STREAM SEALING TO REDUCE SURFACE WATER INFILTRATION INTO UNDERGROUND MINES[1]

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Abstract.--As part of the Bureau of Mines environmental research, a novel approach to identify and seal surface infiltration zones was tested at a stream, near Frostburg, MD, that partially overlies abandoned coal mine workings. Ground electromagnetic conductivity surveys were performed within a stream channel to identify water-saturated zones at relatively shallow depths of 25 and 50 ft (7.5 and 15 m). Zones of increased conductivity were found to be positively associated with areas exhibiting significant loss of flow. Conversely, zones which exhibited declining conductivity values delineated areas where there were no significant flow losses. Using this information, an experimental grouting procedure was used to place an expandable polyurethane several feet (less than a meter) beneath the streambed over 70 ft (23 m) of the stream channel. Before grouting, the section exhibited a 25 pct loss (800 down to 600 gal/min); post-grouting gaging demonstrated a net gain. The conductivity surveys represent a significant cost savings in gaging work necessary for delineating stream loss zones. Also, the cost of grouting was over 50 pct less than the costs associated with conventional rechannelization and clay-lining and rip-rapping techniques.

INTRODUCTION

Underground mining operations frequently induce streamflow losses, which generally infiltrate into underground workings and oftentimes become a source of perpetual water pollution (Hobba 1981, Hollyday and McKenzie 1973, Williams et al. 1986). Streams are considered to be the largest contributor to the overall volume of underground acid mine drainage (AMD), but no quantitative work has ever been performed to test this assumption (U.S. Environmental Protection Agency 1979). In addition to ground water and surface water pollution, large water influxes into the mine can represent hazards to mine workers, hydrostatic heads can "blow out" the outcrop barrier pillars causing subsidence, and overflows can induce surface landslides.

Partial to total streamflow losses can occur, and multiple infiltration zones (both natural and induced) usually exist in a stream channel. Frequently, stream losses are not readily apparent at the surface. It is also difficult to pinpoint infiltration zones from underground mines (assuming accessibility) since waterflow paths may deviate considerable distances through bedrock fracture systems. Although the gob or large caved areas are accessible through the bleeder entries, only limited visual observations are usually possible.

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Surface rechanneling and stream channel liners, such as wooden canals and clay and rock rip-rapping, have been constructed to reduce stream water loss. By reducing the volume of water that enters underground mines from the surface, the volume of water discharged and treated (if contaminated) at the mine site should be considerably reduced. The cost however, of lining entire streams or sections of streams that overlie the underground workings is high. The costs for preventing infiltration can range between $40 and $80 per linear foot for relatively small streams (e.g., 5,000 to 10,000 gal/min (315 to 631 L/s) flows). Significant efforts to reduce stream seepage have been put forth, using the above mentioned techniques, in the anthracite regions of Pennsylvania (Ash and Whaite 1953). However, only limited success had been obtained by these techniques. The long-term effectiveness of such liners is questionable during times of drought or intermittent flow since vegetation, burrowing animals, and insects can affect the integrity of the artificial channel bottoms. The U.S. Bureau of Mines has, in cooperation with other Federal and State agencies as well as with private industry, instituted a research program to identify those sections along a stream channel that appear to be high subsurface infiltration zones. By predetermining these high loss zones, the total length of stream channel that must be lined can be considerably reduced. Therefore, the grouting costs for reducing infiltration are targeted to those particular stream sections which have been identified as zones of infiltration. This paper reports on the methodology used to identify zones of subsurface infiltration, and the experimental results of sealing Staub Run, located near Frostburg, MD, with a polyurethane grout.

ENVIRONMENTAL SETTING

Staub Run is located in northwestern Maryland approximately 5 mi (8 km) south of Frostburg, MD (fig. 1). The section of Staub Run under study is approximately 0.6 mi (0.9 km) in length. Staub Run is considered a natural gaining stream since the stream does flow perennially to the point at which it traverses the old abandoned mined-out coal seam, which also outcrops in the stream channel. Intermittent flow is observed during the summer, within the stream channel section which overlies the abandoned workings, and drains into Georges Creek. Staub Run and Georges Creek are part of the Potomac River Watershed. Annual rainfall is about 41 in (105 cm). Staub Run lies within the Appalachian Plateau Physiographic Province. The area is part of the Georges Creek Basin syncline, the northern extension of the Potomac Basin.

A number of Pennsylvanian-aged coal-bearing strata underlie the area. The coal units extend downward from the Barton Coal within the middle Conemaugh Formation to the top of the Mount Savage Coal which marks the base of the Allegheny Formation (Toenges 1949, O'Hara 1900). The generalized thickness of these coal-bearing strata is some 775 ft (235 m).

The Pittsburgh Coal seam crops out in the upper portion of Staub Run. The outcrop is arcuate along the stream channel, such that the outcrop extends upslope along both sides of the mountain valley after surface exposure within the stream channel. The middle to lower portion of this small mountain stream overlies an abandoned turn-of-the-century coal mine (Carlos Mine). The depth of overburden for the 3,000-ft-(914-m-) long test site

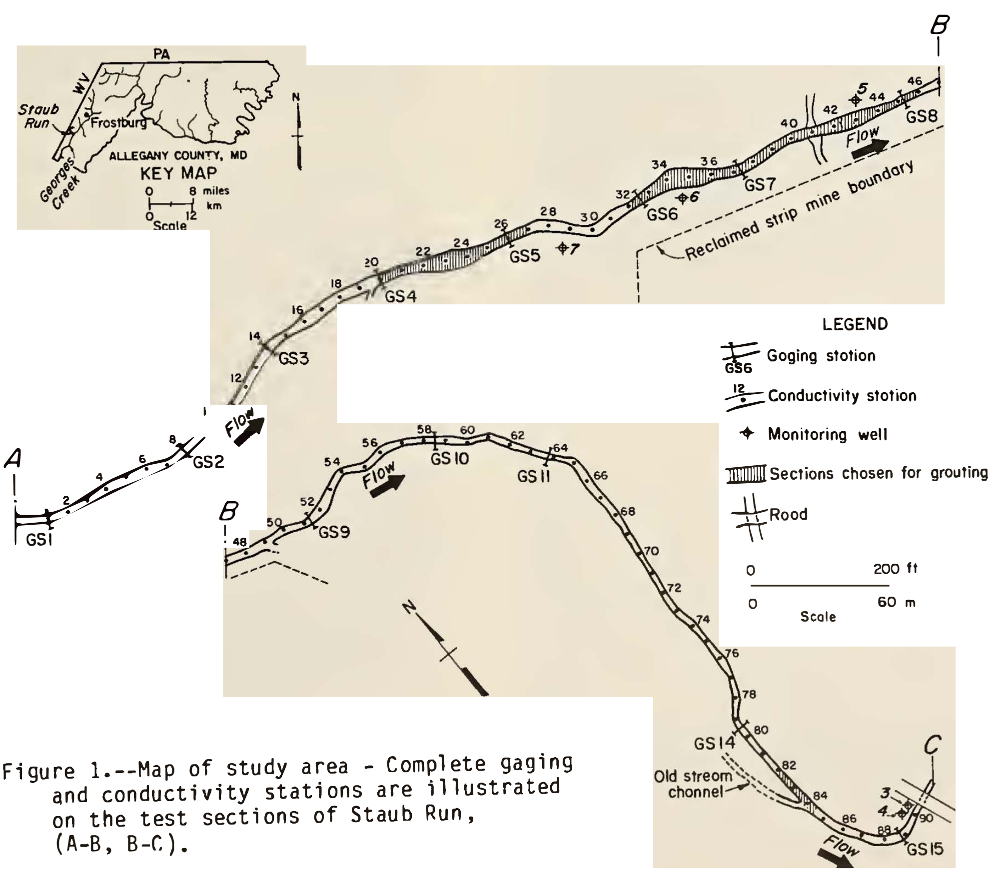

Figure 1.--Map of study area - Complete gaging and conductivity stations are illustrated on the test sections of Staub Run, (A-B, B-C).

ranges between 0 and 63 ft (19 m). Stripping activity (pillar recovery work) has taken place on both sides of Staub Run. In one portion of Staub Run, stripping operations have mined through the stream, thus necessitating re-routing of the flow which re-enters the natural stream channel approximately 1,000 ft (305 m) down gradient (fig. 1). The channel bottom can best be described as alluvial material; the sediments are sands, clays, pebbles, and various cobble-sized boulders. The thickness of this alluvial material, based on former and current drilling records, averages some 12 ft (4 m) at the study site.

METHODOLOGY

Streamflow Gaging

Fifteen stream gaging stations spaced at approximately 200-ft (60-m) intervals were established along Staub Run (fig. 1). Stream gaging began on October 23, 1986, and continued through September 17, 1987. Discharge was measured using a portable flow meter equipped with an electromagnetic sensor, following standard procedures established by the U.S. Geological Survey for determining the velocity/area of the stream. Measurements were taken at about 5-day intervals.

Gaging efforts focused on establishing a flow profile for the study area. The initial profiling efforts included routine flow monitoring of gaging stations 1, 5, 8, 14, and 15 (fig. 1). Stations 1 and 5 served as the control stations (outside the influences of mining operations) while station 15 represented the last gaging station in the study area. It became apparent from gaging data, collected during the first full dry season, that significant loss zones existed in upper portions of the study site. This gaging data targeted the zone(s) for future grouting. Thus, gaging efforts were expanded, beginning in March 1987, to focus upon the upper study site by routinely monitoring gaging stations 1, 5, 6, 7, and 8 (fig. 1), as well as stations 14 and 15 (fig. 2). A series of one-tailed t-tests were computed to test if the downstream station discharge was significantly greater ($p \leq 0.05$) than the corresponding upstream station discharge.

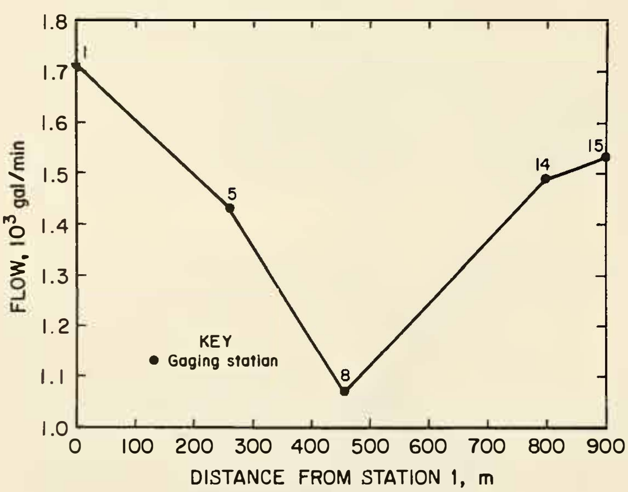

Figure 2.--Mean annual discharge at Staub Run.

Electromagnetic Ground Conductivity Surveys

Electromagnetic ground conductivity surveys were used in a novel attempt to identify stream loss zones by delineating the presence of water-saturated zones directly beneath the stream channel. The equipment consisted of a transmitter, transmitter coil (wire loop), receiver, receiver coil, and connecting cable. A two-person crew is required for using this entirely portable equipment. One person carries the transmitter and transmitter coil and the other person carries the receiver and receiver coil. Readings were taken at a fixed distance of 33 ft (10 m) between transmitter and receiver coils; however, fixed distances of 66 ft (20 m) and 132 ft (40 m) are also available for greater depths of penetration with this equipment.

The surface transmitter induces a current in the subsurface material with this electromagnetic induction technique. An alternating magnetic field is produced from the alternating current generated from the transmitter coil. The magnetic field induces current flow through the substrate as it penetrates the ground surface. The receiver coil senses a secondary magnetic field which is generated by the induced currents. The secondary magnetic field sensed at the coil is a function of: the strength of the primary field; current frequency, distance between transmitting and receiving coils, and ground conductivity. The ground conductivity is the only unknown variable since the primary field, frequency, and coil separation can be controlled. The receiver, which senses the secondary magnetic field, internally converts the signal to terrain conductivity and digitally displays signal in millimhos/meter (mmhos/m). The reader is referred to standard geophysical texts for detailed derivations (McNeill 1980, Grant and West 1965, Keller and Frischknecht 1966, Ladwig 1982) since the mathematical theory behind the induction technique is beyond the scope of this paper.

Theoretically, the magnitude of the ground conductivity should increase when saturated conditions exist. Consequently, the water loss zones should be zones of high conductivity. Thus, the conductivity data and gaging data should have an inverse relationship.

Two series of conductivity measurements were taken within the stream channel between the 15 gaging stations at 33-ft (10-m) spacings. One series of measurements was taken during the wet season and the other during the dry season (figs. 3 and 4). A Geonics EM-34 electromagnetic ground conductivity meter was used to obtain measurements at about 25- and 50-ft (7.5- and 15-m) depths. The observation depth is changed by changing the orientation of the instrument. Several portions of Staub Run, between conductivity stations 2 and 5 and between stations 64 and 69, may have registered erroneous readings with the conductivity instrument due to metallic interference (steel pipes, old appliances, and metal debris).

A statistical comparison between the conductivity and gaging data was performed. The conductivity data from the wet and dry seasons were combined to generate an annual mean conductivity (fig. 5). This was done by taking the difference

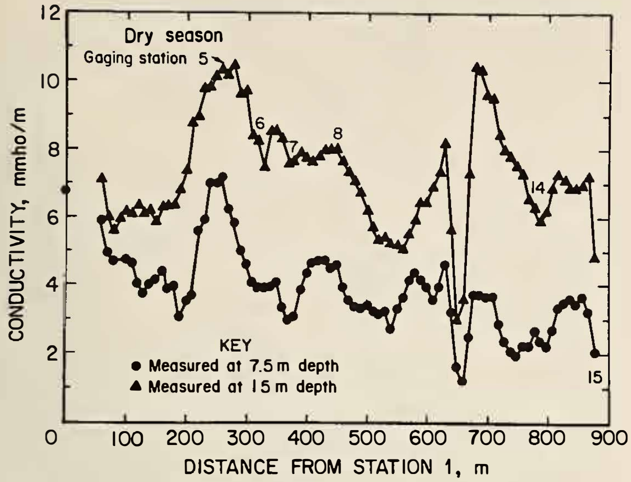

Figure 3.--Conductivity survey (dry season) at Staub Run.

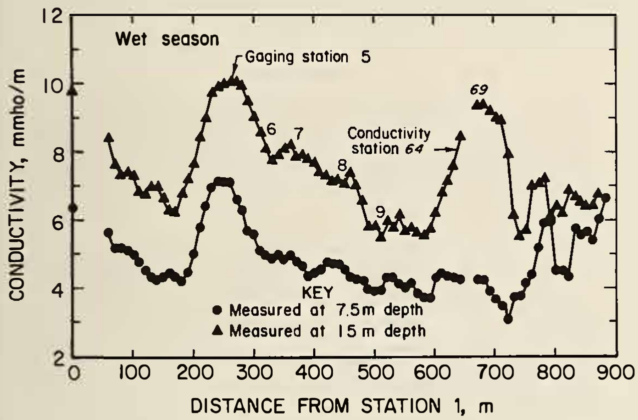

Figure 4.--Conductivity survey (wet season) at Staub Run.

between the two observation depths as a means of normalizing the data. The differences between the vertical and horizontal readings for each station of both series were then added together and divided by 2 to obtain a mean conductivity.

$$\text{Mean Conductivity} = ((V - H)_{\text{WET}} + (V - H)_{\text{DRY}})/2$$

Since the number of stations where conductivity measurements were recorded exceeded those where stream gaging occurred (figs. 1 and 2), comparison between the two data sets was accomplished by using polynomials to predict the statistically best-fit equation for the respective data. In this way the conductivity measurements and the gaging records were each treated as separate mathematical curves. Once a polynomial curve is fit to the respective data, a predicted trend pattern emerges between the two measures whose station to station relationships can be further tested. The mathematics and examples of polynomial curve fitting applications in the earth sciences are numerous (Doornkamp and King 1971, Jones and Cameron 1977, and Fisher et al (in press)).

Corresponding measurements were most complete between gaging stations 1 through 8 and conductivity stations 1 through 45, so these data were used to generate the respective polynomial equations. Furthermore, the mean station gaging discharge (October 23, 1986 to September 17, 1987) and the mean station conductivity measurement (wet season, dry season) are considered representative of the seasonal trends so the respective averages are used as the dependent variables with the conductivity station locations serving as the independent variables. After determination of the best-fit equation for the respective data, predictive values are generated for the station measurements and then compared with Spearman's Rank Order correlation analysis.

Grouting Procedure

Experimental grouting was conducted between gaging stations 14 and 15 (fig. 1). Grout rods 3 ft (1 m) in length were used for injection of the polyurethane material into the alluvial stream sediments. The rods were 3/4-in (1.9-cm) diameter steel pipes with hardened steel points with 1/8-in (0.3-cm) holes drilled through the sidewalls near the lower portion of the rod. The top of the threaded rods incorporated a hardened steel cap which would withstand blows from a sledge hammer and could also be used for mechanical injection of the polyurethane grout. The rods were manually driven into the stream sediments with a sledge hammer to a uniform depth of 2 ft (0.66 m) beneath the stream channel and placed at 10-ft (3-m) centers.

A measure of 5 gal (19 L) or 44.5 lbs (20.2 kg) of a two-component polyurethane grout, 2.5 gal (9.5 L) of each component, was injected into each grout rod. Injection pressures ranged from 400 to 1,200 lb/in^2 (28 to 84 kg/cm^2) with the in situ conditions of alluvial material dictating the pressure. The pump which was used was capable of 2,000 lb/in^2 psi (141 kg/cm^2). Grout was injected at a maximum pressure obtainable until a surface leak developed. After the leak occurred, the injection pressure was reduced to 50 lb/in^2 (3 kg/cm^2) until the leak sealed itself. The pressure was then increased slowly until another leak occurred or the 5 gal (19 L) of material was depleted.

RESULTS

Gaging and Conductivity

In most natural streams there should be a downstream increase in the volume of discharge. To test if the between- station volumes along Staub Run followed this natural pattern, a series of one-tailed t-tests was computed for the contiguous gaging stations 1 to 5, 5 to 6, 6 to 7, 7 to 8, and 5 to 8 (table 1). The one-tailed t-test not only determines if a significant difference ($p \leq 0.05$) exists in discharge measurements between the respective gaging stations, but is directional in that one can test if the discharge at one gaging station is significantly greater than that of another gaging station.

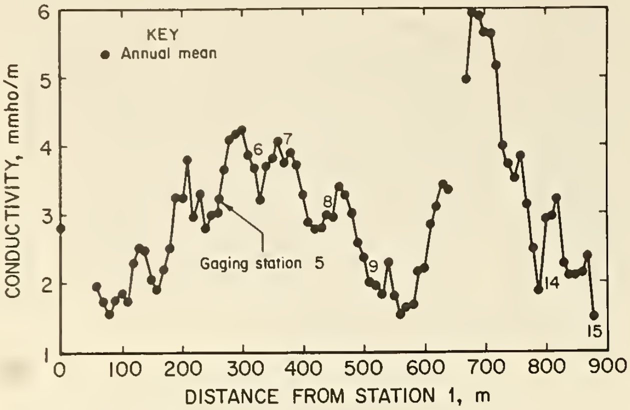

Figure 5.--Mean annual conductivity Staub Run.

Since flow rates should increase in a downstream direction, the test was formulated such that the contiguous downstream station discharge should be significantly greater than the corresponding upstream station discharge. If it can be demonstrated that the reverse is statistically significant, i.e., the upstream station has larger discharges, then it is assumed that the stream segment between the two gaging stations is experiencing a flow loss and thus represents a zone of significant subsurface infiltration. For the t-tests between the two contiguous stations, discharge data are only used when measurements were recorded on the same day at the two stations (table 1).

The results of the t-tests are interpreted to show that significant downstream losses occur between stations 1 and 5, and stations 6 and 7. Significantly greater upstream discharges were not identified between stations 5 and 6 and stations 7 and 8 (table 1). Following the original hypothesis, the stream segments located between stations 1 and 5 and stations 6 and 7 represent zones of statistically significant subsurface infiltration. Although the downstream flow rates are apparently less than the corresponding upstream flow rates between stations 5 and 6 and stations 7 and 8 (table 1), the differences are not statistically significant ($p \leq 0.05$). To further test an overall flow loss pattern, a one-tailed t-test was also computed between stations 5 and 8, again using only those gaging measurements when recorded on the same day at the respective stations (table 1). The t-test results illustrate a significantly ($p \leq 0.05$) higher flow at station 5 as compared to the flow at station 8 (fig. 2). This appears to confirm that infiltration zones are occurring downstream between station 5 and station 8 along this portion of Staub Run.

As noted in table 1, there is a significant discharge loss occurring between gaging stations 1 and 5 (fig. 2). The local bedrock and structural geology indicate that coal could not have been extracted from beneath this area. Examination of stereo paired aerial photographs (1:1000, 1983 series) appears to show the presence of a linear, crossing the stream in the vicinity of gaging station 5. The area of the apparent linear has, however, been significantly altered by man through surface mining, timbering, and the construction of residential and other types of structures so it is difficult to confirm its existence. Field reconnaissance of the area was also unable to follow a continuous linear trace.

The preliminary analysis of the gaging data and conductivity surveys does show a significant loss zone in this area so additional analysis of the aerial photographs for confirmation of the linear is presently being made.

The discharge measurements are best defined by a second-degree equation. The multiple coefficient of correlation (R^2) for the second-degree equation is 0.94. The predicted discharge values by station are presented in table 2 with the predicted curve trend illustrated in figure 6.

The mean conductivity measures are best defined by a sixth-degree equation. The multiple coefficient of correlation (R^2) for the sixth-degree equation is 0.71. The predicted conductivity measurements by station are presented in table 2 with the predicted curve trend illustrated in figure 6.

Comparison of the predicted curve trends between the discharge and conductivity measurements appear to show a negative relationship (fig. 6), i.e., a station increase in conductivity appears to correspond to a decrease in station discharge. To test if this apparent trend is significant, the non-parametric Spearman's Rank Order Correlation was computed (Doornkamp and King 1971).

Table 1.--Paired t-tests for gaging data.

Statistical pairs (gaging stations)	Average flow, gal/m	Maximum flow, gal/m	Minimum flow, gal/m	Sum of flows, gal/m	Number of gaging events	Statistically significant
1	1,060	4,353	6	45,589	43	Yes
5	923	3,629	5	39,687		
5	424	1,695	5	5,939	14	No
6	409	1,384	8	5,720		
6	394	327	35	5,905	15	Yes
7	327	1,114	21	4,905		
7	471	1,114	35	4,713	10	No
8	462	1,249	1	4,616		
5	946	3,629	64	34,986	37	Yes
8	696	2,506	1	25,763		

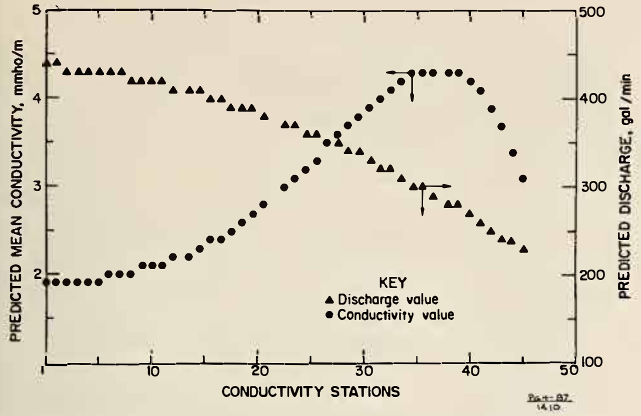

Figure 6.--Predicted curve trends between the discharge and conductivity measurements. The predicted second-degree equation for the discharge is given by: $y = 438.16 - 0.887x - 0.084x^2$, where y = predicted mean discharge and x = station location. The predicted sixth-degree equation for the conductivity is given by: $y = 1.85 + 0.013x + 11.97x^2 + 0.00008x^3 - 17.7x^4 - 18.00x^5 - 0.0000000009x^6$, where y = predicted mean conductivity measurement and x = station location.

The Spearman's Rank Order Correlation coefficient is -0.92 suggesting a strongly negative relationship between the station discharge and conductivity measurements. Thus, the predicted curve trends of the two measurements illustrated in figure 6 do show a negative relationship, such that high conductivity readings generally correspond to lower discharge measurements. In terms of identifying subsurface infiltration zones, the stations exhibiting lower discharges and higher conductivity measurements are areas where streamflows are infiltrating into the underground workings. Alternatively, the stations exhibiting higher discharges and lower conductivity measurements are areas where stream water does not appear to be infiltrating or there is less infiltration into the mine.

Grouting

In order to establish a methodology for surface grout injection, a section of stream channel between conductivity stations 82 and 84 was selected as the test area (fig. 1). Prior to the grout injection procedure previously described discharge measurements were taken at conductivity stations 82 and 84 on May 20 and May 28, 1987 (table 3). The polyurethane grout was injected into the stream at 10-ft (3.3-m) centers between conductivity stations 82 and 84, i.e., seven grout rods were used along the 70-ft (23-m) section of stream following gaging on May 28, 1987. Post-grouting gaging was conducted on May 29, June 4, and June 5, 1987 (table 3). As illustrated in table 3, the discharge rates between conductivity stations 82 and 84 showed a net gain in flow after grouting was completed.

Unfortunately, stream discharge decreased to low flow conditions within the grout test area around mid-June 1987 (approach of the dry season) and eventually the stream flow terminated. The overall gain in discharge between these two stream points for the time of gaging does, however, suggest that the grout injection procedure does prevent subsurface infiltration.

Based on this limited sealing operation, costs are estimated to range between \$25 and \$30 per linear foot of the 10-ft (3.3-m) wide stream channel. Other streams in the watershed of approximately the same size and geological conditions have been rechannelized with heavy equipment and sealed with clay-lining and rock rip-rapping. The costs of these sealing operations were over \$70 per linear foot. In addition to significantly disturbing natural conditions, the effectiveness of the latter technique is questionable based on visual observations of the streams during various flow conditions. Future evaluation of the conventional stream sealing techniques are scheduled.

CONCLUSIONS

This novel approach to identifying infiltration zones has demonstrated that areas of high conductivity trends were associated with significant stream losses, and that areas of declining conductivity trends demonstrated no significant losses in stream flows. This technique demonstrates a potential for accurately locating stream loss zones without flow monitoring for a full hydrological year. The two conductivity surveys (wet and dry season) over the 3,000-ft (910-m) stream segment took only a day each to complete. Thus, by performing conductivity surveys coupled with confirmation gaging, areas of stream infiltration were located with minimal time and effort. In addition, this pinpointing of loss zones was indiscriminate of natural or manmade causes. This implies that the potential for identifying natural fracture zones (linears) exists, and this technique may be a predictive tool for possible roof control problems in active underground workings.

The stream sealing technique which has been developed was demonstrated to be quick and easy, causing minimal disturbance to the natural conditions. This novel approach shows good potential for reducing surface and ground water infiltration into underground workings (both active and abandoned). Limited data have been encouraging in terms of effectiveness. In addition, the potential for 50 pct cost savings exists when compared to conventional clay-lining and rock rip-rapping techniques. Consequently, this technique offers an economical means of reducing pollution in abandoned mines, as well as reducing water-handling and treatment costs in active mines.

Based on data collected thus far, full-scale grouting targets have been identified in the upper project site between conductivity stations 20 to 27 and 32 to 45 (fig.1). This grouting work is scheduled to be completed in the near future and will affect 800 ft (242 m) of stream channel while only actually sealing 600 ft (182 m). Although this project appears promising for alluvial type stream channels, more work needs to be performed with bedrock stream channels. In addition, the bedrock situation is anticipated to be slightly more expensive due to obvious drilling operations which would be required.

Table 2. -- Predicted mean conductivity and mean discharge measurements.

Conductivity station	Gaging station	Predicted conductivity, mmho/m	Predicted discharge, gal/m	Mean Measured discharge gal/m
1	1	1.86	437.19	433
2		1.88	436.05	
3		1.89	434.74	
4		1.91	433.27	
5		1.92	431.63	
6		1.95	429.81	
7		1.97	427.83	
8		1.99	425.69	
9		2.02	423.37	
10		2.06	420.89	
11		2.10	418.24	
12		2.14	415.42	
13		2.19	412.43	
14		2.25	409.28	
15		2.31	405.96	
16		2.37	402.46	
17		2.44	398.81	
18		2.52	394.98	
19		2.61	390.98	
20		2.70	386.82	
21		2.80	382.49	
22		2.90	377.99	
23		3.00	373.32	
24		3.12	368.49	
25		3.23	363.49	
26	5	3.35	358.31	394
27		3.47	352.97	
28		3.58	347.47	
29		3.70	341.79	
30		3.82	335.95	
31		3.93	329.94	
32	6	4.03	323.76	305
33		4.12	317.41	
34		4.20	310.90	
35		4.26	304.21	
36		4.31	297.36	
37		4.33	290.35	
38	7	4.33	283.16	250
39		4.29	275.80	
40		4.21	268.28	
41		4.10	260.59	
42		3.93	252.73	
43		3.71	244.70	
44		3.43	236.51	
45	8	3.08	228.14	249

Table 3. -- Pregrouting and post-grouting discharge change.

	Conductivity station 82 discharge, gal/m	Conductivity station 84 discharge, gal/m	Change, gal/m
May 20, 1987	1,228	1,194	-34
May 28, 1987	845	634	-211
*May 29, 1987	618	693	+75
*June 4, 1987	237	332	+95
*June 5, 1987	262	280	+18

*Post-grouting discharges.

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