Identifying and Sealing Water Loss Zones in the Anthracite Coal Region

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ABSTRACT

The following report is a collaborative effort between the U.S. Department of Energy, U.S. Geological Survey and the U.S. Army Corps of Engineers. Geophysical techniques were used to delineate both areas of stream flow loss through fractured bedrock to underlying mine workings and unsaturated mine voids near the surface. Electromagnetic techniques were successfully used to locate water zones and then target in-stream polyurethane grout injection as an attempt to seal fractures associated with subsidence and resulting in stream flow loss. Through USGS stream flow monitoring and post-grouting geophysical survey, it was found that grouting efforts were largely unsuccessful in sealing the stream and preventing stream loss. Further analysis of geologic conditions and mining techniques used revealed that subsidence features are diffuse and extended across as much as 150 feet for each coal seam under consideration. Because of this, a modified grouting technique based on shallow injection using several injection points has been developed. Trails have been proposed for this modified grouting technique.

BACKGROUND

The anthracite coal region of Pennsylvania suffers from severe environmental strain as a result of extensive mining of multiple seams of anthracite coal by deep as well as surface mining techniques. A 1000 foot reach of Nanticoke Creek in Luzerne County, Pennsylvania, near Wilkes-Barre Pennsylvania. The Nanticoke Creek Basin is a small 7.6 mi^2 sub-watershed of the larger Susquehanna River Watershed and is extensively littered with spoil and refuse piles from more than 100 years of un-reclaimed mining operations. Abandoned underground workings, many of which have openings that are not yet sealed, have flooded and in many locations collapsed. These subsurface collapses express themselves as surface subsidence features. A significant portion of runoff and surface water that passes over these collapsed and subsided areas infiltrates into the mine workings. In the mine, this infiltrated water, representing 40 percent of the total annual precipitation according to one study (Skelly & Loy, Inc., 1975), contacts pyritic material and becomes contaminated with acidity, iron, and sulfate. This contaminated water resurfaces down-gradient (not necessarily in the same sub-watershed) as acid mine drainage (AMD). (Babula and Cravotta, 2001)

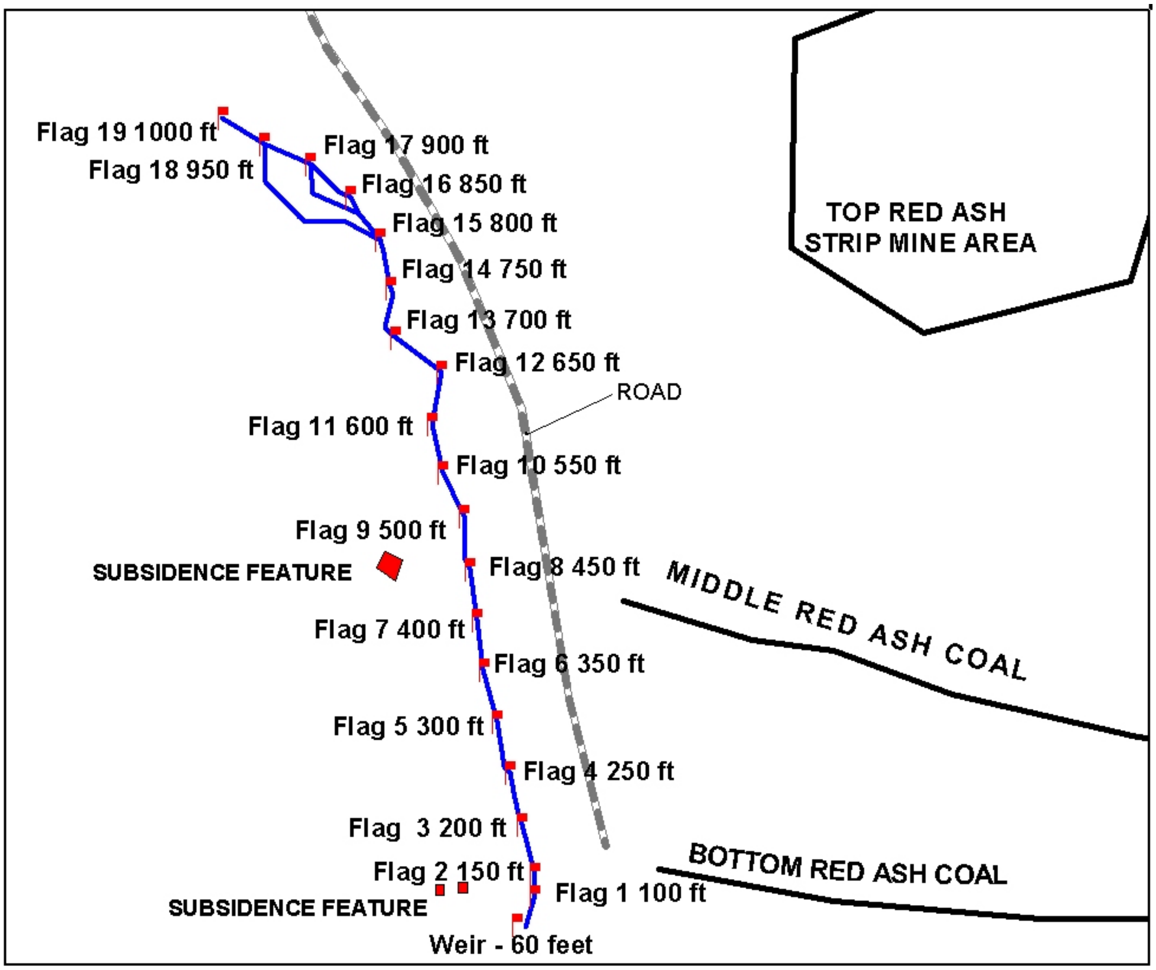

Figure 1. Map of stream segment under consideration, with coal outcrops, stream location flags, and mining related surface features labeled

To date, a number of remediation techniques have been considered, including treatment of AMD at the point of discharge, and preventative techniques such as stream channel lining, flume construction, flow piping, and fly ash injection.

The 1000-foot stream reach under study traverses at least three and possibly four coal seam outcrops. In the sedimentary bituminous coal fields of West Virginia and southwestern Pennsylvania, coal seams run, in general, parallel to the surface of the ground with convex and concave anticline and syncline features. In the metamorphic anthracite fields of northeastern Pennsylvania, coal seams often thrust upwards at angles of 35 to 45 degrees or more (from the earth's surface). A cross-sectional sketch representative of the geologic structure near the Nanticoke Creek study area was drawn at the time of active mining in the site. This illustration (see Figure #1) shows both the angle at which the coal seams dip, as well as the approximate slope of Nanticoke Creek, which flows over the three Red Ash coal seams.

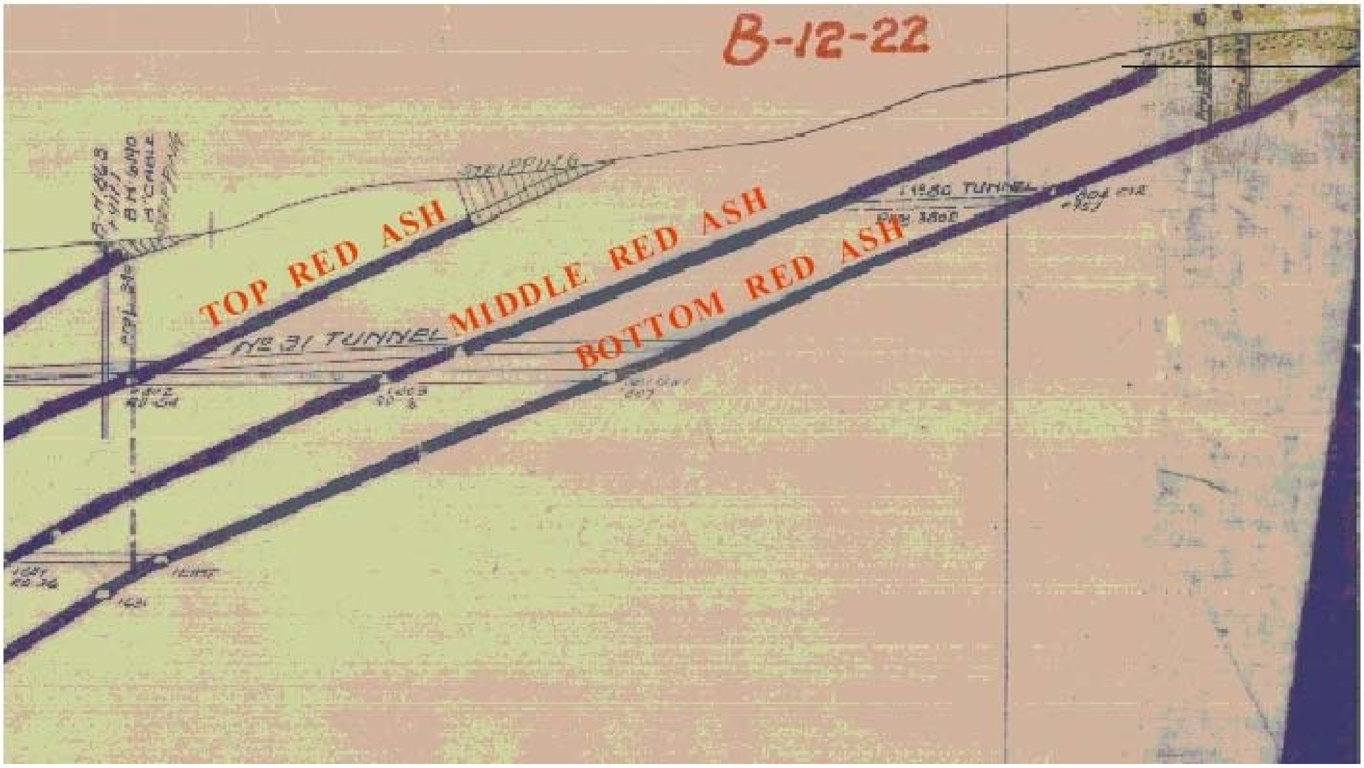

Figure 2. Representation of geologic cross section, showing coal seams and some mine workings near the Nanticoke Creek Study Area.

The upper portion of the 1000-foot stream section dips steeply with the stream bed comprised of large boulders and steeply dipping bedrock outcrops. Water flowed through this portion of the creek in a step/pool fashion. The lower portion of the stream has a more gradual slope, with the stream bed comprised of cobbles, gravel bed material, and aggregated chunks of mine spoil, having been fused together as a result of heating from a refuse pile fire. Along much of the stream reach, banks are steep with significant erosion and uprooted trees.

Preliminary observations and stream flow monitoring indicated that the stream was decreasing in flow across the 1000-foot section in question. During periods of low flow, total loss of stream flow to mining related infiltration could be observed at points 750 feet downstream from the top of the study area. (Babula and Cravotta, 2001)
As an alternative to more costly stream channel lining construction, stream sealing through targeted sub-surface chemical grouting was investigated along this stretch of Nanticoke Creek. The grouting effort was divided into three distinct tasks that included geophysical surveys of the stream and surrounding area, stream flow gauging, and sub-surface grouting.

In cooperation with the United States Army Corps of Engineers/Department of Energy National Energy Technology Laboratory geophysical investigation and grout injection trials, the United States Geological Survey conducted extensive stream flow monitoring of the Nanticoke Creek Headwaters before, during and after grout injection episodes, both above and below targeted stream-loss zones. These data were used to evaluate the effectiveness of selective grouting efforts to decrease infiltration and restore streamflow. (Babula and Cravotta, 2001)

EXPERIMENTAL APPARATUS AND PROCEDURES

Data Collection

Base-line data collected for the Nanticoke Creek site include stream flow, geophysical, mining and geographic data. These data were used to target and evaluate the success of chemical (polyurethane) grouting in the Nanticoke Creek as a means of containing stream flow within the surface channel.

Stream Flow Data

The United States Geologic Survey (USGS) regularly collects stream flow data at several gauging stations across the area of interest on Nanticoke Creek. This data is collected so that areas of stream-loss can be confirmed and quantified within the 1000-foot stream segment. If stream flow at a gauging station downstream is significantly lower than stream flow of an adjacent upstream gauging station, the stream segment between the two gauging stations is targeted as an area of flow loss. Gauging data was also used to determine the effectiveness of stream grouting efforts carried out at the study area by the Clean Water Team.

Flow measurements were conducted with a pygmy (vertical axis) current meter, and carried out at least once a week through the duration of the study. This is the appropriate method for measuring flow of small streams such as Nanticoke Creek. The pygmy meter can accurately measure flow in streams with water depths from 0.3 to 1.5 feet and velocities from 0.2 to 2.5 feet/second (Buchanan and Somers, 1969). At each station, USGS hydro-geologists established a cross section, and depth and velocity measurements were calculated at a minimum of ten points across the stream. These flow measurements were supplemented with timed volumetric measurements for cascading reaches with small discharges.

GEOPHYSICAL DATA

NETL collected three types of ground based geophysical data at the Nanticoke Creek site: shallow electromagnetics (EM), mid-depth EM, and very low frequency (VLF).

Electromagnetic Conductivity

Electromagnetic (EM) conductivity techniques have demonstrated utility for groundwater studies including: (1) groundwater exploration, (2) mapping industrial groundwater contamination, (3) mapping general groundwater quality (i.e., salinity) and saline intrusion, and (4) mapping soil salinity for agricultural purposes. The EM conductivity techniques were used to demonstrate thatnear-surface fracture systems and mine voids that contain water and air can be accurately located.

EM conductivity techniques use a transmitter coil to generate an electromagnetic field (primary field) with a frequency between 100 Hz and 100K Hz. This primary field propagates through the surrounding area until it encounters a conductive body in which it induces a flow of alternating current. This ground current, in turn, induces a second electromagnetic field (secondary field) which has a field strength that is proportional to the conductivity of the geoelectric structure. The secondary field also propagates through the surrounding area, and with the primary field, make up the complete electromagnetic field that is detected at the receiver coils of the EM conductivity instrument.

EM conductivity instruments measure apparent conductivity, which is expressed in millisiemens per meter (mS/m). The apparent conductivity is calculated as follows:

$$\sigma_a = (4/2\pi f F_0 s^2)\,(H_S/H_P)$$

where σ_a is the apparent ground conductivity, H_P is the primary electromagnetic field, H_S is the secondary electromagnetic field, **f** is current frequency, **s** is the distance between the transmitting and receiving coils, and F_0 is the permeability of free space[10]. The typical practice is to compare the H_S with a value H_P, the intensity of the primary field. Since the coil positions and the current in the transmitter coil are known, the value of H_P can be calculated. The apparent conductivity is a composite of true conductivities for each geo-electric layer that comprises the semi-infinite half-space below the ground surface.

Near Surface Ground EM Condcutivity (EM-31)

Using an EM-31 apparent conductivity device manufactured by Geonics, shallow EM data was collected along the length of the stream. By collecting data in the stream bed, it is possible to detect areas of relatively high conductivity associated with vertical water filled fractures and water filled subsidence related voids within the first 6 meters below surface (about 18 feet). EM-31 data are used to pinpoint areas of focus for grouting efforts to areas within the stream channel as small as one square meter.

Mid-Depth Ground EM Conductivity (EM-34)

A Geonics EM-34 conductivity instrument was used with a 20-m inter-coil separation for the survey of the ground adjacent to Nanticoke Creek site. The depth of penetration for this instrument is a function of the inter-coil separation, orientation of the transmitter and receiver coils, and conductivity of the geologic strata. The EM-34 can be operated with transmitter and receiver coils in either a coplanar or a coaxial geometry. The coplanar mode is more effective at detecting flat-lying conductive bodies whereas the coaxial mode is better for detecting vertical conductive features. Each mode gives a significantly different response (sensitivity) with depth. The effective exploration depths for the two modes are approximately 0.75 (coaxial) and 1.5 (coplanar) times the inter-coil spacing in a layered earth geometry. Therefore, the effective depth for the EM-34 with a 20-m inter-coil separation is about 15 m (about 50 ft.) for the coaxial mode and 30 m (about 100 ft.) for the coplanar mode.

EM-34 data collected adjacent to Nanticoke Creek show areas of low conductivity that correlate with mine openings and mapped coal outcrops to the surface. Because air is significantly less conductive than soil, rock or water, large air pockets in the subsurface present as a result of mining appear as regions of low apparent conductivity in mid-depth geophysical data.

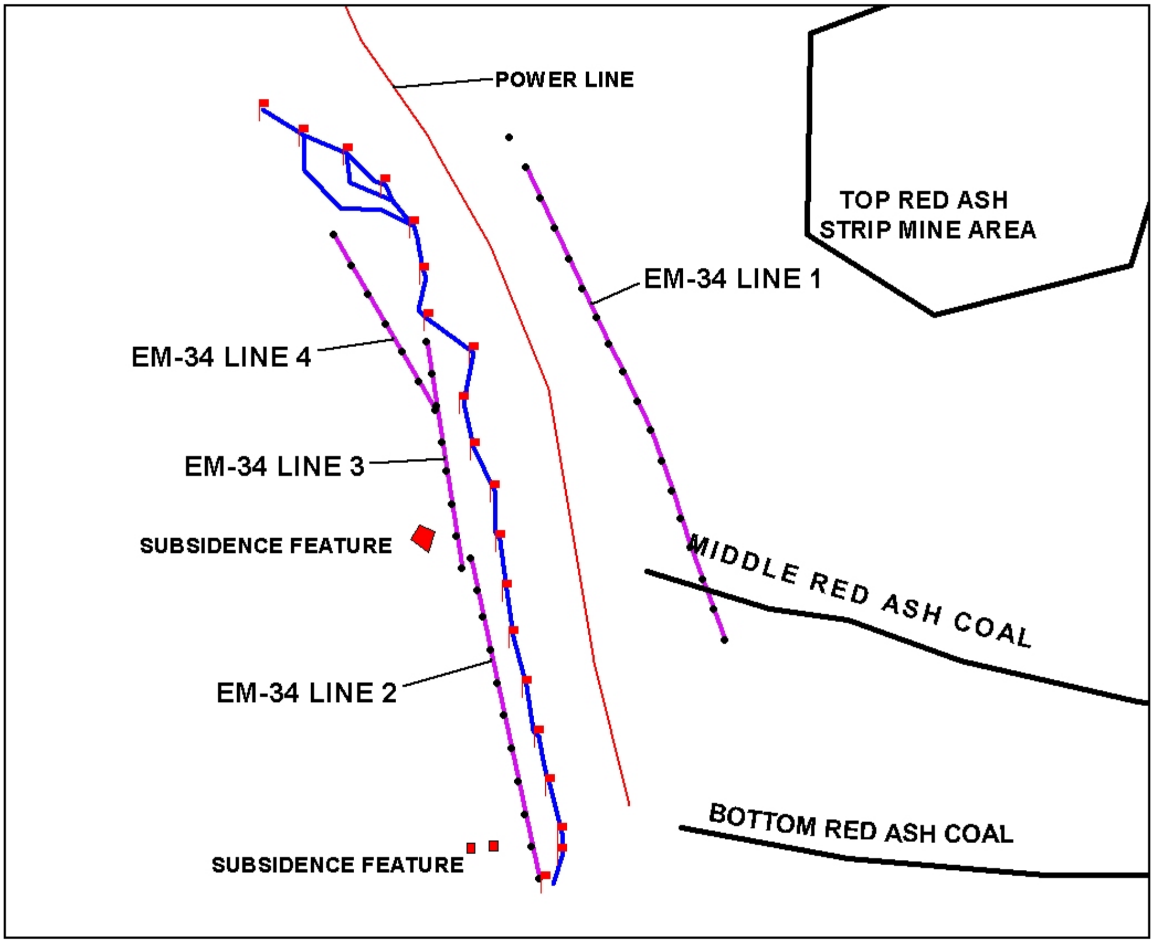

Figure 3. Location of EM-34 Survey Lines Adjacent to Nanticoke Creek

Geographic Data
Survey data was collected for the Nanticoke Creek study area in order to ensure spatial accuracy of collected data and observed relationships. In addition to a high accuracy land survey conducted by NETL employees, differential GPS data was collected to verify location of various points in X,Y, and Z real world coordinate space. Finally, previously acquired data from an aerial survey provided two foot contour data that was used to develop a high resolution digital elevation model for three dimensional visualization and evaluation of data

Site Characterization and GIS development
In order to investigate spatial relationships between data of various sources, data were collected and integrated in a geographic information system (GIS). Development of a GIS allows incorporation of aerial photography, mine maps, high accuracy GPS survey data, high resolution digital elevation model, stream flow, geophysical, and other data into a spatially related database. This allows spatially explicit evaluation of complicated systems and surface/subsurface interactions in three dimensions.

Grouting Efforts at the Nanticoke Creek Study Area

Previous investigation and experimentation by the NETL Clean Water Team have successfully employed a novel stream grouting technique to prevent flow loss from streams to underlying mines in areas of bituminous coal mining (Ackman and Jones,1988). The Nanticoke Creek study is the first attempt to apply this technique to remediate streams impacted by anthracite coal mining. In the current grouting process, holes were drilled using a pneumatic drill to a depth of four to six feet. Hollow rods fitted with expandable mechanical rubber packers are then inserted into the drilled holes. The rubber packer is designed to prevent material from flowing into the drill hole. A single component polyurethane grout was then pumped into the drilled holes under compression (up to 3000 psi) via the hollow rods. The polyurethane grout expands through the existing fracture or void to a volume as much as twenty times it's initial volume. Over a period of approximately five hours, the grout expands and solidifies - effectively sealing the fractures and voids that it occupies. Solidified grout has the following physical properties:

- Compressive strength - 25 pounds per square inch (psi)
- Shear strength - 17.1 psi
- Tensile strength - 29.3 psi
- Elongation capacity – 300 %

Finally, the new single component grout has been deemed environmentally safe and is approved for use by the U.S.D.A., NSF 61-198, and U.L.

Two grouting sessions were carried out at the Nanticoke Creek study area. Prior to grouting, baseline flow and geophysical data were collected to establish existing conditions and pinpoint areas of interest for grouting. Again after stream grouting flow measurements and geophysical data were collected along the stream to determine changes in subsurface hydrologic conditions resulting from grouting efforts. Based on evaluation of these new data, a second session of drilling and stream grouting was carried out to augment stream sealing from the first session. After this second grouting session, flow and geophysical data were again collected to determine success of grouting efforts. To date, grouting efforts at the Nanticoke Creek study area have met with little success. Effective site characterization and increased understanding of site hydrologic conditions and mining history have led to the development of a new strategy for stream grouting at the Nanticoke Creek study area. Maps of the locations of Phase I and II grout injection along the 1000-foot study area are shown in Figures 4 and 5, respectively

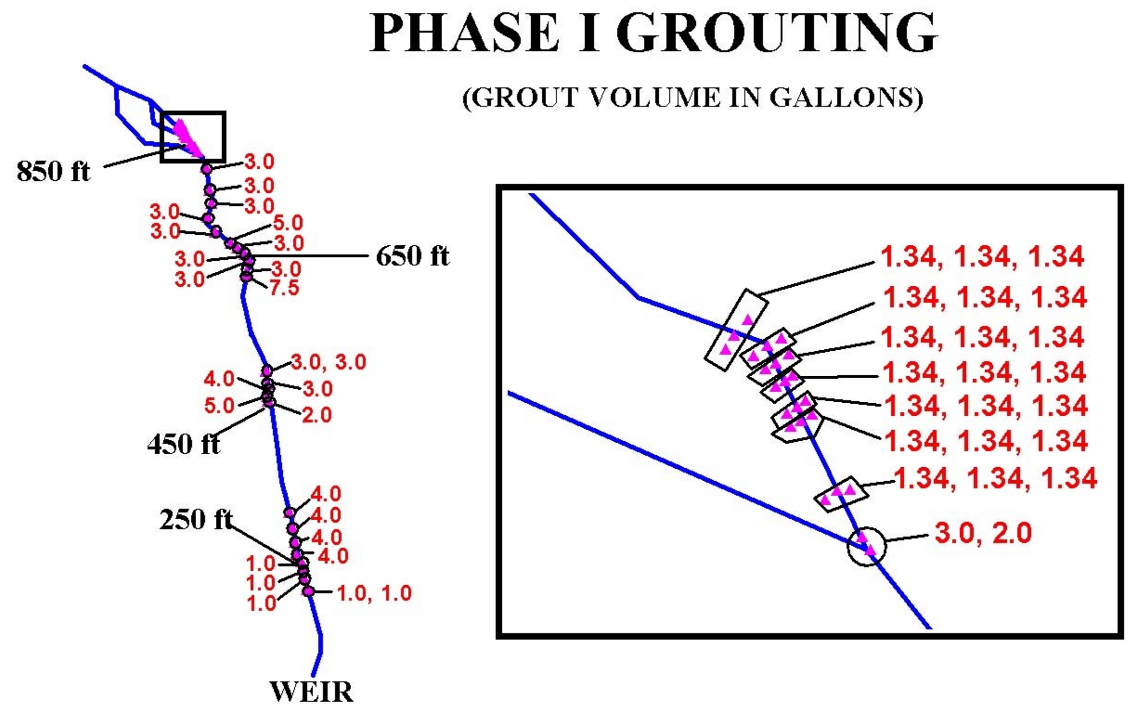

Figure 4. Phase I Grouting Locations and Unexpanded Polyurethane Grout Volumes Injected

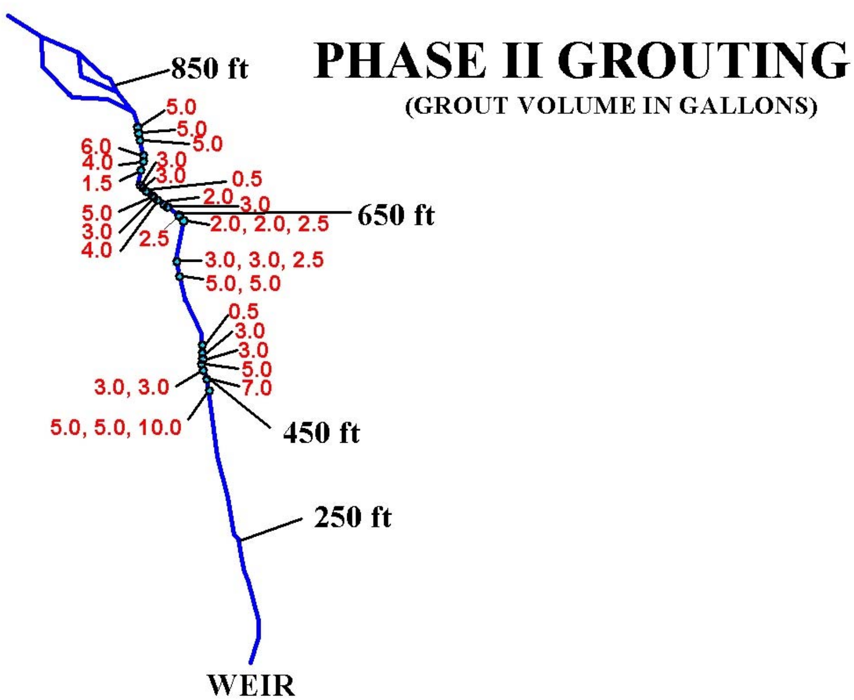

Figure 5. Phase II Grouting Locations and Unexpanded Polyurethane Grout Volumes Injected

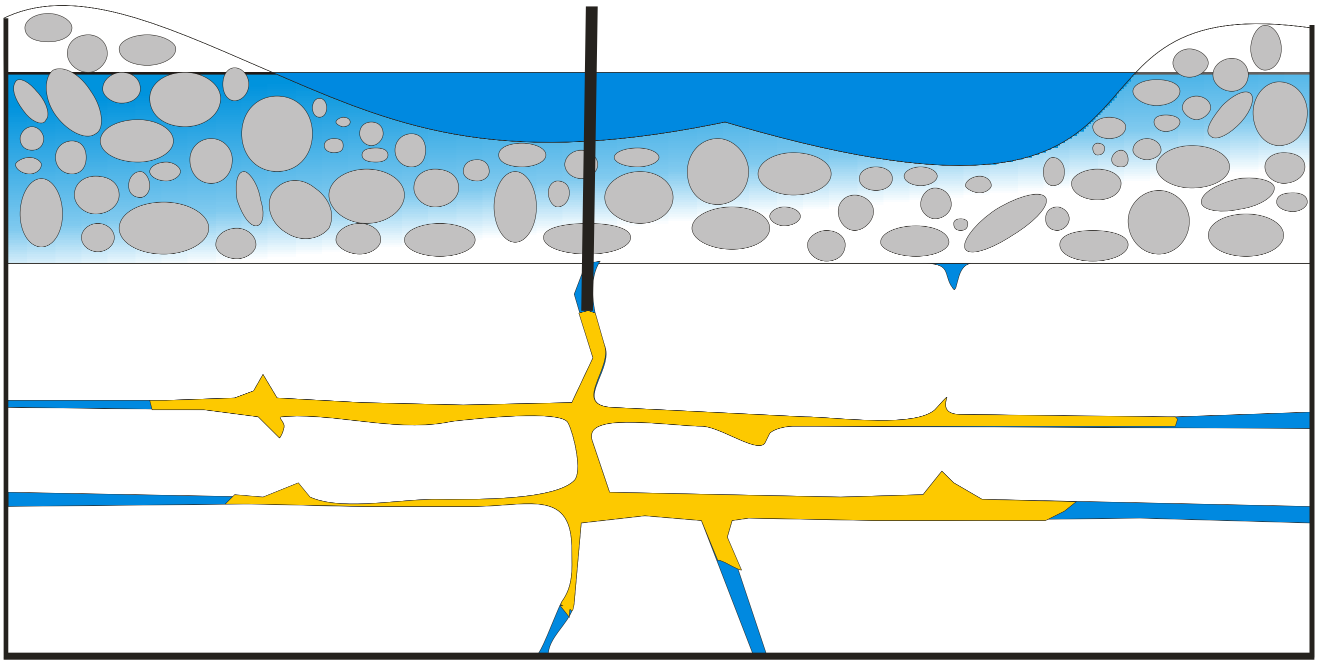

Figure 6. Illustration of grout rod and injection to seal mine subsidence relate overburden fractures

RESULTS AND DISCUSSION

In an attempt to more clearly delineate the location of the coal outcrop, the Nanticoke Creek study area was extensively categorized using a number of methods. First, the site was surveyed for apparent subsidence, mine openings, and other evidence of outcrop location in and around Nanticoke Creek. Locations of these features were logged using a high-resolution global positioning system apparatus. Secondly, historic mine maps were geographically registered and rectified using existing landmarks so that they could be integrated into the existing GIS database. These maps show locations of coal outcrops, much of which is not now detectible from observation with the naked eye. Finally, geophysical tools were used to identify anomalous electromagnetic conductivity responses in and adjacent to the creek. EM-31 data were collected along the stream channel. High EM-31 responses both in the horizontal and vertical dipole configuration corresponded well with adjacent subsidence features, mine openings, and with coal outcrop locations from historical maps. Elevated responses also correlated with stream reaches identified as stream loss zones. In-stream EM-31 data were collected before and after each grouting phase in an attempt observe changes in subsurface water flow resulting from grouting efforts. Results shown in Figures 7 and 8 suggest that grouting between 700 and 760 feet carried out during the second grouting session were successful in decreasing subsurface flow. In addition, it should be noted that decreased response in the horizontal dipole on the first data collection (5/9/01) near 900 feet result from lack of flow in the stream at this point. EM-34 data were collected beside the stream in an attempt to find mine workings (air voids) adjacent to the stream. It was found that the air voids associated with mined out areas have low conductive response (air is a poor conductor). Particularly in the deeper looking vertical dipole (effective depth of 30 m) these voids decrease conductive response to near zero (see Figure 9). Also, it should be noted that as elevation above the stream increases (from left to right on the plot), the EM-34 response in the vertical dipole decreases. This inverse relationship between elevation above conductive material and vertical dipole response is worth noting and could play a role in application where more subtle conductivity is being targeted.

CONCLUSIONS

Geophysical techniques have proven useful in delineating both areas of stream flow loss through fractured bedrock to underlying mine workings, as well as identifying unsaturated air voids near the surface. These techniques were used to target in-stream polyurethane grout injection in attempt to seal fractures associated with subsidence and resulting in stream flow loss. Through USGS stream flow monitoring and post-grouting geophysical survey, it was found that grouting efforts were largely unsuccessful in sealing the stream and preventing stream loss. Further analysis of geologic conditions and mining techniques used revealed that subsidence features are diffuse and extended across as much as 150 feet for each coal seam under consideration. Because of this, a modified grouting technique based on shallow injection using several injection points has been developed. Trails have been proposed for this modified grouting technique.

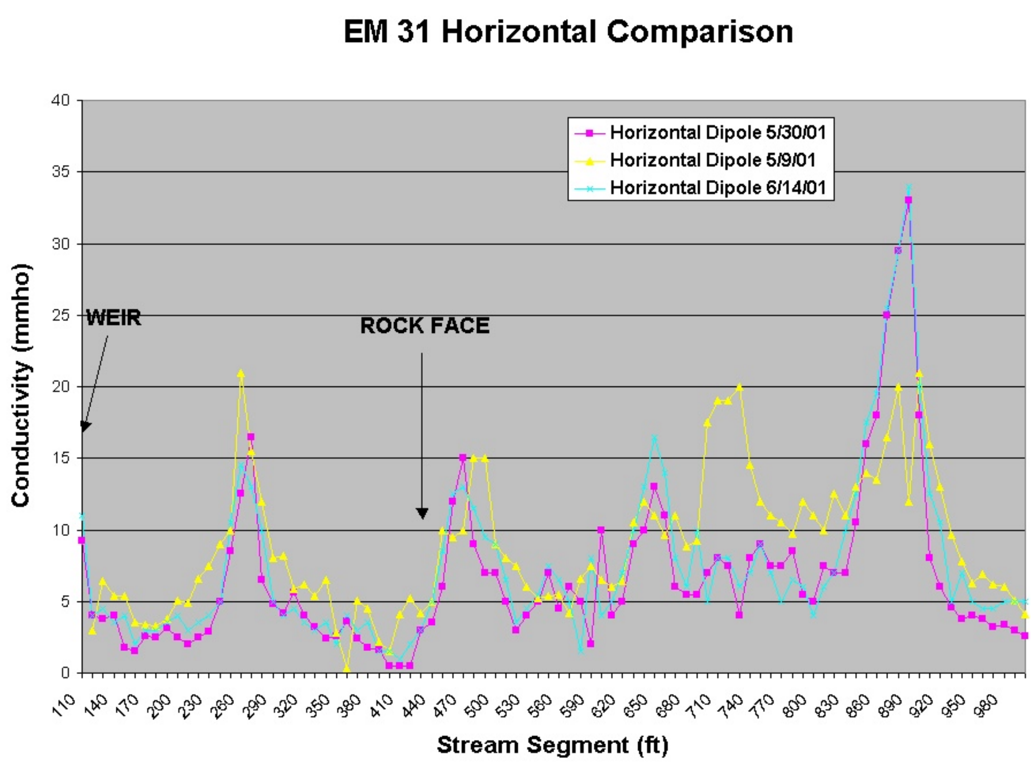

Figure 7. EM-31 horizontal dipole electromagnetic conductivity response measurements along Nanticoke Creek Stream Channel before grouting, after grouting Phase I, and after Grouting Phase II

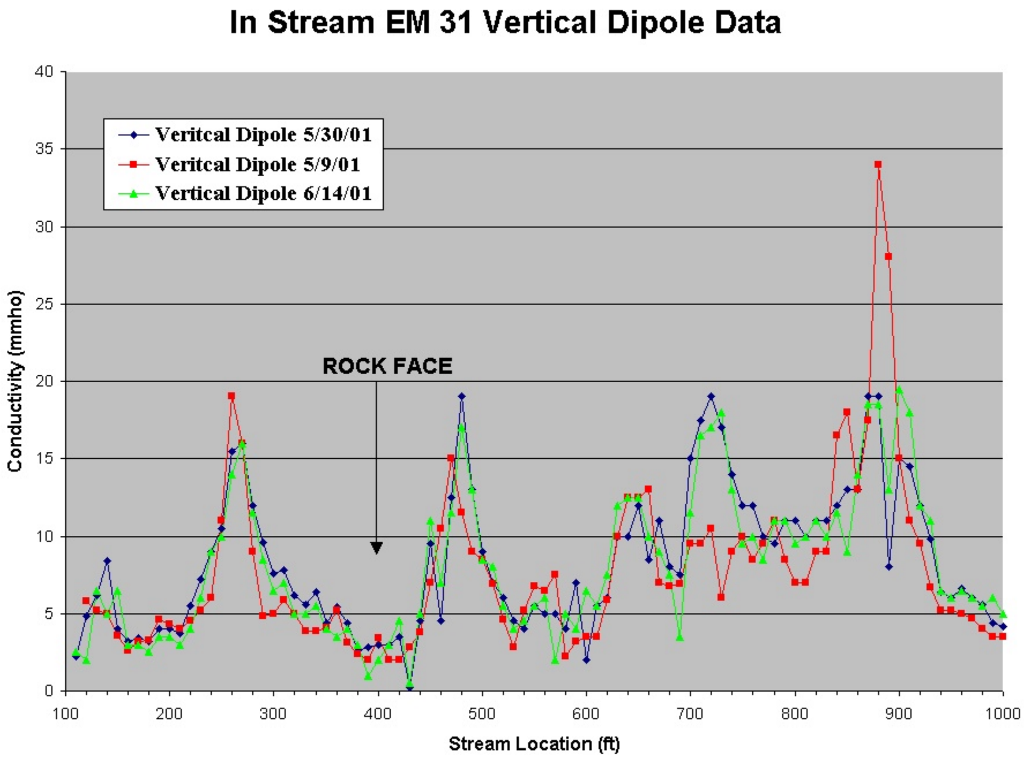

Figure 7. EM-31 vertical dipole electromagnetic conductivity response measurements along Nanticoke Creek Stream Channel before grouting, after grouting Phase I, and after Grouting Phase II

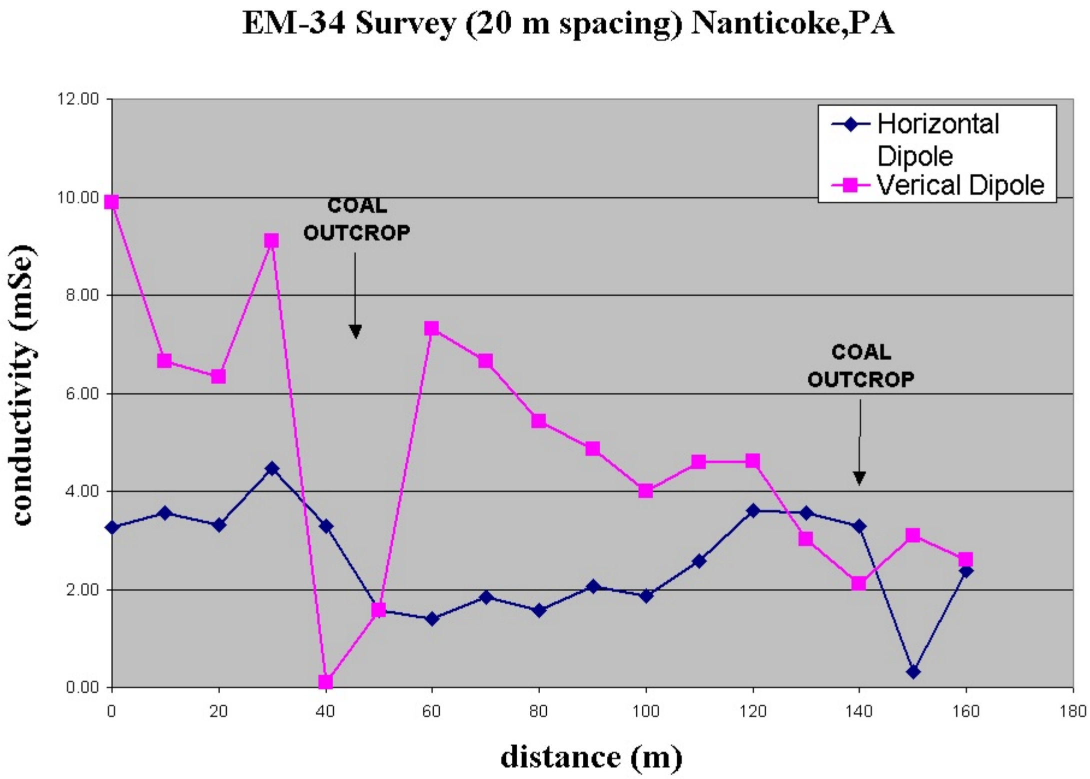

Figure 8. EM-34 Survey Line 1 adjacent to Nanticoke Creek study area – vertical and horizontal dipole response.

RECOMMENDATIONS

Based on NETL Clean Water Team experience to date at the Nanticoke Creek study area, and acquired knowledge of specific mining techniques, application of a modified grouting method is being recommended. Initial grouting efforts were aimed at drilling into fractures in the existing bedrock at specific sites and filling those fractures that served as conduits for flow from the stream to the mine. These holes were usually four to six feet deep and designed to plug specific fractures that caused most of the stream loss. It has been determined that, as a result of mining techniques specific to the mining anthracite in this region, that stream loss is occurring not at specific fracture locations, but over a stretch of several meters. Anthracite was often mined to within about 60 – 100 feet of the surface in areas with overlying streams. Over time, this shallow coal barrier, as well as adjacent areas of shallow overburden, begin to collapse into the mine below (see Figure 9). This results in the collapse of large and small blocks of material into the subsiding area. This area of broken material of various sizes has significant void space, and results in the loss of significant amounts of water to the mine void below (see Figure 10). The stream loss occurs not at specific locations, but over a span of as much as 150 feet. Therefore, the proposed modified grouting technique involves injection of grout into a large matrix or grid of shallow (approximately 2 feet) drill holes over the length of subsidence and unconsolidated stream base. This will effectively create an impervious liner below the stream that will allow water to pass over the subsided area (see Figure 11). This grout lining system will also be flexible such that it can maintain its integrity through shifting and settling of underlying unconsolidated material.

In support of evaluation of this modified stream grouting technique, further data collection will need to be carried out, including continued flow monitoring and geophysical data collection. These data will help to quantify the success of this new technique.

Consideration is also being given to development of a program in cooperation with the US Army Corps of Engineers to compare the technical and cost effectiveness of this stream grouting technique with other conventional stream lining techniques, such as clay lining, flume construction, piping, or fly ash grouting. Because the Nanticoke Creek study area has three stream segments where stream loss is occurring as a result of mining, it would provide a unique opportunity to compare these methods side by side.

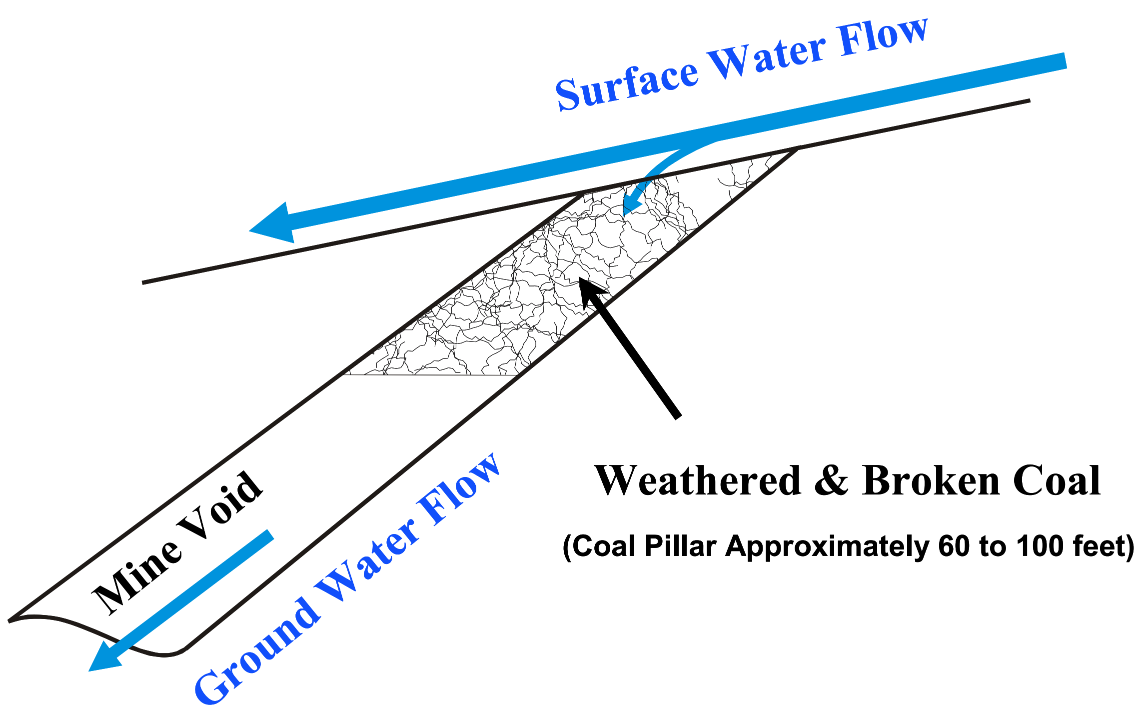

Figure 9. Fractured coal barrier below Nanticoke Creek responsible for stream loss to underlying mine. With time this fractured pillar and the adjacent overburden begin to subside.

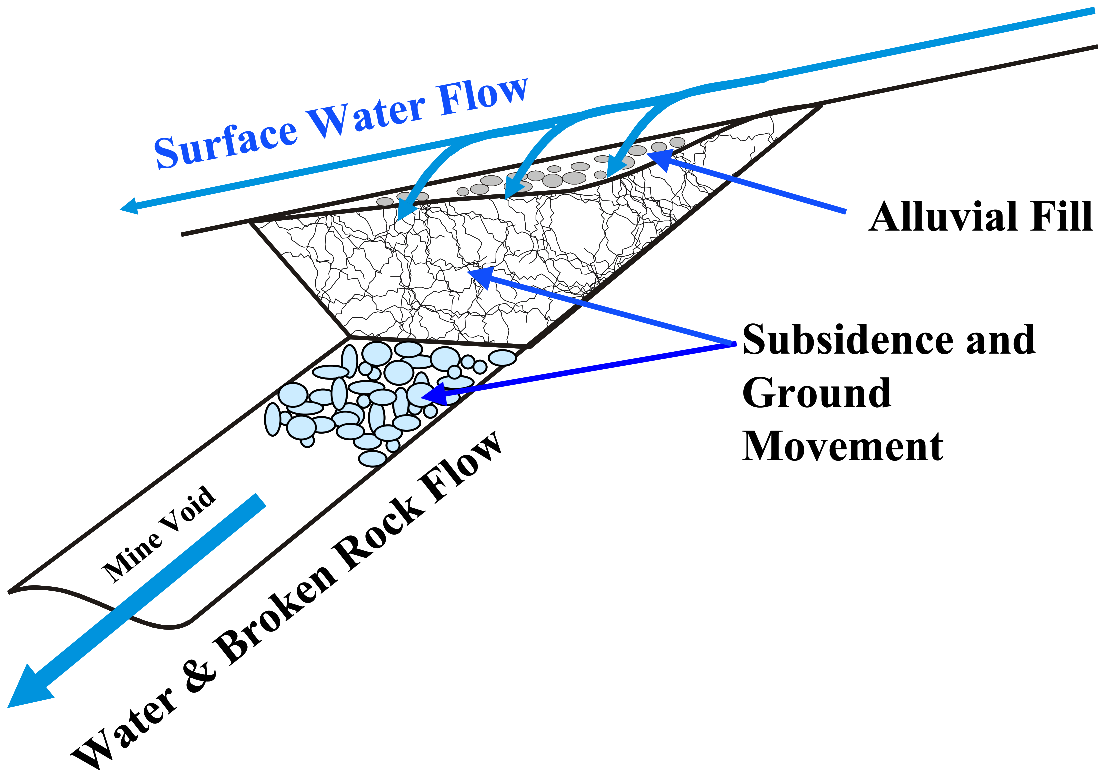

Figure 10. Collapse of fractured coal barrier and adjacent areas of shallow overburden result in increased stream loss over a larger stream segment.

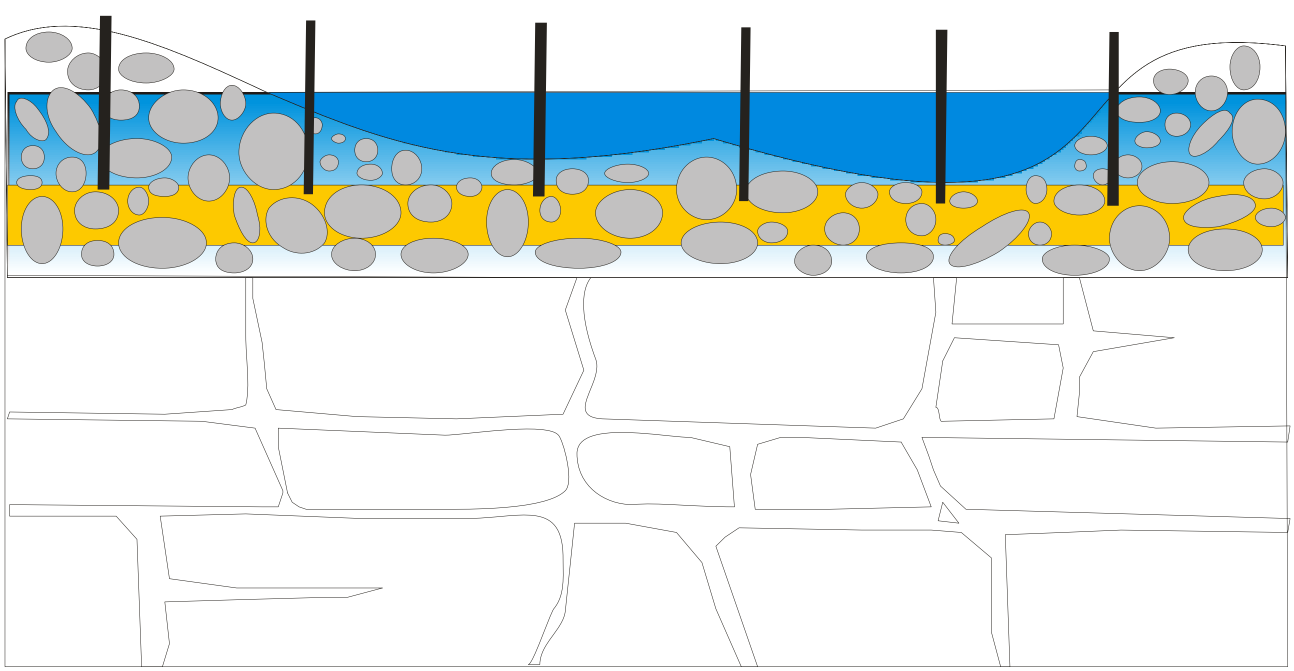

Figure 11. Proposed modification to grouting technique involves shallow Injection of grout at multiple locations to produce a waterproof "blanket" in the sub-stream alluvium.

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