1D and 2D data from boreholes, well logging, and structural analysis) were inputted.32 In the generating of the stratum surface, the ASF method was used to create contours of Z values in the X–Y plane.30,31 Two principles were followed in model construction: (1) according to the individual layer data from each borehole, outliers were smoothed based on an averaging approach to ensure the accuracy of the structural model;20 (2) in areas without boreholes, the individual-layer data from adjacent boreholes were used to estimate surface trends. If no boreholes were present in the area, the structural map was used as the main reference.

A 3D sedimentary microfacies model was established based on an assigned value simulation method, a deterministic modeling method based on the geological information and assessment. The assigned value method is an interactive deterministic modeling method; as a result, the modeling results agreed with the results of sedimentary microfacies identification and the direction of the source material.

5.2. Facies-Controlled Porosity Modeling. The sandstone thickness is mainly reflected by the sedimentary microfacies, and the effective porosity of sandstone can be experimentally measured under specific temperature and pressure conditions. The effective porosity of sandstone was studied using experimental measurements made with a PorePDP-200 porosity tester, which is an overburden pressure tester. Experimental measurements of the effective porosity were obtained from 42 samples in this study (Table 1 of Supporting Information). The samples were from different boreholes and various depths.

Regression analysis of the porosity data from core measurements and the AC values from well logs was performed.15,17 The purpose of the regression analysis was to calculate porosity values in areas without core measurements. This method of determining the effective porosity is
Sequential Gaussian simulation is the first step in facies-controlled porosity modeling and is a widely used algorithm for the stochastic characterization of properties from various earth science disciplines. The basic idea of sequential Gaussian simulation is a sequential simulation, and the simulation data should exhibit a normal distribution. Generally, a nonlinear method was used to translate the original data to normally distributed form, and translation was conducted using modeling software through input truncation and output truncation in the previous research.

The specific processes of sequential Gaussian simulations are as follows: (1) the variable \( Y \) is obtained by the normal distribution transformation of the original data \( Z \); (2) the transformed data are assigned to the closest grid node; (3) a random path is set to make sure all the grid nodes are visited; (4) the data points \( u \) in the neighborhood are found; (5) the Kriging method is used to obtain the parameters of the conditional cumulative distribution function of \( Y(u) \) for the data points (mean and variance); (6) value of simulation \( Y(u) \) is added into the conditional dataset; and (7) the grid node is handled following the random path until all the grid nodes are simulated, then a sequential Gaussian simulation realization is completed. A new sequential Gaussian simulation realization is obtained based on a new random path.

After sequential Gaussian simulation, a spherical variogram model was used to confine the facies-controlled porosity model because the spherical variogram model has a better fitting precision than other variogram theoretical models, such as the exponential model or the Gaussian model. In the process of facies-controlled porosity modeling, parameters of variograms, such as horizontal or vertical range and azimuth, were altered to reflect the spatial correlation of the variable. The theoretical spherical variogram is defined as follows

\[
r(h) = \begin{cases} 
  c \times \left( 1.5 \frac{h}{a} - 0.5 \left( \frac{h}{a} \right)^3 \right) & h \leq a \\
  c, & h > a
\end{cases}
\]

The parameter "a" is a range, which refers to the variation degree or the influence sphere of the regionalized variables. The major range refers to the influence of the sphere on the major source material direction or major flow line, and the range was determined based on the geological background. The minor range direction is orthogonal with respect to the major range direction. The vertical range means the average range of the vertical influence sphere of the regionalized variables. The parameter "c" is a partial sill and represents the total variability level of the variable in space.

The process of modeling is shown in Figure 14. In this modeling workflow, basic data, such as core data, stratigraphy data, and porosity data, were collected and imported as the input information. The structural model was established according to the structural data. Furthermore, each microfacies was transformed into a facies code based on sedimentary research. Subsequently, an analysis of the porosity within the established microfacies framework was conducted before porosity modeling. The final results of facies-controlled porosity modeling were validated using the actual data, such as those of petrophysical experimentation and the hydrological pumping test (Figure 14).

**Figure 14.** Flow chart of facies-controlled modeling.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.0c06166.

Overburden pressure porosity experiment of 42 samples; porosity value to build the porosity model; and hydrochemical experiments of Hongliu coalmine (XLSX)

**AUTHOR INFORMATION**

**Corresponding Author**

Juan Qu — Department of Mechanical and Electrical Engineering, Shandong University of Science and Technology, Taian 271019, China; Email: pxqi0321@163.com

**Authors**

Liyao Li — State Key Laboratory of Nuclear Resources and Environment, East China University of Technology, Nanchang 330000, China; orcid.org/0000-0002-0178-1529

Jiuchuan Wei — College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266000, China

Fei Xia — State Key Laboratory of Nuclear Resources and Environment, East China University of Technology, Nanchang 330000, China

Jindong Gao — State Key Laboratory of Nuclear Resources and Environment, East China University of Technology, Nanchang 330000, China
Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c06166

Notes

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