Using Geophysical Imaging to Track Water Movement through Surface Coal Mine Valley Fills

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Introduction

Surface coal mining (Figure 1) breaks up overburden bedrock into fragments, exposes fresh rock faces to weathering, and leads to elevated concentrations of dissolved minerals in downstream waterways. A key result is increased total dissolved solids (TDS) that can affect aquatic organisms. Rock fragments can range in size from fine powder up to boulders the size of automobiles. After mining is completed, this material is placed back into the original mined area and in excess-spoil disposal fills near the mined area, some of which may be placed in headwater valleys to construct valley fills. Mine spoils may be loose-dumped into the valley fill or placed in compacted lifts, but loose-dumping of durable rock is a common technique for constructing valley fills in Appalachia today. Surface coal mining regulations require that valley fills be constructed to ensure water drainage. Within loose-dump fills, drainage typically occurs within a layer of large-sized rock along the valley floor, at the fill bottom, so that water entering the fill from rainfall and adjacent terrain drains through the channels formed between the rocks. Because of concern with water-resource effects of mining discharge, researchers and industry are investigating alternative valley-fill designs that will reduce TDS concentrations of mine water outflows.

Figure 1. Surface coal mining in Appalachia USA. Active mine areas are in the background, while reclaimed and revegetated mined areas are in the foreground (Photo credit: Erich Hester).

All of these fill construction and reclamation techniques, together with natural settling and weathering processes, combine to create the geologic structure of the fill that is exposed to hydrologic processes. Groundwater from adjacent areas may enter the fill material, and water from precipitation infiltrates the fill surface and moves through the fill material before being discharged to downstream waterways. The hydrologic effects of mining and valley fill construction varies among mine sites, but documented effects include more rapid ("flashier") stormwater runoff, increased volume and duration of baseflow (Miller and Zegre 2014), decreased evapotranspiration, and increased water storage (Zegre et al. 2014) relative to the unmined Appalachian terrain (Evans et al. 2015). Infiltration can be rapid in some locations due to preferential flow paths and minimal in others due to surface compaction, and may change with time due to soil development and growth of plants (Caruccio and Geidel 1984, Hawkins and Aljoe 1992, Guebert and Gardner 2001). These prior studies have generally viewed filled areas as "black boxes" by measuring rainfall and consequent discharge into effluent streams, with little regard to the hydrologic processes occurring within a single mine site or to differences caused by differing fill construction procedures at different mine sites. Such studies rarely have investigated the fill subsurface to determine locations of flow paths, or to understand when or how subsurface flow paths are activated by precipitation.

It is the interaction of these complex and thus-far poorly understood subsurface water flows with the rocks that comprise fills which elevates TDS in mine discharge and downstream waterways. Improved knowledge of where and when flow paths within fills are activated, and how water is stored and released by fills, will improve understanding of where and when rainwater acquires minerals that form TDS, and of surface mining's hydrologic consequences. This knowledge in turn will aid development of mining and fill construction methods that can reduce impacts to water quality and restore a more natural hydrology.

Methods

In summer 2014, we conducted a study of valley-fill hydrology in southwestern Virginia. Geophysical techniques were used to provide spatially continuous information about the subsurface in an effort to increase knowledge beyond that gained from point measurements and other techniques used previously. Electrical resistivity imaging (ERI), also known as electrical resistivity tomography (ERT), was applied to a single 6-year-old valley fill (Figure 2). The fill was constructed of gray and brown sandstone spoil rock using a tiered approach with alternating slopes and benches. A loose-dump approach had been used by the mining firm to construct the fill. Our study was intended to determine the feasibility of using ERI to indirectly visualize and understand the subsurface hydrologic processes occurring in valley fills and on other mined lands.

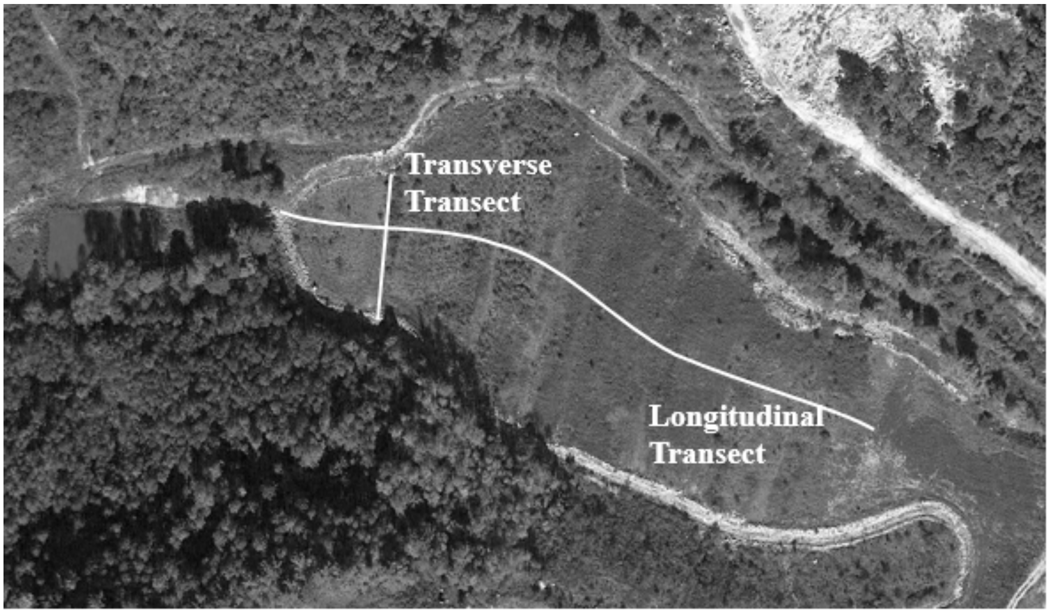

Figure 2. Aerial photo of valley fill used for project showing locations of longitudinal and transverse ERI transects. (Photo from Google Maps).

ERI investigations were conducted by driving foot-long metal electrodes into the ground at a predetermined fixed interval along lines known as transects (Figures 2, 3). The electrodes were connected by cables to an electronic system (SuperSting R8 by Advanced Geosciences Inc. (AGI)) that injected electrical current sequentially into each electrode and simultaneously measured the resistivity of the ground using a different sequence of electrodes. The resulting raw resistivity data were processed using AGI Earth Imager inversion software. The result is an image that maps the spatial distribution of electrical resistivity along a vertical cross section of the subsurface beneath the transect known as a tomogram. Tomograms can be interpreted to yield information regarding the geology and hydrology of the subsurface. ERI was used during dry conditions to image the subsurface geologic structure of the fill and also during artificial rainfall application to image water movement into and through the fill. Artificial rainfall was applied by pumping water from the effluent pond and distributing it with garden sprinklers over a 10 m x 30 m area of a flat bench between fill tiers. Artificial rainfall varied from 1.2 cm/hr to 2.5 cm/hr for 2-4 hours.

Figure 3. ERI equipment: AGI Earth Imager unit (left) and transect of electrodes connected by electrical cables (right). (Photo credit: Breeyn Greer).

Results

The ERI surveys conducted under natural conditions (without artificial rainfall) were used to interpret the geologic structure of the valley fill's interior (Figure 4). These are maps of resistivity for a single point in time. Figure 4a shows a tomogram representing a vertical cross section beneath the ERI transect of electrodes placed down the centerline of the valley fill (Figure 2). This tomogram revealed that electrical resistivity is less (shown in blue) in the upper portion of the fill, closer to the land surface, than in the lower (deeper) portion (shown in orange). This lower resistivity layer is up to 30m thick in the center of the fill, probably due to the presence of smaller/finer rock fragments in shallower areas of the fill. These finer rock fragments make better contact with one another and retain water better after rainfall infiltration events, compared to the larger rocks that occur deeper in the fill. Water retained in the fill's upper section causes an increase in electrical conductivity and therefore a decrease in the electrical resistivity of that portion of the subsurface, as indicated by the blue color. Figure 4b shows a tomogram representing a cross section beneath the ERI transect of electrodes that were positioned (in a transverse direction) at the downslope-most flat bench of the fill (Figure 2). This area is not as deep, but highlights the side drains as areas of high spatial heterogeneity of resistivity at the two locations where the natural side slopes meet the flat fill area between. This high heterogeneity is due to larger boulders and occasional air-filled voids that are more common there.

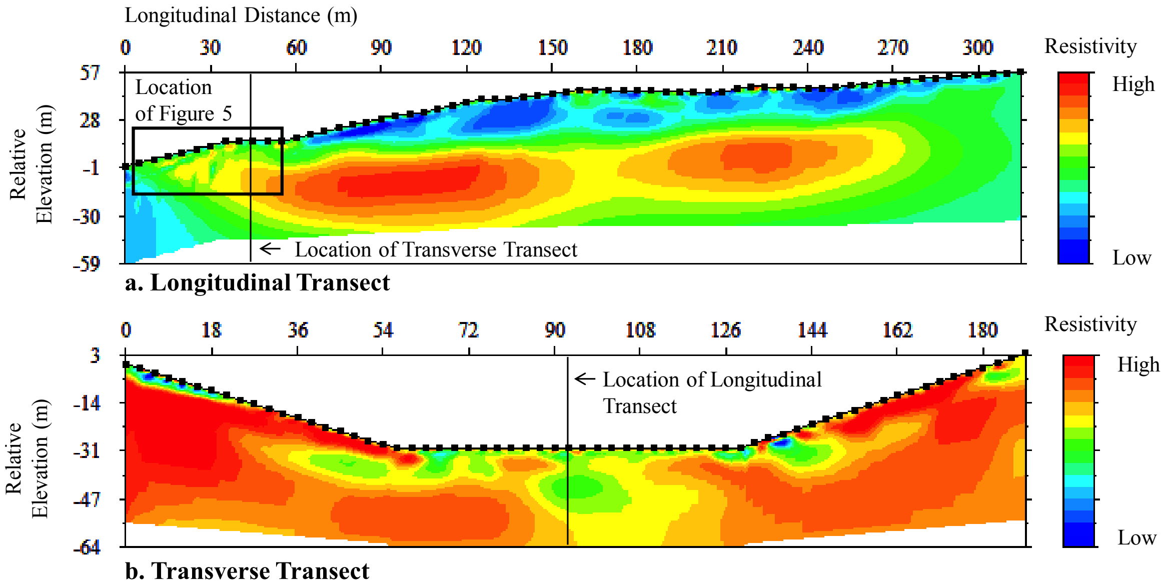

Figure 4. ERI tomograms taken under natural (no artificial rainfall) conditions showing subsurface geologic structure of the valley fill as cross-sectional images. Longitudinal (a) and transverse (b) transects are shown (Figure 2). Blue areas are zones of fine-textured rock materials, with pores that retain moisture easily; while red areas represent rock materials with larger pores that do not retain moisture.

The ERI surveys conducted during artificial rainfall were used to determine the locations of subsurface hydrologic flow paths, the locations of temporary water storage zones, and how quickly the applied water moved through the fill. Figure 5 shows an example tomogram from a longitudinal transect shorter than that in Figure 4a in the vicinity of the downslope-most bench. The shorter transect had more closely spaced electrodes which yielded a more detailed image of the fill subsurface. Figure 5 is a "difference" tomogram, where the resistivity map from a later time is subtracted from the resistivity map for an earlier time. The earlier time (time 0) was just before artificial rainfall began, and the later time was after artificial rainfall had occurred for 2 hours. As artificial rainfall was applied, the spatial distribution of water within the fill changed; hence the "difference" tomogram shows how water moved within the fill over the 2-hour time interval.

Figure 5 indicates that rainwater did not move from the surface into the fill uniformly. Rather, water accumulated at the surface and also moved into deeper fill zones preferentially in localized areas of the fill. The tomogram shows considerable volumes of water being held by spoil materials near the surface, indicated by a nearly contiguous area of dark blue color between 30 m and 48 m longitudinal distance. This water accumulation at and near the surface was visible during field work and was expected due to a hard surface of compacted fine rock fragments and dust. Water also accumulated at several locations in the subsurface, indicating zones where water was able to flow easily from the near-surface into the subsurface. The most obvious deeper water-accumulation zone is visible at about 20 m depth and 33-45 m horizontally. Figure 5 shows infiltrating rainwater reaching depths of approximately 25 m after 2 hours of rainfall, and other ERI surveys (Greer et al. 2016) showed water reaching 10 m depth within only 45 minutes of rainfall. Together, these difference tomograms indicate that preferential flow paths in some cases were rapid and deep. The lack of significant change outside of the rainfall plot (green in color) confirms that the changes in subsurface water content discussed above are caused by the applied rainfall.

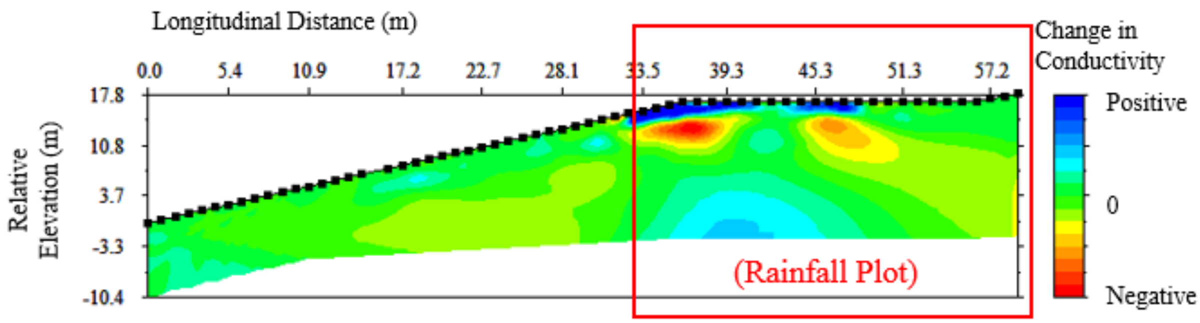

Figure 5. ERI "difference" tomogram shows the difference between just before artificial rainfall began (time 0) and approximately 2 hours after rainfall started. Difference tomograms show locations where electrical conductivity increased during the intervening time period (blue areas) due to increases in water content. Geologic structure is no longer visible, and red areas are artifacts of the inversion algorithm that occur near areas of strong conductivity increases (i.e. they do not represent actual conductivity declines). Artificial rainfall was applied along the horizontal bench within the red box.

Summary

Previous studies have surmised but not demonstrated that water moves through the subsurface of valley fills via preferential flow paths (Caruccio and Geidel 1984, Hawkins and Aljoe 1992). Our study was conducted to test the ability of ERI to determine the location of such preferential flow paths, to estimate how long rainwater takes to infiltrate those flow paths, and to determine the locations of temporary storage areas of infiltrated rainwater within the fill material. Our results indicate that ERI can indeed provide all three types of information, confirming earlier conceptions of preferential flow, and adding spatial and temporal quantification. Continued application of this technique to additional mined landscapes holds promise to improve understanding of how water flows through mine-spoil fill materials. Results will enable insight about where, when, and how TDS are transported through mined landscapes and delivered to effluent streams. This will enable comparison of fill construction or reclamation approaches; will aid efforts to develop fill construction and reclamation methods to reduce TDS impact and hydrologic change; and will aid in monitoring and managing existing mined sites.

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