ASSESSMENT OF POTENTIAL IMPACTS TO SUBSURFACE BODIES OF WATER DUE TO UNDERGROUND COAL MINING

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ASSESSMENT OF POTENTIAL IMPACTS TO SUBSURFACE BODIES OF WATER DUE TO UNDERGROUND COAL MINING

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mining Engineering in the College of Engineering at the University of Kentucky

By

Gabriel Bode-Jimenez

Lexington, Kentucky

Director: Prof. Zacharias Agioutantis, Mining Engineering Foundation Professor

Lexington, Kentucky

2017

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ABSTRACT OF THESIS

ASSESSMENT OF POTENTIAL IMPACTS TO SUBSURFACE BODIES OF WATER DUE TO UNDERGROUND COAL MINING

Underground coal mining operations induce ground movements, which may impact overlying hydrogeologic systems. Potential impacts mainly include changes in the hydraulic conductivity of overlying strata, decreasing of the hydraulic head and changes in water flow. The present research quantifies potential hydrogeologic impacts caused by underground mining through modeling of pre- and post-mining hydrogeologic systems.

Three-dimensional conceptual hydrogeologic models were constructed with the Processing Modflow for Windows software package (PMWiN). The models are based on an actual case study, but were simplified in terms of geometry and material properties. Water flow was simulated under changing hydrogeologic properties. A number of scenarios were investigated including models with horizontal or inclined topography, featuring an aquifer overlying two longwall panels. The hydrogeologic properties of the models were estimated based on empirical relationships between the post-mining hydraulic conductivity and strain in the overburden. The strain regime in the overburden was estimated using the Surface Deformation Prediction System (SDPS) package, which allows calculation of surface deformations due to underground coal mining.

The research focuses on changes in hydraulic heads; results indicate that hydraulic heads may decrease over undermined areas and may rebound as mining ceases. Water infiltration may occur from higher located overburden formations to lower formations due to mining induced changes in hydrogeologic properties.

KEYWORDS:

Subsidence, Groundwater, Hydrogeologic properties, Water flow modeling, Underground mining

Gabriel Bode-Jimenez
Lexington, Kentucky, July 2017
ASSESSMENT OF POTENTIAL IMPACTS TO SUBSURFACE BODIES OF WATER DUE TO UNDERGROUND COAL MINING

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__Gabriel Bode-Jimenez__
Gabriel Bode-Jimenez
Lexington, Kentucky, July 2017
# TABLE OF CONTENTS

ACKNOWLEDGEMENT ............................................................................................................ iii

TABLE OF CONTENTS ............................................................................................................ iv

LIST OF FIGURES ................................................................................................................ vii

LIST OF TABLES ..................................................................................................................... ix

1. **Introduction** ...................................................................................................................... 1

   1.1. Problem Definition ........................................................................................................... 1

   1.2. Research Objectives ......................................................................................................... 2

   1.3. Thesis Outline ..................................................................................................................... 2

2. **Subsidence over Underground Mining** ........................................................................... 4

   2.1. Introduction ......................................................................................................................... 4

   2.2. Continuous and Discontinuous Subsidence ..................................................................... 4

   2.3. Movements .......................................................................................................................... 5

      2.3.1. Subsidence .................................................................................................................... 7

      2.3.2. Horizontal Displacements ........................................................................................... 7

      2.3.3. Horizontal and Ground Strain ..................................................................................... 7

   2.4. Factors Affecting Subsidence due to Underground Mining ........................................... 8

      2.4.1. Properties of the Overburden Strata ........................................................................... 9

      2.4.2. Mining Depth and Height ........................................................................................... 9

      2.4.3. Topography ................................................................................................................... 9

3. **Principles of Groundwater Hydrology** ......................................................................... 11

   3.1. Introduction ........................................................................................................................ 11

   3.2. Potentiometric Surfaces at Confined and Unconfined Aquifers ...................................... 11

   3.3. Total Hydraulic Head ........................................................................................................ 12

   3.4. Groundwater Movement explained through Darcy’s Law ............................................. 13

   3.5. Hydraulic Conductivity ..................................................................................................... 14

   3.6. Storativity of Confined and Unconfined Aquifers ............................................................. 16

4. **Mining under Bodies of Water** ..................................................................................... 18

   4.1. Introduction ........................................................................................................................ 18

   4.2. Observed Impact of Ground Movements on Groundwater ........................................... 19

   4.3. Conceptual Hydrogeologic Changes within the Overburden due to Ground Deformation .................................................................................................................. 20

   4.4. Pre- and Post-mining Hydraulic Conductivity Values for Coal Measure Formations ........ 22

   4.5. Ground Deformation Induced Water Infiltration into Mine Workings ............................ 28

   4.6. Mining Impact Mitigation Measures .................................................................................. 28
5. Subsidence Prediction ................................. 29  
   5.1. Introduction ........................................ 29  
   5.2. Subsidence Deformation Prediction System .......... 30  
   5.3. Workflow within SDPS ................................ 31  
   5.4. Relevant SDPS Inputs and Outputs .................. 33  
6. Modeling Groundwater Flow ............................... 34  
   6.1. Introduction ........................................ 34  
   6.2. Relevant PMWiN Inputs and Outputs ............... 34  
7. Methodology for Determining Impacts to the Hydrogeologic System with respect to Underground Mining Operations ................. 34  
   7.1. Methodology Background .............................. 38  
   7.2. Determining the Mining Induced Subsidence and Strain Regime .... 39  
   7.3. Calculating Post-mining Hydraulic Conductivity ........ 40  
   7.4. Modeling the Hydrogeologic System and Comparing the Hydrogeologic Pre- and Post-mining States .................. 44  
8. Case Study: Evaluating Mining Induced Impacts on the Ground Water System ....................................... 45  
   8.1. Introduction ........................................ 45  
   8.2. Site Description ..................................... 45  
   8.2.1. Site-Specific Hydrogeologic Parameters ........... 47  
   8.3. Determining the Strain Regime over a High Extraction Area ....... 48  
   8.4. Calculating Post-mining Hydraulic Conductivity .......... 50  
   8.5. Simulating Changes in a Hydrogeologic System .......... 53  
   8.6. Description of Models and Model Input Parameters at Pre-mining State ........................................ 55  
   8.7. Model Input Parameters at the Post-mining State ........ 60  
   8.8. Impact of Horizontal and Inclined Topography ........ 63  
   8.8.1. Validating Pre-mining Models for Horizontal Topography ....... 63  
   8.8.2. Comparing Pre-mining and Post-mining Hydraulic Heads for Horizontal Topography .......................... 65  
   8.8.3. Validating Pre-mining Models for Inclined Topography ........ 68  
   8.8.4. Comparing Pre-mining and Post-mining Hydraulic Heads for Inclined Topography .......................... 71  
9. Conclusions and Recommendations .......................... 74  
   9.1. Summary ........................................... 74  
   9.2. Strength and Weaknesses of the Proposed Approach ....... 75  
   9.3. Future Work ........................................ 75
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Development of deformation zones due to full extraction underground mining</td>
<td>5</td>
</tr>
<tr>
<td>2-2</td>
<td>Transverse subsidence trough and subsidence parameters</td>
<td>6</td>
</tr>
<tr>
<td>2-3</td>
<td>Distribution of horizontal strains at and below the surface over an</td>
<td>8</td>
</tr>
<tr>
<td>3-1</td>
<td>Schematic cross section illustrating unconfined and confined aquifers</td>
<td>13</td>
</tr>
<tr>
<td>3-2</td>
<td>Ranges of hydraulic conductivity of selected rocks</td>
<td>15</td>
</tr>
<tr>
<td>4-1</td>
<td>Water infiltration due to mining induced conceptual changes in</td>
<td>21</td>
</tr>
<tr>
<td>4-2</td>
<td>Conceptual hydrogeologic changes within the overburden due to mine-</td>
<td>23</td>
</tr>
<tr>
<td>5-1</td>
<td>Workflow diagram for SDPS</td>
<td>32</td>
</tr>
<tr>
<td>7-1</td>
<td>Methodology flow chart for determining the impact on the hydrogeologic</td>
<td>39</td>
</tr>
<tr>
<td>7-2</td>
<td>Quantification of potential hydrogeologic impacts through comparison of</td>
<td>39</td>
</tr>
<tr>
<td>7-3</td>
<td>Vertical post-mining and horizontal strain relationship according to</td>
<td>42</td>
</tr>
<tr>
<td>7-4</td>
<td>Variation in post- ($K_y$) and pre-mining ($K_{yo}$) HC ratios with respect to the modulus reduction factor and spacing</td>
<td>42</td>
</tr>
<tr>
<td>7-5</td>
<td>Variation in Post- ($K_y$) and Pre-mining ($K_{yo}$) HC ratios with respect to the fracture aperture and spacing</td>
<td>43</td>
</tr>
<tr>
<td>7-6</td>
<td>Variation in Post- ($K_y$) and Pre-mining ($K_{yo}$) HC ratios with respect to the fracture aperture and the modulus reduction factor</td>
<td>43</td>
</tr>
<tr>
<td>8-1</td>
<td>Layout of the study area</td>
<td>46</td>
</tr>
<tr>
<td>8-2</td>
<td>Panel locations with respect to surface topography</td>
<td>47</td>
</tr>
<tr>
<td>8-3</td>
<td>Development of two 3D conceptual mining scenarios within PMWiN</td>
<td>54</td>
</tr>
<tr>
<td>8-4</td>
<td>Mining under horizontal topography (Model 1a)</td>
<td>55</td>
</tr>
<tr>
<td>8-5</td>
<td>Mining under inclined topography (Model 1b)</td>
<td>56</td>
</tr>
<tr>
<td>8-6</td>
<td>Mining under horizontal topography (Model 2a)</td>
<td>60</td>
</tr>
<tr>
<td>8-7</td>
<td>Mining under horizontal topography (Model 3a)</td>
<td>60</td>
</tr>
<tr>
<td>8-8</td>
<td>Mining under horizontal topography (Model 3b)</td>
<td>61</td>
</tr>
</tbody>
</table>
Figure 8-9: Mining under inclined topography (Model 3b) .............................................. 61
Figure 8-10: Comparing Models 1 and 2 at aquifer (CDZ) under stabilized pre-mining flow conditions ........................................................................................................... 64
Figure 8-11: Comparing Models 1 and 2 at CDZ under stabilized pre-mining flow conditions ........................................................................................................... 64
Figure 8-12: Comparing Models 1 and 2 at caving and fracture zone under stabilized pre-mining flow conditions ........................................................................................................... 65
Figure 8-13: Post-mining hydraulic head at aquifer (CDZ) .............................................. 66
Figure 8-14: Post-mining hydraulic head at CDZ ................................................................. 66
Figure 8-15: Post-mining hydraulic head at caving and fracture zone ........................... 67
Figure 8-16: Mining effects under horizontal topography ................................................. 68
Figure 8-17: Comparing Models 1 and 2 at aquifer (CDZ) under stabilized pre-mining flow conditions ........................................................................................................... 69
Figure 8-18: Comparing Models 1 and 2 at CDZ under stabilized pre-mining flow conditions ........................................................................................................... 70
Figure 8-19: Comparing Models 1 and 2 at caving and fracture zone under stabilized pre-mining flow conditions ........................................................................................................... 70
Figure 8-20: Post-mining hydraulic head at aquifer (CDZ) .............................................. 71
Figure 8-21: Post-mining hydraulic head at CDZ ................................................................. 72
Figure 8-22: Post-mining hydraulic head at caving and fracture zone ........................... 72
Figure 8-23: Mining effects under inclined topography ................................................. 73
LIST OF TABLES

Table 4-1: Hydraulic conductivity values in units of m/d (adapted from Newman, et al., 2016) ................................................................. 25
Table 4-2: Hydraulic conductivity values in units of m/d - II (adapted from Newman, et al., 2016) ................................................................. 27
Table 8-1: Input parameters for SDPS models .......................................................... 49
Table 8-2: SDPS results for horizontal strain ($\Delta \varepsilon_x$) ......................................................... 50
Table 8-3: Pre- ($K_{yo}$) and post-mining ($K_y$) hydraulic conductivity and other overburden parameters .......................................................... 52
Table 8-4: Cell dimensions for horizontal and inclined topography scenario ............... 56
Table 8-5: Dimensions of layers for horizontal topography scenario ....................... 57
Table 8-6: Dimensions of layers for inclined topography scenario ......................... 57
Table 8-7: Pre-mining hydrogeologic overburden characteristics and GHB and drain parameters for horizontal and inclined topography scenarios .......... 59
Table 8-8: Pre- and post-mining hydrogeologic overburden characteristics and post-mining GHB and drain parameters for horizontal and inclined topography scenarios ............................................................... 62
1. Introduction

1.1. Problem Definition

It is important that the mining industry be proactive in the design of surface and underground mining operations with respect to potential stream and groundwater impacts. A design methodology should be developed that accurately predicts potential impacts by underground mining operations to surface and subsurface bodies of water.

Mining operations, specifically high-recovery operations such as longwall and room-and-pillar retreat mines, have the potential to generate overburden deformations propagating from the mined seam to the surface (Peng, 2008). Ground movements induced by underground mining operations may lead to quantifiable impacts on surface and groundwater bodies (Walker, 1988; Matetic, et al., 1995; Singh & Jakeman, 2001; Guo, et al., 2012; Li, et al., 2015). The degree to which mining operations may impact surface and/or groundwater and its recovery cycle is influenced by key mining factors (such as mining depth and coal-seam height, topography, and gob width and length), along with geologic and hydrogeologic parameters (such as percent hardrock, effective porosity, hydraulic conductivity, etc.) and the hydrogeologic conditions of the affected system (such as flow direction and flow quantity) (Agioutantis, et al., 2013; Newman, et al., 2016; Newman, et al., 2017).

There is a need to develop a practical approach to assess potential mining induced impacts in surface and subsurface bodies of water. This approach should account for key mining factors and key geologic and hydrologic parameters, and allow changes within the overall groundwater flow system to be quantified. Once a reliable practical approach is developed and becomes accessible to the industry, mining companies may then use it to pro-actively design mining operations in close proximity to surface and subsurface bodies of water.
1.2. Research Objectives

The present research focuses on the effects of mining-induced ground movements on groundwater flow. The specific goals and objectives of this research are as follows:

- Compilation of pre- and post-mining hydraulic conductivity values found within available literature.
- Development of a methodology for assessing potential impacts to groundwater aquifers over fully extracted mining panels.
- Evaluation of pre- and post-mining hydraulic heads on two conceptual hydrogeologic models, one with horizontal and one with inclined topography, both of which are based on an actual case study in southwestern Appalachia.

1.3. Thesis Outline

The thesis is arranged as a series of chapters, each of which contribute to the research objectives and goals as stated above. The first chapter renders a brief overview of the thesis, reporting on the need to promote research on mining induced impacts on surface and groundwater, and providing a quick overview on defined research objectives and the thesis structure. The second chapter provides a theoretical overview on subsurface movements and surface subsidence caused by underground mining. The third chapter provides a basic understanding of hydraulic principles of water movement within an aquifer. A compilation of pre- and post-mining hydraulic conductivity values has been gathered from several published sources. The fourth chapter reports on potential impacts of mining-induced ground movements on surface and ground water, based on introduced principles and concepts of the previous chapters.

The fifth chapter describes the Subsidence Deformation Prediction System (SDPS) software package used for determining subsidence indices. This research is strictly concerned with the overburden and surface strain results reported by SDPS. The sixth chapter describes Processing Modflow for Windows (PMWiN), a groundwater simulation system that supports several groundwater flow and solute transport models and is based on MODFLOW.
Utilizing the information presented in the fifth and sixth chapters, chapter seven describes the proposed methodology for assessing potential impacts to subsurface bodies of water resulting from underground mining operations. The proposed methodology, in the eighth chapter, is applied to a case study where assumptions, input values and output values are stated, and results are analyzed and validated with case study data. Chapter nine concludes the thesis and summarizes the research. It also highlights the strengths and weaknesses of the proposed methodology and provides suggestions for future work to further this research.
2. **Subsidence over Underground Mining**

2.1. **Introduction**

In the following, a theoretical overview on ground movements caused by underground mining is being provided. With respect to this thesis, a clear understanding of underground mining induced ground movements and its resulting overburden deformation is deemed necessary. In order to assess potential mining induced impacts on surface and subsurface bodies of water, subsidence prediction methods should be utilized. A number of factors contribute to the development and the intensity of ground movements at the surface above underground mines including mining depth and height, the properties of the overburden strata, etc.

In underground mining, rock material is extracted resulting in the creation of subsurface excavation. The immediate strata over the excavation may then collapse, creating several zones of deformation. According to Peng and Chiang (1984), see Figure 2-1, typically three deformation zones are identified within the overburden: the caving zone close to the extracted seam, the fracture zone, which lies over the caving zone, and the continuous deformation zone close to the surface. The caving zone may extend about 5 to 10, and the fracture zone about 30 to 50 times, the seam thickness.

The overall movement of the ground surface resulting from underground mining is denoted as subsidence (Harrison, 2011). The intensity of subsidence depends on several factors, such as the geometry of the excavation, the geology of the overburden, and the location of the point of interest with respect to the excavation (Harrison, 2011; Agioutantis & Karmis, 2015).

2.2. **Continuous and Discontinuous Subsidence**

There are two types of subsidence that can occur over underground mines: Continuous and Discontinuous. Continuous subsidence corresponds to a smooth deformation of the surface, while discontinuous subsidence is marked by large vertical
displacements, generally over a limited area (Brady & Brown, 2004). The thesis only considers continuous subsidence.

Figure 2-1: Development of deformation zones due to full extraction underground mining (adapted from Peng and Chiang, 1984)

Continuous subsidence develops above large subsurface excavations, as seen in longwall and room-and-pillar surface subsidence troughs. The resulting smooth surface subsidence profiles have a pointed bottom, or if the size of the gob is large enough compared to its depth, a flat bottom, making an analysis and prediction through theoretical models and numerical methods possible. Continuous surface subsidence profiles are categorized as subsidence troughs or basins (Peng, 2008).

2.3. Movements

The term subsidence collectively refers to all surface movements, where the vertical movement is dominant. In this text the term subsidence will only refer to the vertical movement while other movements will be described by respective ground deformation indices. These deformation indices can be used to assess potential impacts on foreign subsurface and surface bodies in close proximity to the subsidence basin (Peng, 2008).
Figure 2-2 shows a final subsidence profile over a fully extracted panel. The corresponding horizontal surface displacements and strains are also shown. The width and depth of the panel are denoted with $w$ and $h$, respectively. The outer rays of the angle of draw demark the influence limits of ground deformations, and the intercept points of the outer rays with the surface demark the edges of the subsidence basin. Observed angle of draw values may vary by region and at panel edges. Holla and Barclay (2000) note an average of 29 degrees for coalfields, in New South Wales, Australia, while Conroy and Gyarmaty (1983) observed angles of draw of 4, 9 and 21 degrees for the east, west and north sides, respectively, for a longwall panel located in the Pittsburgh seam. For US coalfields, the angle of draw tends to be less than 35 degrees; gathered angle-of-draw values tend to be higher in east and central US (Singh, 1992).

![Figure 2-2: Transverse subsidence trough and subsidence parameters (Agioutantis and Karmis, 2015)](image)

Agioutantis and Karmis (2015) list the following deformation indices: subsidence, displacements, slope, curvature and strain, either as horizontal or ground strain. Peng (2008) lists deformation indices, by including twisting and shearing strain. A brief description of some deformation indices is provided below.
2.3.1. Subsidence

Vertical displacement is referred to as *subsidence*. It is nonexistent at the edges of the subsidence trough and greatest at its center, which is also the actual center of the panel located beneath (Peng, 1992; 2008; Harrison, 2011). Three types of subsidence trough exist, subcritical, critical and supercritical. A subcritical and critical final (static) trough at its cross-section has a pointed bottom at its center, while a supercritical final trough has a flat bottom at its center instead. Maximum possible subsidence is less than the extraction height of the seam, and is reached at critical and supercritical states (Peng, 1992). A panel is considered subcritical, if the ratio of panel width to panel depth is less than 1.2, critical if the ratio is equal to 1.2, and supercritical, if the ratio is beyond 1.2 (Agioutantis & Karmis, 2015).

2.3.2. Horizontal Displacements

Horizontal movement is represented by a horizontal displacement vector. The maximum horizontal displacement occurs close to the panel edges with decreasing magnitudes towards the center of the panel and the edges of the basin, reaching zero at the ends (Peng, 2008; Harrison, 2011). Figure 2-2 shows the displacement curve for a typical subsidence case.

2.3.3. Horizontal and Ground Strain

Horizontal strain develops due to unequally distributed horizontal displacements throughout the overburden (Peng, 2008; Harrison, 2011). It can be either tensile, denoted as positive strain, or compressive, which is denoted as negative strain. Tensile strains develop at the concave segment and compressive strains at the convex segment of the subsidence trough, with the inflection point being the crossover point between those segments. Strains at the inflection points of a trough are zero (Harrison, 2011). Furthermore, an inflection point is a point at which the surface slope is at its maximum (Peng, 2008; Harrison, 2011; Agioutantis & Karmis, 2015). Horizontal strain between two surface points can be calculated by dividing the change of the horizontal distance between the points by the original distance (Peng, 2008).
Ground strain between two surface points can be calculated by dividing the change of the distance (in three dimensions) between the points by the original distance between the two points (Karmis & Agioutantis, 2015). Ground strain is more representative of the straining of the surface compared to horizontal strain, which only assumes deformations on a horizontal plane, i.e., it does not account for changes in elevation due to the topography (Agioutantis, et al., 2016).

Figure 2-3 depicts for a typical horizontal strain distribution across two transverse profile lines at depths of 50 m (165 ft) and 100 m (165 ft) for a rectangular horizontal longwall mining case. As seen in Figure 2-3, strain magnitudes increase as the distance from the extracted panel decreases, while the inflection point remains above the rib throughout the overburden.

![Diagram of horizontal strain distribution](image)

**Figure 2-3: Distribution of horizontal strains at and below the surface over an underground extraction area (Newman, et al., 2016)**

### 2.4. Factors Affecting Subsidence due to Underground Mining

The extent of subsurface and surface deformation depends on the mining geometry (the length and width of the panel, extraction height, mining depth, etc.), surface topography, and geologic conditions (Agioutantis & Karmis, 2015). Peng (2008) indicates that seven components should be taken into account: the properties of the overburden
strata, the seam inclination, the mining depth and height, the gob size, multiple panel mining, topography, and faults or other planes of weaknesses. Three parameters are described below as indicated by the literature.

2.4.1. Properties of the Overburden Strata

In a stiff and hard overburden (e.g., due to the presence of hard rock, such as sandstone and limestone) vertical and horizontal movements will propagate with greater difficulty towards the surface and therefore result in less subsidence as compared to a weaker and softer overburden material (Peng, 1992; 2008). A good measure of the overburden response is the percent hard rock in the overburden. Maximum expected subsidence can be plotted as a function of percent hard rock for critical and supercritical longwall panels, without having to consider the width-to-depth ratio of the panel. An inverse linear relationship between the two can be ascertained (Karmis, et al., 1984).

2.4.2. Mining Depth and Height

As noted by Peng (2008) the extent of surface deformation under equal conditions is inversely proportional to the mining depth. This can be explained through the fact that in order to reach the surface, ground movements have to overcome larger distances in an enlarged area due to their expansive propagating behavior (Harrison, 2011). Hence, they will generate a larger but thinner subsidence trough. At a certain depth, surface subsidence becomes undetectable (Peng, 2008). In combination with properties of the overburden strata, it is possible to plot maximum subsidence as a function of percent hard rock available in the overburden and the width-to-depth ratio of the panel. With higher width-to-depth ratio and with less percent hard rock available, a higher subsidence factor (percentage of subsidence based on extraction height) is to be expected (Karmis, et al., 1984).

2.4.3. Topography

As noted by Gentry (1977) subsidence is greater at hills than at valleys. This phenomenon can be explained through the occurrence of secondary sliding of material on
slopes due to subsidence leading to a downhill accumulation of material (Peng, 2008). In subsidence calculation, site specific adjustments of horizontal displacement due to sloping terrain have to be taken into account in order to better match measured deformation indices. Ground strain tends to be higher at the toe of the slope (Agioutantis & Karmis, 2013; Karmis & Agioutantis, 2015).
3. **Principles of Groundwater Hydrology**

3.1. **Introduction**

In order to assess potential mining induced impacts on surface and subsurface bodies of water, groundwater flow models should be used to estimate the flow of water in the overburden. In the following an overview of the principles of groundwater hydrology is given and the key theoretical concepts such as water pressure, hydraulic head, and hydraulic conductivity are discussed in detail.

An aquifer is defined as a ground formation that contains sufficient saturated permeable material (rock and/or soil) to yield significant quantities of water as well as the ability to store, release and transmit water (Esmail & Kimbler, 1967). Downward water infiltration due to gravity to lower ground formations is hindered as the aquifer has a relatively impermeable bed located directly beneath. Water may collect within the formation from the bottom upwards, giving birth to the concept of saturation thickness, which also implies the formation to have an unsaturated upper portion (Todd, 1980; Weight & Sonderregger, 2001).

A ground formation may also be confined from above, trapping water within the formation. If that is the case, the aquifer may be denoted as a confined aquifer. An aquifer, which is connected to the surface, hence not confined from above, is denoted as an unconfined aquifer (Weight & Sonderregger, 2001). Water within an unconfined aquifer may collect within the formation from the bottom upwards. In a confined aquifer, water may equally distribute throughout the formation, in order to minimize pressure differences within the system.

3.2. **Potentiometric Surfaces at Confined and Unconfined Aquifers**

The overburden might be composed of alternating permeable and impermeable layers, creating water barriers, which confine water flow. Unconfined or confined aquifers may develop as soon as water begins to accumulate. In particular, unconfined aquifers
develop on top of an impermeable layer, while confined aquifers are encompassed between two impermeable layers (Holla, 1991; Iannacchione & Tonsor, 2011).

In an unconfined aquifer the top of the saturated material within the formation is denoted as the water table. While the water table is subjected to atmospheric pressure, water beneath the table is subjected to greater pressures. At confined aquifers the increase in pressure may be caused by overlying strata mass. If the aquifer is connected at its ends to a water source of higher elevation than the aquifer itself, water within the aquifer will also be subjected to elevation pressure, which is induced by gravity. Water pressure is greatest at the bottom due to the weight of the water above (Weight & Sonderregger, 2001). If the aquifer is perforated by a cased water well, the pressure within the system will elevate the water within the well above the confining layers. The height of the water level within the well indicates the location of the potentiometric surface. This potentiometric surface specifies the elevation that water in a single well located at any point within the aquifer can reach under pressure. Each aquifer, confined or unconfined, has its own potentiometric surface. Furthermore, the potentiometric surface of an unconfined aquifer is its water table (Weight & Sonderregger, 2001). Figure 3-1 shows a schematic cross section illustrating unconfined and confined aquifers.

3.3. Total Hydraulic Head

The total hydraulic head, defined as the total pressure at a single point within the groundwater system, is composed of elevation head, pressure head and velocity head. The total hydraulic head is dimensionally measured in units of length. Since the velocity of the groundwater is small in the range of feet per year or feet per day, pressure induced by velocity is negligible. While the pressure head is the weight of water for a given water column height to the bottom of the aquifer, the elevation head is the distance that a water particle may travel downwards to the bottom from a certain elevation. The total hydraulic head at each point at the aquifer is used to create the potentiometric surface (Heath, 1983; Weight & Sonderregger, 2001).
Ground water flow is in the direction of a decreasing potentiometric surface. The rate of the ground water movement depends on the hydraulic gradient, which is the change in head per unit of distance. It is inversely proportional to the hydraulic conductivity, a value that indicates the capacity of a material to transmit water. A steep inclined hydraulic head within flow direction is expected with material with low hydraulic conductivity (Heath, 1983; Weight & Sonderregger, 2001).

### 3.4. Groundwater Movement explained through Darcy’s Law

The movement of groundwater within an aquifer may be described by Darcy’s law (equation (1)), which states that the flow rate through porous media is proportional to the head loss and inversely proportional to the length of the flow path.

\[
Q = KA \frac{\Delta h}{\Delta L} \tag{1}
\]

Groundwater flow rates and directions may be evaluated through proper application of that law (Todd, 1980). As described by Todd (1980), hydraulic conductivity (K) is the
proportionality constant within Darcy’s equation. It relates the amount of flow through a unit cross-sectional area (A) of an aquifer under a unit gradient of hydraulic head ($\frac{\Delta h}{\Delta L}$). Hydraulic conductivity within the overburden may be determined through borehole slug tests or may be back calculated from groundwater monitoring systems (Weight & Sonderregger, 2001).

3.5. Hydraulic Conductivity

Hydraulic conductivity (K) is a parameter of a formation that indicates how fast a specific volume of groundwater is being transmitted through the material under a unit hydraulic gradient; K is expressed in velocity (L/T) (Todd, 1980). It is not to be confused with intrinsic permeability, which is a measure of how well a fluid can be transmitted through a material. Hydraulic conductivity is related to the specific weight, which is the gravitational driving force of the fluid and the dynamic viscosity of the fluid, which indicates the resistance of the fluid to flow. Intrinsic permeability represents only the physical flow properties of the geologic material, i.e., it is essentially a function of the pore size openings only. Hence, intrinsic permeability is a part of hydraulic conductivity (Weight & Sonderregger, 2001).

Hydraulic conductivity of a material unit depends upon a variety of physical factors, such as, porosity, particle size and distribution, shape of particles, and other factors (Todd, 1980). Values may differ with the type of material and from place to place within the same material according to its structural integrity (Heath, 1983). Figure 3-2 shows common ranges of hydraulic conductivity values for selected rocks. The shear variety of physical factors acting together cause hydraulic conductivity values to be found within twelve order of magnitudes (Anderson & Woessner, 1992).
To describe the groundwater flow through a material, hydraulic conductivity may be chosen, which may be determined through auger hole tests, pumping tests of wells, tracer tests, and other testing methods, or be calculated based on available data and formulas (Todd, 1980). However, as described by Weight and Sonderregger (2001), it is very difficult to obtain precise or accurate hydraulic conductivity values at physical tests. Therefore, reported values should always be assessed with caution. Accurate hydraulic conductivity values are necessary for a representative simulation of groundwater flow.
3.6. Storativity of Confined and Unconfined Aquifers

The ability of a material to store and release groundwater is in large part influenced by the material's porosity, which is defined as empty pore space within the material. Water will accumulate within the effective pore spaces; pores, which are interconnected with each other, allow water to flow within the material (Todd, 1980; Heath, 1983).

Storativity, or the storage coefficient, describes numerically, as seen in equation (2), the ability of an aquifer to store and release water per unit surface area of the aquifer per unit change of hydraulic head. The dimensionless value may range between 0 and the effective porosity of the material. A higher storativity value indicates an increased storage and release capability of an aquifer. Typical ranges for unconfined aquifers are found between 0.03 and 0.3, while values for confined aquifers range from $10^{-03}$ to $10^{-06}$ (Fetter, 1994). The value can usually be determined through pumping tests (Weight & Sonderregger, 2001). Storativity may be calculated as the specific storage $S_s$ times the saturated thickness $b$ added to the specific yield $S_y$ (Weight & Sonderregger, 2001).

$$ S = S_y + S_s b $$

According to Heath (1983), specific yield $S_y$ may be defined as the ratio of the volume of water that will drain by gravity to the volume of saturated material. Specific storage $S_s$ is the amount of water released or stored per unit volume of aquifer per unit change in hydraulic head, while remaining fully saturated. At unconfined aquifers, the specific storage equals the specific yield of the material. The specific storage becomes almost negligible, as water release comes hand in hand with a decrease in the saturation thickness.

Within an unconfined aquifer, water may pile up between the effective pore spaces from the bottom of the formation upwards. Release of water is characterized as a drainage of effective pores (Weight & Sonderregger, 2001). In a confined aquifer, water may equally distribute throughout the effective pore spaces of the formation, in order to minimize
pressure differences within the confined system. Release of water is subjected to pressure changes within the aquifer.
4. Mining under Bodies of Water

4.1. Introduction

A “body of water” is a significant accumulation of water at the surface or subsurface. Hydraulic connections between surface and subsurface bodies of water may exist, for instance, through fractures and discontinuities, allowing such bodies to interact with each other. These interactions are characterized through a continuous exchange of water, as either a gaining, losing, or partial regional exchange of both (Winter, et al., 1998).

Previously conducted research has attempted to correlate the effect of mining induced ground deformation indices to impacts on local water sources. An extensive five-year assessment in Pennsylvania provides statistical evidence on the potential impact mining has on bodies of water. Out of approximately 2800 undermined water supplies, about 9% within a 61 m (200 feet) horizontal radius from the mine were deemed to be directly impacted by coal mining operations within the area (Iannacchione, et al., 2011). These effects were categorized with respect to loss of water levels within the body of water.

A basic understanding of ground movements and principles of groundwater hydrology is required in order to understand how mining induced ground movements may affect surface and subsurface bodies of water. A model by Peng and Chiang (1984) depicting the development of deformation zones due to underground mining (Figure 4-1) is being used to describe conceptual hydrogeologic changes within the overburden. The adapted model (Figure 4-2) connects key theoretical concepts and parameters of ground movements (such as overburden fracture development due to deformation) and groundwater flow (such as increase of hydraulic conductivity due to overburden fracture development). A practical approach to assess potential mining induced impacts on surface and subsurface bodies of water may employ the adapted model as the groundwork to reproduce pre- and post-mining overburden conditions of a hydrogeologic system.

Recent research focuses on computer-assisted modeling of ground movement impacts on bodies of water. Studies by Li, et al. (2015) and Bashar (2010) conclude that mining does have a quantifiable impact on bodies of water. Li, et al. (2015) attempted to
predict the pre- and post-mining water table of the overburden subjected to ground movements by a longwall panel in the Appalachian coalfield (U.S.A.). Pre- and post-mining hydraulic conductivity values were determined through slug tests and fed into an appropriate flow model. Bashar (2010) analyzed how surface and groundwater systems have been affected by mining induced ground movements in the locality of Kirchheller Heide in Germany, by developing a hydraulic numerical model and coupling it into an adjusted groundwater model.

4.2. **Observed Impact of Ground Movements on Groundwater**

Ground movements may induce at groundwater, such as aquifers, a change in water level and water level fluctuations - both usually acting together. Water level fluctuations may be characterized as rapid increases and decreases of the water level, while a change in water level may be described as a temporal lasting change (Walker, 1988).

Walker, et al. (1986) and Walker (1988) have observed that water level fluctuations and head loss are greatest in the center of the extraction operation, less severe at its outskirts and almost non-existent at considerable distance from it. Authors attempt to describe this “boundary,” in which any effect of a mine on a water body ceases, through an “angle of hydrologic influence” (Agioutantis, et al., 2013). Its vertex is chosen at the edge of the panel, and its two rays are aligned to the surface – one as a vertical and the other as the demarking limit. According to Agioutantis, et al. (2013) angles between 24 and 45 degrees have been reported.

Walker (1988) reports, that mining may induce a temporal lowering of the water level. A partial or full recovery of the water level may take place in most cases after ceasing of mine operations. Further independent research studies, such as by Pennington, et al. (1984), Dixon and Rauch (1988), Hutcheson, et al. (2000) describe a mine-induced temporal lowering of the water level and its later recovery as well.

Walker (1988) also reports about a complete water level loss – a singular case, while Hutcheson, et al. (2000), reports of higher post-mining water levels than before mining, which may be attributed to delayed water infiltration into lower layers. Differences
during observations make further research necessary in order to clarify the role of mining on changes in water level. According to Dixon and Rauch (1988), a water level recovery may take between eight months and three and a half years.

It is important to note, that changes in water level may also be attributed to other causes, such as weather and climate. These have to be distinguished from mining induced changes. Furthermore, the more complex a ground water flow system is, the more difficult it becomes to attribute a change in water level to mining (Walker, 1988; Iannacchione & Tonsor, 2011).

Water level fluctuations may be correlated to mine-induced ground deformations (Jeran & Barton, 1985; Walker, 1988). In a case study presented by Walker, et al. (1986) and Walker (1988), a water level decline was usually observed with emerging tensile strain, while water level recovery was observed with emerging compressive strain. With passing face, water level reduction usually followed immediate water level recovery. Mining attributed fluctuations emerged at a distance of about 121.92 m (400 ft) to 182.88 m (600 ft) from the measuring point. Their magnitudes usually decreased at neighboring points with increasing relative distance to the mining. Walker (1988) notes that observed smaller fluctuations after mining may be attributed to further adjustments of the local overburden.

4.3. Conceptual Hydrogeologic Changes within the Overburden due to Ground Deformation

Mine-induced ground deformation may change the hydrogeologic conditions of the overburden, and therefore the characteristics of bodies of water. Geological features, such as joints and fractures and their interconnections, allow water to flow through the overburden. The extent of water flow is influenced by the presence of interconnected geological features, and can increase or decrease with a further opening or closing of such features (Holla, 1991). Ground deformation indices such as strain may promote the development of geological features, causing an increase in permeability – both, in horizontal and vertical direction. Permeability may be divided into primary and secondary categories. Wyrick and Brochers (1981) describe primary permeability as water movement through inter-granular pore spaces of strata layers while secondary permeability is the flow
of groundwater through geological features, such as fractures and joints. Pressure from infiltrating water, may further enhance the development of such geologic features (Stoner, 1983; Holla, 1991; Harrison, 2011).

Hydrogeologic changes within the overburden due to mine-induced ground deformation may differ by zones as defined by Peng and Chiang (1984), see Figure 4-1. Typically, three deformation zones are identified within the overburden: the caving zone close to the extracted seam, the fracture zone, which lies over the caving zone, and the continuous deformation zone close to the surface. Mine-induced hydrogeologic changes within the overburden are most severe within the caving zone. Confined or unconfined subsurface bodies of water affected by the caving and fracture zone may yield greater quantities of water to lower layers within the affected regions. In the case of the overburden being traversed by several aquifers located on top of each other, flow exchange between the aquifers may be facilitated in regions affected by the caving and fracture zone, leading to a dewatering and possible loss of affected upper aquifers first (Iannacchione & Tonsor, 2011).

Figure 4-1: Water infiltration due to mining induced conceptual changes in hydrogeologic properties (adapted from Peng and Chiang, 1984)

A more complex model depicting conceptual hydrogeologic changes within the overburden is published by Kendorski (1993; 2006), which assumes five deformation
zones (Figure 4-2), the surface fracture zone, the constrained and unaffected zone, the dilated zone, the fractured and the caving zone. The surface fracture zone may be disrupted with vertical fractures, hence increasing the vertical permeability of the zone. If the extraction operation is deep enough, a strata section might still remain intact from ground deformation, labeled the “constrained and unaffected zone,” with little or no changes in its permeability. The “dilated zone” is characterized by bed separation resulting from sagging of strata layers, which act as beams. Developing voids within the beds may improve the storage capability of the strata. At the same time, little or no increase in vertical secondary permeability may be observed. The fractured and caving zones are zones of high permeability.

4.4. Pre- and Post-mining Hydraulic Conductivity Values for Coal Measure Formations

In recent years, pre- and post-mining hydraulic conductivity values for coal measure formations have been reported by a number of researchers. Newman, et al. (2016) provides values found within the literature in order to facilitate their comparison (Table 4-1 and Table 4-2). The reported hydraulic conductivity values have been determined through diverse conductivity testing methods, such as slug or pumping tests, or have been estimated or calculated based on given values of groundwater monitoring regimes, boreholes and stratigraphic logs. These pre- and post-mining values may be used directly as input values in PMWiN groundwater simulations.

The pre- and post-mining hydraulic conductivity (HC) values shown for specific formations in Table 4-1 and Table 4-2 in general compare well with the ranges of hydraulic conductivity values shown in Figure 3-2, which was compiled by Heath (1983). It should be noted, however, that in some cases the HC values for shale presented in Table 4-1 and Table 4-2 are in the range between $10^{-04}$ and $10^{-01}$, or about four orders or magnitude higher than that indicated by Heath (1983). Depending on the estimation method, researchers may have over- or underestimated HC values. Furthermore, in many cases a detailed description of the properties of the studied rock type are not available and therefore grouping can only be performed by the general formation name. In addition, it is highly likely that in some
cases data may have been erroneously converted from one unit system to a different unit system. According to Newman, et al. (2016) it is likely for Li, et al. (2015) to have mislabeled the reported HC units, since substantially higher HC values, as compared to others, would be generated using ft/d instead of m/s. Accurate pre- and post-mining hydraulic conductivity values are necessary for a representative simulation of groundwater flow.

Figure 4-2: Conceptual hydrogeologic changes within the overburden due to mine-induced ground deformation (Kendorski, 1993)

Based on Table 4-1, the pre- and post-mining HC values for shale vary between one and three orders of magnitude. Pre- and post-mining HCs for sandstone usually vary between one and two orders of magnitude. Booth (2002) reports on one particular borehole located in a sandstone layer in which a HC increased by two orders of magnitude during the subsidence phase, and later recovered to a value similar to pre-mining values.
According to Li, et al. (2015), HC values for limestone may be subjected to a pre- and post-mining variation of about one order magnitude. Pre- and post HC values for coal typically vary between two and four orders of magnitude (see Table 4-2).

Differences between horizontal and vertical hydraulic conductivity within the same formation can also be found for both the pre-mining and the post-mining cases, respectively.

For the pre-mining case, Schubert (1980) determined that horizontal air permeability values for undisturbed material are consistently greater than vertical air permeability values. The average ratio of horizontal to vertical HC values for sandstone and shale is between 2.5 and 10. Based on Schubert's (1980) analysis, Harlow and Lecain (1993) assign sandstone, shale and coal an average ratio of horizontal and vertical hydraulic conductivity of 3, 10 and 10, respectively, arguing that sandstone is generally massively bedded and well cemented, while coal and shale are laminated and contain numerous bedding planes.

For the post-mining case, longwall mining promotes the development of horizontal and vertical fractures, especially the latter one. Due to lack of available field data, Li, et al. (2015) assumes that for layers above the panel, the post-mining vertical HC values are as much as five times larger than the post-mining horizontal HC values. Case study data by Matetic, et al. (1995) do not specify any post-mining horizontal and vertical HC ratios for layers directly above a mining panel.
Table 4-1: Hydraulic conductivity values in units of m/d (adapted from Newman, et al., 2016)

<table>
<thead>
<tr>
<th>Direction</th>
<th>Shale Pre-mining</th>
<th>Shale Post-mining</th>
<th>Sandstone Pre-mining</th>
<th>Sandstone Post-mining</th>
<th>Limestone Pre-mining</th>
<th>Limestone Post-mining</th>
<th>Notes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>6.06x10^{-03} to 6.06x10^{-04}</td>
<td>6.06x10^{00}</td>
<td>6.06x10^{-01} to 6.06x10^{-04}</td>
<td>6.06x10^{00} to 6.06x10^{02}</td>
<td>Recovery Pumping Tests</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>6.06x10^{-03} to 6.06x10^{-04}</td>
<td>6.06x10^{00}</td>
<td>6.06x10^{-02} to 6.06x10^{-04}</td>
<td>6.06x10^{00} to 6.06x10^{01}</td>
<td>Calculated Values</td>
<td></td>
<td>(Matetic, et al., 1995)</td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>6.06x10^{-03} to 6.06x10^{-04}</td>
<td>6.06x10^{00}</td>
<td>6.06x10^{-02} to 6.06x10^{-04}</td>
<td>6.06x10^{00} to 6.06x10^{01}</td>
<td>Recovery Pumping Tests</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>8.23x10^{-03}</td>
<td>1.04x10^{-02} to 3.66x10^{-03}</td>
<td>2.46x10^{00} to 2.98x10^{-01}</td>
<td>1.52x10^{-04}</td>
<td>Slug Test</td>
<td></td>
<td>(Li, et al., 2015)</td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>8.23x10^{-02} to 8.23x10^{-03}</td>
<td>2.93x10^{00} to 2.98x10^{-01}</td>
<td>1.33x10^{-03} to 1.33x10^{-04}</td>
<td>Assumption used in simulations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>4.30x10^{-06} to 1.47x10^{-07}</td>
<td>2.07x10^{-03} to 5.18x10^{-05}</td>
<td>Estimation based on air permeability test</td>
<td></td>
<td></td>
<td>(Schubert, 1980)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical</td>
<td>6.65x10^{-07} to 7.78x10^{-08}</td>
<td>5.18x10^{-05} to 5.18x10^{-05}</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
- Recovery Pumping Tests
- Calculated Values
- Slug Test
- Assumption used in simulations
- Estimation based on air permeability test
<table>
<thead>
<tr>
<th>Direction</th>
<th>Shale Pre-mining</th>
<th>Sandstone Pre-mining</th>
<th>Limestone Pre-mining</th>
<th>Notes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>5.27x10^{-04} to 5.27x10^{-06}</td>
<td></td>
<td></td>
<td>Given values</td>
<td>(Toran &amp; Bradbury, 1988)</td>
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<tr>
<td>Not specified</td>
<td>1.97x10^{-04} to 7.68x10^{-04}</td>
<td></td>
<td>9.42x10^{-04} to 4.69x10^{-05}</td>
<td>Slug Test</td>
<td>(Karacan &amp; Goodman, 2009)</td>
</tr>
<tr>
<td>Not Specified</td>
<td></td>
<td>8.64x10^{-00} to 8.64x10^{-01}</td>
<td></td>
<td>Given values</td>
<td>(Rapantova et al., 2007)</td>
</tr>
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<td>Not specified</td>
<td>2.63x10^{-01} to 1.32x10^{-04}</td>
<td>3.51x10^{-01}</td>
<td>1.32x10^{-02} to 8.78x10^{-05}</td>
<td>1.32x10^{-00} to 2.63x10^{-04}</td>
<td>Pressure Injection Testing, Sandy Shale</td>
</tr>
<tr>
<td>Not specified</td>
<td></td>
<td></td>
<td>3.89x10^{-03} to 3.54x10^{-04}</td>
<td>5.79x10^{-02} to 1.99x^{-04}</td>
<td>Slug Test</td>
</tr>
<tr>
<td>Not specified</td>
<td>1.12x10^{-03}</td>
<td>5.36x10^{-01}</td>
<td>2.59x10^{-01} to 1.56x10^{-02}</td>
<td>1.73x10^{-01} to 1.56x10^{-02}</td>
<td>Slug Test, Post-mining data is taken just before subsidence</td>
</tr>
</tbody>
</table>
Table 4-2: Hydraulic conductivity values in units of m/d - II (adapted from Newman, et al., 2016)

<table>
<thead>
<tr>
<th>Direction</th>
<th>Coal</th>
<th>Aquifer</th>
<th>Notes</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-mining</td>
<td>1.52x10^-04</td>
<td>Pre-mining</td>
<td>Slug Test</td>
<td>(Li, et al., 2015)</td>
</tr>
<tr>
<td>Post-mining</td>
<td></td>
<td>Post-mining</td>
<td>Assumptions used in simulations</td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td></td>
<td>Horizontal</td>
<td>Pumping test; coal seam values measured in or near mine</td>
<td>(Toran &amp; Bradbury, 1988)</td>
</tr>
<tr>
<td>Not specified</td>
<td>2.00x10^+00 to 3.40x10^-05</td>
<td>5.27x10^-01</td>
<td>Packer Tests</td>
<td>(McCoy, et al., 2004)</td>
</tr>
<tr>
<td>Not specified</td>
<td>8.78x10^-02 to 8.78x10^-05</td>
<td>1.32x10^+00 to 4.39x10^-05</td>
<td>Pressure Injection Testing, Sandy Shale</td>
<td>(Hutcheson, et al., 2000)</td>
</tr>
<tr>
<td>Not specified</td>
<td>2.04x10^-01</td>
<td>1.74x10^+00 to 6.52x10^-02</td>
<td>In-situ pumping and slug test</td>
<td>(Kim, et al., 1997)</td>
</tr>
</tbody>
</table>
4.5. Ground Deformation Induced Water Infiltration into Mine Workings

Cases on water infiltration into mine workings have been described by Singh and Jakeman (1999; 2001), Holla (1991), Peng, et al. (1996) and others. Authors agree that ground deformation may facilitate water-infiltration into mine workings by creating pathways and interconnecting pre-existing geologic features and formations. Water infiltration may be understood as simple water seepage and may develop into substantial water inrushes, followed by inundation. These inrushes may cause a temporary halting and even a suspension of works (Holla, 1991).

It is in every mine’s interest to keep water infiltration at a minimum. Holla (1991) warns against the common practice to limit tensile strain values as a method to control water infiltration, since a particular relationship between the two cannot be proven with certainty. For instance, water infiltration is also dependent on the properties of soils and rocks.

4.6. Mining Impact Mitigation Measures

The mitigation of mining impacts begins at the planning stage of a mine. Impacts on bodies of water shall be mitigated or at best be prevented through proper consideration of the geometry of the workings, nature of the surrounding rock mass, induced strains within the overburden, and others (Singh & Jakeman, 1999; 2001; Agioutantis, et al., 2013). Mitigation may continue during mine development, operation and after cease of operations, through the prudent selection of mining methods and the implementation of sustainable mining practices.

Since horizontal surface strains are unavoidable, the objective is to keep them within tolerable limits (Agioutantis, et al., 2013; Harrison, 2011). Recommended damage criteria and threshold values for surface tensile strains for mining under and near bodies of water have been listed and compared by Agioutantis, et al. (2013).
5. **Subsidence Prediction**

5.1. **Introduction**

In order to assess potential mining induced impacts on bodies of water strain needs to be calculated at different elevations within the overburden material. For assessing mining induced ground movements, different prediction methodologies may be chosen, which can be broadly divided into three groups: theoretical models, numerical methods and empirical or semi-empirical methods (Karmis, et al., 1990). Theoretical models determine mining induced deformations by assuming an elastic, plastic, viscoelastic, etc. behavior for the overburden strata. In order to accurately describe the mining induced deformations within the overburden, these theoretical models require several, often difficult to obtain, input parameters. Theoretical models are often limited by the number of input parameters required and resort to site-specific assumptions. Similarly, numerical models also assume a phenomenological overburden model as well as requiring a series of input parameters and site-specific information to mathematically describe the mining induced deformations within the overburden. On the other hand, empirical or semi-empirical prediction methods (profile or influence method) require basic site-specific or regional parameters such as depth, mining height, percent hard rock, etc. Due to the simplicity of the input parameters required, empirical and/or semi-empirical prediction methods are often used within the industry. However, it should be noted, that the results from these prediction models only apply for the site from which the parameters were derived and the methodology was calibrated (Karmis, et al., 1990).

There are several commercially available computer programs available for the assessment and prediction of mining induced subsidence on the surface and within the overburden. The most commonly utilized programs within the mining industry are Comprehensive and Integrated Subsidence Prediction Model (CISPM), LaModel, FLAC, and Subsidence Deformation Prediction System (SDPS).
5.2. Subsidence Deformation Prediction System

The Subsidence Deformation Prediction System (SDPS), developed at Virginia Tech in 1987, is a widely utilized subsidence prediction software within the mining industry, academic research, and regulatory agencies. Although originally developed in 1987, the software has been continuously updated with new features and prediction tools. Within SDPS, users are able to predict mining induced surface and subsurface deformations such as subsidence, horizontal displacements, strain, slope curvature, etc. with respect to site-specific mine geometries (Mine Plan), prediction point locations on the surface or within the subsurface as well as basic parameters for describing the overburden geology. Furthermore, SDPS features multiple calibration routines as well as dynamic subsidence calculations. Calibration routines and dynamic subsidence calculations are not further discussed with respect to this thesis.

SDPS uses the Profile Function Method and Influence Function Method to predict and evaluate mining induced subsidence. For the purpose of this thesis, SDPS is being discussed with respect to the influence function formulation. The influence function method is based on two concepts: The first concept is based on the idea that a subsurface three-dimensional void element or unit caused by extraction will induce subsidence on all overlying layers within its area of influence. The area of influence may be described as a cone, whose cone-end points towards the void in the overburden. The surface point located vertically above the center of the void unit is subjected to most subsidence, while subsidence magnitudes decrease with increasing distance from the midpoint (Agioutantis & Karmis, 2013). The second concept is based on the idea of superposition of influences, meaning, that all mining induced influences (due to unit extractions at seam level) acting on a given point on the surface or within the overburden are cumulative. In combining these individual influences together, the total mining induced impact to the surface and/or subsurface can be determined (Agioutantis & Karmis, 2015). The input parameters and output results discussed in this thesis are based on SDPS version 6.2C. For more information on these topics please refer to the SDPS Manual (Agioutantis & Karmis, 2015).
5.3. **Workflow within SDPS**

The SDPS program follows a very regimented process flow chart as shown in Figure 5-1. The flow chart guides users through the creation of a SDPS analysis with respect to input parameters necessary to perform prediction calculations as well as output options available within the program. Initially, a user is required to specify the type of panel representation and mode of prediction point layout. The mine plan type may be defined as a Rectangular Mine Plan or as a Polygonal Mine Plan, while the prediction points may be depicted as Scattered Points or Points on a Grid (Agioutantis & Karmis, 2015). In the case of the Rectangular Mine Plan, the mine layout is approximated through simple rectangular extraction areas. The user defines the edges of each extraction panel towards all geographical directions. A Polygonal Mine Plan may be chosen to approximate complex mine layouts through closed polygons. Each point of the polygon is defined independently in a counter-clockwise fashion by the user. Prediction points are always defined in three dimensions. For points that are uniformly distributed, the Points on a Grid option can be used, while the Scattered Points option should be used when points are not distributed on a grid and each point has to be defined individually. Mine plan and prediction points can also be imported from CAD as closed polylines (Agioutantis & Karmis, 2015).

Once the prediction points, scatter or grid, have been defined users are now able to begin defining input parameters within SDPS with respect to site-specific mining geometries, overburden/rock mass characteristics, influence angles, etc. With these input parameters defined by the user, project files may be saved and the data entered into the calculation routine. Within the calculation routine, a user is able to specify which deformation indices are to be calculated and in which format the output results are to be saved (grid or XYZ). Within SDPS, output results may be viewed as two-dimensional (2D) and three-dimensional (3D) plots as well as vector graphs for outputs such as horizontal displacements. Output results in 2D can be exported to Excel as an ASCII Data file (XY), while 3D results and vector graphs may be saved as images (.jpg). Project files and results, are saved and stored in external files, whose location may be defined by the user. Output results from SDPS can be read and imported by other software packages such as Microsoft Excel.
<table>
<thead>
<tr>
<th># Step</th>
<th>Workflow</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>Initiate SDPS</td>
<td></td>
</tr>
<tr>
<td>Step 2</td>
<td>Choose Mine Plan type</td>
<td>Based on available data and objectives the user chooses a Mine Plan type</td>
</tr>
<tr>
<td>Step 3</td>
<td>Choose Prediction Point type</td>
<td>Based on available data and objectives the user chooses a Prediction Point type</td>
</tr>
<tr>
<td>Step 4</td>
<td>Import Data or Enter Manually</td>
<td>The user may choose to import or enter data manually if available</td>
</tr>
<tr>
<td>Step 5</td>
<td>Introduce Subsidence Parameters</td>
<td>Introduce available regional parameters and adjust</td>
</tr>
<tr>
<td>Step 6</td>
<td>Save Project File and Run</td>
<td>The user may chose the output format in which the results are saved</td>
</tr>
<tr>
<td>Step 7</td>
<td>View Results and Plot Deformations</td>
<td>The results may be extracted within SDPS, files may also be accessed external and read through other software</td>
</tr>
<tr>
<td>Step 8</td>
<td>Extract Results</td>
<td></td>
</tr>
<tr>
<td>Step 9</td>
<td>Finalize SDPS</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 5-1: Workflow diagram for SDPS (adapted from Agioutantis and Karmis, 2015)**
5.4. Relevant SDPS Inputs and Outputs

With respect to this thesis, a simple mine-plan was created. The mine plan type was defined as Rectangular Mine Plan, and panel length (m), width (m) and elevation (m), as well as extraction thickness (m) were specified by the user. As no information is available within the literature for the supercritical subsidence factor, which is a ratio of the maximum possible subsidence over the extraction thickness of a given profile, the SDPS default value for the region of Pennsylvania was chosen.

Prediction points were depicted as Points on a Grid and transversed on a flat surface the longwall panel at different elevations. The Influence Angle (degree) was extracted from available literature and the Percent Hard Rock (%) was assumed based on given overburden description. An SDPS default value for the horizontal strain coefficient for the region of Pennsylvania was chosen.

Of importance are the results of horizontal displacements, which are unitless, and expressed within SDPS in millistrain. Horizontal displacements are determined as a linear function of the first derivative of subsidence. Horizontal strain is the first derivative of the horizontal displacement. Utilizing the influence function method, SDPS is capable of calculating deformations at any point in three-dimensional space, i.e., at any point on the surface and at any elevation between the seam and the surface.

While SDPS is able to calculate horizontal strain for each surface prediction point defined, it does not calculate vertical strain as this should refer to specific formations within the overburden or to the total overburden elevation. If vertical strain needs to be calculated, it can be approximated using several approaches. A typical approach is to divide the vertical change in displacement over the initial formation thickness. If formation thicknesses are not known, then an average value for vertical strain may be calculated by dividing vertical displacement by the total overburden elevation.
6. Modeling Groundwater Flow

6.1. Introduction

In order to assess potential mining induced impacts on bodies of water the pre- and post-mining hydrogeologic state of the overburden should be compared. Due to the complexity of this task, a numerical groundwater simulation system or groundwater model is being applied as described below.

A groundwater model provides an approximation of a complex subsurface hydrogeologic system; hydraulic heads and groundwater flow rates are simulated within the modeled section of a groundwater flow system. Groundwater models may be classified as either physical or mathematical models. While a physical model attempts to replicate a site-specific groundwater system as an enclosed system, a mathematical model attempts to describe the groundwater system and its boundaries through a set of equations that can computationally be solved (Kumar, 2015). With respect to mathematical models, one must distinguish between analytical models and numerical models. Analytical models use simplifying assumptions of reality to solve a given hydrogeologic system, keeping specific factors, such as overburden properties and water flow, constant in space and time. On the other hand, numerical models do not need to utilize such large assumptions and are able to divide space and/or time into discrete pieces. While analytical models are more commonly used in the field due to their simplicities, numerical models are able to provide a more realistic representation of complex groundwater systems (Kumar, 2015).

Processing Modflow for Windows (PMWiN) is a groundwater simulation system that supports several groundwater flow and solute transport models and is based on the USGS MODFLOW three-dimensional finite-difference code. It can simulate groundwater flow as a function of hydrogeologic properties and flow boundary conditions of the overburden. External flow factors, such as areal recharge, evapotranspiration, or drains can be simulated within the model as well (Chiang, 2005). This thesis utilizes the free Processing Modflow, for Windows 5.3.3 software, and the groundwater flow model MODFLOW-96.
6.2. Relevant PMWiN Inputs and Outputs

Input values within PMWiN are introduced without specified length and time units. This allows the user to use any set of units, as long as the input values are consistent. Results are displayed in the same units as those used in setting up the model (Harbaugh, 2005).

Each model within PMWiN is composed of a number of cells, which form a three-dimensional rectangular grid. The user may specify the number of rows and the number of columns on a horizontal plane and the number of layers in the vertical direction. The grid representing the model volume is then created, composed of a number of grid cells. Each cell contains a point called a node at which the head is calculated (Harbaugh, 2005).

The user may specify the simulation flow type as either steady state or transient (Anderson, et al., 2015). In steady state simulation, the storage equation is set to zero. A single stress period contains only one single time step, and only a single set of simultaneous equations is iteratively solved for each time-period (Harbaugh, 2005). In a transient simulation further hydrogeologic inputs, such as storage parameter and initial conditions are required. A transient model is clearly required to calculate water-level fluctuations induced by temporary pumping or drainage, which is the case within this thesis (Anderson, et al., 2015).

Numerical formulations, which describe groundwater flow and storativity, change based on the type of layer being used. With respect to the thesis, only two types of layers are of importance: confined (type 0) and an unconfined (type 1). Throughout the simulation an unchanged transmissivity is assumed. Transmissivity is the rate at which groundwater flows horizontally through any plane within the cell. For transient simulations, the change in storage is calculated based on the confined storage coefficient. A strictly unconfined layer, also known as water-table layer, is a type 1 layer. Only the uppermost layer of the model may be defined as type 1. The rate of change in storage is calculated through specific yield only. Transmissivity is calculated as the product of hydraulic conductivity and the saturated thickness of that layer for each iteration (Harbaugh, 2005; Chiang, 2005).
PMWiN consists of a Main Program and several independent subroutines, which are grouped into “packages.” The subdivision of hydrologic features into packages has the advantage to model each feature independently. Within this thesis, two packages are of concern; the General Head Boundary (GHB) and the drain package are used to simulate model boundaries of constant rate of water flow - in and out. The user may specify the location of the GHB and drain, and define their flow rates.

The General Head Boundary (GHB) package is used to simulate flow into or out of a cell from an external source in proportion between the head in the cell and the head assigned to the external source. The proportionality of inflow is given by the assigned boundary conductance constant, which is fixed for a steady state simulation and can be changed for individual stress periods in a transient simulation. The boundary conductance constant is defined for every cell by the user. In short, a linear relationship between flow into the cell and the head in the cell is defined (Chiang, 2005).

The drain package is used to simulate removal of water from a cell at a rate proportional to the head difference between the cell and the drain. Water removal occurs as long as the head within the cell is higher than the head of the drain, also called the drain elevation. The proportionality of flow of water into the drain, i.e., groundwater removal in the model, is given by the assigned boundary conductance constant, defined the same as in the General Head Boundary package. If the drain elevation remains above the head in the cell, no water removal takes place (Chiang, 2005). Drainage is defined by the user for each cell individually. Good modeling practice assumes that each cell with drainage just represents the physical part of the drain that overlies that cell (Harbaugh, 2005).

The user may choose a solver package to calculate the set of water flow equations. The Preconditioned Conjugate-Gradient Package (PCG2) is one of the solver packages used within PMWiN, which utilizes the head-change criterion and the residual criterion. The head-change criterion is met if the calculated head-change is within a defined tolerance, while the residual criterion, which is based on the difference between cell inflows and outflows, is met if the maximum change is less than or equal to the specified
tolerance. Both the head change and the residual criteria must be met for the iterative process to converge on a solution and stop (Harbaugh, 2005).

As soon as the model has been solved, the user may access the results within the program. The “Results Extractor” is an interface within PMWiN, which allows the user to read results of interest. Based on the amount of previously defined time steps and time periods, results are available for any cell at any of these time steps within any time period. The user may choose to read the results for each cell in a specific layer in “plan view” or read the results of all cells at a specific row or column. These specific results may be extracted and exported as an ASCII Matrix or as a Surfer file for further use. Of importance are the results of the Hydraulic Head (L).
7. Methodology for Determining Impacts to the Hydrogeologic System with respect to Underground Mining Operations

7.1. Methodology Background

Many researchers agree (Walker, 1988; Matetic, et al., 1995; Singh & Jakeman, 2001; Iannacchione & Tonsor, 2011; Guo, et al., 2012; Li, et al., 2015) that underground mining may cause a measurable impact on overlying bodies of water. A methodology for the assessment of potential underground mining impacts to groundwater is presented in this chapter. This methodology utilizes mine geometries as well as geologic and hydrogeologic characteristics for determining the potential impact a given mine will have on the surface and subsurface hydrogeologic systems. A methodology flow chart is provided in Figure 7-1.

Strain concentrations are commonly used in determining mining induced impacts on surface and subsurface bodies of water (Agioutantis, et al., 2016). In utilizing a subsidence prediction program (for this thesis SDPS), one is able to determine overburden deformations and therefore strain magnitudes throughout the overburden as well as on the surface. While the majority of the literature has focused on mining induced strain damages on the surface, strain magnitudes (SDPS) within the overburden can also cause detrimental impacts to the strata overlying the mined out seam (Newman, et al., 2016). Equations developed by Ouyang and Elsworth (1993) allow for the determination of strain impacts on the hydraulic conductivity of the overburden strata. As shown in Figure 7-1, the hydraulic conductivity results from these equations (see Section 7.3) are used as input parameters in a groundwater model (PMWiN) to determine post-mining hydrogeologic behaviors. In comparing the pre- and post-mining ground water models, one is able to then assess the impact mining induced strains have on the hydrogeologic system (Figure 7-2).
Figure 7-1: Methodology flow chart for determining the impact on the hydrogeologic system due to underground mining induced strains

Figure 7-2: Quantification of potential hydrogeologic impacts through comparison of pre- and post-mining state of a given hydrogeologic system

This methodology, which was developed as part of the present research, was utilized by Newman, et al. (2016) to compare changes in pre- and post-mining hydraulic heads for a simplified hydrogeologic system. Results of that theoretical case study resemble observations made by Walker (1988), depicting a gradual decrease in water levels within an aquifer post longwall mining operations as well as a rebound of water levels over time. The same methodology is utilized in this thesis to evaluate the effects of mining induced strain magnitudes on an aquifer.

7.2. Determining the Mining Induced Subsidence and Strain Regime

As previously discussed in evaluating mining induced impacts to the groundwater system, one must first determine deformations within the overburden strata. Subsidence prediction models are to be used to determine the mining induced subsidence as well as all related indices. However, due to its ability to determine horizontal and ground strain values
at any point along the surface and within the overburden, the SDPS program has been utilized for determining the mining induced strain regime within the overburden. In using the SPDS program for subsidence prediction, one must have accurate data for the mining geometries (plan), surface topography, and overburden characteristics.

7.3. Calculating Post-mining Hydraulic Conductivity

Once the strain regimen within the overburden has been determined one is able to calculate the post-mining hydraulic conductivities by equations (3) and (4) developed by Ouyang and Elsworth (1993).

\[
K_x = K_{xo}(1 + \frac{b+S(1-R_m)}{b} \Delta \varepsilon_y)^3 \quad (3)
\]

\[
K_y = K_{yo}(1 + \frac{b+S(1-R_m)}{b} \Delta \varepsilon_x)^3 \quad (4)
\]

where \( K_x \) and \( K_y \) are the post-mining hydraulic conductivities and \( K_{xo} \) and \( K_{yo} \) are the pre-mining hydraulic conductivities in their respective horizontal \((x)\) and vertical \((y)\) direction. The pre-mining hydraulic conductivity values can be obtained from field and/or laboratory testing or determined with respect to published literature. \( R_m \) is the modulus reduction factor, defined as the ratio of the elastic modulus of the intact rock mass to that of the intact rock, \( b \) is the fracture aperture, \( S \) is the fracture spacing and \( \Delta \varepsilon_x \) and \( \Delta \varepsilon_y \) are the pre- and post-mining strain differences in the direction perpendicular to the fracture plane. \( \Delta \varepsilon \) is positive in extension and negative in compression. The smallest possible change in hydraulic conductivity occurs with an \( R_m \) value of 1.0, which is used if the rock mass and the intact rock material moduli are identical and the strain is uniformly distributed between the fractures and matrix. A decreasing \( R_m \) value indicates an incremented application of strain onto the fracture system, leading to the largest possible change in hydraulic conductivity (Liu & Elsworth, 1997).

As indicated by equations (3) and (4), a positive increase in pre- and post-mining strain differences in horizontal \( (\Delta \varepsilon_x) \) or vertical direction \( (\Delta \varepsilon_y) \) leads to an increase in the post-mining hydraulic conductivity \((K_x \text{ or } K_y)\) in the direction perpendicular to the one
that experiences the pre- and post-mining strain difference (Ouyang & Elsworth, 1993). The horizontal and vertical post-mining hydraulic conductivity are to be calculated for each rock formation within the overburden with respect to the horizontal and vertical strain regimen provided by SDPS. The mathematical relationship for determining post-mining hydraulic conductivities with respect to mining induced strains developed by Ouyang & Elsworth (1993) was further evaluated. Vertical pre-mining hydraulic conductivities and rock parameters were assumed, the spacing at 0.33 m (1.08 ft), the fracture aperture at 0.001 m (0.003 ft), the modulus reduction factor at 0.8 and the vertical pre-mining horizontal conductivity \( (K_x) \) at 6.06x10\(^{-03}\) m/d. A range of pre- and post-mining horizontal strain differences \( (\Delta \varepsilon_x) \) of 1 mm/m and 100 mm/m (0.001 to 0.1), commonly encountered during ground movements, were introduced into the equation. Figure 7-3 displays the post-mining and pre-mining conductivity ratio as a function of the pre- and post-mining horizontal strain differences. As seen in Figure 7-3, post-mining conductivity values increase exponentially with increasing strain magnitudes. Results are equal in the perpendicular case, with horizontal pre-mining hydraulic conductivity and a pre- and post-mining strain difference \( (\Delta \varepsilon_y) \) in vertical direction.

Variation in post- and pre-mining HC ratios with respect to changing rock parameters were further evaluated for the horizontal case. A pre- and post-mining horizontal strain difference \( (\Delta \varepsilon_x) \) of 0.006 and a vertical pre-mining hydraulic conductivity of 6.06x10\(^{-03}\) m/d were assumed. Figure 7-4 shows the variation in post- and pre-mining HC ratios with respect to the modulus reduction factor \( (R_m) \) and the spacing. The Figure assumes a fracture aperture of 0.005 m (0.016 ft). An increase in spacing and a decrease in \( R_m \) leads to an increase in higher post- and pre-mining ratios. Figure 7-5 and Figure 7-6 show the variation in post- and pre-mining HC ratios with respect to the fracture aperture and spacing, and the fracture aperture and \( R_m \). The figures assume an \( R_m \) value of 0.9 and a spacing of 0.6 m (1.97 ft) for each case, respectively. Both figures show that a smaller fracture aperture value leads to an increase in post- and pre-mining HC ratios. Results are equal in the perpendicular case, with horizontal pre-mining hydraulic conductivity and a pre- and post-mining strain difference \( (\Delta \varepsilon_y) \) in vertical direction.
Figure 7-3: Vertical post-mining and horizontal strain relationship according to Ouyang and Elsworth (1993).

Figure 7-4: Variation in post- ($K_y$) and pre-mining ($K_{yo}$) HC ratios with respect to the modulus reduction factor and spacing.
Figure 7-5: Variation in Post- ($K_\text{y}$) and Pre-mining ($K_{\text{yo}}$) HC ratios with respect to the fracture aperture and spacing.

Figure 7-6: Variation in Post- ($K_\text{y}$) and Pre-mining ($K_{\text{yo}}$) HC ratios with respect to the fracture aperture and the modulus reduction factor.
7.4. Modeling the Hydrogeologic System and Comparing the Hydrogeologic Pre- and Post-mining States

Upon obtaining the post-mining hydrologic conductivity values with respect to the overburden strain regime, one now has the parameters necessary to run groundwater models for describing the pre- and post-mining state of the hydrogeologic system. A three-dimensional hydrogeologic model can be created using PMWiN using hydrogeologic parameters and the previously calculated vertical and horizontal pre- and post-mining hydraulic conductivity fields to simulate both pre- and post-mining states of the system, respectively. Hydrogeologic parameters may be extracted from available literature or assumed based on regional conditions. Hydrologic data on pre- and post-mining states may then be extracted from PMWiN and compared to evaluate the impact of underground mining on the groundwater system.
8. Case Study: Evaluating Mining Induced Impacts on the Ground Water System

8.1. Introduction

The methodology for determining mining induced impacts on the groundwater system was used to analyze and compare its results with a case study published by Walker (1988), which describes the effects of a longwall mining operation on the local water table. Relevant data was extracted from within the case study to develop two scenarios - one with a horizontal topography and the other with an inclined topography. Groundwater flow was simulated in two-dimensional space, i.e., panel cross-sections. A three-dimensional model allowed for easier programing within PMWiN, with equal input values across its length, which mirrored the two-dimensional conditions.

Two groundwater flow scenarios were then developed as, which resemble the described site conditions by Walker (1988). The first scenario implements a flat surface topography while the second scenario implements a topography similar to that described by Walker (1988). With respect to the previously described methodology, horizontal strain values were extracted from SDPS within the major zones of deformation for each of the given scenarios. Upon obtaining the strain magnitudes within the overburden, the post-mining hydraulic conductivity was determined by means of equations (3) and (4). Each scenario contains two hydrogeologic models - pre-mining and post-mining. By comparing the results of the pre- and post-mining models, one is able to quantify mining induced impacts to the local groundwater system.

8.2. Site Description

Walker (1988) describes the mine to be located in southwestern Pennsylvania near the city of Waynesburg. It encompasses four longwall panels denoted as A, B, C and D. All panels are 192 m (630 ft) wide and spaced on 275 m (900 ft) centers. Furthermore, Panel A is 1433 m (4700 ft) long, while all other panels are 1615 m (5300 ft) long. Figure 8-1 shows the layout of the study area in which panels, water wells and surface contours are shown; the blue line within the Figure depicts a cross-section of the mine.
The longwall panels are located in the Pittsburgh coal seam, whose average thickness is of 1.8 m (5.8 ft). The surface above the mined out panels varies with elevations. Overburden depth ranges from 213 m (700 ft) to 305 m (1000 ft). The geologic composition may be described as interbedded fine-grained sedimentary rocks with thick layers of sandstone, limestone, and coal. Measured maximum subsidence for panel A is 1.16 m (3.82 ft), for panel B is 0.95 m (3.12 ft) and for panel C is 1.09 m (3.58 ft). No values on subsidence for panel D are given. The angle of influence was measured at 66 degrees (Walker, 1988). Figure 8-2 shows the panel locations with respect to the surface topography, a cross-section similar to the cross section depicted in Figure 8-1. For the
groundwater flow scenario with inclined topography, measured water levels from wells 1 to 4 were compared to simulation results.

![Diagram of panel locations with respect to surface topography](image)

**Figure 8-2: Panel locations with respect to surface topography (Walker, 1988)**

### 8.2.1. Site-Specific Hydrogeologic Parameters

Walker (1988) refers to Stoner (1983) when describing the hydrology of the area. Stoner (1983) describes the groundwater flow system to be complex and strongly controlled by groundwater movement through fractures and bedding plane fractures (secondary permeability). Water circulation occurs within the first 45 m (150 ft). Fractured sandstone and coals are water-bearing. Further water-bearing zones can also be found at the interfaces of different rock types.

Stoner (1983) provides ranges for horizontal and vertical hydraulic conductivity (HC) for different zones within the overburden from which average HC can be calculated. The average horizontal HC within the first 45 m (150 ft) was calculated at $7.70 \times 10^{-01}$ m/d. In deeper depths, up to 250 m (820 ft), the average horizontal HC was calculated at $7.70 \times 10^{-03}$ m/d. Vertical HC for each zone is specified by Stoner (1983) to be 225 times less than horizontal HC. Walker (1988) describes a stream flow from north to south with a
turn towards west-northwest. Direction and quantity of groundwater flow is not mentioned (Stoner, 1983; Walker, 1988).

8.3. Determining the Strain Regime over a High Extraction Area

The strain regime over a longwall panel cross-section was determined with SDPS. Calculations were simplified by taking a single longwall panel instead of two panels into account. Stress and strain resulting from ground movements of multiple adjacent panels may interact and change the overburden stress and strain regime further. However, stress and strain calculations of two panels, instead of one, requires further input values, which adds to an already extensive portfolio of inputs, leading to similar results, and therefore not yielding any further benefit. Calculations were further simplified by assuming a horizontal surface and no edge effect. The extraction thickness was rounded up to 2 m (6.6 ft).

In full extraction underground mining, three deformation zones are typically identified: the caving zone, the fracture zone and the continuous deformation zone (CDZ) (Peng & Chiang, 1984). For simplification, caving and fracture zone, which are the zones of most severe hydrogeologic changes within the overburden, were merged into one layer. The thickness of the layer was assumed to be 100 m (328.1 ft); a value well within the suggested ranges by Peng and Chiang (1984) for the fracture and caving zones, combined. The CDZ was divided into two layers. The upper layer represents the aquifer, and the lower layer represents the remainder of the CDZ, with thicknesses of 45 m (147.6 ft) and 105 m (344.5 ft), respectively. Several sets of prediction points transversed the mined out panels at elevations of 50 m (164 ft), 152.5 m (500.3 ft) and 227.5 m (746.4 ft), with respect to the location of the three deformation zones (caving, fracture and continuous), previously discussed.

As described by Walker (1988), the overburden is strongly interbedded with dominant layers of sandstone, limestone and coal. The majority of the overburden was soft rock, hence a Percent Hardrock of 40 % or less was assumed. The angle of influence was measured at 66 degrees, which is equivalent to a tangent of influence angle of 2.25. For all other unknown input values, SDPS default values for the region of Pennsylvania
were used, with a supercritical subsidence value of 39.5 \% and a horizontal strain coefficient of 0.35. Table 8-1 shows all relevant SDPS input values.

Table 8-1: Input parameters for SDPS models

<table>
<thead>
<tr>
<th>Input Sections</th>
<th>Inputs</th>
<th>Value</th>
<th>Units</th>
<th>Abbr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine Geometry</td>
<td>Panel Length</td>
<td>1600</td>
<td>m</td>
<td></td>
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<tr>
<td></td>
<td>Panel Width</td>
<td>190</td>
<td>m</td>
<td>W</td>
</tr>
<tr>
<td></td>
<td>Parcel Elevation</td>
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<td>m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Extraction Thickness</td>
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<td></td>
<td>Critical/Supercritical Subsidence</td>
<td>39.5</td>
<td>%</td>
<td>a</td>
</tr>
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<td></td>
<td>Factor or Max. Subsidence Factor</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Edge Effect offset</td>
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<td>m</td>
<td>d</td>
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<tr>
<td>Location of Prediction Points</td>
<td>Average Point Elevation</td>
<td>50, 152.5 and 227.5</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>Overburden/Rock Mass Parameters</td>
<td>Influence Angle</td>
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<td>degree</td>
<td>(\beta)</td>
</tr>
<tr>
<td></td>
<td>Horizontal Strain Coefficient</td>
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<td>unitless</td>
<td>(B_s)</td>
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<tr>
<td></td>
<td>Percent Hardrock</td>
<td>40</td>
<td>%</td>
<td>(%HR)</td>
</tr>
</tbody>
</table>

A subsidence value of 0.77 m (2.5 ft) was determined, which is equivalent to a vertical compressive strain value of 0.0031, if taking the overburden elevation as whole. Subsidence values were deemed close enough to the observed subsidence for Panel A, B and C, at 1.16 m (3.8 ft), 0.95 m (3.12 ft) and 1.09 m (3.58 ft), respectively.

Table 8-2 shows calculated results for maximum compressive and tensile Horizontal Strain (\(\Delta \varepsilon_x\)). Horizontal strain results for the deformation zones, excluding results for the aquifer, may be used for both, horizontal and inclined topography scenarios, as strain magnitudes are a function of distance from the extracted panels and therefore equal for both cases. Topographic conditions may affect strain development at the surface and the aquifer. However, changes for the aquifer are deemed small and results may therefore be used for both topography scenarios as well.

49
8.4. Calculating Post-mining Hydraulic Conductivity

Strain values determined from SDPS were introduced into equations (4) and (5) to determine post-mining hydraulic conductivity (HC). Chosen horizontal pre-mining HC values for the aquifer, and layers below, approximate given HC values by Stoner (1983); pre-mining horizontal HC for the aquifer lies at 7.70x10^{-01} m/d and deeper layers have a HC value of 7.70x10^{-03} m/d. After a preliminary run, it was decided not to use vertical HC values provided by Stoner (1983), which are 225 times smaller than horizontal HC values. A lower vertical HC value results in slower vertical water infiltration into deeper layers, leading to substantially longer runtime (years) to observe changes in water levels. Horizontal HC values were set equal to vertical HC values for each layer, respectively. As no site-specific information is provided by Walker (1988) on either the fracture aperture \( b \), the spacing between fractures \( S \) or the modulus reduction factor \( R_m \), these values were then assumed, resulting in a modulus reduction value of 0.8, fracture spacing of 1 m (3.28 ft) and a fracture aperture of 0.001 m (0.003 ft). Values are of similar ranges as given by Matetic, et al. (1995).

The maximum compressive and tensile strain values were used to calculate post-mining HC (\( K_y \)) as shown in Table 8-3. Post-mining HC to pre-mining HC (\( K_{yo} \)) ratios were calculated and found to be within the range of 0 to 65. Post- and pre-mining HC ratios were then compared to pre- and post-mining HC variations, found within the literature (Table 4-1 and Table 4-2). Calculated ratios were found within pre- and post-mining HC variations given by literature, which vary for different rock types between one and four.

### Table 8-2: SDPS results for horizontal strain (\( \Delta \varepsilon_x \))

<table>
<thead>
<tr>
<th>Elevation (m)</th>
<th>Tensile Strain (( \Delta \varepsilon_x ))</th>
<th>Compressive Strain (( \Delta \varepsilon_x ))</th>
<th>Deformations Zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>227.5</td>
<td>0.0041</td>
<td>-0.0041</td>
<td>Aquifer (CDZ)</td>
</tr>
<tr>
<td>152.5</td>
<td>0.0062</td>
<td>-0.0057</td>
<td>CDZ</td>
</tr>
<tr>
<td>50</td>
<td>0.0150</td>
<td>-0.0126</td>
<td>Caving and Fracture Zone</td>
</tr>
</tbody>
</table>
order of magnitudes. Post-mining HC values were simplified; calculated ratios were rounded down to one for the two upper layers (the aquifer, a part of the CDZ and the remainder of the CDZ) and rounded to 100 for the two lower layers (the fracture and caving zone and the coal seam). This was done in order to emphasize an increase in hydraulic conductivity due to increased fracture development within the fracture and caving zones compared to upper layers.

Table 8-3 provides further insight, with tensile strains developing at the concave segment and compressive strains developing at the convex segment of the subsidence trough. With the inflection point being the crossover point between the two segments, it is reasonable to assume that each deformation zone as defined by Peng and Chiang (1984) is subjected to increased post-mining hydraulic conductivity at the concave segments and decreased post-mining hydraulic conductivity at the convex segments, simultaneously. Furthermore, with increasing depth, both, compressive and tensile strain values increase, leading to a wider range in post-mining hydraulic conductivities in lower layers. Referred observation is not further discussed with respect to this thesis.
Table 8-3: Pre- ($K_{yo}$) and post-mining ($K_y$) hydraulic conductivity and other overburden parameters

<table>
<thead>
<tr>
<th>Deformation Zones</th>
<th>$\Delta \varepsilon$</th>
<th>S (m)</th>
<th>b (m)</th>
<th>R_m</th>
<th>$K_{yo}$ (m/s)</th>
<th>$K_y$ (m/s)</th>
<th>$K_y$/K_{yo}</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horizontal Strain</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile</td>
<td>Aquifer (CDZ)</td>
<td>0.0041</td>
<td>1</td>
<td>0.001</td>
<td>0.8</td>
<td>7.70x10^{-01}</td>
<td>4.67</td>
</tr>
<tr>
<td></td>
<td>CDZ</td>
<td>0.0062</td>
<td>1</td>
<td>0.001</td>
<td>0.8</td>
<td>7.70x10^{-03}</td>
<td>8.73x10^{-02}</td>
</tr>
<tr>
<td></td>
<td>Caving and Fracture Zone</td>
<td>0.0150</td>
<td>1</td>
<td>0.001</td>
<td>0.8</td>
<td>7.70x10^{-03}</td>
<td>4.98x10^{-01}</td>
</tr>
<tr>
<td>Compressive</td>
<td>Aquifer (CDZ)</td>
<td>-0.0041</td>
<td>1</td>
<td>0.001</td>
<td>0.8</td>
<td>7.70x10^{-01}</td>
<td>4.19x10^{-03}</td>
</tr>
<tr>
<td></td>
<td>CDZ</td>
<td>-0.0057</td>
<td>1</td>
<td>0.001</td>
<td>0.8</td>
<td>7.70x10^{-03}</td>
<td>-2.38x10^{-05}</td>
</tr>
<tr>
<td></td>
<td>Caving and Fracture Zone</td>
<td>-0.0126</td>
<td>1</td>
<td>0.001</td>
<td>0.8</td>
<td>7.70x10^{-03}</td>
<td>-2.77x10^{-02}</td>
</tr>
<tr>
<td><strong>Vertical Strain</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressive</td>
<td>Overburden Elevation as whole</td>
<td>-0.0031</td>
<td>1</td>
<td>0.001</td>
<td>0.8</td>
<td>7.70x10^{-01}</td>
<td>4.12x10^{-04}</td>
</tr>
</tbody>
</table>
8.5. Simulating Changes in a Hydrogeologic System

Two simplified hydrogeologic models were developed, resembling the described site conditions by Walker (1988). The models use three layers for the overburden and one layer for the coal seam. Water enters the surface aquifer through a General Head Boundary (GHB) source and leaves the system through a drain. Drainage in the coal seam simulates mine dependent pumping.

Pre- and post-mining hydraulic heads within the system were reproduced. Primary objective was to reproduce fairly stable pre-mining water flow conditions of the site and then to introduce mining effects into the system (pumping), in hope of reproducing fairly similar observed post-mining water flow effects as described by papers.

The groundwater flow model that was employed in this analysis, does not allow period dependent input of horizontal and vertical hydraulic conductivity. Therefore, a groundwater flow model simulating the pre-mining state of a flow system (Model 1), was developed as a baseline to validate the usefulness of a further pre-mining model, with post-mining hydraulic conductivities (Model 2). Both models were run for a time period of 30 years to allow water flow conditions to stabilize, and then compared. If the results were deemed close enough, Model 2 was then used as the main pre-mining model instead of Model 1. Model 3 simulated the post-mining state of a system, using post-mining hydraulic conductivity and drainage at the coal seam, to reproduce mine dependent water pumping. Model 3 was run under stabilized water flow conditions from Model 2 for a time period of 10 years. Stabilized water flow conditions from Model 2 and post-mining flow conditions from Model 3 were then compared for any head differences, allowing pre- and post-mining change to be quantified. All three models were created for the horizontal (a) and the inclined (b) topography scenario, respectively. Figure 8-3 shows the development of both three-dimensional conceptual mining scenarios within PMWiN.

The simulation flow type of all models (pre- and post-mining) was specified as transient, which is required in order to calculate water-level fluctuations induced by temporary pumping or drainage. Furthermore, the iteration based Preconditioned Conjugate-Gradient Package (PCG2) was chosen as the solver package to determine pre-
and post-mining hydraulic heads. Generated values by PCG2, which uses both, the head-change and the residual criterion, generate more reliable values than other solver packages, which only rely on one of these two criteria.

Figure 8-3: Development of two 3D conceptual mining scenarios within PMWiN
8.6. Description of Models and Model Input Parameters at Pre-mining State

All three-dimensional groundwater flow models (Model 1, 2 and 3) for the horizontal and the inclined topography scenarios are comprised of four layers. These shall represent the aquifer (Layer 1), which is part of the continuous deformation zone (CDZ), the CDZ (Layer 2), the caving and fracture zone (Layer 3), which are the zones of most severe hydrogeologic change within the overburden, and a coal seam (Layer 4) located beneath all other layers. Layer 1 is defined as unconfined (type 1), while all other layers are defined as strictly confined (type 0). Groundwater flow occurs from a General Head Boundary (GHB) source and leaves the system through a drain (at the eastern boundary of the model). The GHB and the drain are located at opposite ends of the aquifer and ensure a water flow regime from west to east. This constitutes an assumption since regional water flow is not known for the case study, which was used as the basis of this model.

The initial hydraulic head is located in Layer 1 and is constant throughout the model at 15 m below the surface.

Figure 8-4 and Figure 8-5 shows the 3D groundwater flow model for the pre-mining state for the horizontal and the inclined topography scenarios. Both figures are only a graphical representation of the models; they are not to scale.

![Figure 8-4: Mining under horizontal topography (Model 1a)](image-url)
Figure 8-5: Mining under inclined topography (Model 1b)

All flow models are comprised of 125 cells in width, with a cell size of 5 m (16.4 ft) (total model width of 625 m (2050.5 ft)) and 162 cells in length, with a cell size of 10 m (32.8 ft) (total model length of 1620 m (5314.9 ft)). Table 8-4 shows the cell dimensions for both the horizontal and inclined topography scenarios.

Table 8-4: Cell dimensions for horizontal and inclined topography scenario

<table>
<thead>
<tr>
<th>Final Inputs</th>
<th>Cell Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size Column</td>
<td>5 m</td>
</tr>
<tr>
<td>Size Row</td>
<td>10 m</td>
</tr>
<tr>
<td># Columns</td>
<td>125 #</td>
</tr>
<tr>
<td># Rows</td>
<td>162 #</td>
</tr>
</tbody>
</table>

Table 8-5 and Table 8-6 show the dimensions of the layers for both, the horizontal and the inclined topography scenarios.
Table 8-5: Dimensions of layers for horizontal topography scenario

<table>
<thead>
<tr>
<th>Layer</th>
<th>Layer dimensions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height (m)</td>
<td>Elevation Top (m)</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>250</td>
</tr>
<tr>
<td>2</td>
<td>105</td>
<td>205</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 8-6: Dimensions of layers for inclined topography scenario

<table>
<thead>
<tr>
<th>Layer</th>
<th>Layer dimensions</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Height (m)</td>
<td>Elevation Top West (m)</td>
</tr>
<tr>
<td>1</td>
<td>45</td>
<td>306.21</td>
</tr>
<tr>
<td>2</td>
<td>variable</td>
<td>261.21</td>
</tr>
<tr>
<td>3</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>
The parameters that govern the behavior of the GHB and drain conditions are the GHB and drain conductance respectively. According to Winston (2017), the GHB and drain conductance may be calculated as shown in equation (5):

\[ C = \frac{KWL}{M} \]  

(5)

where \( C \) is the GHB or drain conductance, \( K \) is the hydraulic conductivity of the sediment in the boundary condition (average HC of the aquifer), \( W \) is the width of the boundary condition perpendicular to the flow direction (thickness of aquifer), \( L \) the length of the boundary condition within the cell perpendicular to the flow direction and \( M \) the thickness of the formation in the boundary condition perpendicular to flow between the boundary and the cell. The GHB conductance (GHBC) was calculated as shown in equation (6). Same calculated value was adopted as drain conductance.

\[ GHBC = \frac{7.70 \times 10^{-1} \frac{m}{d} \times 45 m \text{ (aquifer thickness)} \times 10 m \text{ (cell length)}}{50 m \text{ (Boundary Distance)}} \]  

\[ = 6.982 \frac{m^2}{d} \]  

(6)

Table 8-7 summarizes the pre-mining hydrogeologic overburden characteristics and GHB and drain parameters for the horizontal and inclined topography scenarios. In order to simplify calculations, typical values for specific storage (1.00x10^{-04}/m) and specific yield (0.25), were chosen.
Table 8-7: Pre-mining hydrogeologic overburden characteristics and GHB and drain parameters for horizontal and inclined topography scenarios

<table>
<thead>
<tr>
<th>Layer</th>
<th>Hydrogeologic Overburden Characteristics</th>
<th>GHB and Drain Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal HC (m/d)</td>
<td>Vertical HC (m/d)</td>
</tr>
<tr>
<td>1</td>
<td>7.70x10⁻⁰¹</td>
<td>7.70x10⁻⁰¹</td>
</tr>
<tr>
<td>2</td>
<td>7.70x10⁻⁰³</td>
<td>7.70x10⁻⁰³</td>
</tr>
<tr>
<td>3</td>
<td>7.70x10⁻⁰³</td>
<td>7.70x10⁻⁰³</td>
</tr>
<tr>
<td>4</td>
<td>7.70x10⁻⁰³</td>
<td>7.70x10⁻⁰³</td>
</tr>
</tbody>
</table>
8.7. Model Input Parameters at the Post-mining State

To simplify the modeling effort, only two longwall panels are modeled. Cells 16 to 55 represent Panel A and cells 71 to 110 represents Panel B. Figure 8-6 and Figure 8-7 show the three-dimensional groundwater flow model for the horizontal topography scenario at post-mining state without and with drain. The increase in hydraulic conductivity in layers 3 and 4 are marked through altered cell colors. Both figures are only a graphical representation of the models; they are not to scale.

**Figure 8-6: Mining under horizontal topography (Model 2a)**

**Figure 8-7: Mining under horizontal topography (Model 3a)**

Figure 8-8 and Figure 8-9 show the three-dimensional groundwater flow model for the inclined topography scenario at post-mining state without and with drain. Again, the increase in hydraulic conductivity in layers 3 and 4 are marked through altered cell colors.
Table 8-8 shows the pre- and post-mining hydrogeologic overburden characteristics and the post-mining GHB and drain parameters for the horizontal and inclined topography scenarios. Flow characteristics at the aquifer (flow from GHB towards drain) remain unchanged in post-mining state. Cells in Layer 3 and 4 (coal seam, and caving and fracture zone), experience an increase in vertical and horizontal HC by two magnitudes, to simulate extraction at the seam, and fracture development above the seam. Drainage at cells representing panel A and B simulate pumping activity, which is for both panels equally strong and simultaneous. A drain value of 0.001 m²/d per cell was chosen; a value strong enough to show post-mining flow trends, without fully draining the aquifer. All other cells within the model are not subjected to any drain or change in HC.
Table 8-8: Pre- and post-mining hydrogeologic overburden characteristics and post-mining GHB and drain parameters for horizontal and inclined topography scenarios

<table>
<thead>
<tr>
<th>Layer</th>
<th>Pre-mining State</th>
<th>Post-mining State</th>
<th>GHB and Drain (Post-mining)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal HC (m/d)</td>
<td>Vertical HC (m/d)</td>
<td>Horizontal HC (m/d)</td>
</tr>
<tr>
<td>1</td>
<td>7.70x10^{-01}</td>
<td>7.70x10^{-01}</td>
<td>7.70x10^{-01}</td>
</tr>
<tr>
<td>2</td>
<td>7.70x10^{-03}</td>
<td>7.70x10^{-03}</td>
<td>7.70x10^{-03}</td>
</tr>
<tr>
<td>3</td>
<td>7.70x10^{-03}</td>
<td>7.70x10^{-03}</td>
<td>7.70x10^{-01}</td>
</tr>
<tr>
<td>4</td>
<td>7.70x10^{-03}</td>
<td>7.70x10^{-03}</td>
<td>7.70x10^{-01}</td>
</tr>
</tbody>
</table>
8.8. Impact of Horizontal and Inclined Topography

Groundwater flow models were run for the horizontal and inclined topography scenarios. Results for the hydraulic head were extracted, analyzed and depicted in diagrams. The version of PMWiN that was used does not allow period dependent input of horizontal and vertical hydraulic conductivity. Therefore, three models had to be developed for each topographic scenario:

- Model 1 simulated the pre-mining state of a flow system. It was used to validate Model 2. The model was run for a time period of 30 years to allow flow conditions to stabilize, i.e., layer depended hydraulic heads to build up.
- Model 2 simulated the pre-mining state of a flow system, with post-mining hydraulic conductivities. The model was run for a time period of 30 years, same as Model 1, making a comparison between both models possible.
- Model 3 simulated the post-mining state of a flow system. It was run for a time period of 30 years in steady state and further 10 years under constant mine depended drainage.

Stabilized hydraulic heads from Model 2 and post-mining hydraulic heads from Model 3, i.e., hydraulic heads after 10 years of mine dependent drainage, were then compared for the top three layers: the aquifer, a part of the continuous deformation zone (CDZ), the CDZ, and the fracture and caving zone embedded as one layer.

8.8.1. Validating Pre-mining Models for Horizontal Topography

Figure 8-10, Figure 8-11 and Figure 8-12 depict pre-mining hydraulic heads for Models 1 and 2 for the aquifer, the CDZ and the caving and fracture zone, respectively. After 30 years of run time, heads of all deformation zones have stabilized close to the level of the initial hydraulic head depicted in Figure 8-10. Hydraulic heads of Model 1 and 2 never differ more than 0.1 m (0.33 ft), therefore validating Model 2 as being equally representative of a pre-mining state of a system. Differences in hydraulic heads of Model 1 and 2 are attributed to changing hydraulic conductivities, whose effects can especially be seen in Figure 8-12; abrupt changes in the head gradient of Model 2. Hydraulic heads at all deformation zones are highest close to the GHB and decrease while approaching the drain.
Furthermore, hydraulic heads close to the GHB tend to be higher in upper deformation zones than in lower ones, adopting similar elevations while approaching the drain.

**Figure 8-10:** Comparing Models 1 and 2 at aquifer (CDZ) under stabilized pre-mining flow conditions

**Figure 8-11:** Comparing Models 1 and 2 at CDZ under stabilized pre-mining flow conditions
8.8.2. Comparing Pre-mining and Post-mining Hydraulic Heads for Horizontal Topography

Figure 8-12, Figure 8-14 and Figure 8-15 depict stabilized pre-mining hydraulic heads from Model 2 and post-mining hydraulic heads from Model 3, i.e., hydraulic heads after 10 years of mine dependent drainage for all deformation zones, the aquifer, the CDZ and the caving and fracture zone, respectively. Observed head decrease is less severe in upper deformation zones than in lower ones. At the aquifer, head decrease is steady from the GHB towards the drain. Furthermore, at the CDZ and the caving and fracture zone, head decrease is steady from the GHB towards the drain, until rebounding beyond Panel B; rebounding being more severe at the caving and fracture zone. While pressure drop is more severe in areas above increased hydraulic conductivity (HC) at the CDZ, pressure drop at the caving and fracture zone is observed mainly around areas of increased HC.
Figure 8-13: Post-mining hydraulic head at aquifer (CDZ)

Figure 8-14: Post-mining hydraulic head at CDZ
Figure 8-15: Post-mining hydraulic head at caving and fracture zone

Figure 8-16 summarizes the mining effects for all deformation zones under horizontal topography. Water levels (hydraulic heads) within the hydrogeologic system are reduced due to mining induced impacts to the overburden from Panel A and Panel B. Water within the aquifer has not been significantly affected and results indicate that water levels at deeper horizons begin to rebound beyond Panel B.
8.8.3. Validating Pre-mining Models for Inclined Topography

Figure 8-17, Figure 8-18 and Figure 8-19 depict pre-mining hydraulic heads for Models 1 and 2 for the aquifer, the CDZ and the caving and fracture zone, respectively. After 30 years of run time, heads of all deformation zones have stabilized. Hydraulic heads of Model 1 and Model 2 at the aquifer are almost equal. Close to the GHB, they can be found at lower elevations than the initial hydraulic head, adopting first similar and then higher elevations, while approaching the drain. Hydraulic heads at lower deformation zones tend to stabilize within smaller elevation ranges than heads at upper deformation
zones; heads at lower zones are observed to have less steep head gradients, while the head is always highest close to the GHB and lowest close to the drain.

Heads of Model 1 and Model 2 differ more substantially at lower deformation zones by up to 10 m at model ends. Differences between hydraulic heads of Model 1 and 2 are more severe, but still deemed within acceptable ranges, therefore validating Model 2 as being equally representative of a pre-mining state of the system. The shape of all stabilized hydraulic heads for Model 1 are attributed to the inclined topography. All stabilized heads for Model 2 are additionally affected by changing hydraulic conductivities, whose effects can especially be seen in Figure 8-19; abrupt changes in the head gradient of Model 2.

![Figure 8-17: Comparing Models 1 and 2 at aquifer (CDZ) under stabilized pre-mining flow conditions](image-url)
Figure 8-18: Comparing Models 1 and 2 at CDZ under stabilized pre-mining flow conditions

Figure 8-19: Comparing Models 1 and 2 at caving and fracture zone under stabilized pre-mining flow conditions
8.8.4. Comparing Pre-mining and Post-mining Hydraulic Heads for Inclined Topography

Figure 8-20, Figure 8-21 and Figure 8-22 depict stabilized pre-mining hydraulic heads from Model 2 and post-mining hydraulic heads from Model 3, i.e., hydraulic heads after 10 years of mine dependent drainage for all deformation zones, the aquifer, the CDZ and the caving and fracture zone, respectively. Observed head decrease is less severe in upper deformation zones than in lower ones. At the aquifer, head decrease is steady from the GHB towards the drain. Same applies to the CDZ, with additional more severe pressure drop in areas above increased hydraulic conductivity (HC). At the caving and fracture zone, head decrease is steady from the GHB towards the drain, until rebounding beyond Panel B. Furthermore, pressure drop at the caving and fracture zone is observed mainly around areas of increased HC.

![Graph showing hydraulic head comparison](image)

**Figure 8-20: Post-mining hydraulic head at aquifer (CDZ)**
Figure 8-21: Post-mining hydraulic head at CDZ

Figure 8-22: Post-mining hydraulic head at caving and fracture zone

Figure 8-23 summarizes the mining effects for all deformation zones under inclined topography. Results show a reduction in water levels (hydraulic heads) within the hydrogeologic system due to mining induced impacts to the overburden material. Water levels within the aquifer have not been significantly affected and results indicate that
hydraulic heads at deeper horizons begin to rebound beyond Panel B. Measured results by Walker (1988) for an inclined topography were compared to simulation results. They show similar trends.

Figure 8-23: Mining effects under inclined topography
9. Conclusions and Recommendations

9.1. Summary

Mine-induced ground movements will result in the development of strain in the overburden, causing changes in hydrogeologic overburden properties. Such changes may impact the hydrogeologic system above an undermined area. A practical approach to assess potential mining induced impacts on aquifers was developed, which is based on a proposed mathematical relationship between strain and hydraulic conductivity by Ouyang and Elsworth (1993). In this approach the horizontal and vertical strain regime due to underground mining is calculated, then the post-mining hydraulic conductivity is calculated by utilizing the pre-mining hydraulic conductivity, several overburden properties and strain through the above mentioned relationships. Finally, pre- and post-mining water elevations are calculated at given locations above a mined panel.

The tools utilized in this research to complete the above tasks include (a) the influence function formulation in the SDPS package which is used to calculate strain in the overburden and (b) the PMWiN package (based on the USGS MODFLOW code) which is used to calculate the pre- and post-mining hydrogeologic water flows over the study area.

The proposed approach was implemented on a case study to study the potential impacts of full extraction mining on a groundwater system: Two simplified hydrogeologic models were developed, resembling described site conditions by Walker (1988) – one with horizontal and one with inclined topography. The top layer of the model was considered an aquifer and water was simulated to flow from west to east using a general head boundary and a drain. The groundwater model was allowed to run for several years to establish the baseline or initial conditions. Mining effects to the groundwater system where then simulated by reducing the hydraulic conductivity in the caving zone and simulating water loss to the mine using a drain. Pre- and post-mining hydraulic heads within the system were calculated and compared.

Results show in both cases a reduction in water levels (hydraulic heads) within the hydrogeologic system due to mining induced impacts to the overburden material. Water
levels related to surface aquifers dropped while panels were mined, but water was not completely lost. Water levels at deeper horizons began to rebound beyond the mined panels. Topography had an effect on the post-mining distribution of water levels. Measured results by Walker (1988) for an inclined topography were adjusted to be comparable with simulation results, and show a similar tendency.

9.2. Strength and Weaknesses of the Proposed Approach

The proposed approach can be used to quantify changes in pre- and post-mining hydraulic systems; results have shown that the approach is applicable on simple mining cases under different topographic conditions. The software packages that were utilized in this approach were easy to use and readily accessible. Other software packages may also be used instead of proposed ones (SDPS and PMWiN), adding flexibility to the approach.

Overall, the proposed approach requires several assumptions and numerous input values for each process step. Assumptions are required for both, modeling of ground deformations as well as modeling of ground water flow. Input values, which are not known or available should be extracted from available literature or be assumed based on user experience. As with any numerical model, output is as good as the input given. Due to the large number of variables and unknown involved in the present study, the effort was concentrated more towards a qualitative comparison of pre- and post-mining hydraulic heads.

9.3. Future Work

The proposed approach was used to study mining effects on groundwater under a horizontal and inclined topography. For that purpose, a three-dimensional groundwater flow model was developed, representing a two-dimensional overburden section above a set of longwall mine panels. Key assumptions included the division of the overburden into three deformation zones, a regional water flow from west to east, a post-mining increase in hydraulic conductivity in zones directly above mining areas, and a post-mining drainage of water at mining areas, which simulates mine dependent pumping. A thorough sensitivity analysis needs to be performed, by changing a single input parameter at a time, among
others, such as water inflow, post-mining hydraulic conductivity above mined areas and mine drainage.

The sensitivity analysis will help identify the critical parameters of the problem and more specifically:

- Mining effects at the caving and fracture zone can be studied in detail by dividing both deformation zones into several thinner layers with different post-mining hydraulic conductivities between and within layers; higher post-mining hydraulic conductivity at lower layers may simulate more intense fracture development.
- The use of more complex models depicting hydrogeologic changes within the overburden due to mine-induced ground deformation (such as a model by Kendorski (1993; 2006), which assumes five deformation zones) may allow a more realistic simulation of pre- and post-mining conditions of a hydrologic system.
- Changes in groundwater flow can be studied after ceasing of mine dependent pumping operations, usually leading to a rebound of water levels.
- Integral three-dimensional models of a mine site, with unique site characteristics, may be developed. The model can include uneven topographic conditions, multiple aquifers and panels, non-horizontal panels, rivers, and other, giving valuable insight on more realistic groundwater flow cases.

Utilization of the proposed approach needs to be further validated using actual case study data. It is recommended that on-site mine studies are conducted involving a thorough analysis of the pre- and post-mining conditions of the overburden and the hydrogeologic system of the mine site. Pre-mining conditions of the overburden and hydrogeologic system shall then be reproduced with appropriate numerical models. Mining information will then be added to these models in order to generate post-mining conditions of the overburden and the hydrogeologic system. Results must then be statistically evaluated to determine the accuracy of the new proposed approach. Field work of this magnitude usually entails a substantial commitment of resources, especially time and funding.
APPENDIX: PUBLICATIONS, PRESENTATIONS AND POSTERS RELATED TO THIS WORK

Publications related to this work


Presentations related to this work


Posters Presentations related to this work


REFERENCES


VITA

Gabriel Bode-Jimenez was born in State College, Pennsylvania, USA to Klaus Böde and Gloria Jiménez León. In 2008 he graduated from the German School of London, U.K. and moved to Bogotá, Colombia, where he completed a Vocational Education as Industrial Clerk, with employment at the German-Colombian Chamber of Commerce and Industry (AHK) and its Subsidiary DEinternational Ltda in 2010. In August 2014 he graduated from Karlsruhe Institute of Technology (KIT) with a Bachelors Degree in Industrial Engineering and Management, followed by employment as Field Engineer (Trainee) until July 2017 at Grup Servicii Petroliere (GSP) in Constanta, Romania. Gabriel joined the Mining Engineering Department in August 2015 working as a graduate research assistant under Dr. Zacharias Agioutantis. He expects to graduate with a Master of Science in Mining Engineering in July 2017. Gabriel is a WAAIME Scholarship recipient (August 2016) and a member of SME since 2015.

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