Using Electrical Resistivity Imaging to Relate Surface Coal Mining Valley Fill Characteristics to Effluent Stream Quality

Kathryn L. Little

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science

In

Environmental Engineering

Erich T. Hester, Chair
Thomas J. Burbey
Mark A. Widdowson
Carl E. Zipper

February 7, 2018
Blacksburg, VA

Keywords: electrical resistivity imaging, preferential flow, infiltration, artificial rainfall, surface coal mine, valley fill, specific conductance

Copyright © 2018 Kathryn L. Little
Using Electrical Resistivity Imaging to Relate Surface Coal Mining Valley Fill Characteristics to Effluent Stream Quality
Kathryn L. Little

Abstract
Surface coal mining has altered Appalachian landscapes, affecting water quality and aquatic ecology. Valley fills created from excess overburden are prominent features of many mined landscapes. Increased total dissolved solids (TDS), as measured by its surrogate specific conductance (SC), is a significant water quality concern related to the exposure of fresh mineral surfaces to weathering in valley fills. Specific conductance levels in waters draining Appalachian mined areas are highly variable, yet the causes for this variability are not well known. Here we sought to improve understanding of such variability by investigating the interior subsurface structure and hydrologic flowpaths within a series of valley fills and relating that to valley fill characteristics such as age and construction method. We used electrical resistivity imaging (ERI) to investigate the subsurface structure of four valley fills in two dimensions. We combined ERI with artificial rainfall to investigate the location and transit time of hydrologic preferential infiltration flowpaths through the fills. Finally, we used our ERI results in conjunction with SC data from effluent streams to improve understanding of SC relationship to fill flowpaths and characteristics. ERI results indicated considerable variability in substrate type and widespread presence of preferential infiltration flowpaths among the valley fills studied. We estimated an average preferential flowpath length of 6.6 meters, average transit time of 1.4 hours, and average velocity of 5.1 m/h or 0.14 cm/s through preferential infiltration flowpaths. ERI successfully distinguished fills constructed using methods of conventional loose-dump and experimental controlled-material compacted-lift construction. Conventional fills had greater ranges of subsurface resistivity, indicating a wider range of substrate types and/or more variable moisture.
content. Conventional fills also showed more accumulation of water within the fill during artificial rainfall, possibly indicating more quick/deep preferential infiltration flowpaths than in the experimental fill. Relationships between other fill characteristics as well as stream effluent SC were not related in a statistically significant way to fill structure or flowpaths. ERI appears to be a robust non-invasive technique that provides reliable information on valley fill structure and hydrology, and experimental compacted-lift valley fill construction produces significantly altered hydrologic response, which in turn affects downstream SC.
Using Electrical Resistivity Imaging to Relate Surface Coal Mining Valley Fill Characteristics to Effluent Stream Quality
Kathryn L. Little

General Audience Abstract
Surface coal mining has altered Appalachian landscapes, affecting water quality and aquatic ecology. Valley fills created from excess mine spoil are prominent features of many mined landscapes. The streams draining valley fills often have very poor water quality, including high levels of increased total dissolved solids (TDS) related to weathering of mine spoils within valley fills. In this work, we investigated the subsurface structure of a series of valley fills and identified preferential hydrologic flowpaths, which are the “paths of least resistance” water follows for rapid infiltration. We related our results to various valley fill characteristics such as age and construction method. We found that the subsurface of a conventionally built fill tends to have more variation in material and/or moisture content than a fill built with an experimental construction method. Conventional fills also showed more accumulation of water within the fill during artificial rainfall experiments, possibly indicating more quick/deep preferential infiltration flowpaths than in the experimental fill.
Acknowledgments

I would like to thank Office of Surface Mining Reclamation and Enforcement (OSMRE) for funding this project through the Applied Science program. I would like to thank Joe Buckwalter for his collaboration on this project; Dylan Honardoust, my field assistant; and Breeyn Greer for her expertise. I would like to thank Contura Energy engineers Jermy Yahya and Jackie Ball, as well as Gene Boyd and Chris Stanley of Cambrian Coal Corporation, for providing access to the field sites and a wealth of useful information. Thank you to my research group and my family for their support and encouragement. Finally, I would like to thank my advisor Erich Hester and my committee members Tom Burbey, Carl Zipper, and Mark Widdowson for all of their guidance and support.
# Table of Contents

Abstract ......................................................................................................................... ii
General Audience Abstract ............................................................................................... iv
Acknowledgments ............................................................................................................... v
Table of Contents .............................................................................................................. vi
List of Tables ...................................................................................................................... vii
List of Figures ................................................................................................................... viii

Chapter 1 - Introduction and Literature Review .............................................................. 1
  1.1 Coal and Surface Mining ......................................................................................... 1
  1.2 Water Quality Concerns Related to Surface Mining .............................................. 2
  1.3 Current Hydrogeologic Knowledge of Reclaimed Mines ................................... 2
  1.4 Electrical Resistivity Imaging .............................................................................. 3
  1.5 Research Objectives ............................................................................................. 4
  1.6 References ........................................................................................................... 4

Chapter 2 - Using Electrical Resistivity Imaging to Relate Surface Coal Mining Valley Fill Characteristics to Effluent Stream Quality .............................................................. 7
  2.1 Abstract ................................................................................................................ 8
  2.2 Introduction .......................................................................................................... 8
  2.3 Site Description .................................................................................................... 10
  2.4 Materials and Methods ....................................................................................... 13
  2.4.1 Long Dry ERI Surveys .................................................................................. 13
  2.4.2 Short Artificial Rainfall ERI Surveys .............................................................. 14
  2.4.3 ERI Data Analysis ....................................................................................... 15
  2.4.4 Preferential Infiltration Flowpath Properties Estimation .............................. 17
  2.4.5 Statistical Analysis of Fill and Flowpath Properties ..................................... 17
  2.5 Results ................................................................................................................ 17
  2.5.1 Long Dry ERI Surveys ................................................................................ 17
  2.5.2 Short Artificial Rainfall ERI Surveys .............................................................. 20
  2.5.3 Preferential Infiltration Flowpath Statistics .................................................. 26
  2.5.4 Statistical Analysis of Fill and Flowpath Properties ..................................... 27
  2.5.5 ERI Error Analysis ..................................................................................... 27
  2.6 Discussion .......................................................................................................... 28
  2.6.1 Surface Coal Mine Valley Fill Internal Structure and Hydrology .................. 28
  2.6.2 Applied Significance for Fill Construction and Monitoring .......................... 29
  2.6.3 Limitations and Future Study ...................................................................... 30
  2.7 Conclusions ...................................................................................................... 31
  2.8 References ........................................................................................................ 33

Chapter 3 - Engineering Significance ............................................................................. 36

Appendix A – Field Setup Photographs .......................................................................... A-1
Appendix B – Electrical Resistivity Imaging Procedure ................................................. B-1
Appendix C – Statistical Analysis of Fill and Flowpath Properties ............................... C-1
Appendix D – Rainfall and Flow Monitoring .................................................................. D-1
Appendix E – Procedure for Scaling Time-Lapse Tomograms ....................................... E-1
List of Tables
Table 2-1: Valley Fill Field Site Properties ................................................................. 12
Table 2-2: Summary of Long Dry ERI Surveys ............................................................ 14
Table 2-3: Summary of Short Artificial Rainfall ERI Surveys....................................... 15
Table 2-4: Preferential Infiltration Flowpath Properties............................................. 27
Table 2-5: Data Removal in Long Dry ERI Survey Inversions.................................... 28
Table 2-6: Error in Inversion Results........................................................................... 28
Table C-1: Fill and Flowpath Properties Linear Regression Results............................. C-1
Table C-2: Preferential Infiltration Flowpath Properties from Powell River Project......... C-1
**List of Figures**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-1</td>
<td>Valley Fill Schematic</td>
<td>1</td>
</tr>
<tr>
<td>2-1</td>
<td>Field Sites and Properties</td>
<td>11</td>
</tr>
<tr>
<td>2-2</td>
<td>Structure of Barton Hollow Valley Fill</td>
<td>13</td>
</tr>
<tr>
<td>2-3</td>
<td>Long Dry ERI Survey Tomograms</td>
<td>18</td>
</tr>
<tr>
<td>2-4</td>
<td>Long Dry ERI Survey Tomograms with Uniform Resistivity Scale</td>
<td>20</td>
</tr>
<tr>
<td>2-5</td>
<td>Office Fill Short ERI Survey Conductivity Comparison</td>
<td>21</td>
</tr>
<tr>
<td>2-6</td>
<td>End Fill Short ERI Survey Conductivity Comparison</td>
<td>22</td>
</tr>
<tr>
<td>2-7</td>
<td>Bearwallow Short ERI Survey Conductivity Comparison</td>
<td>23</td>
</tr>
<tr>
<td>2-8</td>
<td>Barton Hollow Short ERI Survey Conductivity Comparison</td>
<td>25</td>
</tr>
<tr>
<td>A-1</td>
<td>Electrode Setup</td>
<td>A-1</td>
</tr>
<tr>
<td>A-2</td>
<td>Switch Box Setup</td>
<td>A-2</td>
</tr>
<tr>
<td>A-3</td>
<td>Resistivity Meter Setup</td>
<td>A-3</td>
</tr>
<tr>
<td>A-4</td>
<td>Short Transect Setup</td>
<td>A-4</td>
</tr>
<tr>
<td>A-5</td>
<td>Water Pump</td>
<td>A-5</td>
</tr>
<tr>
<td>A-6</td>
<td>Fire Hose Approaching Transect</td>
<td>A-6</td>
</tr>
<tr>
<td>A-7</td>
<td>Garden Hose and Sprinkler Setup</td>
<td>A-7</td>
</tr>
<tr>
<td>A-8</td>
<td>Intake Hose and Water Tank</td>
<td>A-8</td>
</tr>
<tr>
<td>D-1</td>
<td>Specific Conductance during Field Season</td>
<td>D-1</td>
</tr>
<tr>
<td>D-2</td>
<td>Streamflow and Precipitation during Field Season</td>
<td>D-2</td>
</tr>
</tbody>
</table>
Chapter 1 - Introduction and Literature Review

1.1 Coal and Surface Mining
Energy production is a critical industry to maintaining quality of life. We use energy to heat and cool buildings, transport people and goods, produce and prepare food, and manufacture goods. We rely heavily on electricity to light our homes and workplaces, power electronics, heat electric stoves, and much more. Coal is a major component of electricity production, as 41% of global electricity production comes from coal-fired power plants (World Coal Association [WCA], n.d.-b). While this is not sustainable in the long term due to high emissions of pollutants and greenhouse gases associated with coal combustion, it is the present state of the energy industry and needs to be considered as such. Coal is also a key ingredient in steel and serves as an energy source for energy-intensive cement production (WCA, n.d.-b). Thus, demand for coal remains high and coal mining is the only way to meet that demand.

There are two broad categories of coal mining: underground mining and surface, or opencast, mining (Kentucky Geological Survey [KGS], 2017; WCA, n.d.-a). Surface mining is more common in America due to better productivity and safety (National Research Council of the National Academies [NRC], 2007; U.S. Energy Information Administration [EIA], 2012), and Appalachia is home to many surface mines. In the mountaintop removal method used, the upper geologic strata of a mountain are fragmented using explosives and removed to allow access to the coal seams below (NRC, 2007; U.S. Environmental Protection Agency [EPA], 2016). During site reclamation, the mountain must first be reshaped to “the approximate original contour” according to the Surface Mining Control and Reclamation Act of 1977 (SMCRA), after which spoil is brought to a valley on site and used to fill it in, creating a steep slope (KGS, 2017; NRC, 2007). These filled-in areas are appropriately called valley fills (EPA, 2016) (Figure 1-1). Valley fills are typically constructed for both geotechnical stability and maximization of volumetric storage per areal footprint.

![Figure 1-1: Valley Fill Schematic](image)

Diagrams of a typical valley fill: side view (left) and front/top view (right).
1.2 Water Quality Concerns Related to Surface Mining

However, despite the benefits of surface mining relative to underground mining, concerns remain. These include practical problems like disposal of mine spoil as well as issues that persist after the mining has been completed at a site, such as acid mine drainage and stability of the reclaimed slopes (NRC, 2007). Evans et al. (2015) point out that while acid mine spoil handling procedures have improved over the past 40 years, many ions and metals are still gaining recognition as water quality problems resulting from coal mining (Herlihy et al., 1990). These include $\text{SO}_4^{2-}$, $\text{HCO}_3^-$, $\text{Ca}^{2+}$, $\text{Mg}^{2+}$, and $\text{Se}$ (Cormier et al., 2013; Evans et al., 2015; Palmer et al., 2010; Pond et al., 2008), which are released through acid weathering and increase effluent streams’ pH, resulting in alkaline mine drainage (Griffith et al., 2012; Nippgen et al., 2017; Palmer et al., 2010). Cravotta (2008) provides a detailed characterization of various metals and other minerals found in mine waste and their interactions.

The ions that contribute to alkaline drainage, as well as others resulting from weathering of fractured rock, lead to the elevated levels of total dissolved solids (TDS) commonly found in effluent from mines (Nippgen et al., 2017; Palmer et al., 2010). The specific effects depend on the subsurface flowpaths and structure of the reclaimed land. For instance, a deep and slow flowpath that contacts mine spoil material for extended periods of time is likely to contribute high TDS levels when it eventually discharges (Evans et al., 2015; Murphy et al., 2014). However, strategic use of natural soils and weathered spoil in the construction of valley fills has both benefits for reforestation growth and the potential to reduce effluent TDS levels because they have less TDS generation potential than unweathered spoil (Daniels et al., 2014; Evans et al., 2015; Orndorff et al., 2010; Zipper et al., 2013). Evans et al. (2015) found no mine reclamation practices being developed to restore hydrologic flowpaths to their pre-mining state or reduce the hydrologic impacts of mining. To that end, it is important to study the hydrogeology of reclaimed surface coal mines in order to understand how water currently interacts with the landscape and search for possible solutions to the increased levels of TDS.

1.3 Current Hydrogeologic Knowledge of Reclaimed Mines

Evans et al. (2015) state that mined landscapes often have compacted layers and low vegetation levels, leading to increased flow peaks and decreased response time (Griffith et al., 2012; Weiss & Razem, 1984). On the other hand, in some cases enlarged pore spaces due to fragmentation and the formation of cavities and channels by roots and other means can have the opposite effect and promote rapid infiltration of water into the bulk-fill zone. Infiltration rates have shown to increase as a fill ages, especially from a new fill with very little vegetation to an older one (Evans et al., 2015; Guebert & Gardner, 2001; Shukla et al., 2004). Although these patterns are known, conventional hydrogeologic techniques cannot identify both the locations and approximate transit times of preferential flowpaths in valley fills, and therefore to our knowledge these remain largely unknown. Evans et al. (2015) emphasize that more research needs to happen, because effects of mining on hydrology are not well understood or documented, particularly in Appalachia.

Clark et al. (2016) gathered precipitation, stage, and specific conductance (SC) data at five mountaintop removal coal mine valley fills in southwestern Virginia and analyzed these for general patterns as well as a possible relationship between SC and stage. Specific conductance is easier to measure than directly measuring TDS levels and is therefore often used as a highly correlated proxy variable (Clark et al., 2016; Daniels et al., 2016; Timpano et al., 2010). Clark et
al. (2016) found that the chemistry of the streams at the five fills was variable based on seasonal and climatic factors, precipitation, and between the different fills themselves. Specific conductance was observed to be higher in low flows and have lower concentrations during high flows, suggesting that the groundwater contributing to baseflow has higher SC, possibly from mine spoil content, and the surface runoff from storms has lower SC. However, it is unknown what sort of subsurface flowpaths contributed to the groundwater with the presumably higher SC.

1.4 Electrical Resistivity Imaging

Electrical conductivity is a common concept; we use conductive materials as wires to power our homes and electronics, and we know to avoid metals during thunderstorms because they are good conductors. Electrical resistivity, the reciprocal of electrical conductivity, quantifies how much a medium opposes an electric current. With the exception of superinsulators, all materials will conduct at least a small amount of electric current, and some more than others. By extension, this is true of geologic material, and electrical resistivity imaging (ERI) technology makes use of this property. It measures the subsurface resistance of an entire 2D or 3D area, which is converted to a resistivity using software so it can be visualized in a tomogram and interpreted based on hydrogeologic knowledge. Good conductors such as copper have very low resistivities, on the order of $10^{-8}$ ohm-meters, while wet soils may be about 10 ohm-meters and poorly conductive rocks such as sandstone have high resistivities up to the order of $10^8$ ohm-meters (Herman, 2001). Thus, we typically associate a high-resistivity region in a tomogram with either solid rock or materials with large void spaces that drain water rapidly. A low-resistivity region usually represents soil-sized particles, often fines, with smaller pore spaces that retain more water and therefore can conduct more current. ERI’s noninvasive nature makes it a beneficial tool for hydrogeologic study.

While Clark et al. (2016) and most other studies on mined landscapes have used flow gauging and/or chemical studies (i.e., isotope monitoring or tracer studies) to assess surface water-subsurface flow patterns, Greer et al. (2017) employed ERI. Similarly to Clark et al. (2016), Greer et al. (2017) focused on a valley fill in southwest Virginia that had been reclaimed following mountaintop removal coal mining at the site. They employed ERI technology at the site under both dry and wet conditions. The resulting dry-condition images were interpreted for information about the internal structure and showed that the upper layers were mainly soil-sized particles but were underlain by rockier layers with more void spaces. The wet-condition results helped highlight both horizontal and vertical preferential flowpaths through the subsurface, which were much more significant in the transport of water than the small amounts of uniform infiltration that also occurred. However, the work of Greer et al. (2017) was a case study on a single valley fill, and it is unknown whether these patterns are prevalent among valley fills in general or were specific to their site.

ERI has been used in a number of subsurface investigations, such as imaging underground coal mines (Das et al., 2017; Krishnamurthy et al., 2009). Furthermore, time-lapse ERI has been used to study infiltration and subsurface flow on numerous other sites as well. Bass et al. (2017) surveyed two hillslopes in New Mexico during a drought to monitor subsurface moisture distribution. They found the top three meters became increasingly dry over the course of the drought, except around certain bushes that drew moisture from deeper underground to create localized water redistribution. Clémence et al. (2017) used 3D ERI on a streambed in France to
ascertain preferential flowpaths in the hyporheic zone using a solute tracer, while Fernández de Vera et al. (2017) used a saline tracer and ERI in conjunction with a vadose zone monitoring system to perform an infiltration test on a brownfield in Belgium. Hübner et al. (2017) and Travelletti et al. (2012) have both used artificial rainfall with ERI to study infiltration pathways, on a hillslope in Germany and a landslide site in France, respectively. Scaini et al. (2017) performed an artificial rainfall experiment on a trenched hillslope in Luxembourg and used time-lapse ERI to identify both the wetting front and preferential flow. These and other studies highlight ERI’s usefulness in hydrogeologic investigations, but few researchers have addressed surface coal mine valley fills with ERI.

1.5 Research Objectives
This study’s research objectives were to: (1) survey and evaluate the variability of subsurface structure of a series of valley fills; (2) locate preferential infiltration flowpaths in the subsurface of a series of valley fills exposed to artificial rainfall and assess their variability among fills; (3) estimate the lengths, transit times, and flow velocities of the preferential flowpaths; (4) evaluate possible relationships between flowpath properties such as transit time, length, and velocity, and fill properties such as construction method, age, vegetative cover, and size, and (5) evaluate the possible relationship between flowpath properties such as transit time, length, and velocity and effluent stream SC.

1.6 References


Chapter 2 - Using Electrical Resistivity Imaging to Relate Surface Coal Mining Valley Fill Characteristics to Effluent Stream Quality

In Preparation for Publication

Erich T. Hester*, Kathryn L. Little, Joseph D. Buckwalter, Carl E. Zipper, Thomas J. Burbey

*Corresponding Author:
Erich T. Hester
The Charles E. Via, Jr. Department of Civil and Environmental Engineering
Virginia Polytechnic and State University
220-D Patton Hall
Blacksburg, VA 24061
Email: ehester@vt.edu
Phone: 540-231-9758

Other Authors:
Kathryn L. Little
The Charles E. Via, Jr. Department of Civil and Environmental Engineering
Virginia Polytechnic and State University
220-D Patton Hall
Blacksburg, VA 24061

Joseph D. Buckwalter
Department of Crop and Soil Environmental Sciences
Virginia Polytechnic and State University
425A Smyth Hall
Blacksburg, VA 24061

Carl E. Zipper
Department of Crop and Soil Environmental Sciences
Virginia Polytechnic and State University
416 Smyth Hall
Blacksburg, VA 24061

Thomas J. Burbey
Department of Geosciences
Virginia Polytechnic and State University
5041 Derring Hall
Blacksburg, VA 24061
2.1 Abstract
Surface coal mining has altered Appalachian landscapes, affecting water quality and aquatic ecology. Valley fills created from excess overburden are prominent features of many mined landscapes. Increased total dissolved solids (TDS), as measured by its surrogate specific conductance (SC), is a significant water quality concern related to the exposure of fresh mineral surfaces to weathering in valley fills. Specific conductance levels in waters draining Appalachian mined areas are highly variable, yet the causes for this variability are not well known. Here we sought to improve understanding of such variability by investigating the interior subsurface structure and hydrologic flowpaths within a series of valley fills and relating that to valley fill characteristics such as age and construction method. We used electrical resistivity imaging (ERI) to investigate the subsurface structure of four valley fills in two dimensions. We combined ERI with artificial rainfall to investigate the location and transit time of hydrologic preferential infiltration flowpaths through the fills. Finally, we used our ERI results in conjunction with SC data from effluent streams to improve understanding of SC relationship to fill flowpaths and characteristics. ERI results indicated considerable variability in substrate type and widespread presence of preferential infiltration flowpaths among the valley fills studied. We estimated an average preferential flowpath length of 6.6 meters, average transit time of 1.4 hours, and average velocity of 5.1 m/h or 0.14 cm/s through preferential infiltration flowpaths. ERI successfully distinguished fills constructed using methods of conventional loose-dump and experimental controlled-material compacted-lift construction. Conventional fills had greater ranges of subsurface resistivity, indicating a wider range of substrate types and/or more variable moisture content. Conventional fills also showed more accumulation of water within the fill during artificial rainfall, possibly indicating more quick/deep preferential infiltration flowpaths than in the experimental fill. Relationships between other fill characteristics as well as stream effluent SC were not related in a statistically significant way to fill structure or flowpaths. ERI appears to be a robust non-invasive technique that provides reliable information on valley fill structure and hydrology, and experimental compacted-lift valley fill construction produces significantly altered hydrologic response, which in turn affects downstream SC.

2.2 Introduction
Appalachia is home to many surface coal mines, which in America are more common than underground mines due to better productivity and safety (EIA, 2012; NRC, 2007). In the mountaintop removal method used at many of these mines, the upper geologic strata of a mountain are fragmented using explosives and removed to allow access to the coal seams below (EPA, 2016; NRC, 2007). During site reclamation, the spoil is first used to reshape the mined land to “approximate original contour” (EPA, 2016; SMCRA, 1977). The excess spoil is then used to fill in surrounding valleys, creating landform structures called valley fills (EPA, 2016; NRC, 2007).

Surface mining creates environmental problems that persist after the mining has been completed, such as stability of the reclaimed slopes, altered downstream hydrology, water quality concerns, elevated total dissolved solids (TDS), acid mine drainage where mine spoils are high in sulfur, and other pollutants (Daniels et al., 2016; NRC, 2007). Mined landscapes often have compacted layers and low vegetation levels, leading to increased flow peaks and decreased hydrologic response time (Evans et al., 2015; Griffith et al., 2012; Weiss & Razem, 1984). However, in some cases, the presence of large fragments and formation of cavities and channels by roots and other means can lead to enlarged pore spaces, which allows more rapid infiltration. Infiltration
rates have shown to increase with fill age, especially in the first few years after reclamation as vegetation increases (Evans et al., 2015; Guebert & Gardner, 2001; Shukla et al., 2004). Nevertheless, conventional hydrogeologic techniques cannot identify both the locations and approximate transit times of preferential flowpaths in valley fills, and therefore to our knowledge these remain largely unknown (Evans et al., 2015; Greer et al., 2017).

While handling procedures for acidic spoils have improved, thus reducing acid mine draining problems, over the past 40 years since the institution of the Surface Mining Control and Reclamation Act of 1977 (SMCRA), other water quality problems result from surface coal mining in Appalachia (Evans et al., 2015; Herlihy et al., 1990). For example, accelerated weathering enabled by rock fracturing releases \( \text{SO}_4^{2-} \), \( \text{HCO}_3^- \), \( \text{Ca}^{2+} \), \( \text{Mg}^{2+} \), and Se and other elements (Cormier et al., 2013; Evans et al., 2015; Palmer et al., 2010; Pond et al., 2008), causing elevated effluent TDS levels (Griffith et al., 2012; Nippgen et al., 2017; Palmer et al., 2010). Cravotta (2011) provides a detailed characterization of various metals and other minerals found in mine waste and their interactions.

The quality of mine and valley-fill effluent depends on the nature of the geologic materials constituting the fill materials (Daniels et al., 2016), and on internal structure of, and subsurface flowpaths within, the fills. A deep and slow flowpath is likely to acquire significant levels of TDS because it contacts mine spoil material for extended periods of time (Evans et al., 2015; Murphy et al., 2014), while rapid preferential flow may show the opposite effect. By contrast, natural soils and weathered spoils have less TDS generation potential than unweathered spoils, and therefore strategic use of these materials in valley fill construction has potential for effluent TDS-concentration reduction (Daniels et al., 2014; Evans et al., 2015; Orndorff et al., 2010; Zipper et al., 2013). Nevertheless, to our knowledge, prior studies have not evaluated how the distribution and flow velocities of hydrogeologic flowpaths through valley fills vary among coal surface mine landscapes. Such studies are necessary for improved understanding of how water interacts with mined landscape, and for mitigation of the elevated concentrations of TDS, metals, and ions in waters draining from those landscapes.

Specific conductance (SC) is easier to measure than directly measuring TDS levels and is therefore often used as a highly correlated proxy variable (Clark et al., 2016; Daniels et al., 2016; Timpano et al., 2010). Clark et al. (2016) found that stream chemistry at five mountaintop removal coal mine valley fills was variable among fills and also varied with season, climatic factors, and precipitation. Specific conductance was higher during low flows and lower during high flows, suggesting that the groundwater feeding baseflow has higher SC, possibly from mine spoil content, and the surface runoff from storms has lower SC. However, the distribution and flow velocities of the hydrogeologic flowpaths involved, and how that varies among valley fills, is unknown.

To truly address these questions, spatially resolved characterization of hydrogeologic flowpaths through surface mined areas is needed. The non-invasive near-surface geophysical technique known as electrical resistivity imaging (ERI) can image subsurface structure and flowpaths in multiple dimensions and has been used to study infiltration and subsurface flow (Bass et al., 2017; Clémence et al., 2017; Fernández de Vera et al., 2017; Hübner et al., 2017; Scaini et al., 2017; Travelletti et al., 2012) as well as to image underground coal mines (Das et al., 2017;
Krishnamurthy et al. 2009). Until recently, however, the technique had not been applied to surface mined lands. Greer et al. (2017) used ERI to determine valley fill internal structure, and used ERI with artificial rainfall to determine the location and transit times of preferential infiltration hydrogeologic flowpaths. These preferential flowpaths were more significant in the transport of rainwater than the small amounts of uniform infiltration that also occurred. However, the work of Greer et al. (2017) was a case study on a single valley fill; hence, still unknown are the prevalence of these preferential flowpaths among valley fills generally, the variability of flow patterns among different fills, and whether flowpath characteristics by fill characteristics such as age or construction technique control flowpath characteristics.

This study sought to build on those mentioned above by applying ERI, both with and without artificial rainfall, to study the hydrogeology of multiple mountaintop removal coal mine valley fills. As such, our research objectives were to: (1) survey and evaluate the variability of subsurface structure for a series of valley fills; (2) locate preferential infiltration flowpaths in the subsurface of valley fills exposed to artificial rainfall and assess their variability among fills; (3) estimate the lengths of the preferential flowpaths, and the transit times and flow velocities of waters in the preferential flowpaths; (4) evaluate possible relationships between flowpath properties such as transit time, length, and velocity, and fill properties such as construction method, age, vegetative cover, and size, and (5) evaluate the possible relationship between flowpath properties such as transit time, length, and velocity and effluent stream SC.

2.3 Site Description
This study involved four field sites in southwestern Virginia, which we refer to as Barton Hollow, Office Fill, End Fill, and Bearwallow. They are all valley fills of reclaimed surface coal mines but vary in age, land cover, and size (Figure 2-1, Table 2-1).
Figure 2-1: Field Sites and Properties

Aerial view of the four field sites: (a) Barton Hollow; (b) Office Fill (top left) and End Fill (bottom right); (c) Bearwallow. White solid lines denote the approximate location of fill boundaries. White dashed lines denote the locations of long ERI transects. Red dashed lines denote the locations of short ERI transects with artificial rainfall. Areal map (d) shows the relative locations of the four sites. All views are oriented such that north is up.
Table 2-1: Valley Fill Field Site Properties

<table>
<thead>
<tr>
<th>Fill</th>
<th>Approximate Time since Revegetation (yr)</th>
<th>Land Cover</th>
<th>Fill Area* (ha)</th>
<th>Watershed Area* (ha)</th>
<th>Mean Effluent Stream SC during Study (µS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barton Hollow</td>
<td>2</td>
<td>Long grass with sparse small trees</td>
<td>7</td>
<td>53</td>
<td>1722</td>
</tr>
<tr>
<td>Office Fill</td>
<td>9</td>
<td>Dense underbrush, some trees, a few grassy areas</td>
<td>3</td>
<td>42</td>
<td>2540</td>
</tr>
<tr>
<td>End Fill</td>
<td>21</td>
<td>Mature forest</td>
<td>2</td>
<td>30</td>
<td>1989</td>
</tr>
<tr>
<td>Bearwallow</td>
<td>11</td>
<td>Dense underbrush, some trees, a few grassy areas</td>
<td>15</td>
<td>25</td>
<td>2199</td>
</tr>
</tbody>
</table>

*We estimated valley fill areas using Google Earth imagery and watershed areas using ArcGIS and the 2013 10-meter National Elevation Dataset. For SC, see Figure D-1. Typical SC values for forested, unmined watersheds are <200 µS/cm (Clark et al., 2016; Evans et al., 2014).

Office Fill, End Fill, and Bearwallow were all constructed using a conventional loose-dump method, in which material is dumped typically from the top of the slope. The largest boulders tend to roll all the way down the slope, gathering near the toe of the fill. Finer material comes to rest higher up. Bulldozers then arrange the slope into its final shape. At Bearwallow, a majority of the fill material is hard sandstone, which serves as a durable material for the bulk of the fill (C. Stanley, personal communication, January 8, 2018). Office Fill is composed of a variety of materials, such as hard sandstone, weathered material from the surface layers, and softer material including siltstone and soft sandstone. End Fill is very near to Office Fill (~800 meters between fills’ toes), thus we assume the two have similar types of fill material, although the ratios of the various fill materials used are unknown and may differ. The details of construction for both fills are also unknown, such as whether different types of fill material were mixed or separated prior to dumping and, if separate, in what order they were added to the fill.

Barton Hollow was constructed with an experimental structure. The goal of the construction method was to reduce the TDS in the valley’s effluent stream, and thus the fill contained primarily weathered rocks and spoil material that would contribute low levels of TDS. This would be compacted, if possible, a few meters from the surface to help fines settle into a lower-permeability layer. Any remaining higher-TDS material would be placed “high and dry,” i.e., higher up the slope in a region farther from the main drains and not prone to flooding, to reduce its contact time with water (Zipper et al., 2015). To accomplish this plan, Barton Hollow was constructed as a series of vertical lifts with compacted surfaces, separated by horizontal benches (Figure 2-2).
The lifts were built separately and sequentially, from the bottom of the fill to the top. However, each individual lift was built from right to left in the diagram. Trucks backed out toward the left, compacting the surface in the process, and dumped material over the edge to extend the lift farther to the left. Rocks naturally segregated over the 25-foot depth of the lift, with larger rocks rolling to the bottom to lodge upon the compacted surface of the lift directly below. To complete each lift, soil-sized material was added on top of the mine spoil on the lift’s surface for revegetation. The mine spoil rock materials are of two types: hard sandstone with boulders and weathered rock, the latter of which is finer and thus should compact more easily. By contrast, Office Fill and End Fill have a terraced structure similar to that of Barton Hollow but lack the intentionally compacted internal surfaces and were not constructed as separate lifts, while Bearwallow is less structured and has only one notable horizontal bench within the transect we surveyed.

Throughout the field season, there was ongoing monitoring (Appendix D) of the SC and flow of the four fills’ effluent streams, as well as precipitation at each fill. For these three respective parameters, the equipment used were a HOBO U24 electrical conductivity logger by Onset Computer Corp., a HOBO U20 water level logger by Onset, and a Rain Collector II rain gauge by Davis Instruments in conjunction with a HOBO UA-003-64 event logger by Onset. We later obtained the monitoring data from those collecting it.

2.4 Materials and Methods
We addressed the first objective of the study by performing a 2D ERI survey on a long transect at each fill site and interpreting the resulting tomograms. To address the second and third objectives, we performed consecutive ERI surveys on a small part of slope at each fill while sprinkling it with water at a rate similar to that of natural rainstorms in the region. We then estimated short-term transit times from the results of these consecutive ERI surveys. The fourth and fifth objectives required the combination of the aforementioned field study results, ongoing flow and water quality monitoring data from the effluent streams, and knowledge of the fill characteristics to analyze the behavior of the water.

2.4.1 Long Dry ERI Surveys
We gathered ERI data at each of the four field sites using a SuperSting R8 resistivity system, consisting of a resistivity meter, switch box, stainless steel electrodes, and various cables, all...
manufactured by Advanced Geosciences, Inc. (AGI) (Appendix B). We performed one overall linear survey on each fill. These transects covered the entire lengths of End Fill and Office Fill, from toe to crest. At the larger Barton Hollow and Bearwallow fills, the transects covered most but not the entire lengths of the fills due to factors including fill size, equipment limitations, and active roads. The transects ranged from 167 meters to over 400 meters (Table 2-2).

We used all four cables (64 electrodes) available in order to achieve the maximum resolution possible, except at Bearwallow where we used 32 electrodes due to bear-induced damage to a cable. Electrode spacing varied among long transect surveys and ranged from 2.65 m to 10.0 m (Table 2-2). We ran an automatic ERI survey with a dipole-dipole array, which provides more reliable data at depth and better resolution of vertical structure changes than other arrays can (Herman, 2001; Seaton & Burbey, 2002) while still maintaining a fairly quick survey time of about 33 minutes for a 64-electrode setup and about 8 minutes for a 32-electrode setup. These surveys (Table 2-2) were performed under dry conditions, i.e., it had not rained for over 48 hours.

Table 2-2: Summary of Long Dry ERI Surveys

<table>
<thead>
<tr>
<th>Date</th>
<th>Fill</th>
<th>Transect Length (m)</th>
<th>Electrode Spacing (m)</th>
<th>Days since Last Rainfall*</th>
</tr>
</thead>
<tbody>
<tr>
<td>06/12/2017</td>
<td>Barton Hollow</td>
<td>422.1</td>
<td>6.7</td>
<td>7</td>
</tr>
<tr>
<td>07/12/2017</td>
<td>Office Fill</td>
<td>210</td>
<td>3.33</td>
<td>6</td>
</tr>
<tr>
<td>08/25/2017</td>
<td>End Fill</td>
<td>167</td>
<td>2.65</td>
<td>2</td>
</tr>
<tr>
<td>10/03/2017</td>
<td>Bearwallow</td>
<td>310</td>
<td>10.0</td>
<td>19</td>
</tr>
</tbody>
</table>

*Figure D-2

2.4.2 Short Artificial Rainfall ERI Surveys

We also performed a series of surveys on shorter transects near the bottom of each fill slope, typically on the bottommost lift, to monitor rainfall infiltration into the fill. We conducted artificial rainfall sprinkling on short transects to achieve better spatial ERI resolution and due to the impracticalities of pumping water over the entire fill. The short transect usually spanned about one lift, but the location of the top boundary depended on the vertical distance from the pump and the water pressure of the sprinkler flow (Table 2-3).

We again used all 64 electrodes for all of these surveys except at Bearwallow, where we used 32 electrodes due to a broken cable. The setup process for the electrodes, cables, and box was essentially the same as that for the long transects, described above. The electrode spacing was reduced due to the shorter lengths of the transects (Table 2-3), and we also covered all cable connections with plastic wrap and duct tape in order to prevent water damage. Once setup was complete, we again performed a contact resistivity test and adjusted electrodes as necessary before proceeding with the ERI surveys.

The first survey in each series was performed under dry conditions, i.e., after at least 48 hours of no precipitation as measured by the rain gauges on each fill (Figure D-2). Following the dry survey, water was pumped from the bottom of the fill through sprinklers spaced along the transect in order to simulate rainfall at a volume representative of a typical storm in the region. The intensity varied among fills based on the water pressure available from the pump; in Bearwallow’s case, the pressure was likely higher because water was flowing strongly into the
pump from a water tank, while at the other fills the pump was drawing water up from an open effluent stream. We performed subsequent ERI surveys after one, two, three, and four hours of sprinkling. At Bearwallow, the effluent stream is intermittent and was dry during much of the field season, so the water source was a tank stationed at the bottom of the fill. At the other three sites, the effluent stream served as the water source for the artificial rainfall. The artificial rainfall setup consisted of a Koshin SERH-50V pump with a Honda GX160H OHV engine, used with a 2-inch diameter, 3.5-meter (11.5-foot) inlet tube and anywhere from 30.5 to 83.8 meters (100 to 275 feet) of 2-inch diameter fire hose carrying water up the slope. The fire hose was then connected to three Orbit oscillating sprinklers via 17 to 18.8 meters of standard garden hoses (Figure A-5 through Figure A-8).

Table 2-3: Summary of Short Artificial Rainfall ERI Surveys

<table>
<thead>
<tr>
<th>Date</th>
<th>Fill</th>
<th>Transect Length (m)</th>
<th>Electrode Spacing (m)</th>
<th>Length of Fire Hose (m)</th>
<th>Total Length of Garden Hose (all branches, m)</th>
<th>Average Rainfall Intensity (cm/h)</th>
<th>Days since Last Rainfall</th>
<th>Average SC of Pumped Water* (µS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>08/18/2017</td>
<td>Barton Hollow</td>
<td>50.4</td>
<td>0.8</td>
<td>45.7</td>
<td>17</td>
<td>1.04</td>
<td>2</td>
<td>1519</td>
</tr>
<tr>
<td>08/21/2017</td>
<td>Office Fill</td>
<td>63</td>
<td>1.0</td>
<td>30.5</td>
<td>17</td>
<td>1.04</td>
<td>3</td>
<td>2508</td>
</tr>
<tr>
<td>08/26/2017</td>
<td>End Fill</td>
<td>63</td>
<td>1.0</td>
<td>83.8</td>
<td>17</td>
<td>1.12</td>
<td>3</td>
<td>2151</td>
</tr>
<tr>
<td>09/22/2017</td>
<td>Bearwallow</td>
<td>43.4</td>
<td>1.4</td>
<td>45.7</td>
<td>18.8</td>
<td>2.82</td>
<td>8</td>
<td>988</td>
</tr>
</tbody>
</table>

*Figure D-1, Figure D-2

2.4.3 ERI Data Analysis

We downloaded the data files from the resistivity meter to a computer and then processed them using EarthImager 2D, a software produced by AGI for use with the SuperSting resistivity system (AGI, 2009). The basic inversion process begins with an assumption of homogeneous earth and proceeds to optimize for a model that minimizes the differences between the model and the surveyed apparent resistivity while also maintaining a specified degree of smoothness in the model (AGI, 2009). We first adjusted the initial settings in the program to values recommended in the software manual. These initial settings filtered out any raw apparent resistivity data points that were negative, below 1 ohm-meter or above 10000 ohm-meters, as well as any measurements for which the voltage was below 0.2 millivolts. The minimum absolute value of the voltage normalized by the current was 0.0005 ohms. The maximum repeat error acceptable was 3% while the maximum reciprocal error was 5%. These settings are similar to those used by Greer et al. (2017), Johnson et al. (2012), Langston et al. (2011), and Travelletti et al. (2012).

We read the data file of a dry survey into the program and viewed the data editing statistics that EarthImager produced. These statistics detailed how many raw data points, if any, did not meet the criteria specified in the initial settings; the program would automatically remove these prior to the inversion process. Next, we read a terrain file into the program, written using the clinometer data gathered at each fill. The terrain file provides the horizontal location and z-component (elevation) of each change in slope along the transect, and the software calculates the coordinates of each electrode in the survey line.
We ran the inversion using the settings suggested for surface models in the 2009 AGI manual. We used a smooth model inversion method and a finite element forward model method with a Cholesky decomposition and a Dirichlet boundary condition. The model had 2 mesh divisions, and the thickness incremental factor and depth factor were both 1.1 (Greer et al., 2017). The smoothness and damping factors were both 10, default values. We maintained the default estimation that 3% of the data were noisy, and opted to suppress the weights of noisy data during the inversion process to improve the quality of the results and reduce the L2-norm, an error statistic (AGI, 2009). Furthermore, we restricted the calculated resistivity values to the default range of 1-10,000 ohm-meters to reduce noise. We set the inversion to stop after any of the following criteria were met: after the eighth iteration, when the root mean square error was below 3%, or when the root mean square error decrease between iterations was below 5% (AGI, 2009; Greer et al., 2017). These settings reduced the overall error in our results, as evidenced by the root mean square error (Equation 1) and L2-norm (Equation 2) statistics we obtained, and this translated to less noise in the tomograms.

\[
\text{RMS} = \sqrt{\frac{\sum_{i=1}^{N} \left( \frac{d_{i}^{\text{pred}} - d_{i}^{\text{meas}}}{d_{i}^{\text{meas}}} \right)^2}{N}} \times 100\% \quad (1)
\]

\[
L2_{\text{Norm}} = \frac{\sum_{i=1}^{N} \left( \frac{d_{i}^{\text{pred}} - d_{i}^{\text{meas}}}{w_{i}} \right)^2}{N} \quad (2)
\]

where \(N\) is the number of data points; \(d_{i}^{\text{pred}}\) and \(d_{i}^{\text{meas}}\) are respectively the predicted and measured data point, and \(W\) is the weight of the data point assigned using a diagonal data weighting matrix determined by assumed data error (AGI, 2009; LaBrecque et al., 1996).

Once the initial inversion was complete, we removed any data points with over 50% misfit, defined as the percent error of the calculated data with respect to the measured apparent resistivity (AGI, 2009), and reran the inversion. We repeated this process until all of the processed data points were less than 50% misfit, signifying low noise levels within the data. For each survey, less than 10% of the data points ultimately needed to be removed, with the exception of the long transect survey at Bearwallow where we removed 17% of the data points. Most of the data points removed in the Bearwallow long transect survey were linked to one electrode that returned poor data; this was likely a result of a malfunction or poor electrode-earth connection.

For the artificial rainfall surveys, we subsequently conducted the time-lapse inversion, with the later wet surveys compared to the initial dry survey. This yielded a net difference in electrical conductivity (reciprocal of resistivity) between the dry and wet surveys. The program produced four tomograms comparing each of the four wet surveys to the dry survey, showing by what percentage the conductivity of each data point changed.

Once we had produced and scaled all of the tomograms (Appendix E), we cropped them to a reasonable depth of investigation, i.e. a maximum depth of roughly one-fifth of the surface
length of the survey (Greer et al., 2017; Oldenburg & Li, 1999). This had the result of removing some potentially misleading information at the bottom of each tomogram.

2.4.4 Preferential Infiltration Flowpath Properties Estimation
Using the short artificial rainfall tomograms, we identified accumulation zones, or regions at depth where conductivity increased rapidly, suggesting the presence of preferential infiltration flowpaths from the surface to those points. We estimated each flowpath’s length as the depth to the center of the accumulation zone, and the transit time as the time the accumulation zone first appeared on our tomograms relative to the beginning of the artificial rainfall. We then calculated the approximate linear velocity of water within each flowpath using the flowpath length and transit time.

2.4.5 Statistical Analysis of Fill and Flowpath Properties
We performed simple linear regressions on a variety of quantitative fill and flowpath properties. Independent variables were age of the fill since reclamation, fill area, and drainage basin area (Table 2-1). We analyzed these in relation to the potential dependent variables of preferential infiltration flowpath length, transit time, and velocity. Finally, we analyzed SC of the fills’ effluent streams as a possible variable dependent on any of the named fill or flowpath properties.

2.5 Results

2.5.1 Long Dry ERI Surveys
Figure 2-3 shows tomograms, which are vertical cross sections of estimated electrical resistivity distribution beneath the transects shown by white dashed lines in Figure 2-1 and summarized in Table 2-2. In general, we associate low resistivity values with fine materials and soil-sized particles that retain water well, as the water will conduct an electrical current and thus lead to a low electrical resistivity. Meanwhile, high resistivity values may represent boulders, bedrock, or large void spaces (Greer et al., 2017).
Figure 2-3: Long Dry ERI Survey Tomograms

Tomograms depicting long transects of the four sites: (a) Office Fill; (b) End Fill; (c) Bearwallow; (d) Barton Hollow. Each tomogram uses the default resistivity color scale generated by EarthImager 2D based on the range of resistivities calculated for that section. Elevation values are relative to the base of the transect at the toe of the fill. Note differences in spatial and resistivity scales among fills.

There are a number of interesting features of the tomograms for each individual fill. At Office Fill (Figure 2-3a), the upper half of the slope shows a large section of low resistivity at shallow depth. This suggests a thick layer of soil-sized particles that retains water near the surface in the absence of large pore spaces, which are often associated with larger voids between boulders or other coarse material. Office Fill experienced natural rainfall within a week prior to the survey (Table 2-2), and this likely contributed to the wide low-resistivity layer.

At End Fill (Figure 2-3b), a low resistivity layer exists at very shallow depths over the lower half of the fill. Because End Fill is 21 years old, there has been time for forest and associated soil development at the surface with associated moisture retention capacity, and the rain that fell just two days prior to the survey may have stayed near the surface. By contrast, the low-resistivity area near the top of End Fill is less extensive, occurs at greater depths, and is overlain by a high-resistivity area. This would be consistent with layers leached of conductive salts over time as described by Greer et al. (2017) or with a thin layer of soil-sized particles and more boulders nearer to the surface. There is also a very large area of high resistivity at greater depths, observed around 60-80 horizontal meters. The combination of low resistivity at shallow depths and greater resistivity at greater depths is expected from conventional fill construction, which consists of dumping boulders down the slope and then covering them with finer material, consistent with Greer et al. (2017).
Neither Bearwallow (Figure 2-3c) nor Barton Hollow (Figure 2-3d) shows the same large sections of homogeneous resistivity as Office Fill and End Fill, indicating more structural heterogeneity in the subsurface. The absence of large regions of low resistivity may also be due to the longer elapsed time between a natural rain event and the surveys (Table 2-2), associated with less antecedent moisture in the ground. Additionally, the different colored resistivity sections in the Bearwallow tomogram do appear more elongated than those in Barton Hollow. This may be due to the increased electrode spacing at Bearwallow; the software was interpolating data points over a relatively longer lateral distance.

At Bearwallow, the top of the transect was non-fill material, i.e., unmined land. This transition from fill to unmined occurred between the 26th and 27th electrodes from the bottom, or around 224 horizontal meters. The tomogram shows a solid slab of high resistivity near the surface of this unmined section; given our knowledge about the undisturbed section of land, this slab may signify unbroken bedrock or leached material as described above. This high-resistivity region transitions downslope to an area with more moderate resistivity and ends around 215 horizontal meters. There is no clear break in the tomogram where the shift from fill material to non-fill material occurs, likely because the software is cross-referencing data from multiple electrodes to create this image, thereby smoothing any sharp gradients that might otherwise appear. Another high-resistivity area appears around 150 horizontal meters, but we know this area contains deep fill material and therefore the slab cannot realistically be undisturbed bedrock. In this case, it may represent large boulders near the surface that do retain much fine-grained materials and therefore moisture.

At Barton Hollow, low and high resistivity sections are interspersed throughout the fill, and none of these regions are laterally or vertically extensive. High resistivity regions often appear above low resistivity, suggesting the presence of high-resistivity boulders with sizable intervening void spaces that allow water to migrate deeper past the boulders.

There are also a number of interesting patterns that emerge when considering all of the fills together. Figure 2-4 assists this comparison process by showing tomograms where the resistivity color bars have uniformly set to the same resistivity scale.
Office Fill shows by far the largest range in resistivity of the four fills, followed by Bearwallow with a much more moderate range. Barton Hollow and End Fill, by contrast, did not show nearly as much variation in resistivity (Figure 2-4).

The tomograms of Barton Hollow and Bearwallow show the most heterogeneity on a small scale. In other words, they show many small regions of different resistivity compared to End Fill and the top of Office Fill, which show fewer large regions of different resistivity. It is worth noting that Office Fill and End Fill’s small sizes make their areas of different resistivity seem larger in Figure 2-4 than they really are when compared to those found in Barton Hollow and Bearwallow. Therefore, it is vital to consider the scale of each tomogram and the absolute size of each resistivity region in addition to its relative appearance. Still, End Fill and particularly Office Fill display large resistivity regions, even when the tomogram scales are taken into account.

### 2.5.2 Short Artificial Rainfall ERI Surveys

Figure 2-5 through Figure 2-8 show time-lapse tomograms from the short surveys with artificial rainfall. Unlike the long transect tomograms in Section 2.5.1, which simply depict a snapshot of the resistivity within the fill’s subsurface, these images compare the fill at the time of the survey to a dry baseline state. As such, EarthImager can represent this comparison as percent difference of either resistivity or conductivity, and the latter is recommended for decreasing-resistivity...
scenarios such as the water infiltration we implemented (AGI, 2009). Increasing conductivity indicates increasing moisture due to water’s ability to conduct an electrical current. Note that any apparent decreases in electrical conductivity are artifacts of the inversion process that appear in response to a contrast boundary, in this case a nearby increase in conductivity (AGI, 2009; Nimmer et al., 2008). They cannot be realistically interpreted as sections of the ground becoming drier during the four-hour rainfall period (Greer et al., 2017; Miller et al., 2008; Mojica et al., 2013; Pellicer et al., 2012).

The time-lapse tomograms are helpful for identifying preferential flowpaths of infiltrating rainwater. We distinguish two main types of preferential infiltration flow in terms of how they manifest in the tomograms. Type I results in wetted regions at depth, referred to as accumulation zones by Greer et al. (2017), without a pathway visible in successive ERI surveys. This suggests rapid and mainly vertical water movement along a flowpath where the flowpath itself does not retain a noticeable amount of water after the fact. It is also possible that the flowpath retains a significant amount of water but that its shape or positioning makes it difficult for an ERI survey to image. In Type II preferential infiltration flow, the flowpath itself appears on the tomogram but does not result in an isolated accumulation zone; these flowpaths tend to be more diagonal or horizontal. Type I flowpaths appear in our tomograms far more frequently than Type II.

Figure 2-5: Office Fill Short ERI Survey Conductivity Comparison
Tomograms of the artificial rainfall plot at Office Fill, cropped to show only the wetting zone. Each tomogram shows the percent difference in electrical conductivity, relative to a dry baseline survey, after (a) one; (b) two; (c) three; and (d) four hours of sprinkling. Elevation and horizontal distance values are relative to the toe of the fill.
At Office Fill, the rainfall plot covered most of the fill’s bottommost lift and a small part of the second lift. The tomograms reveal a consistent layer of increasing conductivity (Figure 2-5). This overlays a thicker layer that does not increase in conductivity during the rainfall period. The is consistent with structural interpretations from the long surveys, including a top layer that is likely primarily finer materials that retain water well overlaying larger rocks and boulders which do not. There is an accumulation zone at approximately 33 horizontal meters and 10.5 meters of depth from the surface. It first appears in Figure 2-5b after two hours of sprinkling and is roughly beneath a point near the surface that also becomes noticeably wetter over time.

**Figure 2-6: End Fill Short ERI Survey Conductivity Comparison**

Tomograms of the artificial rainfall plot at End Fill, cropped to show only the wetting zone. Each tomogram shows the percent difference in electrical conductivity, relative to a dry baseline survey, after (a) one; (b) two; (c) three; and (d) four hours of sprinkling. Elevation and horizontal distance values are relative to the toe of the fill.

At End Fill, the water applied via artificial rainfall fell on the top half of the bottommost lift. It then made its way to many different locations in the fill, indicated by blue increasing-conductivity areas that appear in later tomograms (Figure 2-6). Some of these increased saturation areas occur in shallow layers, perched atop regions that do not increase in conductivity, for example near 20, 25-27, 32-37, and 40-43 horizontal meters. This indicates that the surface became wetter and retained water, but this zone is much thinner than those observed at Office Fill and Barton Hollow. This pattern of very shallow retention is consistent with the development of a soil-like layer at the surface, to a depth of approximately 0.5 to 1 meter, through the action of plants and root development. One other notable pattern that may be a
visible flowpath to depth, representing Type II preferential infiltration flow, occurs just below the surface at approximately 30 horizontal meters and develops in size and degree of saturation over time.

Multiple deeper accumulation zones also occur at End Fill. A few of these areas appear after one hour of sprinkling, at 23.5 horizontal meters and 5.5 meters of depth and at 37 horizontal meters and 10.5 meters of depth. Because the tomograms show no visible vertical flowpaths (i.e. areas of increasing conductivity) connecting these areas to the surface, these deeper accumulation zones represent Type I preferential infiltration flow. The water appears to have rapidly infiltrated down heterogeneous pathways, i.e., pathways through layers of various resistivities and particle sizes (Figure 2-3). The saturated region at depth also appears to spread out and migrate downslope into a consistent horizontal region underground, from about 22 to 40 horizontal meters, over the course of the sprinkling. It is unclear whether this is due to horizontal motion of water already at depth, or to additional vertical flowpaths developing that did not contribute to the moisture at depth after one hour. In either case, the manner this accumulation zone flattens out deep in the fill suggests that it may have reached the bottom of the dumped fill material, which would be underlain by more compact or rockier undisturbed materials.

Figure 2-7: Bearwallow Short ERI Survey Conductivity Comparison
Tomograms of the artificial rainfall plot at Bearwallow, cropped to show only the wetting zone. Each tomogram shows the percent difference in electrical conductivity, relative to a dry baseline survey, after (a) one; (b) two; (c) three; and (d) four hours of sprinkling. Elevation and horizontal distance values are relative to the toe of the fill.
The artificial rainfall plot at Bearwallow was near the bottom of the fill, although there was not a clear lift structure at the site. At Bearwallow, there are fewer areas of increasing electrical conductivity at shallow depth relative to other fills (Figure 2-7). The only notable area is from 25-29 horizontal meters, with a more minor area at 29-34 horizontal meters. These shallow areas saturate slowly, continuing to grow in size late in the four-hour sprinkling period (Figure 2-7c, d). These areas may be composed of fine particles which the water infiltrates but does not flow through quickly. They overlie areas that appeared to decrease in conductivity, which are artifacts of the data inversion rather than a physical phenomenon and contrast the surface wetting. Still, these areas’ apparent decrease in conductivity suggests that they did not become and remain significantly wetter during the rainfall period. One possible explanation for these areas is the presence of boulders or other materials with large pores.

There are a few visible accumulation zones due to Type I preferential flow. For example, such regions appear at 3.5 meters below the surface at 23 horizontal meters, and also at 3.0 meters deep at 17.5 horizontal meters, after one hour of sprinkling (Figure 2-7a). The latter disappears in subsequent tomograms, suggesting that the water continued to move away so that the region was no longer significantly wetter than its base case state. After two hours, an accumulation zone appears at 5.0 meters deep at approximately 15.5 horizontal meters, and another at 32 horizontal meters and 9.0 meters deep (Figure 2-7b). Water may have collected in these deeper areas due to the presence of fine particles that allow only slow flow through them. The accumulation could also be due to an impermeable layer below them preventing further downward flow; we do not know how deep below the fill surface the undisturbed bedrock lies.
The wetting zone at Barton Hollow spanned from the bottom of the fill to about two-thirds of the way up the bottommost lift. At Barton Hollow, a roughly one-meter layer at the surface retains moisture well, from the toe of the fill up to about four horizontal meters (Figure 2-8). One possible explanation for this is the grassy land cover of the fill, similar to that of the valley fill site discussed in Greer et al. (2017). Long grasses have fibrous roots that help to stabilize fine and organic materials, especially those that accumulated at the toe of the fill before the uphill grasses could grow significantly. These materials may in turn help keep the water near the surface and prevent most of it from infiltrating to depth quickly. Indeed, Clark and Zipper (2016) found that hydraulic conductivities and infiltration rates were lower at reclaimed surface coal mines with grassy or herbaceous vegetation than at those with sylvan vegetation. The intentional compacting of a near-surface layer of the Barton Hollow fill, as mentioned in Section 2.3, may also contribute to this water retention. It is quite possible that the moisture retained near the surface, both in high amounts near the toe and in lesser quantities along nearly the entire length of the rainfall plot, confirms the presence of this compacted layer and its success in keeping much of the infiltrating rainfall in the shallowest zones rather than allowing it to percolate deeper into the fill material. The upslope regions of the rainfall plot that experienced minimal or no
change in resistivity near the surface may result from some of the rainfall running downslope over the surface prior to infiltrating, or from a lower rainfall rate due to lower water pressure near the top of the plot.

However, despite the potential presence of this shallow moisture barrier, we also see a noticeable accumulation zone at approximately 7.0 horizontal meters and 6.0 meters of depth from the surface. It appears in Figure 2-8a after only one hour of sprinkling, and it grows in size and degree of saturation over the course of the experiment. This is likely the product of a primarily vertical preferential infiltration flowpath, perhaps indicating that the compaction was inadequate to fully prevent water from penetrating the fill’s interior.

2.5.3 Preferential Infiltration Flowpath Statistics
Type I preferential flow that results in accumulation zones at depth without visible flowpaths in the tomograms can be used to form rough estimates of velocity and transit time within the presumed near-vertical flowpath. Here we summarize notable accumulation zones at depth, based on the observations discussed in Section 2.5.2, in Table 2-4. There may have been smaller accumulations present during the experiment, but ERI only images accumulations smaller than the ERI’s spatial resolution and therefore any flowpaths that resulted in smaller accumulations are invisible in the tomograms. Additionally, some of the subsurface moisture increases captured in the tomograms may have been antecedent moisture moving from prior positions to new ones, particularly at Office Fill, End Fill, and Barton Hollow. Bearwallow experienced less precipitation over the course of the field season than the other three sites, as well as the longest intervening time between its last natural rainfall event and the artificial rainfall experiment; therefore it likely had the least moisture initially present.

The time to first appearance of each accumulation zone listed is approximate, since surveys were taken only once per hour. Thus, our reported transit times are overestimates, being greater than or equal to the actual times. The development of the first accumulation zones could have occurred in well under an hour, making the upper end of the uncertainty ranges for transit time potentially quite high. This is likely the largest contributor to uncertainty in transit times. We then approximated the depth of each accumulation zone by visually estimating its center point on the tomogram, measuring the vertical distance to the surface, and performing calculations using the tomogram’s vertical scale. Because flowpaths may be non-vertical, and also due to tortuosity of flow around rocks, our reported flowpath lengths are underestimates, being less than or equal to the actual lengths. The uncertainty in both the time and depth measurements in turn both affect the linear water velocity, calculated by dividing the two measured values. Therefore, the water velocity values are useful for observing general patterns but not for calculations requiring precision. Nevertheless, given that the numerator (flowpath length) is an underestimate and the denominator (transit time) is an overestimate we can say that the velocities are underestimates, with the true values likely being higher. The velocities are loosely correlated to the

Calculated transit times range from 1 to 2 hours, with an average of 1.4 hours and a mode of only 1 hour. Calculated vertical depth range from 3.0 to 10.5 meters, with an average of 6.6 meters. Velocities range from 2.5 to 10.5 m/h with an average of 5.1 m/h, which is 0.14 cm/s, and the actual values are almost certainly higher. These data support the presence of a large number of relatively fast infiltration flowpaths.
Table 2-4: Preferential Infiltration Flowpath Properties

<table>
<thead>
<tr>
<th>Fill (Figure)</th>
<th>Horizontal Location (m)</th>
<th>Time to First Appearance, or Flowpath Transit Time (h)</th>
<th>Approximate Vertical Depth from Surface, or Flowpath Length (m)</th>
<th>Approximate Linear Water Velocity along Flowpath (m/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office Fill (Figure 2-5)</td>
<td>33.0</td>
<td>2</td>
<td>10.5</td>
<td>5.25</td>
</tr>
<tr>
<td>End Fill (Figure 2-6)</td>
<td>23.5</td>
<td>1</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>End Fill (Figure 2-6)</td>
<td>37.0</td>
<td>1</td>
<td>10.5</td>
<td>10.5</td>
</tr>
<tr>
<td>Bearwallow (Figure 2-7)</td>
<td>23.0</td>
<td>1</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Bearwallow (Figure 2-7)</td>
<td>17.5</td>
<td>1</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Bearwallow (Figure 2-7)</td>
<td>15.5</td>
<td>2</td>
<td>5.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Bearwallow (Figure 2-7)</td>
<td>32.0</td>
<td>2</td>
<td>9.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Barton Hollow (Figure 2-8)</td>
<td>7.0</td>
<td>1</td>
<td>6.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

2.5.4 Statistical Analysis of Fill and Flowpath Properties
As discussed in Section 2.4.5, we performed various linear regressions with fill properties and flowpath properties (Appendix C). However, this analysis did not result in a compelling outcome; all but one $R^2$ value were below 0.5, and all were below 0.6. Although our sample size was small, there were no strong correlations between any two of the variables we analyzed when all flowpaths and fills were considered.

2.5.5 ERI Error Analysis
As with any field measurements, variability and associated potential for error occur with ERI. There was variability in the contact and placement of electrodes; we sometimes needed to place them up to a meter away from the center line laterally, or up to about 25 centimeters up and down the transect due to rocks or vegetation. The transect itself had a small degree of sinuosity rather than being completely straight. The surveys’ temperature and antecedent moisture conditions also varied throughout the field season; all surveys followed at least 48 hours with no precipitation, but in some cases there had been rain a few days prior and in others the weather had been dry for weeks. Finally, during the data collection we obtained occasional error messages on the resistivity meter, which corresponded to either uncollected or unusable data points later in the process. These errors are all within normal ranges for studies of this kind and through proper filtering and interpretation do not undermine the conclusions we present from this study.

The error incurred in the field was addressed during the data processing, as we removed data points both prior to and after inversion. The raw apparent resistivity data points that did not meet the criteria specified in EarthImager’s initial settings were not incorporated into the inversion. After inversion, EarthImager’s data misfit histogram feature provides a quantitative display of which inverted resistivity data points do not make sense considering the rest of the picture and allows for their removal. We used this feature and repeated the inversion as many times as necessary to eliminate all points that exhibited over 50% data misfit (Table 2-5). The resulting tomogram still included a bit of error, which was reported as the root mean square (RMS) error and the normalized L2 value (Table 2-6).
Table 2-5: Data Removal in Long Dry ERI Survey Inversions

<table>
<thead>
<tr>
<th>Fill</th>
<th>Survey</th>
<th>Raw Data (# Points)</th>
<th>Initial Data Removal (# Points)</th>
<th>Data Removal During Inversion (# Points)</th>
<th>Data Points Remaining (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barton Hollow</td>
<td>Long</td>
<td>895</td>
<td>55</td>
<td>4</td>
<td>93.4%</td>
</tr>
<tr>
<td></td>
<td>Short dry</td>
<td>942</td>
<td>0</td>
<td>1</td>
<td>99.9%</td>
</tr>
<tr>
<td>Office Fill</td>
<td>Long</td>
<td>942</td>
<td>26</td>
<td>8</td>
<td>96.4%</td>
</tr>
<tr>
<td></td>
<td>Short dry</td>
<td>942</td>
<td>0</td>
<td>2</td>
<td>99.8%</td>
</tr>
<tr>
<td>End Fill</td>
<td>Long</td>
<td>942</td>
<td>0</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Short dry</td>
<td>942</td>
<td>0</td>
<td>4</td>
<td>99.6%</td>
</tr>
<tr>
<td>Bearwallow</td>
<td>Long</td>
<td>274</td>
<td>29</td>
<td>18</td>
<td>82.3%</td>
</tr>
<tr>
<td></td>
<td>Short dry</td>
<td>273</td>
<td>9</td>
<td>14</td>
<td>91.6%</td>
</tr>
</tbody>
</table>

Table 2-6: Error in Inversion Results

<table>
<thead>
<tr>
<th>Fill</th>
<th>Survey(s)</th>
<th>Number of Iterations</th>
<th>RMS Error (%)</th>
<th>L2-norm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barton Hollow</td>
<td>Long</td>
<td>4</td>
<td>7.43</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Short dry</td>
<td>4</td>
<td>6.15</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>Short wet</td>
<td>1</td>
<td>1.76-3.10</td>
<td>0.29-0.89</td>
</tr>
<tr>
<td>Office Fill</td>
<td>Long</td>
<td>5</td>
<td>7.79</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>Short dry</td>
<td>4</td>
<td>5.57</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>Short wet</td>
<td>1-2</td>
<td>1.92-2.62</td>
<td>0.16-0.84</td>
</tr>
<tr>
<td>End Fill</td>
<td>Long</td>
<td>4</td>
<td>6.72</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>Short dry</td>
<td>3</td>
<td>8.01</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Short wet</td>
<td>2</td>
<td>2.55-6.36</td>
<td>0.25-0.53</td>
</tr>
<tr>
<td>Bearwallow</td>
<td>Long</td>
<td>4</td>
<td>11.16</td>
<td>2.55</td>
</tr>
<tr>
<td></td>
<td>Short dry</td>
<td>4</td>
<td>8.56</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>Short wet</td>
<td>2-3</td>
<td>3.58-6.68</td>
<td>0.69-1.02</td>
</tr>
</tbody>
</table>

2.6 Discussion

2.6.1 Surface Coal Mine Valley Fill Internal Structure and Hydrology

Our four field sites taken together show significant variation in subsurface structure and preferential hydrologic flowpaths. Most notably, the experimental thin-lift with compaction construction method implemented at Barton Hollow seems to have affected both subsurface structure and preferential infiltration flow patterns during our four-hour experimental storm. The range of subsurface resistivities and the number of deep accumulation zones beneath the artificial rainfall plot were both reduced relative to otherwise similar conventional (i.e. loose-dump) fills. The relatively small resistivity range suggests more consistent structural distribution throughout the fill and may be the result of the intentional construction method used (Figure 2-2), in which most or all of the fill material was likely to produce low levels of TDS (Zipper et al., 2015). This is consistent with the effluent stream SC values, which are the lowest of the four fills (Figure D-1). There are many possible causes, including the placement of high TDS generating rocks
away from infiltrating rainwater, but another may be the physical structure of the fill allowing less water to infiltrate deep into the fill relative to other fills.

Based on our estimated flowpath length and transit time values, the average of the preferential infiltration flow velocities was 5.1 m/h, or 0.14 cm/s (Section 2.5.3). These values indicate faster infiltration than observed on many natural lands and disturbed lands alike (Evans et al., 2015; Shukla et al., 2004; Simmons et al., 2008). For example, Rogowski and Pionke (1984) observed infiltration velocities of 0.053 and 0.421 m/h on two natural soil plots and velocities ranging from 0.003 to 0.028 m/h on mine spoils, all at a reclaimed strip mine site in Clearfield County, Pennsylvania. Reynolds and Reddy (2012) studied two reclaimed surface coal mines in Wyoming and observed slower infiltration rates than ours. Even their most rapid infiltration rate, which occurred in the first five minutes, was much less than 1 m/h. Meanwhile, Travelletti et al. (2012) found that a site disturbed by a landslide exhibited rapid infiltration via preferential flowpaths similar to those we observed. In their case, water infiltrated to bedrock at about 5 meters of depth within the first 5 hours (i.e. 1 m/h) of a 67-hour artificial rainfall experiment, while the larger wetting front took 12-15 hours to reach the bedrock (Travelletti et al, 2012).

Regressions of quantifiable fill and flowpath properties did not reveal any statistically significant patterns among all the valley fills (Section 2.5.4). Some fill properties, such as age since reclamation and vegetation, are understood to affect infiltration and subsurface flow, although vegetation’s influence is only relevant within about a meter of the surface (Evans et al., 2015). For example, Ritter and Gardner (1993) found that young fills in Pennsylvania had low infiltration rates, but over a twelve-year study most of their sites’ infiltration capacities increased, possibly due to vegetation growth. Similarly, Guebert and Gardner (2001) observed low infiltration capacities on recently reclaimed lands, but two years later they found that vegetation growth had helped to create macropores and increase infiltration. The variability within these general patterns remains such that flowpath development cannot be predicted well (Evans et al., 2015).

The time-lapse tomograms of Office Fill, Bearwallow, and Barton Hollow fills (Figure 2-5 – Figure 2-8) all seem to roughly agree with the corresponding sections of the long dry ERI surveys (Figure 2-3: Long Dry ERI Survey Tomograms). Regions that displayed low resistivity (blue) on the long dry surveys and may have been fine-grained enough to hold small amounts of antecedent moisture often were also blue in the time-lapse tomograms, suggesting that water accumulated there. Regions of high resistivity (red) in the long dry surveys usually corresponded with the yellow-red inversion artifacts in the time-lapse surveys, which were not getting any wetter. However, the tomograms of End Fill did not seem to agree in this way. The regions of increasing conductivity and inversion artifacts found in the time-lapse tomograms suggest much fewer large, consistent regions are in the subsurface than the long dry survey results would otherwise imply. The consistency between our two types of tomograms in all but one fill suggests that our field and interpretation methods are useful but would benefit from additional refinement.

2.6.2 Applied Significance for Fill Construction and Monitoring

It would be impractical to significantly rebuild established, conventionally built fills, but it may be worth investigating if relatively minor changes could have comparatively large effects. For example, if the shallow compaction layer within the Barton Hollow experimental fill was the key
factor behind reduced infiltration and lowered SC, perhaps there is potential to create such a compaction layer on the top of existing fills or part of existing fills for similar effects. Even this effort would be substantial, but easier to apply to younger fills where vegetation is less re-established. ERI could be conducted before and after such applications to determine the net effect of both vegetation clearing and compaction on flowpaths and SC.

The knowledge gained from this study can also inform the design and construction of future fills. For the most part, water flow patterns are not considered during fill design and construction beyond ensuring sufficient drainage for geotechnical stability. The subsurface water flow and accumulation patterns observed in this study exhibited wide variation among fills, and the behavior of the water influences the release of TDS from spoils, which leads to variation in effluent SC levels. The study results highlight the need for more intentional fill design and construction methods that incorporate the effect of water flow patterns on water quality.

If more mine sites adopt the thin-lift with compaction approach, the corresponding effluent stream quality may well improve as a result. Furthermore, the construction of additional fills using the Zipper et al. (2015) construction guidelines would allow future studies to determine the variability of flowpaths among such fills. Daniels et al. (2016) tested SC levels over time as a result of leaching in a lab column and found that SC levels started out high and then dropped and stabilized fairly quickly. Field measurements have shown the same trend in valley fill effluent streams, but on a much slower scale of years (Daniels et al., 2016; Evans et al., 2014).

Because infiltration of water along preferential infiltration flowpaths in valley fills can be very fast, yet accumulations of water within the fill occur on longer timescales, it would be beneficial to conduct paired rainfall and effluent flow/SC monitoring at high temporal resolution at a series of fills to hopefully better understand the relationship between rainfall events, flowpath activation, and flow/SC response in the effluent stream. Finally, if more experimental fills were constructed, monitoring their effluent streams would provide valuable feedback on the efficacy of those construction methods.

2.6.3 Limitations and Future Study
The methods employed in this study are beneficial because they are far less invasive than conventional methods such as borings and excavations, and because they produce continuous two-dimensional data rather than point data. Nevertheless, the results are more uncertain than direct physical methods in that we do not directly observe the subsurface. There is uncertainty in the data themselves, particularly on the edges of a tomogram. Furthermore, even in regions that displayed water accumulation with high confidence, we cannot quantify how much of the imaged wetness came from our artificial rainfall experiments and how much from water already in the vadose zone.

One of the major challenges of ERI is the tradeoff between survey dimensions and resolution. A long survey’s tomogram will cover greater length and depth, but the spatial resolution of the data will be lower than a shorter survey. To increase data resolution over a long survey, it is possible to decrease electrode spacing with a roll-along survey, which is performed one ERI cable at a time, but this limits the depth of the data obtained proportionally to the length of a single survey within the roll-along sequence. For this reason, we opted not to perform any roll-along surveys. Furthermore, ERI is not instantaneous; our 64-electrode surveys took approximately 33 minutes
and our 32-electrode surveys 8 minutes, during which the subsurface may have changed, particularly during artificial rainfall. Thus, the temporal resolution of our results has limits.

There are practical concerns with the equipment we used; the ERI equipment is more fragile than many conventional investigation methods, which do not include electrical circuits or sensitive cables. In our case this had the practical effect of reducing the number of cables we were able to use at one of the fills, reducing the tomograms’ spatial resolution. The artificial rainfall system in this study was somewhat inconsistent, as the sprinklers were prone to clogging with sediment or organic material, and water pressure varied based on the positioning of the pump in relation to the sprinklers. If we were to repeat this study, we would try to ensure greater consistency of the artificial rainfall system so that each rainfall plot received more uniform sprinkling over space and time among fills. This could be achieved by using another type of filter on the water pump intake to prevent sprinkler screen clogging. Another limitation of our approach is that the SC of the artificial rainfall varied among fills (Table 2-3). This variation may have had a minor effect on the ERI results in comparison to the effect of the increased subsurface saturation.

Future studies using ERI on other reclaimed surface coal mines would ideally perform both dry and sequential wet surveys on a conventional, i.e. loose dump, fill and an experimentally planned and constructed fill that are otherwise similar over all basic fill characteristics. This would all but eliminate variables such as fill size, drainage basin size, fill age measured since revegetation, land cover, and underlying geology/fill materials, thereby isolating the variable of fill construction method.

2.7 Conclusions

We found a significant amount of variation in subsurface structure in the tomograms of our four field sites. One of the most visible differences among fills was that the experimentally constructed Barton Hollow had a relatively small range of resistivity compared to the three conventionally constructed fills, suggesting more consistent internal structure throughout the fill. Using time-lapse ERI surveys, we were able to identify a total of eight deep accumulation zones beneath the artificial rainfall plots across the four fills. We observed fewer of these accumulation zones at Barton Hollow than at the other three fills, suggesting that the internal structure of the fill helps keep water infiltration shallow.

Based on the identified accumulation zones, we estimated an average flowpath transit time of 1.4 hours, average length of 6.6 meters, and average velocity of 5.1 m/h or 0.14 cm/s. These transit time and velocity values indicate faster infiltration than that observed on many natural lands. These velocities are likely underestimates due to our measurement methods, such that the true velocities are likely higher.

Regressions of quantifiable fill and flowpath properties did not reveal any statistically significant relationships. Thus, we are unable to assert that the age, fill size, or drainage basin size of a fill affects the preferential infiltration flowpath lengths, transit times, or flow velocities observed there. We also did not find any statistically significant patterns between fill or flowpath properties and effluent streams’ SC when we included all four valley fills in our regression. Removing Barton Hollow from that analysis revealed a negative correlation between fill age and SC, suggesting that younger fills typically contribute higher levels of TDS to their effluent
streams but that Barton Hollow’s experimental construction method and associated altered flow patterns may help keep its effluent stream’s SC low.

Our study confirms the usefulness of ERI as a noninvasive tool for hydrogeologic analysis of valley fills, as it is able to image internal structure under dry conditions and subsurface flowpaths under rainfall conditions. Our results suggest that the intentionally planned structure of valley fills may help control infiltration to the deep bulk fill and thereby improve effluent water quality.
2.8 References


Chapter 3 - Engineering Significance

Surface coal mining is prevalent in Appalachia, and mountaintop removal coal mines are particularly common due to their productivity and safety relative to other types of coal mines. Under the Surface Mining Control and Reclamation Act of 1977, reclamation of used mine sites is required, and this often takes the form of valley fills around the reshaped mountain that contain excess mine spoil under a layer of topsoil or other fines. Effluent water quality from these valley fills is an ongoing concern, as it often contains high levels of various metals and ions and therefore high total dissolved solids (TDS). Studies have shown that longer water-mine spoil contact tends to lead to more leaching, so it is crucial to understand subsurface flow patterns in valley fills. Electrical resistivity imaging (ERI) is a noninvasive method for geologic investigation, and numerous studies have used time-lapse ERI to study subsurface flowpaths in a variety of settings (Bass et al., 2017; Clémence et al., 2017; Fernández de Vera et al., 2017; Hübner et al., 2017; Scaini et al., 2017; Travelletti, 2012). However, to our knowledge only one study has applied it to a reclaimed surface coal mine (Greer et al., 2017).

Chapter 1 - details the basis for this study and outlines our objectives, which involved using ERI and artificial rainfall to evaluate the subsurface structure and preferential infiltration flowpaths at four Appalachian valley fills. In particular, we hoped to estimate flowpath properties like length, transit time, and linear velocity; to assess possible relationships between fill properties, like age and area, and the aforementioned flowpath properties; and to evaluate fill or flowpath properties correlated with the effluent stream’s specific conductance (SC).

Through ERI surveys of the dry fills (Chapter 2 -) we were able to identify differences between the subsurface structure of conventionally constructed, i.e. loose-dump, valley fills and an experimentally constructed one. The latter had a narrower range of subsurface resistivity values than any of the other fills, implying a consistent internal structure. We then used time-lapse ERI and artificial rainfall to study infiltration and preferential flow at the fills and found that the experimental fill had fewer deep accumulation zones where water had infiltrated rapidly. This was the first study to use ERI in the evaluation of the effects of an experimental valley fill construction method on its hydrogeology.

Most of the flowpath and valley fill properties that we analyzed did not show significant correlations. However, conventional valley fills seemed to have an inverse relationship between fill age since reclamation and effluent SC, which is consistent with prior studies. Our one experimental fill, though the youngest by far and therefore expected to have the highest effluent SC, had the lowest. This indicates that the construction method not only led to a different internal structure but also successfully reduced water-mine spoil contact time and therefore also reduced effluent SC.

This study sets the stage for additional research on valley fills. ERI is highly effective in evaluating subsurface flow and can be used on fills of any age and construction method. Future work could involve tasks such as verifying the effect of fill construction method by studying other experimental fills, monitoring a variety of fills’ effluent streams’ flow and water quality, and creating command files and experimental setups to improve on our temporal resolution of time-lapse ERI surveys.
The data from this study can help spur improvements to existing valley fill construction methods. The design and construction processes of valley fills do not typically involve consideration of subsurface flow beyond that needed to ensure geotechnical stability, even though flow patterns significantly affect TDS release from mine spoils and thereby affect effluent water quality. Based on the results of this study, we also suggest that future fills be constructed in an experimental manner rather than a conventional loose-dump method. Because the thin-lift with compaction construction method seems to help improve effluent water quality, new fills ought to follow this technique. Furthermore, alternative experimental methods ought to be drawn and implemented. For example, different size lifts could be constructed, or material types could be specified for each lift. Once fills have been constructed using various experimental methods, they can be evaluated, compared, and improved through studies using both ERI and stream monitoring.

It will be difficult, but perhaps possible, to alter existing fills to retroactively improve their structure and thereby their effluent stream quality. Restructuring existing loose-dump fills into thin lifts as at Barton Hollow is impractical and would not significantly change the distribution of fill material that resulted from the original construction; for example, all the largest boulders would remain near the toe of the fill, rather than spread throughout the fill at the toe of each lift. However, retroactive compaction of the upper layers of a fill may be feasible, especially on younger or less-vegetated fills. Later, when other experimental fill construction methods have been tested, some qualities of those methods may be transferrable to existing fills.

Outside of surface coal mine valley fills, ERI has already been used as an exploration tool for underground coal seams. With further development, the technology has the potential to be used for safety and location optimization prior to any sort of operation involving disturbing the subsurface, including mining of any minerals, drilling, and construction.
Figure A-1: Electrode Setup
Figure A-2: Switch Box Setup
The two passive cables are attached to the switch box on the right, while on the left a cable connects the switch box to the resistivity meter.
Figure A-3: Resistivity Meter Setup
The resistivity meter is connected to the switch box (right) and the marine battery (front).
Figure A-4: Short Transect Setup
Note that the resistivity system setup is under the tarp and in the middle of the transect.
Figure A-5: Water Pump
The intake hose (bottom) draws water from the fill’s effluent stream. The outlet hose (top) carries the water up the slope.
Figure A-6: Fire Hose Approaching Transect
The fire hose coming up the hill from the pump flows into a four-way splitter, which directs the water into three garden hoses.
At Bearwallow, the effluent stream was not reliable and we pumped water from a tank instead.
Appendix B – Electrical Resistivity Imaging Procedure

The resistivity system used in this study, the SuperSting R8 by Advanced Geosciences, Inc., is an eight-channel resistivity meter used in conjunction with a centralized switch box and passive cables. Before beginning survey setup, it is necessary to know the length of the desired transect in order to determine the appropriate spacing for even electrode placement. Topographical data should also be gathered if the survey is not on flat ground; this information is used in a terrain file during data processing. To set up a survey, the stainless steel electrodes must be hammered into the ground about 0.3 meters, and good contact with the earth should be ensured. The electrodes should be placed in as close to a straight even line as possible, although sometimes obstructions in the subsurface such as rocks may require electrode installation to deviate from the center line. Next, passive ERI cables must be laid out and connected to the electrodes via the metal contact points on the cables. The length of these cables may vary between systems; we used cables that connected to 16 electrodes each. Once the cables are in place, they are connected to the switch box. For a 64-electrode (four-cable) setup, the switch box goes between the second and third passive cables. For a 32-electrode (two-cable) setup, the switch box is placed at the top of the transect and connected to the second cable only. Finally, the switch box connects via short cables to the resistivity meter, which in turn is connected to a 12-volt marine battery for portable power (Figure A-1 through Figure A-4).

Once all the parts are connected, it is suggested to perform a contact resistance test, which is one of the diagnostic test features available on the resistivity meter. It measures the resistance between pairs of consecutive electrodes and provides a measure of the earth-electrode contact. If the resistance is too high (generally >5000 ohms), the connection is considered inadequate and would not produce acceptable results. In these cases, the corresponding electrodes may be improved by relocating them or pouring small amounts of water over them to improve earth-electrode contact. Once all electrode contact resistance values are satisfactory, the ERI survey can be run. We used an automatic survey in this study, meaning that the resistivity meter will run the entire survey based on the specified preprogrammed command file (AGI, 2017). For each line of the command file, the resistivity meter will distribute current into the ground through two electrodes, referred to as A and B (AGI, 2017; Herman, 2001). The potential difference between two other electrodes, referred to as M and N, is recorded. The resistivity meter calculates the apparent resistivity by dividing the observed voltage by the injected current (Herman, 2001). Command files may structure the patterns of electrodes for measurement in various ways, known as arrays. We selected a command file structured as a dipole-dipole array, in which electrodes A and B are near each other, and M and N are near each other on the other end of the measurement. Dipole-dipole arrays provide more reliable deep measurements than other arrays (Herman, 2001).
Appendix C – Statistical Analysis of Fill and Flowpath Properties

In these regressions (Table C-1) we included all flowpaths estimated from the significant accumulation zones at depth (Table 2-4). We took all fill properties, including mean SC of the fills’ effluent streams, from Table 2-1. In all linear regressions not involving SC, we also included accumulation zones from the surveys of Greer et al. (2017) for the sake of increasing the sample size (Table C-2). However, we do not have information about the SC of the Powell River Project site’s effluent stream, so the last six regressions include only data from this study. The transit times of more lateral flowpaths are more difficult to distinguish with any degree of accuracy, and therefore we have not included them in this analysis.

Table C-1: Fill and Flowpath Properties Linear Regression Results

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Dependent Variable</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill area (ha)</td>
<td>Transit time (h)</td>
<td>0.12</td>
</tr>
<tr>
<td>Fill area (ha)</td>
<td>Flowpath length (m)</td>
<td>0.20</td>
</tr>
<tr>
<td>Fill area (ha)</td>
<td>Flowpath velocity (m/h)</td>
<td>0.52</td>
</tr>
<tr>
<td>Drainage area (ha)</td>
<td>Transit time (h)</td>
<td>0.01</td>
</tr>
<tr>
<td>Drainage area (ha)</td>
<td>Flowpath length (m)</td>
<td>0.06</td>
</tr>
<tr>
<td>Drainage area (ha)</td>
<td>Flowpath velocity (m/h)</td>
<td>0.01</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>Transit time (h)</td>
<td>0.00</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>Flowpath length (m)</td>
<td>0.03</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>Flowpath velocity (m/h)</td>
<td>0.03</td>
</tr>
<tr>
<td>Fill area (ha)</td>
<td>Mean SC (µS/cm)</td>
<td>0.00</td>
</tr>
<tr>
<td>Drainage area (ha)</td>
<td>Mean SC (µS/cm)</td>
<td>0.11</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>Mean SC (µS/cm)</td>
<td>0.03</td>
</tr>
<tr>
<td>Transit time (h)</td>
<td>Mean SC (µS/cm)</td>
<td>0.41</td>
</tr>
<tr>
<td>Flowpath length (m)</td>
<td>Mean SC (µS/cm)</td>
<td>0.04</td>
</tr>
<tr>
<td>Flowpath velocity (m/h)</td>
<td>Mean SC (µS/cm)</td>
<td>0.15</td>
</tr>
<tr>
<td>Time since last rainfall (d)</td>
<td>Flowpath velocity (m/h)</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Table C-2: Preferential Infiltration Flowpath Properties from Powell River Project

<table>
<thead>
<tr>
<th>Figure in Greer et al. (2017)</th>
<th>Horizontal Location (m)</th>
<th>Time to First Appearance, or Flowpath Transit Time (h)</th>
<th>Approximate Vertical Depth from Surface, or Flowpath Length (m)</th>
<th>Approximate Linear Water Velocity along Flowpath (m/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 7</td>
<td>52.5</td>
<td>1.25</td>
<td>10.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Figure 7</td>
<td>35</td>
<td>1.25</td>
<td>5.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Figure 8</td>
<td>40</td>
<td>0.75</td>
<td>5.5</td>
<td>7.33</td>
</tr>
<tr>
<td>Figure 8</td>
<td>50</td>
<td>0.75</td>
<td>5.0</td>
<td>6.67</td>
</tr>
</tbody>
</table>
The data show a slight negative association between flowpath velocity and antecedent moisture conditions (Table 2-3), suggesting that water might infiltrate and flow more slowly in drier earth, but the correlation is not strong enough to be statistically significant.

Notably, when the experimentally constructed Barton Hollow is removed from the data, two apparent correlations appear for the SC of conventionally constructed fills’ effluent streams. A negative relationship between SC and fill age since reclamation had an $R^2$ value of 0.77, and a positive relationship between SC and total drainage area had an $R^2$ value of 0.61. However, with a sample size of only three conventional fills, these two correlations remain very uncertain but give a sense of which fill characteristics may affect effluent SC. They suggest that younger fills’ effluent streams typically have higher levels of TDS, perhaps because the very water-spoil contact that leads to high effluent TDS in general may gradually reduce the TDS contribution potential of the spoils. Barton Hollow’s deviation from this pattern suggests that its construction method and observed limited deep infiltration may help maintain a relatively low-TDS effluent even as a young fill. Indeed, Evans et al. (2014) observed declining SC of waters in an analysis of long-term fill effluent monitoring results. However, Merricks (2003) and Clark et al. (2016) did not find a significant relationship between the age and effluent SC of the valley fills they studied. Considered together, these studies suggest that other factors such as subsurface materials and structure affect the effluent water quality, but that any given fill’s effluent stream quality will likely improve over time.
Appendix D – Rainfall and Flow Monitoring

The following figures represent ongoing monitoring of the four field sites and their effluent streams. The date range shown is our field season, 05/22/2017 – 10/03/2017. In the legends, BH represents Barton Hollow, BW is Bearwallow, OF is Office Fill, and EF is End Fill.

Figure D-1: Specific Conductance during Field Season
The logger sensor at Barton Hollow was dewatered from 08/11/17 – 09/08/17. The data file from Bearwallow from 07/10/17 – 07/31/17 was corrupt. The logger sensor was buried and/or lost at Office Fill from 06/05/17 – 06/07/17, 07/11/17 – 08/21/17, and 10/23/17 – 10/31/17.
The data file from Bearwallow from 06/06/17 – 07/10/17 data file was corrupt. The Office Fill streamflow data is irregular because the streambed was unstable, such that the flume frequently was clogged or bypassed. The precipitation data shown is for Office Fill, End Fill, and Barton Hollow, which were all at the same mine.
Appendix E – Procedure for Scaling Time-Lapse Tomograms

The initial time-lapse inversion on each set of raw data from our ERI surveys with rainfall (Section 2.4.3) yielded tomograms with a change in conductivity color scale ranging from -100% (red) to 100% (blue) by default (AGI, 2009). On many of these tomograms, the changes in conductivity were difficult to see because of the broad scale range.

The inversion also produced data files providing numerical values for the changes in conductivity that the tomograms display visually. We examined these files to determine the most extreme change in conductivity observed, i.e., the percent difference with the largest absolute value, whether an increase or decrease in conductivity. We then specified this most extreme value as the outer end of the scale for the time-lapse batch inversion tool, so that the changes in conductivity would be as visible as possible in the resulting images, and reran the inversion. For example, if the largest change in conductivity observed was by 50%, we reran the inversion to create final tomograms with a color scale showing from -50% (red) to 50% (blue) change in conductivity.