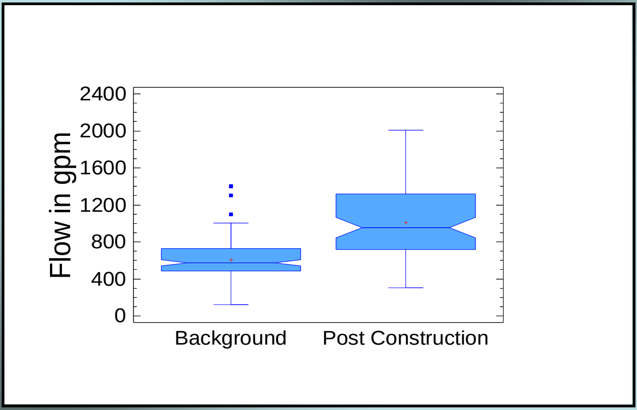

Investigation and Site Characterization of the Surface and Underground Mines Hydrologically Connected to the Brandy Camp Discharge

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Explanation: This investigation and report were conducted by personnel of the Office of Surface Mining and Reclamation Enforcement, Technical Support Division, Water and Engineering Services Branch of the Appalachian Region based in Pittsburgh, PA. This work was performed at the request of and in conjunction with the Pennsylvania Department of Environmental Protection (PADEP), Bureau of Abandoned Mine Reclamation (BAMR), Cambria Office in Ebensburg, PA. The hydrogeologic work was primarily conducted by hydrologist Jay W. Hawkins with considerable help of Jon Smoyer, Licensed Professional Geologist, of BAMR. The extensive mapping for this project was conducted by Lukus Monette, physical scientist, Technology Services Branch.

Cover Photographs: Pre-aeration of the Brandy Camp discharge (upper left), sludge pond clean out at the Toby Creek treatment facilities (upper right), original broad-crested weir (middle left), notched box-and-whisker plot comparing background discharge rate to the rate post-plant construction (lower left) and well used for the test injection of Toby Creek facilities sludge (lower right).

Acknowledgements: The author wishes to thank Joe Tarantino of the Knox District Office of the PADEP for his help in data collection in the course of this investigation. Gratitude is also extended to Bill Sabatose of the Toby Creek Watershed Association and Rich Beam of BAMR, Cambria Office for their help with this study. Thank you goes out to Clifford Dodge of the Pennsylvania Geological Survey for graciously sharing mine maps and his own work for this project. Thanks are also extended to Dan Sammarco of the BAMR, Cambria Office for affording us the opportunity to conduct this study. The aid provided by the Brandy Camp crew, Tim Shaw, Michael King, and John Belkowski, during this study was invaluable.

Introduction

This report is the culmination of the hydrogeologic characterization of underground and surface mines that are hydrologically connected to the discharge located adjacent to the Brandy Camp treatment facilities. Here on out, this mine discharge will be referred to as the Brandy Camp discharge. Dan Sammarco of the BAMR initially requested that the Water and Engineering Services Branch of the Technical Support Division from the Office of Surface Mining and Reclamation Enforcement (OSM), Appalachian Region office in Pittsburgh conduct a hydrologic characterization of the aforementioned discharge and associated hydrologically-connected mines.

Specifically, BAMR requested OSM to answer two salient questions. Shortly after the Brandy Camp treatment plant was completed and operational, it was determined to be significantly undersized. On the average, the plant was capable of treating slightly more than one half of the mine water discharge quality. During high-flow conditions, the plant treats well less than 50% of the mine discharge. Therefore, the first question to be answered is why were the baseline (background) discharge measurements much lower than those recorded since the plant came online. These baseline discharge measurements caused the plant to be under sized.

The second task of this project was to determine potential locations within the hydrologically-connected underground mines for the injection of iron sludge produced at the plant by the belt press and settling ponds. At present, this sludge is disposed of and buried in nearby surface mines. Once the last of these surface mines is closed, a new disposal site and/or method will be needed. Toward that end, the environmental viability of underground injection of the iron sludge has been studied. Selection of potential injection sites initially targeted the larger Elbon Mine in the Lower Kittanning. However, the overlying Shawmut Mine in the Middle Kittanning coal seam now appears to be a better option for various reasons. The Shawmut Mine is separated by an average of 38.4 feet from the Elbon Mine by mainly siltstones, claystones and shales which cause the formation of a perched mine pool. The water quality within the Shawmut Mine pool is more conducive to prevent remobilization of the injected iron hydroxide.

Background

Site Location

The Brandy Camp discharge and associated mines are located adjacent to the town of Brandy Camp in southern Elk County, Pennsylvania (Figure 1). Brandy Camp is a small former coal mine (“Patch”) town approximately nine miles north east of Brockway along State Route 219. The Brandy Camp discharge point is located approximately 1000 feet south-southeast of the town.

Geology

The study area is underlain by coal-bearing strata of the Allegheny Group, Pennsylvanian System. The Lower and Middle Kittanning Coal seams are the two main units mined in this region. However, some additional mining, primarily surface mining, has occurred on the Lower Freeport, Upper Freeport, Clarion and various localized split and rider seams. The strata associated with these coals are mainly shales and siltstones with a few thinly bedded sandstone beds. Yost Associates, Inc. (undated) noted the presence of the Lower Freeport Limestone capping several of the hilltops to the north and east within the drainage area of the Brandy Camp discharge.

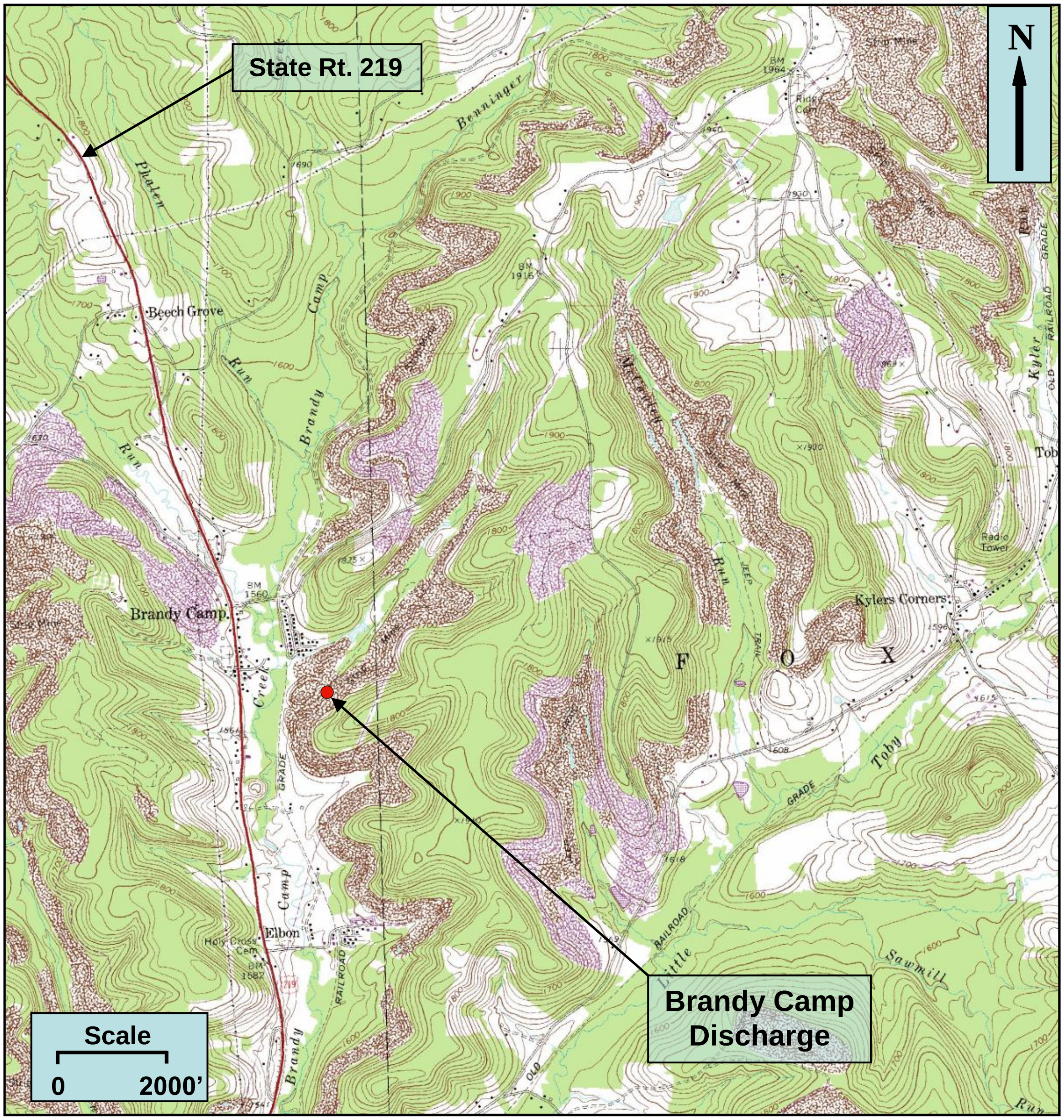

Figure 1. Topographic map of the Brandy Camp study area.

The strata within the Brandy Camp discharge drainage area are generally low dipping (generally, 2 degrees or less). The southwest to northeast trending Shawmut Syncline bisects the drainage area (Figure 2). The synclinal axis lies just north of the Brandy Camp discharge. This structural setting in concert with the deeply-incised topography cause the Brandy Camp discharge to be the principal mine water relief point for the underground mines.

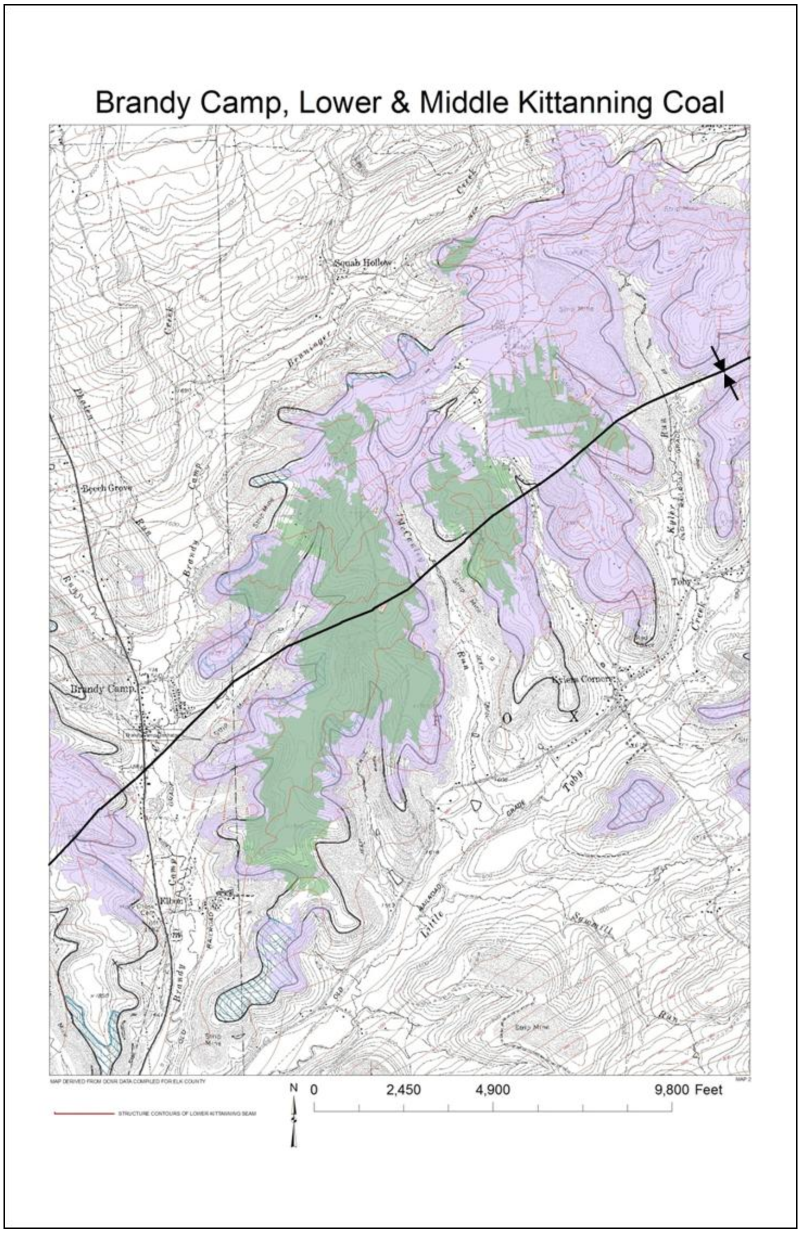

Figure 2. Structure contour map illustrating underground mines in the Middle (green) and Upper Kittanning (amethyst) coals.

Like much of this region, most ground-water movement through undisturbed strata is via the secondary permeability and porosity of fractures in the rock. The sedimentary rocks throughout much of the Appalachian Plateau are highly cemented and well indurated; thus primary (intergranular) porosity and permeability are very low and their influence to the ground-water regime is generally negligible. At shallow depths, generally less than 150 to 200 feet, fractures were created in large part by stress-relief (release) forces. Stress-relief forces are generated by rock mass removal from natural erosion processes over a considerable time period (Ferguson, 1967; 1974; Ferguson and Hamel, 1981). Stress-relief fractures tend to be vertical or near vertical along the hillsides paralleling the main valleys and horizontal bedding-plane separations become common approaching the valley bottoms (Wyrick and Borchers, 1981). Ground water flows from the hilltops and hillsides down toward the adjacent streams following a quasi stair-step path. The frequency and aperture size of stress-relief fractures tend to decrease with increasing depth (Wright, 1985; Hawkins et al., 1996). So, most of the shallow ground-water flow in this region is limited to a depth of less than 200 feet. Shales and other clay-rich strata generally have closely spaced fractures with very narrow (tight) apertures. These types of strata tend to act plastically and can exhibit swelling with hydration. Thus, they can behave as somewhat self-healing. These characteristics keep the apertures narrow and inhibit ground-water movement. Whereas, sandstones tend to have more widely spaced fractures, but the fracture apertures are wider and open. Sandstones tend to be harder, better self-supporting and have a low clay content; so, once a fracture forms the aperture tends to remain open. Therefore, sandstones tend to transmit ground water more readily and are by-and-large better aquifers (Ferguson, 1967, Miller and Thompson, 1974, Peffer, 1991).

Tectonic activity has also created fractures and prominent fracture zones that can greatly influence ground-water movement. These fractures tend to be more oblique (subvertical) than stress-relief factures and generally extend to much greater depths. Photo lineaments, noted primarily through remote sensing means, often indicate the existence of long relatively-narrow, heavily-fractured zones which substantially facilitate ground-water movement. The fracture zones indicated by the lineaments are frequently expressed in the subsurface at mine level and are associated with in-mine roof control problems and ground water inflow zones (Phillipson and Tyrna, 2002).

Underground mining in this region began as early as 1864. The underground mines in the Lower Kittanning Coal draining to the Brandy Camp discharge began in earnest in the 1870s and continued until the 1930's (See Figure 2.). About the time of closure on the Elbon Lower Kittanning mine, mining on the overlying Middle Kittanning coal seam began in the Shawmut Mine. The Shawmut Mine underground operations continued until about 1959 (Yost Associates, Inc., undated). After the Second World War, surface mining began on the coal outcrop barriers areas left between the underground mines and the surface. Surface mining on the Lower and Middle Kittanning coals and overlying coal seams has continued up until the past few years.

Analysis of the Brandy Camp Discharge

The discharge rate of the Brandy Camp discharge was analyzed with respect to hydrologic characteristics of the surface and underground mines (Elbon and Shawmut mines), the overall hydrologic regime and specifically, why the flow rate is significantly higher since the treatment plant was completed.

Analysis of Possible Causes of Changes to the Discharge Flow Rate

The treatment plant was designed and built based on baseline discharge rates of the Brandy Camp discharge. So, the initial focal point of this hydrologic characterization study was to determine why the flow rates measured at the discharge after the treatment plant was completed were significantly higher than the baseline measurements.

The first task of this portion of the study was to determine if the pre- and post-plant construction discharge rate differences are definite (not just random variation) and, if so, are they significant statistically. A determination has been made that the pre- and post-plant construction differences in the discharge rate are clear-cut and statistically significant. Figure 3 illustrates that the median flow rate after plant construction (955 gallons per minute (gpm)) is significantly higher (95% confidence level) than the pre-construction median flow rate (572 gpm). Pre-construction data include flows recorded during plant construction as well. The horizontal center line in each box is the median, while the box represents the first and third quartiles (25% of the data) above and below the median, respectively. Vertical lines (whiskers) extend from the end of the box to the farthest point within 1.5 interquartile range. Values that fall beyond the whiskers, but within 3 interquartile ranges (suspected outliers), are plotted as individual points (squares). The plus sign here is the mean or average. The notch on the box sides represents an approximate 95% confidence interval about the median (McGill et al., 1978). The use of two or more notched box-and-whisker plots allows you to determine if the medians are significantly different, with a 95% confidence. The lack of an overlap of the two notches about the median on the notched box-and-whisker plot (Figure 3) indicates the post-construction flows are significantly higher.

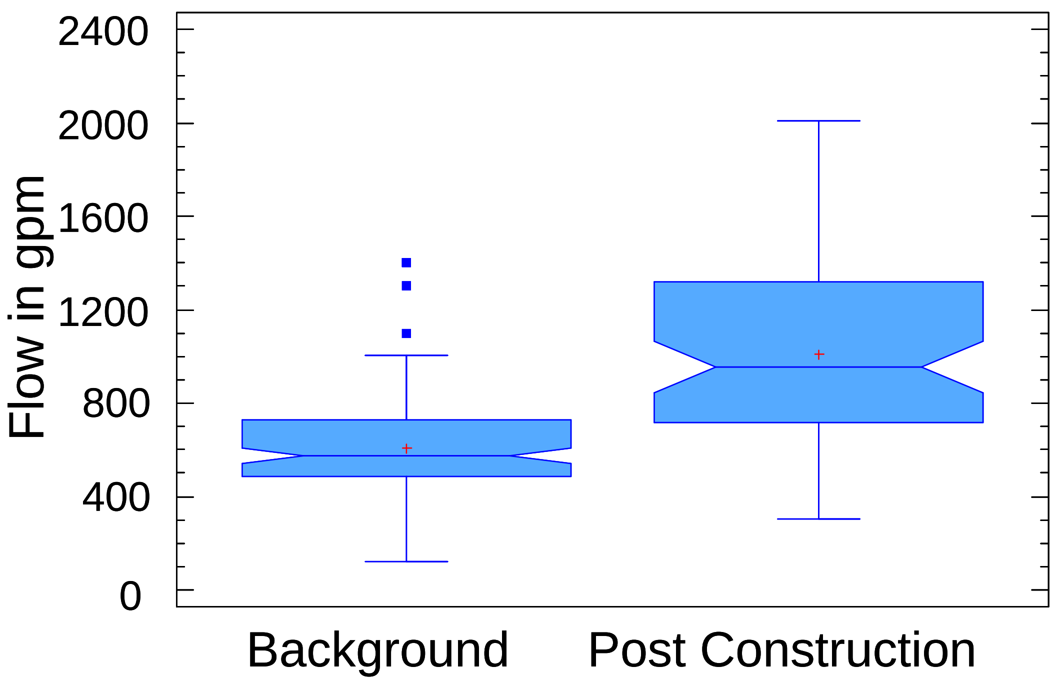

Figure 3. Notched box-and-whisker plot illustrating the discharge flow rate differences observed before and after construction of the treatment plant.

Analysis using the Student's T-test likewise indicated that the mean flow prior to the treatment plant construction was significantly lower at a 95% confidence level (P-value <0.01) than the mean flow recorded since completion of the plant. The data sets were transformed to approximate a normal distribution prior to conducting the Student's T-test. The Wilcoxon Mann-Whitney U (a nonparametric version of the Student's T-test) and the Kruskal-Wallis tests also showed that the post-construction median was significantly higher than pre-construction levels at 95% confidence levels (P-value <0.01). The Kolmogorov-Smirnov test illustrated that the distributions of the two data sets were significantly different at a 95% confidence level (P-value <0.01). The bottom line of all these statistical tests is that flow changes are real and significant, assuming the actual flow measurements are accurate.

Several potential reasons for the pre- verses post-plant construction flow disparity were postulated: 1) the measurements prior to plant construction were conducted improperly or the flow measuring device was malfunctioning, 2) the post-construction measurements are incorrect or the present weir is not working correctly, 3) the measurement point location changed substantially from background allowing for an increase in flow, 4) surface mining in the basin during this period impacted the recharge rates, 5) the precipitation/climatic conditions changed substantially during this period, or 6) other anthropogenic activities in the recharge area have considerably impacted the hydrologic regime. Each of these possible reasons are covered the following sections. However, the impacts of precipitation and/or surface mining were considered the most probable causes a priori.

Measuring Techniques or Measurement Point Location

Weir location and construction: BAMR provided OSM with information on the techniques and locations that the baseline flow measurements were conducted. A sharp-crested weir near the discharge point was installed to determine flow rates prior to construction of the plant (Figure 4). The weir was moved a "few feet downstream" from its original location during the period of plant construction. This short-distance move should have no impact on the flow measurements, given that no loss of flow or other inflows occurred between the two points.

Based on BAMR's experience and ability in conducting surface water flow measurements under a variety of conditions there is no reason to suspect that the weir was improperly installed, maintained or read. All available information and data indicate that the discrepancies in flows were not introduced by the mechanics or logistics of the background measurements themselves. A discussion with Bill Sabatose, of the Toby Creek Watershed Association, who was involved with the collection of the background flow measurements, also indicates that the measurements were properly conducted. Photographs provided by Mr. Sabatose likewise indicate that the weir was functioning properly (Figure 4).

Post-plant construction weir and flow measurement equations: The present discharge measurements are based primarily on the flow through a 4-foot (crest length) broad-crested weir (Figure 5). When the discharge flow is too high to process all the water through the plant, the overflow was originally routed through a laterally-adjacent pipe and the flow rate was determined (mainly estimated). Subsequently, an H-type flume was installed to allow for a more accurate overflow discharge rate determination (Figure 6). The present broad-crested weir is properly constructed for its intended use. One possible source of the differences in flow measurements may be attributable to the use, at one point, by BAMR of the equation for a sharp-crested weir when a broad-crested weir is present at the plant. This could be contributing to some of the differences noted between the background data and the data collected since the plant was constructed. A sensitivity analysis of the differing equations is presented below. The pipe overflow discharge rate was determined using the Manning's formula and a roughness coefficient of 0.12 (P. J. Shah, personal communication).

Figure 4. Brandy Camp discharge sharp-crested weir employed for flow monitoring prior to plant construction.

The equation for sharp-crested weir compared to a broad-crested weir differs substantially. Additionally, there are differing weir coefficients (C) for broad-crested weirs depending on the reference employed. Since the treatment plant was brought online, the flows recorded at the weir are determined using the equation 1, which was designed for a sharp-crested weir (ISCO, 2006).

$$\mathbf{Q = 3.33\ (L - 0.2H)\ H^{1.5}} \qquad (1)$$

Where: L = the crest length (4 feet)
H = head on the weir
Q = discharge rate in cubic feet per second

This formula for a sharp-crested rectangular weir yields flow in cubic feet per second (cfs) (ISCO, 2006). As previously stated, the present weir at the plant is a broad-crested rectangular weir. There are separate formulae for recording the flows at broad-crested weirs. A commonly used broad-crested weir formula is equation 2.

$$\mathbf{Q = CLH^{1.5}} \text{ (after Brater and King, 1976; Kay, 1998)} \qquad (2)$$

Where: C = the weir coefficient

Figure 5. Present Brandy Camp 4-foot broad-crested weir at the treatment plant.

Based on the table in Brater and King (1976), the weir coefficient ranges from 2.38 to 2.69 for heads between 0.2 and 1.5 feet for a four-foot weir. Note that the higher head range is somewhat greater than anticipated at the Brandy Camp Discharge. Ponce (2007) uses equation 3 below to calculate a single C value of 3.087 to determine flow in cfs.

$$\mathbf{C = (2/3)^{3/2}\, g^{0.5}} \qquad (3)$$

Where: g = the gravitational acceleration = 32.17 feet per second squared

A comparison (sensitivity analysis) of flows calculated using the sharp-crested weir equation, the broad-crested weir equation using C values of 2.38 to 2.69 (Brater and King, 1976) and the broad-crested weir equation with a C value of 3.087 (Ponce, 2007) shows that the discharge rate differences vary with the head measurements (Figure 7). The discharge rates using the C value of 3.087 with the broad-crested weir equation are relatively close to the discharge rates obtained using the ISCO (2006) equation for a sharp-crested weir. The discharge rates calculated for the broad-crested weir, using a C value of 3.087, ranged from -0.32 to 0.05 cfs (-143.6 to 22.4 gpm) or -6.8 to 0.23% difference compared to the sharp-crested weir calculations.

The discharge rates for the broad-crested weir, using the range C values (2.38 to 2.69) from the tables given by Brater and King (1976), compared to the values determined using the sharp-crested weir equation started out lower than the discharge rates using the Ponce (2007) C value and increasingly diverged toward lower rates with increasing head measurements. Discharge rate difference ranged from -0.13 to -3.09 cubic feet per second (cfs) (-58.35 to -1387 gpm) or -30.58 to -13.64% difference. As the actual discharge rate disparity increased, the relative differences decreased in terms of percentage of the total discharge rate.

Figure 6. H-type flume installed to measure the overflow discharge rate.

The sharp-crested weir equation tends to yield discharge measurements near or generally higher than either of the two broad-crested weir methods used to calculate the discharge rate. At least in part of the observed higher flow rates recorded since the plant was constructed may be just a perception of a higher discharge rate skewed by how the flow rates were calculated. However, the higher recorded rates using the sharp-crested weir equation does not account for the statistically significant higher discharge rates observed. This is especially true because the heads measured at the weir are below 0.5 feet where the differences of flow between the equations are small in the relative sense. These data are shown in their entirety in the appendix.

Influence of Surface Mining on the Discharge Rate

The large amount of surface mining and subsequent reclamation within the recharge area for the Brandy Camp discharge from 1989 to 2002 appears to have had a substantial impact on the discharge flow rate. The bulk of the surface mining was on coal seams overlying the Middle Kittanning Coal. However, some surface mining was conducted on the Middle Kittanning as well. There were significant surface mining activities in this region for several decades prior to 1989, but the surface mining within the recharge area for the Brandy Camp discharge for the period slightly before, during, and after background data collection was of specific interest for this characterization study. A positive correlation was observed between increasing area affected by surface mining and a higher mean flow rate at the Brandy Camp Discharge (Figure 8). Given the difficulties in determining flow rate and inherent uncertainties common to natural data, the correlation here (R-squared = 68.6%) is comparatively strong. The P-Value of 0.0012 shows that the mean discharge rate to mining affected acres relationship is significant above the 99% confidence level.

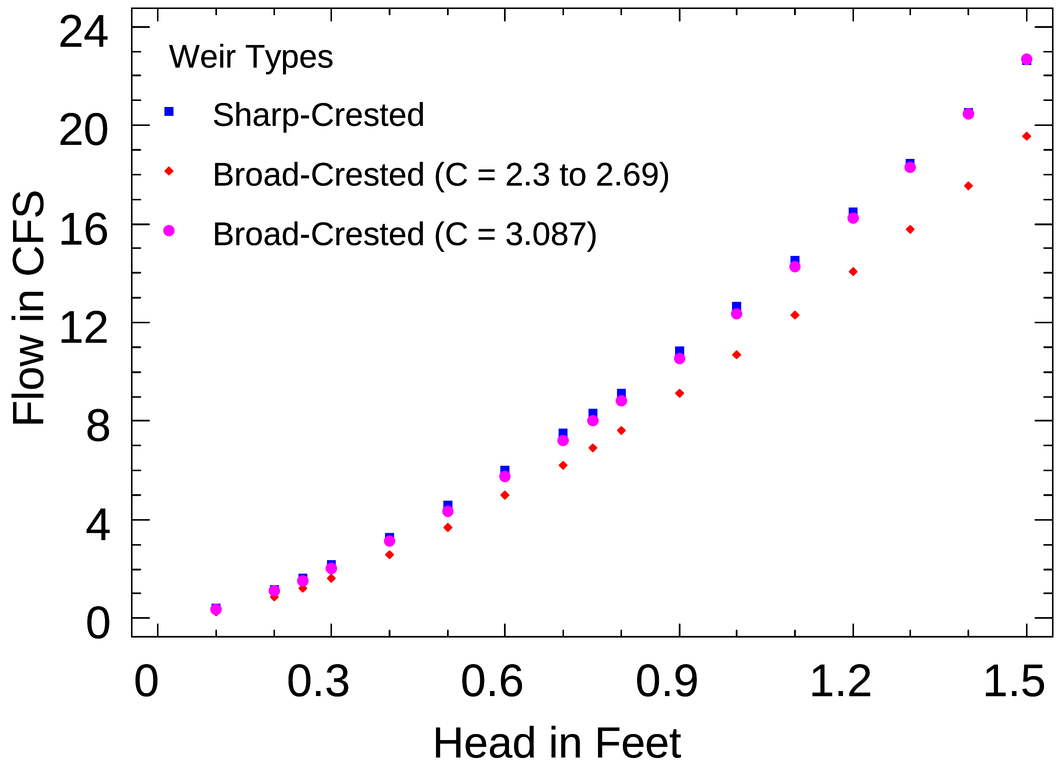

Figure 7. Broad-crested weir discharge rate calculations sensitivity analysis.

When background monitoring for the discharge started in July of 1993, recent surface mining had affected about 99 acres with 72 acres already reclaimed (Figure 9). Approximately 430 acres had been affected with 299 acres reclaimed by the time background sampling ended in June of 1996. Toward the tail end of the background sampling period the discharge rates were beginning to noticeably rise (Figure 10). An additional 657 acres were surface mined and 786 acres were reclaimed subsequent to the background sampling, 2004 and 2005, respectively. The discharge rates continued to rise during this period more than can be attributed to precipitation variation alone. While the much higher than normal precipitation in 2004 is reflected in the relative discharge average for that year, there was a noticeable trend of increasing flow rates at the Brandy Camp discharge beginning as early as 1996 (Figure 10). The impacts of precipitation and climatic conditions are discussed in more detail in the following section.

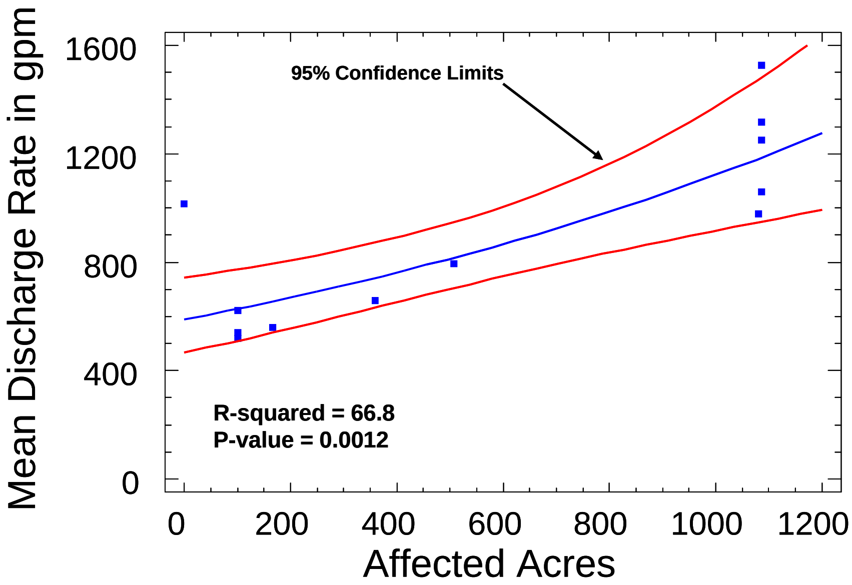

Figure 8. Regression analysis illustrating the relationship of mean discharge rate to amount of drainage area affected by surface mining.

In all a total of 1,087 acres were surface mined during this period of interest. The total recharge area for the mines that the Brandy Camp discharge drains is approximately 1,285 acres, so the surface mining during this period effected approximately 85% of the recharge area. The surface mining caused an increase of 67% in the median flow rate at the Brandy Camp discharge. However, note that the total drainage area could be slightly larger or smaller than 1,285 acres due to uncertainties in structure and mine workings which influence the ground-water divides in the underground mines.

During surface mining activities surface and ground waters are physically controlled to a large extent. Surface water is collected and diverted to impoundments via ditches. The impoundments and ditches are engineered to prevent infiltration of the water. These structures are designed to collect runoff and hold it until effluent standards are reached then the water is discharged into the nearest natural drainage way. Ground water encountered in the pit and elsewhere is pumped to treatment ponds and discharged once effluent standards are achieved. This efficient handling of encountered water precludes to a great degree recharge to underlying deep mines. Therefore, much of the precipitation falling on the areas where active surface mining activities are occurring will be intercepted and diverted until mining is completed and the erosion and sedimentation controls are removed; thus vertical recharge to underlying mines is minimized while the mines were active.

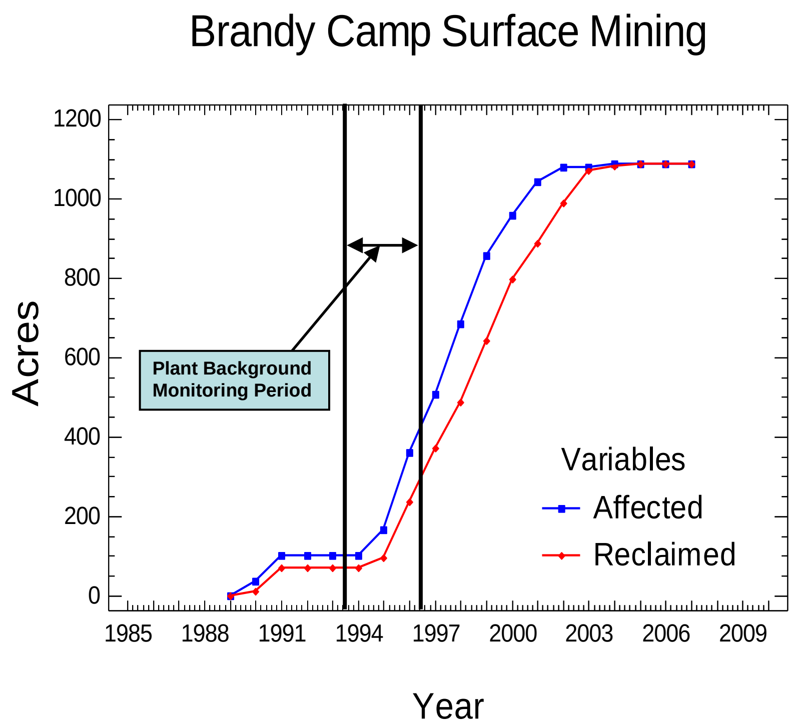

Figure 9. Acreages of affected and reclaimed surface mines in the Brandy Camp discharge watershed before, during and after plant construction.

Once the site is backfilled and revegetated, the ditches and ponds are removed. At that point, surface water is no longer collected and routed from the site. A substantial percentage of the water falling directly on the site from precipitation or flowing on to the site from adjacent areas will infiltrate into the spoil and eventually will recharge the underlying Middle Kittanning Shawmut mine. The Shawmut Mine discharges very little water directly to the surface (Yost Associates, Inc., undated), but instead the infiltrating recharge water forms a perched mine pool. There are a few small discharge points that emanate directly from the Shawmut Mine from isolated sealed or covered portals, but most of the water in the Shawmut Mine pool infiltrates vertically into the underlying Elbon Mine. The water in Lower Kittanning Elbon Mine is subsequently expressed at the Brandy Camp discharge. The Elbon Mine exhibits no significant pooling; instead flows along the mine floor toward the Brandy Camp discharge point and out to the surface.

The post-surface mining changes in water handling along with stark alterations in soil structure and vegetation are the major factors in the amount of recharge now occurring in the drainage area for the Brandy Camp discharge.

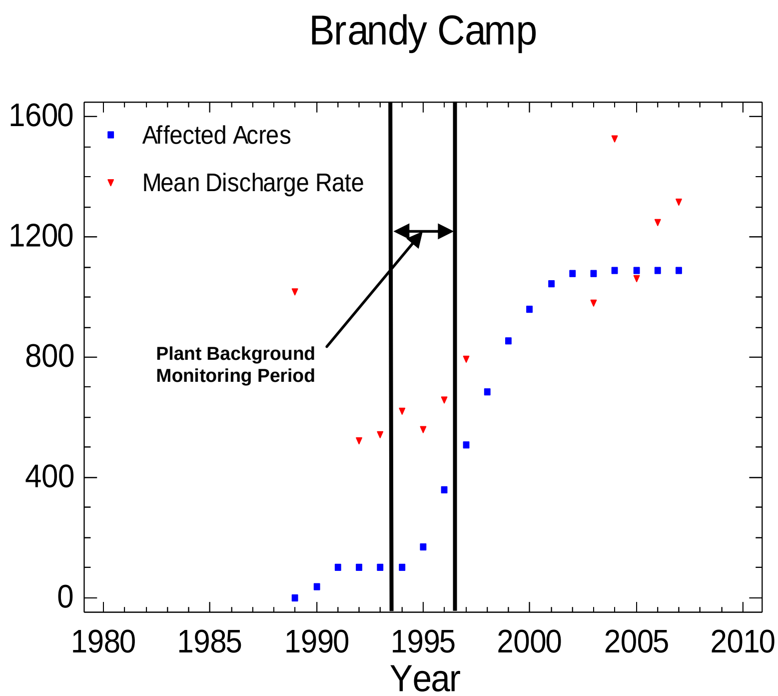

Figure 10. Relationship of surface mine affected acres and mean discharge rate of the Brandy Camp discharge.

Some earlier studies of the impacts of surface mining and reclamation indicate that frequently precipitation infiltration rates are reduced from pre-mining conditions due to loss of soil structure, soil compaction and lack of vegetative cover (Jorgensen and Gardner, 1987). However, within approximately four years after reclamation, infiltration rates tend to recover to near background levels. Infiltration rate recovery is due to re-establishment of the soil structure, increases to the vegetative cover and increasing surface roughness. Guebert and Gardner (2001) noted that infiltration rates on newly reclaimed minesoils tend to exhibit low steady state rates of infiltration (0.40-0.79 inches per hour (in/h)), but within four years after reclamation the infiltration rates of "some minesoils" near the premining rates of 3.15 in/h. The increased infiltration rates were facilitated by the development of macropores in the minesoil which caused the effective reduction of peak runoff rates and dramatically increased the recession limb of storm events. Analysis of a "heavily mined" watershed in Indiana showed that the storm runoff averaged 62% of that of an adjacent "lightly mined" watershed (Corbett, 1965).

Infiltration of precipitation also depends on the degree the material has been regraded or degree of surface roughness. Deane (1966) recorded infiltration rates for ungraded spoils of 4.0 and 9.3 in/hr for ungraded spoils and 0.6 and 0.9 in/hr for the same spoils that were regraded in Ohio and Illinois, respectively.

Numerous other studies indicate that surface mining greatly increases the infiltration and storage of precipitation. Streams fed by baseflow in heavily mined areas tend to continue flowing through protracted drought; whereas streams in adjacent unmined areas exhibit substantially lower baseflow or tend to go dry during these periods (Corbett, 1965). This is indicative of not only higher recharge rates of the mine spoil, but also that spoil aquifers tend to have higher storage capacity (i.e. effective porosity) of this additional water than undisturbed strata.

The deforestation that precedes the mining may also be a major factor in the increased infiltration. Deforestation greatly reduces the water interception and evapotranspiration, thus increases the amount of ground water going into storage (Lieberman and Hoover, 1951; Douglass and Swank, 1975; Dickens et al., 1989). The increase in stream flow, previously noted, was due mainly to the higher baseflow during summer low-flow periods, which is promoted to some degree by the decrease in evapotranspiration. The conversion of the original hardwood forest cover to grasses greatly contributes to the increased infiltration. The commensurate increases in stream baseflow have been shown to be directly proportional to the area of deforestation (Douglass and Swank, 1975).

Messinger and Paybins (2003) noted that during low-flow periods the normalized discharge rate (i.e. discharge rate per unit area drained) of a heavily surface mined watershed in West Virginia was more than twice the rate of an adjacent unmined watershed. For a complete two year period, total unit flow (gallons per second per square mile) of the heavily-mined watershed was about 1.75 times greater than the unmined watershed. They attributed much of this change to decreased evapotranspiration due to deforestation, changes in the plant species and soil characteristics (thin soils retaining less water). The heavily-mined watershed continued to discharge during a protracted dry spell when the unmined watershed stopped flowing. They did, however, attribute some of the continued baseflow through the summer to increased storage capacity of mine spoil. The substantially increased ground-water storage exhibited by mine spoil, coupled with the increased infiltration facilitated by decreased evapotranspiration will support stream flow down gradient of reclaimed mine sites when nearby streams in unmined watersheds tend to go dry during periods of drought.

Wiley and others (2001) observed that the 90-percent duration flow (percent of the time the flow is equaled or exceeded) of streams that originate at the toe of valley fills is six to seven times greater flows than nearby streams draining unmined watersheds. Truax (1965) observed that at a time when mined watersheds in southwestern Indiana were yielding about 121 gpm per square mile (September and October 1964), other nearby lightly or unmined watersheds were dry. Curtis (1979) stated that spoil can store large quantities of water that eventually discharge as baseflow to the streams. He further stated that they “function as reservoirs” of ground-water storage.

Peak storm discharge rates show reductions commensurate with the area of the watershed disturbed. Spoil itself is capable of storing much larger quantities of ground water than the pre-existing strata, so if more water infiltrates into the spoil much of it can be stored and released gradually over longer periods of time. Agnew (1966) likened mine spoil to a "sponge" when it comes to recharge from precipitation. Effective porosity of mine spoils has been measured in the field nearing 20%; and likely at times approaches 25% effective porosity (approximately equal to the spoil swell factor) (Hawkins, 1998). Laboratory spoil porosity values have been recorded as high as 36% (Wells et al., 1982). Whereas, pre-mining porosity values in fractured strata are generally well less than 1% (Mackay and Cherry, 1989).

An aerial photo taken in October 1968 of the contributing area for the Brandy Camp discharge shows that the majority of the land, denoted by the areas with mottled appearance, was heavily forested (Figure 11). Preparation for surface mining removed the trees. Initially, grasses were planted as a vegetative cover once the mines were reclaimed (Figure 12). This drastic change in vegetative cover alone can account for the higher infiltration rates for the areas hydrologically connected to the Brandy Camp discharge, which in turn will yield higher flow rates once the increased ground water enters the underlying Middle and then the Lower Kittanning mines subsequently flowing to the discharge point. Slowly through plantings and volunteer growth, trees are returning as a significant cover on the reclaimed mine sites (Figure 13). Eventually, recharge rates may return to near pre-mining levels, but this may take decades. Douglass and Swank (1975) noted that areas replanted in conifers, specifically white pine, eventually exhibit recharge rates similar to or exceeding that of the pre-existing hardwoods. This is due to the higher water interception rate and transpiration losses associated with white pine compared to the pre-existing hardwoods.

The increased infiltration of precipitation, hence subsequent recharge to the Elbon Mine, caused by surface mining and reclamation is illustrated by the mean percentage of the precipitation that is recorded discharging at the Brandy Camp discharge (Figure 14). The average percent of precipitation expressed at the Brandy Camp Discharge from 2003 through 2009 was slightly more than 36%. Whereas, the average percent of precipitation yielded by the Brandy Camp discharge from 1993 through 1996 (the background sampling period) was 20%. The percent of precipitation of the Brandy Camp discharge in 1988 and 1989 (38.5%) was similar to the values recorded in the 2003 to 2009 time period. This earlier high recharge rate appears to be related to previous surface mining activities that occurred during the preceding years. The extremely low percentage of precipitation noted at the Brandy Camp discharge in 1969 (approximately 7%) was likely caused by considerable evapotranspiration occurring due to the heavier forest cover over the discharge drainage area at that time (Figure 11).

Impacts of Precipitation on Discharge Rates

Given that the Brandy Camp discharge rate is closely related to the antecedent precipitation, if the underestimation of the discharge rate was related to below or above normal precipitation, then this should be reflected in the records for those years the background data were collected or the post-plant construction period, respectively. The precipitation rates for the period for which background discharge rates were collected (July 1993 through June 1996) fluctuated about the average annual values, but exhibited no unusual trend below or above normal that would have resulted in below normal discharge rates (Figure 15). The annual and mean precipitation data for the area is based on the precipitation at the Ridgway station obtained from the database of the National Oceanic and Atmospheric Administration (NOAA). The Ridgway station, the closest NOAA recording site available, is approximately 7.5 miles to the north of the center of the study area.

Figure 11. October 1968 aerial photograph showing much of the recharge area overtop the mines contributing to the Brandy Camp discharge was forested.

The precipitation amounts for 1993 through 1996 were well within two standard deviations of the mean of 43.4 inches per year (95% confidence interval). Thus, an underestimation of the discharge rate does not appear to be related to abnormal climatic conditions during background data collection. In fact, both 1994 and 1996 exhibited well above average precipitation; 18.7% and 13.3% above the mean, respectively.

The precipitation levels in the 2002 to 2009 post-plant construction time period were also well within the 95% confidence interval about the mean (Figure 15). This indicates that the higher discharge rates exhibited since the plant came on line are not due to periods of abnormally high precipitation. Additionally, the precipitation amounts for the time period after the plant construction were more often below the average than above. For instance, precipitation for 2001 was more than 18% below the average.

Figure 12. Grasses growing on recently-reclaimed surface mined areas within the recharge area for the Brandy Camp discharge.

Figure 13. Small planted and volunteer trees beginning to populate reclaimed surface mined areas within the recharge zone for the Brandy Camp discharge.

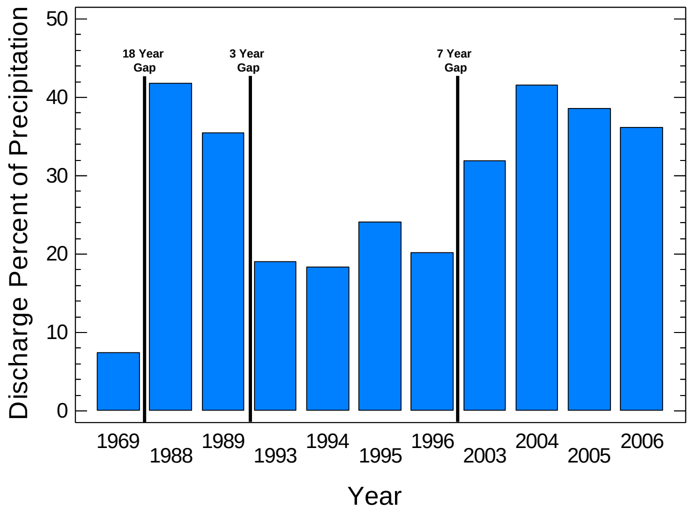

Figure 14. Changes in the percentage of mine recharge from precipitation before and after construction of the treatment plant.

This is not to say that precipitation has no impact on the discharge rate. Since the bulk of the recent surface mine reclamation activities has been completed (2003), the discharge rate has begun to exhibit a somewhat positive correlation with precipitation albeit relatively weak (R-square value = 48.1%, P-value = 0.084) with sparse data (Figure 16). Whereas, during the period from 1988 to 2002, when substantial surface mining and reclamation was occurring no remotely reasonable correlation was seen (R-square value = 8.6%, P-value = 0.572). Precipitation has always exerted some influence on the discharge, but its influence was masked from 1988 to 2002 by the apparently stronger control that water handling during surface mining had on the recharge rate for this area. As previously mentioned, much of the precipitation falling on active surface mines was collected and routed to ponds via pumping and diversion ditches. These ponds are commonly sealed to prevent leakage and the water is discharged as directly as possible into the nearest stream. Thus, there is less opportunity for ground-water recharge while an operation is active.

In the late summer and early fall of 2001, BAMR conducted stream sealing or grouting on the unnamed tributary to Little Toby Creek located due east of the Brandy Camp discharge. Previous to the grouting, BAMR had determined with the help of Bill Sabatose of the Toby Creek Watershed Association that during runoff events a “significant loss of surface water into the underlying abandoned mine” was occurring. The stream sealing appeared to initially reduce the direct inflow to the underlying Elbon underground mine. However, reconnaissance of the sealed sections in November 2006 and April 2008 indicated that additional subsidence has reopened some fractures in the overburden strata and breached the grout-sealed stream sections. Those sections of the stream again visually indicate significant surface water flow losses under low-flow conditions (Figures 17 and 18). Thus, a portion of the in-stream water once again directly infiltrates into the substrate and apparently recharging the underlying mine. This maybe another contributing factor to the higher discharge rates that are exhibited by the Brandy Camp discharge starting a few years after the plant came online in 1999. It should be noted that, the stream flow losses could not be quantified occurring with the high flows observed during the April 2, 2008 field work.

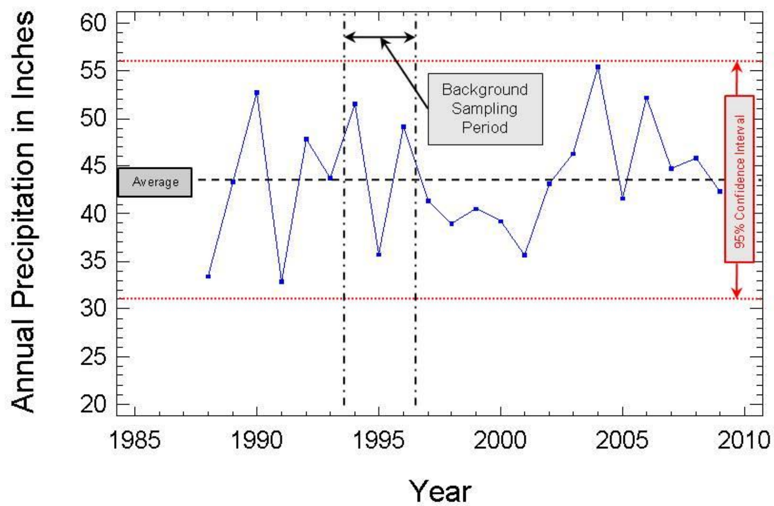

Figure 15. Annual precipitation totals for 1988 through 2006 from the NOAA Ridgway station.

Analysis of mine pool levels and Brandy Camp discharge rate hydrographs with respect to significant precipitation events does not indicate that the stream flow losses in the unnamed tributary have a major influence on the recharge rate to the Elbon Mine. The response to major precipitation events and increases in the hydrographs are similar to other mines in the region where stream dewatering is not occurring. Analysis of several major storm events coupled to mine discharge rates indicates that the responses are typically a general upward trend indicative of a gradual more diffuse recharge from a wetting front rather than a rapid spike that one would expect from a massive influx of water over a brief interval. While clearly some surface water is lost to the mine, by comparison to the overall recharge amount, it appears to be a very minor percentage.

Hydrologic Characterization of the Underground Mine Workings

The second major task in this study was to determine the possibility of disposing the iron hydroxide-rich sludge generated at the Brandy Camp treatment facilities into the Elbon Mine in the Lower Kittanning Coal and/or the Shawmut Mine in the Middle Kittanning Coal. Critical to this undertaking is to determine if there is sufficient storage capacity in either of the mines and if the connection between open entries is unrestricted to allow free flow of the sludge a substantial distance from the borehole. In order for the borehole injection to be efficient, the sludge needs to propagate considerable distances from the injection point before the solids settle out. Another paramount concern is whether the quality of the water in the mine(s) is such that the iron in the iron hydroxide will not be redissolved and mobilized. Treatment of iron at the Brandy Camp discharge that has been reintroduced (recycled) during the sludge injection is undesirable.

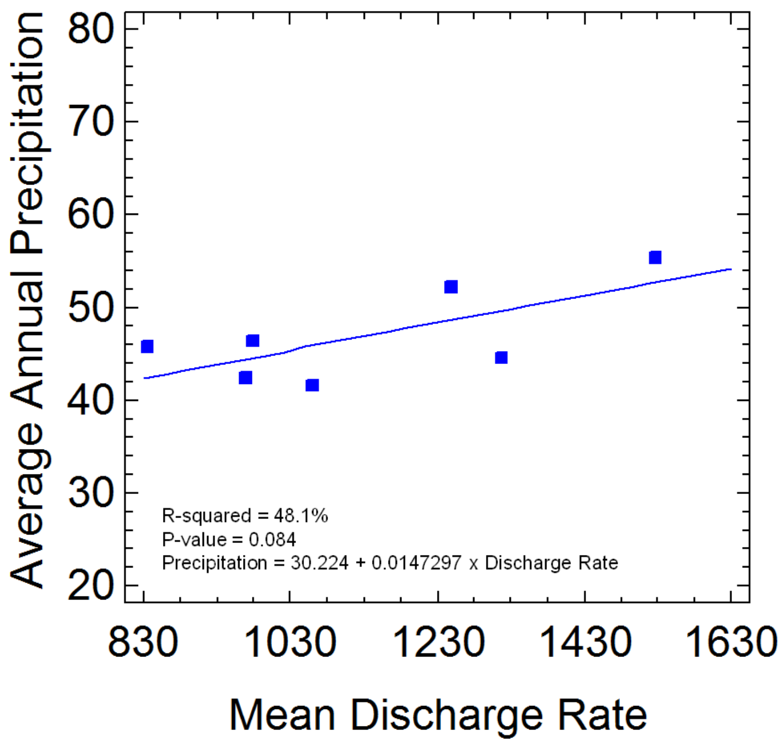

Figure 16. Simple linear regression correlation of annual precipitation in inches and average mine discharge rate in gpm from 2003 through 2009.

In the Appalachian Plateau, vertically stacked mines elevated above the adjacent drainage system tend to drain freely down to the lowest coal seam mined discharging laterally from a structural low point from that stratum. Fractures in the interburden generated by subsidence and/or fractures formed naturally which may or may not be accentuated by subsidence tend to be transmissive enough to permit the mine water to drain to the lowest coal seam mined. This usual scenario is not the case for the study area. The mine water hydrologic regime within the study area is distinctly atypical because a mine pool is located in the Middle Kittanning Coal of the Shawmut Mine that overlies the Elbon Mine in the Lower Kittanning Coal from which the Brandy Camp discharge drains. Essentially, the mine pool is a perched aquifer system above lower mine workings. The pooled mine water from the Shawmut Mine subsequently flows down through the interburden in a somewhat restricted broadly disseminated fashion through discrete fractures into the Elbon Mine. There is no known significant pooling within the Elbon Mine. Instead, the mine water flows laterally through the open entries and discharges from a structural low point within the mine at the Brandy Camp discharge.


Figure 17. Polyurethane grout exposed in the stream bed in November 2006.

Several monitoring wells installed into the two mines confirm the existence of a perched mine pool in the overlying Shawmut Mine. Long term monitoring with pressure transducers/data loggers illustrates, as expected, that the Shawmut Mine pool varies in water level and aerial extent seasonally. Figure 19 illustrates the variability of the Shawmut Mine pool as measured in monitoring well B-22. Whereas, monitoring wells into the underlying Elbon Mine show no measurable pooled water its workings throughout the year. Mine water in the Elbon Mine flows along the pit floor and discharges at the intersection of a structural low point and a topographic low elevation.

From Figure 19, it appears that the mine pool stays below 1657.4 feet a.m.s.l. and fluctuates narrowly (1655.32 to 1657.72 feet a.m.s.l.) about an average 1656.68 feet a.m.s.l. since a portal into the Shawmut Mine was excavated and a pipe discharge was installed. This portal was opened up in an attempt to ultimately reduce the amount of water discharging at Brandy Camp. The excavation of this portal is discussed in more detail below in the section titled “Spring 2008 High Flow Flushing Event.”


Figure 18. Unnamed tributary exhibiting flow loss in November 2006.

The interburden between the two coals ranges from 32.8 to nearly 44.6 feet with a mean of 38.4 feet. The interburden strata are comprised primarily of light to dark gray clay-rich shales, claystones, and siltstones. The immediate seat rock for the Middle Kittanning Coal is light gray pliable claystone. Corehole logs and inspection with a borehole camera show that the main headings and sections with minimal second or retreat mining in the Elbon Mine tend to be open and show few collapse features. Whereas, heavily second mined areas exhibit partial to complete collapse at mine level. The strata above the collapsed sections of the Elbon Mine have high-angle fracturing up to at least 29 feet above the mine. The drilling logs show that the subsidence-induced fractures extend close to or completely up to the Middle Kittanning horizon. The fractures are iron stained indicating that some weathering and/or mineral precipitation has occurred due to ground-water flow through them (Figure 20).

The high clay content of the interburden strata attenuates fracture propagation from the Lower toward the Middle Kittanning Coal level. The clay-rich strata are somewhat pliable and may deform in addition to fracturing when subjected to stress. Additionally, the clay-rich strata tend to behave somewhat plastically and can swell when hydrated allowing some self-healing of subsidence-induced and naturally-created fractures. This plasticity reduces permeability and restricts downward ground-water movement.

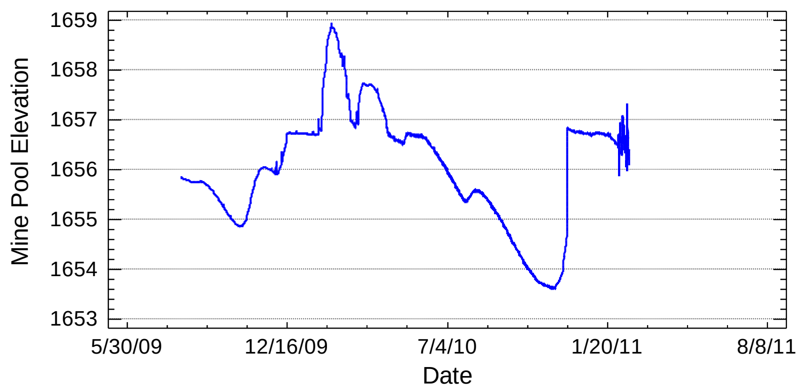

Figure 19. Hydrograph of the Shawmut Mine pool illustrating seasonal variation as measured in monitoring well B-22.

The relatively low permeability of the interburden strata is illustrated by the perched mine pool in the Middle Kittanning Coal Shawmut Mine supported by a relatively thin stratigraphic interval. Vertical hydraulic conductivity (Kv) values corroborate that the interburden as a whole regulates mine water flow from the Shawmut Mine pool to the underlying Elbon Mine. The Kv values estimated under varying hydrologic conditions (mine pool levels) were calculated. The Kv values were determined using measured mine pool levels, total flooded area, mean interburden thickness and the total discharge rate from the Elbon Mine at the Brandy Camp discharge. Vertical hydraulic conductivity of the strata between the two coals ranged from 3.6×10^{-8} to 2.3×10^{-7} meters per second (m/s) (1.0×10^{-2} to 6.5×10^{-2} feet per day (fpd)) with a median of 1.0×10^{-7} m/s (2.8×10^{-2} fpd). These values are similar to the lower Kv values determined for unfractured fine-grained sandstones and mid-range values calculated for unfractured siltstones (Fetter, 1980). Fidler (1997) recorded a Kv of 2.5×10^{-8} m/s (7.1×10^{-3} fpd) for a 40 meter thick glaciolacustrine clay unit in southwestern Ontario, Canada. While much lower values (e.g., 10^{-12} to 10^{-15} m/s (8.6×10^{-8} to 10^{-11} fpd)) have been estimated for true aquitard units (Eaton and Bradbury, 2003; Kleeschulte and Seeger, 2005). The interburden between the two mines here has sufficiently low permeability to support the perched mine pool system.

Drilling into the Shawmut Mine indicates that most of the workings encountered are open with minor amounts of gob. The drilling targeted primarily main entries which tended to be mined at much greater heights than the coal itself and better supported for prolonged use. The coal thickness ranges from 1.9 to 3.1 feet with an average of 2.2 feet thick. A few of the drill holes indicate that some collapse and convergence has occurred, but the bulk of the entries intersected appeared close to full mining height. The voids averaged 6.2 feet with a range of 2.6 to 8.9 feet for main entries. This illustrates that at least the main entries are accessible and able to accept large quantities of iron sludge.

Figure 20. Interburden core sample exhibiting high-angle subsidence-induced fracture in a siltstone unit with iron staining due to ground water contact.

Factors that influence the stability of iron hydroxide sludge in general include the type neutralizing agent used to treat water, age of the sludge, whether the sludge was aged submerged in water verses aged while subaerially exposed and the pH of the environment (water) in which the sludge is placed for disposal. Watzlaf and Casson (1990) noted that iron hydroxide sludge produced using sodium hydroxide (NaOH), calcium hydroxide ($Ca(OH)_2$) and calcium oxide (CaO) as neutralizing agents were more stable than sludge produced using sodium carbonate (Na_2CO_3). They further observed that iron sludge that was exposed to the atmosphere for a period of time became more stable (insoluble) than sludge that was held in a subaqueous state. Prolonged aging produces more stable iron hydroxide sludge especially if the material is subaerially exposed during the aging period (Watzlaf and Casson, 1990). Watzlaf (1988) noted from lab testing that iron hydroxide was relatively stable down to pH values approaching 3.5 standard units (S.U.). However, Watzlaf and Casson (1990) noted in their bench studies that regardless of the treatment chemical, aging time and conditions under which the sludge was held (submerged or subaerially exposed), the iron remained insoluble down to a pH of 5.5 (S.U.).

The quality of the mine pool water in the Shawmut Mine is considerably better than what ultimately discharges at Brandy Camp. The Shawmut Mine water becomes more degraded once it recharges the underlying Elbon Mine. This Shawmut Mine pool water is a geochemically suitable environment for the introduction of iron hydroxide sludge. Samples were collected by pumping from monitoring wells and from a portal that was excavated to laterally drain off some of the mine pool water. The geometric average pH is

5.9 (S.U.) with alkalinity concentrations ranging from 77 to 134 mg/L. Acidity concentrations range from 0 to 29 mg/L. Dissolved iron collected directly from the pool via monitoring wells is low, ranging from 0.03 to 0.24 mg/L.

The Elbon Mine water at the Brandy Camp discharge for 2009 averaged 165 mg/L net acidity (acidity - alkalinity) with a geometric average pH of 5.1 (S.U.). The mean for total iron was 69 mg/L. The pH of the Brandy Camp discharge has been slowing rising from approximately 3.0 (S.U.) in July 1988 to 4.6 to 5.4 (S.U.) at the present time (Figure 21). This improvement in pH is due to a slight decrease in the total acidity and an increase in the alkalinity.

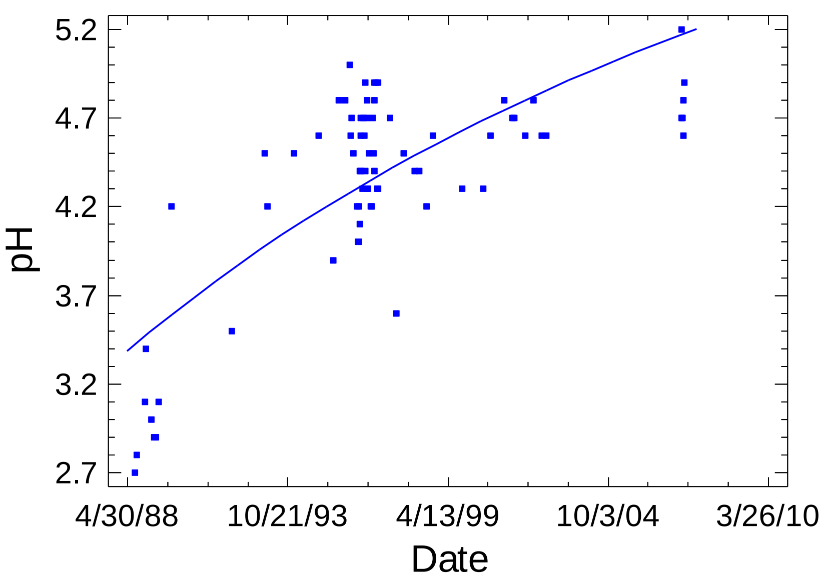

Figure 21. Increasing pH at the Brandy Camp discharge over time.

The Brandy Camp water is treated with hydrated lime (calcium hydroxide) to increase the alkalinity and thus raise the pH. Prior to the lime addition, minor aeration of the mine water allows for some of the excess dissolved carbon dioxide to exsolve, which will reduce the carbonic acid content and thus decreasing the amount of lime needed to raise the pH of the water. The mine water is suboxic at the discharge point (≈ 1.2 mg/L dissolved oxygen) and virtually all of the dissolved iron is in the ferrous state. So, subsequent to the lime addition, the water is aerated a second time by bubbling air through it to speed the dissolution of oxygen which facilitates ferrous iron oxidation to the ferric state (Figure 22). The water is then pumped through a series of inclined plate clarifiers where a polymer is added to speed coagulation of the iron. A filter belt press is used to remove the precipitated iron. Any water in excess of the plant capacity is sent to settling ponds after the second aeration step or is completely by-passed near the discharge point as previously mentioned. The sludge yielded at the plant from the filter belt press or the settling ponds should remain relatively stable if injected into the Shawmut Mine.

Figure 22. Aeration of the mine water after lime addition. The greenish color is caused by ferrous iron.

A test injection of sludge derived from nearby sister treatment plant (Toby Creek) which uses hydrated lime to neutralize the water and baffled ponds to settle the precipitating iron hydroxide was conducted on July 12 through 14, 2010. Over three days 740,000 gallons of sludge was injected into one of the main entries in the Shawmut Mine during daytime hours. Tanker trucks holding slightly more than 5,000 gallons were used to haul the sludge to the site. The sludge averaged 2.43% solids with a range of 1.59 to 3.91% solids. Water level monitoring noted no change in the mine pool level due to the injection. Only the expected diurnal fluctuations were observed (Figure 23). Similar diurnal fluctuations were observed by Moebs and Krickovic (1970) in an above drainage underground mine, which are attributable to daily barometric pressure changes caused by heating and cooling during a 24 hour period. This response to barometric pressure changes indicates that the Shawmut Mine, even though it is only partially flooded and has a definite air water interface, behaves as a confined or more likely a semi-confined aquifer.

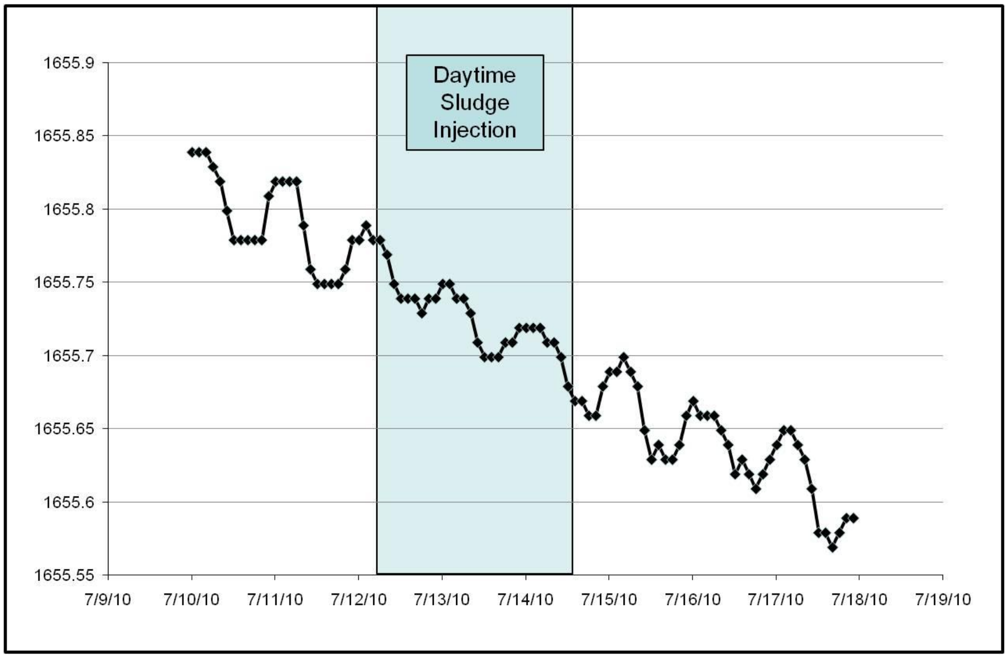

Figure 23. Mine pool water levels (elevations) exhibiting diurnal fluctuations before, during and after sludge injection test.

Water quality at the Brandy Camp discharge was collected twice daily during the injection and the following two days. Sampling was conducted daily the following week, but was reduced to every other day for the next two weeks and decreased further to twice per week for the next three weeks. The following three weeks the discharge was sampled once each week. Discharge rates were also recorded at the time of sampling. No definite change in the concentration of iron, calcium, sulfate, alkalinity or acidity was observed in the samples collected at the Brandy Camp discharge. No flow rates changes were noted as well. The median total iron concentration before sludge injection (63.5 mg/L) was unchanged afterward (median of 65.0 mg/L) at a significance level of 95%. No trend in the total iron overtime was observed (Figure 24). The iron load showed a definite downward trend after the injection with the median iron load (498 lb/day) being significantly lower after injection compared to before (595 lb/day). This is due primarily to the decreasing discharge rate during this time interval. The injected sludge also contained considerable residual calcium with a concentration of 332 mg/L in the decanted water. The calcium concentration and loads at the Brandy Camp discharge exhibited similar trends as the total iron; no statistically significant change attributable to the sludge injection into the middle Kittanning Shawmut Mine.

Spring 2008 High Flow Flushing Event

Between March 15th and April 5th of 2008, the Brandy Camp discharge experienced flow rates considerably higher than previously recorded at the site. The Brandy Camp area received about 5.3 inches of rain during that period which also melted the existing thick snow pack. This snow melt and precipitation caused considerable recharge to the mines over a short period of time and the Brandy Camp discharge increased to over 3,000 gpm. The exact maximum discharge rate could not be determined due to much of the water being bypassed from the plant through the then-existing non-gauged pipe and ditch system. As previously mentioned, the bypass system has since been modified with the addition of an H-type flume. Flow rates are now monitored with a pressure transducer/data logger. However, mine water is rarely bypassed, except periodically when the plant is down for maintenance.

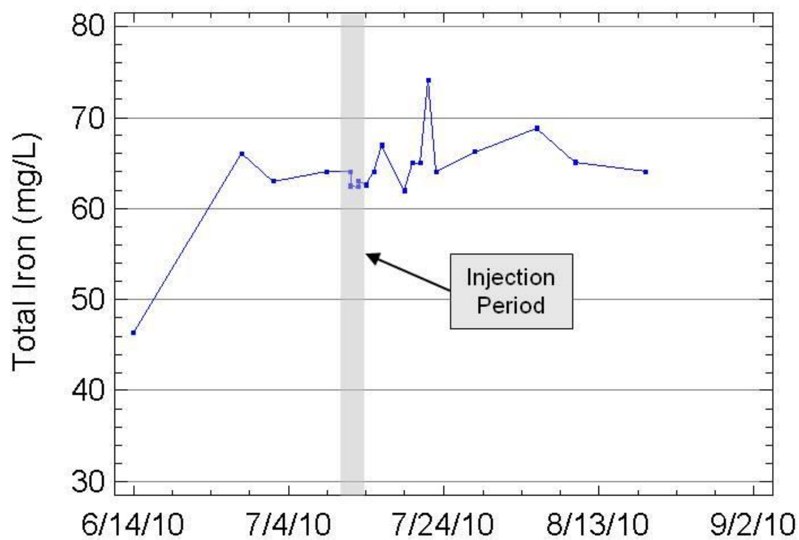

Figure 24. Total iron concentration before, during and after iron hydroxide sludge injection test.

Commonly, when mine water flow rates increase the contaminant (e.g., acidity, iron, and sulfate) concentrations decrease; an inverse relationship caused by dilution (Smith, 1988). This was not the case for the Brandy Camp discharge in the spring of 2008. This high-flow event also raised the concentration of acidity, iron, sulfate and other dissolved parameters. Similar flushing events have been observed periodically for large underground mines and mine complexes in this region. For example, a similar event occurred in the Casselman River in the spring of 1993 when the Shaw Mines complex experienced flushing due to the melting of a higher than normal amount of snow (Ziemkiewicz and Brant, 1997).

Depending on hydrologic conditions, significant portions of underground mines can remain unflooded for several years under normal precipitation rates. During these time periods, pyrite and other acid-forming minerals in the coal, roof, floor, and gob will oxidize forming large quantities of readily-soluble sulfate salts. Periodically, higher than normal precipitation in the form of snow and/or rain can cause significantly greater recharge to the mines. This high recharge in turn will cause the water levels in the mine to rise well above normal and flood areas where the sulfate salts have been building up for several years. The salts rapidly dissolve and subsequently hydrolyze creating additional acid mine drainage. Thus, a flushing event occurs with higher than normal flows and increased concentrations of acidity, iron and sulfate. This is a similar scenario that Ziemkiewicz and Brant (1997) reported occurring at the Shaw Mine complex in 1993.

During the recharge event, there was a distinct change or break in the slope of the regression hydrograph at approximately the 1,512 gpm discharge rate (Figure 25). This is directly attributable to a substantial change in the recharge rate to the Elbon Mine from the Shawmut Mine.

The break in the line slope and the lower slope below the 1,512 gpm discharge rate is interpreted to indicate that the recharge from the Shawmut Mine is declining at a slower rate more consistent with diffuse flow vertically through fractures in the interburden and regulated largely by the head within the Shawmut Mine. Whereas, when the discharge rate is above the 1,512 gpm rate the regression slope is significantly steeper indicative that a substantial portion of the recharge is more direct and less restricted. The higher discharge rates appear to occur when the mine water rises to a level in the Shawmut Mine where it will spill over the buried surface mine highwalls down through the more transmissive spoil (Hawkins, 1998) to the Lower Kittanning mine pit floor, flow along the pit floor down gradient and recharge the Elbon Mine through exposed entries buried by previous surface mining. The water level at which the spillover occurred in 2008 was not known; no monitoring wells existed into the Shawmut Mine at the time of the flushing event and the total extent of the surface mining on the Middle Kittanning Coal is unclear. However, on February 9, 2010 the flow rate briefly exceeded 1,512 gpm and the water elevation in the Shawmut Mine was about 1658.85 feet a.m.s.l., which indicates this is the point above which the recharge characteristics become less restricted as spillover occurs and the recharge rates greatly increase.

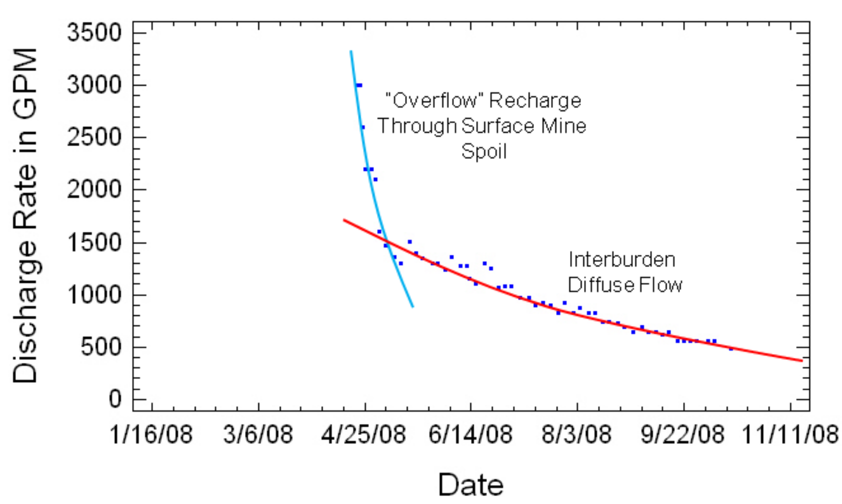

Figure 25. Brandy Camp discharge rate from the spring of 2008.

In an effort to prevent similar high flow events in the future, an abandoned portal into the Shawmut Mine was excavated (opened up) on September 15, 2009 (Figure 26). An eight-inch drainpipe was installed to maintain drainage. During excavation, the original terra cotta drainpipe into the mine was uncovered. The original drainpipe into this portal had collapsed and became plugged with debris and iron hydroxide. This procedure was performed in an attempt to allow this mine to discharge laterally to the surface and into a natural drainageway (Bodoroco Run). When mine pool water levels are elevated, drainage at this portal is designed to reduce mine water from the Shawmut Mine recharging the Elbon Mine. The water quality of the Shawmut Mine by-and-large meets effluent standards without treatment. If this water can be decanted before it recharges the Elbon Mine and becomes degraded, the Elbon Mine will have a reduced flow and better quality water can be added directly to Bodoroco Run.

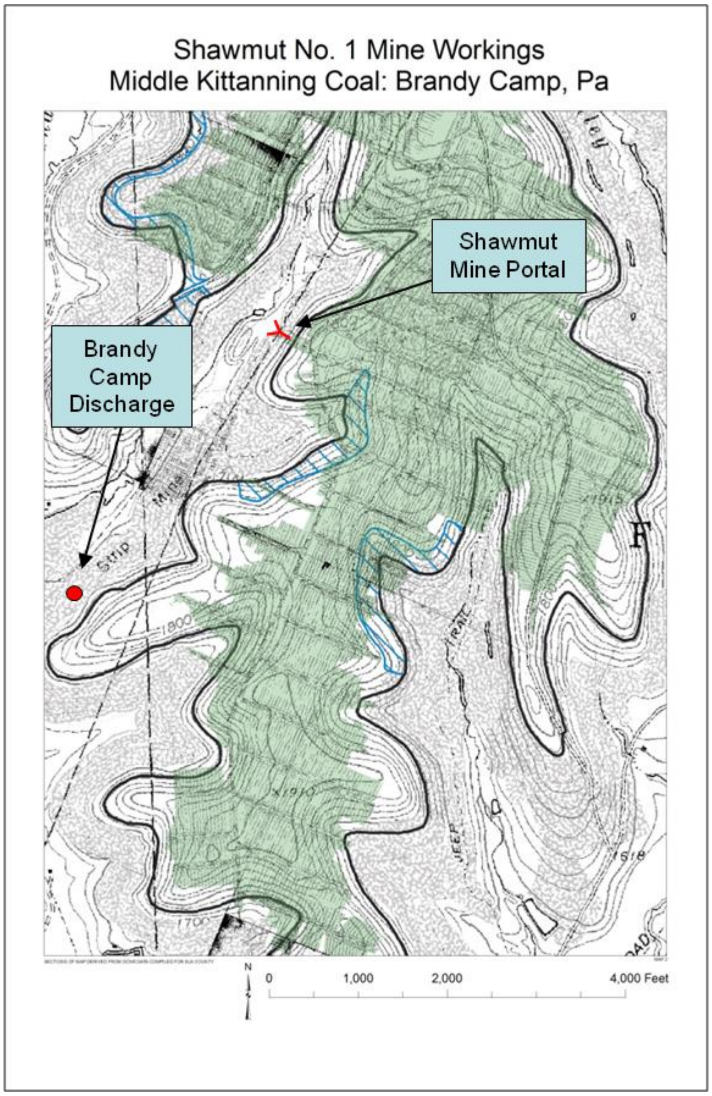

Figure 26. Location map of the Shawmut Mine portal.

At the initial opening up of the portal a large volume of water was encountered (Figure 27). There was a considerable amount of water impounded behind the seal. An initial estimate of the amount of water impounded by the portal was about 19 million gallons. However, the storage estimate, once the water was drained, was closer to 8 million gallons (Jon Smoyer, personal communication).

The initial flow rate from the portal was estimated at 1,400 gpm. Once the mine water was allowed to drain, the flow rates at the portal decreased considerably. Flow rate is measured with an H-type flume and a pressure transducer/data logger (Figure 28). Within a month the flow rate dropped to less than 2 gpm. The flow rose to over 100 gpm by mid December 2009 and over 150 gpm by mid January 2010 when recharge rates to the mine had increased. During low-flow periods, the flow rate is generally less than 5 gpm. The flow has remained below 5 gpm from July 14, 2010 through October 18, 2010. For a short time period, the piping system became obstructed with a piece of wood, which was subsequently removed.

The elevation at the portal opening is approximately 1,650 feet a.m.s.l., so based on the calculations above on the elevation at which the Shawmut Mine begins to spill over the buried highwalls and recharge the Elbon Mine more directly (about 1,658.85 feet a.m.s.l.), this portal should function as a mine pool relief point to prevent extraordinarily high flows at the Brandy Camp discharge similar to those that occurred in the Spring of 2008. The water level data from Figure 19, indicates that the pipe at this portal maintains the mine pool below 1657.5 feet a.m.s.l. and will generally hold the pool to no more than 1656.68 feet a.m.s.l.

Figure 27. Shawmut Mine portal immediately after excavation.

Injection Locations and Volumes

The calculations as to the amount of iron hydroxide sludge to be injected into the Middle Kittanning underground mine (Shawmut Mine) are important. First, and perhaps foremost, is that the mine section(s) chosen for injection have to be able to accommodate that amount of sludge for a reasonable period of time. Second, the mechanism for injection needs to be able to handle the volumes produced. The following sludge volume estimates for the Brandy Camp treatment facilities are based on the present conditions. The sludge is approximately 5% solids by volume coming off the filter press belt (Figure 29) (P. J. Shah, personal communication). However, the belt will likely be eliminated and the sludge will be pumped to the injection point without major dewatering. The Brandy Camp sludge will likely have a solids fraction similar to that from the Toby Creek plant used in the injection test, which averaged 2.43%. When fully functioning, the filter press yields an average of 12 tons of sludge per day.

Figure 28. H-type flume below the Shawmut Mine portal.

The volume of just the solids fraction created from the sludge is estimated to be 6.8 to 7.8 cubic feet per day or 2,475 to 2,840 cubic feet (0.057 to 0.065 acre feet) per year. These estimates are based on a specific gravity for iron hydroxide range of 3.4 to 3.9 and the average loading rate for iron at the discharge from November 2008 through November 2009 (860 lbs/day). The iron load was converted to mass and volume of iron hydroxide. It should be noted that these solids fraction calculations are estimated on the smallest volume possible from 2.5% solids (i.e. completely dewatered). It is probable that in the flooded environment of the abandoned underground mine, the sludge will retain some of its water composition that it has coming from the plant. Therefore, an upper level quantity estimate of sludge material, based on no loss of water, indicates that the volume will be approximately 271 to 311 cubic feet per day or 99,000 to 113,500 cubic feet (2.3

to 2.6 acre feet) per year. The actual sludge volume once injected into the mine should eventually be closer to the 100% solids than that of the raw sludge as the sludge settles out and the water decants over time.

Potential in-mine storage volumes for possible injection sites were calculated. The Middle Kittanning Coal seam averages 26.4 inches thick across the area. While much of the Shawmut Mine was mined only using room-and-pillar methods, there also appears to be some sections that were retreat mined with the "pillars removed" (Yost Associates, Inc., undated). The amount of coal removed during first and retreat mining is unclear and the existing mine maps are not conducive to estimating a reasonably accurate extraction rate. Therefore, an experiential estimate as to the extraction percentage for the Shawmut Mine was made.

Figure 29. Iron hydroxide peeling off the filter press at the Brandy Camp treatment plant.

Based on experience, it is assumed that the extraction rate for the Shawmut Mine was approximately 60%. Since, the underground mine was abandoned in the late 1950s there undoubtedly has been subsequent subsidence which ultimately reduced the effective porosity. Hawkins and Dunn (2007) calculated an effective porosity of 11% for a similarly mined underground mine in Cambria County, Pennsylvania, the Barnes & Tucker Lancashire 15 mine complex. The Lancashire 15 complex mines have likely experienced greater reduction of the voids than the Shawmut Mine due a to slightly higher extraction rate (about 63%) and the greater stresses created by the thicker overburden, up to 640 feet over much of the complex. Both of those factors tend to induce greater subsidence. Based on the aforementioned information, it is likely that the effective porosity of the Shawmut Mine will be substantially greater than that given by

Hawkins and Dunn (2007) for the Lancashire 15 mine complex but less than the assumed 60% extraction rate.

A significant effective porosity of the Shawmut Mine is also indicated by the open mine voids encountered by the core drilling of monitoring wells. The voids ranged from 2.6 to 8.9 feet. Given that the Middle Kittanning Coal averages 26.4 inches (2.2 feet) thick, clearly the main entries were mined to a greater height than the coal and they remain open to a large degree.

A range of effective porosity values of 10 to 60% were used to estimate the amount of potential storage available for the injected sludge. Table 1 below illustrates the approximate mine area that would be filled each year depending on whether just the solids fraction or the total sludge are used in the calculation. The areas filled per year are based on the production estimate averages of 2,660 cubic feet of iron hydroxide and 106,200 cubic feet of total sludge (roughly 97.5% water) per year at the Brandy Camp treatment plant.

The void-filling rate range is estimated between about 0.05 and a maximum of 11.1 acres per year at the current sludge production rate. The central value of 35% effective porosity is probably a reasonable starting point to estimate the area needed to inject sludge for a prescribed period of time. An effective porosity of 35% should have a sludge filling rate of 0.08 and 3.2 acres per year. Given the propensity of iron hydroxide to settle out of solution at extremely slow flow rates of mine water within underground mines (commonly in feet per day), it is logical to assume that the sludge in-filling rate will closer to the 0.08 acres per year and in any event should be well below an acre per year.

Table 1. Annual iron sludge-injection void-filling estimates.

Effective Porosity Range in Percent	Potential Void Volume in Cubic Feet per Acre	Acres Filled per Year of Solids	Acres Filled per Year of Total Sludge
10	9,583	0.28	11.09
15	14,375	0.18	7.39
20	19,166	0.14	5.54
25	23,958	0.11	4.43
30	28,750	0.09	3.70
35	33,541	0.08	3.17
40	38,333	0.07	2.77
45	43,124	0.06	2.46
50	47,916	0.06	2.22
55	52,708	0.05	2.02
60	57,499	0.05	1.85

Based on the injection history in the Barnes & Tucker mine complex from sludge derived from the Duman plant, each of the injection holes should last several years. However, it is recommended that BAMR budget for drilling new injection holes on a periodic basis. The need for additional holes will be predicated to some extent by the ability for the sludge to flow within the mine. Testing of the sludge with various mixtures of water will help determine the amount of propagation that can be anticipated.

There are large sections of the Shawmut Mine located to the northeast of the treatment plant that appear to be the optimal area of the mine to begin injection of the sludge. This general area is shown on Figure 30. There are large sections of the mine in that area that, based on the mine map, have not been second or retreat mined. Secondarily, there is a considerable distance, at least 1000 feet, from the projected injection to the closest original coal outcrop or possible buried highwall. The condition of these sections will not be known until more drilling is initiated. It is recommended that the drilling targets be focused on the main entries.

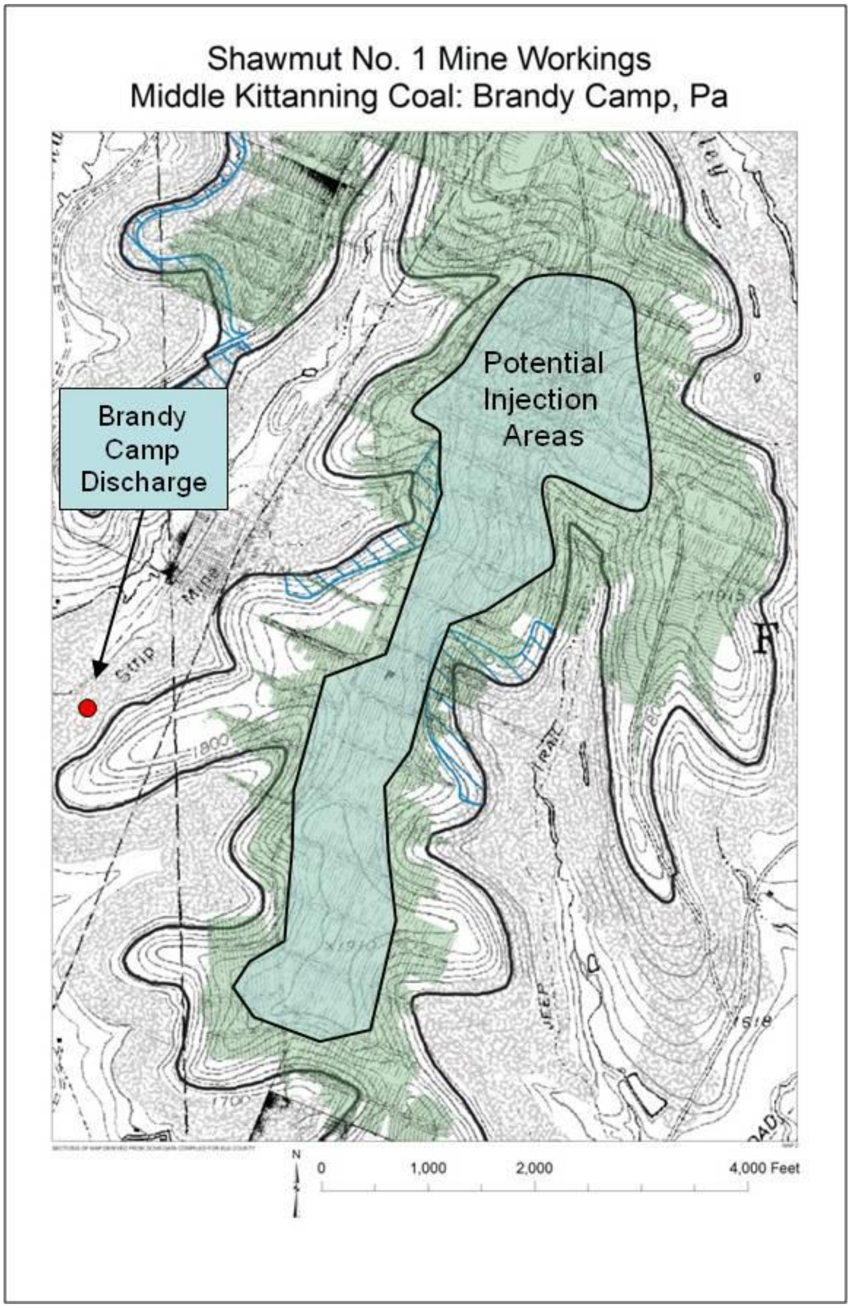

Figure 30. Map illustrating the proposed area for installing sludge injection holes in to the Shawmut Mine.

A secondary but salient concern that must be included in the determination of potential injections sites is the possibility of unchecked blowouts or discharges of this sludge to the surface. Therefore, potential sludge injections sites must be great enough distance (≈1000 feet) from the coal outcrop or buried highwalls to preclude these blowouts. However, it is important to note that water levels within the Shawmut Mine have risen to as high as 1664 feet a.m.s.l. without a blowout or even noticeable seepage along the coal cropline. Creating a mine pool or sludge deposit above 1658 foot a.m.s.l., which is the approximate elevation at the excavated portal, is not advisable.

Minimizing the cost of drilling and other infrastructure components is also a consideration for injection site selection. Sections of the mine that can accept the projected sludge volumes for protracted injection periods need to be more clearly delineated.

The location of the proposed injection locations are roughly 2,000 to 6,000 feet from the treatment plant. The elevation difference ranges between 200 and 300 feet. The plant is located near 1,600 feet a.m.s.l. while the area for proposed injection holes is 1,820 to 1,880 feet a.m.s.l.

The mine area (lobe) due north of the treatment plant was originally reviewed as a possible injection area. The relatively isolated nature of this portion of the mine should preclude recycling of iron hydroxide back to the discharge point. However, the limited size of this section of the mine makes it a less than optimal choice for long-term sludge disposal. Additionally, the narrowness of this lobe makes injection at any point too close to the original coal outcrop. Recent surface mining has eliminated the original coal outcrop, so the margin of safety from unchecked discharges due to over injection of sludge is further diminished.

Based on the test injection discussed above, the proposed injection areas on Figure 30 appear to be suitable. The core drilling indicates that the entries area open and thus will promote sludge propagation away from the injection site. The wide open nature of the Shawmut Mine should also accommodate a considerable amount of sludge before filling or plugging, which would necessitate the drilling and installation of another injection hole at a new location within the mine. Given the size of the potential injection area, the estimated effective porosity, and the rate of sludge production, it is projected that the time period sludge injection into this mine should easily exceed 100 years.

Summary and Discussion

Discharge Rate Breakdown: Analysis of the data clearly indicates that the present discrepancies noted in the discharge rate compared to the background data are in large part caused by the disturbances of deforestation and subsequent surface mining. There is a moderately strong relationship (R-squared ≈ 67%) between the annual discharge rate and the acreage that was affected by surface mining (Figure 7). While the relationship of the discharge to precipitation is weak, the annual precipitation rate also has an impact on the discharge rate.

Analysis of the area affected by surface mining compared to the average annual discharge rate indicates that the flow rate increases approximately 0.78 gpm for each acre disturbed. While this does not appear to be a significant amount compared to the total discharge rate, once several hundred acres were disturbed, the overall flow rate exhibited a substantial increase. It is doubtful that this exact formula or conversion factor will be applicable to all mine sites but it is a reasonable starting point for mines in this immediate area with similar geologic, hydrologic, and topographic characteristics. It also may be a used as starting point for other mining situations within the coal fields of the Appalachian Region but should be refined as site-specific data become available. Regardless of its widespread applicability, increases in recharge rates clearly must be factored into hydrologic assessments and projections when it is known that deforestation and surface mining are going to occur in the mine recharge areas in the future.

Figure 16 above illustrates that there is an expected trend of increasing discharge rate with greater annual precipitation. However, the fit of the line is relatively weak (R-squared = 48.1%) and the P-Value of 0.084 shows that the significance of the relationship between the discharge rate and annual precipitation is below a 95% confidence.

Use of multiple regression to predict the mean annual discharge rate (dependent variable) in gallons per minute based on the independent variables of percent of the recharge area affected and annual precipitation, illustrates that the impact of those two variables combined is much stronger than either single parameter. An R-squared value of 88.5% was obtained for an equation for the fitted line (Equation 4). The P-Value of 0.0002 indicates there is a statistically significant relationship between the variables at greater than a 99% confidence.

$$\text{Mean annual discharge rate} = -43.42 + (7.98 \times A) + (12.49 \times P) \qquad (4)$$

Where: A = percentage of the recharge area affected
P = precipitation in inches

Future situations where a substantial portion of the recharge area for surface and/or underground mine discharges will be impacted by additional surface mining, both the percentage of the total recharge area to be disturbed and the annual precipitation need to be factored into expected and observed changes in the mean annual discharge rate. Of the two parameters, the deforestation and physical disturbance associated with surface mining exert the biggest impact. Equation 4 or something similarly developed on a region-specific basis could be employed to predict future discharge rates.

Other factors that were considered during this assessment to possibly have an impact on the discharge rate were improper flow determination techniques, significant changes in the location of flow measurement point and/or other anthropogenic activities in the basin that may impact recharge rates. While these factors were initially considered to possibly have the potential to influence the recharge rate for the Elbon Mine, this study has shown that this is not the case.

Conclusions: Substantial increases in infiltration rates in overlying reclaimed surface mined areas have caused a significant increase in the flow rate at the Brandy Camp discharge. The reclaimed mine spoil not only allows a greater percentage of precipitation to infiltrate, it is capable of storing larger quantities of ground water and releasing it to the underlying mines slowly so flow rates during dry spells are higher than they were previously. Replacement of hardwood forest cover with grasses contributes to the increased infiltration rates. As tree cover, specifically white pine, increases over time, the infiltration rates will likely decrease and should eventually return to near pre-surface mining levels.

The present water quality within the Shawmut Mine pool, especially the pH (geometric average of 5.9 S.U), is conducive to preventing the injected iron hydroxide from redissolving. The use of calcium hydroxide as a neutralizing agent also works in favor of keeping the iron hydroxide precipitate stabilized (Watzlaf and Casson, 1990). The results of test sludge injection indicate that the iron hydroxide is stable and is not being redissolved when placed into the Shawmut Mine.

The open conditions of the Shawmut Mine workings and the quality of the water in the mine make it a feasible option for iron sludge disposal by injection through boreholes drilled and constructed specifically for that purpose. The test iron sludge injection was on all accounts successful. The water quality of the Shawmut Mine is such that redissolution of the iron hydroxide is unlikely to occur at any noticeable rate. The rate of mine void filling from the iron sludge is calculated to be well less than one acre of mine area per year. With the amount of available abandoned underground works associated with the Shawmut mine and at the present sludge production rate, there should be sufficient space for injection disposal for well over 100 years. It is anticipated that the sludge production will diminish with time as the effluent iron and acidity concentrations likewise decrease from natural amelioration. Lower acidity concentrations will allow the use of less lime. Sludge production will decrease as the iron concentration and the lime usage both diminish with time. The excess alkalinity in the sludge that is injected should also work to decrease the acidity of the mine water. While it is not likely all of the alkalinity will be released into the mine water, some alkalinity from the sludge will ultimately lower the acidity as well as raise the pH of the discharge water.

The relatively low vertical hydraulic conductivity (median 1.0×10^{-7} m/s) of the thin (38.4 feet) interburden between the Middle and Lower Kittanning coals supports a perched mine pool within the Middle Kittanning Shawmut Mine. The low vertical hydraulic conductivity is directly related to the clay-rich strata of the interburden which inhibits subsidence-induced fractures from extending from the Elbon Mine up to Shawmut Mine.

When the Shawmut Mine pool elevation exceeds 1658.85 feet a.m.s.l. some of the water recharging the lower Elbon Mine was flowing less restrictedly through the mine spoil over the buried highwall and down into the lower mine. Monitoring of the mine pool indicates that the installation of a drainpipe at approximately 1656.68 feet a.m.s.l. into an abandoned portal of the Shawmut Mine now should prevent this more direct recharge to the Elbon Mine from occurring.

Recommendations: While additional drilling has revealed that there is considerable void space available in the Shawmut Mine for sludge injection. It is recommended that a moderate drilling program be conducted in the potential sludge injection area to obtain a better understanding of the mine workings in the Middle Kittanning Shawmut Mine and to enhance the assessment of the openness and free interconnection of the mine workings. These additional data will allow a more detailed quantitative evaluation of the available storage volume. However, all information and data collected to date indicate that injection of iron hydroxide sludge into the Shawmut Mine is a viable disposal option from both a volumetric and economic standpoint.

It may be a good idea to reassess all the stream reaches that overlie the mines that could contribute water to the Brandy Camp discharge to determine where direct infiltration is occurring and to what degree. Using geophysical means (e.g., WADI) and direct flow measurements, the losing sections can be delineated. The losing stream reaches could then be grouted. Injection of a water-activated expanding polyurethane grout is recommended. However, shotcrete or some other type of topical liner may also be an option to create an impervious channel.

In order to further reduce the amount of mine water that ultimately must be treated, the recharge rate needs to be reduced for the bulk of the overlying areas that drain to the mine. Reforestation of the overlying areas which are hydrologically connected to the Elbon Mine and the Brandy Camp discharge is highly recommended. White Pine, based on its propensity to intercept and utilize infiltrating water, may be the optimal tree species choice. Planting of various high water-use hardwoods are also a good recommendation.

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Appendix A

Head (H)	Weir Type			Percent Difference Compared to Broad Type 1	Percent Difference Compared to Broad Type 2	Difference between Sharp-Crested and Broad Type 1 in cfs	Difference Between Sharp-Crested and Broad Type 2 in cfs
	Sharp in cfs	Broad Type 1 in cfs	Broad Type 2 in cfs				
0.1	0.42	0.29	0.39	-30.58	-6.82	0.13	0.03
0.2	1.18	0.85	1.10	-27.81	-6.35	0.33	0.07
0.25	1.64	1.21	1.54	-26.41	-6.11	0.43	0.10
0.3	2.16	1.62	2.03	-25.00	-5.87	0.54	0.13
0.4	3.30	2.57	3.12	-22.17	-5.39	0.73	0.18
0.5	4.59	3.71	4.37	-19.30	-4.91	0.89	0.23
0.6	6.00	5.00	5.74	-16.72	-4.42	1.00	0.27
0.7	7.53	6.23	7.23	-17.22	-3.92	1.30	0.30
0.75	8.33	6.91	8.02	-17.01	-3.67	1.42	0.31
0.8	9.15	7.61	8.84	-16.79	-3.42	1.54	0.31
0.9	10.86	9.12	10.54	-16.04	-2.92	1.74	0.32
1.0	12.65	10.68	12.35	-15.60	-2.41	1.97	0.30
1.1	14.52	12.32	14.25	-15.15	-1.89	2.20	0.27
1.2	16.46	14.04	16.23	-14.70	-1.37	2.42	0.23
1.3	18.46	15.77	18.30	-14.57	-0.84	2.69	0.16
1.4	20.52	17.56	20.46	-14.43	-0.31	2.96	0.06
1.5	22.64	19.55	22.69	-13.64	0.23	3.09	-0.05