Correlating Airborne Geophysical Survey Data to Conductive Strata

by

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Abstract

Accurately delineating acid mine discharge sources and flooded mine workings is a key component in planning for mitigation of acidic mine water discharge to the surrounding surface water systems. The nature of the water chemistry in the flooded tunnels theoretically should create a high electrical conductivity signature. Accordingly, an airborne geo-electrical survey was undertaken to determine if flooded mine tunnels and acid mine drainage sources could be delineated through the resulting spatial patterns of the data collected. The raw measured survey data was reduced with standard geophysical processing techniques to help eliminate extraneous noise and smooth erroneous data points. The processed data included measurement location coordinates, elevations, and electrical conductivity for subsurface depth intervals encompassing the mine tunnel workings. The processed survey data was imported into ArcGIS as point data and converted to raster formats for statistical analyses. Through spatial analyses of survey data and correlations to existing mine maps, refined estimates of flooded mine workings extents were developed.

The data generated by the analyses in this study will be used by the Maryland Department of Natural Resources Power Plant Research Program (PPRP) to optimize the massive beneficial use of Coal Combustion Products (CCPs) to reduce acid formation in groundwater and surface water. The CCPs can be used to cap unreclaimed mine spoils piles or mixed with water to form a grout that can be injected into the mine tunnels. The injected grout will harden, seal, and isolate pyritic rock from the acid forming chemical combination of oxygen and water.

Introduction

Funded in part by the Maryland Department of Natural Resource Power Plant Research Program (PPRP), the U.S. Department of Energy's National Energy Technology Laboratory (NETL) conducted helicopter electromagnetic (HEM) surveys during 1999 over an area that included the Kempton Mine Complex (Figure 1) straddling the Maryland-West Virginia border. The purpose of these surveys was to determine if HEM survey data can provide useful insight to characterize abandoned mine workings and to develop strategies for addressing Acid Mine Discharge (AMD). Useful information that could be derived from the survey data would include identification of flooded mine workings, abandoned mine discharges, acid mine water recharge zones, extent of mine spoils piles, and groundwater flow directions. PPRP intends to use this data to optimize strategies for the beneficial use of massive amounts of CCPs to reduce AMD.

OBJECTIVES

This paper focuses on a key aspect of the project which included evaluating subsurface conductive features related to potential mine characteristics of interest. These characteristics included AMD sources and flooded mine tunnels. Although the extent of the flooded mine tunnels has been estimated by measuring water levels in the few available boreholes and mine shafts (PPRP, 2000), a refinement of the flooded tunnel extent using the HEM data and signatures was a desired outcome of the study.

BACKGROUND

In the mine tunnel network, groundwater seeping into the tunnels had resulted in corrosive acidic water conditions and had flooded portions of the mine tunnel network. Airborne electromagnetic (EM) surveys measure the electrical resistance or conductivity of surface and subsurface features. Acidic groundwater and the water in the flooded mine tunnel network is typically much more conductive than that the surrounding rock layers. These conductive signatures typically become readily apparent in the survey data as zones or layers of higher conductivity. The majority of water contained in the flooded mine tunnels is not acidic. Field studies (PPRP, 2000) have measured neutral pH values a few feet below the piezometric surface of the mine pool within the tunnels. The stratified nature of the acid in the mine pool is consistent with the formation of AMD requiring oxygen which is available at the air/water pool interface.

AMD results when the mineral pyrite (FeS_2) is exposed to oxygen and water, resulting in the formation of sulfuric acid and iron hydroxide. The chemical equation for AMD formation is:

$$FeS_2 + 3.75\ O_2 + 3.5\ H_2O \Leftrightarrow Fe(OH)_3 + 2\ H_2SO_4 \quad \text{(Equation 1)}$$

Pyrite is commonly present in coal seams and in the rock layers overlying coal seams. AMD formation occurs during surface mining when oxygenated surface water infiltrates the mine spoils that were generated during mining activities. AMD can also occur in deep mines which allow the entry of oxygen or oxygenated water to come into contact with pyrite-bearing coal seams, high sulfur mine pavement, and collapsed tunnel roof debris. These reactions raise the water acidity (i.e., lower the water pH) to levels that are toxic to flora and fauna. Identifying AMD source areas by a spatial analysis of the geophysical survey data was a key objective of this study.

During mining activities, groundwater seeping into the mine was pumped to the surface to keep the mine tunnel network from flooding. With the cessation of mining activity, underground pumping ceased and portions of the mine tunnel network gradually filled with groundwater. The large volume of water (1.1 billion gallons), contained by the tunnel network (PPRP, 2000) creates a large pressure gradient that may eventually rupture the overburden permitting a catastrophic release of mine water and flooding of down gradient stream and river valleys.

To evaluate the diverse and voluminous spatial data sets involved in the project work, ArcGIS was used for filtering the data, correlating spatial trends, and creating new data sets to aid in the analyses of the electromagnetic data signatures. Spatial Analyst was particularly useful in filtering the data sets, developing raster surfaces of the EM and other data, and mathematically manipulating combinations of raster surfaces.

Survey Methods

The survey was conducted with an EM transmitter/receiver sensor (“bird”) towed over the project area by a helicopter (Figure 2). Over the project area, 124 east-west flight lines were flown spaced approximately 50 meters (m) apart. Transmitter coils within the front of the bird apply magnetic fields to the earth which generates secondary magnetic fields that can be measured by receiver coils at the back of the bird. The strength of the primary (applied) magnetic field (H_p) and secondary magnetic field (H_s) are measured by the coils contained in the bird. The ratio of the primary to secondary electromagnetic field (H_s/H_p) is proportional to the ground conductivities. The units derived from the survey and used in the analyses are millisiemens per meter (mS/m) and are a measure of the electrical conductance of a material.

Horizontal coils in the bird broadcast at variable frequencies with the lower frequencies applying EM fields that penetrate deeper into the earth than the higher frequencies at each sounding location. The responses are measured at over one hundred GPS derived X Y locations along each flight line. With the variable frequencies penetrating progressively deeper into the subsurface, conductivities along the depth profile were generated at each of the X Y location. Approximately two million records of EM data were generated after filtering and post-processing of the survey data. For each flight line, the individual conductivity/depth profiles are assembled to generate cross-sections of conductivity with depth. These cross-sections are referred to as conductivity depth images (CDIs) and represent surface conductors and layered conductors in the subsurface.

Data Manipulation and Analyses

EM survey data is typically interpreted in the context of known site specific spatial data including geological and land surface (natural and man-made) features. Conductors detected by the EM survey are evaluated using a priori knowledge of conductive targets and any features that may create noise in the survey data. Because the survey measures electromagnetic fields, surface conductors such as metal towers, power lines, and other metal objects may create significant and undesirable noise in the survey data.

Utilizing ArcMap, aerial photographs were overlain with the flight line paths to provide insight into ground surface features that could distort the survey data signals along a flight line. Overlays of topographic maps were used to evaluate groundwater and surface water drainage patterns, and surface water features that could affect the EM signals. With ArcMap, the examination of features in the topographic maps and aerial photographs along each corresponding flight line was critical to correctly interpreting the EM anomalies related to the desired targets of flooded mine tunnels and AMD sources versus those anomalies associated with metal/man-made objects.

Maps of mine spoils piles were developed from recent and historical aerial photographs, and were used as overlays along the flight lines. This information was used to correlate changes in conductivities along the CDI profiles with potential AMD sources. In some portions of the study area, significant increases in conductivity were associated with the mine spoils piles. These areas of high conductivity form a relatively persistent and highly conductive layer originating at the mine spoils piles (Figure 3). The spoils piles are susceptible to high surface water recharge due to the reworked and permeable nature of the surface soils. Within the mine spoils piles, surface recharge coupled with natural weathering processes can create acidic water (Equation 1) that typically will have a high conductivity signature. Electrical conductivity of water is directly proportional to all ions in solution including those ions produced by higher acidity. With the higher acidity of water, more hydronium (H^+) ions come into solution and contribute to a relatively high electrical conductivity signature.

The high conductivity layers extending down gradient from selected spoils piles indicate that these piles may be continually producing AMD plumes which travel towards the head waters of streams and creeks. However, not all spoils piles have conductive signatures in the project area. The production of AMD from the spoils piles is dependent on geographic considerations such as proximity to surface water recharge sources (e.g., creeks and streams), and gradient of land surface slopes, and permeability of surface soils. AMD emanating from areas of spoils piles would not be unexpected and has been observed in other surface mining areas (e.g., PADEP, 2000 and U.S. EPA, 2001). The CDIs provided information concerning conductive features along a flight line, however, an aerial view of the conductive zones was needed to identify the areas and groups of spoils piles that may be actively producing AMD.

To better evaluate the extent of the conductive areas beneath the mine spoils piles and identify which piles have relatively conductive signatures, the maximum conductivity value in the conductive layer at each coordinate along each flight line was extracted for creation of a raster surface within Spatial Analyst. The total number of data points used to create the raster surface was approximately 200,000. Overlays of the raster surface on USGS topographic maps revealed that relatively large areas of conductive zones originating at certain mine spoils piles extend down gradient from the piles for hundreds of meters (Figure 4). These types of overlays helped identify which areas of the spoils piles are actively generating acidic mine discharge and contributing to the acidic conditions in the aquifer and the underground mines. Using ArcMap, field measurements of high acidity at groundwater seeps (Peter Skylstad, personal communication 2005) down gradient of the spoils piles provided corroborating evidence of acidic zones extending from the spoils piles to locations of surface water discharge points and wetlands.

Simulations of conditions similar to those encountered in the study area (Hammack, 2000) indicate that the maximum depth of investigation for survey methods was approximately 50 m. To evaluate the areas of mine tunnels above a 50 m depth, a raster surface of the mine tunnel elevations needed to be developed. Existing maps of the tunnel floor elevations consisted of polyline shape files. Through Visual Basic scripts, the polylines were converted to a point data grid consisting of coordinates and elevations. The point data was interpolated to a raster surface with Spatial Analyst. Using U.S. Geological Survey digital elevation models for the project area, a land surface elevation raster surface was developed.

The mine elevation surface was subtracted from land surface with Spatial Analyst to derive the area of the tunnel network that was above the maximum exploration depth of 50 m (Figure 5). For evaluating the signature of flooded mine tunnels, the resulting map of tunnel depths within the exploration depth was crucial to eliminate misinterpretation of conductive signatures attributed to flooded tunnels and those signatures due to other subsurface conductors. The majority of the flooded tunnels were found to be too deep to be detected by the EM survey methods. However, the survey did reveal valuable information concerning areas that are actively contributing to AMD in the aquifer and mine tunnel network and flooded tunnels.

The mine spoils piles in the western study area are located along the highest mine tunnel floor elevations. These spoils piles are roughly parallel to topographic contours in the highlands of the watershed. Due to the reworked nature of the soil in the spoils piles, streams and surface runoff water traveling over the spoils infiltrates relatively easily through the piles creating favorable conditions for acidic water production. In some cases, the surface mining has breached the mine tunnel network. In these areas, recharge from the spoils piles can infiltrate onto the mine floor pavement where additional AMD is created by the reaction of the water with the exposed minerals. This AMD is then carried down gradient towards the mine pool progressively increasing the water acidity along the flow path (Figure 6).

AMD Mitigation and Mine Sealing

Acid mine discharge is currently treated and neutralized with a number of methods including calcium carbonate to neutralize acidic conditions and anoxic systems to reverse the AMD chemical equation through biomass treatment. Although effective, these methods of remediation treat only the symptoms of the AMD and do not address the source or root cause of AMD production; exposure of the mined minerals to oxygenated water. To prevent the AMD from forming, the minerals must be isolated from the oxygenated water. An ideal method of sealing the minerals from oxygen-rich water is to apply a very low permeability cement or grout cap. PPRP has developed successful pilot projects using CCPs as grout caps and seals (Petzrick et. al, 2005). CCPs are a result of the coal burning process and include pozzolanic fly ash, and bed ash which is not pozzolanic. However CCPs produced in Fluid Bed Combustion (FBC) Plants which co-fire coal and limestone, such as the North Branch Power Plant adjacent to the Kempton Mine Complex, are self cementing when the baghouse (filtered particulate) material and bed material are mixed with water in the proportions produced in normal plant operations. The durability and leaching characteristics of the resulting solid material has been monitored under acidic conditions in a small mine on Winding Ridge, MD (Petzrick et. al, 2005) for nine years.

The use of CCPs in capping and sealing AMD producing areas provides a substantial volumetric and beneficial use for a product that may otherwise be placed in landfills. CCPs are readily available from coal burning power plants that are relatively close to the mine complex. CCP grout is relatively inert in a natural environment and has been proven to pose no threat to flora or fauna. CCP grout may be hydraulically placed into mines to selectively seal acid producing surfaces such as the mine pavement and debris against acid production and also may be used as an impermeable cap on the spoils piles to prevent surface water infiltration and the subsequent formation of AMD. With proper preparation, the CCP grout will harden and cure under water.

Summary and Discussion

ArcGIS provided the tools required for spatial analyses of a complex data set comprised of electromagnetic data soundings, and the entire suite of point, line, polyline, polygon, and raster GIS feature types. Spatial Analyst was instrumental in the processing and filtering of the data sets. Selected EM point data converted to raster surfaces provided clear delineation of highly conductive areas that have a high probability of being AMD sources. For correlating the location of mine spoils piles with trailing plumes of high conductivity in the project area, ArcMap was a critical tool in identifying key targets for further investigation as AMD recharge sources.

Currently, models developed utilizing ArcGIS components are being evaluated for suitability in simulating the movement of CCP grout paths along the mine tunnel floors to mitigate AMD sources. These models will provide valuable information for delineating the most effective points for drilling grout injection boreholes, given the physical characteristics of the mine tunnels and geology. Preliminary model simulations show great promise in utilizing ArcGIS in predicting the path of grout along the mine tunnel network to assist in the prevention and remediation of acid mine discharge sources.

Acknowledgements

The work described in this paper is part of a larger scope that involved beneficial use of CCPs sponsored by PPRP. Within the project area, extensive work has been done by the Maryland Bureau of Mines and the Geospatial Research Group at Frostburg State University, MD in developing mine maps and associated spatial information from

historical documents. Maps developed by these organizations were used extensively as overlays and for correlation of the EM survey data with mine tunnel configurations, and subsurface hydrogeologic features.

Figures

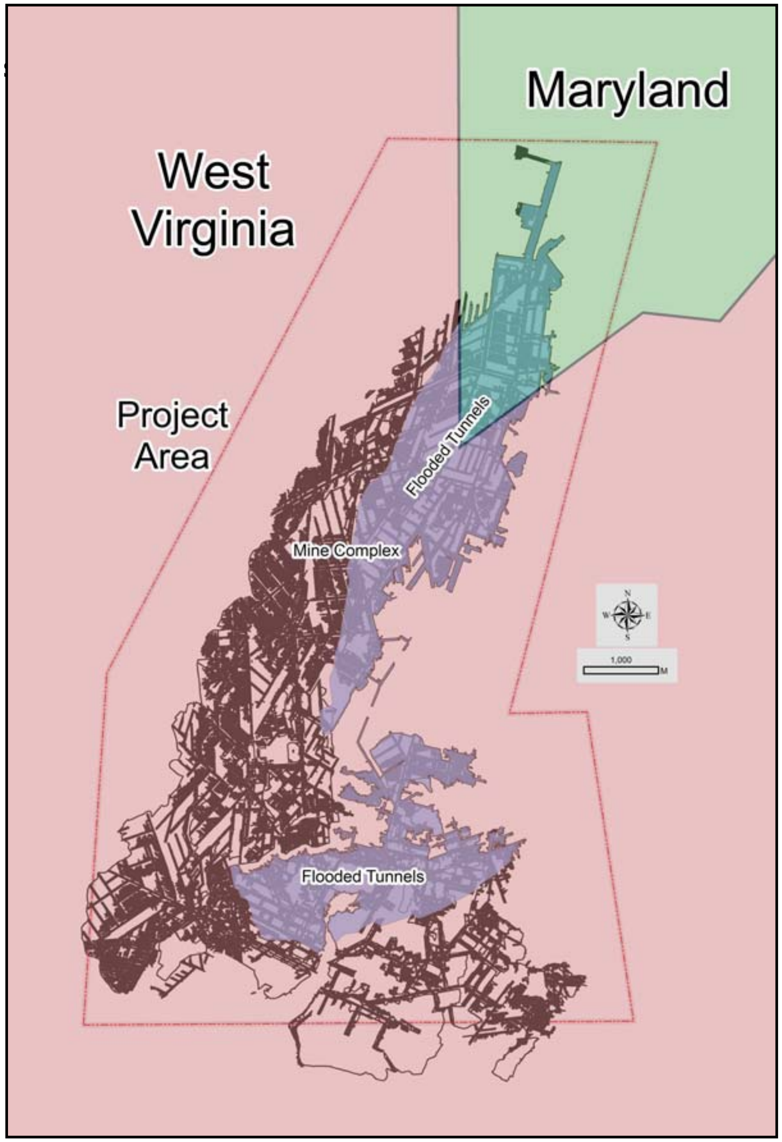

Figure 2. Project Area.

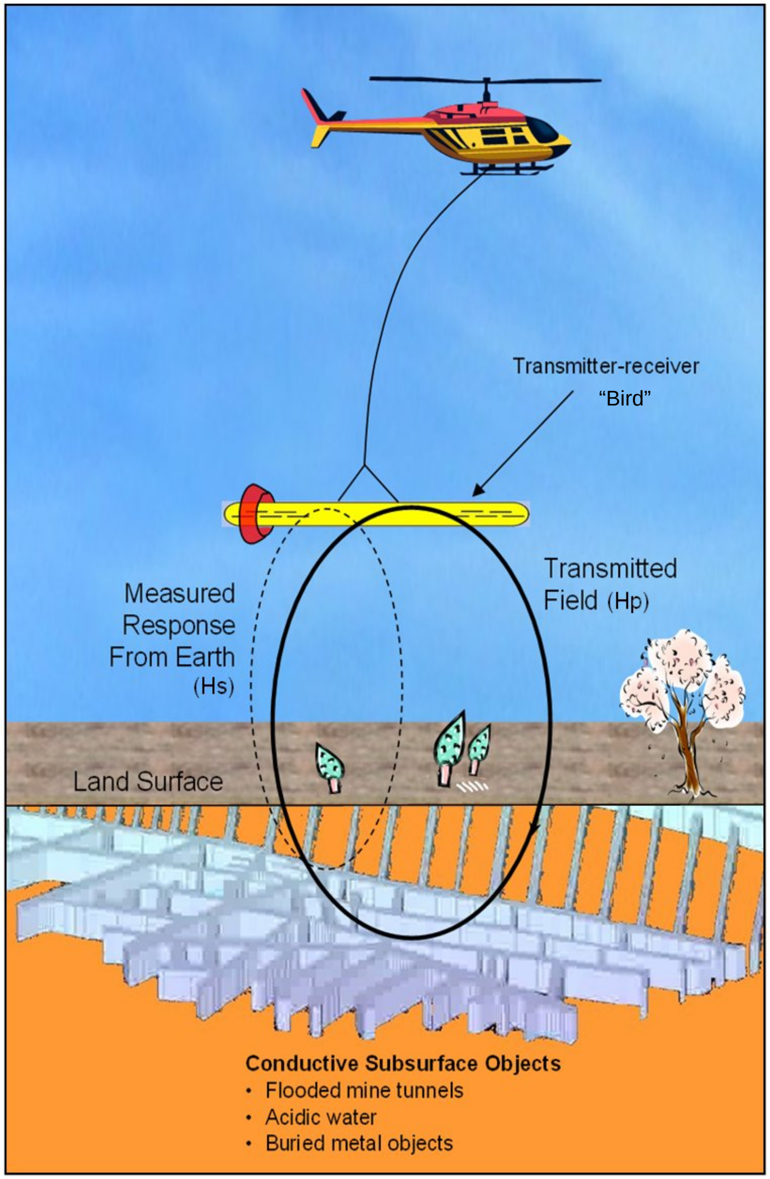

Figure 1. Helicopter Electromagnetic Survey Configuration.

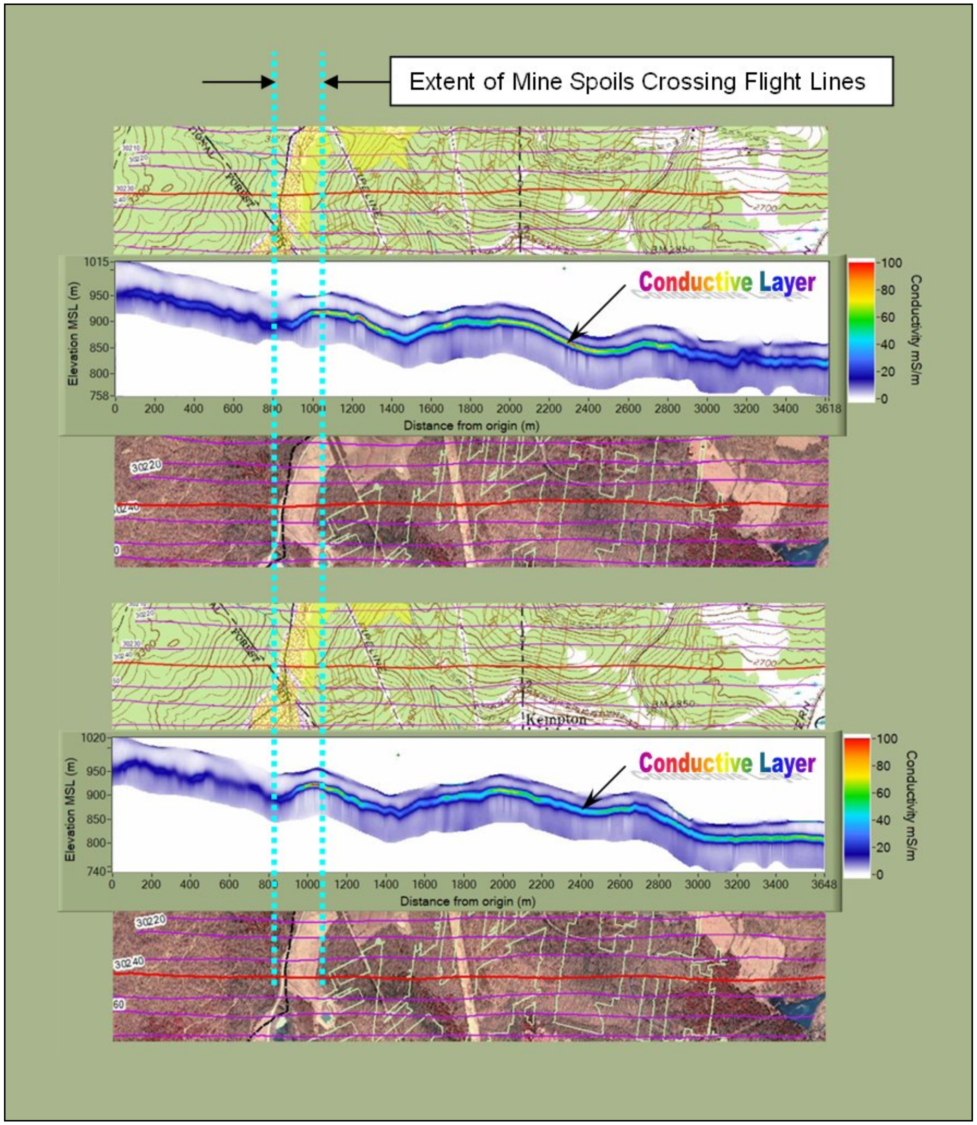

Figure 3. Conductivity Depth Images and Mine Spoils Piles.

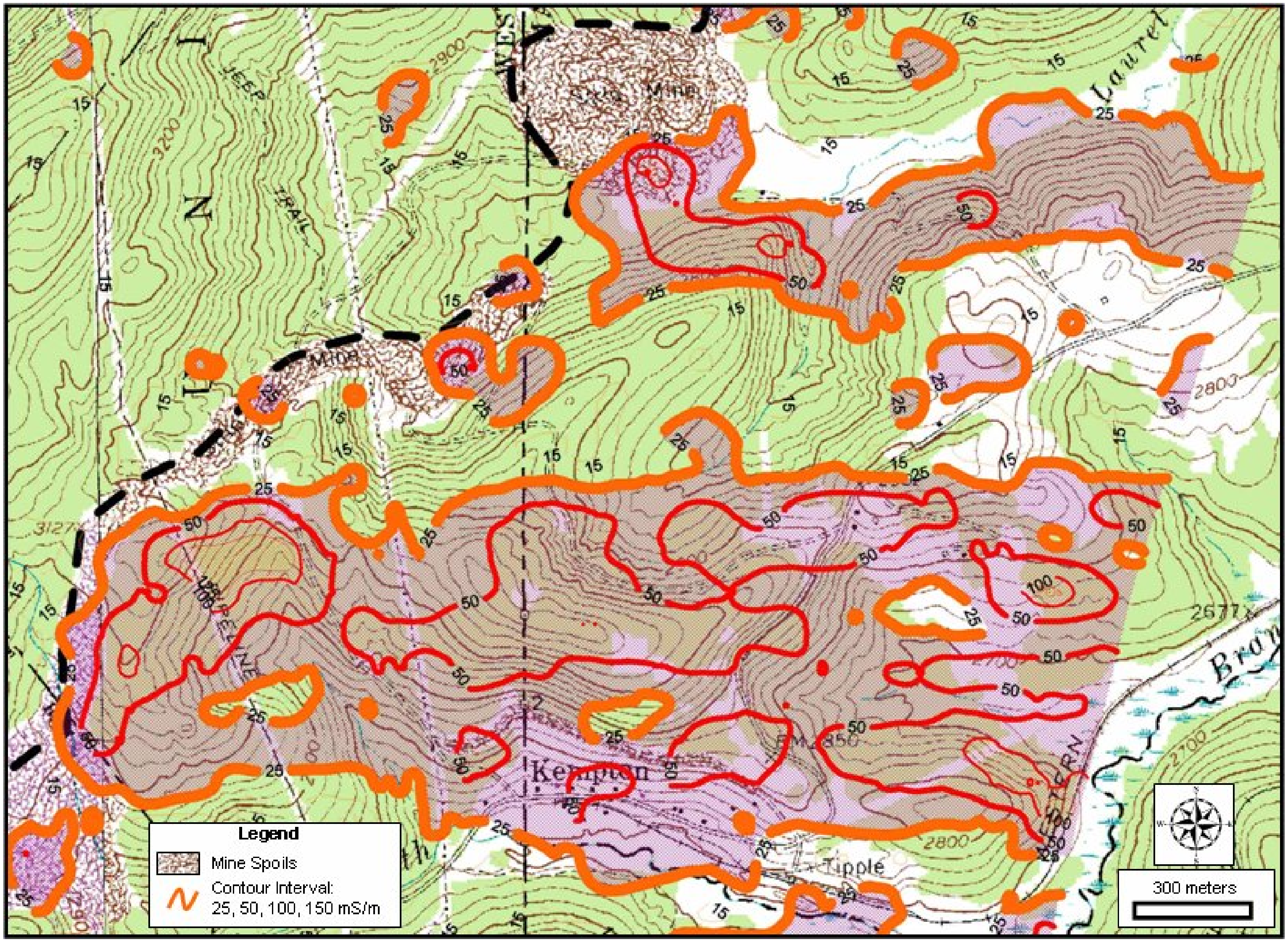

Figure 4. Conductive Plumes and Mine Spoils Piles.

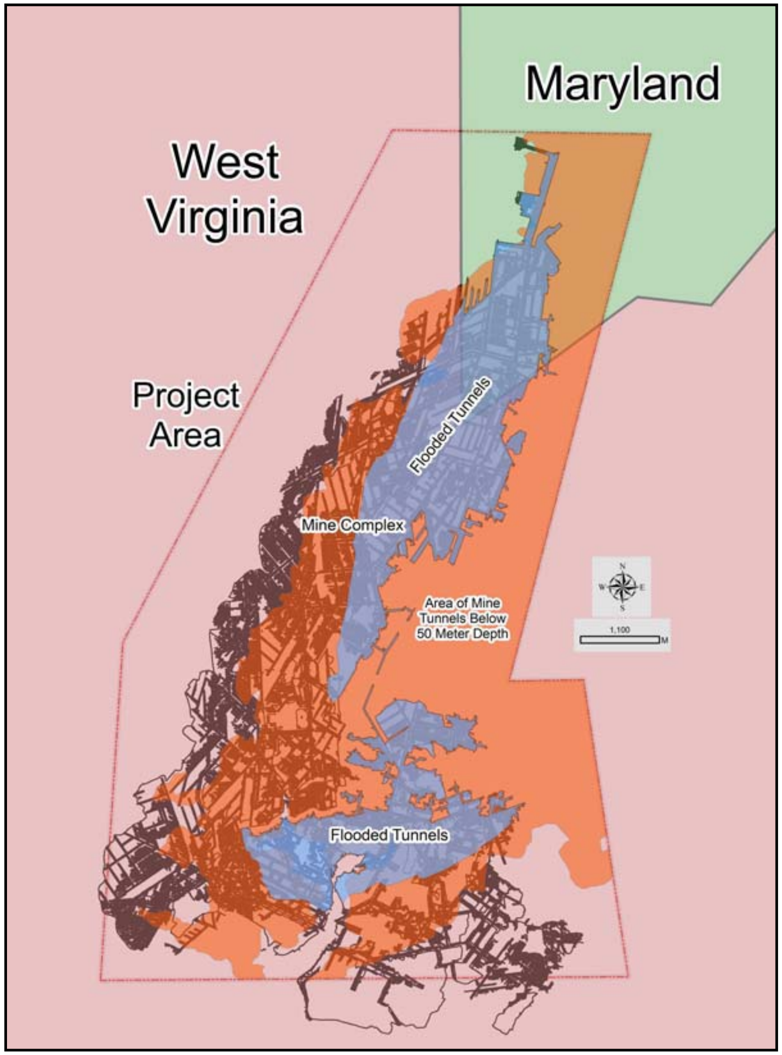

Figure 5. Area of Tunnels Below Exploration Depth.

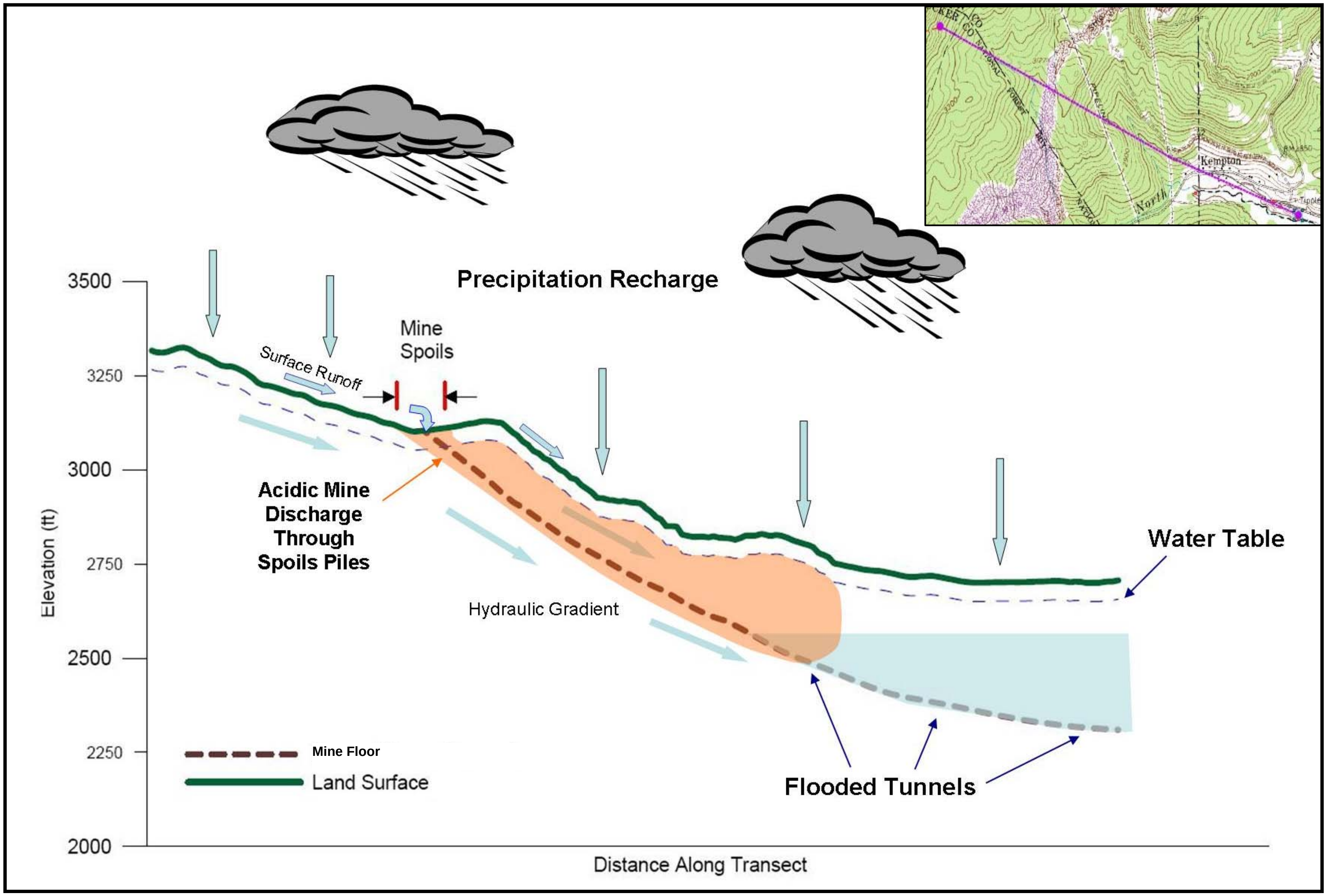

Figure 6. Conceptual Cross Section Through Spoils Piles.

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