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*Original Research*

# The Law of Sedimentary Water Control of the Bottom Aquifer in Xutuan Mine, Huaibei Mining Area, China

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## Abstract

Studying the law of sedimentary water control of aquifers is crucial for correctly understanding the water-richness of aquifers. This knowledge ensures the safe, efficient, and environmentally friendly mining of coal seams. To address the insufficient research on sedimentary control mechanisms in loose pore aquifers, this study focuses on the bottom aquifer of the Cenozoic loose layer (called the Bottom Aquifer) in Xutuan Mine, Huaibei Mining Area, China. It analyzes sedimentary facies/ subfacies /microfacies characteristics of the Bottom Aquifer, the contact types and connectivity of the sand bodies in the vertical and horizontal dimensions, and combines water physical property testing and pumping test results to discuss the relationship between sedimentary characteristics and water-richness. The research unveils the sedimentary control mechanism influencing water-richness in the Bottom Aquifer, establishes sedimentary water control modes, and proposes the superimposed replenishment mode of fan middle subfacies sand bodies in the alluvial fans of groundwater in the Bottom Aquifer to address the phenomenon of water inrush at the 32 mining areas of Xutuan Mine, where the amount of water inrush is not large, but the duration is continuous. The results provide a scientific basis for the prevention and control of water damage in the Bottom Aquifer.

**Keywords**: loose pore aquifer, sedimentary water control, water-richness, water inrush, coal mine

## Introduction

Coal plays an important role in China's energy structure and will continue to be its main energy source for a long period [1-3]. It will also be a crucial component of national energy security and drive high-quality socio-economic development for a long time [4, 5]. However, the extensive and intense mining of coal resources in China has led to a growing issue of water damage to coal seam roofs across various mining areas. The problem is becoming increasingly prominent, causing occasional water inrush disasters that pose a serious threat to the safe, efficient, and environmentally friendly mining of coal resources in China [6-8]. The geological water control laws in coal mines and the water-richness of aquifers are key issues that need to be considered for

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the prevention and control of water damage in the roof [9, 10]. Due to the low degree of hydrogeological exploration in some mines and the uneven water-richness of aquifers, there are large discrepancies between expected and actual mine water influx during exploration. This can lead to severe mine roof water damage, resulting in substantial economic losses and harm to groundwater resources and the mine's ecological environment [11, 12]. Prior research has primarily focused on the law of structural water control, emphasizing that faults, folds, and other tectonic factors mainly control groundwater storage. In contrast, investigations into the law of sedimentary water control are still in their early stages [12, 13]. Insufficient in-depth research on the fundamental theories of aquifer water distribution and its sedimentary control mechanism is a key factor contributing to frequent water accidents during coal seam mining beneath aquifers. This, in turn, raises production costs for mines.

In recent years, guided by the analysis of "groundwater controlled by depositional architecture", scholars have conducted many studies on the sedimentary characteristics of aquifers and their relationship with water-richness, achieving relatively robust results in effectively guiding the prevention and control of mine water hazards [14-16]. Wu et al. [9] applied sedimentary water control characteristics to construct an evaluation index system to ascertain the water-richness of porous aquifers. They used a comprehensive weighting method and a comprehensive multi-index uncertain measurement coupling model for zoning the aquifer water-richness. Ma et al. [14] revealed the genetic mechanism of the differences in water abundance in the Zhiluo Formation from the perspective of sedimentary history. Feng et al. [12, 16] clarified the concept of "sedimentary water control", analyzed the relationship between sedimentary facies and water-richness, and indicated that the sedimentary characteristics of aquifers are the most basic factors controlling their formation and groundwater occurrence. Wang et al. [17] analyzed the plane and lateral spatial distribution patterns of the water-bearing aquifers and the control of the water-richness distribution with the sediment control method and achieved accurate zoning and evaluation of aquifer water richness. Hou et al. [18] conducted a systematic analysis of the factors affecting the water-richness of weathered bedrock in the Hongliulin Mine of the Shenfu Mining Area and concluded that weathered bedrock with coarse-grained sandstone, large thickness, strong weathering, and developed fracture pores has better water-richness. As research advances, scholars have applied reservoir science methods to investigate the link between sandstone pore structure and water-richness at the microscopic level, yielding positive results [19, 20]. For example, Wang et al. [21] analyzed the relationship between sandstone microporous structure and water-richness by testing the sandstone microporous structure and comparing the unit water inflow with the results of borehole pumping tests. The above research results have greatly enriched the understanding of sedimentary water control and provided guidance to effectively carry out water control activities in mines. However, the water-filled aquifers in China's coal beds are diverse and complex, and the aquifers affecting coal mining can be divided into three categories based on the water-bearing medium and the state of groundwater storage; these are loose layer pore aquifers, bedrock fissure aquifers, and carbonate karst aquifers [10]. In the past, sedimentary water control studies have primarily focused on fissure aquifers in bedrock and karst aquifers in limestone. Limited attention has been given to sedimentary water control in loose aquifers, and the mechanisms involved in this context remain incompletely understood [2, 10]. The features of a pore aquifer in a loose layer fundamentally differ from fissure aquifers in bedrock and karst aquifers in limestone. Pore aquifers in loose layers are basically unaffected by tectonic factors and mainly affected by the depositional environment, including different sedimentary facies/ subfacies/ microfacies, and there are big differences in the spatial distribution of the sedimentary thickness, lithology, structure, etc. [9]. Accordingly, the permeability and water-richness characteristics also show extremely heterogeneous characteristics. However, it is unclear how this aquifer's sedimentary facies/ subfacies/ microfacies control the spatial distribution and type of the sand body and its relationship with the sedimentary facies/ subfacies/ microfacies. Additionally, the relationship between sand body distribution in various sedimentary phases and water-richness is poorly defined. Further exploration is needed to understand how sedimentary characteristics control the water-richness difference in loose aquifers.

This study focuses on the Bottom Aquifer in the Xutuan Mine in the Huaibei Mining Area of China. The Bottom Aquifer's sedimentary facies/ subfacies/ microfacies characteristics are analyzed to reveal the contact types and connectivity of the sand bodies with different sedimentary facies/ subfacies/ microfacies. The Bottom Aquifer's hydrophysical properties were determined through sediment hydrophysical property testing. The effect of different sedimentary phases on the water-richness of the Bottom Aquifer is investigated by combining the unit water inflow $q$ values obtained from pumping tests. In addition, sedimentary water control modes of the Bottom Aquifer are established to unveil the sedimentation control mechanism influencing water-richness differences. This is done to offer technical guidance and theoretical support for water prevention and control efforts in the Xutuan Mine and other mines in the Huaibei Mining Area grappling with water damage from the Bottom Aquifer.

## Materials and Methods

### Overview of the Study Area

The Xutuan Mine is located in Mengcheng County, Anhui Province, China, in the southern part of the

Huaibei Mining Area, with an area of 52.5923 km$^2$, as shown in Fig. 1. The study area is in the middle of the Huaibei Plain, with a relatively flat topography that is higher in the north than in the south. The climate is mild, with a north temperate monsoon oceanic-continental climate, and the area is in the Huaihe River Basin. The Beifei River, a seasonal river and a tributary of the Huaihe River, flows from the south side of the mine. Thick and loose layers cover the study area, and the regional stratigraphy is of the North China type. The main stratigraphic sequences exposed by boreholes are Ordovician, Carboniferous, Permian, Paleocene, Neoproterozoic, and Quaternary (Q), which are covered by thick loose layers without bedrock outcrops in the field. The coal-bearing strata are the Carboniferous and Permian strata. Among them, the Carboniferous coal beds are thin and unstable, and the Permian coal beds are the object of exploration in the mine; they have a thickness of about 999 m, containing several coal seams (groups) numbered from top to bottom as 1, 2, 3, 4, 5, 6, 7, 8, 10, and 11 coal seams (groups). Currently, four coal seams are being mined: No. $3_2$ coal, No. $7_1$ coal, No. $7_2$ coal, and No. $8_2$ coal. The elevation of the mining area ranges from -800 m to -360 m. The Xutuan Mine is generally characterized by a monocline structure that runs in a nearly north-south direction and tilts eastward, but secondary fold and fault structures are relatively developed within the mine's area.

Based on the groundwater storage medium characteristics, the aquifers can be divided into the loose layer aquifer of the Cenozoic, the sandstone fissure aquifer of the main Permian coal seam, and the karst fissure aquifer of the Taiyuan Group and Ordovician limestone. Among them, the loose layers of the Neogene and Quaternary in the Cenozoic can be divided into four aquifer groups and three aquitard groups. The aquifer groups are the fourth aquifer, the third aquifer, the second aquifer, and the first aquifer from bottom to top, and the water-resisting layer groups are the third water-resisting layer, the second water-resisting layer, and the first water-resisting layer from bottom to top. Among them, the fourth aquifer in the mine has a large variation in thickness and complex lithology. It is the bottom aquifer of the Cenozoic loose layer (referred to as the Bottom Aquifer), most of which directly covers the coal-bearing strata. It is one of the main water sources filling the Xutuan Mine and is the research object of this study. Above the Bottom Aquifer is the third water-resisting layer, with an average effective thickness of 123.30 m. The middle and upper parts of the third water-resisting layer are mainly composed of clay and sandy clay, while the lower part is mainly composed of clay, sandy clay, and calcareous clay. The third water-resisting layer has good plasticity, strong expansion, large thickness, and stable distribution. It is composed of sediment deposited in the still water environment of lakes and lakeside backwater bays and can effectively block the hydraulic connection between surface water and groundwater in the first, second, and third aquifers and groundwater in the Bottom Aquifer and bedrock aquifers. It is an important water-resisting layer in the Xutuan Mine.

The 32 mining area of the Xutuan Mine is relatively close to the Bottom Aquifer, and mining of the No. $3_2$ coal seam is threatened by water damage from the Bottom Aquifer. Two water inrush accidents occurred when the No. $3_2$ coal seam was being mined. According to the unit water inflow $q$ values, the water-richness of the Bottom Aquifer in the study area has weak to moderate water-richness, but the distribution of $q$ values varies greatly, ranging from 0.00062 to 0.33580 L/(s·m),

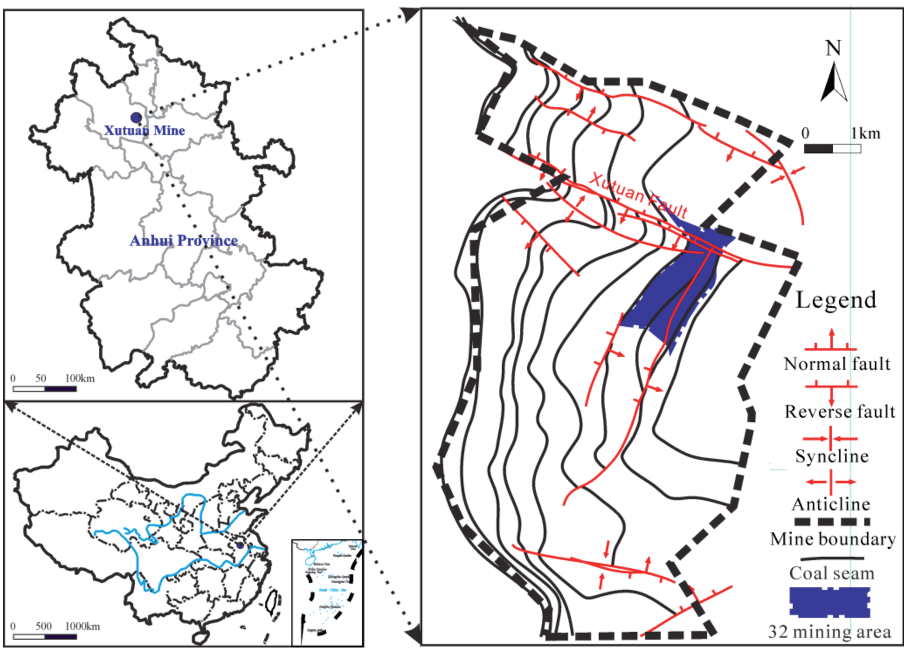



Fig. 1. Location of the Xutuan Mine and its tectonic outline.

indicating extremely uneven water-richness. After the mining of the working face is completed, the mine water inflow in the goaf is 50 $m^3/h$, but the duration of water inflow is continuous, and the water inflow is stable, far exceeding the expected mine water inflow during the exploration stage. This has changed the understanding of the water-richness of the Bottom Aquifer in the exploration stage, affected the normal production of the mine, and damaged the mining area's underground water resources and ecological environment. Therefore, the Bottom Aquifer's sedimentary water control characteristics and uneven water-richness require immediate attention.

### Sample Collection and Analysis

A total of 384 sets of drilling data were collected for statistical analysis of the thickness and lithological characteristics of the Bottom Aquifer from Xutuan Mine. Sediment samples of the Bottom Aquifer were collected from 8 drilling sites in the 32 mining areas of Xutuan Mine, as shown in Fig. 2. The observed lithological characteristics of the Bottom Aquifer at the 8 drilling sites indicated high gravel proportions (over 65%) in the sediments at sites No. 1, No. 2, and No. 3, with low mud and sand proportions. The gravel particles exhibited a yellow color, with abundant sandstone and limestone fragments. In addition, these particles showed a diameter range of 2~6 cm, with rounded to sub-rounded shapes. The sand layer consisted of fine particles with a light-yellow color, a high quartz proportion, and poor-to-medium sorting. In total, four sites (No. 3-4, No. 4, No. 5, and No. 6) of the Bottom Aquifer contained high mud and sand contents, with low gravel contents. The clay-gravel mixture sediments exhibited a brownish-yellow, with a loose structure and a relatively low gravel content of about 15%. The gravel layers consisted mainly of sandstone and limestone fragments, with a diameter range of about 1~2 cm and a poorly rounded shape. The lithological characteristics of the Bottom Aquifer sediments at the No. 7 and No. 8 sites showed a dominance of fine sand, with a brownish-yellow color and low gravel proportions.

In addition, 8 sets of sediment samples were taken from the No. 2010-Shui 1 hole and tested for sediment hydrophysical properties at depths ranging from 317.74 m to 355.14 m. The test contents included sediment water content, pore compaction, deformability, dilatability, and fractal dimension values. The test results are shown in Table 1.

## Results and Discussion

### Sedimentary Characteristics of the Bottom Aquifer

The Bottom Aquifer is widely distributed in the study area, but there is a large difference in its sedimentary thickness, which ranges from 0 to ~76.35 m (average thickness of 14.60 m). In the northern part of the study area, the Bottom Aquifer in the buried hills and the western and southern structural protrusions exhibit limited or thin sediment, primarily ranging between 0 and 5 m in thickness. The sedimentary thickness

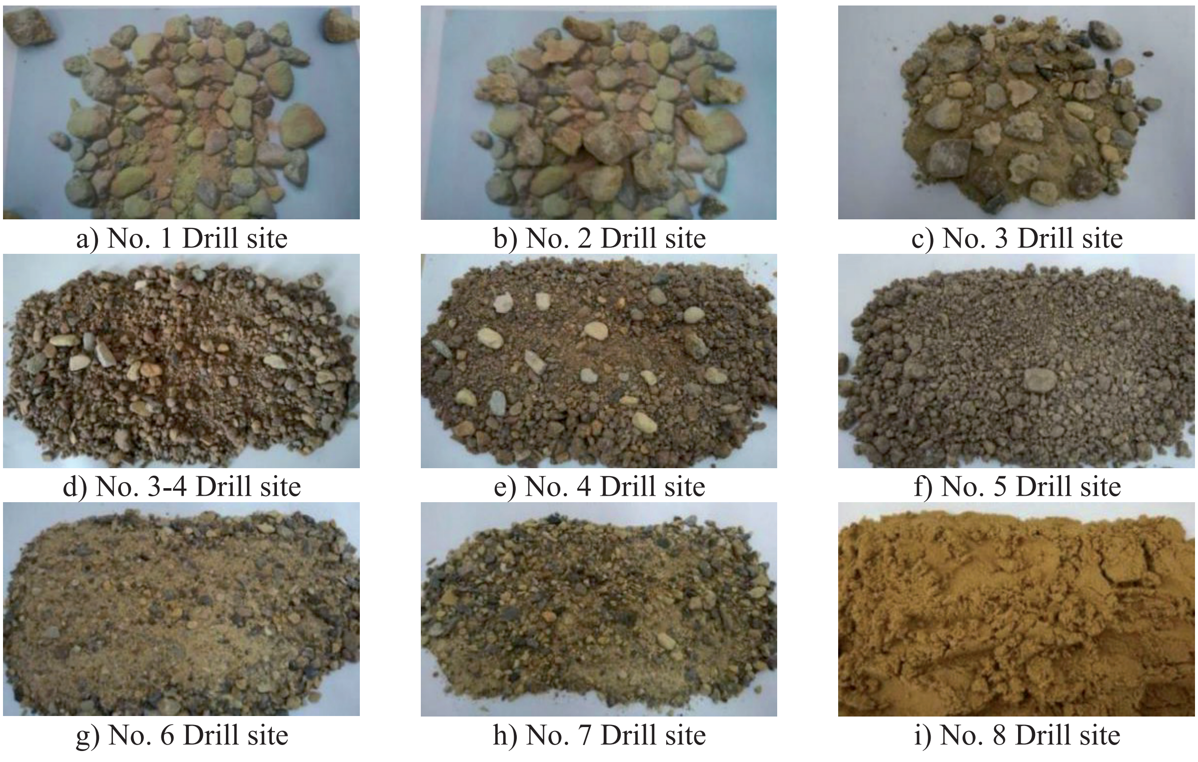



Fig. 2. Lithological characteristics of the Bottom Aquifer sediments in the Xutuan Mine.

Table 1. Test results of water physical properties of sediment samples of the Bottom Aquifer from the No. 2010-Shui 1 hole in the Xutuan Mine.

| Sample number | Unit weight ($G$) | Pore ratio ($e$) | Saturated water content ($Wc$)/% | Fractal dimension value ($D$) | Liquid limit ($W_L$) | Plastic limit ($W_P$) | Liquidity index ($I_{P1}$) | Plasticity index ($I_{P2}$) | Plasticity classification | Saturation liquidity index ($I_L$) | Saturation consistency classification | No-load expansion rate / % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.818 | 0.515 | 18.27 | 2.6996 | 33.5 | 18.5 | -0.45 | 15.0 | Solid state | -0.45 | Hard | 40 |
| 2 | 3.037 | 0.543 | 17.87 | 2.7672 | 32.6 | 17.3 | -0.4 | 15.4 | Solid state | -0.4 | Hard | 30 |
| 3 | 2.789 | 0.538 | 19.29 | 2.7066 | 33.6 | 19.2 | -0.54 | 14.4 | Solid state | -0.54 | Hard | 48 |
| 4 | 2.807 | 0.44 | 15.67 | 2.7045 | 31.5 | 18.3 | -0.87 | 13.2 | Solid state | -0.87 | Hard | 32 |
| 5 | 3.004 | 0.536 | 17.84 | 2.7862 | 29.5 | 16.9 | -0.45 | 12.6 | Solid state | -0.45 | Hard | 62 |
| 6 | 2.521 | 0.408 | 16.18 | 2.6714 | 31.4 | 15.4 | -0.57 | 16.0 | Solid state | -0.57 | Hard | 48 |
| 7 | 2.684 | 0.42 | 15.64 | 2.7829 | 31.5 | 18.5 | -0.56 | 13.0 | Solid state | -0.56 | Hard | 30 |
| 8 | 2.833 | 0.431 | 15.21 | 2.7666 | 30.4 | 16.7 | -0.52 | 13.7 | Solid state | -0.52 | Hard | 88 |

in the central part of the study area is relatively thin, mainly ranging from 5 to 10 m. The thickness of the Bottom Aquifer in the area north of the Xutuan Fault and near the southern part of the Xutuan Fault is large, mainly ranging from 20 to 50 m. The Bottom Aquifer in the study area not only has significant differences in thickness but also has complex lithology, mainly consisting of gravel, sandy gravel, coarse sand, medium sand, fine sand, silt, clayey sand, clay interbedded with gravel, clay, sandy clay, calcareous clay, etc. The Bottom Aquifer in the study area has both single-layer and multi-layer composite structures, which are predominantly comprised of multi-layer composite structures. The sediment of the Bottom Aquifer exhibits a multi-layer composite structure characterized by changes in particle size and alternating sedimentation of sand and clay in the vertical direction. Generally speaking, there is a layer of gravel or sandy gravel developed at the bottom of the Bottom Aquifer's sediments; above this, there are multiple layers of sand interspersed with single or multiple layers of clay. The sand layers are mainly composed of impure medium sand, fine sand, and clay sand, while the clay layers are dominated by sandy clay with varying thicknesses. The uppermost layer is generally dominated by fine sand. Horizontally, each individual layer exhibits poor stability, and the gravel, sand, and clay layers are vertically interlaced and deposited.

The sedimentary system of the Bottom Aquifer was established, as shown in Table 2, based on its color, lithology, sedimentary structure, sedimentary textures (grain size, fractal characteristics, etc.), and logging curve characteristics combined with data on the ancient topographic features of the study area. During the deposition of the Bottom Aquifer in the study area, the sedimentary environment was mainly composed of alluvial and slope-residual environments under arid climate conditions. Therefore, the Bottom Aquifer is divided into two categories: slope-residual facies and alluvial fan facies. The alluvial fan facies is further divided into 3 subfacies – fan root, fan middle, and fan end – and 5 microfacies – fan root debris flow sedimentation, fan root main channel sedimentation, fan middle braided channel sedimentation, fan middle overflow sedimentation, and fan end overflow sedimentation. The Bottom Aquifer in the study area is characterized by unequal deposition time and is dominated by alluvial fan facies sediments, which are the superimposed products of four stages of the retrogressive sedimentation of alluvial fans continuously migrating from the southeast to the northwest. The slope-residual facies are mainly distributed in the northern buried hills and the study area's western and southern structural protrusions.

In the ancient buried hills in the northern part of the study area, as well as in the structural protrusions in the western and southern parts, the Bottom Aquifer's sediments are products of a slope-residual environment, and the sediment thickness is thin, with a relatively

Table 2. Sedimentary system division of the Bottom Aquifer in the study area.

| Sedimentary facies | Sedimentary subfacies | Sedimentary microfacies |
|---|---|---|
| Slope-residual facies | / | / |
| Alluvial fan | Fan root | Debris flow sedimentation |
| | | Main channel sedimentation |
| | Fan middle | Braided channel sedimentation |
| | | Overflow sedimentation |
| | Fan end | Overflow sedimentation |

simple lithological structure. In the area north of the central part of the study area, the Bottom Aquifer's sediments are products of the superposition of multiple phases of fan bodies under an alluvial environment; here, the Bottom Aquifer has a larger sediment thickness and is a composite structure of various lithologies. The lithology of different sedimentary stages corresponds to different subfacies of alluvial fans, and multiple subfacies are stacked in space, with rapid phase transitions and poor regularity. It is also difficult to study the distribution of sedimentary facies on the plane. Therefore, it is necessary to determine the main and representative sedimentary facies, namely the dominant facies. By analyzing the thickness ratio of different sedimentary facies/subfacies vertically within the exposed Bottom Aquifer in each borehole and integrating this data with the distribution of sand gravel layer thickness and the ratio of sand gravels in the aquifer, the dominant phase type in each borehole was determined, and this was used to characterize the sedimentary facies/subfacies of the Bottom Aquifer in each borehole. Then, the distribution of the Bottom Aquifer's sedimentary facies in the study area was finally determined, as shown in Fig. 3.

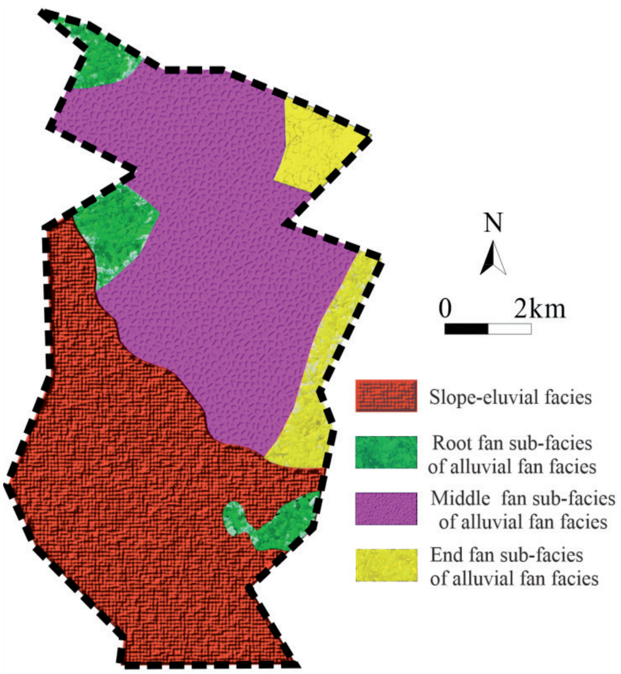



Fig. 3. Distribution of the sedimentary facies of the Bottom Aquifer in the Xutuan Mine.

## Sand Body Contact Type

Studying the contact type of sand bodies between boreholes is crucial for understanding the water-bearing characteristics of aquifers. Analyzing the contact type of sand bodies can help to reasonably explain the connectivity between sand bodies. This analysis is essential for further exploring groundwater connectivity and establishing a scientific basis for preventing and controlling mine water hazards. According to the aforementioned sedimentary facies analysis, the sediment in the Bottom Aquifer of the study area is mainly the product of slope-residual deposits and the superposition of alluvial fan bodies deposited over multiple periods. Based on the analysis of drilling core and logging data, combined with sedimentary facies analysis, the contact types and connectivity of the Bottom Aquifer sand bodies exposed by drilling in the study area during the same sedimentary stage were analyzed vertically and horizontally. The vertical stacking of sand bodies in the Bottom Aquifer of the study area can be divided into 4 types: isolated distribution type (single sand body and multi-stage sand bodies), vertical stacking type, dislocated stacking type, and horizontal lap type, as shown in Fig. 4. There are 3

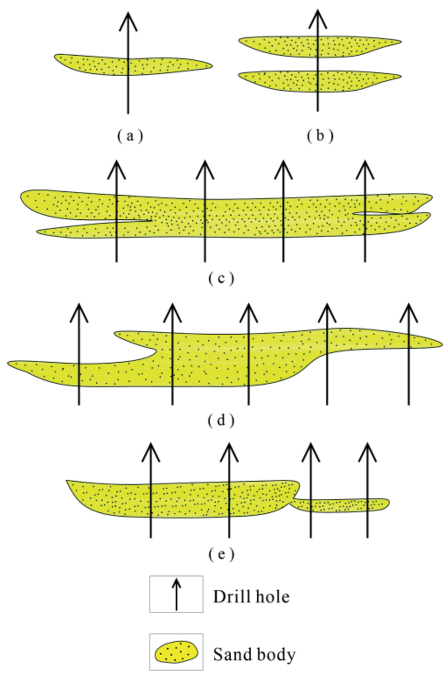



Fig. 4. Vertical stacking types of sand bodies.

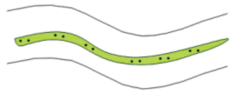
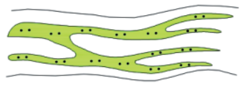
| Genetic type of sand body | Planar distribution type | Schematic diagram | Development environment of sand bodies |
|---|---|---|---|
| Slope-residual | Isolated scattered distribution type |  | Slope-residual environment |
| Alluvial fan | Isolated strip distribution type |  | Transition area between the fan middle and the fan end |
| | Intersecting strip distribution type |  | Transition area between the fan root and the fan middle |

Fig. 5. Contact type of the sand bodies of the Bottom Aquifer on the plane.

types of planar sand body distribution: isolated scattered distribution type, isolated strip distribution type, and intersecting strip distribution type, as shown in Fig. 5.

In alluvial sand bodies, as braided channels migrate from the middle to the fan end, frequent migration, diversion, and branching reduce the size of individual river sand bodies. This results in a continuous decrease in the stacking degree of sand bodies. The sand body stacking type gradually changes from the vertical stacking type and dislocated stacking type with good sand body connectivity to the horizontal lap type or isolated distribution type with poor sand body connectivity. Therefore, special attention should be paid to the sediment in the middle part of the alluvial fan to effectively assess the water-bearing space and groundwater connectivity in the research area.

The sand bodies caused by slope-residual deposits have obvious zonality, are mostly distributed in isolated and scattered areas, and are horizontally discontinuous. The isolated strip distribution type is a single strip, mainly distributed in the transition area from the alluvial fan middle to the alluvial fan end area. There is no large connected area between the sand bodies, and the sand body has a fine particle size, a small range, and poor connectivity. Intersecting strip distribution-type sand bodies are characterized by each branch channel sand body having a specific connected area on the plane. Channels frequently bifurcate and merge and are mainly distributed in the transition area from the fan root to the fan middle and the main part of the fan middle. The sand body has a coarse particle size, a large distribution range, and good connectivity.

Based on the above analysis, it can be concluded that the sand bodies in the Bottom Aquifer located in the fan middle of the alluvial fan during the same sedimentary stage have a wide distribution range, coarse particle size, and large water storage space. Groundwater has good connectivity in both horizontal and vertical directions and should be a key target area for preventing water damage from the Bottom Aquifer. The sediment in the Bottom Aquifer, resulting from the stacking of alluvial fan bodies at various sedimentary stages, demonstrates effective hydraulic connectivity in both horizontal and vertical directions. This is achieved through the spatial stacking of sand bodies in the middle of each alluvial fan.

## Analysis of the Sediments' Hydrophysical Properties

Sedimentary characteristics fundamentally affect the hydrophysical properties of sediments, serving as an important basis for understanding water distribution in water-bearing sediments. This analysis is vital for analyzing the water-richness of the Bottom Aquifer. The Bottom Aquifer sediment sampling hole of the No. 2010-Shui 1 is located in an ancient gully on the south side of the Xutuan Fault, and according to the aforementioned sedimentary facies analysis, the 8 sets of sediment samples of the Bottom Aquifer here are the product of the stacking of three periods of alluvial fan deposits. Among them were 2 sets of samples belonging to the fan middle overflow sedimentation microfacies (sample numbers 1~2) and 6 sets belonging to the fan root debris flow sedimentation microfacies (sample numbers 3~8).

As seen in Table 1, the water content $W_C$ values of the sediment samples ranged from 15.21% to 19.29%, with an average value of 17% and a maximum value of less than 20%. This indicates that the Bottom Aquifer at the sampling borehole location lacks a typical water-rich sandy layer, exhibiting low inherent water content and hydraulic conductivity. It is characterized by high clay content in all layers, resulting in poor water permeability and sediment-water content. Among them, the $W_C$ values of the samples belonging to the fan middle overflow sedimentation microfacies range from 17.87% to 18.27%, with an average value of 18.07%, while the $W_C$ values of the samples belonging to the fan root debris flow sedimentation microfacies range from 15.21% to 19.29%, with an average value of 16.64%. This indicates that the water content of the sediment in the fan middle overflow sedimentation microfacies is stronger than that in the fan root debris flow sedimentation microfacies in general.

Table 1 shows that the pore ratio *e* values of the sediment samples are between 0.408 and 0.543, with an average of 0.4789, which are all consistent with sandy soils with pore ratios of less than 0.7. According to engineering geological classification, they belong to high-density soil, reflecting the Bottom Aquifer's deep burial depth in the study area and high compaction. Therefore, the sediment pore ratio is low overall, and the water-richness is not strong. The pore ratio *e* values of the samples belonging to the fan middle overflow sedimentation microfacies are 0.515~0.543, with an average of 0.529. The pore ratio *e* values of samples belonging to the fan root debris flow sedimentation microfacies are 0.408~0.538, with an average of 0.462. This indicates that the pore ratio of the sediment samples of the fan middle overflow sedimentation microfacies is generally higher than that of the fan root debris flow sedimentation microfacies.

Deformability can reflect the ability of sediment to release water under water-containing conditions. Generally, the ability of soil to resist plastic deformation under external forces can be determined by analyzing the relationship between water content and plastic limit. Table 1 shows that the majority of the tested sediment samples have a water content below the plastic limit, and the liquid limit index of the measured samples is less than 0, indicating that the soil is in a solid or semi-solid state. This indicates that the sediment has been strongly compacted for a long time, with low porosity and water content.

The ability of cohesive soils to increase in volume due to an increase in water content is called dilatability. In this experiment, the no-load expansion rate index was used to represent the expansion of cohesive soil. Table 1 shows that the no-load expansion rate of the samples tested is 30%~88%, mainly concentrated between 30%~62%, with sample No. 8 reaching a maximum of 88%. According to relevant research, the mechanism of expansive behavior comes from the double-layer effect of clay minerals, and the more developed the double layer of clay minerals, the lower their permeability. Therefore, the highly expansive behavior of sediments actually means that their water-richness is weak. Among them, the samples belonging to the fan middle overflow sedimentation microfacies have expansion rates of 30% to 40%, with an average value of 35%. The samples belonging to the fan root debris flow sedimentation microfacies have expansion rates of 30% to 88%, with an average value of 51.33%. This indicates that the overall dilatability of the sediment samples of the fan middle overflow sedimentation microfacies is stronger than that of the fan root debris flow sedimentation microfacies.

The fractal dimension value (*D*) can be used to characterize the physical properties of water in sediments [22]. The *D* value is positively correlated with the clay mass fraction and the non-uniformity coefficient while negatively correlated with the permeability coefficient. If the *D* value of the sediment is larger, the non-uniformity coefficient and clay mass fraction are larger, while the permeability coefficient is smaller, indicating that the permeability of the sediment is poorer, which, to some extent, reflects poorer water-richness. According to Table 1, the *D* values of the tested samples are 2.6714~2.7862, with an average value of 2.7356. Compared with the *D* value of fluvial facies sediments, the *D* value of the Bottom Aquifer is relatively large, indicating that its water-richness is generally weak. The *D* values of the samples belonging to the fan middle overflow sedimentation microfacies are 2.6996~2.7672, with an average value of 2.7334. The *D* values of samples belonging to the fan root debris flow sedimentary microfacies are 2.6714~2.7862, with an average value of 2.7364, indicating that the *D* values of sediments in the fan middle overflow sedimentation microfacies are generally smaller than those in the fan root debris flow sedimentation microfacies. Therefore, the water-richness of sediments in the fan middle overflow sedimentation microfacies is stronger than in the fan root debris flow sedimentation microfacies.

## Analysis of Unit Water Inflow of the Bottom Aquifer

The Bottom Aquifer in the study area is mainly composed of slope-residual deposits and the products from multiple periods of alluvial fan deposition. Due to the different sedimentary characteristics, the lithology and structure are quite different, resulting in obvious differences in the water-bearing properties of the sediments. Previous studies on the classification of sedimentary facies, their relationship with water-richness, and the relationship between lithology and its combination with water-richness have mostly focused on qualitative research. They have been mostly based on the qualitative analysis of the relationship between sedimentary facies and water-richness, including the analysis of sand body thickness and underground water drainage [12, 16]. The unit water inflow *q* value is the most direct and accurate parameter for evaluating the water-richness of aquifers, and the detailed rules for coal mine water prevention and control stipulate that the water-richness of the aquifer is divided into four levels according to the value *q* of specific water yield [23]. Specifically, it is divided into weak water richness (*q* value less than 0.1 L/(s·m)), medium water richness (*q* value between 0.1 (s·m) and 1 (s·m)), strong water richness (*q* value between 1 (s·m) and 5 (s·m)), and extremely strong water richness (*q* value greater than 5 (s·m)). In this study, we quantitatively analyzed the degree of water-richness of the sediments with different sedimentary facies/ subfacies/ microfacies from the perspective of unit water inflow *q* values.

The unit water inflow *q* values of the pumping test section were collected from the pumping test data of the Bottom Aquifer in the Xutuan Mine over the years. Based on sedimentary facies analysis, the sedimentary facies/ subfacies/ microfacies types in the pumping test section were determined, and the corresponding relationship between the lithology of the pumping test section of the Bottom Aquifer's sediments with different

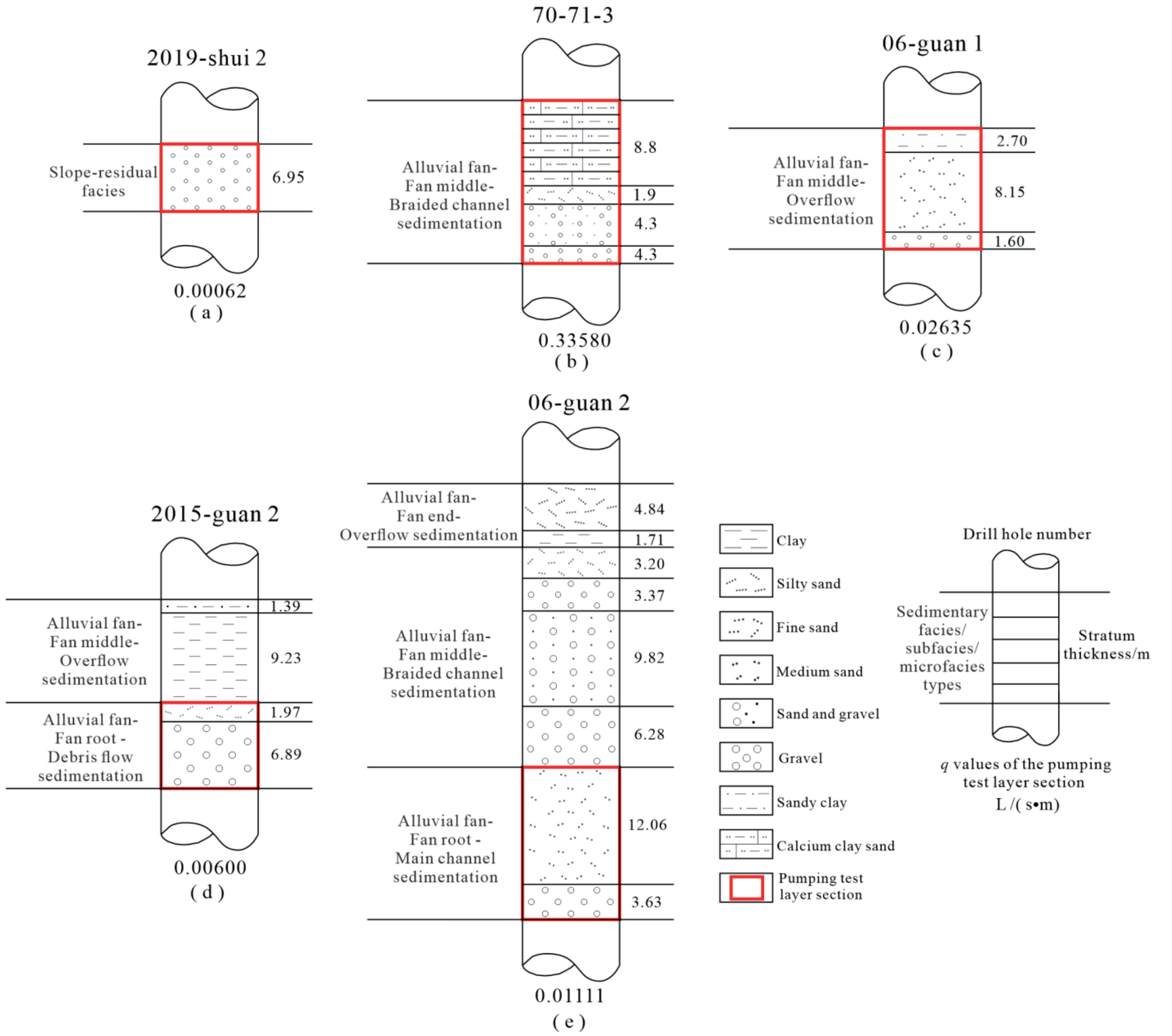



Fig. 6. Values of the unit water inflow of the sediments with different sedimentary facies/ subfacies/ microfacies.

sedimentary facies/ subfacies/ microfacies and their unit water inflow $q$ values are shown in Fig. 6.

Fig. 6 shows an obvious correspondence between sediments of different sedimentary facies and their water-richness. The $q$ values of the Bottom Aquifer in the study area are 0.00062~0.33580 L/(s m), indicating that the overall water-richness of the Bottom Aquifer is not strong and has weak to medium water-richness. However, there is a significant difference in the distribution of $q$ values, and the water-richness is extremely uneven. The $q$ values of the sediments in the Bottom Aquifer caused by slope-residual deposits are very small, with $q$ values ranging from 0.00062 to 0.00253 L/(s m). The sediments in the Bottom Aquifer obtained from alluvial deposits have different sedimentary microfacies, resulting in significant differences in the $q$ values, with $q$ values ranging from 0.00600 to 0.33580 L/(s m). Among them, the fan middle braided channel sedimentation microfacies sediment has coarser particle size, a thicker sand body, good permeability and connectivity, and the highest $q$ value. Although the particle size of the fan root debris flow sedimentation microfacies is coarse, the space between coarse particles is filled with a large amount of clay and other fine particles, resulting in a mixture of coarse and fine particles. This has resulted in limited water storage space and poor connectivity of the sand body, with very small $q$ values. Overall, the water-richness of the alluvial sediment deposits is significantly higher than that of the slope-residual deposits.

## Sedimentary Water Control Modes

The above analysis shows that the sedimentation of the Bottom Aquifer in the study area significantly affects its water-richness. The water-richness of alluvial deposit sediments in the study area is significantly stronger than that of slope-residual deposits but has obvious non-homogeneity. There are significant differences in sediment water-richness between different

Table 3. Relationship between sediments of different sedimentary facies and water-richness.

| Sedimentary facies | Sedimentary subfacies | Sedimentary microfacies | $q$ (L/(s·m)) | Relative water-richness ranking |
|---|---|---|---|---|
| Slope-residual facies | / | / | 0.00062~0.00349 | No. 6 |
| Alluvial fan facies | Fan root | Debris flow sedimentation | 0.006~0.00752 | No. 5 |
| | | Main channel sedimentation | 0.01111 | No. 3 |
| | Fan middle | Braided channel sedimentation | 0.1369~0.3358 | No. 1 |
| | | Overflow sedimentation | 0.02047~0.03317 | No. 2 |
| | Fan end | Overflow sedimentation | / | No. 4 |

sedimentary subfacies of the same sedimentary facies and between different sedimentary microfacies of the same sedimentary subfacies. Significant differences in sand layer distribution and reservoir performance in different types of sand bodies will be observed due to differences in sedimentary subfacies and microfacies. Using borehole coring data, pumping test data, particle size testing, and hydrophysical property testing data, the relationship between different sedimentary facies and water-richness has been analyzed based on lithological and structural features, sand body contact type, connectivity, and water storage properties of the Bottom Aquifer sediments, and the relative water-richness rankings have been given, as shown in Table 3.

Table 3 shows that the sediment of the fan middle braided channel sedimentation microfacies has the best water-richness, while the slope residual sediment has the worst water-richness, and in the middle are fan middle overflow sediment, fan root main channel sediment, fan end overflow sediment, and fan root debris flow sediment in the order of better to worse water-richness. Based on the relative water-richness and the size of the unit inflow $q$ values, the Bottom Aquifer is divided into two water control modes: the slope-residual sedimentary water control mode and the alluvial fan sedimentary water control mode.

1) Slope-residual sedimentary water control mode

In this sedimentary water control mode, the lithology is mixed, with poor sorting and rounding, loose structure, and other particles of different sizes filling the space between particles. The sand and gravel layers in the aquifer have fewer layers (mostly 1~2 layers) and thin sedimentary thickness, and their distribution has obvious zonality. The sand bodies are not connected, with the isolated distribution type in the vertical direction and the isolated scattered distribution type in the plane. The water storage space is limited, and the permeability is poor, with poor water-richness.

2) Alluvial fan facies sedimentary water control mode

The lithology is complex in this sedimentary water control mode, and the sedimentary characteristics of the different sedimentary subfacies/microfacies are different. The sediment's water-richness has obvious heterogeneity, and the water control characteristics also show significant differences. Based on the differences in water control characteristics, it can be further divided into 5 types: medium water-rich type of the braided channel sedimentation in the fan middle, weak water-rich type of the overflow sedimentation in the fan middle, weak water-rich type of the main channel sedimentation in the fan root, weaker water-rich type of the overflow sedimentation in the fan end, and weaker water-rich type of the debris flow sedimentation in the fan root.

(1) Medium water-rich type of braided channel sedimentation in the fan middle

In this sedimentary water control type, the sediment is poorly to moderately sorted and rounded to sub-angular to sub-circular in shape, with coarse particle size. It is mainly composed of gravel, sand, and coarse to fine sand, with a relatively pure composition. Fewer fine particles, such as clay, are filled between the coarse particles. The connectivity between sand bodies is good, with vertical stacking and dislocation stacking being the main types in the vertical direction and intersecting strip distribution being the main type in the plane. It is mainly composed of relatively pure coarse particles and has good water storage space, good permeability, and stronger water-richness than the other types.

(2) Weak water-rich type of overflow sedimentation in the fan middle

In this sedimentary water control type, the sediment is poorly sorted to medium sorted and rounded to sub-angular to sub-circular in shape. It is mainly composed of coarse, medium, and fine sand, silt, clayey sand, clay, and sandy clay. The particle size is finer than the fan middle braided channel sedimentation. The sand body is mainly of a horizontal lap type in the vertical direction, with poor connectivity. In the plane, it is mainly distributed in the form of intersecting strips with good connectivity. Coarse sand, medium sand, fine sand, and other sand layers are developed, with good water storage space and good permeability. The water-richness is weaker than the medium water-rich braided channel sedimentation in the fan middle.

(3) Weak water-rich type of main channel sedimentation in the fan root

In this sedimentary water control type, the sediment is poorly sorted to average, with poor roundness and coarse particle size. It is mainly composed of gravel, sand gravel, sand, and clay sand, but the area between the coarse particles is filled with a small amount of clay, fine sand, silt sand, etc. There is a certain degree of connectivity between sand bodies, with isolated and stacked types of multi-phase sand bodies in the vertical direction and intersecting strip distribution in the plane as the main type. The sedimentary particles have coarse particle size but impure composition and are partially filled with fine particles, thus having lower water storage space and poor permeability. The water-richness is weaker than the weak water-rich type of overflow sedimentation in the fan middle.

(4) Weaker water-rich type of overflow sedimentation in the fan end

In this sedimentary water control type, sediment sorting is moderate to good, and the sediments are rounded to sub-angular to circular in shape, being mainly composed of fine sand, silt, clayey sand, and clay particles. Overall, it exhibits the characteristic of "more clay and less sand". The connectivity between sand bodies is poor and mainly characterized by horizontal overlap with isolated distribution in the vertical direction and isolated strip distribution in the plane. The sediments have a fine particle size and exhibit the characteristics of "clay-wrapped sand". Therefore, they have limited water storage space and poor permeability. The water-richness is weaker than that of the weak water-rich type of the main channel sedimentation in the fan root.

(5) Weaker water-rich type of debris flow sedimentation in the fan root

In this sedimentary water control type, the sediment has poor or no sorting, poor rounding, and a mixture of coarse and fine particles such as gravel, sand, and clay. The space between coarse particles is filled with a lot of clay, leading to its characteristics of "clay-wrapped gravel" or "gravel-wrapped clay". The sand bodies are not connected or have poor connectivity, with isolated distribution types of multi-stage sand bodies in the vertical direction and isolated scattered distribution types in the plane as the main type. The water storage space is limited, and the permeability is poor due to the mixing of coarse and fine particles. The water-richness is weaker than the weaker water-rich type of overflow sedimentation in the fan end.

## Discussion

Finding out the sedimentary water control laws affecting aquifers is an urgent problem that needs to be solved in order to predict water abundance and prevent water in mines [24]. However, there has been limited research on the loose pore aquifers' sedimentary water control behavior [25]. This study investigates the sedimentary control mechanism influencing the water-richness disparity in the Bottom Aquifer of the Cenozoic loose layer at Xutuan Mine, Huaibei Mining Area. The analyses in this study show that sedimentation significantly affects the water-richness of the Bottom Aquifer. The sedimentation's effect on the water-richness difference in the Bottom Aquifer in the study area is mainly manifested in two aspects: on the one hand, the water-richness of different sedimentary facies/ subfacies/ microfacies shows obvious heterogeneity. There are significant differences in sediment water-richness between different sedimentary subfacies of the same sedimentary facies and between different sedimentary microfacies of the same sedimentary subfacies. On the other hand, the alluvial-originated sediments in the study area are characterized by vertical non-homogeneity in the aquifer due to the overlapping of different sedimentary subfacies, and their water-richness also shows obvious non-homogeneity. This study is based on the analysis of the Bottom Aquifer's sedimentary facies/ subfacies/ microfacies and the contact types and connectivity between sand bodies with different sedimentary facies/ subfacies/ microfacies. Based on the results of testing the physical properties of sediment water and combining this with the unit water inflow $q$ values, 2 sedimentary water control modes are established, and 6 kinds of water-rich types are identified. This reveals the mechanism of control of the sedimentary environment on the water-richness difference in the Bottom Aquifer.

Based on the analysis of aquifer sedimentary characteristics, some researchers have studied the occurrence characteristics and migration laws of groundwater in aquifers and discussed the impact of aquifer water sources on mine inflows, providing guidance for mine water hazard prevention and control [26, 27]. The sedimentary environment of the Bottom Aquifer in the 32 mining areas of the Xutuan Mine is the alluvial fan facies sedimentary environment. The Bottom Aquifer is the product of the deposition of multiple periods of superimposed alluvial fan deposits, as shown in Fig. 7a). The alluvial fan subfacies mainly consist of the alluvial fan middle braided channel sedimentary microfacies, and the water-rich type is mainly the medium water-rich type of the braided channel sedimentation in the alluvial fan middle. Due to the frequent oscillation of braided river channels and the high degree of sand body stacking, the Bottom Aquifer has a large area of vertically and horizontally connected sand bodies. When the development height of the water-flowing fractured zone reaches the bottom of the Bottom Aquifer due to the influence of faults during coal mining, water inrush accidents will occur in the Bottom Aquifer. Due to its unique sedimentary characteristics, when water inrush occurs in the Bottom Aquifer, a superimposed replenishment model of fan middle subfacies sand bodies is formed, as shown in Fig. 7b). The Bottom Aquifer in the 32 mining areas has dynamic replenishment conditions, so the mine water inflow time in the goaf is continuous, and the mine water inflow is stable. The research results provide a scientific basis for the prevention and control of water damage in the Bottom Aquifer.

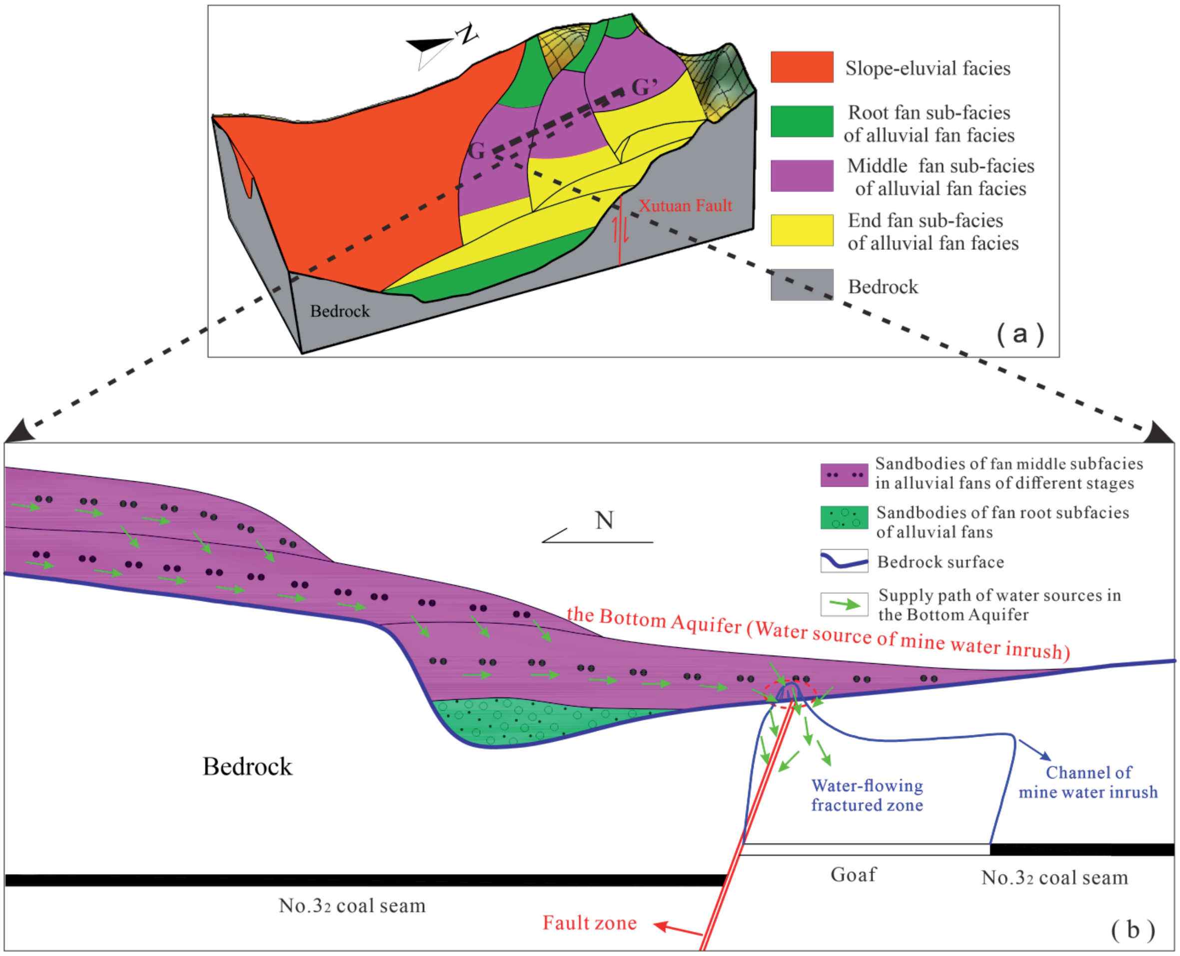



Fig. 7. Schematic diagram of the superimposed replenishment mode of fan middle subfacies sand bodies of groundwater in the Bottom Aquifer.

However, this study still has certain limitations. Due to lithology's control of sedimentary facies, different subfacies/microfacies types correspond to different lithological combinations. Lithology, in turn, governs microstructure, encompassing factors such as pore size, pore connectivity, permeability, and other characteristics. It can be stated that sedimentary facies are the macroscopic manifestation of the water-richness of aquifers and that microscopic pore structure is the microscopic manifestation of the water-richness of aquifers. The interaction and interconnection between macroscopic sedimentary facies and microscopic pore structures form an organic unity, jointly characterizing the water-richness of aquifers [28]. However, this study only investigated the influence of sedimentation on the water-richness of the Bottom Aquifer from a macro perspective; the response characteristics of the micropore structure to water-richness from a micro perspective were not analyzed. At present, there are many methods to study the pore structure characteristics of sand bodies from a microscopic perspective; these mainly include casting thin sections, scanning electron microscopy, nuclear magnetic resonance, and mercury intrusion testing [28, 29]. Meanwhile, due to limitations in conditions and difficulty in sampling, the sediment samples from the Bottom Aquifer taken in this study were relatively few. In the future, we must take more sediment samples from the Bottom Aquifer and conduct further testing and research on the microscopic pore structure characteristics based on the analysis of sedimentary facies characteristics of the Bottom Aquifer [30]. This will allow for a comprehensive and detailed study of the sedimentary control mechanism influencing the water-richness disparity in the Bottom Aquifer. More importantly, this can not only provide a scientific basis for the prevention and control of water damage in the Bottom Aquifer of the mining area but also have important significance in protecting the ecological environment and groundwater resources of the mining area.

## Conclusions

(1) The sedimentary facies of the Bottom Aquifer in the study area were divided into two categories: slope-residual facies and alluvial fan facies. The Bottom Aquifer in the southern part of the study area is mainly

composed of slope-residual facies, while in the central and northern parts, it is mainly composed of multiple deposits of alluvial fan facies overlaid in a retrograde manner from east to west and from south to north.

(2) The contact types and connectivity of sand bodies in the Bottom Aquifer from both vertical and planar perspectives were analyzed. Among them, the vertical stacking types of sand bodies include isolated distribution types (single sand and multi-stage sand bodies), vertical stacking types, dislocated stacking types, and horizontal lap types. The planar distribution types include isolated scattered distribution type, isolated strip distribution type, and intersecting strip distribution type. For the same alluvial fan, the sand body located in the middle of the fan has a wide distribution range, coarse particle size, and larger water storage space. Groundwater has good connectivity in both horizontal and vertical directions and should be a key target area for preventing water damage in the Bottom Aquifer. The Bottom Aquifer's sediment, formed by stacking multiple alluvial fan bodies, also achieves good hydraulic connectivity performance in both horizontal and vertical directions due to the spatial stacking of the fan middle subfacies and sand bodies in each fan.

(3) Two sedimentary water control modes, namely the slope-residual facies water control mode and the alluvial fan facies water control mode, were established, and six kinds of water-rich types were identified: medium water-rich types of braided channel sedimentation in the fan middle, weak water-rich type of the overflow sedimentation in the fan middle, weak water-rich type of the main channel sedimentation in the fan root, weaker water-rich type of the overflow sedimentation in the fan end, weaker water-rich type of the debris flow sedimentation in the fan root, and extremely weak water-rich type of the slope-residual facies sedimentation. The modes and classification reveal the sedimentary control mechanism of the water-richness disparity in the Bottom Aquifer.

(4) Based on the sedimentary water control theory, the superimposed replenishment mode of fan middle subfacies sand bodies in the alluvial fans of groundwater in the Bottom Aquifer was proposed to address the phenomenon of water inrush at the 32 mining areas of Xutuan Mine, where the amount of water inrush is not large, but the duration of water inrush is continuous.

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## Conflicts of Interest

The authors declare no conflict of interest.

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