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Impact of longwall mining on groundwater above the longwall panel in shallow coal seams

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ABSTRACT

Since longwall mining causes subsidence through the overlying strata to the ground surface, the surface water and groundwater above the longwall panels may be affected and drained into the lower levels. Therefore, loss or interruption of streams and overburden aquifers is a common concern in coal industry. This paper analyzed the potential effects of longwall mining on subsurface water system in shallow coal seam. In order to monitor different water level fluctuations throughout the mining period, three water wells were drilled down to the proposed deformation zone above the longwall panel. A GGU-SS-FLOW3D model was used to predict water table contours for the periods of pre- and post-mining conditions. The field data from the three water wells were utilized to calibrate the model. The field test and numerical model can help to better understand the dewatering of shallow aquifers and surface waters related to ground subsidence from longwall mining in shallow coal seam.
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1. Introduction

Longwall mining method is a highly productive underground mining method in which a panel or a block of coal is completely extracted (Peng, 2006, 2008; Qian and Shi, 2003; Wang, 2009). When a longwall panel with sufficient width and length is excavated, the overburden roof strata are disturbed in order of severity from the immediate roof toward the surface, or even the aquifers, which can lead to serious mine-flooding accidents and increasing damages to ecological environments (Miao and Qian, 1995; Qian and Miao, 1995; Qian et al., 1996). Thus it is absolutely essential to determine the degree of dewatering for prevention of water inrush and protection of groundwater resources (Li, 2011; Li and Qiu, 2012). In this paper, three water wells drilled in site and a GGU-SS-FLOW3D model are used to monitor different water level fluctuations throughout the mining period. The potential effects of longwall mining on subsurface water system are analyzed in shallow coal seam with the field data measured from the three water wells and the numerical model.

2. Geology and mining conditions of study area

The geology of the study area includes sedimentary rocks of Pennsylvanian and Permian ages (Paleozoic). Alluvial deposits of Quaternary age occupy the valley bottom of the dissected topography. The boundary between the Pennsylvanian and Permian systems is indistinct, but it is generally defined by the sequence of rocks extending from the base of the Waynesburg coal bed to the present topographic surface.

The Dunkard Group consists of the Greene Washington and Waynesburg formations. The lower section of the Dunkard Group resembles that of the Monongahela Group which contains laterally persistent Pittsburgh coal. The top bedrock unit is the Dunkard Group, which belongs to the Permian age.

The longwall panels B5 and B6 studied in this paper are located in the Appalachia Coalfield, United States (Fig. 1). The overburden depth varied from 600 ft to 900 ft (1 ft = 0.3048 m). The average mining height was 7 ft. The length of panels B5 and B6 was 12,000 ft and 5700 ft, respectively. The width of the both panels was 1433 ft. The width of headgate and tailgate entries was 16 ft. The chain pillar system between panels B5 and B6 was 200 ft wide. The average longwall face retreat rate was 30–50 ft/d during the longwall face mining in the study area.

3. Groundwater monitoring

In order to determine the water system distribution in the study area, three water wells W1, W2 and W3 have been drilled above the panel B6 before longwall face mining in panels B5 and B6. The

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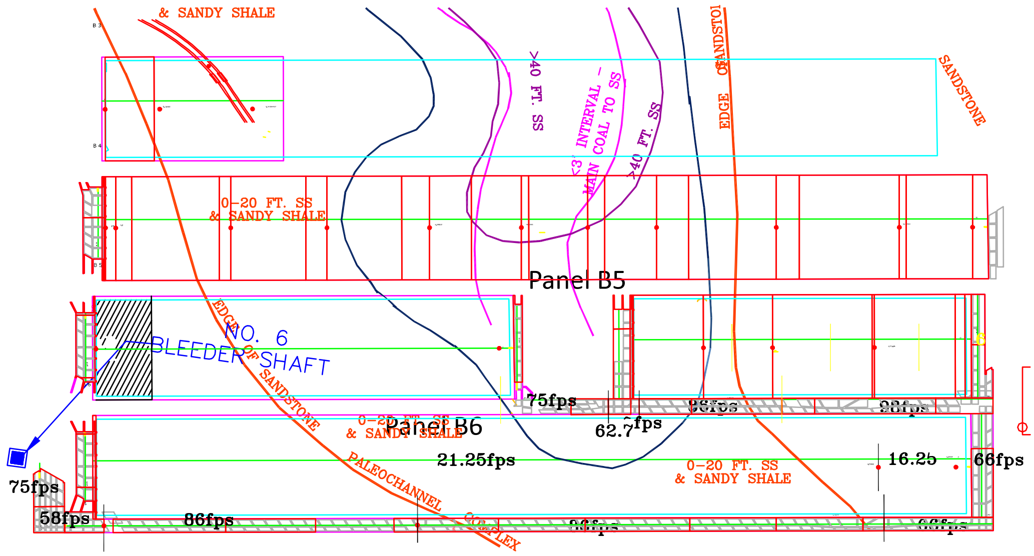

Fig. 1. Layout of longwall panels B5 and B6.

water well W1 contained three wells of different depths (Fig. 2). The well W1S was the top well, which was located in the limestone and shale. The average water column in the well was 22 ft. The deep well W1D was located between Waynesburg and Uniontown sandstones. The average water column in the well was 70.76 ft. The shallow well W2S was located in the shale. The average water column in the well was 32 ft. The well W2I (intermediate well) was located in the sandstone above a little Washington coal. The average water column in the well was 18 ft. The deep well W2D was located at the bottom of Waynesburg sandstone layer and the water column in the well was 190.4 ft. The well W3S was located in the shale. The average water column in the well was 15.17 ft (before mining of panel B5). The well W3I was located in the shale and the average water column in the well was 49 ft. The well W3D was located between the bottom of Waynesburg sandstone and upper Waynesburg coal. The water column in the well was 21.38 ft.

The water well W4 was located over the center of panel B5. Before mining this panel, the water levels in shallow well W4S and intermediate well W4I located in the shale were 23.4 ft and 21.7 ft, respectively. The water level in well W4D located in the Waynesburg sandstone was 22.8 ft.

The water level in well W2D was higher than that in W2I. This was not reasonable as compared to those in wells W1D and W3D. It was, therefore, postulated that surface water seeped into the Waynesburg aquifer because of the sealing construction.

Fig. 3 shows the cross-section of water wells and water levels before panels B5 and B6 longwall faces passed the study area.

Water enters the subsurface in Greene County mainly as precipitation or stream flow. When precipitation hits the ground, some is evaporated, some flows overland and some seeps into the subsurface. Of the portion that percolates into the subsurface, some returns to the atmosphere by transpiring plants and the remainder percolates downward to the subsurface unconfined aquifers. The water in the unconfined aquifers flows from the higher hydraulic heads toward the lower ones. The water flow rate depends on hydraulic conductivity and hydraulic head gradient.

The hydraulic conductivity K is the most important quantitative parameter charactering the flow of groundwater. It is defined as the ratio of Darcy's velocity to the applied hydraulic gradient. It is dependent only on the physical properties of the porous medium, grain size, grain shape, arrangement of pore size, and interconnection in general. The dimension of K is the same as that for velocity, that is, length per unit of time (LT^{-1}).

The properties of hydraulic conductivity before mining at the study area were measured by the slug test. The slug test consists of measuring the recovery of head in a well after near-instantaneous change in head at that well.

4. Determining the post-mining hydraulic conductivity of panel B6

The post-mining hydraulic conductivity of panel B5 should be determined in order to analyze the groundwater flow system after the panel B6 is mined out. The slug tests for wells W1–W3 were performed 10 months after the longwall face of panel B6 passed under the three well locations, i.e. the slug tests were performed in September 2009. Before the slug test, all wells were checked carefully in order to determine whether they were needed to inject or withdraw volumes of water during the slug test. Wells W1S, W1D, W3S, W3I and W3D were warped severely due to subsidence when panel B6 was mined, and wells W2S, W2I and W2D were completely dewatered. Therefore, all slug tests in water wells W1–W3 were performed by instantaneously injecting a volume of water, and measuring and recording the depth to water and the time at each reading. Fig. 4 shows the cross-section depicting a slug test in a monitoring well. Table 1 summarizes the hydraulic conductivity in both pre- and post-mining conditions.

5. GGU-SS-FLOW3D model

5.1. Purpose of groundwater modeling

A numerical groundwater flow model is the mathematical representation of an aquifer in a computer. Groundwater models describe groundwater flow and transportation processes using mathematical equations based on certain assumptions. These assumptions typically involve directions of flow, geometries of aquifers, heterogeneity or anisotropy of sediments or bedrocks within aquifers. Because of the assumptions embedded in the mathematical equations and many uncertainties in the values of

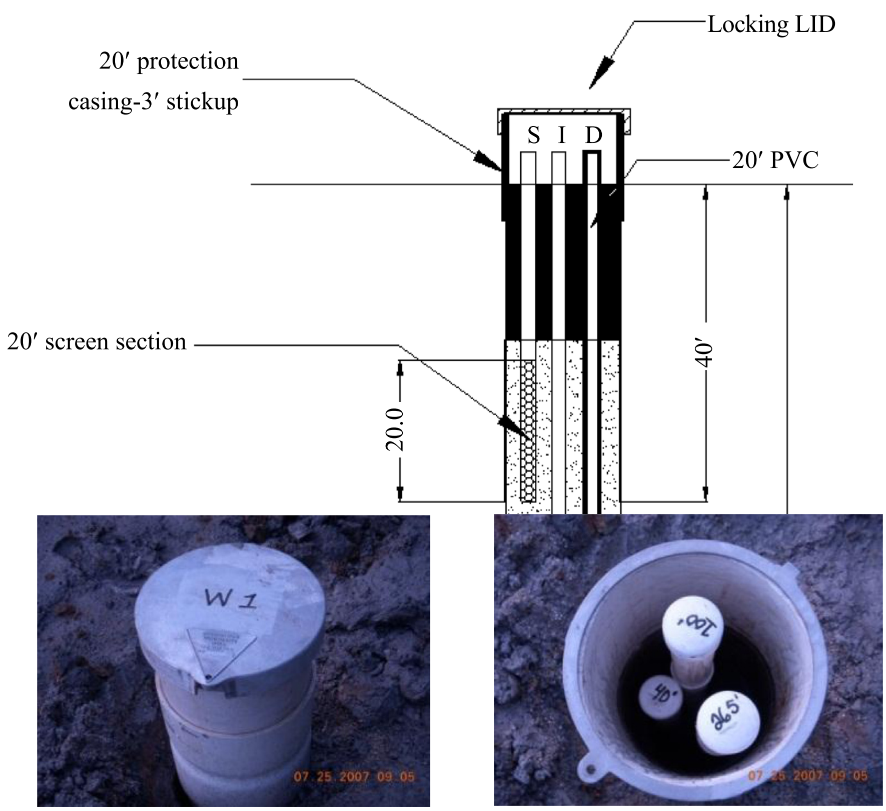

Fig. 2. Construction detail of water well W1.

data required by the model, the model was viewed as an approximation and not an exact duplication of field conditions.

The purpose of the modeling was to simulate groundwater flow directions and transportations over the mined panels B5 and B6. It was used to (1) predict the groundwater flow system of pre- and post-subsidence of panels B5 and B6; and (2) evaluate whether the longwall subsidence affects the groundwater regimes.

In this study, groundwater flow models were used to calculate the groundwater flow and direction of movement throughout the shallow aquifers. The simulation of groundwater flow requires a

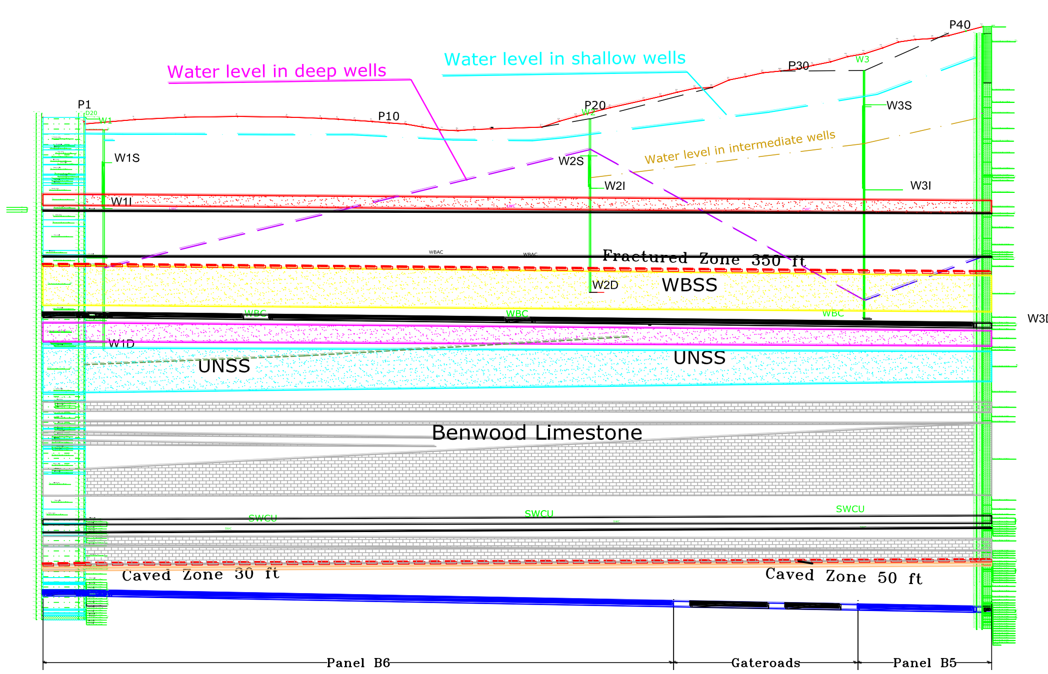

Fig. 3. The water level in the wells.

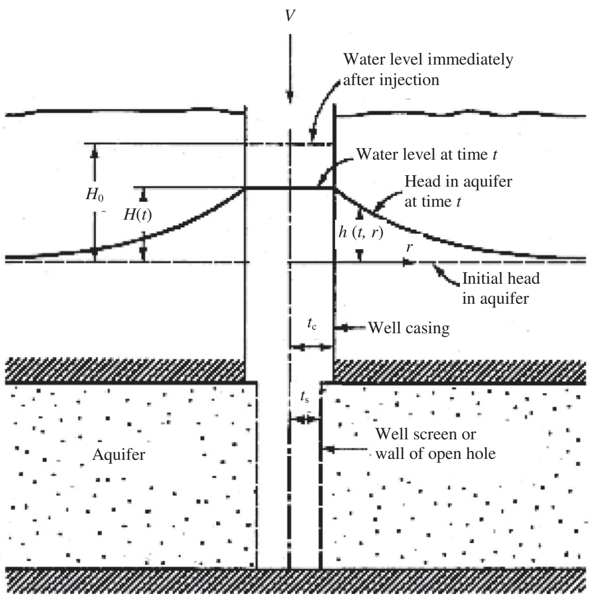

Fig. 4. Slug test performed by injecting a volume of water.

thorough understanding of hydrogeologic characteristics of the study area. The hydrogeologic investigation should include a complete characterization of the following factors:

(1) Subsurface extent and thickness of aquifers and confining units (hydrogeologic framework).
(2) Hydrologic boundaries (also referred to as boundary conditions), which control the rate and direction of movement of groundwater.
(3) Hydraulic properties of the shallow aquifers and confining units.
(4) Description of the horizontal and vertical distributions of hydraulic heads throughout the study area for beginning (initial) and equilibrium (steady-state) conditions.
(5) Distribution and magnitude of groundwater recharge rate, evapotranspiration, leakage to or from surface-water bodies. The outputs from the model simulations were the hydraulic heads and groundwater flow directions which were in equilibrium with the hydrogeologic conditions (hydrogeologic framework, hydrologic boundaries, hydraulic properties, and sources or sinks) defined for the modeled area.

The groundwater model used in this study is to predict how water levels change before, during, and after mining at a site located over longwall panels B5 and B6. The study deals specifically with water level fluctuations in aquifers utilized for domestic water supplies — the top layer water resources. The model also can make water levels prediction over future panel layout using the similar methods in this research.

Table 1
Summary of hydraulic conductivities by slug tests.

Water wells	Hydraulic conductivity (ft/d)	
	Pre-mining	Post-mining
W1S, shallow well of W1	0.65625	0.4902
W1D, deep well of W1	0.6825	1.69
W2S, shallow well of W2	0.683	0.1023
W2I, intermediate well of W2	0.03421	0.0524
W2D, deep well of W2	0.034175	8.088
W3S, shallow well of W3	2.15	8.299
W3I, intermediate well of W3	4.95765	0.187
W3D, deep well of W3	0.08396	0.9787

5.2. Groundwater modeling program

In this study, the GGU-SS-FLOW3D program was used to model the groundwater system. The GGU-SS-FLOW3D program allows analysis of steady-state groundwater flow in three-dimensional (3D) groundwater systems using finite element methods (FEMs). The program includes a powerful mesh generator and routines (contours, 3D graphics, etc.) for comfortable evaluation of the analysis results.

The real solution is a linear approximation for each element. Triangular prisms are used as finite elements. To simplify data input, the mesh is initially generated in plane. The projection of the triangular prisms onto the plane surface results in triangles, while a triangular mesh must be firstly generated. Depending on the complexity of the system, a number of height ordinates are associated with each node of this basic mesh, which describe the system in the third dimension. The height ordinates can possess different values at each node. The only condition is that every node has the same number of height ordinates. This allows complex systems to be generated.

5.3. Theory of groundwater modeling

Water flows from high elevation to low elevation. In 1856, French hydraulic engineer Henry Darcy proposed an equation for flow through a porous medium:

$$Q = -KA\frac{h_2 - h_1}{l} \tag{1}$$

where K is the hydraulic conductivity, A is the cross-sectional area, h_1 is the height of the inlet head, h_2 is the height of the outlet head, and l is the path length of the flow.

Eq. (1) is called the Darcy's law equation. The rate of fluid flow through a porous medium is directly proportional to the cross-sectional area and the loss of the hydraulic head between two points of measurement, and it is inversely proportional to the travel length.

The volume rate of flow per unit area is

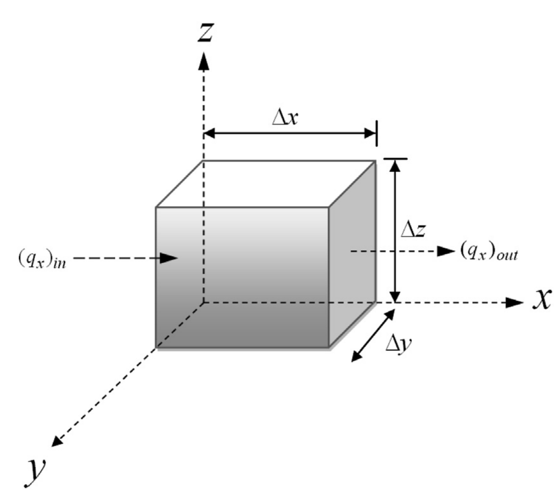

Fig. 5. Net flow of the representative elementary volume (REV).

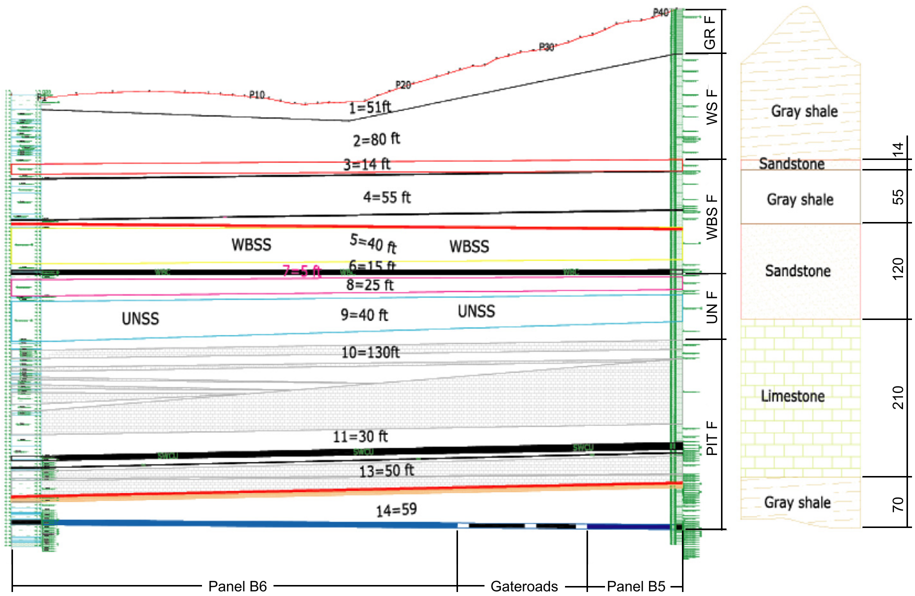

Fig. 6. Translation of geologic information into a conceptual model suitable for numerical modeling (unit: ft).

$$q = -K\frac{\mathrm{d}h}{\mathrm{d}l} \tag{2}$$

where h is the piezometric head.

The hydraulic conductivity is dependent on the properties of both the porous medium and the fluid:

$$K = k\frac{\rho g}{\mu} \tag{3}$$

where k is the permeability, ρ is the density of the fluid, g is the acceleration of gravity, and μ is the absolute viscosity of the fluid.

Fig. 5 shows the water flow into and out of an elemental cube whose side lengths are Δx, Δy, and Δz. The water balance is expressed as

$$\text{Outflow} - \text{inflow} = \text{change in storage} \tag{4}$$

Outflow along the x-axis is $[(q_x)_{\mathrm{out}} - (q_x)_{\mathrm{in}}]\Delta y\Delta z$. Therefore, the general governing equation for steady-state, homogeneous, and isotropic conditions with a source/sink term is

$$K_x\frac{\partial^2 h}{\partial x^2} + K_y\frac{\partial^2 h}{\partial y^2} + K_z\frac{\partial^2 h}{\partial z^2} = -R \tag{5}$$

where (x, y, z) is the orthogonal coordinate system, and R is the recharge/discharge rate.

The hydraulic conductivities are very heterogeneous in the study area, and there is no pattern to find a function of the hydraulic conductivities. It is impossible to drill many wells to test the hydraulic conductively everywhere. Therefore, to simplify the study methods, the general governing equation for steady-state, homogeneous, and isotropic conditions is used to solve the groundwater flow system in the study area.

6. Concept model and grid design

The purpose of building a concept model is to simplify the field problem and organize the associated field data so that the system can be analyzed more readily. The concept model represents our best idea of how the aquifer works. A good conceptual model requires compiling detailed information on the geology, water quality, recharge, rivers, water levels, and hydraulic parameters.

(1) Concept model design

In order to simplify the study field environment, the geologic formations from the ground surface to the Pittsburgh coal seam level were reduced to six layers of aquifers and confining bed units (Fig. 6). The top layer was defined from the real topographic map of the study area to roof of sandstone of upper Waynesburg formation.

(2) FEM mesh generation and boundary conditions

Fig. 7 shows the model group of geologic formation for numerical modeling. The model was 3100 ft wide and 4000 ft long, the height varied from 600 ft to 900 ft. The width included the widths of panel B5 (1433 ft), panel B6 (1433 ft), and pillar system (200 ft). The lengths of panels B5 and B6 were 12,000 ft and 5700 ft, respectively. That was too long for a model, so 4000 ft long was used for part of these two panels. The height represented the overburden depth, and it varied in 600–900 ft.

From the bottom to the top, there are 6 layers in the model: gray shale and Pittsburgh coal, limestone, WBSS and UNSS, gray shale, sandstone, and gray shale.

Fig. 8 shows the flow chart for groundwater modeling.

7. Post-subsidence groundwater flow system

The post-subsidence horizontal hydraulic conductivities at layers 1 and 4 over the panel B6 were determined by slug tests after the longwall face passed the wells 10 months. The post-subsidence horizontal hydraulic conductivities were approximately several orders of magnitudes larger than the pre-subsidence ones at the panel edges. The post-subsidence hydraulic conductivities appeared to have decreased over the center of the panel B6. Some values were very localized such as W2D and W3D which were at the panel edges but there was ten times difference in hydraulic conductivity. For layers 2, 3, 5 and 6, the post-subsidence hydraulic conductivities were not estimated because some layers, especially

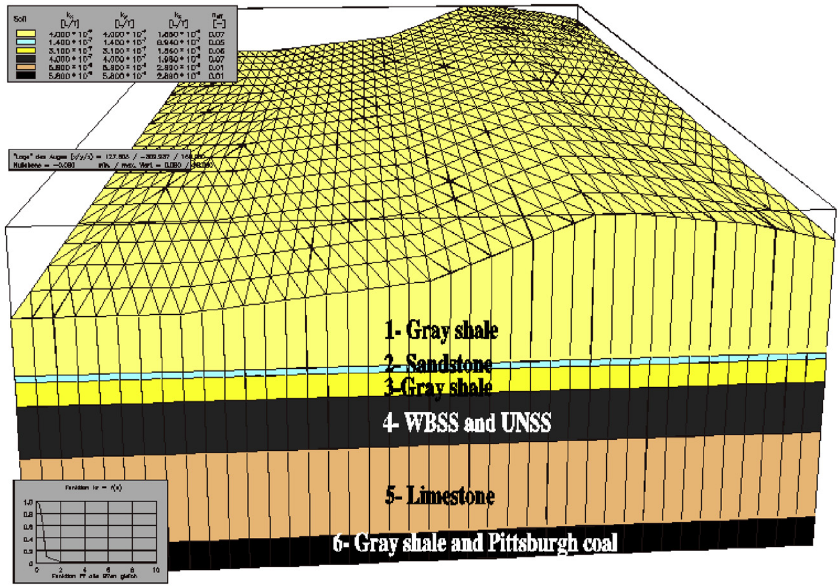

Fig. 7. Geologic formations group for numerical modeling.

deeper layers were not be tested by the slug tests in the field due to the fact that the diameters of PVC pipe became too warped after subsidence. Those data were acquired from published research results in Greene County.

The water pumped from the panels B5 and B6 was estimated to be about 10,000 gal/d (1337 ft^3/d) after longwall mining.

Longwall mining causes fractures and separations of overburden strata, especially vertical fractures. Therefore, the vertical one is usually larger than the horizontal hydraulic conductivity. Due to the lack of field data, the vertical hydraulic conductively is assumed to be 5 times larger than the horizontal one. Table 2 shows the pre- and post-subsidence hydraulic conductivities in the groundwater flow model.

Table 3 presents the comparison of water elevation between observation and model prediction (post-mining). The top layer groundwater in the model, where the shallow and intermediate wells were located, did not drop so much after mining the panel B5 and B6. Especially in W1S and W2S, the observation in the model was 472 ft and 565 ft, but the model prediction was 570 ft and 600 ft, respectively. The error percentages are −9.8% and −3.2%, respectively. For wells W3S and W4S, the water was totally lost just like the field observation.

For the intermediate wells in the model, the prediction of well W1I was 560 ft. But there was no comparison to the observation, because the well W1I was destroyed when the panel face passed. The water level in wells W2I and W3I was higher when the panel B6 was mined. This abnormal situation was attributed to an aquifer or a less permeable layer underlying the bottom of wells W2I and W3I, and the overlying layers recharging the intermediate wells W2 and W3. In the model, the water level was less different from that in the case where the panel was pre-mined. The error percentages are 0.64% and −2.79% for W2I and W3I, respectively. The

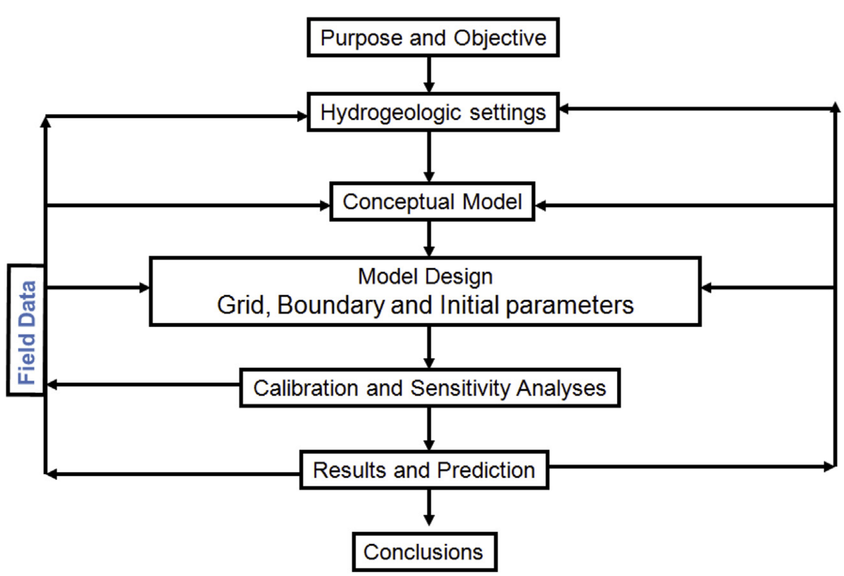

Fig. 8. Groundwater modeling flow chart.

Table 2
The pre- and post-subsidence hydraulic conductivities.

Layers	Location	Symbols of conductivity	Conductivity by slug tests (m/s)								Conductivity in model (m/s)	
			W1S	W1D	W2S	W2I	W2D	W3S	W3I	W3D	Horizontal	Vertical
Layer 1: Shallow overburden layer (W1S, W2S, W3S, W3I)	Pre-subsidence	K1	0.03241								0.03241	0.16205
	Panel edge (post-subsidence)	K7			0.1023	0.0524		8.299	0.187		0.187	0.935
	Panel center (post-subsidence)	K8	0.4902								0.03421	0.17105
Layer 2: Washington sandstone layer	Pre-subsidence	K2	0.012								0.012	0.06
	Panel edge (post-subsidence)	K9									0.1	0.5
	Panel center (post-subsidence)	K10									0.01	0.05
Layer 3: Gray shale layer	Pre-subsidence	K3	0.027								0.027	0.135
	Panel edge (post-subsidence)										0.27	1.35
	Panel center (post-subsidence)										0.027	0.135
Layer 4: Waynesburg sandstone and Uniontown sandstone layer	Pre-subsidence	K4	0.034175								0.034175	0.170875
	Panel edge (post-subsidence)	K13					8.08			0.9787	8.08	40.4
	Panel center (post-subsidence)	K14		1.69							1.69	8.45
Layer 5: Benwood limestone layer	Pre-subsidence	K5	0.0005								0.0005	0.0025
	Panel edge (post-subsidence)	K15									0.00436	0.0218
	Panel center (post-subsidence)	K16									0.000436	0.00218
Layer 6: Lower Pittsburgh formation layer	Pre-subsidence	K6	0.0005								0.0005	0.0025
	Panel edge (post-subsidence)	K17									10	50
	Panel center (post-subsidence)	K18									6	30

W4I was totally dried out in the field, but in the model the fracture zone did not develop to the top layers where W4I was located. The predicted water level for the well W4I was 630 ft.

The water in well W1D was completely lost in three days. Subsequently, the water level in W1D began to recover to the original one from 863.97 ft to 934.54 ft. It continued to rise up until reaching 985.64 ft. Well W1D recovered very rapidly and the water level was higher than that under the pre-mining condition. But in the model, the water level dropped 10 ft–410 ft. The observed water level in well W2D was not so much different from the model prediction. The error percentage was only −0.32%. Wells W3D and W4D were located in the panel B5, and they were apparently affected by longwall subsidence in panels B5 and B6. After the panel B6 was mined, the fracture zone above the panel B5 developed higher than that above the panel B6. So the water in both of these two deep wells was totally lost and never recharged afterward. Fig. 9 shows the post-subsidence groundwater table contour predicted by the model. The water lost zone can be seen from this figure.

8. Conclusions

Groundwater flow models using the GGU-SS-FLOW3D program were developed to predict the pre- and post-subsidence water tables in panels B5 and B6 based on the pre- and post-mining hydraulic parameters. Initially, these input parameters such as hydraulic conductivity, evapotranspiration and recharge were calibrated by the monitoring results of water wells when the hydraulic heads were predicted. The hydraulic heads contours predicted by groundwater flow model reflected the changes in the groundwater flow system before and after longwall mining.

The groundwater model of pre-mining subsidence predicted an accurate hydraulic heads compared with the observation of water wells during the pre-mining periods. However, the post-subsidence groundwater models predicted much different water tables from observations in wells W1S, W2S and W1D.

The longwall face in panel B6 passed through the water wells on 11 September 2008. The water in wells W2S, W2I and W2D was totally lost after the longwall face passed. The water table recovered to 1090 ft on 10 February 2009. The water table in well W3I declined slightly and substantially restored to 1110 ft.

There existed an aquifer layer or a low-permeability layer to prevent the water level in intermediate well from dropping below the underlying aquifers. The post-mining water level in well W2I was higher than the pre-mining one. This phenomenon indicated that the effective porosity and storativity were increased, enlarging the vertical connection between the surface aquifers and intermediate well. Surface water recharged the underlying aquifers.

The wells W3D and W4D were located in the panel B5, and they were apparently affected by longwall subsidence in panels B5 and B6. After the panel B6 was mined, the fracture zone above the panel B5 developed higher than that above the panel B6. So the water in both deep wells was totally lost and never recharged afterward. It is better to find a way to control the development of fracture zone and protect the groundwater resource, just like increasing the velocity of face advance.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Table 3
Comparison of water elevation between observation and model prediction (post-mining).

Location	Water elevations (ft)				Difference between observation and model prediction (ft)	Percentage (%)
	Well	Observation	Observed water level in model	Model prediction		
Shallow well	W1S	1002	472	570	−98	−9.8
	W2S	1100	565	600	−35	−3.2
	W3S	N/A	N/A	N/A		
	W4S	N/A	N/A	N/A		
Intermediate well	W1I	N/A	N/A	560		
	W2I	1080	575	570	5	0.46
	W3I	1110	569	600	−30	−2.79
	W4I	N/A	N/A	630		
Deep well	W1D	985	455	410	45	4.6
	W2D	932	397	400	−3	−0.32
	W3D	N/A	N/A	N/A		
	W4D	N/A	N/A	N/A		

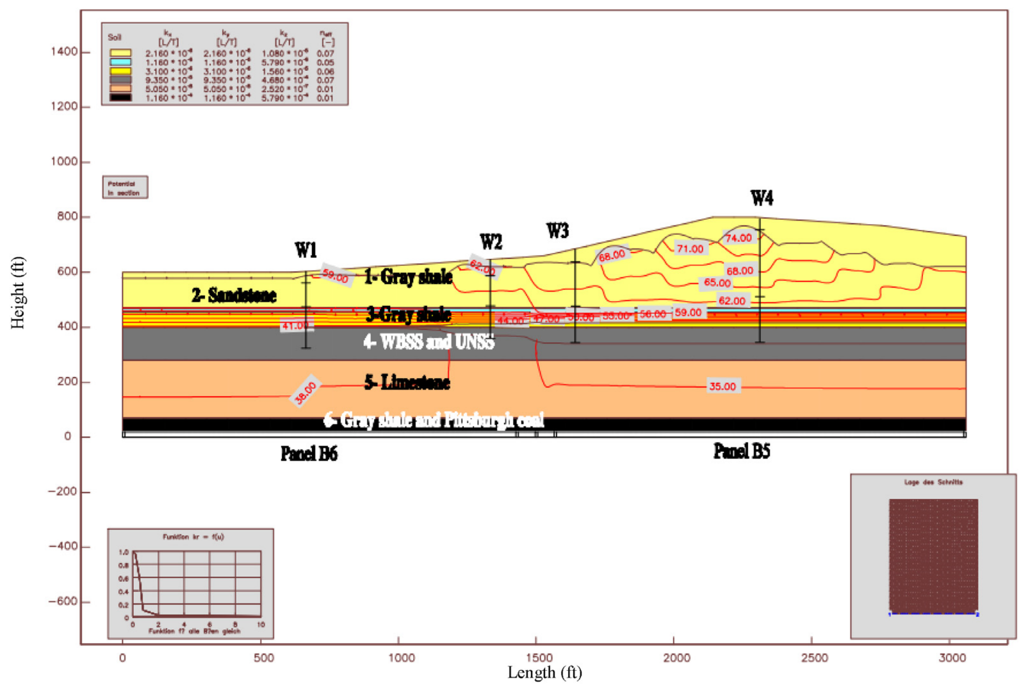

Fig. 9. Post-subsidence groundwater table cross-section in the model.

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