The Hydrogeology of an Old Growth Forest with Implications for Defining Impact Zones

Associated with Underground Mining

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Master of Science

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This thesis titled

The Hydrogeology of an Old Growth Forest with Implications for Defining Impact Zones
Associated with Underground Mining

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ABSTRACT

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Dysart Woods is a predominantly oak and hickory old-growth forest that was given to Ohio University by The Nature Conservancy for research and public use. After a long discussion in the government and against the desires of the environmental organizations that opposed mining in the vicinity of this forest, a permit was issued and the Dysart Woods watershed is being undermined via longwall mining methods and the old-growth forest areas are being undermined via room-and-pillar mining methods. Buffer zones based upon the angle of influence have been placed around Dysart Woods to protect it from the influence of longwall mining. While this concept is sufficient for architectural structures it was not designed to prevent changes in hydrogeologic properties that typically accompany underground mining. The purpose of this work is to assess hydrogeologic impacts in a watershed context beyond the recharge area delineated by a buffer zone that has been determined by the angle of influence. Results of the physical model show that the water table elevations of the northeast portion of the water table of the shallowest aquifer underneath the Dysart Woods watershed have lowered as a result to longwall mining. Results of transient numerical modeling show a decline in the calculated heads from pre-mining head elevations to post-mining head elevations inside the buffer zone proposed by the mining company. The transient simulation was modeled...
to 12/1/2014, which showed that the upper hydrostratigraphic units dried up as a result of underground mining. If perching layers do not recover with time, this could have detrimental effects on Dysart Woods. This suggests new considerations for underground mining regulations with respect to preserving ecosystems that are dependent on groundwater systems. In particular, the groundwater system protection zone should be defined on the basis of watershed-scale hydrology as opposed to buffer zones based on the angle of influence.
This thesis is dedicated to Dr. Mary Wilder Stoertz
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I would like to thank Dr. Mary Stoertz for giving me the opportunity to work with Dysart Woods. Dr. Stoertz has taught me many valuable lessons that I will always take with me wherever I go. I would like to thank my thesis advisor, Dr. Dina Lopez for agreeing to take me on as one of her graduate students in the middle of the academic year, for all of the time she spent with me, and all of the guidance she has given me. I would also like to thank my thesis committee, Dr. Gregory Nadon and Dr. Douglas Green and the staff of the Geological Sciences Department of Ohio University in addition to the Ohio University Legal Office for funding monitoring and research assistantships.

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CHAPTER 1: INTRODUCTION

1.1. Significance of Study

Dysart Woods is an old growth forest located in eastern Ohio in central Belmont County (Fig. 1.1). It has been listed as a National Natural Landmark by the U.S. Department of the Interior (National Park Service, 2004). Forests once covered 95% of Ohio. However, at the deforestation peak in Ohio around 1940, 88% of Ohio’s forests had been eliminated (Ervin et al., 1994). Dysart Woods is the largest old growth forest remaining in Ohio (Moorman, 2005) with some trees exceeding 400 years old (Ground Water Associates, 1991). Dysart Woods belongs to Ohio University. It is located in an area that has an intensive history of coal mining. In recent years Ohio University and local environmentalist organizations have been trying to protect the woods from the effect of coal mining. A legal debate has been generated between these organizations and the mining company (Ohio Valley Coal Company) that has the legal right to exploit the coal. However, the lack of a strong scientific basis regarding the effect of underground mining on the overlying soils and vegetation has been evident and it has been used against the protection of the forest. This study responds to the need to understand those effects and provide a strong scientific basis for the protection of Dysart Woods and other similar forests.
In 1970, Ohio University and the local community established the only protection that exists for this forest. This protection is an area placed around Dysart Woods of 0.5 to 1.5 miles from the old growth perimeter where surface mining should not occur (Ground Water Associates, 1991). However, this measurement did not protect the forest from underground mining of coal seams below the Meigs Creek No. 9 coal seam, which overlies the Pittsburgh No. 8 coal seam (DMRM, 2003).
The Ohio Valley Coal Company (OVCC) is currently mining the Pittsburgh No. 8 coal seam that underlies this portion of central Belmont County and has been mining in the area since 1969 (Ground Water Associates, 1991). The mine entrance is known as the Powhatan No. 6 Mine and is located on Pleasant Ridge Rd near Alledonia in Washington Township of Belmont County approximately 4.5 miles south of Dysart Woods. OVCC obtained Permit No. D-0360 in 1984 to continue mining north of the mine entrance. Room and pillar mining was the only mining method incorporated from 1969 to 1987. In 1987, OVCC proposed another revision to Permit No. D-0360 to incorporate longwall mining methods to the permit area (Ahmad, 1988). On August 15, 2003, the 12th revision of Permit No. D-0360 (Permit # D-0360-12) was issued conditionally to OVCC to begin longwall mining operations underneath the Dysart Woods watershed and room-and-pillar mining operations underneath the old growth portions of Dysart Woods (DMRM, 2003). The conditional issuance of Permit # D-0360-12 was dependent on several conditions to be met before any mining activities could take place. These conditions included a land survey of surface elevations above entry ways for the longwall panels, the development of a subsidence monitoring program over longwall panels adjacent to the delineated old growth forest areas, a monthly progress report by OVCC to the Division of Mineral Resources Management stating the progression of room-and-pillar mining directly below or adjacent to the old growth forest areas within the proposed buffer zone by OVCC, and to move one of the boundaries of a longwall panel east to include two undeveloped springs into the 300 ft buffer zone (DMRM, 2003). The timeframe for completion of Permit # D-0360-12
extends to 2009 with the completion of longwall panels to the west of Dysart Woods (OVCC, 2003c).

Long-wall mining methods have been known to alter groundwater regimes and flow properties of the bedrock (Liu et al., 1997; Booth et al., 1999; Singh and Kendorski, 1981). The Dysart Woods surficial ecosystem is dependent on groundwater; specifically, groundwater discharge via springs to replenish soil moisture. Any alteration of flow may have serious consequences for the forest.

The buffer zones placed around the perimeters of Dysart Woods are based upon what is termed the angle of influence. While this concept is sufficient for architectural structures it was not designed to prevent changes in hydrogeologic properties (i.e., recharge, residence time and etc.) that typically accompany underground mining. Therefore, buffer zones to preserve groundwater sustaining natural ecosystems should be based on watershed boundaries and groundwater divides and not simply on the angle of influence.

1.2. Purpose of Study

The purpose of this study was to assess hydrogeologic impacts in a watershed context beyond the recharge area delineated by a buffer zone that was determined by the angle of influence. This was achieved by hydrogeological field data and meteorological information to construct an appropriate physical and hydrogeological model of pre- and post-mining conditions, modeling of the system using the program MODFLOW, and evaluating pre- and post-mining groundwater residence times. The final objective was to
determine the evolution of the water table with time because variations in the water table affect the discharge at springs and the extent of the unsaturated zone.

1.3. Site Description

1.3.1. Physiography

Dysart Woods is located in the western portion of Smith Township of Belmont County (Fig. 1.2) on the Little Switzerland Plateau of the Kanawha section of the Western Allegheny Plateau.

![BELMONT COUNTY MAP SHOWING LOCATION OF DYSART WOODS](image)

Fig. 1.2. Location of Dysart Woods in Belmont County.
The Little Switzerland Plateau is bounded to the north by a transitional boundary from fine- to medium-grained rocks, by the Ohio River to the east, and by the Flushing Divide to the south and to the west (Fig. 1.3). The Little Switzerland Plateau is different than other sections of the Western Allegheny Plateau due to the absence of the Minford Clay derived from the Pleistocene drainage of the Teays River (Brockman, 1998). Overall, Belmont County is hilly and well- to moderately well-drained (Phillips, 1927). The relief in Dysart Woods is 336 ft with elevations ranging from 1346 ft to 1010 ft with narrow and well rounded ridges separating dissected valleys (Anderson, 2001). Dysart Woods is divided by a NNE-SSW trending ridge with a southerly drainage pattern. Dysart Woods lies on two small subwatersheds draining into Joy Fork, which discharges into Bend Fork, a tributary of Captina Creek that discharges into the Ohio River (Fig. 1.4).
Fig. 1.3. Physiography of Ohio (from Brockman, 1998).
The soils in the Dysart Woods region are dominated by various slope classes of Lowell-Westmoreland silty clay loams (Fig. 1.5) (Holt and Craig, 1997). The Lowell-Westmoreland soils series is approximately 45% Lowell soils and 25% Westmoreland soils with the remaining 30% consisting of other various soils such as Hartshorn soils in the valleys (Holt and Craig, 1997), Brookside soils located on the lower elevation slopes, and Elba soils located on some ridges (Rubel et al., 1981). Lowell soils in this region are moderately well-drained and formed from limestone, siltstone, and shale. Westmoreland soils in this region are similar to Lowell soils; however, Westmoreland soils are formed
from sandstone rather than limestone, which is why Westmoreland soils are classified as well-drained (McCarthy et al., 2001). The NNE-SSW trending ridge that divides the Dysart Woods watershed into two subwatersheds is composed of Westmoreland-Upshur and Westmoreland soils. The water transmitting properties of Westmoreland-Upshur and Westmoreland soils are rated moderately high to high with velocity values ranging from 0.20 to 2.00 inches/hour. The water transmitting properties of Lowell-Westmoreland and Lowell soils are rated very low to moderately high with velocity values ranging from 0.00 to 0.60 inches/hour (USDA, 2007).
1.3.2. Geology

Belmont County is the highest producer of coal in Ohio. The Pittsburgh (No. 8), the Meigs Creek (No. 9), the Uniontown (No. 10), the Waynesburg (No. 11), and the Washington (No. 12) are coal beds that have been mined in Belmont County (Fig. 1.6,
Axon, 1996). The average thickness of the Pittsburgh No. 8 coal seam in the region is 72 inches and is found at depths of between 330 ft to 580 ft depending on the overlying topography (Marino, 2003). Structural dip is to the southeast at approximately 20 ft per mile with a N27E strike (OVCC, 2003a).

Bedrock at higher elevations in Dysart Woods consists of the Dunkard Group of probable Permian Age (Siplivy, 2001). Bedrock at lower elevations in Dysart Woods consists of Monongahela Formation of Pennsylvanian Age (Siplivy, 2001). The top of the Monongahela Formation occurs at approximately 1010 fasl (Ground Water Associates, 1991). The bottom of the Pittsburgh (No. 8) coal is the base of the Monongahela Formation. The Monongahela Formation is on average 250 ft thick while the Dunkard Group may reach 350 ft thick (Ground Water Associates, 1991). Lithologies within the Dunkard Group and Monongahela formation consist of shales, claystones, limestones, siltstones, sandstones, and coals (Anderson, 2001).
Fig. 1.6. Generalized stratigraphic column for Belmont County (after Axon, 1996).

1.3.3. Hydrogeology

Dysart Woods has a continental climate with seasonal and daily variations in temperature (Siplivy, 2001). The average annual temperature is approximately 51°F (Harstine, 1991) with an average winter temperature of 28°F and an average summer temperature of 81°F (Siplivy, 2001). Average annual precipitation is approximately 42 inches (Holt and Craig, 1997). Potential evapotranspiration in the area is approximately 25 inches (Holt and Craig, 1997). Groundwater recharge in the study area is solely from precipitation (Anderson, 2001) and varies between 4.2 and 7.6 inches per year (Ground Water Associates, 1991).
The major aquifer type for eastern Ohio is sandstone (Fig. 1.7) (Slattery, 2006). The major aquifer lithologies underneath Dysart Woods from the Pittsburgh No. 8 coal seam to the ground surface are siltstone, sandstone, limestone, coal, and unconsolidated material (Anderson, 2001). Shallow aquifer systems in Dysart Woods do not extend laterally for great distances and are bounded by the dissected topography, which also limits the amount of recharge to that particular area (Ground Water Associates, 1991). Therefore, groundwater divides for shallow flow systems often mimic the watershed drainage basins (Ground Water Associates, 1991). Four major aquifers occur between the Pittsburgh No. 8 coal seam and the ground surface. They occur at each one of the cyclothsms identified in the region (Fig. 1.6). In ascending order from the Pittsburgh No. 8 coal seam, they are identified as the Sewickley No. 9 Cyclothem that occurs between the Sewickley (Meigs) No. 9 coal seam and the Waynesburg No. 11 coal seam, the Waynesburg No. 11 Cyclothem that occurs between the Waynesburg No. 11 coal seam and the Washington No. 12 coal seam, the Washington No. 12 Cyclothem that occurs between the Washington No. 12 coal seam and the surface of the consolidated bedrock, and unconsolidated material that occurs from the surface down to the consolidated bedrock (Anderson, 2001) (Fig. 1.6). Aquifers bounded by topography in Dysart Woods are within the Waynesburg No. 11 Cyclothem, the Washington No. 12 Cyclothem, and unconsolidated material (Fig. 1.6). The Pittsburgh No. 8 coal seam is the exploited seam beneath Dysart Woods and exists at approximately 750 fasl (Marino, 2003).
In 2001, a study was performed on 52 domestic well logs in the vicinity of Dysart Woods to determine aquifer characteristics. The average yield for these wells was 3 gpm with a majority of wells producing 2 gpm or less (Siplivy, 2001), which was the result of low values for primary porosity and permeability (Ground Water Associates, 1991). The higher yields occurred in unconsolidated or highly fractured material along stream
valleys (Siplivy, 2001). This was due to predictable fracture patterns due to unloading that creates vertical fractures along valley walls and horizontal bedding separations as a result to the stress (Wyrick and Borchers, 1981) (Fig. 1.8). Average transmissivity values were less than 1,000 gpd and storage coefficients ranged from $10^{-2}$ to $10^{-4}$ (Siplivy, 2001). Overall geologic structure in this area is not considered to be a significant controlling factor for groundwater flow (Siplivy, 2001).

Fig. 1.8. Fracturing patterns due to unloading (from Wyrick and Borchers, 1981).

1.3.4. Buffer Zones

Buffer zones are used with underground mining to preserve surface structures and are calculated by the angle of influence. The angle of influence is determined by the lateral distance from the boundaries of the longwall panel to the point of zero subsidence (Bell and Genske, 2001); therefore, the greater the angle of influence, the greater the
lateral extent of the buffer. A 70 degree angle of influence, equaling a maximum of 1594 ft of lateral distance from the edge of the longwall panels was once considered the safest distance to prevent any dewatering of the overlying aquifers in Dysart Woods (Ground Water Associates, 1991). The average angle of influence in the Northern Appalachian Plateau is 30° +/- 10° (Ground Water Associates, 1991). The Ohio Valley Coal Company has reported angles of influence of 13° adjacent to Dysart Woods (OVCC, 2003a). However, the data were recorded 1 to 6 months after mining had occurred, which did not allow sufficient time for the subsided overburden to settle (Marino, 2003). The study area adjacent to Dysart Woods was resurveyed at a later date in which the maximum angle of influence was determined to be 49° (Marino, 2003), which would result in approximately 700 ft buffers. However, these angles of influence are for the protection of the solid materials underlying Dysart Woods and do not include any parameters for the movement of fluids. The buffer zones proposed by Ohio Valley Coal Company may not be adequate enough to protect the perched aquifers in Dysart Woods.

Fig. 1.9 shows the current mining plan for permit D-360-12 (OVCC, 2003c). Fig. 1.10 shows an enlargement of the Dysart Woods area (OVCC, 2003d). The current buffer zone is based on the 13° angle of draw and results in a minimum of 300 ft buffers around designated old growth forests (Fig. 1.10) (OVCC, 2003a). Comparing Figure 1.9 (below) to Figure 1.4 (above), it can be observed that the subwatershed boundaries (where Dysart Woods is located) extend well beyond that of the current buffer zones. Since precipitation is the only source of recharge in this area (Anderson, 2001) the extent of the subwatershed boundaries should be taken into consideration when defining no-
impact zones. Note in Figure 1.9 that the room and pillar section of the mine passes underneath Dysart Woods at approximately 750 fasl from south-southeast to north-northwest. This room-and-pillar section was designed to prevent subsidence within the Dysart Woods old growth forests because the old growth forest areas are deemed to be “fragile lands” (Marino, 2003). Room-and-pillar areas below the delineated old growth forests have a maximum extraction ratio of 50% whereas other room-and-pillar areas have an extraction ratio of 65% (OVCC, 2003a). Pillars in the room-and-pillar sections were designed by a modified Holland-Gaddy formula to determine the appropriate pillar strength needed to prevent subsidence in the old growth areas (OVCC, 2003a). However, this measurement does not consider the groundwater impacts. The tunnel creates a drainage below the forest.
Fig. 1.9. Mining layout for Ohio Valley Coal Company’s permit #D-360-12 including Dysart Woods old growth areas. Mines and gates are synonymous with room-and-pillar areas.
Fig. 1.10. Enlargement of Dysart Woods area showing the current buffer zone in relation to the mining layout and watershed boundaries.
CHAPTER 2: EFFECTS OF MINING ON AQUIFERS AND FLOW

2.1. Aquifers

Longwall mining affects the surface and subsurface to a greater extent than room-and-pillar mining. Longwall mining incorporates planned subsidence of the overburden. As the overburden collapses into the mine, it fractures the overlying rock and dilates pre-existing fractures, which can increase the rate of flow through the overburden by several orders of magnitude (Fetter, 2001). In areas experiencing increased rates of flow, or hydraulic conductivity for the system to remain steady, a greater magnitude of inflow from precipitation is needed to compensate for the increased hydraulic conductivity. Otherwise the result will be reduced hydraulic heads related to fracturing of the overburden due to subsidence (Booth et al., 1999), increased downward flows, and lowering of the water table.

The planned subsidence that occurs as a result of longwall mining typically averages approximately 60% to 70% of the thickness of the coal seam (t) that is excavated (Fig. 2.1) (Bauer et al., 1995). Subsidence on the surface is greatest over the center of the panel and decreases gradually to a zero-subsidence zone. The lateral distance to zero subsidence from the edge of the mine is determined by what is termed the angle of influence (Fig. 2.1). This distance is determined by multiplying the depth (D) of the coal seam to the surface by 0.35 to 0.45.

The subsided overburden is divided by depth into four zones (Fig. 2.1); the caved zone, the fractured zone, the aquiclude zone or zone of continuous deformation, and the zone of surface cracking (Bauer et al., 1995; Booth, 2002). However, it should be noted
that the vertical displacement shown in Fig. 2.1 in the subsidence trough is exaggerated. The caved zone is represented by overburden that collapses into the mine above the coal seam that extends vertically two to eight times the thickness of the coal seam. The fractured zone includes the caved zone and extends vertically 30 to 40 times the thickness of the coal seam. The fractured zone is often intensely fractured both vertically and horizontally. The aquiclude zone overlies the fractured zone and extends vertically to approximately 50 ft. below the surface. The aquiclude zone contains strata that bend, but do not break and therefore is also referred to as the zone of continuous deformation. The zone of surface cracking begins at the surface and typically extends the 50 ft. down to the aquiclude zone. The zone of surface cracking contains subsidence-derived cracks as a result of tension on the sides above the longwall panel within the zone affected by the angle of influence (Booth, 2002). The surface directly above the center of the panel experiences compression and may exhibit buckling (Bauer et al., 1995).

Fig. 2.1. Subsidence relative to longwall mining (modified from Singh and Kendorski, 1981).
2.2. Hydrogeologic Properties

The hydrologic properties of the overburden of a mined longwall panel are affected by subsidence. Fracturing due to subsidence can increase the hydraulic conductivity by several orders of magnitude (Fetter, 2001). Fracturing of perching layers due to subsidence can increase the vertical hydraulic conductivity, which will decrease the residence time of groundwater in the shallowest perched aquifer. Hilltop, or perched, aquifers are more sensitive to fracturing than valley aquifers because valley aquifers have a much larger recharge area than perched aquifers (Johnson, 1992). Underground mining can also affect the storage, spring discharge, and residence time of groundwater beyond the zone of surface cracking. In instances where an aquifer is drained or the storage is reduced, groundwater reserves up- or down-dip can be affected (Zipper et al., 1997).

2.3. Legalities

OVCC (Ohio Valley Coal Company) obtained a permit on August 15, 2003 (Permit D-360-12) to mine the Pittsburgh No. 8 coal seam under Dysart Woods (Marino, 2003). Obtaining an underground coal mining permit requires a subsidence control plan, which is a report to accompany the permit application that states the type of proposed mining, the geology above and below the mine, groundwater flow systems, and structures or land features on the ground surface that may be affected by underground mining. If domestic, agricultural, or industrial water supplies are impacted due to mining operations within 48 hours of subsidence, the mining company must offer an alternative water source to the affected area and continue to supply the affected areas with water until a
permanent source of water is achieved (DMRM, 2007). However, water supplies
affected by subsidence outside of domestic, agricultural, or industrial use, such as the
water supplies in Dysart Woods, are not protected. Therefore, current mining regulations
may fail to fully address the impact on this ecosystem.
CHAPTER 3: PREVIOUS WORK AT DYSART WOODS

Several theses and assessment reports have been completed in regards to Dysart Woods. Schillig (2005) presented a Bachelor’s thesis to the College of Arts and Sciences at Ohio University with the purpose of developing a pre-mining hydrostratigraphic model for Dysart Woods for comparison with post-mining aquifer properties to be collected at a later date. Hypotheses tested were 1) that groundwater exists as perched aquifers and 2) that springs within Dysart Woods could be correlated to the perched aquifers (Schillig, 2005).

Schillig (2005) oversaw the installation of eight groundwater monitoring wells grouped into three well nests (WN1, WN2, and WN3 in Fig. 3.1) in Dysart Woods along Ault Dysart Rd in Smith Township, Belmont County. Depths of the monitoring wells were determined by spring elevations and observations during drilling. Well Nest 1 was positioned over a proposed longwall panel, Well Nest 2 was positioned over the proposed room-and-pillar mine and Well Nest 3 was positioned over a proposed non-mined area. Table 3.1 lists the monitoring wells, the well nest to which they belong, surface and bottom elevations, and the depth to the top of the Pittsburgh No. 8 coal seam. Fig. 3.2 shows the relative depths of each monitoring well. GMW-04-5 was drilled for a core sample. The water table was not reached in GMW-04-1.
Fig. 3.1. Watershed map of Dysart Woods showing locations of well nests.

Table 3.1. Surface and bottom elevations of groundwater monitoring wells (from Cook, 2006). Elevation of No. 8 coal seam is approx. 750 fasl (Ground Water Associates, Inc., 1991).

<table>
<thead>
<tr>
<th>Well Identification</th>
<th>Surface Elevation (fasl)</th>
<th>Depth to Bottom (ft)</th>
<th>Elevation at Bottom (fasl)</th>
<th>Depth to Top of No. 8 Coal (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMW-04-8</td>
<td>1295</td>
<td>74.1</td>
<td>1220.9</td>
<td>545</td>
</tr>
<tr>
<td>GMW-04-7</td>
<td>1295</td>
<td>50.9</td>
<td>1244.1</td>
<td>545</td>
</tr>
<tr>
<td>GMW-04-6</td>
<td>1295</td>
<td>24.6</td>
<td>1270.4</td>
<td>545</td>
</tr>
<tr>
<td>GMW-04-5</td>
<td>1320</td>
<td>154.8</td>
<td>1165.2</td>
<td>570</td>
</tr>
<tr>
<td>GMW-04-4</td>
<td>1320</td>
<td>68.5</td>
<td>1251.5</td>
<td>570</td>
</tr>
<tr>
<td>GMW-04-3</td>
<td>1320</td>
<td>26.9</td>
<td>1293.1</td>
<td>570</td>
</tr>
<tr>
<td>GMW-04-2</td>
<td>1320</td>
<td>85.5</td>
<td>1234.5</td>
<td>605</td>
</tr>
<tr>
<td>GMW-04-1 (dry)</td>
<td>1320</td>
<td>29.9</td>
<td>1290.1</td>
<td>605</td>
</tr>
</tbody>
</table>
Kerogen Resources Inc. performed the drilling for the groundwater monitoring wells with an air-rotary drill rig using a 7 7/8-in tricone bit. However, GMW-04-5 was drilled with a mud-rotary drill rig with a core barrel to obtain core for the construction of a stratigraphic column. A 6-in steel casing extending to a depth of 10-ft from the surface was placed around each monitoring well for protective purposes. The deepest well of each well nest was drilled first to aid in the detection of saturated zones to determine the placement of the screens. Machine cut 2-in inner diameter 10-ft long PVC screens with a slot size of 0.01-in and PVC casings with 2-in inner diameter were installed in wells drilled with the air-rotary drill rig. A similar screen and casing combination was installed in GMW-04-5 with the exception of the inner diameter of the PVC decreasing from 2 in to 1 in. The well screens are surrounded by a 430 silica stone sand pack. The well
casings are surrounded by bentonite grout from the top of the well screen to the surface of the well (Schillig, 2005).

Data logging devices were deployed in each well (with the exception of GMW-04-1 since the water table was not intercepted) to collect continuous data in one hour increments to retrieve head elevations within each well to produce continuous hydrographs of the hydraulic head. These data were plotted in Excel to determine pre-mining hydrograph decay constants for later comparison with post-mining decay constants. Slug tests were also performed to determine pre-mining hydraulic conductivity (K) values for comparison with post-mining K values (Table 3.2, Schillig, 2005).

Schillig (2005) constructed a localized strat column from the core taken from GMW-04-5 (Fig. 3.3). The core consisted of 46.1% claystone, 15.4% limestone, 14.3% mudstone, 12.4% shale, 6.5% siltstone, and 5.3% sandstone. Water bearing zones for Schillig’s (2005) localized strat column were determined by iron-stained deposits on fracture walls within the core. However, it should be noted that aquifers exist beyond the fracture areas in the core as evidenced by the other groundwater monitoring wells and springs in the Dysart Woods area. The water bearing zones in Schillig’s (2005) strat column were determined only from iron-stained vertical or horizontal joints in the extracted core.

Slug tests were performed by the addition of a known volume of water to a well. Data were recorded in log time with data loggers and were analyzed in AquiferTest 3.5 by the Hvorslev method and the Bouwer-Rice method, then averaged (Schillig, 2005).
Data were plotted in semi-log space with the head elevation at any time divided by the head elevation change with the addition of the slug plotted in log space (y-axis) versus time plotted in arithmetic space (x-axis). These data are given in Table 3.2. The initial value is given as $K_1$ in Table 3.2. Additional $K$ values ($K_2$ in Table 3.2) are provided for double trends within an analysis that may be the result of the increased initial permeability due to the sand packs around the well screens, localized fracture systems, or drilling induced fractures. In instances where a double trend exists, such as in GMW-04-2 and GMW-04-5 in Table 3.2, the secondary hydraulic conductivity values are given as $K_2$. The $K_2$ hydraulic conductivity values for GMW-04-2 and GMW-04-5 may be more representative of the hydraulic conductivity values because the initial value for hydraulic conductivity may only reflect the hydraulic conductivity of the sand packs around the well screens, localized fracture systems, or drilling induced fractures, whereas the secondary hydraulic conductivities ($K_2$) reflects the velocity of water moving through the porous media (Schillig, 2005). Fig. 3.4 shows AquiferTest results for GMW-04-2 showing the double trend. The secondary hydraulic conductivity reflecting the primary permeability ($K_2$) is on the left and the initial hydraulic conductivity reflecting the secondary permeability ($K_1$) is on the right (Schillig, 2005).
Fig. 3.3. Localized stratigraphic column for Dysart Woods (from Schillig, 2005).
Table 3.2. Pre-mining hydraulic conductivity values determined with slug tests (from Schillig, 2005).

<table>
<thead>
<tr>
<th>Well</th>
<th>( K_1 ) cm/s (Hvorslev)</th>
<th>( K_1 ) cm/s (Bouwer-Rice)</th>
<th>( K_1 ) mean cm/s</th>
<th>( K_2 ) cm/s (Hvorslev)</th>
<th>( K_2 ) cm/s (Bouwer-Rice)</th>
<th>( K_2 ) mean cm/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMW-04-1</td>
<td>1.8E-05</td>
<td>1.72E-05</td>
<td>1.80E-05</td>
<td>3.40E-06</td>
<td>2.82E-06</td>
<td>3.11E-06</td>
</tr>
<tr>
<td>GMW-04-2</td>
<td>1.83E-06</td>
<td>8.40E-07</td>
<td>1.24E-06</td>
<td>3.40E-06</td>
<td>2.82E-06</td>
<td>3.11E-06</td>
</tr>
<tr>
<td>GMW-04-3</td>
<td>3.26E-04</td>
<td>2.77E-04</td>
<td>3.02E-04</td>
<td>7.02E-07</td>
<td>8.00E-07</td>
<td>0.000000751</td>
</tr>
<tr>
<td>GMW-04-4</td>
<td>6.40E-06</td>
<td>6.27E-06</td>
<td>6.34E-06</td>
<td>7.02E-07</td>
<td>8.00E-07</td>
<td>0.000000751</td>
</tr>
<tr>
<td>GMW-04-5</td>
<td>1.10E-05</td>
<td>8.34E-06</td>
<td>9.67E-06</td>
<td>7.02E-07</td>
<td>8.00E-07</td>
<td>0.000000751</td>
</tr>
<tr>
<td>GMW-04-6</td>
<td>5.16E-06</td>
<td>4.96E-06</td>
<td>5.06E-06</td>
<td>7.02E-07</td>
<td>8.00E-07</td>
<td>0.000000751</td>
</tr>
<tr>
<td>GMW-04-8</td>
<td>3.97E-09</td>
<td>2.33E-09</td>
<td>3.15E-09</td>
<td>7.02E-07</td>
<td>8.00E-07</td>
<td>0.000000751</td>
</tr>
</tbody>
</table>

Fig. 3.4. Slug test results from AquiferTest showing secondary (K2) and initial (K1) trends for hydraulic conductivity values in GMW-04-2 (from Schillig, 2005).

Pre-mining hydrograph decay data are given in Table 3.3 (Schillig, 2005).

Recession curves were selected from the hydrographs based on magnitude and frequency of precipitation (recharge) events. These data were then plotted separately in Excel and fitted with an exponential trendline. Two replicates were performed for each well with the exception of GMW-04-1 (Schillig, 2005).
Table 3.3. Hydrograph decay constants (from Schillig, 2005).

<table>
<thead>
<tr>
<th>Well</th>
<th>R1</th>
<th>R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMW-04-2</td>
<td>4.60E-03</td>
<td>2.90E-03</td>
</tr>
<tr>
<td>GMW-04-3</td>
<td>2.80E-03</td>
<td>4.80E-03</td>
</tr>
<tr>
<td>GMW-04-4</td>
<td>1.79E+00</td>
<td>4.47E+00</td>
</tr>
<tr>
<td>GMW-04-5</td>
<td>1.57E+00</td>
<td>1.01E+00</td>
</tr>
<tr>
<td>GMW-04-6</td>
<td>3.43E-02</td>
<td>7.05E-02</td>
</tr>
<tr>
<td>GMW-04-7</td>
<td>3.18E-02</td>
<td>3.99E-02</td>
</tr>
<tr>
<td>GMW-04-8</td>
<td>1.20E-03</td>
<td>1.40E-03</td>
</tr>
</tbody>
</table>

Cook (2006) tested the hypothesis that longwall mining altered the permeability of shallow perched aquifers over a longwall panel adjacent to Dysart Woods with a possible impact to perched aquifers within Dysart Woods. Cook’s (2006) study was a continuation of Schillig’s (2005) for a comparison of pre- and post-mining aquifer properties.

Cook (2006) monitored the same wells from the previous study and collected data using the same data loggers for the purpose of creating continuous hydrographs, slug test data for K values, and decay constants from the hydrographs. Precipitation and barometric pressure data were also collected on site. Mining started on the Pittsburgh No. 8 Coal below Well Nest 1 on October 3, 2005. Comparison of pre- and post-longwall mining for hydraulic conductivity and decay constant values was performed using a t-test of equality of two sample means for samples with unequal variances. Continuous hydrographs were plotted together using units of feet above sea level with precipitation on the secondary y-axis for observations of isolated recession events (Fig. 3.5; Cook, 2006). Hydrograph data span September 4, 2004 to April 29, 2006. GMW-
04-6 and GMW-04-7 experienced head loss in response to the October 3, 2005 longwall mining event. GMW-04-8 also exists in Well Nest 1; however, due to instrumental error, hydrograph data from GMW-04-8 was not used. Fig. 3.6 shows the hydrographs only for wells in Well Nest 1 that were directly affected by longwall mining. GMW-04-6 and GMW-04-7 were affected approximately one week after the longwall miner passed underneath the well nest. Fig. 3.7 shows yearly hydrographs for GMW-04-6 and GMW-04-7 to show the effect of longwall mining on hydraulic heads. Throughout the duration of Cook’s (2006) study, GMW-04-6 did not recover. Water existed in GMW-04-7 and GMW-04-8 at the end of the study and never appeared to go dry (Cook, 2006)

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**Fig. 3.5.** Continuous hydrograph for Dysart Woods data (from Cook, 2006).
Water Level in Groundwater Monitoring Wells in Well Nest 1, Dysart Woods, Belmont County, Ohio

October 3, 2005: The date the longwall miner passed underneath Well Nest 1

Fig. 3.6. Expanded view hydrographs for Well Nest 1 (from Cook, 2006).

Yearly Comparison for GMW-04-6 in Well Nest 1

Fig. 3.7. Yearly comparisons for wells in Well Nest 1 (from Cook, 2006).
Tables 3.4 and 3.5 summarize the data for hydrograph decay constants and slug tests, respectively (Cook, 2006). Decay constant and slug test data values were analyzed similar to the methods used by Schillig (2005). However, Cook (2006) performed a separate analysis of pre-mining hydrograph decay constants from the pre-mining data shown previously in Table 3.3 from Schillig (2005) to get an equal amount of replicates for each sample set. It was concluded with a 95% confidence level that pre- and post-mining hydrograph decay constants (Table 3.4) in wells GMW-04-6 and GMW-04-7 of Well Nest 1 increased significantly with a pre-mining average of 0.0276 to a post-mining average of 2.487. Decay constants in wells in Well Nest 2 were not statistically different.

Hydraulic conductivity values in well GMW-04-06 changed by two orders of magnitude (Table 3.5). However, it was concluded with a 95% confidence level that pre- and post-mining hydraulic conductivity values (Table 3.5) in well GMW-04-7 of Well Nest 1 did not increase significantly. Due to the lack of pre-mining hydraulic conductivity samples (only 1 for each well), this data may contain error due to the limitation of one data sample (Cook, 2006). Another possibility is that the hydraulic conductivity at the site of the well GMW-04-7 has not changed significantly but that in other regions of the aquifer, new fractures are withdrawing water limiting the water available at this well and its head.

Cook’s (2006) study confirmed that longwall mining altered the shallow perched aquifer systems near Dysart Woods.
Table 3.4. Hydrograph decay constant data for wells from Well Nest 1 and Well Nest 2. Different shades represent different wells in each corresponding well nest (from Cook, 2006).

<table>
<thead>
<tr>
<th>WELL NEST 1</th>
<th>BEFORE LONG-WALL MINING</th>
<th>AFTER LONG-WALL MINING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well #</td>
<td>a</td>
<td>Well #</td>
</tr>
<tr>
<td>GMW-04-6</td>
<td>0.0248</td>
<td>GMW-04-6</td>
</tr>
<tr>
<td>GMW-04-6</td>
<td>0.0288</td>
<td>GMW-04-6</td>
</tr>
<tr>
<td>GMW-04-6</td>
<td>0.0491</td>
<td>GMW-04-6</td>
</tr>
<tr>
<td>GMW-04-6</td>
<td>0.0171</td>
<td>GMW-04-6</td>
</tr>
<tr>
<td>GMW-04-6</td>
<td>0.0184</td>
<td>GMW-04-6</td>
</tr>
<tr>
<td>GMW-04-7</td>
<td>0.0044</td>
<td>GMW-04-7</td>
</tr>
<tr>
<td>GMW-04-7</td>
<td>0.0075</td>
<td>GMW-04-7</td>
</tr>
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<td>GMW-04-7</td>
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<td>GMW-04-7</td>
</tr>
<tr>
<td>GMW-04-7</td>
<td>0.0085</td>
<td>GMW-04-7</td>
</tr>
<tr>
<td>GMW-04-7</td>
<td>0.0077</td>
<td>GMW-04-7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WELL NEST 2</th>
<th>BEFORE LONG-WALL MINING</th>
<th>AFTER LONG-WALL MINING</th>
</tr>
</thead>
<tbody>
<tr>
<td>WELL #</td>
<td>a</td>
<td>WELL #</td>
</tr>
<tr>
<td>GMW-04-5</td>
<td>0.0205</td>
<td>GMW-04-5</td>
</tr>
<tr>
<td>GMW-04-5</td>
<td>0.0312</td>
<td>GMW-04-5</td>
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<td>GMW-04-5</td>
</tr>
<tr>
<td>GMW-04-5</td>
<td>0.1489</td>
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<td>0.0091</td>
<td>GMW-04-4</td>
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</tr>
<tr>
<td>GMW-04-4</td>
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</tr>
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<td>0.0088</td>
<td>GMW-04-4</td>
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<tr>
<td>GMW-04-4</td>
<td>0.0033</td>
<td>GMW-04-4</td>
</tr>
</tbody>
</table>

Table 3.5. Slug test data for wells from Well Nest 1 and Well Nest 2 (from Cook, 2006).

<table>
<thead>
<tr>
<th>WELL NEST 1</th>
<th>BEFORE LONG-WALL MINING (ft/s)</th>
<th>AFTER LONG-WALL MINING (ft/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Well #</td>
<td>K</td>
<td>Well #</td>
</tr>
<tr>
<td>GMW-04-6</td>
<td>Hvorslev</td>
<td>9.21E-08</td>
</tr>
<tr>
<td></td>
<td>Bouwer &amp; Rice</td>
<td>5.21E-08</td>
</tr>
<tr>
<td></td>
<td>Hvorslev</td>
<td>3.40E-07</td>
</tr>
<tr>
<td></td>
<td>Bouwer &amp; Rice</td>
<td>2.98E-07</td>
</tr>
<tr>
<td>GMW-04-7</td>
<td>Hvorslev</td>
<td>3.04E-07</td>
</tr>
<tr>
<td></td>
<td>Bouwer &amp; Rice</td>
<td>2.78E-07</td>
</tr>
<tr>
<td></td>
<td>Hvorslev</td>
<td>2.41E-07</td>
</tr>
<tr>
<td></td>
<td>Bouwer &amp; Rice</td>
<td>2.18E-07</td>
</tr>
<tr>
<td></td>
<td>Hvorslev</td>
<td>1.46E-07</td>
</tr>
<tr>
<td></td>
<td>Bouwer &amp; Rice</td>
<td>1.32E-07</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WELL NEST 2</th>
<th>BEFORE LONG-WALL MINING (ft/s)</th>
<th>AFTER LONG-WALL MINING (ft/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMW-04-4</td>
<td>Hvorslev</td>
<td>9.40E-06</td>
</tr>
<tr>
<td></td>
<td>Bouwer &amp; Rice</td>
<td>5.81E-06</td>
</tr>
<tr>
<td>GMW-04-5</td>
<td>Hvorslev</td>
<td>1.30E-10</td>
</tr>
<tr>
<td></td>
<td>Bouwer &amp; Rice</td>
<td>7.64E-11</td>
</tr>
</tbody>
</table>
Burgess (2006) assessed the soil moisture concentration possible in the soils at Dysart Woods and whether or not groundwater contributes to the soil moisture, particularly where groundwater is discharged via spring seepage to the surface providing water to the soil moisture. The study found, based on $^2$H and $^{18}$O isotopic signatures of the groundwater relative to the $^2$H and $^{18}$O isotopic signature of summer precipitation, that trees and soil water down slope as well as up slope of springs had the isotopic signature of groundwater. Burgess (2006) concluded that the contribution of groundwater is an important factor to the biohydrology of Dysart Woods.
CHAPTER 4: METHODOLOGY

4.1. Physical Model

Using the information of the topography, subwatershed boundaries, stratigraphy, permeable layers, spring locations, and hydrogeological parameters (e.g. hydraulic conductivity, porosity), physical models (diagrams) of the ground water system of Dysart Woods were constructed for the pre and the post mining situation. The upper most saturated layer was emphasized because it is the aquifer that could provide water to the forest. Hydrologic data reported in section 1.3 of this thesis (Site Description) were used as variables for the model. Other data were collected from recognized data sources, such as meteorological data. These data were used to create a physical model of the Dysart Woods watershed to analyze the initial system (pre-mining) and the perturbed system (post-mining).

A topographic watershed map was created with ArcMap in ArcGIS 9.2 to define the boundaries of the watershed. A water table map was created by using the kriging option in Surfer 7.0 (Anderson and Woessner, 2002) by inputting survey, well, and spring data. Current buffer zones proposed by OVCC were considered in the model. Drill logs were correlated to create cross sections of the local geology to find the dominant lithologies. This information was used to determine the hydrostratigraphic units of the Dysart Woods area of the watershed, which helped in the determination of flow paths in addition to the determination of average hydraulic conductivity values. Water table maps showed the direction of groundwater flow in addition to pre- and post-mining static water levels. A table of aquifer properties was generated to summarize the variables for the
physical model and to be used as initial values for the numerical model prior to calibration.

Groundwater monitoring wells GMW-04-6 and GMW-04-7 of Well Nest 1 and groundwater monitoring well GMW-04-4 of Well Nest 2 were used to determine water table elevations for the physical and numerical models. These monitoring wells were used because they gave the best monitoring data of the monitoring wells in Dysart Woods. Other wells within and near Dysart Woods could not be used due to instrumental problems with the data recording devices or because the water table was never reached (as was the case for GMW-04-1 in Well Nest 3).

4.2. Numerical Model

The constructed physical model was used to create a numerical model of the upper most aquifer at Dysart Woods using the computer program MODFLOW (Anderson and Woessner, 2002). MODFLOW is a finite differences model that solves the groundwater flow equation for a large variety of boundary conditions (Anderson and Woessner, 2002). Watershed boundaries of the catchment basin were used as vertical no-flow boundaries for the physical model and input into MODFLOW. Surface elevations and bedrock elevations were input into Surfer and then imported into MODFLOW for layer boundaries.

Water table maps created in Surfer showed the direction of groundwater flow, which determined the orientation of the model to be created in MODFLOW. Watershed boundaries served as the boundaries of the model, which also served as a no-flow
boundary. The two streams within the Dysart Woods watershed were input as river boundaries. A constant head boundary was placed to the south boundary of the model based on head elevations obtained from the water table map. Well and spring data that were used to create water table maps for the physical model were input into the numerical model as head observation wells for the purpose of calibration of the model. Storage data was found in literature (Anderson and Woessner, 2002) and assessment reports previously carried out on the Dysart Woods region (OVCC, 2003b; Ahmad, 1988).

Precipitation data was obtained from meteorological sources (Harstine, 1991; Roth et al., 1981), previous assessment reports (Siplivy, 2001; Holt and Craig, 1997; Cook, 2006), and onsite weather stations. River data and the conductance of the river sediments were calculated from field data and literature (Fetter, 2001; Anderson and Woessner, 2002). Average hydraulic conductivity values were determined by representative values corresponding to the lithologies shown by the geologic cross sections (Fetter, 2001).

The steady state model (pre-mining model) was calibrated with the data collected prior to mining. Transient simulations were carried out to determine the evolution of the water table with time. The calibrated model was changed to simulate the underground mining and leakage of the aquifer due to mining by assigning drains to the lowest layer. Calibration was achieved by changing the conductance of the drains in the model to match post-mining results of the water table.

Once all the necessary data was input into MODFLOW, recharge, hydraulic conductivity, and storage values were changed for calibration purposes to determine the most likely values to replicate observed head values. The final calibrated model was
determined by the model that gave the lowest RMS value. Once the final calibrated model was reached, a sensitivity analysis was performed to determine how sensitive the model was to specific changes in the calibrated values. After the sensitivity analysis had been performed, transient simulations were carried out to determine the amount of leakage needed to reach current post-mining conditions. The leakage was simulated as drains placed at the locations of the long wall panels to achieve the correct amount of drawdown to reproduce post-mining head elevations. The transient model was then run for a total of 10 years to determine the evolution of the water table into the future.
5.1. Watershed Map

A watershed map of the Dysart Woods watershed was created to determine the extent of the watershed. Fig. 5.1 shows the extent of the Dysart Woods watershed in addition to the 300 ft buffer proposed by OVCC. The 300 ft buffer has an area of 153.1 acres whereas the watershed has an area of 1382.5 acres—a difference of 1229.4 acres. As seen in Fig. 5.1, the watershed boundary extends well beyond that of the proposed buffer zone to protect Dysart Woods from the effect of underground mining.

Fig. 5.1. Dysart Woods watershed map showing 300 ft buffer proposed by OVCC.
5.2. Topographic Map

Surface elevation data were collected from a land survey, well locations and elevations, and springs locations and elevations. A land survey of the designated old growth areas was carried out by R. D. Zande and Associates, Inc. Well locations were collected from Ohio Valley Coal Company’s permit application (OVCC, 2003d) and Ohio Department of Natural Resources Division of Water (ODNR, 2005). Spring locations were also collected from OVCC’s permit application (OVCC, 2003d). Field data were collected from a hand-held GPS unit. All horizontal coordinates were converted to the NAD83 datum and all vertical coordinates were converted to the NAVD88 datum by CORPSCON for Windows Version 5.11.08 (Geospatial Applications Branch, 2008) with horizontal units in meters and vertical units in US survey feet. Fig. 5.2 shows the result for the topographic map created by Surfer. The red rectangle in Fig. 5.2 represents the area of the watershed that was modeled. X-axis coordinates are given in eastings (m) and y-axis coordinates are given in northings (m). The contour interval is 20 ft. A color scale to aid in the determination of elevation is also provided.
Fig. 5.2. Topographic map of Dysart Woods area created with Surfer showing area to be modeled with MODFLOW (red rectangle).

5.3. Geologic Cross Sections

To determine the dominant lithologies underneath Dysart Woods and the surrounding areas, stratigraphic columns were reproduced from core obtained from GMW-04-5 (Schillig, 2006), well logs from OVCC’s permit application (OVCC, 2003d), and domestic well logs from Ohio Department of Natural Resources Division of Water (ODNR, 2005) (Fig. 5.3). These data were mapped together to determine which
stratigraphic columns would best represent the lithologies present underneath Dysart Woods. The construction of continuous cross-sections was not possible due to the discontinuity of some of the stratigraphic layers.

Fig. 5.3. Map showing cross sections constructed for Dysart Woods and vicinity.
From Fig. 5.3 above, cross section A to A’ consists of GMW-04-5, N86-21, and N94-01, cross section B to B’ consists of N97-04, GMW-04-5, and N94-06, and cross section C to C’ consists of N97-05, GMW-04-5, and N97-02. All wells in the cross sections, with the exception of GMW-04-5, continue to the Pittsburgh No. 8 coal seam (OVCC, 2003d); however, the stratigraphic columns reproduced for this research terminate at the Waynesburg No. 11 coal seam, which is the base of the Waynesburg No. 11 cyclothem (Anderson, 2001). The top of the Waynesburg No. 11 coal seam is the boundary between the Dunkard Group of the Permian System and the underlying Monongahela Group of the Pennsylvanian System (Axon, 1996). The base of the Waynesburg No. 11 cyclothem serves as the base for the physical and numerical model confined by the Dysart Woods watershed.

The following figures (Figs. 5.4-5.6) are the stratigraphic cross sections shown in Fig. 5.3 above. Fig. 5.4 shows the A to A’ cross section, Fig. 5.5 shows the B to B’ cross section and Fig. 5.6 shows the C to C’ cross section. Due to the complexity of the geology, it is not possible to correlate all the different strata in all the stratigraphic columns. Therefore, it was assumed that the stratigraphy in the Dysart Woods region is similar to the core derived from GMW-04-5 and that the strata beneath Dysart Woods tilt based on the reported regional dip of 20 ft per mile to the SE. The Washington No. 12 coal seam is labeled and correlated where present. All units are given in feet above sea level.
Fig. 5.4. Stratigraphic cross section of A to A’ shown in Fig. 20.
Fig. 5.5. Stratigraphic cross section of B to B’ shown in Fig. 20.
Fig. 5.6. Stratigraphic cross section of C to C' shown in Fig. 20.
For modeling purposes, a simplification of the modeled layers was needed. It was not possible to model all the different strata types. In addition, due to the complex geology, the continuity of some of the individual lithologic units was unknown. For that reason, the different lithologic layers were combined into hydrostratigraphic units for the model. The hydrostratigraphic units were determined by water bearing zones recorded while drilling and the location of springs and perching layers determined by Schillig (2005). The various lithologies for each layer were then calculated based on the percentage of that particular lithology found within the corresponding layer. Layer 1 consisted of 45% claystone, 39% sandstone, 15% shale, and 1% limestone. Layer 2 consisted of 53% claystone, 37% limestone, and 10% shale. Layer 3 consisted of 100% shale. Layer 4 consisted of 100% limestone. Layer 5 consisted of 100% claystone. Layer 6 consisted of 92% claystone and 8% limestone. Layer 7 consisted of 49% claystone, 44% shale, 6% limestone, and 1% sandstone. Layer 8 consisted of 42% shale, 30% claystone, 20% sandstone, 5% limestone, and 3% coal. Fig. 5.7 shows the different hydrostratigraphic units, the percentages of each lithology found in each layer and the elevations of each layer.

Hydraulic conductivity ranges were taken from tables (Anderson and Woessner, 2002) and literature (McCoy, 2006) based on the percentage of each lithology present in each layer. The hydraulic conductivity range was $10^{-7} - 10^{-9}$ ft/sec for layer 1, $10^{-7} - 10^{-9}$ ft/sec for layer 2, $10^{-8} - 10^{-10}$ ft/sec for layer 3, $10^{-4} - 10^{-7}$ ft/sec for layer 4, $10^{-8} - 10^{-10}$ ft/sec for layer 5, $10^{-7} - 10^{-9}$ ft/sec for layer 6, $10^{-7} - 10^{-9}$ ft/sec for layer 7 and $10^{-6} - 10^{-8}$ ft/sec for layer 8. These values may vary due to varying thicknesses of each layer within
the study site in addition to the result of vertical fracturing and horizontal bedding separation due to unloading (Wyrick and Borchers, 1981).

Fig. 5.7. Hydrostratigraphic units of Dysart Woods and the proportion of various lithologies for each layer.
5.4. Water Table Maps

Water table maps were created of the Dysart Woods area with the kriging option in Surfer 7.0 (Anderson and Woessner, 2002). Data used to create water table maps consisted of spring elevations, stream elevations, and elevations of the static water level determined by groundwater monitoring wells located in and near Dysart Woods (Well Nest 1 and Well Nest 2) that correspond to the shallowest aquifer to be modeled numerically in Chapter 6.

Pre-mining and post-mining water table maps of the model area shown in Fig. 5.8 (green rectangle) were created to determine the change in the static water level. Pre-mining water table maps were created from 9/20/2004 heads data. Post-mining water table maps were created from 4/8/2008 heads data. All longwall panels had been mined east of Dysart Woods and the room-and-pillar section passing underneath Dysart Woods had begun by 4/8/2008. The longwall panels west of Dysart Woods had not been mined by this date. Fig. 5.9 shows pre-mining conditions of the static water level of the shallowest aquifer. Fig. 5.9 shows the water table in relation to the model area, approximate boundaries of the OVCC proposed buffer zone (white polygon) and locations of data collection points. Fig. 5.10 shows post-mining conditions of the static water level of the shallowest aquifer. A perceivable difference can be seen in the east portion of the water table maps (Figs. 5.9-5.10) in regards to the drop in elevation of the water table from pre-mining to post-mining. The main direction of groundwater flow shown in Figs. 5.9 and 5.10 is 24° SW.
Fig. 5.8. Model area used to create water table maps.
Fig. 5.9. Pre-mining water table map of the shallowest aquifer showing water table and location of data points. Approximate boundaries of the OVCC proposed buffer zone are shown with the white thatched polygon.
Fig. 5.10. Post-mining water table maps of the shallowest aquifer showing water table and location of data points. Approximate boundaries of the OVCC proposed buffer zone are shown with the white thatched polygon.

Fig. 5.11 shows the change in the water table elevation from the pre-mining (9/20/2004) water table map to the post-mining (4/8/2008) water table map. Data points shown are for Well Nest 1, Well Nest 2, and DW-303, which is a domestic well located to the east of Dysart Woods. The contours represent the amount of decrease in the water table with a color scale showing the amount of decrease. It should be noted, however, that the water table may have not dropped 30 ft, but that the shallowest aquifer dried up as a result of mining and the perched aquifer below the shallowest aquifer is now the first saturated zone encountered from the surface. It is not possible to determine the exact
network of fracturing below Dysart Woods and below the vicinity of Dysart Woods. Nonetheless, a drop in the water table elevation occurs within the NE corner of the buffer zone determined by the Ohio Valley Coal Company and above the room-and-pillar zone underneath Dysart Woods. The effect of mining below Dysart Woods and the vicinity of Dysart Woods on water table elevation is evident.
Fig. 5.11. Difference between pre- and post-mining with color scale emphasizing the affected area.
5.5. Summary

The watershed boundary of the Dysart Woods watershed serves as the boundary for the physical model because precipitation is the only source of recharge for this area (Anderson, 2001). Therefore, the watershed boundary serves as the vertical no-flow boundary for the model. The base of the model is the top of the Waynesburg No. 11 coal seam, which is found on average at 1000 fasl in the Dysart Woods watershed. The model was then divided into 8 hydrostratigraphic units based on the local stratigraphy. Water table maps were constructed and showed a decrease in the water table along the northeast boundary of Dysart Woods. Even though Well Nest 1 is not within the current buffer zone proposed by OVCC, drop in the static water level of the shallowest aquifer may affect groundwater reserves up or down dip (Zipper et al., 1997), which includes the groundwater reserves of the shallowest aquifer beneath Dysart Woods. The total area of the watershed is 1382.5 acres whereas the total area of the buffer zone proposed by OVCC is 153.1 acres. Because watershed divides often mimic groundwater divides in this region (Ground Water Associates, 1991), the entire area of the watershed should be considered when defining no-impact zones to protect “fragile lands” such as Dysart Woods. Additionally, in a post-mining period, abandoned mines may carry water through surface watershed boundaries, extending the hydrologic influence zone even further.

Table 5.1 lists the properties of the shallowest aquifer of Dysart Woods based on variables determined by Ground Water Associates (1991) and Siplivy (2001) discussed in the site description (Chapter 1.3) of this report and variables determined previously in
this chapter by Anderson and Woessner (2002) and McCoy (2006). These variables were used as initial values that were input into Visual MODFLOW to produce a numerical model of the shallowest aquifer underneath Dysart Woods. Table 5.1 gives a summary of the variables that were used as initial inputs to produce the numerical model.

Table 5.1. Aquifer variables of the hydrostratigraphic units underneath the Dysart Woods area. See Fig. 5.7 for corresponding layer lithologies.

<table>
<thead>
<tr>
<th>Hydrostratigraphic Unit</th>
<th>Hydraulic Conductivities (K) (ft/sec)</th>
<th>Specific Storage (ft$^{-1}$)</th>
<th>Specific Yield</th>
<th>Effective Porosity %</th>
<th>Total Porosity %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer</td>
<td>K_x</td>
<td>K_y</td>
<td>K_z</td>
<td>Storage</td>
<td>Yield</td>
</tr>
<tr>
<td>1</td>
<td>$10^7$ to $10^9$</td>
<td>$10^7$ to $10^9$</td>
<td>$10^7$ to $10^9$</td>
<td>6.9E-5 to 3.3E-6</td>
<td>0.01 to 0.39</td>
</tr>
<tr>
<td>2</td>
<td>$10^7$ to $10^9$</td>
<td>$10^7$ to $10^9$</td>
<td>$10^7$ to $10^9$</td>
<td>6.9E-5 to 3.3E-6</td>
<td>0.01 to 0.39</td>
</tr>
<tr>
<td>3</td>
<td>$10^8$ to $10^{-10}$</td>
<td>$10^8$ to $10^{-10}$</td>
<td>$10^8$ to $10^{-10}$</td>
<td>6.9E-5 to 3.3E-6</td>
<td>0.01 to 0.39</td>
</tr>
<tr>
<td>4</td>
<td>$10^{-4}$ to $10^{-7}$</td>
<td>$10^{-4}$ to $10^{-7}$</td>
<td>$10^{-4}$ to $10^{-7}$</td>
<td>6.9E-5 to 3.3E-6</td>
<td>0.00 to 0.36</td>
</tr>
<tr>
<td>5</td>
<td>$10^{-8}$ to $10^{-10}$</td>
<td>$10^{-8}$ to $10^{-10}$</td>
<td>$10^{-8}$ to $10^{-10}$</td>
<td>4.0E-4 to 2.8E-4</td>
<td>0.01 to 0.18</td>
</tr>
<tr>
<td>6</td>
<td>$10^{-8}$ to $10^{-8}$</td>
<td>$10^{-8}$ to $10^{-8}$</td>
<td>$10^{-8}$ to $10^{-8}$</td>
<td>4.0E-4 to 2.8E-4</td>
<td>0.01 to 0.18</td>
</tr>
<tr>
<td>7</td>
<td>$10^{-6}$ to $10^{-8}$</td>
<td>$10^{-6}$ to $10^{-8}$</td>
<td>$10^{-6}$ to $10^{-8}$</td>
<td>6.9E-5 to 3.3E-6</td>
<td>0.01 to 0.39</td>
</tr>
<tr>
<td>8</td>
<td>$10^{-6}$ to $10^{-8}$</td>
<td>$10^{-6}$ to $10^{-8}$</td>
<td>$10^{-6}$ to $10^{-8}$</td>
<td>6.9E-5 to 3.3E-6</td>
<td>0.01 to 0.39</td>
</tr>
</tbody>
</table>
CHAPTER 6: RESULTS II—NUMERICAL MODEL

6.1. Steady State Model

A steady state model was created using MODFLOW, a finite differences model that solves the groundwater flow equation for a large variety of boundary conditions (Anderson and Woessner, 2002). Before constructing a model grid in MODFLOW, the direction of groundwater flow was determined for proper orientation of the groundwater flow model. Water table maps created with Surfer (Figs. 5.9 and 5.10) revealed the main direction of groundwater flow, which resulted in an overall groundwater flow direction orientated 24° SW. Therefore, the model area had to be rotated -24° to align the flow direction suitable to the construction of the model. Fig. 6.1 shows the natural orientation of the area to be modeled (green rectangle) in addition to the watershed boundary and the current buffer zone proposed by OVCC.
Fig. 6.1. Orientation of model area prior to rotation.
The model area was rotated to comply with MODFLOW guidelines using the equations

\[ X' = (X_n - X_0) \cdot \cos \theta - (Y_n - Y_0) \cdot \sin \theta \quad (1) \]

\[ Y' = (X_n - X_0) \cdot \sin \theta + (Y_n - Y_0) \cdot \cos \theta \quad (2), \]

where \( X_n \) is the easting value of the nth coordinate, \( X_0 \) is the easting point of origin that the model was rotated around and is equal to 499092.35 E, \( Y_n \) is the northing value of the nth coordinate, \( Y_0 \) is the northing point of origin that the model was rotated around and is equal to 4425406.0 N, \( \theta \) is the angle that the model is rotated, and \( X' \) and \( Y' \) are the new easting and northing coordinates, respectively, of the rotated model. These Equations (1) and (2) were used to rotate the model area by -24° (\( \theta \)) around the point \((X_0, Y_0)\) or (499092.35, 4425406.0), which is the southwest corner of the model area (green rectangle in Fig. 6.1). By subtracting \((X_0, Y_0)\) from each \(X_n\) and \(Y_n\), the coordinates for \((X_0, Y_0)\) after the model was rotated became \((0, 0)\) with horizontal units in meters and vertical units in U.S. survey feet. The horizontal units were converted to feet to match the vertical units. The new coordinates were then plotted again using Surfer and then imported into MODFLOW to be used as the surface layer. Fig. 6.2 shows the result of the grid rotation.
ROTATION OF THE MODEL AREA BY -24°

Fig. 6.2. The Figure on the top is prior to rotation whereas the Figure on the bottom is after the model area was rotated -24°. Units for both maps are meters.
The elevation of the bottom layer was based on the bottom of the Waynesburg No. 11 Cyclothem and the regional strike and dip. The regional dip is 20 ft per mile with a N27E strike (OVCC, 2003a). Points were taken along strike at known perching layers indicated by the stratigraphic column of GMW-04-5. Once the coordinates along the strike bisecting GMW-04-5 were known, coordinates paralleling the strike were derived while taking into account the vertical change in distance due to the dip. Elevations were then added or subtracted to the lines paralleling the strike bisecting GMW-04-5 in accordance with the dip. These data were then plotted in Surfer with the polynomial regression option to create the bottom layer of the model, which was imported into MODFLOW.

Once the surface layer and the bottom layer were imported into MODFLOW, the model grid was divided into eight layers based on the eight hydrostratigraphic units determined from Section 5.3 (Fig. 5.7). The eight different hydrostratigraphic units were further refined by adding extra layers to each unit. The final grid for the model consisted of 94 rows, 71 columns and 18 layers.

Boundary conditions, such as constant head, river, and no flow boundaries, were added after the surface and bottom elevations were imported into MODFLOW. Fig. 6.3 shows the location of the various boundary conditions. Constant head boundaries were added to the southwestern boundary of the model and are shown as yellow in Fig. 6.3. Constant head boundary data were retrieved from a GRD file produced with Surfer 7.0 (Fig. 5.9). River boundaries were added where the two streams exist in the Dysart
Woods watershed and are shown as blue in Fig. 6.3. River boundary data were retrieved from field data and the conductance variable was derived from the equation

\[ CRIV = K_r L W / M \] (3),

where \( K_r \) is the vertical hydraulic conductivity of the bottom sediments, \( L \) is the length of the stream in a cell, \( W \) is the width of the stream in a cell, \( M \) is the thickness of the bottom sediments in the stream and \( CRIV \) is the conductance of the streambed (Anderson and Woessner, 2002). The vertical hydraulic conductivity of the bottom sediments \( (K_r) \) was taken from Fetter (2001), the length \( (L) \) and width \( (W) \) of the streams and the thickness of the bottom sediments \( (M) \) were measured on site. No-flow boundary data were added based on the location of the watershed boundary.
Recharge boundary data were retrieved from Ground Water Associates (1991) and Anderson (2001) other literature reports. These data were added to the model based on the different soil types and their infiltration rates found in the watershed area. Soils along the ridge bisecting Dysart Woods into two subwatersheds are composed of Westmoreland-Upshur and Westmoreland soils, which have a greater infiltration rate than Lowell-Westmoreland and Lowell soils that are found on the slopes of the
subwatersheds (USDA, 2007). Because the soils along the ridge have a greater infiltration rate, a different recharge rate was given to these areas as compensation. The dark blue area in Fig. 6.4 corresponds to the ridge area composed of Westmoreland-Upshur and Westmoreland soils. The white area represents the other soils in the Dysart Woods watershed dominated by Lowell-Westmoreland and Lowell soils. The initial recharge rate given to the white area (R1) was 4.2 inches/year. The initial recharge rate given to the dark blue area (R2) was 5.9 inches/year. These recharge values were changed for calibration purposes until the appropriate calibrated heads were reproduced. Green and white squares represent head observation wells used for calibration purposes. The green area surrounding the watershed consists of inactive cells, which creates a no-flow boundary.
Fig. 6.4. Grid layout for MODFLOW model showing the two different areas for recharge. Green area represents inactive cells. Green and white squares within the model area are head observation wells.

The dark blue lines in Fig. 6.5 show the locations of the two streams in the Dysart Woods watershed. The streams were input as line features with the River Package in MODFLOW. Table 6.1 gives the values needed to assign the streams in MODFLOW. River elevations were measured in the field. The conductance of the streambed was calculated by Eq. 3 above. The sediments of the stream beds were silty sands with a vertical hydraulic conductivity range of 2.83 to 0.0283 ft/day ($10^{-3}$ to $10^{-5}$ cm/sec) (Fetter, 2001).
Fig. 6.5. Grid layout for MODFLOW model showing the two watershed streams (blue). Green area represents inactive cells. Green and white squares within the model area are head observation wells.

Table 6.1. Values used for River Package in MODFLOW.

<table>
<thead>
<tr>
<th>Stream</th>
<th>Stream Location</th>
<th>River Stage Elevation (ft)</th>
<th>River Bottom Elevation (ft)</th>
<th>Streambed Sediment Thickness (ft)</th>
<th>Conductance of the Streambed (ft/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left Stream</td>
<td>Beginning</td>
<td>1200</td>
<td>1200</td>
<td>3</td>
<td>190</td>
</tr>
<tr>
<td></td>
<td>End</td>
<td>1033</td>
<td>1032</td>
<td>4</td>
<td>201</td>
</tr>
<tr>
<td>Right Stream</td>
<td>Beginning</td>
<td>1200</td>
<td>1200</td>
<td>5</td>
<td>127</td>
</tr>
<tr>
<td></td>
<td>End</td>
<td>1092</td>
<td>1091</td>
<td>4</td>
<td>222</td>
</tr>
</tbody>
</table>

Fig. 6.6 shows the different hydraulic conductivity values for surface cells in map view. The values given for each hydrostratigraphic unit are prior to calibration and are taken from Table 5.1. The different hydraulic conductivity values follow the contours
because each value is assigned to a particular hydrostratigraphic unit. Fig. 6.7 shows
cross sections of the model, which show how the different values of hydraulic
conductivity correspond to each hydrostratigraphic unit. Fig. 6.7a shows the cross
section of the model at Well Nest 1 and is shown in Fig. 6.6 as a yellow line from A to
A’. Fig. 6.7b shows the cross section of the model at Well Nest 2 and is shown in Fig.
6.6 as a green line from B to B’. The vertical exaggeration of the model in Fig. 6.7 is
9.0X.

Fig. 6.6. Grid layout for MODFLOW model showing initial hydraulic conductivity
values prior to calibration. Green and white squares within the model area are head
observation wells.
Fig. 6.7. Cross sections of the model showing the hydraulic conductivity assigned to each hydrostratigraphic unit. Fig. 6.7a shows a cross section of the model area at Well Nest 1. Fig. 6.7b shows a cross section of the model area at Well Nest 2. Vertical teal boundaries represent inactive cells.
A steady state numerical simulation was carried out once all the necessary variables were input into MODFLOW. Variables (i.e., recharge rates, hydraulic conductivity values, storage values, etc.) were changed until the model converged. At that point, the model was calibrated based on recharge values for the two recharge areas and the hydraulic conductivity for each hydrostratigraphic unit. The steady state model was calibrated until the lowest RMS value based on calculated heads and observed heads was obtained. For steady state conditions, altering the specific storage and specific yield had no effect on the model. In addition, effective porosity and total porosity had no effect on the head elevations of the output. Also, manipulating the river conductance (calibrating for the vertical hydraulic conductivity of the bottom sediments of the streambeds) did not affect the head elevations of the output in MODFLOW; therefore, the river conductance was not calibrated in the model and initial values were used. The final calibrated model was achieved with an RMS value of 2.7 ft. Fig. 6.8 shows the calculated heads versus the observed heads graph for the steady state simulation given by MODFLOW and the corresponding RMS value used for calibration purposes.
Table 6.2 gives the calibrated hydraulic conductivity values for each hydrostratigraphic unit. Table 6.3 gives the calibrated recharge values for each recharge area. It should be noted that 2.7 ft (0.8m) is still a relatively large error. However, due to the geometric complexity of this model and the fact that we probably have perched water tables instead of a continuous saturated zone in the upper layers, this error is considered acceptable. In addition, the change in heads observed after mine exploitation is one order of magnitude higher at around 12 ft.
Table 6.2. Calibrated hydraulic conductivity values for the steady state model.

<table>
<thead>
<tr>
<th>Hydrostratigraphic Unit</th>
<th>Color</th>
<th>Corresponding K Value (ft/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Kx</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>5.00E-5</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>5.00E-5</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>3.00E-4</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>1.00E-4</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>1.00E-4</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>1.18E-5</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>1.00E-7</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>5.00E-7</td>
</tr>
</tbody>
</table>

Table 6.3. Calibrated recharge values for the steady state model.

<table>
<thead>
<tr>
<th>Property</th>
<th>Color</th>
<th>Recharge (inches/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td></td>
<td>1.25</td>
</tr>
<tr>
<td>R2</td>
<td></td>
<td>4.72</td>
</tr>
</tbody>
</table>

Figs. 6.9 and 6.10 show the output of the calibrated steady state model. Fig. 6.9 shows the flow regime for the shallowest aquifer (hydrostratigraphic units 1-3). The equipotential lines of the shallowest aquifer are shown in blue and have a contour interval of 10 ft. The portion of the model area shown in white represents the saturated area. The
portion of the model shown in olive represents dry cells in the model area (areas of unsaturated zone). Fig. 6.10 shows the flow regime for the bottom hydrostratigraphic unit (unit 8). As seen in Figs. 6.9 and 6.10, the flow paths follow the same pattern as shown in the water table maps created in section 5.4 of this report. Groundwater flows longitudinally (according to the model coordinates) to the streams and towards the bottom of the model (in map view).

Fig. 6.9. Water table elevation of the shallowest aquifer. Equipotentials are shown in blue with a contour interval of 10 ft. Model coordinates are given in ft. Green area represents inactive cells. Olive areas represent dry cells. Green and white squares within the model area are head observation wells.
MODFLOW OUTPUT SHOWING THE FLOW REGIME OF THE DEEPEST MODELED AQUIFER UNDER STEADY STATE CONDITIONS ON 9/20/2004

Fig. 6.10. Water table elevation of the deepest modeled aquifer. Equipotentials are shown in blue with a contour interval of 10 ft. Model coordinates are given in ft. Green area represents inactive cells. Green and white squares within the model area are head observation wells.

Figs. 6.11 and 6.12 show the cross section views of the calibrated model at Well Nest 1 and Well Nest 2, respectively. The equipotentials in Figs. 6.11 and 6.12 are near vertical, which reveals that the dominant direction of groundwater flow is horizontal as
opposed to vertical. Cross sections shown are along the same lines for each well nest shown in Fig. 6.6. Vertical exaggeration in Figs. 6.11 and 6.12 is 9X.

Fig. 6.11. Cross section from A to A’ showing the flow regime of the calibrated steady state model along Well Nest 1. Equipotentials are shown in 2 ft intervals. Vertical teal boundaries represent inactive cells. Olive areas represent dry cells.
A sensitivity analysis was carried out on the calibrated model to determine how sensitive the model is when a certain variable is altered while all other variables remain constant (Anderson and Woessner, 2002). A sensitivity analysis was performed for both recharge properties (R1 and R2) and the top three hydrostratigraphic units (1, 2 and 3). The head elevation output of each model run was exported into a text file and then imported into Microsoft Access. The result was a table comprised of 120,132 rows of data separated into five columns: an identifier assigned by Access, the x-coordinate of the calculated head elevation, the y-coordinate of the calculated head elevation, the z-coordinate of the calculated head elevation and the elevation of the water table at the given coordinates. Once all tables for a given variable (i.e., R1) were imported into
Access, a query was ran relating each manipulated run to the calibrated run based on the unique identifier assigned by Access. Once the tables were related, the maximum absolute value of the difference between the calculated heads of the calibrated run and the calculated heads of the manipulated run was extracted and recorded. The maximum absolute value of the difference was then plotted on the y-axis with the value of the tested variable plotted on the x-axis for a graphical representation of the sensitivity of that variable.

Both recharge properties (R1 and R2) were altered in equal increments adding to and subtracting from the calibrated value. Fig. 6.13 shows the sensitivity analysis performed for the R1 recharge variable where $H_{\text{CAL}} - H_{\text{N}}$ was the difference between the calculated calibrated heads ($H_{\text{CAL}}$) and calculated manipulated heads ($H_{\text{N}}$) in units of ft. Since recharge cannot be less than 0 inches/year, the decrease in recharge from the calibrated value was terminated at 0 inches/year. At zero recharge the water was coming from the constant head boundary region instead of the surface. The R1 recharge variable was more sensitive to a decrease in recharge than an increase as determined by the slope of the lines from the calibrated value of 1.25 inches/year. Fig. 6.14 shows the sensitivity analysis performed for the R2 recharge variable. The R2 recharge variable was highly sensitive to an initial change in recharge, and then slightly more sensitive to a decrease in recharge from the calibrated value of 4.72 inches/year.
Recharge Sensitivity Analysis for R1 Variable

![Graph showing sensitivity analysis for R1 recharge variable. The calibrated value was 1.25 inches/year. Y-axis units are in feet.](image1)

Fig. 6.13. Sensitivity analysis for R1 recharge variable. Calibrated value was 1.25 inches/year. Y-axis units are in feet.

Recharge Sensitivity Analysis for R2 Variable

![Graph showing sensitivity analysis for R2 recharge variable. The calibrated value was 4.72 inches/year. Y-axis units are in feet.](image2)

Fig. 6.14. Sensitivity analysis for R2 recharge variable. Calibrated value was 4.72 inches/year. Y-axis units are in feet.
Hydraulic conductivity values were also altered in equal increments adding to and subtracting from the calibrated value. The anisotropy within hydrostratigraphic units was minimal; therefore, the change in hydraulic conductivity values for the graphical representation of the sensitivity analyses were given for the hydraulic conductivity in the horizontal plane. Similarly to the sensitivity analysis performed for the recharge properties (Figs. 6.12 and 6.13) $H_{\text{CAL}} - H_N$ was the difference between the calculated calibrated heads ($H_{\text{CAL}}$) and calculated manipulated heads ($H_N$) in units of ft. The change in hydraulic conductivity from the calibrated value was plotted on a logarithmic scale on the x-axis. Fig. 6.15 shows the sensitivity analysis performed for the hydraulic conductivity of hydrostratigraphic unit 1. Hydrostratigraphic unit 1 was very sensitive to an initial decrease in hydraulic conductivity. An initial increase in the hydraulic conductivity had a lower effect, but became greater with the increase of hydraulic conductivity. The calibrated values for hydrostratigraphic unit 1 were 5.00E-5 for $K_x$, 5.00E-5 for $K_y$ and 3.99E-5 for $K_z$ (units are in ft/sec). Fig. 6.16 shows the sensitivity analysis performed for the hydraulic conductivity of hydrostratigraphic unit 2. Hydrostratigraphic unit 2 was similar to unit 1 in the sense that it was highly sensitive to an initial decrease in hydraulic conductivity, and then became less sensitive. The behavior for an increase in hydraulic conductivity also followed the same pattern as found in unit 1, but to a slightly greater magnitude. Unit 2 was also very sensitive to a high increase in hydraulic conductivity ($10^{-2}$ to $10^{-1}$ ft/sec). Fig. 6.17 shows the sensitivity analysis performed for the hydraulic conductivity of hydrostratigraphic unit 3. Hydrostratigraphic unit 3 was highly sensitive to an initial increase in hydraulic conductivity.
conductivity. After this sharp increase, it became less sensitive, then increasingly more sensitive as the hydraulic conductivity increased. A decrease in hydraulic conductivity had a lower effect on unit 3 than an increase in hydraulic conductivity. Our model is very sensitive to variations in hydraulic conductivity. The highest values of $|H_{\text{CAL}} - H_{\text{N}}|_{\text{max}}$ occurred at moderate decreases of $K$ for units 1 and 2 and a moderate increase for unit 3. Extremely high values of $K$ ($10^{-2}$ to $10^{-1}$ ft/sec) also produced high values of $|H_{\text{MAX}} - H_{\text{N}}|_{\text{max}}$.

Fig. 6.15. Sensitivity analysis for the hydraulic conductivity of hydrostratigraphic unit 1. Calibrated value was 5.00E-5 for $K_x$, 5.00E-5 for $K_y$ and 3.99E-5 for $K_z$ (units in ft/sec). Y-axis units are in feet.
Fig. 6.16. Sensitivity analysis for the hydraulic conductivity of hydrostratigraphic unit 2. Calibrated value was 5.00E-5 for Kx, 5.00E-5 for Ky and 4.00E-5 for Kz (units in ft/sec). Y-axis units are in feet.

Fig. 6.17. Sensitivity analysis for the hydraulic conductivity of hydrostratigraphic unit 3. Calibrated value was 3.00E-4 for Kx, 3.00E-4 for Ky and 2.00E-4 for Kz (units in ft/sec). Y-axis units are in feet.
6.2. Transient Model

A transient simulation was carried out on the calibrated model to determine the evolution of the water table with time. All variables remained the same as in the calibrated steady state model. Values for specific yield, effective porosity and total porosity were taken from Table 5.1. Hydraulic conductivity values were taken from Table 6.2. Recharge values were taken from Table 6.3. Values for specific storage were increased by one order of magnitude because of the effect of longwall mining on storativity (Booth et al., 1998). Drains were added to the bottom layer (hydrostratigraphic unit 8) to simulate dewatering of the overlying aquifers. Drains were placed along the center of each panel to simulate the leakage induced by underground mining because the exact location of fracturing cannot be determined. As the longwall panels were not excavated all at the same time, the drains were activated at different times simulating the progression of mining in the area. The transient simulation was modeled for 1225 days beginning on 12/1/2004 and ending on 4/8/2008. Fig. 6.18 shows the placement of the drains in the bottom layer of the model (hydrostratigraphic unit 8) and the various times the drains were activated to simulate underground mining. The vertical separation between the drains in hydrostratigraphic unit 8 and the Pittsburgh No. 8 coal seam is approximately 250 ft.
The transient model was calibrated based on the conductance ($\text{ft}^2/\text{day}$) of the drains. The conductance of the drains was calculated using the same equation used to calculate the conductance for the streams in the model area (Eq. 3 from Anderson, 2002) and applied to each drain, which would simulate leakage when the drain was activated (Fig. 6.18). The calibrated value for conductance of the drains was 14.00 $\text{ft}^2/\text{day}$, which gave an RMS value of 0.643 ft on the final day of the simulation (day 1225; 4/8/2008). Fig. 6.19 shows the calculated heads versus the observed heads graph for the transient simulation that ended on 4/8/2008 given by MODFLOW and the corresponding RMS
value used for calibration purposes. GMW-04-7 was incorporated on the time step beginning on the 304\textsuperscript{th} day of the simulation in Well Nest 1 because GMW-04-6 went dry as a result of longwall mining. GMW-04-4 was used as the head observation well for Well Nest 2. Data for the other wells in Well Nest 2 were not used because of instrumental error.

![Graph showing the calculated heads versus the observed heads for the transient simulation that ended on 4/8/2008.](image)

The transient simulation was divided into 21 different time steps. Head elevations were input into the head observation wells at the end of each time step to compare the observed and calculated heads for calibration of the transient model. After the model was run, the observed and calculated heads were recorded and plotted to represent the evolution of the water table with time. Fig. 6.20 shows the evolution of the water table as
observed from wells GMW-04-6 and GMW-04-7 of Well Nest 1. GMW-04-6 could not be simulated past the 4th time step because GMW-04-6 began to dry up as a result of underground mining. Fig. 6.21 shows the evolution of the water table as observed from GMW-04-4 of Well Nest 2. Decreasing variations of the observed heads can be seen in each Figure (Fig. 6.20 and 6.21) while the calculated heads show the overall decrease of the water table with time in each monitoring well. Well Nest 1 is outside of the buffer zone proposed by OVCC. Well Nest 2 is inside the buffer zone proposed by OVCC and is positioned above the room-and-pillar zone passing underneath the designated old growth forests. On average, the observed and the calculated heads show good agreement indicating a decrease in water table elevation as a consequence of the coal mining in the area. Note the seasonal variations in heads (sinusoidal curves in Figs. 6.20 and 6.21) in the measured data. The seasonal variations cannot be modeled because we assumed a constant rate of recharge for the duration of the model.
Fig. 6.20. Observed vs. calculated heads of Well Nest 1 for transient simulation.

Fig. 6.21. Observed vs. calculated heads of Well Nest 2 for transient simulation.
Figs. 6.22 and 6.23 show the output of the calibrated transient model. Results shown are from the final day of the transient simulation (4/8/2008). Fig. 6.22 shows the groundwater flow regime for the shallowest aquifer. Fig. 6.23 shows the groundwater flow regime for the bottom layer of the model (hydrostratigraphic unit 8). The influence of the drains can be seen in both figures, but more so in Fig. 6.23 that shows the bottom layer of the model where the drains are located.

**MODFLOW OUTPUT SHOWING THE FLOW REGIME OF THE SHALLOWEST AQUIFER UNDER TRANSIENT CONDITIONS ON 4/8/2008**

Fig. 6.22. Water table elevation of the shallowest aquifer under transient conditions. Equipotentials are shown in blue with a contour interval of 10 ft. Model coordinates are given in ft. Green area represents inactive cells. Olive areas represent dry cells. Green and white squares within the model area are head observation wells.
MODFLOW OUTPUT SHOWING THE FLOW REGIME OF THE DEEPEST MODELED AQUIFER UNDER TRANSIENT CONDITIONS ON 4/8/2008

Fig. 6.23. Water table elevation of the shallowest aquifer under transient conditions. Equipotentials are shown in blue with a contour interval of 10 ft. Model coordinates are given in ft. Green area represents inactive cells. Green and white squares within the model area are head observation wells.

Figs. 6.24 and 6.25 show the cross section views of the calibrated transient model at Well Nest 1 and Well Nest 2, respectively. The equipotential lines in Figs. 6.24 and
6.25 are also near vertical, similarly to the cross sections shown for the steady state simulation, which shows that the groundwater flow is still more horizontal than vertical. However, the influence of the drains as shown by the equipotential lines indicates downward flow. Cross sections shown are along the same lines for each well nest shown in Fig. 6.6.

Fig. 6.24. Cross section showing the flow regime of the calibrated transient model along Well Nest 1. Equipotentials are shown in 2 ft intervals. Vertical teal areas represent inactive cells. Olive areas represent dry cells.
A sensitivity analysis was carried out on the calibrated transient model to determine how sensitive the model was to a change in the conductance of the drains while all other variables remained constant. The method of performing the sensitivity analysis on the transient simulation was similar to the method used to create sensitivity analyses for the steady state model. Fig. 6.26 shows the sensitivity analysis for the conductance of the transient model. As seen in Fig. 6.26, the model was more sensitive to a decrease in conductance of the drains. Nonetheless, a noticeable difference between the observed and calculated heads can be seen with an increase in conductance. The calibrated value for conductance was 14.00 ft$^2$/day. The observed heads are for 4/8/2008 (day 1225 of the transient simulation).
Fig. 6.26. Sensitivity analysis for conductance. Calibrated value was 14.00 ft²/day. Observed heads are for 4/8/2008.

The transient model was simulated for 10 years beginning on the initial transient simulation date of 12/1/2004 and running until 12/1/2014 to model the future evolution of the shallowest aquifer. Fig. 6.27 shows the result of the transient simulation on 12/1/2014. The shallowest aquifer of the model dried up as a result of the leakage created by the drains. The saturated areas of Fig. 6.27 are areas of saturation in the stream valleys. Fig. 6.28 shows the groundwater regime for the bottom layer of the model (hydrostratigraphic unit 8). This figure shows that the effect of the drains is still influencing the dewatering of the overlying aquifers 10 years later if the fracture-flow system does not recover.
Fig. 6.27. Shallowest aquifer of the transient model after being run for 10 years. Model coordinates are given in ft. Green area represents inactive cells. Olive areas represent dry cells. Green and white squares within the model area are head observation wells.
MODFLOW OUTPUT SHOWING THE FLOW REGIME OF THE DEEPEST MODELED AQUIFER AFTER 10 YEARS ON 12/1/2014

Fig. 6.28. Deepest modeled aquifer of the transient model after being run for 10 years. Model coordinates are given in ft. Green area represents inactive cells. Green and white squares within the model area are head observation wells.

Figs. 6.29 and 6.30 show the results of the cross sections of Well Nest 1 and Well Nest 2 after the model was run for 10 years. The drop in the water table elevation was very evident in both cross sections. Both wells at each cross section dried up as a result
of the drains. At Well Nest 1 (Fig. 6.29) the only partially saturated layer was
hydrostratigraphic unit 8. At Well Nest 2 (Fig. 6.30), hydrostratigraphic unit 8 was still
only partially saturated and a small portion of hydrostratigraphic unit 7 was saturated.
Hydrostratigraphic units 1—6 dewatered as a result of leakage induced by the drains.

![CROSS SECTION OF TRANSIENT FLOW REGIME AT WELL NEST 1 ON 12/1/2014](image)

Fig. 6.29. Well Nest 1 cross section after a 10 year transient simulation. Equipotentials
are shown in 2 ft intervals. Vertical teal areas represent inactive cells. Olive areas
represent dry cells.
Fig. 6.30. Well Nest 2 cross section after a 10 year transient simulation. Equipotentials are shown in 2 ft intervals. Vertical teal areas represent inactive cells. Olive areas represent dry cells.

6.3. Summary

Prior to numerical modeling using MODFLOW, the model area had to be rotated -24° to allow proper orientation of the model. Following rotation of the model, the surface, bottom and stratigraphic layers were imported into MODFLOW from Surfer. Boundary conditions and properties were added to the steady state model and altered until the steady state model began to converge. When the model began to converge, it was calibrated to determine the best value for each variable. The recharge and hydraulic conductivity variables had the greatest effect while changing other variables, such as storage, porosity, conductance of the stream sediments, etc., had little if no apparent affect on the output of the model. Therefore, a sensitivity analysis was performed on
recharge and hydraulic conductivity. The steady state model was more sensitive to a
decrease in both recharge properties and a moderate decrease or increase in hydraulic
conductivity for the top three hydrostratigraphic units. Tables 6.2 and 6.3 give the
calibrated values for the steady state model. The output of the heads for the calibrated
model were extracted to be used as initial heads for the transient simulation.

The transient simulation began on 12/1/2004 and ended on 4/8/2008. This time
period was divided into 21 time steps. Observed head elevations were input into the head
observation wells at the end of each time step to see the evolution of the water table.
Drains were assigned to the bottom layer of the model to simulate leakance as a result to
the underground mining and activated at different times in accordance to the progression
of the mining. Initial heads were imported from the previous calibrated steady state
model. The transient simulation was calibrated by the conductance (ft²/day) of the
drains. The calibrated value for the conductance of the drains was 14.00 ft²/day. The
observed and calculated head elevations were extracted for each time step and plotted to
determine the evolution of the water table with time (Figs. 6.20 and 6.21). Variations
were evident in both monitoring wells. Seasonal variations were observed in the
measured well heads but were not modeled in this work. However, the decreasing of
average heads with time is evident. A noticeable decline in the water table (that
coincides with the observed values) with time exists as shown by the calculated water
table plots in Figs. 6.20 and 6.21. The transient model showed that the drains have a very
significant effect on the hydrostratigraphic units within the model. The dominant
groundwater flow direction in both the steady state and transient simulations was
horizontal. However, once the drains were activated, a downward flow gradient
developed, which resulted in a decline of the shallowest aquifer. A sensitivity analysis
was performed on the conductance of the transient simulation. The sensitivity analysis
showed that the transient model was more sensitive to a decrease in conductance. The
transient simulation was then run for a total of 10 years from the initial start date
(12/1/2004) into the future (terminating on 12/1/2014) to predict the evolution of the
water table. Output of the final day of the simulation (12/1/2014) showed that
hydrostratigraphic units 1-7 dried up underneath Well Nest 1 and hydrostratigraphic units
1-6 dried up underneath Well Nest 2.
CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

Dysart Woods, a National Natural Landmark (National Park Service, 2004), is an
old growth forest located in eastern Ohio. This area of Ohio has an intensive history of
coal mining. Currently, OVCC is mining the Pittsburgh No. 8 coal seam underneath the
old growth portions of Dysart Woods via room-and-pillar mining methods and
underneath the watershed of Dysart Woods via longwall mining Methods with Permit #
D-0360-12 (12th revision of Permit # D-360) issued by the Division of Mining Resources
Management of the Ohio Department of Natural Resources (DMRM, 2003). The original
mining permit called for longwall mining to occur throughout the entire permit area;
however, due to concerns of environmental groups and Ohio University, the original
permit was altered to incorporate a buffer zone around the delineated old-growth forest
sections from the influence of underground mining. Even though buffer zones are used
to preserve features, in instances where an aquifer is drained or the storage is reduced,
groundwater reserves up- or down-dip can be affected (Zipper et al., 1997). Therefore,
buffer zones to preserve groundwater sustaining natural ecosystems should be based on
watershed boundaries and groundwater divides.

To address this issue, a physical model of the Dysart Woods watershed was
created to determine the necessary variables to input into Visual MODFLOW for the
creation of a steady state numerical model. The steady state numerical model was
calibrated based on recharge and hydraulic conductivity variables to determine the best
values for recharge and hydraulic conductivity. Altering other variables, such as storage,
porosity, and riverbed conductance, had little to no effect on the numerical model. A
sensitivity analysis performed on the steady state model revealed that the model was more sensitive to a decrease in recharge and an increase in hydraulic conductivity.

Transient simulations were then performed on the model area to determine the evolution of the water table from pre-mining steady state conditions on 12/1/2004 to post-mining conditions on 4/8/2008. Underground mining for the transient simulation was simulated in MODFLOW by assigning drains to the bottom layer of the model (hydrostratigraphic unit 8). The transient simulation time period was divided into 21 time steps to compare the observed elevation of the water table with the calculated elevation of the water table. Plots of the observed head elevations with the calculated head elevations showed a gradual decline in the water table as the transient simulation progressed to the post-mining date of 4/8/2008. One of the plots was of Well Nest 1, which is directly above a mined longwall panel where a decline of the water table was expected. However, this well nest is located within the Dysart Woods watershed. The other plot that compared observed and calculated head elevations was above the room-and-pillar zone within the proposed buffer zone determined by OVCC. Water table elevations of the well nest within the current buffer zone experienced a decline in both observed and calculated head elevations. Model outputs of the transient simulation showed that the drains have a very significant effect on the hydrostratigraphic units within the model. The transient simulation was modeled into the future for a length of 10 years from the initial start date of 12/1/2004 and terminating on 12/1/2014. Hydrostratigraphic units 1 through 7 of the model became totally dewatered underneath Well Nest 1. Hydrostratigraphic units 1
through 6 became totally dewatered underneath Well Nest 2. This large decline in the water table was the result of the drains in hydrostratigraphic unit 8.

As previously stated, in instances where an aquifer is drained or the storage is reduced, groundwater reserves up- or down-dip can be affected (Zipper et al., 1997). With the observed water table decline in Well Nest 2, it is demonstrated that underground mining beyond the current limits of the buffer zone proposed by OVCC has partially dewatered the shallowest aquifer of Dysart Woods. Furthermore, if the perched aquifers (hydrostratigraphic units 1 through 8) do not recover, the top 6 hydrostratigraphic units may become dewatered with time. Due to the fact that watershed divides often mimic groundwater divides (Ground Water Associates, 1991) and precipitation is the only source of recharge (Anderson, 2001), the total area of the watershed should be protected instead of the area of the 300 ft buffer zone proposed by OVCC.

Future recommendations for the Dysart Woods area would be to continue monitoring the groundwater monitoring wells within and around Dysart Woods to determine whether or not the perched aquifers recover with time. In-Situ, the manufacturer of the data loggers in the monitoring wells no longer services the devices and new data loggers are needed to properly record necessary data. The existing weather station at Dysart Woods needs to be reactivated to determine meteorological data necessary to construct monthly water budgets to create numerical models that incorporate the seasonal variations of the water table as opposed to the yearly average precipitation and yearly average recharge rates. This would give better values for error when performing transient simulations. Groundwater discharge rates via springs need to be
collected to determine the amount of groundwater discharging at each spring within the watershed and to have discharge rates to compare with future discharge rates.

Continued monitoring of the aquifers in Dysart Woods is needed to determine the effect of underground mining on aquifers and aquifer properties when protected by buffer zones not defined by groundwater divides. New considerations for underground mining regulations are needed when preserving groundwater systems that support ecosystems. This applies to all types of mining and is not limited to coal mining. Current mining laws are not sufficient to maintain groundwater systems. Studies focusing on buffer zones encompassing entire watersheds are needed when preserving ecosystems.
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