

Surface Water Impacts from Active Underground Mining

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Abstract

High extraction mining techniques have produced the need to mitigate and understand ground movements associated with this technology. Tools such as the Surface Deformation Prediction System (SDPS) facilitate sound scientific decision making in the industry and has continually improved since its inception in 1987. The capabilities of SDPS have expanded on an as-needed basis. Currently, the regulatory climate has emphasized the need to understand the impact of underground mining on surface waters, physically and chemically.

The SDPS program is used to conduct an analysis of ground movements to assess optimal barrier pillar size for stream protection. Typical analytical and empirical methods used in mine planning were compared against SDPS methods to ensure the validity and advantage to the use of SDPS for this purpose.

Finally, underground mining effects on stream chemistry and health were explored by studying the heavily mined and industrialized watershed of Dumps Creek located in Russell County, Virginia. This watershed has been identified as being impaired since the Virginia 303(d) List of Impaired Waters was created in 1994. Currently, there are two pumps staged in the headwaters region of Dumps Creek that help to maintain water levels in an inactive underground mine. The pumping is necessary to control methane levels that rising water could

force into an active underground mine that lies stratigraphically above the inactive mine. Water is pumped on an as-needed basis and discharges directly into Dumps Creek. Historic measurements of stream conductivity and benthic health scores were compared to assess whether a correlation exists between the two measurements. These measurements were compared based on regulatory decisions that emphasized that conductivity is a direct indicator of stream health in all watersheds.

Scientific contributions associated with this research include: further developments in the use of SDPS programming in order to account for stream protection on a case by case basis for both mine panel and surface water protection by optimizing barrier pillar size in relation to a nearby stream; the analysis of available and currently obtained water chemistry data in a mining impacted watershed in attempt to further research to appropriately characterize and mitigate specific problems in order to improve stream health; and, assessment of the complexity of water chemistry impacts from underground mining as related to stream health indicators in different chemically dominated watersheds.

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Chapter 1. INTRODUCTION

Preface

This thesis contains the contents of three primary documents which have been submitted to peer reviewed conference proceedings. Additionally, a literature review pertaining to water influence from active underground mining and background research directly related to the study area is included. “*A Review of Subsidence Prediction and Control Methodologies in the USA – Experiences and New Developments*” was submitted to the peer reviewed AIMS 2012 conference proceedings, May 30-31, 2012, Aachen, pp. 13-23. The other two papers, “*Application of Subsidence Prediction Methodologies for Sizing Barrier Pillars for Stream Protection in Appalachia*” and “*Exploring Benthic Impairment and Total Dissolved Solids in the Dumps Creek Watershed*” were both submitted to the Symposium on Environmental Considerations in Energy Production, SME, April 14-18, 2013, Charleston, West Virginia and were published in pp. 319-335 and pp. 362-370, respectively.

“*A Review of Subsidence Prediction and Control Methodologies in the USA – Experiences and New Developments*” and “*Application of Subsidence Prediction Methodologies for Sizing Barrier Pillars for Stream Protection in Appalachia*” were both sponsored by the Appalachian Research Initiative for Environmental Science (ARIES). ARIES is an industrial affiliates program at Virginia Tech, supported by members that include companies in the energy sector. The research under ARIES is conducted by independent researchers in accordance with the policies on scientific integrity of their institutions. The views, opinions and recommendations expressed herein are solely those of the authors and do not imply any endorsement by ARIES employees, other ARIES-affiliated researchers or industrial members. Information about ARIES can be found at <http://www.energy.vt.edu/ARIES>. The third paper, “*Exploring Benthic Impairment and Total Dissolved Solids in the Dumps Creek Watershed*” was prepared under the direction of the Virginia Department of Mines, Minerals and Energy through money specified to research initiatives acquired by a court settlement originating from water quality violations to the Dumps Creek watershed.

1.1. Background

Surface water impacts from underground mining have proven hard to quantify given the different conditions that can be found at every mine location. Regulatory bodies have increasingly put an emphasis on water impacts, in general, related to coal mining. This research was performed to further the understanding and body of research related to the physical and chemical impacts that underground mining can have on surface waters. A portion of the research associated with this project was outlined in three individual manuscripts for submittal in applicable peer reviewed conferences. This dissertation includes the research objectives of the

project, a literature review of previous published works related to surface water impacts from active underground mining.

1.2. Research Objectives

Two primary research objectives were defined at the beginning of the research project. The objectives are designed such that outcomes of the research will benefit entities with interest in designing underground mine scenarios that will minimize the influence and impact to surface waters. These objectives are listed below and outlined in detail in the following sections.

- Research Objective 1: Investigate whether subsidence calculations of proximity of a surface water body to an underground full extraction area and the sizing of a required barrier pillar would be more beneficial economically and environmentally than current standards used for stream protection from underground mining.
- Research Objective 2: Analyze the flow and chemistry of a southwest Virginia underground mine water discharge scenario and determine how this discharge negatively impacts surface water.

1.2.1. Research Objective 1

Over time and experience, protection of surface water resources from underground mining has become a strong regulatory and social objective. As with any industry, underground mining has developed from using simple methods that extracted less coal to using more complex, mechanized methods that can extract coal at much higher rates, increasing the potential for overlying disturbance. Subsidence from underground mining influencing manmade structures created a need to understand the surface impact of underground mining (New South Wales Coal Association, 1989). Gaining a scientific understanding of subsidence allowed mine developers to predict subsidence impacts prior to and during mine development to decrease surface impact, while maximizing mine recovery.

Subsidence research has ultimately built upon this foundation and as technology advanced so did prediction methods. The Surface Deformation Prediction System (SDPS) is a suite of software modules that can address both surface deformations due to underground mining, as well as pillar stability issues. SDPS was originally developed by the Department of Mining and Minerals Engineering at Virginia Tech in 1987 (VPI & SU, 1987). Since this time SDPS has been constantly updated and enhanced to include more complex prediction methodologies (Agioutantis and Karmis, 2013).

Barrier pillars are typically used in high extraction mining between extraction panels for stability and safety during mining. These pillars do not necessarily protect against surface subsidence. Research Objective 1 uses SDPS and presents a novel approach to protect overlying surface waters while at the same time optimizes barrier pillar design for surface deformation calculations as well as ALPS for pillar stability estimation.

Currently, the analytical methodology found in the Analysis of Longwall Pillar Stability (ALPS) can be used to calculate stability factors on chain pillars designed to support headgate and tailgate configurations during longwall extraction (Mark, 1992). Additionally, a number of empirical design methods used to estimate the width of a solid barrier pillar are detailed in Kohler and Tadolini (1995) and gained through conversations with Mullins, P. (2012). Kendorski and Bunnell (2007) published a study where these formulations are utilized for the design of an underground water barrier pillar. ALPS and the empirical methods referenced in the above study do not consider strains on the surface and are based on the mechanical loading of the pillar. Research Objective 1 proposes a methodology where SDPS can be used to calculate surface tensile strains for barrier pillar sizes estimated using empirical and analytical tools and

calculates the optimal proximity of a surface water body to an underground full extraction area needed to protect the form and function of nearby surface waters.

1.2.2. Research Objective 2

Research Objective 2 diverts from assessing the physical effects that underground mining can have on a surface water resource and instead investigates the chemical impact. The Dumps Creek watershed located in southwestern Virginia is used as a case study area due to the immense amount of historic data from both mining companies and the Virginia Department of Environmental Quality (VDEQ). Dumps Creek is influenced by the discharge of pumped water into the Dumps Creek headwaters from nearby underground mines.

Research Objective 2 assesses stream health utilizing historic data. All available historic data was gathered and additionally independent current data was also obtained. Graphs are constructed that compared corresponding conductivity values and benthic scores, derived from the Virginia Stream Condition Index (VSCI). This approach is taken based on a recent regulatory assumption that conductivity is directly related to stream health, although, previous literature on this relationship is unclear. Through this assessment, a determination is made as to whether a correlation exists in this watershed between the two aforementioned constituents.

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Chapter 2. LITERATURE REVIEW

2.1. Effects of Underground Mining on the Physical Form and Function of Surface Waters

Subsurface coal mining operations may affect the geologic material directly above the mine and all material up to the ground surface. The deformation of the strata above the mine results in changes of their hydraulic properties and may impact both the overlying underground and surface water bodies in addition to surface subsidence. Typically impacts to water resources are greater above and in close proximity to the subsided area (Walker, 1988; Rauch, 1985; Hill and Price, 1983). Considering, the close association of the effects of underground mining on both the hydrologic regime and surface deformations, many researchers traditionally have employed similar conceptual frameworks for describing and assessing their extent and magnitude. Such criteria may be defined on the basis of an angle or zone of influence (Tieman and Rauch, 1987), which even though quite easy to apply they are of empirical nature and subsequently of limited accuracy and transferability.

2.1.1. Conceptual Models for Groundwater Circulation

A number of conceptual models have been developed to describe the groundwater movement related to the undermining induced strata deformation for both the Appalachian (Wyrick and Borchers, 1981; Stoner, 1983; Booth, 1986; Bruhn, 1986; Kipp and Dinger, 1987) and Illinois (Kendorski 1993; Booth, 2002; Booth; 2007) coal basin.

For the Appalachian plateau, Wyrick and Borchers (1981) observe that groundwater movement is controlled by stress relief fractures. They describe that vertical fractures commonly occur in valley walls, while horizontal bedding plane fractures are found in valley floors allowing for groundwater to discharge to springs. Stoner (1983) found that strata permeability

decreases about one order of magnitude every 100 ft from the surface. However at high depths the hydraulic head suffices to cause vertical leakage into a deep confined aquifer. In the case of shallow depths confining layers render the overlying aquifers perched, causing lateral migration of the groundwater to hillsides where it discharges as a seep or spring. Similarly, Kipp and Dinger (1987) provide a conceptual model of ground-water flow for small basins. They propose that groundwater movement is controlled by stress relief fractures, moving downwards through vertical fractures until it reaches a confining layer (unfractured clay or mudstone), where it moves laterally to discharge to the hillside at seeps or springs.

Booth, (1986) developed a conceptual model linking the strata deformation, hydraulic property changes, and ground-water impacts due to underground coal mining. He distinguished several cases depending on the type of mine (longwall or room and pillar) and the depth of mine and the aquifer (shallow or deep). Shallow aquifers could be affected by deep longwall mines due to fracture induced increased hydraulic connectivity. Werner and Hampel (1992), also argue that perched aquifers are very sensitive to disruption from enhancement of preexisting fractures, leading to increased vertical leakage and lowering of ground-water levels (Hobba, 1993).

Booth (2002) and Booth (2007) provide a conceptual model for the hydrogeological effects of deep subsurface mining with reference to coalfields of Illinois. Booth (2007) proposes that undermining may increase the permeability of an aquifer rendering it from confined to unconfined. Increased leakage from overlying water units as well as inflow to the potentiometric depression from outlying areas, are outlined as the two major mechanisms by which bedrock aquifers are impacted due to coal mining (Booth and Bertsch, 1999). Booth (1992) summarizes the main differences between the Illinois basin and Appalachian coalfields. Sgambat et al.,

(1980), summarize the effects of underground coal mining on aquifer and stream dewatering for mines located at the eastern United States.

2.1.2. Quantitative Effects of Mining on the Surface Waters

Underground mining deforms and changes the hydraulic properties of overlying strata, disrupting the hydrologic regime, which inevitably affects the form and function surface waters. Literature has been gathered studying the varied effects and is presented below.

In Pennsylvania, Moebs and Barton, (1985) studied the effects of deep mines on perennial streams at Greene County, PA, and using precipitation records attributed any insignificant flow rate variations to climate effects. Locally the water levels of shallow aquifers declined more than 30m near the mine edge, but had no effect beyond a distance of 177-387m or 581-1,270 ft. Leavitt and Gibbens (1991) assessed the effects of longwall mining on rural water supplies of southwestern Pennsylvania, northern West Virginia, and southeastern Ohio. They found that streams recharge wells at a distance up to 100-150 ft. Out of 22 springs only 57% remained unaffected with regard to form and flow rates. Some of the springs dried up locally possibly due to near surface fractures, circulated as groundwater in the near surface and discharged downslope as new springs. Similarly, Tieman (1986) and Tieman and Rauch (1987) observed that at deep mines at northern West Virginia and at a mine in southern Pennsylvania, stream water migrated to a shallow sandstone unit rather than towards the mine, to eventually discharge to a surface stream. Streams above regional base level were partly to fully dry during baseflow conditions. Streamflows were restored to near normal flow rates after 2-3 years since the area was undermined (also Dixon and Rauch, 1990).

Dixon, (1988) studied the impact of deep (500-600ft) longwall mines on 3 nearby streams in northern West Virginia. Dewatering initiated two weeks before the panel face advanced and streams up to 380ft from the mine were fully dewatered. They report that dewatering occurs locally over the room and pillar section between the two panels. The greater the overburden thickness is the less the extent of dewatering and the greater the potential for complete recovery is. Streams recovered in eight months to five years.

Rauch et al. (1984) also report significant dewatering over the longwall panel and mine edges due to fracturing. Rauch (1985) and Cifelli and Rauch (1986) discuss the effects of shallow longwall and room and pillar mines on four streams, in northern Preston County, Monongahela River basin, Upshur and Philippi County, in north-central West Virginia. Most streams are significantly impacted and only 20% of the water supplies recovered to some extent. In a similar manner to Stoner (1983), they express impacts in terms of the percentage of soft rock (such as mudstone, coal, and fireclay) in the overburden and the percentage of undermined watershed area. They predict complete dewatering if 25-30% of the watershed area undermined, while even when this level is about 10% significant effects are expected.

Bowers (1979) studied deep mines with pillar extraction in the Scotts Run watershed in northern West Virginia. He observed significant water loss from streams, as shown by the decrease of the average stream discharge per square drainage area with downstream distance, He predicts significant dewatering, if 28% of the stream's length has less than 50ft overburden thickness and 57% of its length has less than 100ft.

Hobba (1981) found that streams above deep mines in Farmington, western Marion County, West Virginia, have reduced flow rates due to increased water infiltration caused by artificially lowered potentiometric groundwater surface.

Peng et al. (1994) and Peng et al. (1996) observed effects of deep longwall mining on stream ponding in West Virginia. Stream ponding depends mainly on the angle of stream flow and the change in streambed gradient. Migratory ponds form and move along as the face of the panel advances. After the surface has completely subsided a stationary pond is formed near the chain pillar area of high-tension, where dewatering may occur.

Sidle et al. (2000) reports temporary effects (most lasting only for 1-2 years) on a mountain stream due to a longwall deep mine at Burnout Creek, Utah. These effects include increased length of cascades, due to channel profile adjustment, increased volume of pools and increased D50.

2.2. Effects of Underground Mining on Surface Water Quality

2.2.1. Chemical Effects of Underground Mining to Surface Waters

Chemical impacts to surface waters from underground mining is most often due to the discharge of underground mine water to the surface. The primary constituents in discharged underground mine water include high levels of TSS, TDS, heavy metals, hardness, nitrate, and sulfate or carbonate depending on the given area (Tiwary, 2000).

A study focused on Deckers Creek located in northern West Virginia studied the change in the chemical composition of the surfaced water due to the effects of mining and other industrial uses over a 20 year period (Stewart and Skousen, 2003). The Deckers Creek watershed is similar to the Dumps Creek watershed, in that it has a long industrial history that

has affected the watershed. One of the main sources of surface water influence in the Deckers Creek watershed is an untreated underground mine. The Deckers Creek watershed was once mined for coal that contained high-sulfur. As is typical in these areas, the coal and surrounding strata include high levels of pyrite. When pyrite is unnaturally exposed to water and oxygen during mining, pyrite changes chemically and releases sulfate, proton acidity, and iron (Geidel and Caruccio, 2000). When unnaturally high levels of iron are introduced into surface waters, the iron forms iron hydroxides through oxidation and hydrolyzation (Rosseland et al., 1992). As the pH of the system is raised above very acidic conditions the iron hydroxides precipitate out of the water because they can no longer be soluble, this is commonly known as Acid Mine Drainage (AMD) (Younger, 1998). The introduction of the groundwater to the surface water generally lowers the pH conditions in the surface water and accelerates weathering and therefore causes the release of other elements such as aluminum and manganese into the water (Kittrick et al., 1982). Essentially, the introduction of one water system into another alters the water chemistry and therefore the original function of the surface water resource.

2.2.2. Interaction of Surface Water and Groundwater Quality

A U.S. Geological Survey (1986) publication on water related impacts from mining in both Buchanan and Dickenson Counties in Virginia, which is very near to the study area in Research Objective 3, looks at the relationship between groundwater and surface water. This study observed that in a mined basin the surface water had calcium sulfate dominance during both high and low flow conditions. However, in an unmined basin, the water during high flow periods is dominated by calcium sulfate and during low flow periods the surface water is dominated by calcium bicarbonate which is very similar to surrounding observation wells. Conclusions show that sulfate levels tended to be higher in mined basins as compared to

unmined basins for this area. This study primarily emphasizes the strong interaction between surface water and groundwater resources, especially during low flow conditions. At times and in some areas surface water and groundwater can be very hard to separate into two different entities.

2.2.3. Biological Effects of Underground Mining to Surface Waters

The above described chemical compositional change of surface waters from underground mine water influence ultimately affects organisms supported by the surface water system. Verb and Vis (2000) analyzed benthic samples from a variety of streams that had drainage influence from mining complexes. The authors observed that watersheds dominated by a strong chemical influence, either low pH or high conductivity, etc. supported benthic life suited to these conditions. Therefore, the watershed exhibited adaptability to the given condition presented.

Unimpacted watersheds in the Appalachian coal mining region are very rare due to the long natural resource developmental history of this area which included support activities such as residential development or timbering (Pond et al., 2008). It is undisputed that underground mine influence on surface waters can alter a watershed (Pond et al., 2008), however, it is unclear from the collective group of research already gathered on this topic, as to whether this actually damages stream health. The metric of stream health is currently based on different indices, not specific to mountainous or headwater regions and therefore may prove to be too broad of a metric in order to appropriately characterize stream health (Barbour, et al., 1992).

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Chapter 3. NEW APPROACH TO STREAM PROTECTION IN APPALACHIA USING SUBSIDENCE PREDICTION METHODOLOGIES

Preface

This Chapter is based on two papers that were published in peer reviewed conference proceedings. The paper names, authors, and conference details are summarized below:

- “*A Review of Subsidence Prediction and Control Methodologies in the USA – Experiences and New Developments*”
M. Karmis, L. Kirby, M. Valyrakis, Virginia Tech, USA
Z. Agioutantis, Technical University Crete, GR
Published in: AIMS 2012, May 30-31, 2012, Aachen, pp. 13-23.
- “*Application of Subsidence Prediction Methodologies for Sizing Barrier Pillars for Stream Protection in Appalachia*”
Z. Agioutantis, M. Karmis, and L. Kirby
Virginia Center for Coal and Energy Research, Virginia Tech, Blacksburg, Virginia
Published In: Environmental Considerations in Energy Production. Edited by J. Craynon, Society for Mining, Metallurgy, & Exploration. Englewood, Colorado, pp. 319-335.

This chapter corresponds directly to the second paper; however, the second paper was built upon the first. In order to avoid repetition, the second paper was used as the most recent reference for this research.

Abstract

The prediction of ground movements due to underground mining is a mature methodology in subsidence engineering used to assess potential impacts to surface structures, facilities and water resources and to implement appropriate methods of control. Predictions of anticipated surface ground movements can be correlated to impact threshold levels for buildings, bodies of water, pipelines, railway and power lines, tailings dams, etc., to estimate the potential impact zone and the magnitude of damage, and to develop risk assessment plans. One methodology widely used for such predictions is the application of influence functions to calculate a number of deformation indices, including subsidence, slope, horizontal strain and surface curvature, at any point on the surface or at any elevation above the extracted seam. This methodology has been successfully implemented in the Surface Deformation Prediction System (SDPS) package.

One specific application of subsidence control is stream protection, particularly in shallow depths. While the stream must be protected, a very conservative approach may leave unnecessarily large blocks of unmined coal (i.e., barrier pillars or barrier pillar systems), without any particular benefit to the protection of surface waters. In this paper, typical barrier pillar

sizing methodologies are compared and an approach is recommended for optimum pillar design that can provide stream protection from permanent dewatering. This approach is based on subsidence principles and sound empirical knowledge of ground movement characteristics, which have been developed for different mining, geological and topographic conditions in Appalachia.

3.1. Introduction

3.1.1. Mining Near Surface Water Structures

A number of studies have been reported in the published literature discussing the factors influencing the extent and magnitude of subsidence impacts on surface water resources due to underground mining. The discussion below focuses mostly on research results related to the Appalachian coalfields in the eastern USA, where this particular issue is receiving considerable attention.

Several studies have addressed dewatering of stream resources in relation to the type of underground mining and overburden geology and thickness. The deformation of the overburden strata above the mine results in changes in hydraulic properties and may impact both the overlying underground and surface water bodies in addition to causing surface subsidence. Typically, impacts to water resources are greater above, and in close proximity to, the subsided area (Walker 1988; Rauch 1985; Hill and Price 1983). Considering the close association of the effects of underground mining on both the hydrologic regime and surface deformations, researchers traditionally have employed similar conceptual frameworks for describing and assessing their extent and magnitude. Such criteria may be defined on the basis of an angle or zone of influence (Tieman and Rauch, 1987). From a study of the effects of deep (500-600 ft, or 152-183 m) longwall mining on three nearby streams in northern West Virginia (Dixon and Rauch, 1988), the most significant stream flow change occurred before the longwall panel edge reaches the stream. However, it was reported that the streams recovered in a period of time

ranging from eight months to five years. This study also showed that the greater the overburden thickness, the less the extent of dewatering and the greater the potential for complete recovery of the water resource.

In addition to overburden thickness, studies have also addressed the angle of hydrologic influence and the distance between the mine edge and the surface water body and how this parameter can influence form and function (i.e., discharge capacity, sediment transport, etc.), of the surface water resource. Angle of hydrologic influence is defined in a similar manner to the angle of draw, as the angle between the vertical and the line joining the edge of the mine panel to the limits delimiting the extent of hydrologic response. Several authors have reported values for angles of hydrologic influence, ranging from 24 to 45 degrees (Cifelli and Rauch, 1986; Dixon, 1988; Tieman and Rauch 1987; Walker, 1988; Dixon and Rauch, 1990; Tieman and Rauch, 1992). The extent of hydrologic effects of mining may also be defined in terms of the zone of influence as the buffer area above the mine panel that has been hydrologically affected. Typically these affects extend from about one to five hundred meters (Rauch, 1985; Booth, 1986; Walker et al., 1986; Tieman and Rauch, 1987; Dixon, 1988; Walker, 1988; Matetic and Trevits, 1990; Booth 2003). With regard to the horizontal distance of a water supply from the mine, Booth (1986) denotes that as the face of the panel approaches, the effects of dynamic strata movement increase, followed by a decrease of the hydraulic conductivities, due to the "traveling wave" extension and compression. This produces a drop and partial recovery of water levels with the highest impact above the centerline of the mine panel. In addition, a study that focused on the effects of deep mines on perennial streams in Greene County, Pennsylvania, concluded that, locally, the water levels of shallow aquifers dropped near the mine edge, but had no effect beyond a distance of 581-1,270 ft (~177-387 m) (Moebs and Barton, 1985).

In summary, studies show that longwall panels, or room-and-pillars sections with secondary pillar extraction, have the potential to affect surface water resources in the Appalachian coal basin. Overburden geologic structure and thickness, distance from the mine edge, mine conditions and extent of surface movements all are key drivers in determining the extent of impacts on streams and the recovery cycle of the water resource.

3.1.2. Guidelines for Mining Near Surface Water Bodies

When considering the impacts of ground movements on surface bodies of water, the most comprehensive analyses of damage criteria and threshold values are derived from case studies from Britain, Australia and the USA. Different criteria have been proposed and can be divided into three broad categories: (a) mining geometry parameters, (b) surface deformation threshold values and (c) combinations of a) and b).

Table 3-1 summarizes different guidelines for mining under or near bodies of water. In many cases, mining under bodies of water depends on the depth between the mine and the surface water feature and/or the tensile strains that will develop on the surface, under the mass of the water or the water retaining structure. Where appropriate, the mining system is also given.

Table 3-1: Summary of different guidelines for mining under or near bodies of water (adapted from a report prepared for MSHA by D'Apollonia Engineering, 2009)

| Criteria | Description | Underground mining | Reference |
|--|---|------------------------------|---------------------------|
| Criteria based on Mine Geometry | | | |
| 10t or 5s | Minimum solid overburden | Room and Pillar first mining | Babcock and Hooker (1977) |
| <10t or 5s provided competent bed is > 1.75s | Minimum solid overburden with competent bed | Room and Pillar first mining | Babcock and Hooker (1977) |
| max (3w or 270 ft) | Minimum solid overburden | Room and Pillar | Babcock and Hooker (1977) |
| w ≤ h/3 | Maximum width of extracted panel | Room and Pillar | Babcock and Hooker (1977) |

| | | | |
|---|---|----------------------|-------------------------------|
| max (100 t or > 700 ft) | Minimum overburden | Total extraction | Skelly and Loy (1977) |
| 60t | Minimum solid overburden | Total extraction | Babcock and Hooker (1977) |
| 60t to 117t (worst case) 37t to 105t (limited potential) | Minimum overburden | Total extraction | Kendorski <i>et al</i> (1979) |
| Criteria based on surface ground deformation | | | |
| < 0.010 | Surface tensile strain | Total extraction | Skelly and Loy (1977) |
| <= 0.010 (worst case) <= 0.015 (limited potential) | Surface tensile strain | Total extraction | Kendorski <i>et al</i> (1979) |
| 0.010 | Surface tensile strain | Mining under the sea | NCB (1968) |
| 0.010 | Surface tensile strain | Mining under the sea | Whittaker and Reddish (1989) |
| Criteria based on mine geometry and surface ground deformation | | | |
| <=0.005; overburden >= 60t | Surface tensile strain and minimum overburden | | Singh and Bhattacharya (1984) |
| <= 0.005; suggested overburden >= 60t | Surface tensile strain and minimum overburden | | Singh (1992) |
| where, h = overburden depth, w = maximum panel width, t = extraction thickness, s = entry width (all units in ft) | | | |

The guidelines presented in Table 3-1, can be summarized as follows:

- The British National Coal Board, as early as 1968, has recommended a maximum tensile strain value of 10 mm/m when mining under the ocean floor. Whittaker and Reddish (1989) have provided further discussion in support of this limit.
- A similar threshold value (8.75 mm/m) was also recommended by Babcock and Hooker (1977) in the Bureau of Mines Information Circular 8741, a document generally accepted as the “best practice” guide in the USA. The information in this circular was compiled based on the results of two research projects completed by Skelly and Loy and by Wardell and Partners under contract to the USBM.

- Tensile strains on the surface should generally be less than 10 mm/m (0.010)
- A conservative maximum strain value between 5 mm/m and 7 mm/m (0.005-0.007) can be assumed for design purposes depending on the specific conditions.
- The minimum overburden for total extraction under a body of water is approximately 60 times the extraction thickness ($60t$).

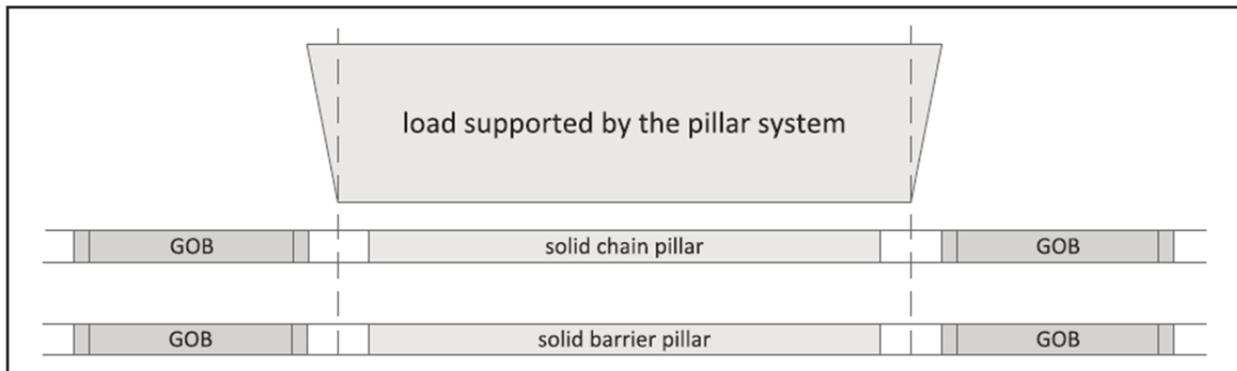


Figure 3-1: Conceptual diagram of supported load over solid barrier pillars using the ALPS methodology

3.2. Design of Stable Barrier Pillars for Stream Protection

Barrier pillars for stream protection (or stream protection pillars) are designed based on the strength of the material compared to the expected loads from the overburden and the abutment pressures generated due to mining on one or both sides of the pillar. Such pillars are usually designed so that mine operations in adjacent panels are safe for the duration of mining. It should be noted, however, that stable pillars underground will not necessarily prevent ground deformations on the surface.

3.2.1. Analytical Methods

The width of barrier pillars can be calculated using analytical methods that account for the abutment angles due to the gob areas adjacent to the pillars. For the case of full extraction

panels adjacent to solid barriers, the analytical methodology found in the Analysis of Longwall Pillar Stability (ALPS) can be utilized. The ALPS methodology was developed by NIOSH (Mark, 1992) and allows calculation of stability factors on chain pillars designed to support headgate and tailgate configurations during longwall extraction. In the case of fully extracted room-and-pillar section, the ARMPS methodology may be used (Mark and Chase, 1977; Mark et al. 2011).

For this application, ALPS was used to simulate the loads on a barrier pillar as follows: A very long chain pillar between two entries was created for a longwall panel width of 1,000 ft and an extraction thickness of 5 ft (Figure 4-1). The stability factor for isolated loading was calculated. The chain pillar was then assumed to be the barrier pillar between two full extraction panels.

Figure 3-2 shows a nomogram that was generated using the ALPS Classic formulation where the curves correspond to stability factors. Given the pillar width and the overburden depth, the corresponding stability factor for the solid pillar can be easily estimated for an extraction thickness of 5 ft. The ALPS Classic formulation calculates lower pillar stability factors than the ALPS Revised formulation and it is thus considered more conservative. The stability factors calculated in the following sections are based on the Classic formulation of ALPS.

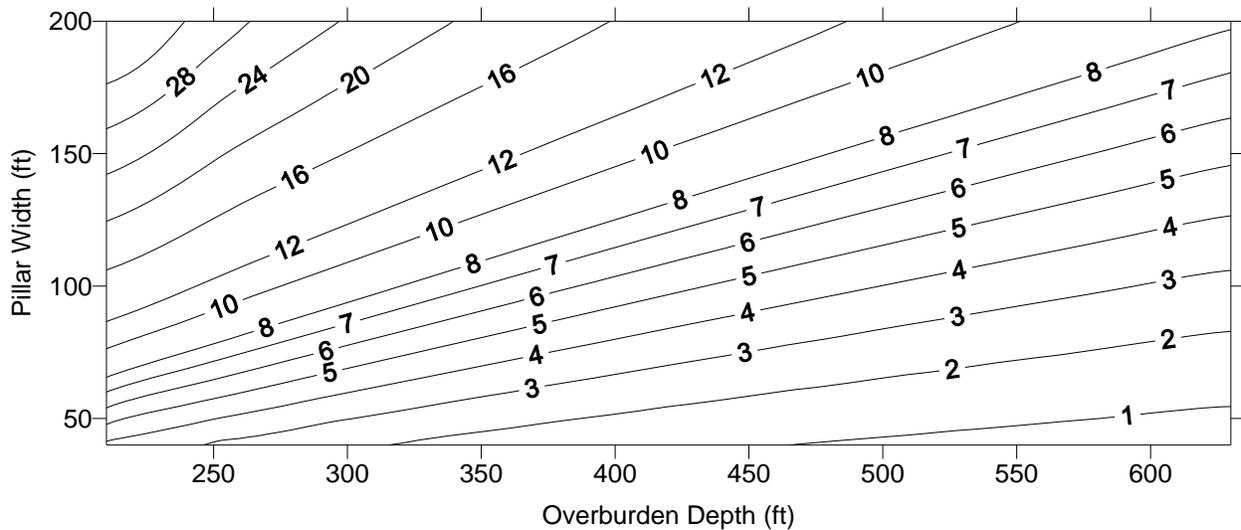


Figure 3-2: Nomogram for the calculation of solid barrier pillar stability factors based on pillar width and overburden depth using the ALPS Classic formulation (extraction thickness = 5ft)

Pillars between two full extraction panels may be partially mined ensuring, however, that the pillar system still remains stable. ALPS can be utilized to estimate stability factors for these pillar systems as well. Figure 3-4 shows a nomogram that was generated using the ALPS Classic formulation (using the isolated loading calculations) where the curves correspond to stability factors for pillar systems with a 50% extraction ratio and an extraction thickness of 5 ft. Pillar Stability Factor is defined under ALPS as the ratio of the pillar bearing capacity to the actual pillar load. When this ratio is greater than one then the pillar is considered stable (Figure 3-3).

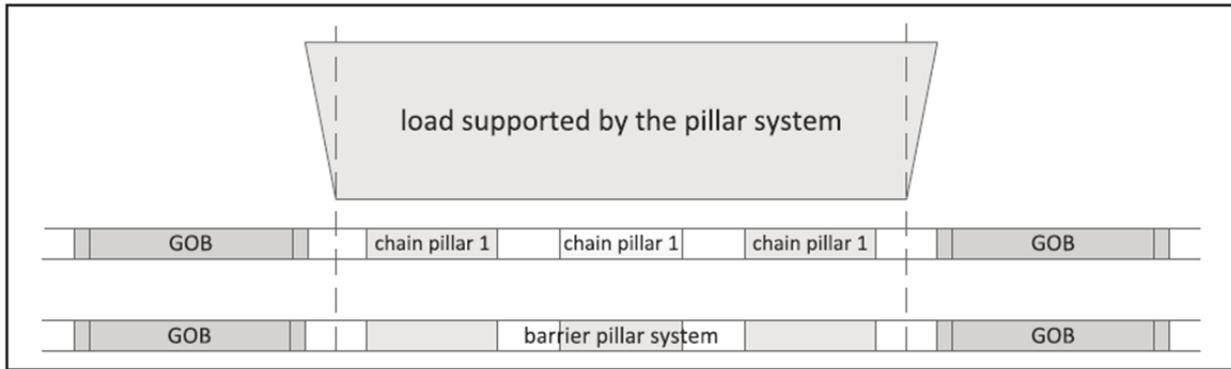


Figure 3-3: Conceptual diagram of supported load over barrier pillar systems using the ALPS methodology

For a given overburden depth, the stability factor of the pillar system remains constant as the pillar system width increases, as long as the extraction ratio remains the same.

Based on the ARMPS 2010 analysis (Mark et al. 2011), NIOSH recommends minimum stability factors for solid barrier pillars ranging from 1.5 to 2.0, depending on mine layout conditions and parameters. Table 3-2 lists the pillar widths calculated using the ALPS methodology for two different depths for solid pillars and pillar systems with 50% extraction.

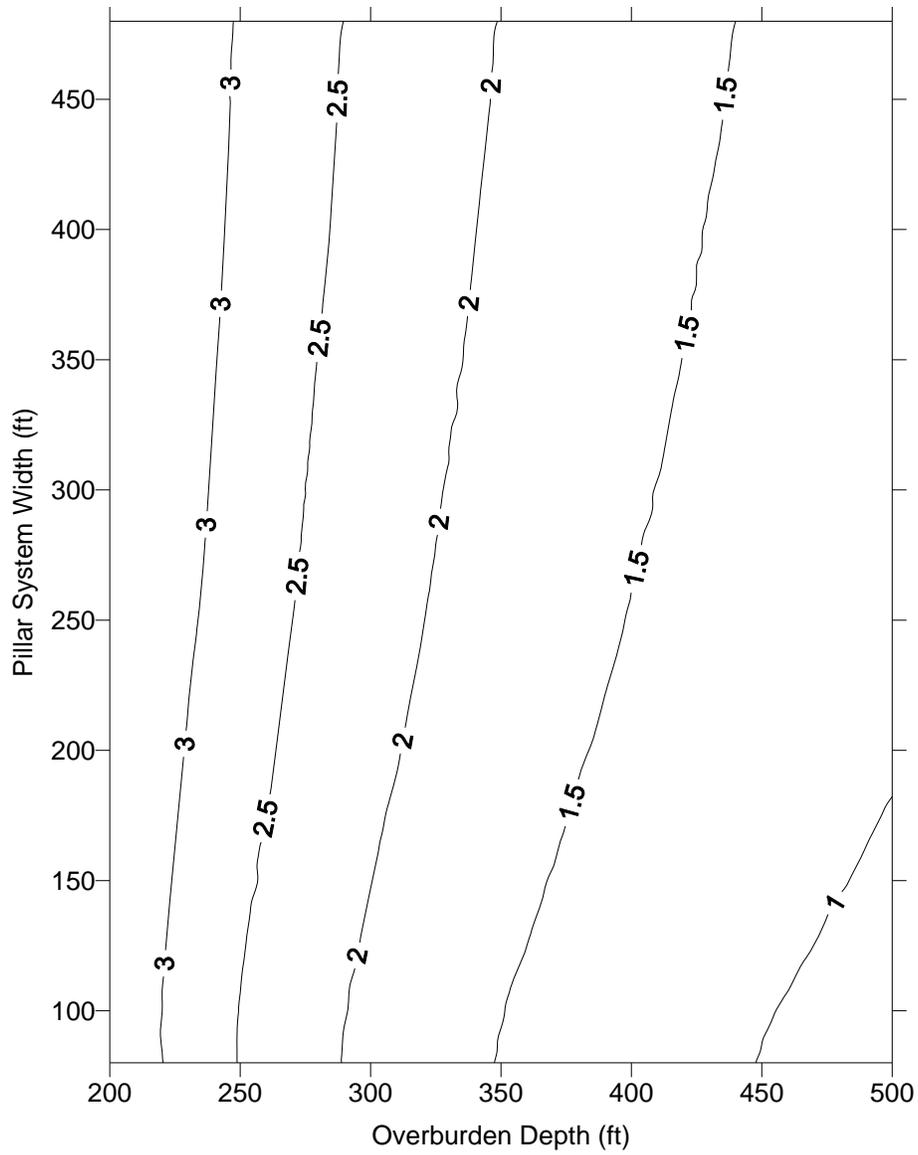


Figure 3-4: Nomogram for the calculation of barrier system stability factors based on pillar system width and overburden depth using the ALPS Classic formulation (extraction thickness = 5ft, extraction ratio =50%)

Table 3-2: Summary of Stability factors for Barrier Pillars and Barrier Pillar Systems using ALPS and extraction thickness = 5ft

| Depth (ft) | Barrier Pillar System Width (ft) | ALPS SF for Solid Barriers | ALPS SF for Barrier Systems at 50% extraction |
|------------|----------------------------------|----------------------------|---|
| 300 | 50 | 3.0 | - |
| 300 | 80 | 6.3 | 1.88 |
| 300 | 100 | 8.9 | 1.91 |
| 300 | 120 | 11.6 | 1.94 |
| 350 | 50 | 2.4 | - |
| 350 | 80 | 5.0 | 1.48 |
| 350 | 100 | 7.0 | 1.51 |
| 350 | 120 | 9.3 | 1.55 |

3.2.2. Empirical Methods

A number of empirical design methods used to estimate the width of a solid barrier pillar are detailed in Kohler and Tadolini (1995). Kendorski and Bunnell (2007) published a study where these formulations are utilized for the design of an underground water barrier pillar. The methods referenced in these studies do not consider strains on the surface and are based on the mechanical loading of the pillar.

These formulations include:

- The Pennsylvania Mine Inspector’s formula, where $W = 20 + 4t + 0.1h$
- The Pressure Arch method, where $W = 2.625 * (h/20 + 20)$
- The British Coal Rule of Thumb, where $W = (h/10) + 45$
- The North American Method, where $W = (h * P)/(7000 - h)$ and P is the adjacent panel width

Table 3-3 summarizes the estimated pillar widths for the above mentioned four methods for an overburden depth of 300 ft and 350 ft and an extraction thickness of 5 ft. In the case of the

North American Method, an adjacent panel width of 2,000 ft was applied. Pillar widths range from 70 ft to 92 ft for a depth of 300 ft and from 75 ft to 105 ft for a depth of 350 ft. Also the ALPS stability factor (Classic formulation) is given as calculated in the previous section.

Table 3-3: Solid barrier pillar widths estimated using pillar design formulations based on mechanical loading for an extraction thickness of 5ft and two different overburden depths

| Formulation | Solid Pillar width (ft) for h=300ft | ALPS SF |
|---------------------------------------|-------------------------------------|---------|
| Pennsylvania Mine Inspector’s formula | 70 | 5.2 |
| Pressure Arch method | 92 | 7.8 |
| British Coal Rule of Thumb | 75 | 5.7 |
| The North American Method | 90 | 7.6 |
| | | |
| | Solid Pillar width (ft) for h=350ft | |
| Pennsylvania Mine Inspector’s formula | 75 | 4.5 |
| Pressure Arch method | 98 | 6.8 |
| British Coal Rule of Thumb | 80 | 5.0 |
| The North American Method | 105 | 7.6 |

3.3. Design of Barrier Systems for Stream Protection

Mine planning engineers and regulators have often applied empirical rules for the protection of surface structures. For example, the Pennsylvania Bituminous Mine Subsidence Act of 1966, provided protection for certain surface structures by using an offset from the structure and a protection angle assumed to be 15°. Although this specific formulation is not used for stream protection, it is of interest as in a similar manner, a protection angle and offset distance are also used to develop an empirical stream protection barrier method.

Other “rules of thumb” are applied to determine the size of barrier pillars or barrier systems for stream protection and the distance required between the edge of the mine panel or mined area and the surface stream above, to ensure that potential impacts on the surface water

structure are minimized. Such formulae are usually empirical, conservative, inflexible and limiting, as they ignore a number of parameters affecting the propagation of movement from the mine level to the surface water structures. A commonly utilized empirical rule that has been accepted in the Appalachian region (Mullins 2012) is depicted in Figure 3-5.

This rule assumes both a horizontal and a vertical buffer zone, and uses mining and subsidence empirical parameters, i.e., overburden thickness, coal seam height, and an upper limit value for the angle of draw. The boundaries of the horizontal buffer area are defined from the horizontal distance ($W/2$) between the panel rib and the centerline of the stream (as in Figure 3-5). This horizontal distance is a function of the angle of draw (γ), the overburden depth (h) and a constant offset ($B/2$) (from Figure 3-5). The empirical rule assumes a minimum offset distance ($B/2$) of 50 ft (~17 m) from the stream centerline, an acceptable limit for most Appalachian headwater streams. However, for very wide streams this width can increase accordingly, to better protect the stream bed, bank and adjacent alluvial floodplain. For the Appalachian region, the angle γ is taken as the upper limit of the angle of draw for the region, which assumes a value of $\gamma = 28$ degrees (Karmis et al., 1983). Thus, the rule of thumb equation is given below:

$$\frac{W}{2} = \frac{B}{2} + h * \tan(\gamma) \leq W = B + 2h * \tan(\gamma) \quad (1)$$

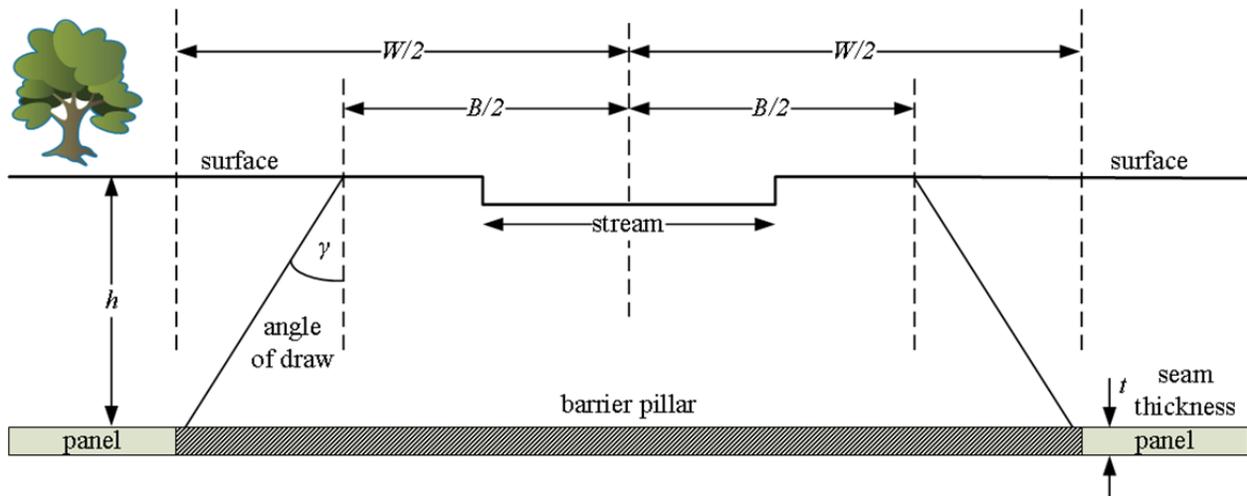


Figure 3-5: Buffer zone for full extraction panels in the proximity of streams

The vertical buffer zone is used to ensure that the stream is at a safe distance from the fracture zone (FZ) that develops around the caved area of the mine panel (Peng 1992). The vertically applied buffer zone determines whether complete, or partial, extraction of the coal seam below a water structure is allowed. Figure 4-6 shows a conceptual diagram of the different zones that develop over a fully extracted area. The caving zone that develops immediately above the panel has a height ranging from $5t$ to $10t$, where t is the extraction thickness. This is followed by the FZ, which may extend from $30t$ to $50t$ (Peng and Chiang 1984). From the top of the FZ to the surface is the continuous deformation zone (CDZ) which often includes (particularly on valley bottoms) cracks, fractures, etc., because of tectonic stresses and structural features. It is assumed that water can be drained in this zone to a distance of about 100 ft (~ 31 m).

If the overburden depth of the seam under a stream is less than $50t + 100$ ft (where t is in ft) then a protection pillar should be left in place as defined in Figure 3-5. First mining can occur in this pillar up to 50% extraction, or to an extraction ratio that will avoid surface movements. For depths greater than $50t + 100$ ft, the stream can be fully undermined, since an intermediate zone (Figure 3-6) is present and the drainage zone does not communicate with the FZ to allow dewatering towards the mine level. The above logic is given mathematically below.

$$H_c = 50t + 100 \text{ ft} \begin{cases} \text{if } h > H_c \text{ then full undermining is possible} \\ \text{if } h \leq H_c \text{ then only first mining is allowed} \end{cases} \quad (2)$$

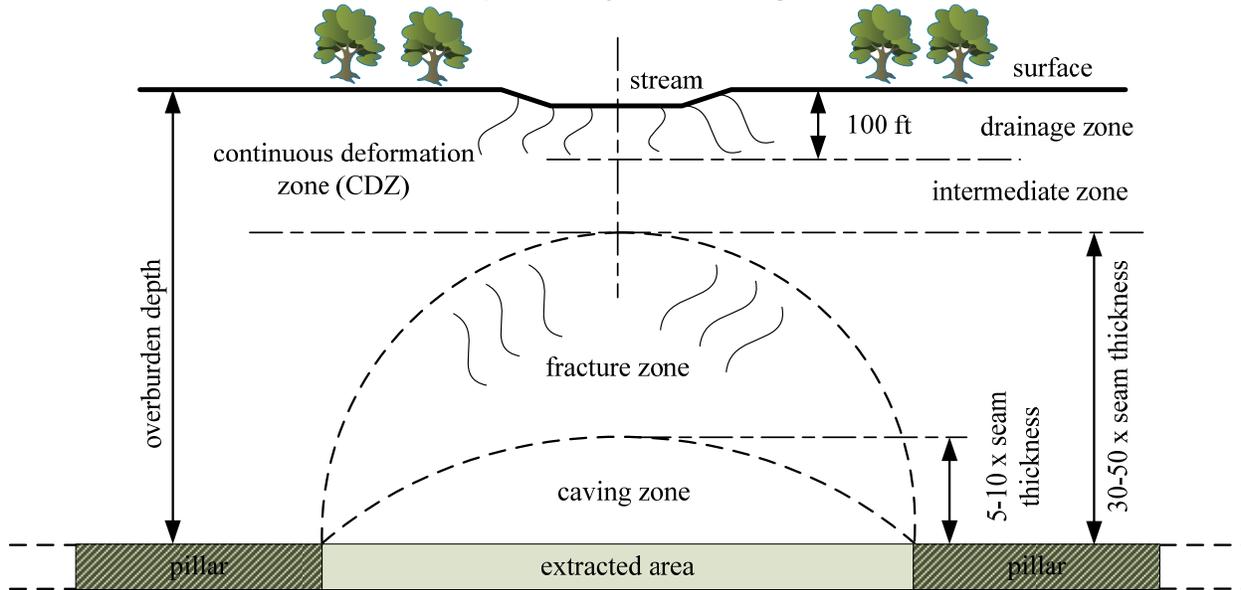


Figure 3-6: Caving zone, fracture zone and continuous deformation zone (adapted from Peng and Chiang 1984)

According to the rule of thumb for a 5-foot extraction, the CDZ is in contact with the FZ when $H_c = 50t + 100 \Rightarrow H_c = 50 \cdot 5 + 100 = 350$ ft, i.e., the maximum depth for which a protection pillar may be required under the stream. In this particular layout, for mining depths over 350 ft, full extraction under the stream is allowed, while for less depth, only partial extraction is allowed. As a result, the overburden depths for the two case scenarios are set to 300 ft (~91 m) and 350 ft (~107 m), respectively, as in Figure 3-8. The two depth values selected also satisfy the 60t rule, i.e., $60t = 60 \times 5 = 300$ ft.

The minimum (W_{min}) values for the barrier pillar half-widths using the empirical protection rule are determined using equation (1) as follows:

$$\frac{W_{min}}{2} = \frac{B}{2} + h * \tan(28^\circ) \Rightarrow \frac{W_{min}}{2} = \begin{cases} \text{for } h = 300 \text{ ft} \rightarrow \frac{W_{min}}{2} = 210 \text{ ft} \Rightarrow W_{min} = 420 \text{ ft} \\ \text{for } h = 350 \text{ ft} \rightarrow \frac{W_{min}}{2} = 236 \text{ ft} \Rightarrow W_{min} = 472 \text{ ft} \end{cases} \quad (3)$$

The above results are summarized in Table 3-4. Also the ALPS stability factor (Classic formulation) is presented to allow comparison between the different designs.

Table 3-4: Barrier pillar widths estimated using pillar design formulations based on rule of thumb formulations for water body protection for an extraction thickness of 5ft and different overburden depths

| Depth (ft) | Pillar System width | ALPS SF for 50% extraction along the whole pillar system |
|------------|---------------------|--|
| 300 | 420 | 2.35 |
| 350 | 472 | 1.98 |

3.4. Design of Pillars and Barriers for Stream Protection Using a Surface Movement Approach

3.4.1. Prediction of Ground Deformations Due to Underground Mining

The development of rigorous and well-accepted ground deformation prediction methodologies for assessing mining impacts on surface structures, facilities and water resources is important for subsidence control. This task can be extremely complex because of the number and nature of the parameters affecting ground deformation induced by underground mining, including surface morphology, mine plan, coal structure elevation and characteristics, rate of mining, overburden lithology, and the type of surface facility or water resource to be protected.

A number of subsidence prediction methodologies have evolved and have reached considerable maturity and acceptance in recent years. This can be attributed to both a need for more accurate estimation of potential impacts and damages, as well as the ability to execute more sophisticated calculations. In addition, subsidence impacts and protection of surface and underground water resources have received considerable attention by the mining industry and the regulatory and permitting agencies.

The Surface Deformation Prediction Software (SDPS) is a suite of software modules that can address both surface deformations due to underground mining and mine stability issues. This package was originally developed by Virginia Tech in the 1980s, but since then has been constantly updated and expanded. Prediction of ground deformations is mainly accomplished using the influence function method (Karmis et al. 1990). Several static or dynamic (i.e., dependent on the rate of mining) surface deformation indices can be calculated at any location, given a digitized mine plan, digitized surface topography and knowledge of appropriate subsidence parameters. Calculations are based on several empirical relationships, developed through the statistical analysis of data from a number of case studies (VPI&SU1987; Karmis et al. 1992). Calculated deformation indices include horizontal and ground strain (i.e., strain on a horizontal plane at a given surface point, or strain that accounts for the aspect and slope of the surface in the vicinity of the point), principal strains and maximum strains, either compressive or tensile.

Ground deformation prediction can also be applied in the case of surface water resources. Maximum allowable tensile strains on the surface is considered one of the best indicators for controlling the development of new cracks or extending existing cracks on the surface. Using SDPS, surface deformations including tensile strains as well as final surface profiles can be calculated at any surface point, e.g., the bottom of a stream. It should be noted that strain on the surface decreases with the increasing depth of cover to the extracted seam. Figure 3-7 presents the decrease of the maximum tensile strain on the surface for different overburden depths in the case of a supercritical fully extracted area and an extraction thickness of 5 ft. The calculations were performed using default subsidence parameters for the Appalachian region (Agioutantis and Karmis 2012).

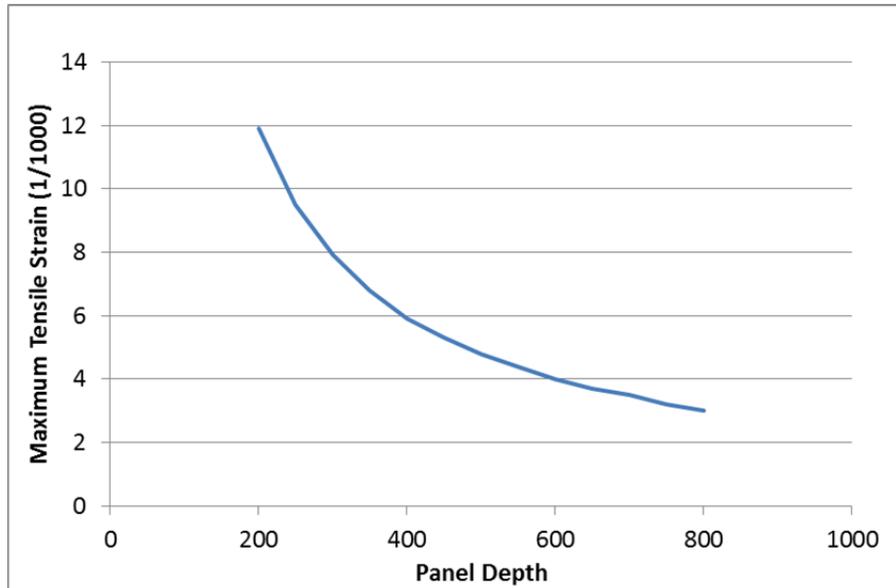


Figure 3-7: Maximum tensile strain with depth for extraction thickness = 5ft

In the next section tensile strains are calculated for a range of stream protection barrier pillar sizes and an approach is recommended for optimum pillar design given Appalachian underground mining conditions. All calculations given below refer to final subsidence effects after all mining has ceased. Movements while mining is in progress (dynamic movements) are expected to be much less than final movements (Karmis et al. 2008).

3.4.2. Pillar System Design Based on Surface Deformations

Pillar design methodologies based on loading and stability do not account for surface deformations. As already mentioned, pillars or pillar systems may be stable, but deformations may occur on the surface above the pillar. In this section, ground movements on the surface due to underground mining are related to barrier pillar geometries.

An example is presented below to illustrate this concept using the following assumptions:

- Calculations are completed using one mine geometry for two different overburden depths. In each case the maximum ground strain is calculated for different barrier pillar widths under the protected surface body.
- The overlying surface is horizontal. A set of surface points in a dense grid is set to correspond to a stream bed. The location of the edges of two high extraction panels (i.e., longwall panels) located on either side of the stream are varied with respect to the stream centerline.
- The rectangular longwall mine panels are assumed to have the same geometrical characteristics, i.e., width = 1,000 ft (~300 m), length = 1,800 ft (~550 m) and extraction thickness of $t = 5$ ft (~1.5 m). The dimensions of the panels are selected such that they will be supercritical, i.e., width-to-depth > 1.2 .
- The overburden geology is assumed to be represented by 50% hard rock. The supercritical subsidence factor for these conditions is about 40%.
- The influence angle used in this analysis is the default value for the eastern Appalachian coalfields (i.e., $\tan\beta=2.31$ or $\beta\approx 67^\circ$).
- The strain coefficient used in this analysis is the default value for the eastern Appalachian coalfields (i.e., $B_s=0.35$ ft).
- It is assumed that the stream section of interest has a width of 20 ft (~6 m), an initial depth of 0.5 ft (~0.15 m) and vertical banks.

The parametric analysis was run by varying the width of the barrier pillar (W). The analysis was completed using the influence function method available in the latest version of the

SDPS software (Agioutantis and Karmis 2012), which can easily be applied to any mining geometry, in order to calculate the ground strain at the stream centerline for different stable barrier pillar system widths (W).

Figure 3-9 presents the calculated values of maximum strain plotted for the different depths of 300 ft and 350 ft (~100 m and ~117 m). Under those conditions, the recommended pillar width assuming a tensile strain threshold value of 5mm/m is approximately 80 ft. It should be noted that the parametric analysis was conducted assuming that the barrier pillar underneath the stream is stable (i.e., not yielding). When stable pillar systems are developed next to full extraction areas, then an edge effect develops for that extraction area, which shifts the inflection point of the resulting subsidence profile towards the gob. This edge effect accounts for the cantilevering of the overburden strata above the gob. The edge effect was automatically estimated using the SDPS package as a function of the overburden (Agioutantis and Karmis 2012). It is immediately evident that pillar system widths greater than 300 ft (~100 m) result in zero surface strains in the area under examination.

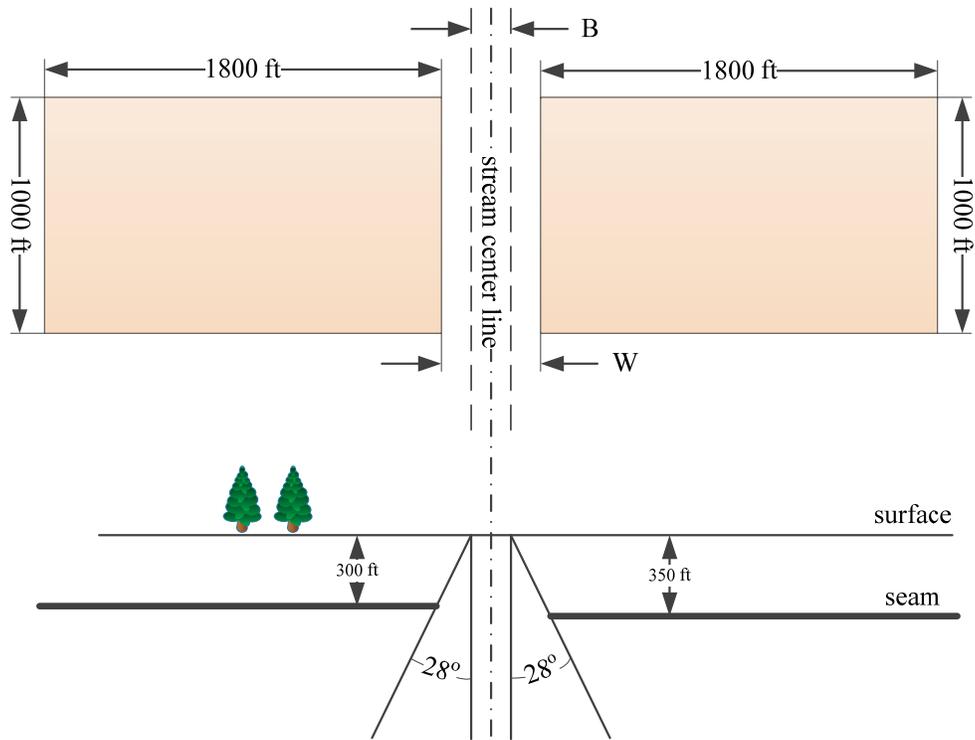


Figure 3-8: Plan view and section of two mine panels in the proximity of a stream (distances in ft). Protection/buffer zones are calculated using the “rule of thumb” for $\gamma = 28^\circ$ and for depths of 300 ft (~100 m) and 350 ft (~117 m)

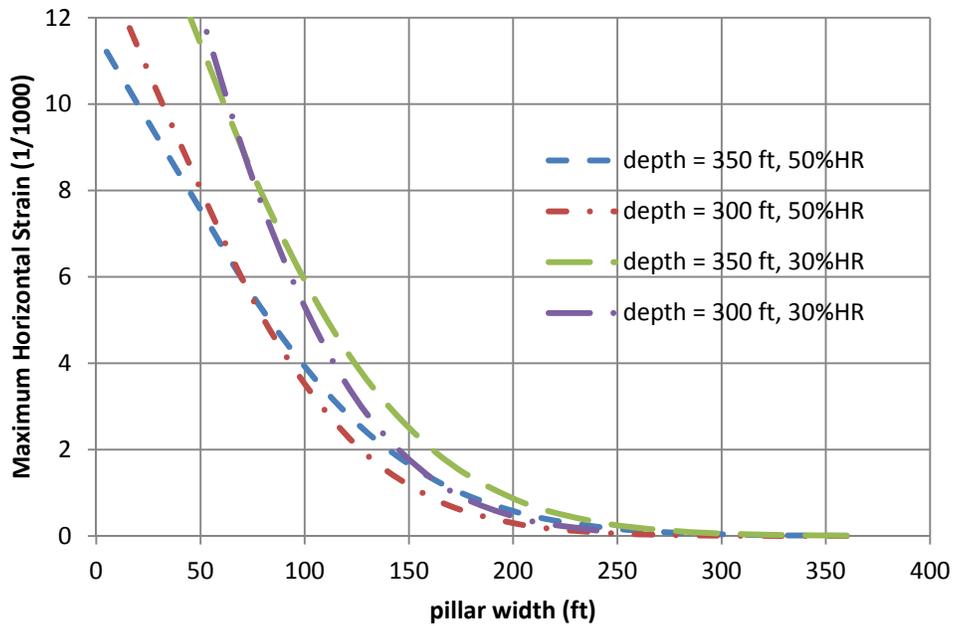


Figure 3-9: Maximum strains at the stream centerline as a function of barrier pillar width for a 5 ft extraction thickness under 300 ft and 350 ft of overburden for 50% and 30% hardrock

Using the SDPS capabilities, alternative assumptions and scenarios can be calculated and compared. For example, Figure 4-9 also shows the calculated tensile strain on the surface for the same selected depths, assuming a different geology, i.e., 30% hardrock. In this case, due to the softer overburden, higher strains will be encountered and, therefore, assuming a horizontal strain threshold value of 5mm/m, the recommended barrier pillar width is in the order of 110 ft.

Hardrock percentages in the overburden when calculating tensile strains on the surface are important because they can greatly change the surface tensile strains, given the same depth of overburden cover. SDPS defines percent hardrock as “...*the sum of the strong rocks (e.g., sandstone, limestone), having a minimum thickness of 5 feet, expressed as a percentage of the total overburden thickness*” (Agioutantis and Karmis 2012). SDPS uses a default value of 50% hardrock if this variable is unknown, in order to give a middle range value that will not bias the program since hardrock values can vary from one area to another. Lower percentages of hardrock will increase surface tensile strains and may prove crucial in SDPS calculations under streams.

Figure 3-10 presents a nomogram where barrier pillar width (W) can be calculated as a function of depth (h) for different maximum values for tensile strains on the surface. Figure 3-11 presents a similar nomogram relating pillar width and overburden depth for different subsidence values on the surface for an extraction thickness of 5 ft. The subsidence values are given here in inches.

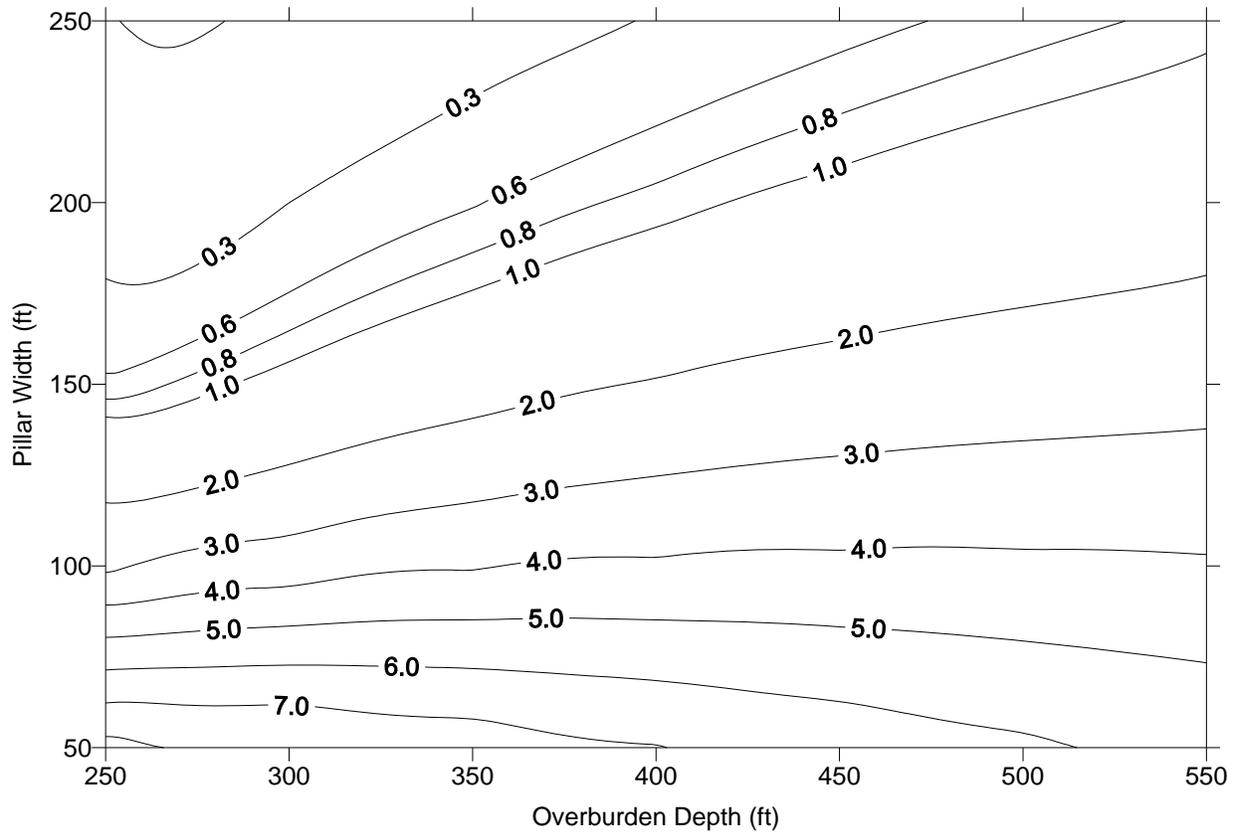


Figure 3-10: Nomogram relating pillar width and overburden depth for different maximum strains on the surface (1/1000) for an extraction thickness of 5 ft

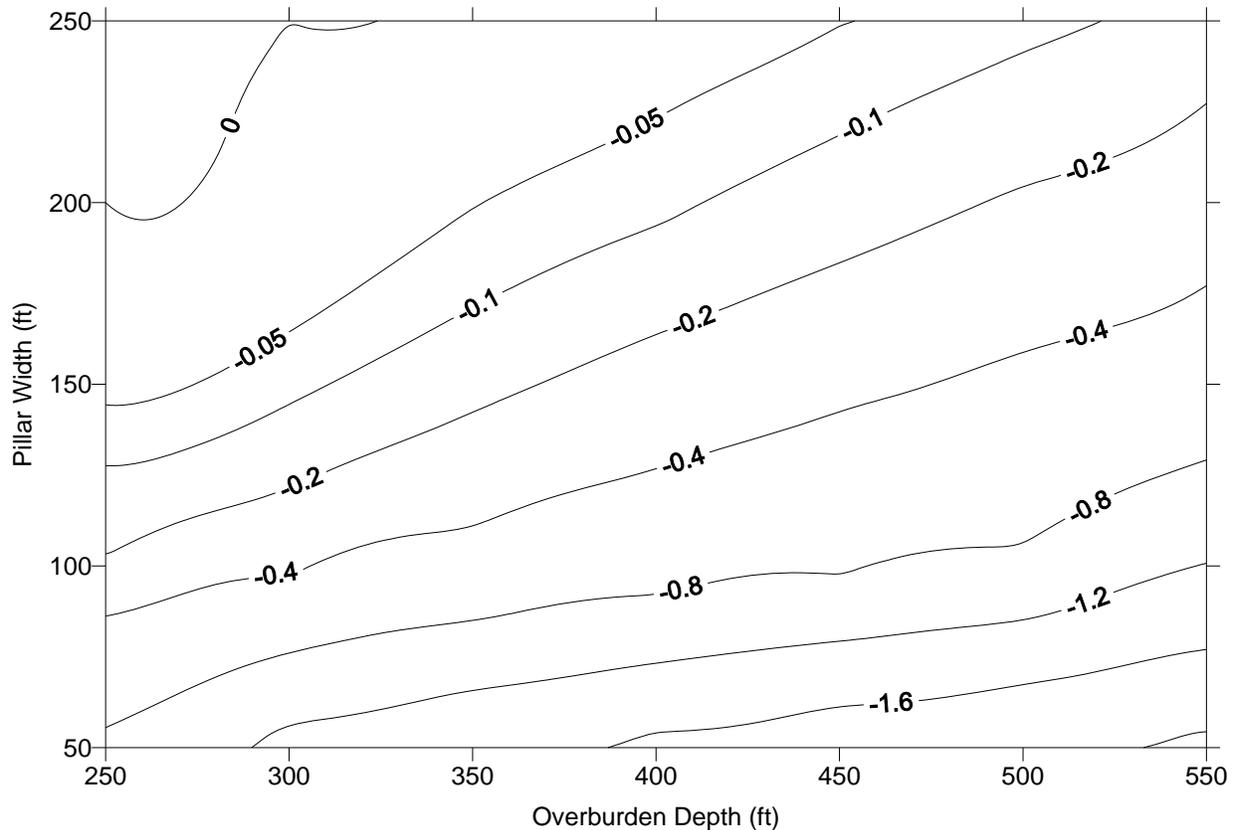


Figure 3-11: Nomogram relating pillar width and overburden depth for different subsidence values on the surface (in inches) for an extraction thickness of 5 ft

3.5. Discussion

Barrier pillar widths for the protection of surface water resources were calculated using an analytical approach as given by the ALPS formulation. Nomograms were generated for solid barriers as well for barrier pillar systems with 50% extraction. In addition solid barrier pillar dimensions using several empirical formulas were also calculated. Pillar system widths were estimated using a rule of thumb for water body protection, applied in the Appalachian region. Crossing such pillar systems via mains, or other low extraction works, will not compromise the overall stability of the barrier system. All of the above calculations were mainly performed for typical mine plan geometries, i.e., extraction thickness of 5ft and depths ranging from 300 ft to 350 ft.

Due to the rationale behind these formulations, none of these approaches can estimate the potential surface tensile strains that may lead to drainage of a surface water resource. The application of a well-accepted ground deformation prediction methodology allows the calculation of barrier system pillar widths, for given maximum allowable surface tensile strains. To facilitate this task, nomographs were generated relating barrier system pillar width and overburden depth to surface tensile strains, as well as surface subsidence. Thus, pillars can be designed by minimizing the potential surface effects. In all cases these pillars should also demonstrate an acceptable stability factor.

Table 3-5 summarizes the findings for all approaches. Results indicate that the width of barrier pillar systems calculated using rules of thumb significantly overestimate the protection zone and thus may sterilize coal reserves. Using ground strain as the driving criterion, coupled with analytical calculations of stability factors for barrier pillar systems, may result in an optimum design of such barriers pillars left underground for the protection of surface water bodies.

Table 3-5: Summary of Barrier Pillar Design formulations that can be considered for water body protection. Data refer to extraction thickness = 5 ft, 50% hardrock and overburden depth ranging between 300-350 ft

| Pillar Design Approach | Depth (ft) | Solid Barrier Pillar Width (ft) | Barrier System Width (ft) | Strain on the surface | Subsidence (in) | Comments |
|---|-------------------|--|----------------------------------|------------------------------|------------------------|--|
| Empirical methods for water body protection | 300 | | 420 | - | | An overall extraction of 50%, ALPS SF = 2.35 |
| | 350 | | 472 | - | | An overall extraction of 50%, ALPS SF = 1.98 |
| Empirical methods based on | 300 | 70-92 | | - | | ALPS SF = 5.2-7.8 |

| | | | | | | |
|---------------------------------|-----|------------|--------|----------------|------------------|---|
| mechanical loading | | | | | | |
| | 350 | 75-105 | | - | | ALPS SF = 4.5 – 7.6 |
| Analytical (ALPS) | 300 | 50-120 | 80-120 | - | | ALPS SF (solid)= 3.0 – 11.6 ALPS SF (50%)= 1.88-1.94 |
| | 350 | 50-120 | 80-120 | - | | ALPS SF (solid)= 2.4 – 9.3 ALPS SF (50%)= 1.48-1.55 |
| Ground deformation calculations | 300 | ~60 ~80 | | 0.007 0.005 | 1.1 in 0.4 in | ALPS SF = 4.1 ALPS SF = 6.3 |
| | 350 | ~60 ~80 | | 0.007 0.005 | 1.3 in 0.6 in | ALPS SF = 3.2 ALPS SF = 5.0 |

Most empirical approaches for stream protection operate on the assumption that a stream will be protected from dewatering if the fractures extending down from the continuous deformation zone will not meet with the fractures propagating up due to the caving/disturbed gob zone. This approach, although simplistic, provides the basis for all empirical formulations for the protection of streams or other surface water bodies. This methodology has allowed estimates of protection pillars to be made and does not in any way replace a full hydrologic investigation for the area of interest. In this paper, the same rationale was used, but in this case, the barrier pillar for stream protection was calculated using surface tensile strains.

Finally, the SDPS model has the ability to provide tensile strain calculations that can be used for stream protection for a range of depths, topographic conditions and lithologic environments.

3.6. Conclusions

Potential impacts on surface water bodies may be avoided when tensile strains on the surface are kept to low values. It is well documented in the literature that surface cracks and

water impacts can be contained if the surface tensile strains, due to underground mining, are kept below 10mm/m (0.010in/in). In this study, even more conservative values were utilized which ranged from 5 to 7mm/m.

The methodology presented was developed for the design of barrier pillars and barrier pillar systems for stream protection based on a different approach than the traditional barrier pillar stability. In this case the maximum expected tensile strain on the surface (under static or dynamic conditions) is used to estimate the width of the barrier system as a function of depth. The nomogram generated in this paper corresponds to a specific extraction thickness, but similar nomograms can be generated for different extraction thicknesses using the SDPS package. Thus, mine planners and regulators can use these nomograms to design barrier systems based on a specific maximum tensile strain criterion. Subsidence and stability factor nomograms can also be utilized for a comprehensive analysis of each case. It is also possible to cross such pillar systems via mains or other low extraction configurations which are not expected to compromise the overall stability of the barrier system.

Results indicate that the width of barrier pillar or barrier pillar systems calculated using rules of thumb overestimate the protection zone and thus may sterilize significant coal reserves without offering additional protection benefits. Using ground strain as the design criterion, coupled with analytical calculations of barrier pillar stability factors, may result to a barrier pillar system that optimizes extraction and also provides protection to surface water bodies.

This approach presents a novel method for estimating barrier pillars for stream protection. The examination and analysis of additional case studies will be important to further establish, validate and utilize this methodology in practice.

3.7. Acknowledgements

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Chapter 4. EXPLORING BENTHIC IMPAIRMENT AND TOTAL DISSOLVED SOLIDS IN THE DUMPS CREEK WATERSHED

Preface

This Chapter is based on the following paper that was published in a peer reviewed conference proceedings. The paper name, authors, and conference details are summarized below:

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Abstract

This study looks at the Dumps Creek watershed located in Russell County, Virginia which has a long history of mining and industrialization. Dumps Creek was placed on the first Commonwealth of Virginia 303(d) List of Impaired Waters in 1994 due to benthic impairment and has not been removed from this list to-date. The U.S. Environmental Protection Agency (EPA) and other regulators have used total dissolved solids (TDS) and/or conductivity as a metric to characterize overall stream health. Historically, other benthic indicators have also been used as a stream characterization metric. This study, was conducted in Dumps Creek in Russell County, Virginia, used the Virginia Stream Condition Index (VSCI) as a rating for benthic community health and compared this rating to conductivity measurements in order to assess whether a correlation exists between these two measurements. Both historical data, collected by the Commonwealth of Virginia and by mining companies, and data collected under this study were used for these comparisons. This work suggests that the current practice of the universal use of conductivity as an indicator of stream health may be premature, without further understanding of how TDS/conductivity correlates to benthic health metrics.

4.1. Introduction

The southwest Virginia watershed of Dumps Creek is currently used for surface and underground mining and has been industrialized since the turn of the century. The watershed was placed on Virginia's 303(d) List of Impaired Waters when in the list was first established in 1994. The watershed was regarded as impaired due to poor benthic health. Due to the 303(d) listing, the state of Virginia also assigns total maximum daily load (TMDL) values for the watershed, in order to facilitate improvement of the impairment. Total dissolved solids (TDS) is

one of the metrics that is listed on the TMDL and that this watershed regularly exceeds due to the need to pump water out of an inactive underground mine. This water is then discharged near the headwaters of Dumps Creek. This study explores the historic and current relationship between TDS/conductivity and benthic health in this watershed.

4.2. Previous Studies

Using TDS/conductivity as a metric is a relatively new approach to understanding water chemistry in order to enforce regulation. In particular, based on the work of Pond and Passmore (2008), EPA and state water quality agencies have recently used conductivity in regulating the Appalachian coal mining industry. In contrast, the Illinois Environmental Protection Agency (2006) and Iowa Department of Natural Resources (2009) concluded from their TDS studies that TDS (and conductivity) is an inappropriate indicator of toxicity to benthic organisms because toxicity is ion-specific. The Illinois study indicates that 2,000 milligrams per Liter (mg/L) TDS with chloride dominance is toxic, but the same level TDS with sulfate dominance is not. Many authors have suggested a direct correlation between conductivity and benthic health, mostly in relation to surface mining; currently the body of literature appears split on whether conductivity is a good stand-alone metric for regulatory purposes.

The EPA contracted various research consultants to study the environmental effects of mountaintop coal mining (MTM) in Appalachia. Conclusions of this research, which focused on a broad array of ecological impacts, were published in both the draft Programmatic Environmental Impact Statement (PEIS) (EPA 2003) and the final PEIS (U.S. EPA 2005) on mountaintop mining and valley fills. Much of this work indicated that surface coal mining resulted in impacts on stream biota, particularly benthic macroinvertebrates.

In a later work, Griffith, et al. (2012) focused on studies included in both PEIS publications with respect to stream conductivity, individual ion concentrations and chemistry, in general. Their work concludes that a correlation was found between benthic health and conductivity levels below MTM valley fills as compared to nonmining areas. However, they concluded that, “no studies have quantified the change in conductivity, individual ion concentrations, pH or precipitates as the water progresses downstream...” (Griffith, et al. 2012). Although correlations are shown through much of the research published in the EPA produced draft and final PEIS, few specifics to understanding this correlation are explored in sufficient detail to explain the mechanisms for the correlations that were found.

Echols, et al., (2009) conducted controlled laboratory tests on a sensitive Ephemeroptera order species, concluding that in exposure to coal processing impoundment effluent, the threshold of impairment-inducing TDS/conductivity concentrations are higher than the benchmark value of 300 – 500 $\mu\text{S}/\text{cm}$ selected by EPA.

Armstead, et al., (2004) collected quantitative and qualitative samples over four seasons. Statistical comparisons were made between the categories of “unmined” (reference), “valley filled”, and “valley filled/residential” sampling sites. Results showed that water chemistry did change from a reference condition, however, those changes were not substantial in “valley filled” category streams, and biological impairment was most severe in “valley filled/residential” streams.

The Virginia Stream Condition Index (VSCI) is a multi-metric scoring protocol for benthic macroinvertebrates. This protocol was developed by the Virginia Department of Environmental Quality in order to identify biological impairment of non-coastal streams. The

VDEQ used benthic macroinvertebrate data from both impacted and reference streams throughout Virginia in order to determine which family-level macroinvertebrate metrics best evaluated stream condition in all 5 Virginia ecoregions. The metrics chosen are shown in Table 4-1 below.

Table 4-1: Macroinvertebrate metrics use in 5 Virginia ecoregions (adapted from Burton and Gerritsen (2003))

| Metrics, grouped by Category | Definition |
|--|--|
| Taxonomic Richness: Counts of different taxa within selected taxonomic groups | |
| Total Taxa | Number of distinct taxa in the entire sample; measures the overall variety of the macroinvertebrate assemblage |
| EPT Taxa | Sum of distinct taxa in the generally pollution-sensitive insect orders of Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) |
| EPT Taxa less Hydropsychidae | Sum of taxa in the insect orders Ephemeroptera, Plecoptera, and Trichoptera, not including the generally pollution-tolerant caddisfly family Hydropsychidae. |
| Ephemeroptera taxa | Number of Ephemeroptera taxa (mayfly nymphs) |
| Plecoptera taxa | Number of Plecoptera taxa (stonefly naiads) |
| Trichoptera taxa | Number of Trichoptera taxa (caddisfly larvae) |
| Trichoptera taxa less Hydropsychidae | Number of Trichoptera taxa not including the pollution tolerant caddisfly family Hydropsychidae |
| Diptera taxa | Number of Diptera taxa (“true” fly larvae and pupae) |
| Chironomidae taxa | Number of taxa in the family Chironomidae (midge larvae) |

Table 4-1 Continued

| Composition: Percent abundance (of individuals in the sample) of... | |
|--|--|
| %EPT | ... Ephemeroptera (mayfly nymphs), Plecoptera (stonefly naiads), and Trichoptera (caddisfly larvae) |
| %EPT less Hydropsychidae | ... Ephemeroptera, Plecoptera, and Trichoptera not including pollution tolerant caddisflies in the family Hydropsychidae |
| % Ephemeroptera | ... mayfly nymphs |
| % Plecoptera | ... stonefly naiads |
| % Trichoptera | ... caddisfly larvae |
| % Trichoptera less Hydropsychidae | ... caddisfly larvae not including those in the pollution tolerant family Hydropsychidae |
| % Plecoptera plus Trichoptera less Hydropsychidae | ... stonefly naiads plus caddisfly larvae not including those in the pollution tolerant family Hydropsychidae |
| % Diptera | ... "true" fly larvae and pupae |
| % Chironomidae | ... Chironomidae (midge) larvae and pupae |
| % Oligochaeta | ... aquatic worms |
| Trophic Groups: Percent abundance of individuals in the sample, or number of taxa in the sample, whose primary functional mechanism for obtaining food (functional feeding group, FFG) is to... | |
| % Collectors | ... collect/gather depositional organic matter |
| % Filterers | ... filter and collect suspended organic matter |
| % Predators | ... attack prey and ingest whole organisms or their parts |
| % Scrapers | ... graze on substrate- or periphyton-attached algae and associated material |
| % Shredders | ... shred and chew leaf litter and detritus |
| Scraper taxa | (number of taxa classified primarily as scrapers) |
| Diversity: Percent abundance in the sample of individuals belonging to... | |
| % Dominant | ... the single most abundant taxon |
| % 2 Dominant taxa | ... the two most abundant taxa |
| % 5 Dominant taxa | ... the five most abundant taxa |
| Tolerance: Counts, proportions, or weighted scores of taxa based on ability to survive exposure to stressors | |
| Intolerant taxa | Number of taxa with Tolerance Values 3 |
| % Tolerant | Percent abundance of organisms with a Tolerance Value 7 |
| HBI | Abundance-weighted average tolerance of assemblage of organisms (Family taxonomic level) |
| Habitat: Organisms having the specified dominant behavior for moving and maintaining physical position in their habitat | |
| % Clingers | Percent abundance of insects having fixed retreats or adaptations for attachment to surfaces in flowing water |
| Clinger taxa | Number of taxa having fixed retreats or adaptations for attachment to surfaces in flowing water |

In order for the VSCI protocol to encompass all streams in Virginia, some resolution is often lost on local scales. For example, the VSCI is used on streams ranging from coastal Piedmont streams (Region 45) to central Appalachian streams (Region 69). Scores in central Appalachian streams, even on reference streams, tend to be lower than other regions of Virginia. This may be due to natural regional differences that the VSCI does not account for or it may be due to the low number of reference sites used in central Appalachia. Of the 62 reference sites used in the development of the VSCI, only 5 of these sites were in central Appalachia (Burton and Gerritsen 2003).

A study by Northington, et al. (2011), assessed the physical habitat, water quality field parameters (including conductivity), and dissolved major ions and metals, to evaluate relationships between TDS concentrations and the VSCI. VSCI scores, which are based on the Commonwealth of Virginia's implementation of stream condition assessment required under the Clean Water Act, assess stream quality based on the population of various organisms in the stream. Findings have shown that certain streams with elevated conductivity values maintain a better VSCI score than some reference streams with very low conductivity.

Pond and Passmore have collaborated on several scientific papers focused on this issue of conductivity. However, even their research appears to yield some different conclusions. Their study in the Straight Creek, Virginia watershed (Passmore and Pond 2009) reached different results than an earlier Pond and Passmore, et al., (2008) study. These differences include the toxicity impacts of conductivity, the comparative impacts of stressors, the ionic makeup of mine-related drainage, and the threshold value of conductivity-associated benthic impairment. The results of this recent investigation, and its contrasting findings to previous studies by the same investigators, shows that the science on these issues is unsettled.

The Passmore and Pond (2009) investigation found that residential land use with improper control of sewage is a major stressor of sensitive benthic life throughout the region. This study also concluded that stream sites near mines were often in better condition than at points farther downstream where residential and other land use impacts occur. The authors offer the opinion that conductivity may be useful as an indicator of general conditions and of trends. They also recommend the construction of sewage systems as an obvious first step to improve the streams studied. Further, the data in this report also confirms that some sites studied in that investigation had unimpaired conditions even with conductivities higher than the levels that had been considered in the previous study to definitely be associated with impairment. Reasons for that difference are discussed, but not fully explained, and may relate to the differences in ionic composition between areas.

Mount, et al. (1997), evaluated specific ion effects on aquatic organism toxicity. The report evaluation indicates that sulfate, bicarbonate, calcium, magnesium, sodium, and potassium ions comprise 99% of the total ions in the MTM discharges studied (the ions above are listed from highest concentration to lowest concentration). Sulfate leads the ion composition by approximately six times the concentration of bicarbonate, the next leading ion in the test waters. That being said, the study's toxicity testing indicates that sulfate is the least toxic of the test ions. This study emphasizes the importance of analyzing what individual constituents are being collectively measured by TDS rather than looking at TDS as a singular value.

4.3. Historic Data

Dumps Creek is located in Russell County, Virginia, just northwest of the town of Cleveland. Dumps Creek was placed on the Commonwealth of Virginia's 1994 303(d) List of Impaired Waters because of repeated violations of the general standard based on benthic life

criteria and is still on this list today. The impaired stream segment has a length of 3.40 miles, and extends from the Hurricane Fork Confluence to the mouth where Dumps Creek flows into the Clinch River. This stream confluence is near the Appalachian Power Plant in Russell County that discharges to the Clinch River. The land area of the Dumps Creek Watershed is approximately 20,300 acres, with forest and mining as the primary land uses. Dumps Creek has been heavily industrialized since the turn of the Century, as a munitions manufacturing facility, and then was heavily surface and underground mined, with a processing facility also located along Dumps Creek. Most mining in Dump's Creek took place before the establishment of environmental protection legislation such as the Clean Water Act (CWA) of 1972 and the Surface Mining and Control Reclamation Act (SMCRA) of 1978.

Currently, there are two pumps staged in the headwaters region of Dumps Creek that help to maintain water levels in an inactive underground mine. The pumping is necessary to control methane levels that rising water could force into an active underground mine that lies stratigraphically above the inactive mine. Water is pumped on an as-needed basis and discharges directly into Dumps Creek.

Conductivity and VSCI data have been collected periodically, although not annually, from 2001 to 2012. We analyzed all the historical data available from the Commonwealth of Virginia and other sources. A linear regression analysis of these data show an R^2 of 0.192 (Figure 4-1), which indicates little direct correlation between conductivity and stream impairment as determined by the VSCI. Further, an outlier test was performed on both the conductivity values and the VSCI values, eliminating any points that were beyond two standard deviations of the mean. This eliminated four historic data points. This data, excluding the

outliers was again plotted against a linear regression equation to get an R^2 value of 0.0736 (Figure 4-2).

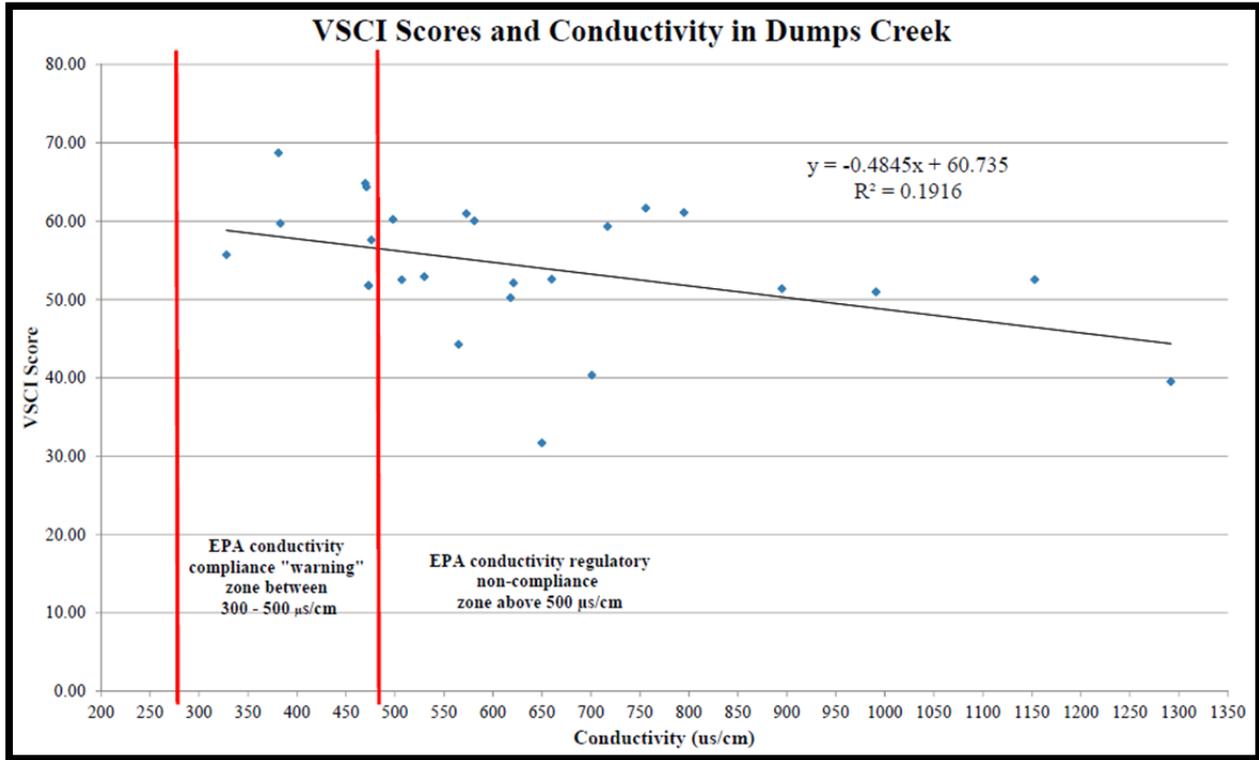


Figure 4-1: Historic VSCI scores and conductivity in Dumps Creek including outliers

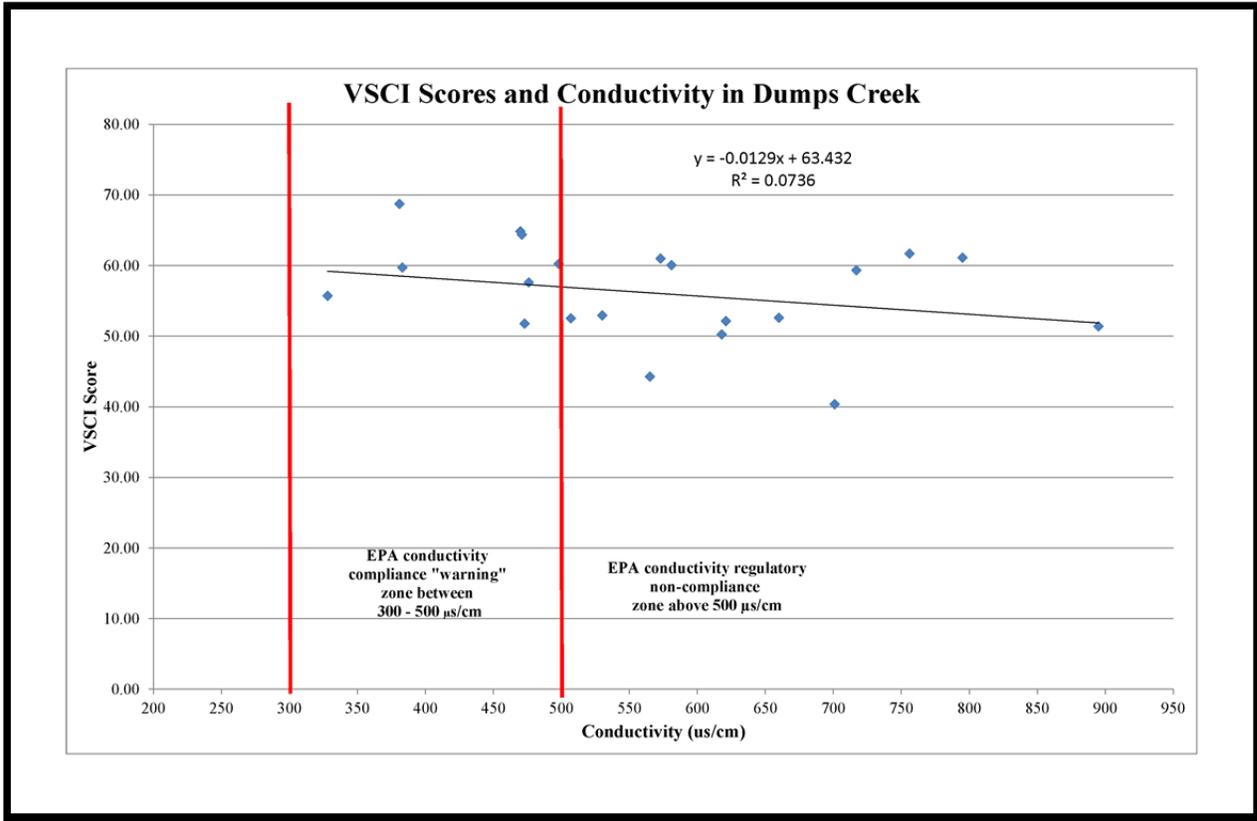


Figure 4-2: Historic VSCI scores and conductivity in Dumps Creek excluding outliers

4.4. Current Sampling Data Verification

To verify the historic data collection and trends, Appalachian Technical Services (ATS) was contracted, as a third party, to collect water chemistry and benthic samples for five locations along Dumps Creek. ATS sent these samples to Research Environmental Industrial Consultants, Inc. (REIC) in Beaver, West Virginia for analysis. REIC is an accredited Virginia laboratory. Current sampling locations are depicted on Figure 4-3, below. The southernmost two locations (6BDUM000.23 and 6BDUM001.09) are in close proximity to the locations that are sampled by the Commonwealth of Virginia for the 303(d) listing; the next sample north in the watershed (Abv S Clinchfield) is located above a discharge that drains a community called South

Clinchfield, and the two northernmost samples located near the headwaters of Dumps Creek focused on influence associated with pumped water from a nearby underground mine in the watershed. One sample was specifically of the pumped water (Pumps) and one sample was of the surface water in Dumps Creek, prior to reaching the pumps (Abv Pumps).

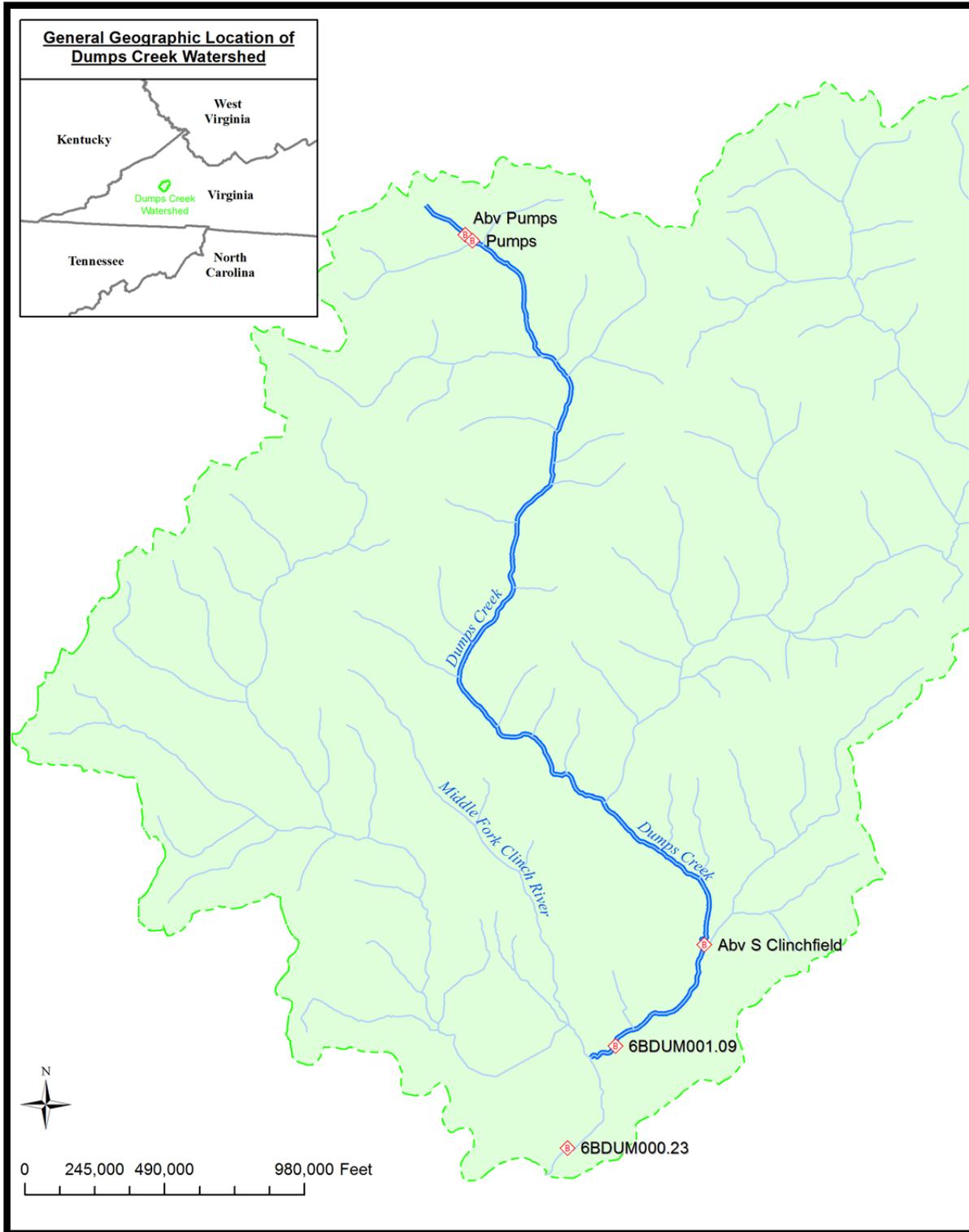


Figure 4-3: General map of Dumps Creek watershed and current sample locations

Water chemistry was taken of the discharged pump water and both water chemistry and benthic macroinvertebrates were sampled above the pump discharged water influence. When this data was added to 2001 to 2012 data, the trend also shows a low correlation between the conductivity and VSCI scores with an R^2 of 0.1588 (Figure 4-4). Again, the outlier test was performed on both the conductivity values and the VSCI values, eliminating any points that were beyond two standard deviations of the mean. This eliminated four historic data points. This data, excluding the outliers was again plotted against a linear regression equation to get an R^2 value of 0.0505 (Figure 4-5).

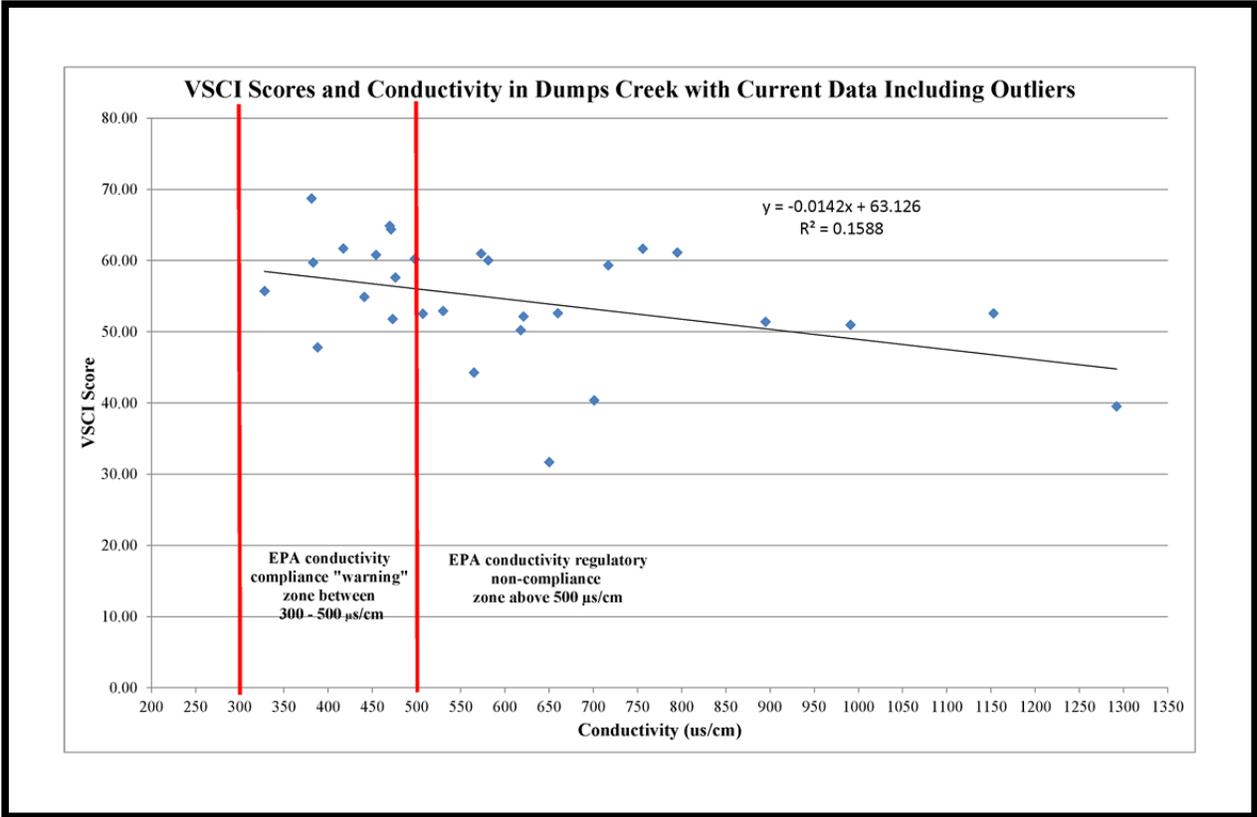


Figure 4-4: Graph of VSCI scores and conductivity in Dumps Creek including current data and outliers

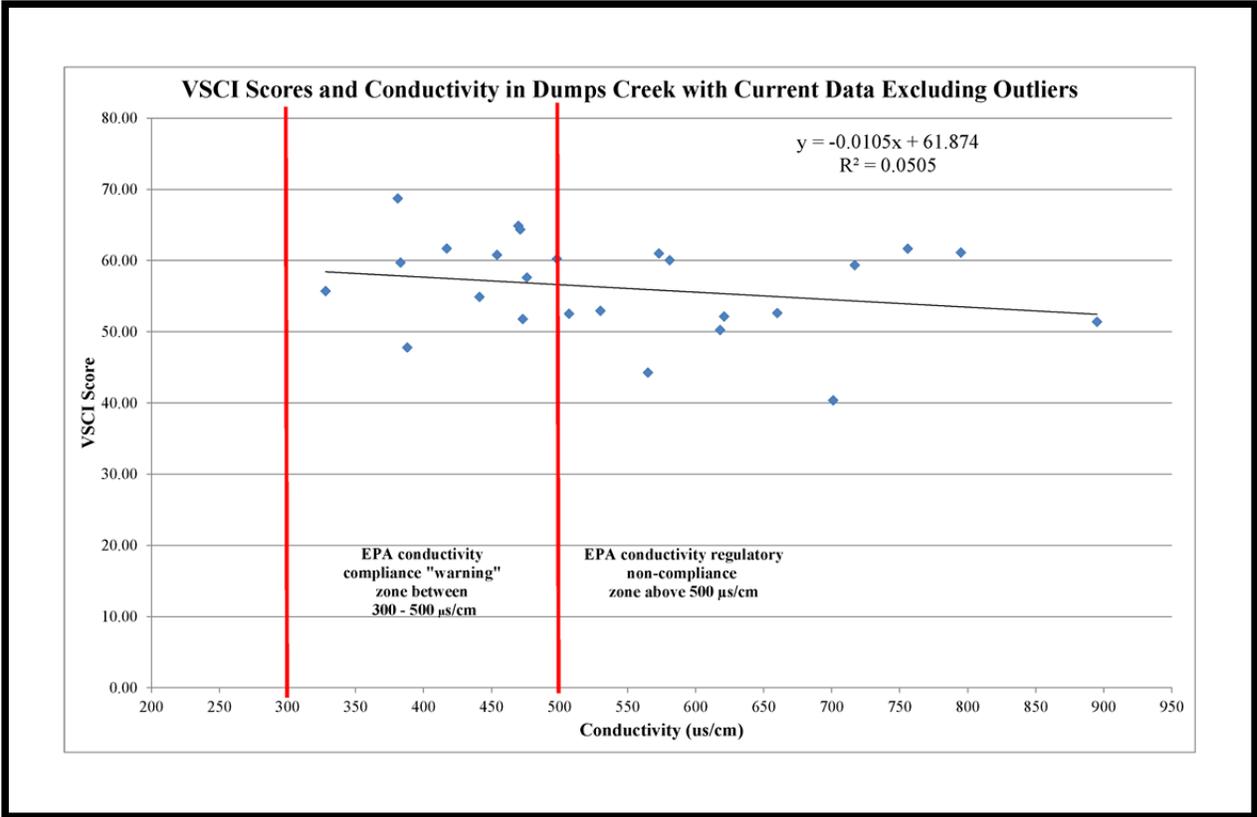


Figure 4-5: Graph of VSCI scores and conductivity in Dumps Creek including current data excluding outliers

Passmore and Pond (2009) conducted a study in Lee County on Straight Creek where VSCI scores and conductivity values were taken. Although the authors did not plot the data against each other we plotted the data below (Figure 4-6) as a comparison watershed with the same metrics. Again, the correlation coefficient of this data is also very low (1.388) which was similar to what was found in Dumps Creek.

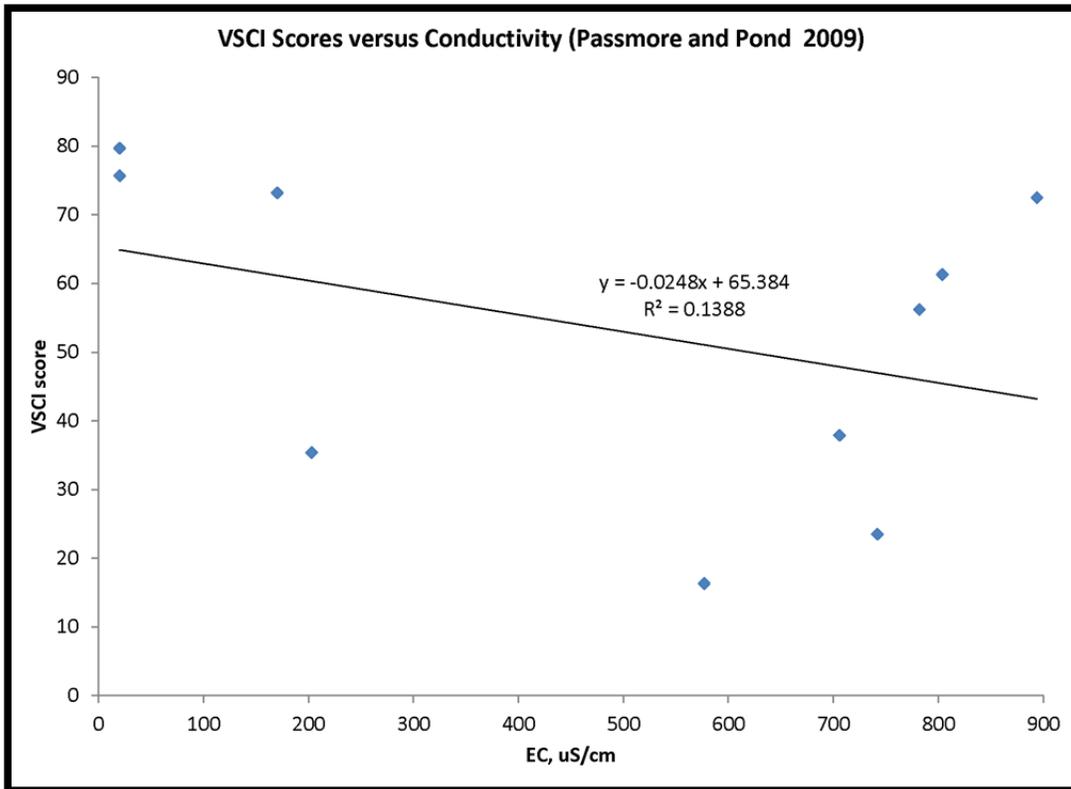


Figure 4-6: Graph of VSCI scores and conductivity in Straight Creek (compiled from Passmore and Pond 2009)

In addition to the above assessment of linear correlation, several statistical parameters were checked on the entire dataset gathered at Dumps Creek, again, including outliers and excluding outliers. VSCI data that corresponded to conductivity data below 500 $\mu\text{S}/\text{cm}$ were considered one dataset and VSCI data that corresponded to conductivity data above 500 $\mu\text{S}/\text{cm}$ were considered a second dataset. To first assess the normality of the data, frequency histograms were constructed including outliers and excluding outliers and plotted for comparison against a normal distribution for both conductivity and VSCI data and are shown in Figures 4-7, 4-8, 4-9 and 4-10 below:

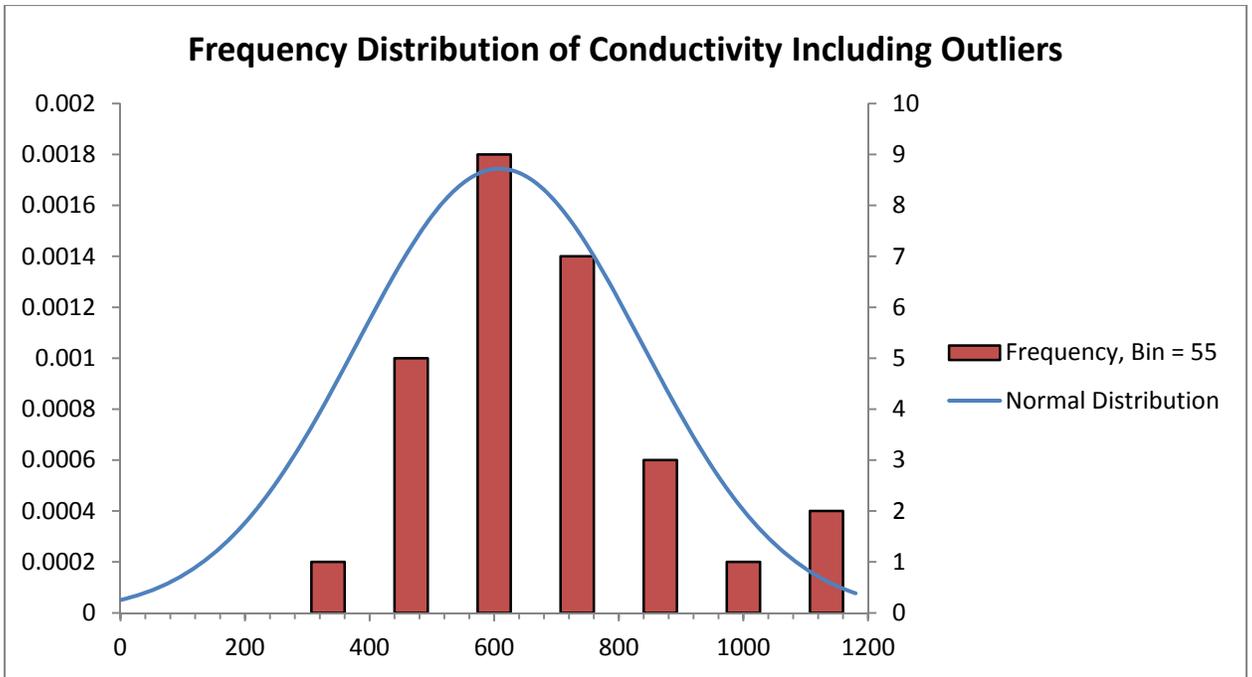


Figure 4-7: Frequency distribution of conductivity in Dumps Creek including outliers

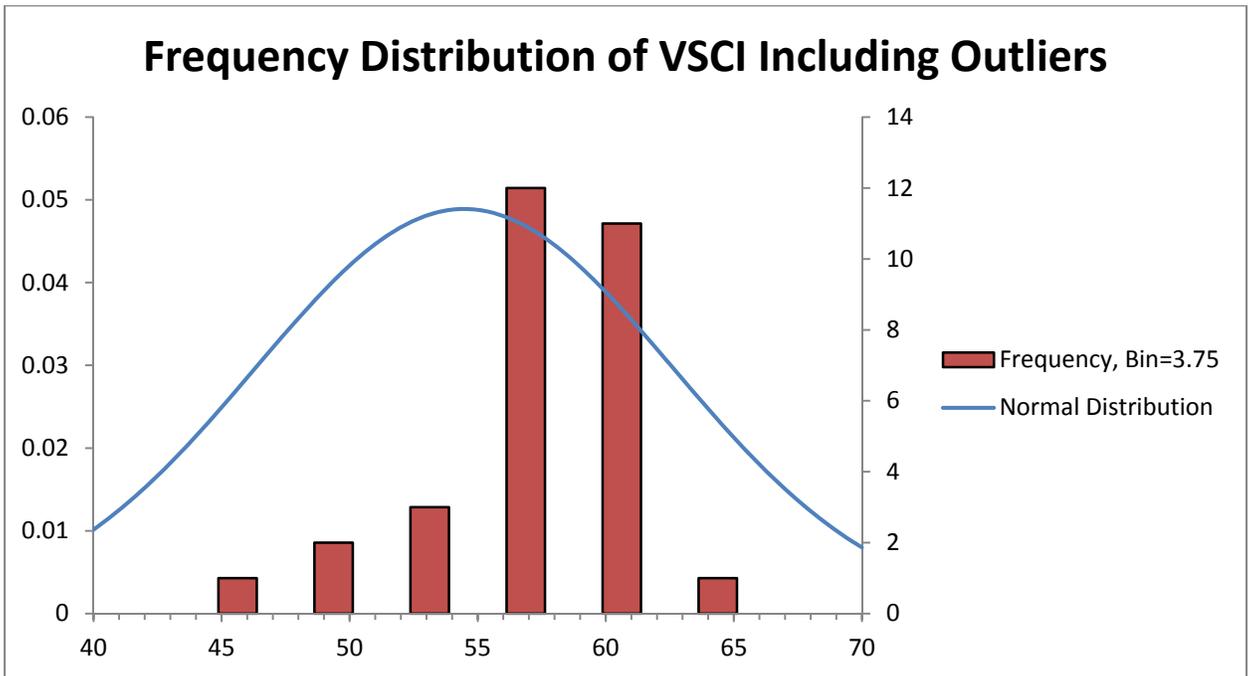


Figure 4-8: Frequency distribution of VSCI scores in Dumps Creek including outliers

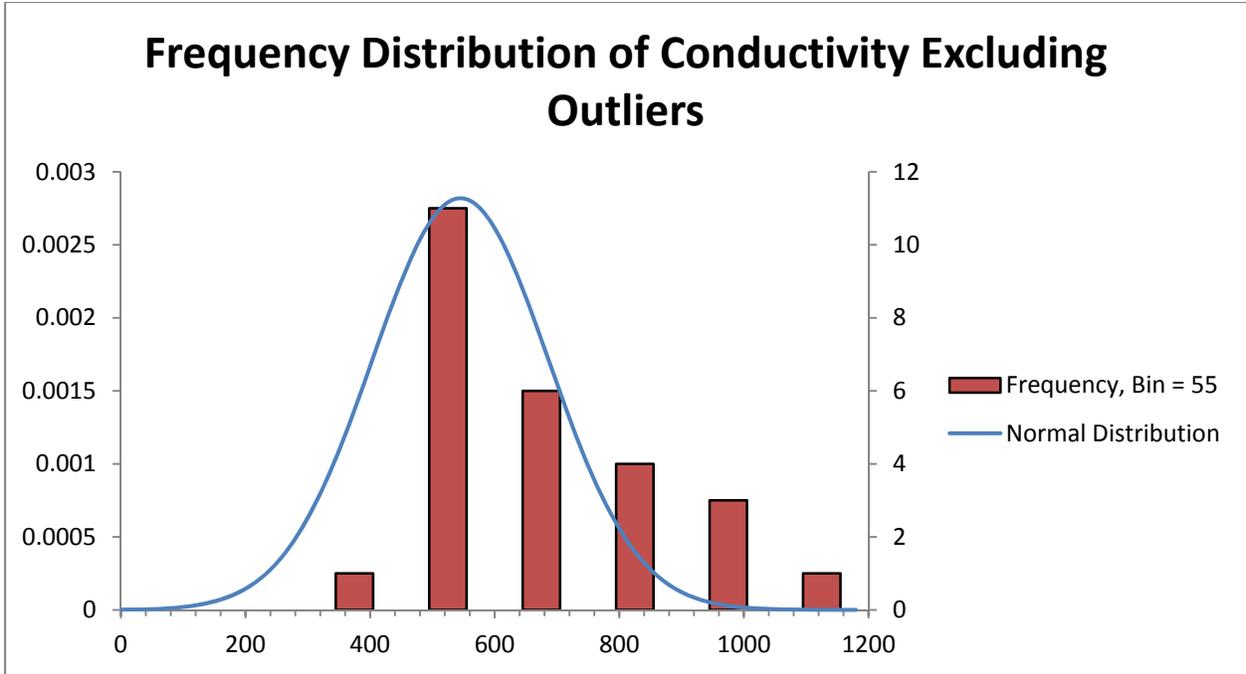


Figure 4-9: Frequency distribution of VSCI scores in Dumps Creek excluding outliers

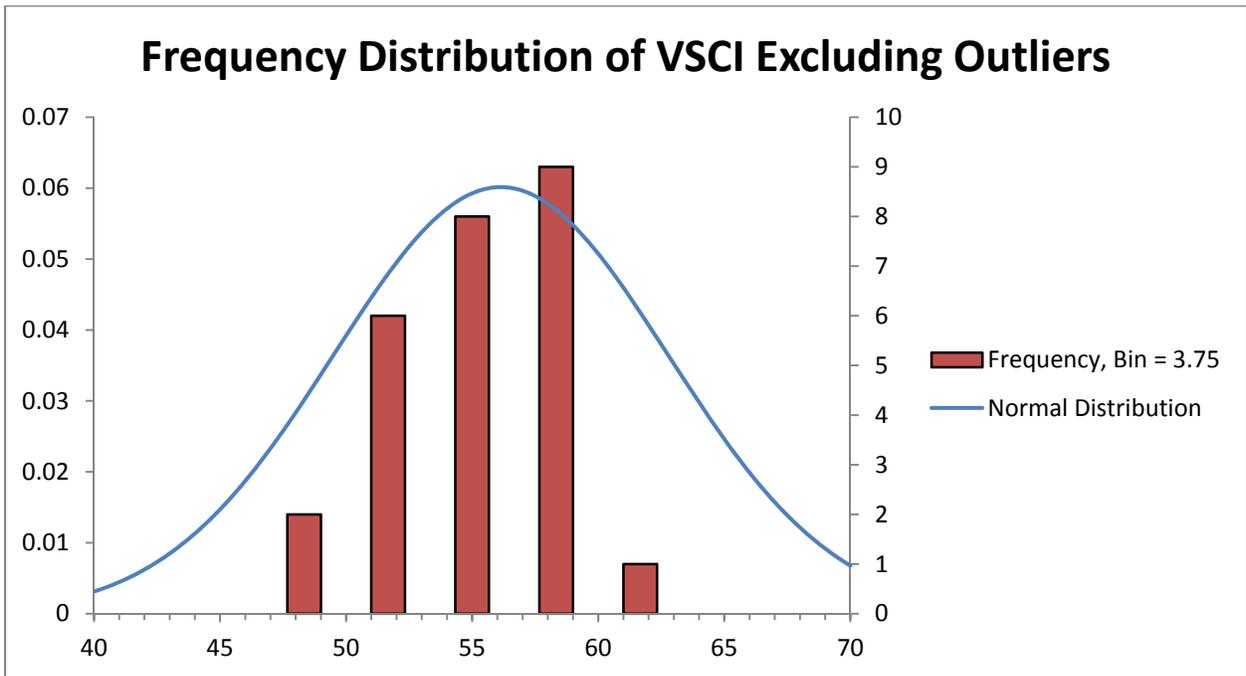


Figure 4-10: Frequency distribution of VSCI scores in Dumps Creek excluding outliers

The frequency distributions show that for both conductivity and VSCI data the concentration of the frequency is centered about the mean and is less at the tails, approximating a normal distribution. Compiling more data would solidify this assumption.

After normality can be assumed an F-Test was performed comparing VSCI data corresponding to conductivity data above 500 $\mu\text{s/cm}$ and below 500 $\mu\text{s/cm}$ with and without outliers, at a 95% confidence level, to assess whether these datasets would be considered to either belong to the same population or not. Tables 4-2 and 4-3 below, shows the results of the F-Tests performed:

| F-Test Two-Sample for Variances | | α | 0.05 |
|---------------------------------|--|--------------|----------|
| | <i>Data1</i> | <i>Data2</i> | |
| Mean | 51.42564 | 58.46127 | |
| Variance | 71.26266 | 35.47373 | |
| Observations | 17 | 13 | |
| df | 16 | 12 | |
| F | 2.01 | | |
| P(F<=f) one-tail | 0.113 | 0.226 | Two-tail |
| F Critical one-tail | 2.60 | 3.15 | Two-tail |
| One-tail | Accept Null Hypothesis because $p > 0.05$ (Variances are the same) | | |
| Two-tail | Accept Null Hypothesis because $p > 0.05$ (Variances are the same) | | |

Table 4-2: F-Test Comparing VSCI data corresponding to conductivity data above 500 $\mu\text{s/cm}$ and below 500 $\mu\text{s/cm}$ including outliers

| F-Test Two-Sample for Variances | | α | 0.05 |
|---------------------------------|--|--------------|----------|
| | <i>Data1</i> | <i>Data2</i> | |
| Mean | 53.80885 | 58.46127 | |
| Variance | 44.44253 | 35.47373 | |
| Observations | 13 | 13 | |
| df | 12 | 12 | |
| F | 1.25 | | |
| P(F<=f) one-tail | 0.351 | 0.702 | Two-tail |
| F Critical one-tail | 2.69 | 3.28 | Two-tail |
| One-tail | Accept Null Hypothesis because $p > 0.05$ (Variances are the same) | | |
| Two-tail | Accept Null Hypothesis because $p > 0.05$ (Variances are the same) | | |

Table 4-3: F-Test Comparing VSCI data corresponding to conductivity data above 500 $\mu\text{s}/\text{cm}$ and below 500 $\mu\text{s}/\text{cm}$ excluding outliers

As shown, the null hypothesis was accepted, showing that the two datasets are from the same population. This test shows that at a 95% confidence level conductivity values below 500 and above 500 do not change the population of benthic scores within the two regulatory regions. Table 4-4 below shows corresponding confidence levels where the null hypothesis would start to be rejected for both a one and two tailed F-test as shown above, including and excluding outliers:

| Outlier Inclusion | Confidence Level | Test Type |
|--------------------------|-------------------------|------------------|
| Including Outliers | 85% | One-Tailed |
| Including Outliers | 75% | Two-Tailed |
| Excluding Outliers | 60% | One-Tailed |
| Excluding Outliers | 20% | Two-Tailed |

Table 4-4: F-Test Confidence levels where Null Hypothesis is rejected

This shows that rejecting the null hypothesis and concluding that these datasets are from the same population can only be done at statistically low confidence level, especially if outliers are excluded.

Further, a T-Test assuming equal variances, gathered from the F-Test, at a 95% confidence level, with and without outliers was performed on the same data (Table 4-5 and 4-6):

| t-Test: Two-Sample Assuming Equal Variances | | α | 0.05 |
|---|--------------|--------------|--|
| Unequal Sample Sizes | | | |
| | <i>Data1</i> | <i>Data2</i> | |
| Mean | 51.42564 | 58.46127 | |
| Variance | 71.26266 | 35.47373 | |
| Observations | 17 | 13 | |
| Pooled Variance | 55.92454 | | |
| Hypothesized Mean Difference | 0 | | |
| df | 28 | | |
| t Stat | -2.554 | | |
| | | | Reject Null Hypothesis because $p < 0.05$ |
| P(T<=t) one-tail | 0.008 | | (Means are Different) |
| T Critical one-tail | 1.701 | | |
| | | | Reject Null Hypothesis because $p < 0.05$ |
| P(T<=t) two-tail | 0.016 | | (Means are Different) |
| T Critical Two-tail | 2.048 | | |

Table 4-5: T-Test Assuming Equal Variance Comparing VSCI data corresponding to conductivity data above 500 $\mu\text{s}/\text{cm}$ and below 500 $\mu\text{s}/\text{cm}$ including outliers

| | | |
|---|--------------|---|
| t-Test: Two-Sample Assuming Equal Variances | α | 0.05 |
| Unequal Sample Sizes | | |
| | <i>Data1</i> | <i>Data2</i> |
| Mean | 53.80885 | 58.46127 |
| Variance | 44.44253 | 35.47373 |
| Observations | 13 | 13 |
| Pooled Variance | 39.95813 | |
| Hypothesized Mean Difference | 0 | |
| df | 24 | |
| t Stat | -1.876 | |
| P(T<=t) one-tail | 0.036 | Reject Null Hypothesis because $p < 0.05$ (Means are Different) |
| T Critical one-tail | 1.711 | |
| P(T<=t) two-tail | 0.073 | Accept Null Hypothesis because $p > 0.05$ (Means are the same) |
| T Critical Two-tail | 2.064 | |

Table 4-6: T-Test Assuming Equal Variance Comparing VSCI data corresponding to conductivity data above 500 $\mu\text{s}/\text{cm}$ and below 500 $\mu\text{s}/\text{cm}$ excluding outliers

As shown above in Table 4-3, the null hypothesis was rejected for both the one and two-tailed tests when outliers were included at a 95% confidence level. When outliers are excluded the null hypothesis is again rejected for the one-tailed test, however, the null hypothesis was accepted with the two-tailed test. Rejecting the null hypothesis means that the two VSCI datasets have a different average value, accepting the null hypothesis means that the two VSCI datasets have the same average value, above a level of 500 $\mu\text{s}/\text{cm}$ conductivity and below 500 $\mu\text{s}/\text{cm}$ conductivity. The confidence level of this data concludes that there may be a difference in means between the two datasets. The reason for this difference is unknown however, as shown by the linear regression coefficients in Figures 4-1, 4-2, 4-4 and 4-5 above, this difference is not due to a linear correlation between conductivity and VSCI scores and requires further research.

Further, a one-tailed T-Test was performed using a t-statistic of the correlation coefficient including outliers (Figure 4-11) and excluding outliers (Figure 4-12). The null hypothesis assumes that the true correlation is either positive or ≥ 0 and the alternative hypothesis assumes

that the correlation is negative, which is what regulations have purported. The test assumes a confidence level of 95% in the ability to correctly interpret the null hypothesis. Given a t-statistic of the correlation coefficient (derived from Pearson's Correlation Coefficient) which measures the strength of the linear relationship between conductivity and VSCI scores, the test statistic must be lesser than the Critical T-Value in order to reject the null hypothesis. For a 99% confidence level, including outliers, the Critical T-Value was -2.47 and the test statistic was -2.30 and for a 95% confidence level, including outliers, the Critical T-Value was -1.70 and the test statistic was -2.30; therefore, the null hypothesis is accepted at a 99% confidence level and begins to be rejected at a 95% confidence level. Excluding outliers at a 95% confidence level the Critical T-Value was -1.71 and the test statistic was -1.13, therefore, the null hypothesis is accepted using just the 95% confidence level. When the null hypothesis is accepted, this one-tailed T-test shows that, with the given confidence level, that the true correlation of the data is either positive or ≥ 0 . Excluding outliers, the null hypothesis would begin to be rejected at an 87% confidence level. This shows that, within the confidence levels defined, a negative correlation, as expected by regulatory metrics, may not exist for the given data set at the confidence levels defined. Again, more data would help to give further statistical verification.

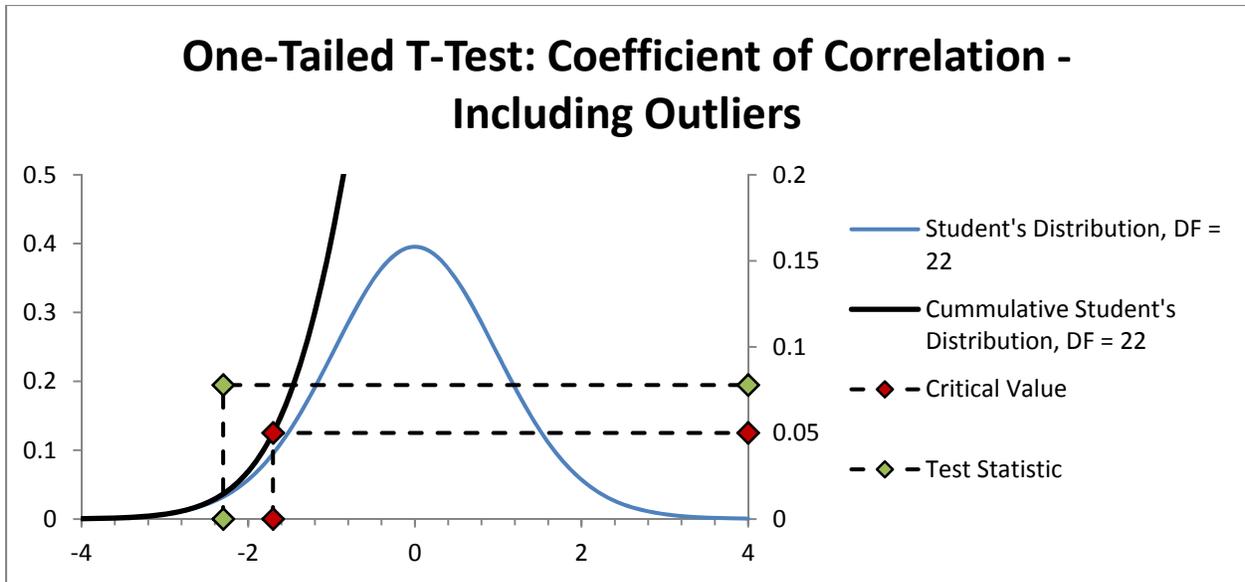


Figure 4-11: One-tailed T-Test for the coefficient of correlation including outliers

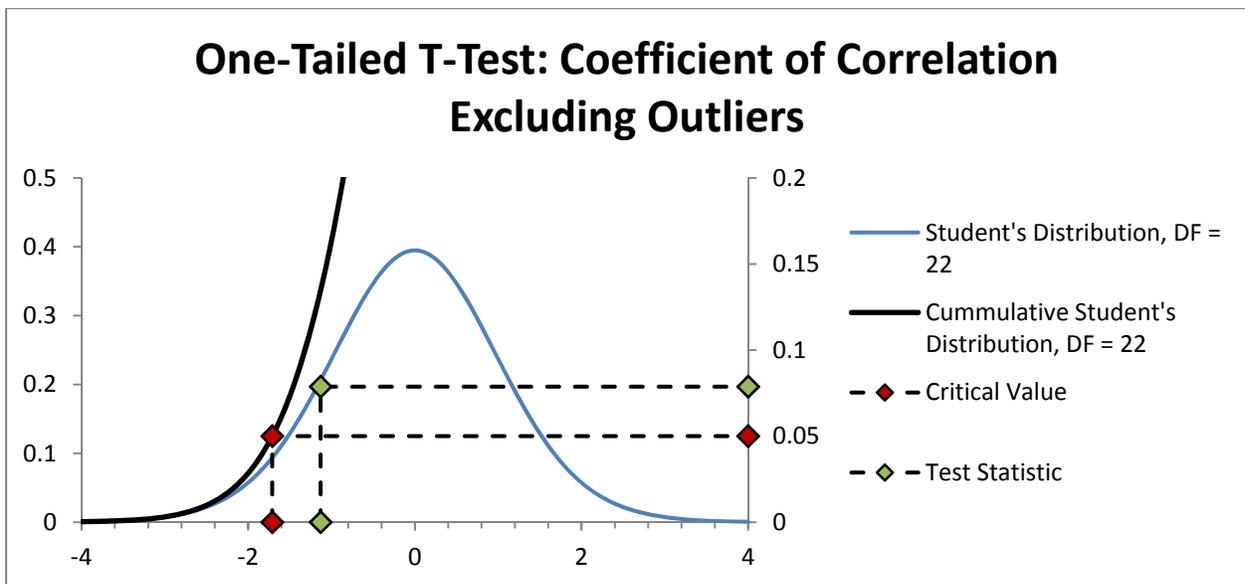


Figure 4-12: One-tailed T-Test for the coefficient of correlation excluding outliers

4.5. Water Chemistry

The current five samples shown previously on Figure 4-2 were analyzed for metals, specific conductivity, TDS, and major ions and anions. Table 4-7, below, shows the results obtained for the major ions and anions. The data show that this watershed is characterized by bicarbonate anions (rather than sulfate or chloride) and has very low loading in iron, manganese

and aluminum. While previous work has concluded that bicarbonate-dominated systems may demonstrate a correlation between conductivity and benthic community health (e.g., Timpano et al. 2011), Dumps Creek appears to deviate from previous work. The work of Timpano et al. concluded that there was a negative relationship between VASCI scores and TDS/specific conductance/sulfate which they also found to be generally consistent with bicarbonate dominated systems. This research also used a linear regression analysis in their conclusions.

Table 4-7: Dumps Creek Water Chemistry, Fall 2012

| Sample ID | Date | Iron (mg/L) | Manganese (mg/L) | Aluminum (mg/L) | Chloride (mg/L) | Sulfate (mg/L) | Bicarbonate (mg/L) |
|---|-----------|-------------|------------------|-----------------|-----------------|----------------|--------------------|
| 6BDUM000.23 | 10/3/2012 | <0.100 | <0.100 | <0.100 | 5.23 | NA | 128 |
| 6BDUM001.09 | 10/3/2012 | 0.103 | <0.100 | <0.100 | 4.54 | 71.0 | 132 |
| ABV S Clinchfield | 10/3/2012 | <0.100 | <0.100 | <0.100 | 4.39 | 60.8 | 132 |
| ABV PUMPS | 10/3/2012 | 0.241 | <0.100 | <0.100 | 2.07 | 89.2 | 85.6 |
| PUMPS | 10/3/2012 | 0.834 | 0.118 | <0.100 | 18.1 | 25.0 | 540 |
| Note: | | | | | | | |
| mg/L - Milligrams per Liter | | | | | | | |
| NA - Not Analyzed | | | | | | | |
| <0.100 - This shows that the constituent was less than the Practical Quantitation Limit | | | | | | | |

4.6. Conclusions

The Dumps Creek watershed has a long history of activities that have had potential to cause impairment to water chemistry and the health of stream biota. Both mining operators and regulators have struggled with the impairment of the stream for many years. It has been difficult to adequately quantify and specify what is causing the identified impairment to benthic macroinvertebrate communities in the stream, as evidenced by low VSCI scores over many years.

Recently, the use of conductivity and/or TDS has been suggested as a regulatory metric to quantify stream health. However, historic and current conductivity data and VSCI scores show that, in this specific watershed, these metrics do not appear to have a correlation. This conclusion, while in contrast to the conclusion of Pond and Passmore (2008), is nonetheless

consistent with work done by other researchers, including Passmore and Pond (2009). A lack of correlation between conductivity and benthic scores also contrasts with the work of Timpano et al. (2011) in a watershed with similar bicarbonate anion dominance.

Dumps Creek historic benthic and water chemistry data and current, third-party verified, benthic and water chemistry data was analyzed statistically. The statistical tests showed the following conclusions (Table 4-8) below:

| Outliers | Test Type | Confidence Level | Conclusion |
|--------------------|---|-------------------------|--|
| Including Outliers | F-Test One-Tailed | Between 99% and 85% | VSCI data corresponding to conductivity data above 500 $\mu\text{s}/\text{cm}$ and below 500 $\mu\text{s}/\text{cm}$ are from the same population within this confidence level |
| Including Outliers | F-Test Two-Tailed | Between 99% and 75% | VSCI data corresponding to conductivity data above 500 $\mu\text{s}/\text{cm}$ and below 500 $\mu\text{s}/\text{cm}$ are from the same population within this confidence level |
| Excluding Outliers | F-Test One-Tailed | Between 99% and 60% | VSCI data corresponding to conductivity data above 500 $\mu\text{s}/\text{cm}$ and below 500 $\mu\text{s}/\text{cm}$ are from the same population within this confidence level |
| Excluding Outliers | F-Test Two-Tailed | Between 99% and 20% | VSCI data corresponding to conductivity data above 500 $\mu\text{s}/\text{cm}$ and below 500 $\mu\text{s}/\text{cm}$ are from the same population within this confidence level |
| Including Outliers | T-Test Assuming Equal Variances - One-Tailed | 99% | VSCI data corresponding to conductivity data above 500 $\mu\text{s}/\text{cm}$ and below 500 $\mu\text{s}/\text{cm}$ have different means |
| Including Outliers | T-Test Assuming Equal Variances - Two-Tailed | Between 99% and 95% | VSCI data corresponding to conductivity data above 500 $\mu\text{s}/\text{cm}$ and below 500 $\mu\text{s}/\text{cm}$ have the same mean |
| Excluding Outliers | T-Test Assuming Equal Variances - One-Tailed | Between 99% and 95% | VSCI data corresponding to conductivity data above 500 $\mu\text{s}/\text{cm}$ and below 500 $\mu\text{s}/\text{cm}$ have the same means |
| Excluding Outliers | T-Test Assuming Equal Variances - Two-Tailed | Between 99% and 90% | VSCI data corresponding to conductivity data above 500 $\mu\text{s}/\text{cm}$ and below 500 $\mu\text{s}/\text{cm}$ have the same mean |
| Including Outliers | T-Test: Coefficient of Correlation - One-Tailed | Between 99% and 95% | VSCI data and conductivity data could have a positive correlation |
| Excluding Outliers | T-Test: Coefficient of Correlation - One-Tailed | Between 99% and 85% | VSCI data and conductivity data could have a positive correlation |

Table 4-8: Statistical Conclusions Summary

Statistical data show that further research is warranted in this watershed and that the use of conductivity as a measure of watershed health may be premature given the inconclusive statistical results of all available data. This study analyzed data that was available although a larger data set would be beneficial in drawing further conclusions to assess whether improving the conductivity and therefore the load to this watershed would improve benthic health in order to remove the watershed from the Virginia 303(d) List of Impaired Waters. These conclusions suggest that benthic health, in this watershed, may be more greatly affected by other influences in the watershed that have yet to be identified.

Further, on April 11, 2013, the U.S. EPA Region 3 (U.S. EPA, 2013) commented on ARIES Technical Bulletin Number 1, which was derived from the original paper submitted in the Charleston, West Virginia conference proceedings. We agree that the benefit of continuing to collect and apply data to the above conclusions, both spatially and in quantity, would be helpful to better assess the chemistry and benthic health of this watershed. If more data were available, the seasonality of the data would have been taken into account and data from different seasons would not have been analyzed together. However, given the small dataset, an assessment of all available data was more beneficial. EPA stated that no data was presented that represented background levels of conductivity and associated VSCI scores; however, data does not exist for low levels of conductivity due to the decades of heavy industrialization of this watershed, prior to available data collection. Therefore, this data was not ignored or left out, it simply does not exist for this watershed and for many heavily coal mined or industrialized watersheds. For studies such as this one, conclusions have to be made from available data set whether or not this data may be considered ideal.

Additionally, we also agree that the use of one metric to assess watershed health is limiting and assessing the chemistry and therefore benthic health stressors on a case study basis is far superior in maintaining watershed health than using one broad metric to understand the overall health of the watershed. This study was the start of further assessment in order to understand the history relationships between conductivity and stream health in this watershed to determine if the current use of conductivity/TDS values to assess the health of the watershed was an appropriate metric, for this purpose, in this watershed. Although our conclusions may appear simplistic, it is clear that the many confounding factors call for a more holistic approach to fully understand the benthic health and trends in the Dumps Creek watershed. Through collaboration with the EPA and further assessment, research hopes to gain a further synergy between industry practices used to improve watershed health and regulatory metrics used to direct these practices in order to further water chemistry and benthic health understanding.

Finally, the conclusions of this work underscore the inconsistencies between results of studies with this similar topic. There is a need for continued research related to the relationship of water chemistry, as measured by conductivity and specific ion concentrations, and the relative health of benthic macroinvertebrate communities. This work suggests that the current practice of the universal use of conductivity as an indicator of stream health may be premature, without further understanding of how TDS/conductivity correlates to benthic health metrics.

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Chapter 5. CONCLUSIONS

Surface water impacts from active underground mining can influence the form and function of a surface water resource, as well as the overall chemical composition of the water. The regulatory environment in the coal mining industry has increasingly become more aware and therefore more protective of water resources. The influence of underground mining on surface water is complex due to the various factors involved in each mining and surface water interactive situation and is therefore hard to research and quantify on a large scale. An approach that can account for variability is crucial in understanding and regulating this interaction. This paper presented two original Research Objectives, one that focused on the relationship of underground mining and its influence on the form and function of surface waters and one that focused on the chemical influence of surface waters from underground mining.

The SDPS program was used in the first Research Objective in order to use an approach that would account for case study variability and would formulate mine planning tools that could be used to protect surface waters from mine subsidence. Empirical and analytical pillar sizing methods for stream protection were compared using SDPS program outputs to assess the validity and usefulness of each approach.

Research Objective 1 evaluated the use of SDPS to calculate the optimal proximity of a surface water body to an underground full extraction area needed to protect the form and function of nearby surface waters. Comparing the predicted values for the same panel depth, it was observed that conventional mine planning methods based on empirical rules significantly overestimate the panel edge distance from the centerline of the stream. Empirical and analytical methodologies cannot account for surface tensile strains that may lead to drainage of a surface

water resource, as SDPS can. Using ground strain as the driving criterion, coupled with analytical calculations of stability factors for barrier pillar systems, may result in an optimum design of such barriers pillars left underground for the protection of surface water bodies. Employing a more sound engineering method to estimate a stream protection pillar may increase extraction, while at the same time providing the same amount of environmental protection for the overlying stream bed form and function. Calculations of the proximity of a surface water body to an underground full extraction area and the sizing of the required barrier pillar can be greatly facilitated by using SDPS rather than conventional practices.

The final point of research in this paper focused on the chemical impact to surface water from active underground mining. This point, in particular, warrants further research due to the complexity and the divided body of research that covers this topic. Research Objective 2 focused on the Dumps Creek watershed located in southwest Virginia. Historically, this watershed has had heavy industrialization from mining, as well as a variety of other activities. Due to the impact to this watershed, it has been monitored for quality and benthic life for a number of years, yet an analysis of compiled data has not been published to date. Dumps Creek historic benthic and water chemistry data and current, third-party verified, benthic and conductivity data was analyzed statistically to see if data sets above 500 $\mu\text{s}/\text{cm}$ conductivity and below 500 $\mu\text{s}/\text{cm}$ conductivity, showing data sets that included and excluded determined outliers. This data was analyzed to determine confidence levels that indicated that the datasets were gathered from the same or different populations, had the same or different means and/or had a positive or negative linear correlation. Statistical results for the data that excluded outliers showed that between statistical confidence levels of 99% and 20% the data came from the same population, between statistical confidence levels of 99% and 90% the data had the same mean,

and between statistical confidence levels of 99% and 85% the all VSCI and conductivity data did not have a negative linear relationship. The water chemistry verified that the watershed was bicarbonate anion dominated, which, compared to previous studies, shows a deviation from previous conclusions gained from other anion dominated watersheds. This study analyzed all available data, given the heavily industrialized history of this watershed and to assess whether improving the conductivity and therefore the load to this watershed would improve benthic health in order to remove the watershed from the Virginia 303(d) List of Impaired Waters. These conclusions suggest that benthic health, in this watershed, may be more greatly affected by other influences in the watershed that have yet to be identified, rather than high conductivity.

In summary, the research results presented above do not answer all the questions related to the impacts of underground coal mining on water, but provide additional basis for future research. As stated previously, the results herein rely greatly on specific conditions and may not be readily transferable to other situations. Therefore, great care is recommended in using this work as a basis for universal conclusions. By exercising due diligence and care, the impacts of underground mines on surface waters can be understood and either prevented or mitigated. Protection of surface water resources from the impacts of active underground mining is desirable from both an ecological and economic standpoint.