HYDROLOGIC CHARACTERIZATION OF MULTIPLE SEAM UNDERGROUND AND SURFACE MINING IN NORTHERN APPALACHIA[1]

J. W. Hawkins[2] and J. J. Smoyer

Abstract. A hydrologic assessment of an underground mine complex overlain by extensive surface mining in north central Pennsylvania has been conducted. The mine complex is drained principally by one discrete discharge point which the flow rate (median of 2,167 L/min.) increased significantly (67%) above background (median of 1,317 L/min.) during the period it took to construct a treatment plant. The source of this major discharge rate increase and other unusual hydrologic characteristics were investigated. Subsequent to background monitoring, about 440 hectares of surface mining and reclamation (85% of the recharge area) occurred on numerous seams overlying the underground mines which greatly increased infiltration rates. A direct correlation was observed between the surface mined area and increased recharge to the underlying deep mines.

Atypically, in-mine water storage does not exist to any substantial degree in the basal Lower Kittanning underground mine from which the main discharge emanates. The overlying Middle Kittanning (Shawmut) mine is the main storage unit for mine water. The Middle Kittanning mine behaves like a perched aquifer system because of a moderate vertical hydraulic conductivity (median rate of 1.0×10^{-7} m/s) of the thin clay-rich shale and siltstone interburden (mean of 11.7 m) and local structural features. During periods of low recharge, pool levels decline to a point where the majority of the mine water flowing downward from the Middle Kittanning mine to the underlying Lower Kittanning mine is widespread and diffuse in nature. The discharge rate is consistently within a narrow range of 1,745 to 2,381 L/min. about a median of 2,040 L/min. When surface infiltration rates are high causing the mine pool levels to rise, a portion of the recharge from the Middle Kittanning mine to the lower seam mine is more channelized flowing through the backfill from outcrop surface mining over the buried highwalls and into the underlying Lower Kittanning mine. During these periods, the flow ranges more broadly from 5,725 to over 11,356 L/min. about a median of 8,328 L/min.

The openness of the Shawmut mine workings and the water quality of the mine pool make it viable to inject iron sludge. A test injection of 2.8 million liters of iron sludge into the mine was successful. Testing of the mine workings indicates that sufficient space exists to accommodate iron sludge disposal for more than 100 years.

Additional Key Words: spoil, interburden, mine pool, recharge, infiltration rate, vertical hydraulic conductivity, iron hydroxide, underground sludge injection

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[1] Paper was presented at the 2012 National Meeting of the American Society of Mining and Reclamation, Tupelo, MS ***Sustainable Reclamation*** June 8 – 15, 2012. R.I. Barnhisel (Ed.) Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502

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Proceedings America Society of Mining and Reclamation, 2012 pp 189-218
DOI: 10.21000/JASMR12010189

http://dx.doi.org/10.21000/JASMR12010189

Introduction

The work conducted during this study was performed at the request of and in cooperation with the Pennsylvania Department of Environmental Protection (PADEP), Bureau of Abandoned Mine Reclamation (BAMR), Cambria Office in Ebensburg, Pennsylvania. This manuscript is the result of the hydrogeologic characterization of the interrelationship of the underground and surface mines hydrologically connected to a discharge located at the Brandy Camp treatment facilities. From this point forward, this mine discharge will be referred to as the Brandy Camp discharge. An additional assessment of the potential to inject the iron hydroxide sludge from the plant into the underground mine workings was conducted.

Shortly after the Brandy Camp treatment plant was completed and operational, it was found to be significantly undersized. During high-flow conditions, the plant was treating well less than 50% of the mine discharge and the remainder is bypassed. The baseline (background) discharge measurements were much lower than those recorded since the plant came online. This study was originally undertaken to determine why the discharge rates were so dramatically different. A second objective of this project was to conduct a hydrologic characterization of related underground mines to determine potential locations for injection of iron sludge from the treatment plant and settling ponds. At present, this sludge is disposed of and buried in nearby surface mines. Once the last of these surface mines closes, a new disposal site and/or method will be necessary. The sludge injection areas within the underground mines require sufficient storage capacity to allow periodic disposal over an extended time period, while at the same time precluding remobilization of the iron into the mine water. The sections of the mines that receive the iron sludge need to have adequately open entries to allow for flow of the sludge away from the injection point and store the solids portion. The mine water quality needs to be such that the iron hydroxide in the sludge does not redissolve and thus recycled back to the Brandy Camp discharge.

Portions of this work were previously covered in Hawkins and Smoyer (2011); however salient additional information has been added herein. The authors also believe that attendees of ASMR not privy to the earlier publication will equally benefit from this offering.

Background

Site Location

The Brandy Camp discharge and hydrologically associated mines are located adjacent to the town of Brandy Camp in southern Elk County, Pennsylvania, U.S.A. (Fig. 1). Brandy Camp is a small former coal mine company town approximately 14.5 kilometers northeast of Brockway along State Route 219. The Brandy Camp discharge is located approximately 305 meters south-southeast of the town (Fig.1).

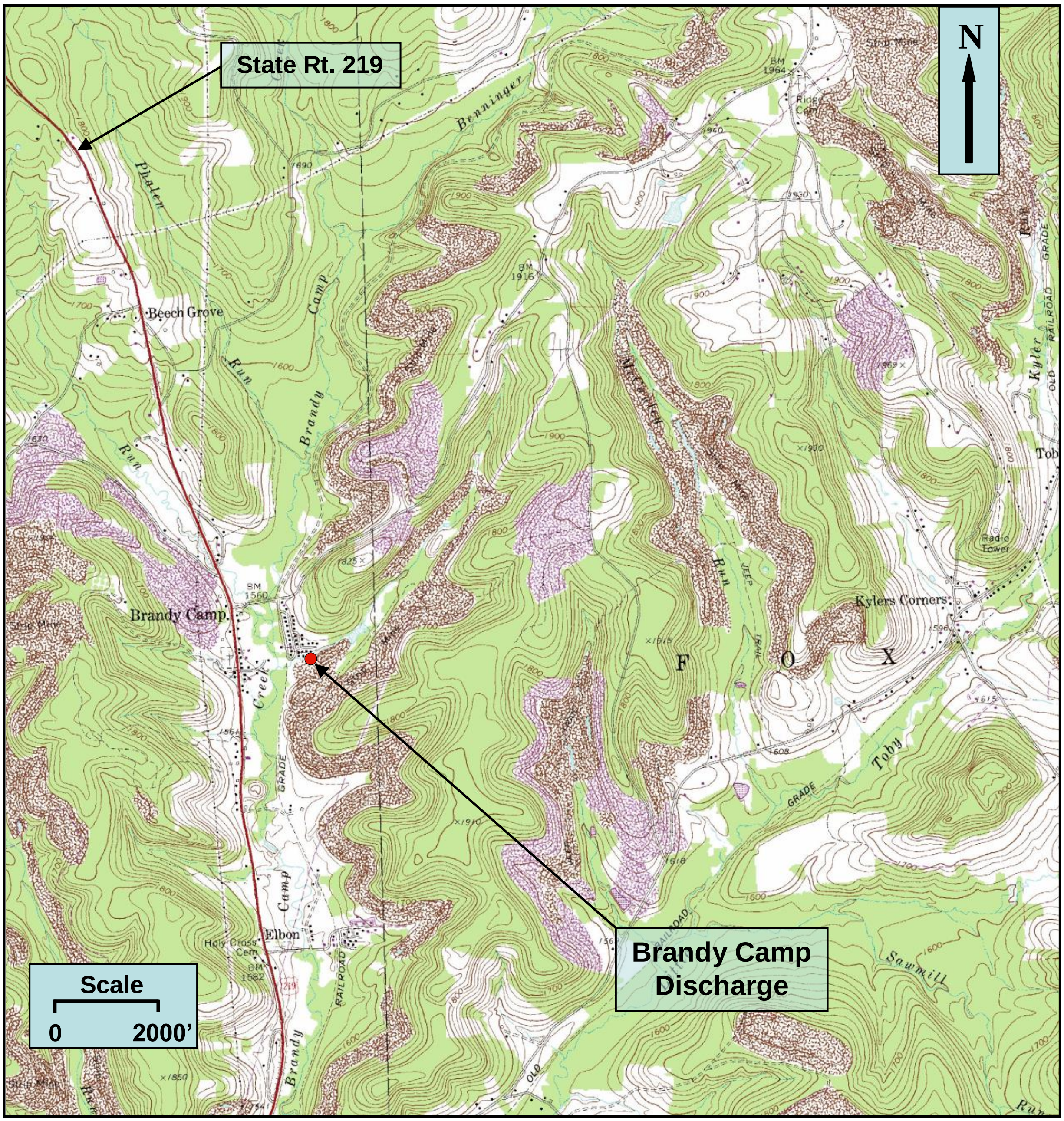

Figure 1. Topographic map of the Brandy Camp discharge and surrounding area.

Geology

The area of interest 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, surface and underground, in this region. However, some additional mining, primarily surface mining, has occurred on the Upper Kittanning, Lower Freeport, Upper Freeport, Clarion and various localized split and rider seams. The strata associated with these coals are mainly shales with a few thinly bedded sandstone units. Yost Associates, Inc. (undated) noted the presence of the Lower Freeport Limestone capping the hilltops to the north and east within the drainage area of the Brandy Camp discharge.

The strata within the Brandy Camp discharge drainage area are gently dipping (generally, 2 degrees or less) toward the southwest to northeast trending Shawmut Syncline which bisects the drainage area (Fig. 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.

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 porosity and permeability are very low and their influence to the ground-water regime is negligible. At shallow depths, generally less than 45 to 60 meters, 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 time (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; Kipp and Dinger, 1987). Ground water flows from the hilltops and hillsides down toward the adjacent streams in a quasi stair-step manner. 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 ground-water flow in this region is limited to the upper 60 meters.

Underground mining in this region began as early as 1864. The underground mines draining to the Brandy Camp discharge began in earnest in the 1870s. Underground mining in the Lower Kittanning continued until the 1930's (Fig. 2). Around 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 seams continued until the past few years.

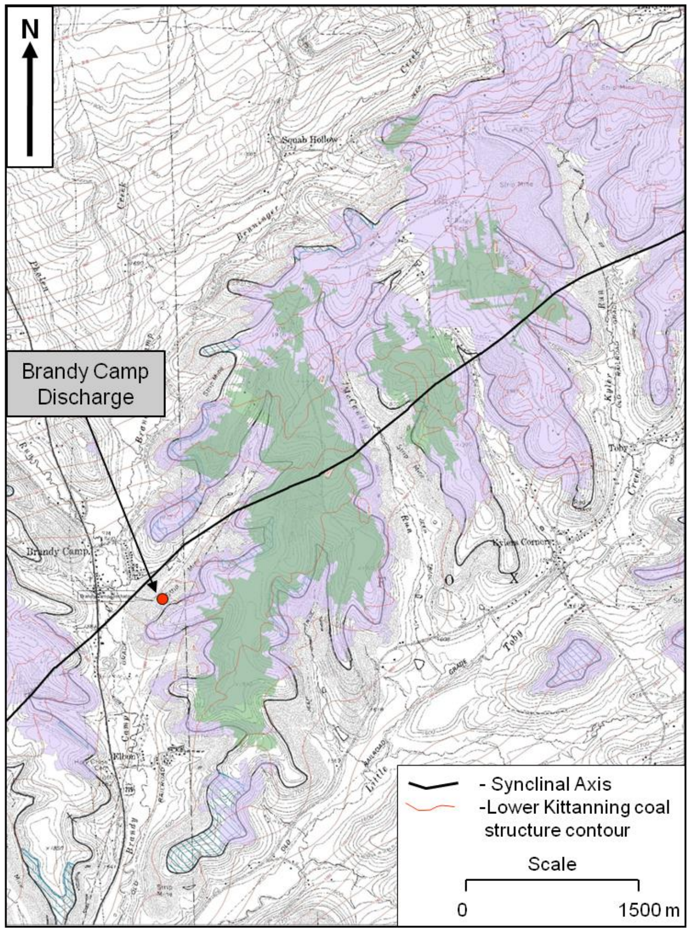

Figure 2. Underground coal mining on the Middle (green) and Lower Kittanning (amethyst) coals in the Brandy Camp area. Structure contours on based on the bottom of the Lower Kittanning Coal.

Analysis of the Brandy Camp Discharge

The initial task of this study was to determine if the pre- and post-plant construction discharge rate differences are definite (not random variation) and, if so, are they statistically significant. Pre-construction data also include flows recorded during plant construction. Figure 3 illustrates that the median flow rate after plant construction (3,617 L/min.) is significantly higher ($p \leq 0.05$) than the pre-construction median flow rate (2,167 L/min.). The lack of an overlap of the two notches about the median on the notched box-and-whisker plot indicates the post-construction flows are significantly higher. Similar results were obtained analyzing these data using the Student's T-test and Wilcoxon Mann-Whitney U (a nonparametric version of the Student's T-test). The data sets were transformed to approximate a normal distribution in order to conduct the Student's T-test. The Kruskal-Wallis test determined that the distribution of the two data sets was also significantly different ($p \leq 0.05$).

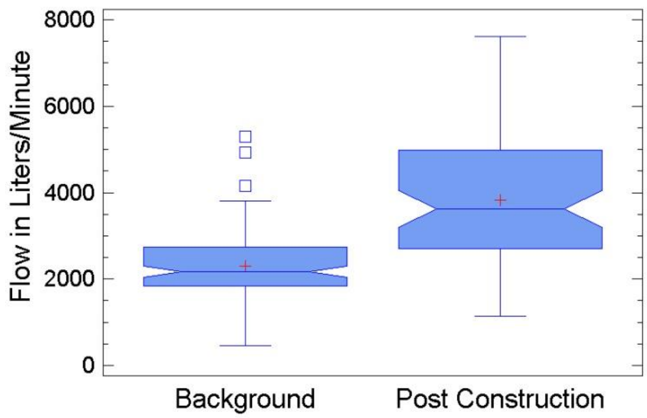

Figure 3. Notched box-and-whisker plot illustrating the flow rate differences observed before and after construction of the treatment plant.

Initially several potential reasons for the pre- verses post-plant construction flow disparity were postulated: the pre-plant measurements were conducted improperly or the flow measuring device was faulty, the post-construction measurements are incorrect, the measurement point location changed substantially from background, the surface mining within the basin during this period impacted the recharge rates, and/or the precipitation/climatic conditions changed substantially during this period. Each of these possible reasons was explored. However, the impacts of precipitation and/or surface mining were considered the most probable causes a priori.

Flow Measurements

A sharp-crested rectangular weir near the discharge point was initially installed to determine flow rates prior to plant construction. A replacement broad-crested rectangular weir was installed a "few feet downstream" from the original location during the plant construction (P.J. Shah, personal communication). This short-distance move had no impact on the flow measurements, given that no gain or loss of flow occurred between the two points. A review of the weirs (Fig. 4 and 5) indicates that they were constructed and functioning properly.

Discussions with plant personnel indicate that they were reading and recording the discharge rates accurately.

Figure 4. Brandy Camp discharge flow-monitoring weir prior to plant construction.

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

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. There were surface mining activities in this region for several decades prior to 1989, but the surface mining within the watershed for the period slightly before, during and after background data collection were of specific interest for this study. A positive correlation was observed between increasing area affected by surface mining and a higher average flow rate at the Brandy Camp Discharge (Fig. 6). Given the difficulties in determining flow rate and inherent uncertainties common to natural data the correlation here (R-squared = 68.6%) is comparatively strong.

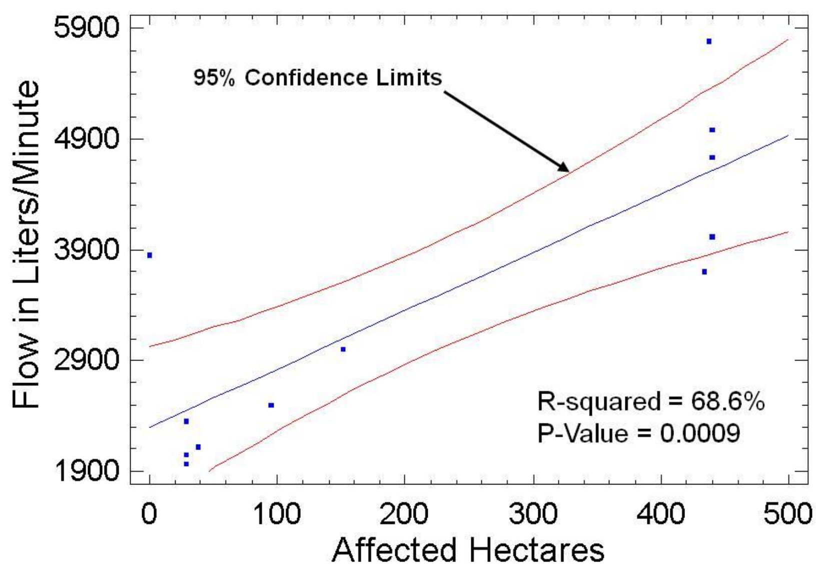

Figure 6. Regression analysis illustrating the relationship of discharge rate to amount of drainage area affected by surface mining.

When background monitoring for the discharge began in July of 1993, recent surface mining had affected about 40 hectares with 29 hectares already reclaimed. Approximately 174 hectares had been affected with 121 hectares 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 (Fig. 7). An additional 266 hectares were surface mined and 318 hectares 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 fluctuations alone. While 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 when slightly over 23% of the recharge area had been mined and reclaimed (Fig. 7). The impacts of precipitation and climatic conditions are discussed in more detail in the following section.

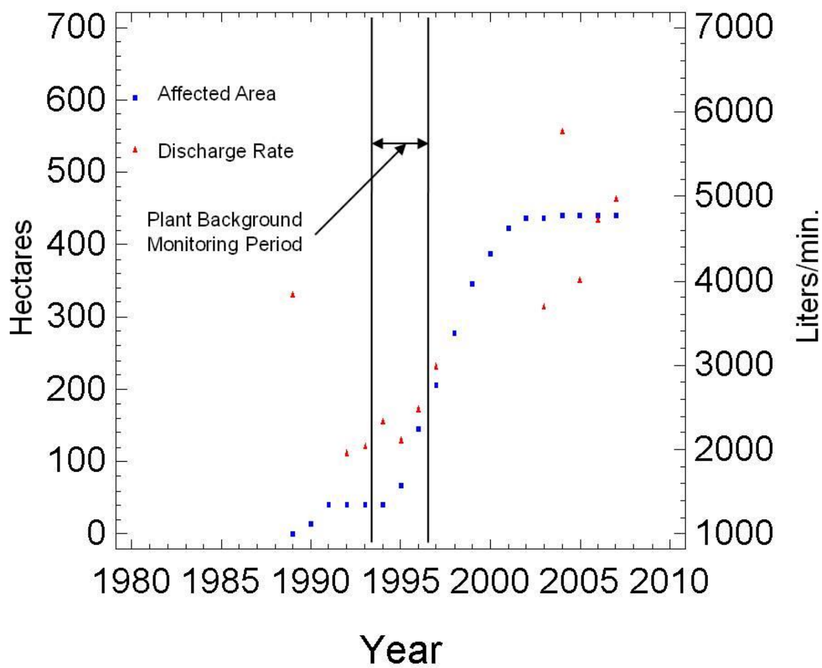

Figure 7. Relationship of surface mine affected acres and average flow rate of the Brandy Camp discharge.

In all, a total of 440 hectares were surface mined during this period of interest. The total-recharge area for the mines that the Brandy Camp discharge-drains is approximately 520 hectares, so the surface mining during this period effected approximately 85% of the recharge area. This caused an increase of 67% in the median flow rate at the Brandy Camp discharge.

During surface mining activities, surface and ground waters are controlled to a large extent. Surface water is collected and diverted to impoundments via ditches. The ditches and impoundments are engineered to prevent infiltration of the water. Impoundments are designed to hold the runoff water until effluent standards are reached then discharge it into the nearest natural drainage way below the mine. 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 inhibits vertical recharge to underlying deep mines as much as possible. Therefore, much of the precipitation falling on the areas where surface mining activities are occurring will be intercepted and diverted until mining is completed and the erosion and sedimentation controls are removed.

Once the site is backfilled and sufficiently revegetated, the collection ditches and ponds are removed. Thus, surface water is no longer intercepted and routed from the site. A portion of 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. Water entering the Shawmut mine does not discharge directly (Yost Associates, Inc., undated), but instead flows downward into the underlying Lower Kittanning Elbon Mine and is subsequently expressed at the Brandy Camp discharge. This post surface mining change in water handling is a major factor in the increased amount of recharge occurring in the drainage area for the Brandy Camp discharge. Changes in the vegetative cover, ground disturbance from mining, and changes in the soil structure post mining play a significant role in the changes in the vertical recharge rates.

Some earlier studies of the impacts of surface mining and reclamation indicate that 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 about four years after reclamation, infiltration rates tend to return 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 infiltration rates of 1-2 centimeters per hour (cm/h), but within four years after reclamation the infiltration rates of “some minesoils” approach the premining rates of 8 cm/h. The increased infiltration rates were facilitated by the development of macropores in the minesoil and 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 an adjacent “lightly mined” watershed (Corbett, 1968).

Infiltration of precipitation also depends on the extent that the material has been regraded or degree of surface roughness. Deane (1966) recorded infiltration rates of 10.2 and 23.6 cm/hr for ungraded spoils and 1.5 and 2.3 cm/hr for the same spoils that were regraded in Ohio and Illinois, respectively.

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 of the mine spoil, but also spoil aquifers tend to have higher storage capacity (effective porosity) of this additional water than undisturbed strata.

The deforestation that precedes the mining may be a major factor in the increased infiltration. Deforestation greatly reduces the evapotranspiration and 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 base flow 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 increase in infiltration. The commensurate increases in stream base flow are 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 un-mined watershed. For a complete two year period, total unit flow of the heavily-mined watershed was about 1.75 times greater than the un-mined watershed. They attributed much of this change to decreased evapotranspiration due to deforestation and 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 un-mined watershed stopped flowing. They did, however, attribute some continued baseflow through the summer to increased storage capacity of mine spoil. The substantially increased ground-water storage common to mine spoil (Hawkins, 1998), coupled with the increased infiltration facilitated by decreased evapotranspiration would support stream flow down gradient of reclaimed mine sites when nearby streams in unmined watersheds tend to stop flowing during dry spells.

Wiley et al., (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 un-mined watersheds. Truax (1965) observed that at a time when mined watersheds in southwestern Indiana were yielding about 177 liters per minute per square kilometer (September and October 1964), other nearby watersheds were dry. Curtis (1979) stated that spoil can store large quantities of water that eventually discharge as base flow to the streams. He further states 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 held 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 approaches 25% effective porosity at times (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 the fractured strata are well less than 1% (Mackay and Cherry, 1989).

An aerial photograph taken in October 1968 of the contributing area for the Brandy Camp discharge indicates that the majority of the land (mottled areas) was heavily forested (Fig. 8). Preparation for surface mining removed the trees. Initially, grasses were planted as a vegetative cover once the mines were reclaimed (Fig. 9). This drastic change in vegetative cover alone may account for higher infiltration rates for the areas hydrologically connected to the Brandy Camp discharge. Slowly through plantings and volunteer growth, trees are returning as a significant cover on the reclaimed surface mines (Fig, 10). Eventually, recharge rates may return to pre-mining levels, but this may take many decades. Douglass and Swank (1975) noted that areas replanted in conifers, specifically white pine, eventually exhibit recharge rates at or somewhat below that of the pre-existing hardwoods. This is due to the higher water interception rate and transpiration losses associated with white pine compared to most hardwoods.

The increased infiltration, hence subsequent recharge to the Elbon Mine, caused by surface mining and reclamation is illustrated by the mean percentage of the precipitation that is discharging at the Brandy Camp discharge (Fig. 11). The average percent of precipitation expressed at the Brandy Camp Discharge from 2003 through 2009 was slightly more than 36%. 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 may be related to previous surface mining

Figure 8. Aerial photograph from October 1968 showing that much of the recharge area for the mines contributing to the Brandy Camp discharge was forested.

Figure 9. Example of grasses growing on recently-reclaimed surface mined areas within the recharge area for the Brandy Camp discharge.

Figure 10. Planted and volunteer trees beginning to populate reclaimed surface mined areas within the recharge zone for the Brandy Camp discharge.

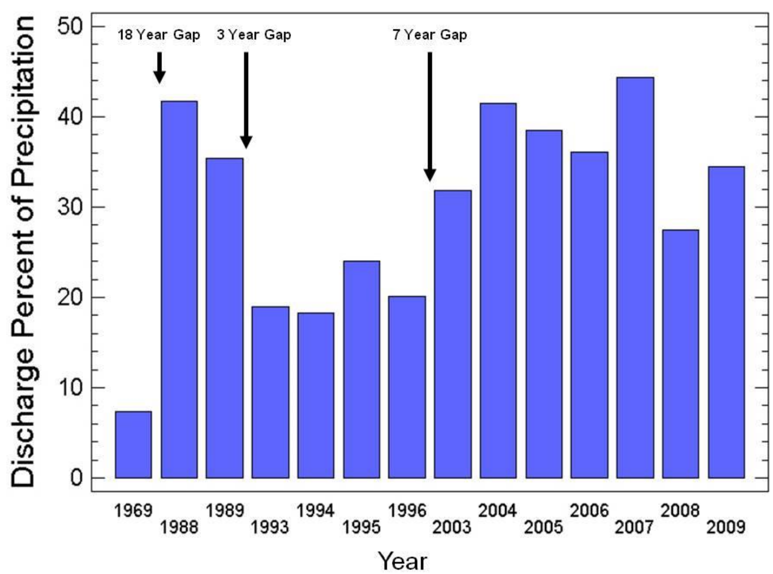

Figure 11. Changes in the percentage of recharge from precipitation before and after construction of the treatment plant.

activities that occurred during the preceding years; however, percentage appears more likely to be skewed high because most of the flows recorded during that period were visual estimates. The extremely low percentage of precipitation noted at the Brandy Camp discharge in 1969

(~7%) was likely caused by considerable evapotranspiration occurring due to the heavy forest cover over the discharge recharge area at that time.

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 normal precipitation, then this should be reflected in the records for those years the background data were collected. 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 unusual discharge rates (Fig. 12). The annual precipitation data for the area is based on the precipitation at the Ridgeway station obtained from the database of the National Oceanic and Atmospheric Administration (NOAA). The Ridgeway station, the closest NOAA recording site available, is approximately 12.1 kilometers to the north of the center of the study area.

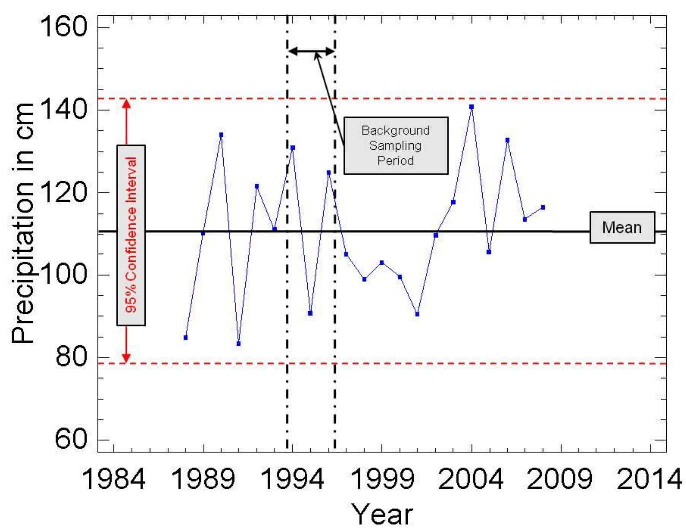

Figure 12. Annual precipitation amounts from 1988 through 2006.

The precipitation amounts for 1993 through 1996 were well within two standard deviations of the mean of 110.2 centimeters 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 slightly above average precipitation levels; 18.7 and 13.3% above the mean, respectively. The precipitation levels in the time period 2002 to 2008 were also well within the 95% confidence interval about the mean (Fig. 12). This indicates that the higher discharge rates exhibited since the plant came on line are not due to periods of abnormally high precipitation.

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 in 2003 continuing through 2007, the discharge rate exhibits a positive correlation (R-squared = 51.2 with a P-Value of 0.174) with precipitation albeit weak with sparse data. Whereas, during the period from 1989 to 2002, when substantial surface mining and reclamation was occurring no such correlation was seen. Precipitation has always exerted some influence on the discharge, but its influence was masked from 1989 to 2002 by the strong water management practices employed during surface mining.

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 13.5 centimeters of rain during that period which also melted the existing thick snow pack. This snow melt and precipitation caused considerable recharge to the mines and the Brandy Camp discharge increased to over 11,350 L/min. The exact maximum discharge rate could not be determined due to much of the water being bypassed from the plant through a non-gauged pipe and ditch system. This extreme recharge event also raised the concentration of acidity, iron, sulfate and other dissolved parameters through a flushing action within the mine.

There was a distinct change or break in the slope of the regression hydrograph at approximately the 5,725 L/min. discharge rate (Fig. 13). This is directly attributable to a substantial change in the recharge mode and rate to the Elbon Mine from the Shawmut Mine.

The break in slope and the lower slope angle below the 5,725 L/min. discharge rate indicates that the recharge from the Shawmut Mine is declining at a rate more consistent with diffuse flow vertically through fractures in the interburden and regulated by the head within the Shawmut Mine. Whereas, when the discharge rate is above the 5,725 L/min., the angle of the regression slope is considerably steeper indicative that a substantial portion of the recharge is more direct and less restricted. The higher discharge rates appear to be caused when the mine water rises to a level where it will spill over the buried surface mine highwalls down through the more transmissive spoil (Hawkins, 1998) to the Lower Kittanning pit floor, then flow along the pit floor down gradient and recharge the Elbon Mine through entries buried by previous surface mining. The water level at which the spillover occurs 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 is unclear. However, on February 9, 2010 the flow rate briefly exceeded 5,725 L/min. and the water elevation in the Shawmut Mine was 505.62 meters above mean sea level, which indicates this is the point above which the recharge characteristics become less restricted as spillover and the rates greatly increase. The median flow rate quadrupled from 2,040 L/min below the hydrograph line break to 8,328 L/min. above the break (Fig. 13).

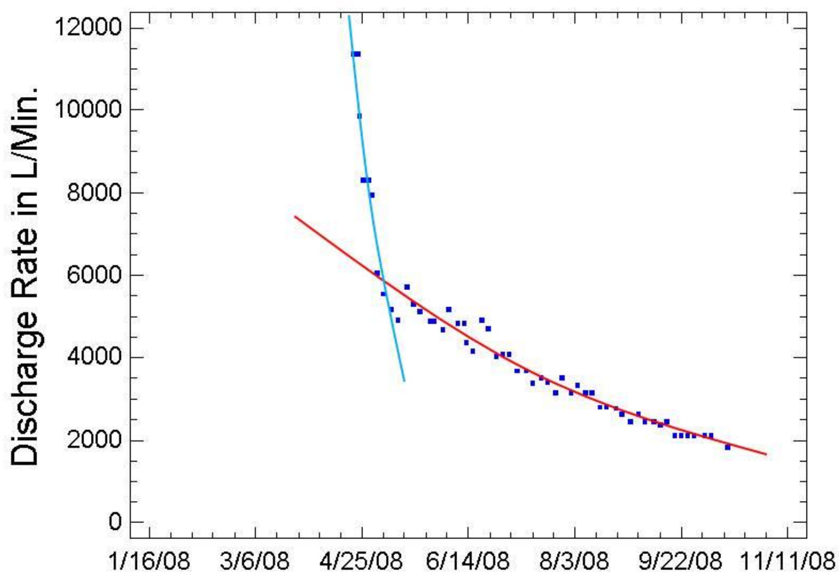

Figure 13. Brandy Camp discharge rate from the spring of 2008.

Hydrologic Characterization of the Underground Mine Workings

The second major task in this study was to determine the potential for disposal of iron hydroxide-rich sludge generated at the treatment facilities into the Shawmut Mine in the Middle Kittanning Coal and/or the Elbon Mine in the Lower Kittanning Coal. Critical to this undertaking is determining if there is ample storage capacity in the mines and if the connection between open entries is unrestricted to allow free flow of the sludge away from the borehole. In order for the borehole injection to be efficient, the sludge needs to flow considerable distances from the injection point before the solids settle out. Another paramount concern is if the quality of the water in the mine(s) is such that the iron will not be re-dissolved and mobilized. It is undesirable to treat iron that is reintroduced by sludge injection.

In the Appalachian Plateau, vertically stacked mines situated above the local drainage system tend to drain freely down to the lowest coal seam mined discharging laterally from a structural low point from that stratum. This scenario is not the case for the study area. The hydrologic regime within the study area is distinct 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 Shawmut mine pool is a perched aquifer system above the lower coal seam. The pooled mine water from the Shawmut Mine subsequently flows down through the interburden in a disseminated fashion into the Elbon Mine. There is no significant pooling within the Elbon Mine known. Instead, the mine water flows laterally through the open entries and discharges from a structural low point within the mine as the Brandy Camp discharge.

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 indicates that the Shawmut mine pool varies in water level and aerial extent seasonally. Whereas, monitoring wells into the underlying Elbon Mine shows that it has no notable pooled water. Water flows along the floor in the Elbon Mine and discharges at the intersection of a structural low point and a topographic low.

The interburden between the two coals ranges from 10.0 to nearly 13.6 meters with a mean of 11.7 meters. 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 is light gray pliable claystone. 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 have high-angle fracturing up to at least nine meters above the Lower Kittanning mine. The drilling indicates that the subsidence-induced fractures extend close 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 (Fig. 14).

Figure 14. Interburden core sample exhibiting high angle subsidence-induced fracture with iron staining due to ground water contact in a siltstone unit.

The high clay content of the interburden strata attenuates fracture propagation from the Lower toward the Middle Kittanning level. The clay-rich strata are somewhat pliable and may deform in addition to fracturing when subjected to stress. Additionally, the clay tends to behave somewhat plastically allowing some self-healing of subsidence-induced and naturally-created fractures; thus the reducing permeability and in turn restricting ground-water movement.

The relatively low permeability of the strata is illustrated by the perched mine pool in the Middle Kittanning supported by relatively thin interburden. 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 rearranging the Darcy's law (Equation 1) and using measured mine pool levels, total flooded area, mean interburden thickness and the total discharge rate from the Elbon Mine. Hydraulic conductivity for vertical flow through the strata between the two coals ranged from 3.6×10^{-8} to 2.3×10^{-7} meters per second (m/s) with a median of 1.0×10^{-7} m/s. These values are similar to lower Kv values for unfractured fine-grained sandstones and mid-range values for unfractured siltstones (Fetter, 1980). Fidler (1997) recorded a Kv of 2.5×10^{-8} m/s for a 40 meter thick glaciolacustrine clay unit in southwestern Ontario, Canada. While much lower values have been estimated for true aquitard units (e.g., 10^{-12} to 10^{-15} m/s) (Kleeschulte, 2005; Eaton and Bradbury, 2003), the interburden here has sufficiently low permeability to support the perched mine pool system.

$$Kv = Q/A \times (dh/dL) \quad \text{(modified from Fetter, 1980)} \tag{1}$$

Where: Kv = vertical hydraulic conductivity in meters per second
Q = discharge in cubic meters/second
A = area in meters squared
dh/dL = hydraulic gradient or change in head over distance in meters

Drilling into the Shawmut Mine indicates that most the workings encountered are open. The drilling targeted primarily main entries which tended to be mined to much greater heights than the coal itself and better supported for continued use. The coal ranges from 0.58 to 0.94 meters thick with an average of 0.67 meters. A few of the drill holes indicate that some collapse and nearly complete convergence has occurred, but the bulk of the entries intersected were close to the original full mining height. The voids averaged 1.9 meters with a range of 0.8 to 2.7 meters for main entries. This illustrates that at least the main entries are accessible and able to accept large quantities of iron sludge.

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 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 from NaOH, $Ca(OH)_2$ and (CaO) were more stable than that produced from (Na_2CO_3). They further observed that sludge exposed to the atmosphere for a period of time became more 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 that iron hydroxide was relatively stable down to pH values approaching 3.5 (standard units). 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.

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. The 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 opened up to laterally drain off some of the mine pool water. The geometric average pH is 5.9 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 mine water at the Brandy Camp discharge for 2009 averaged 165 mg/L net acidity (acidity-alkalinity) and had a geometric average pH of 5.1. 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. The mean for total iron was 69 mg/L. This water is treated with hydrated lime ($Ca(OH)_2$) 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 decrease the amount of lime needed to raise the pH of the water. The mine water is suboxic at the discharge point ($\approx$ 1.2 mg/L dissolved iron) 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 introduction of oxygen which will facilitate ferrous iron oxidation to ferric. The water is then pumped through a series of tanks where a polymer is added to cause the iron to coagulate. A filter belt press is used to remove the coagulated iron. Any excess water more than the plant can accommodate is sent to settling ponds after the second aeration step. The sludge yielded at the plant from the filter belt press or the settling ponds is expected to remain relatively stable if injected into the Shawmut Mine.

Sludge Injection Testing

A test injection of sludge derived from a nearby mine water treatment plant that uses settling ponds to remove the iron hydroxide was conducted on July 12 through 14, 2010. Over a three day period, more than 2.8 million liters of iron sludge was injected into one of the main entries in the Shawmut mine. Tanker trucks holding slightly more than 19,600 liters 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 recorded no change in the mine pool level due to the injection (Fig. 15). Only the expected diurnal fluctuations were observed.

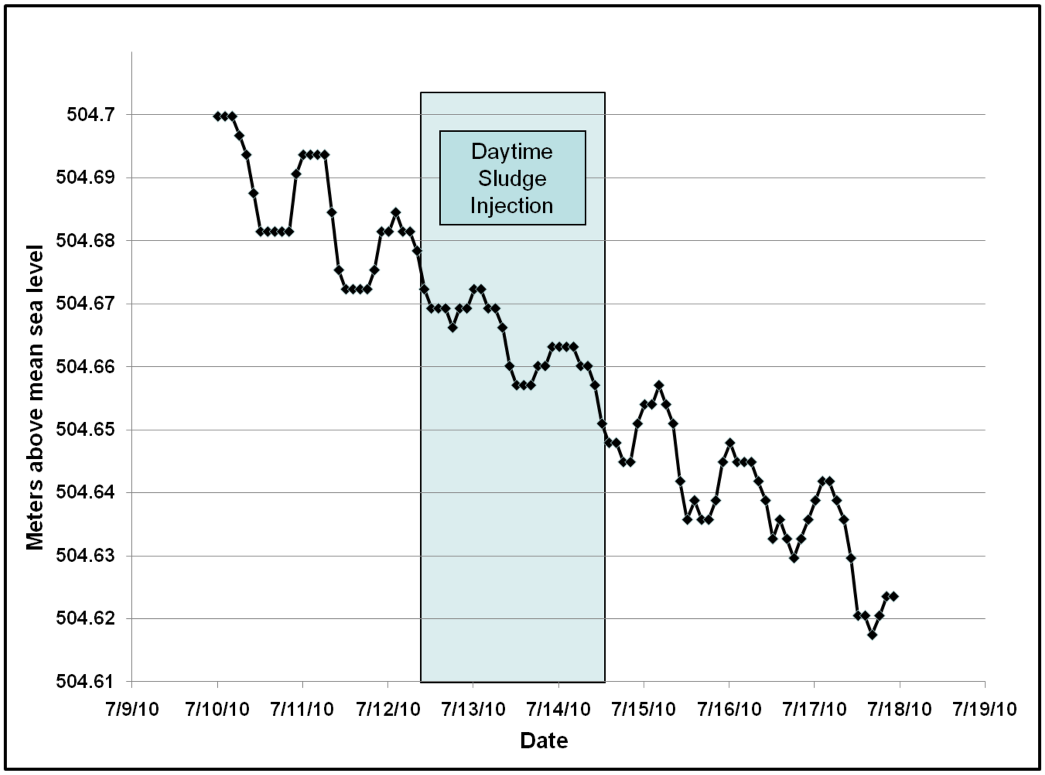

Figure 15. Water levels of the Shawmut Mine pool before, during, and after the test sludge injection. Note the diurnal fluctuations only.

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. Sampling 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 change in the concentration of iron, calcium, sulfate, alkalinity or acidity related to the injection was observed in the raw samples collected at the Brandy Camp discharge. 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 (Fig. 16). The iron load showed a definite downward trend after the injection with the median iron load (226 Kg/day) being significantly ($p \leq 0.05$) lower after injection compared to before (270 Kg/day). This was caused by slowing reducing flow rates. The sludge also contained considerable residual Ca with a concentration of 332 mg/L in the decant water. The Ca concentration and loads at the Brandy Camp discharge exhibited a similar lack of change as the total iron.

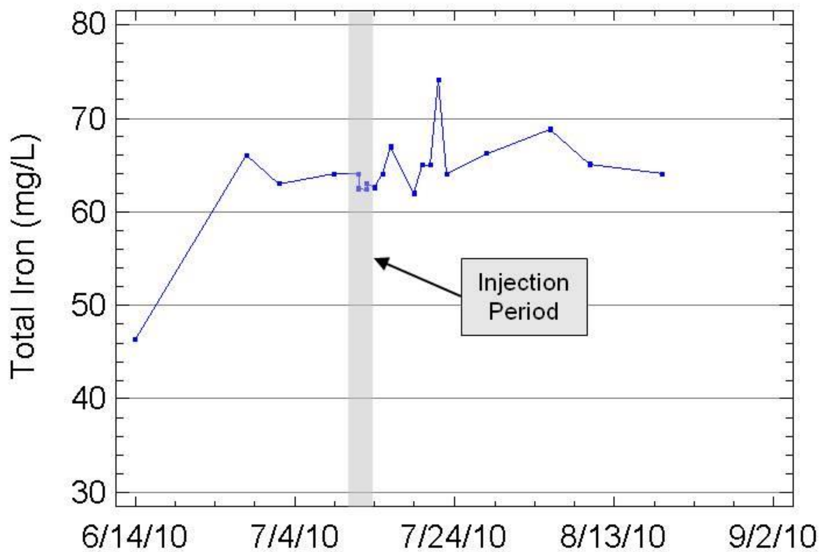

Figure 16. Total iron concentration before, during and after iron hydroxide sludge injection test.

In July 2011, a second iron sludge injection test was conducted at two injection holes recently drilled and developed specifically for that purpose. Approximately 2.3 million liters were injected. As with the July 2010 sludge injection testing, no adverse impacts were noted at the Brandy Camp discharge in terms of quantity or quality. No response in the Shawmut mine pool water levels was recorded.

The Brandy Camp iron hydroxide sludge will likely have a solids fraction similar to the sludge used in the injection test, which averaged 2.43%. At the present rate, the volume of just the solids fraction of the sludge is estimated to be 0.19 to 0.22 cubic meters per day or 70 to 80 cubic meters 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 (390 kilograms/day). 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 the sludge will retain some of its water composition. Therefore, an upper level quantity estimate of sludge material, based on no loss of water, indicates that the volume will be approximately 7.7 to 8.8 m^3 per day or 2,800 to 3,215 m^3 per year. The actual sludge volume once injected into the mine should eventually be closer to the 2.5% solids than that of the raw sludge as the excess water decants from the sludge over time.

The Middle Kittanning Coal seam averages 0.67 meters thick across the area. The extraction rate for the Shawmut Mine was estimated at approximately 60%, but the drilling indicates there has been subsequent subsidence which reduces the effective porosity. Hawkins and Dunn (2007) calculated an effective porosity of 11% for similarly-worked underground mines in Cambria County, Pennsylvania 40 years after abandonment. Those mines have likely experienced greater reduction of the voids than the Shawmut Mine due a to slightly higher extraction rate (about 63%) which leaves less support and the greater stresses created by the thicker overburden, up to 640 feet over much of the complex. Based on the aforementioned information, it is likely that the effective porosity of the Shawmut Mine will be greater than the value given by Hawkins and Dunn (2007), but considerably less than the assumed 60% extraction rate.

Established by a series of calculations using the total sludge volume, solids fraction volume, and an effective porosity range of 10 to 60 percent, the rate of void-filling is estimated between 0.02 and a maximum of 4.50 hectares per year at the current sludge production rate (Table 1).

Table 1. Annual iron sludge-injection void-filling estimates at an average of 75 cubic meters of solids per year and 3,010 total cubic meters of sludge per year.

Effective Porosity Range in Percent	Potential Void Volume in Cubic meters per hectares	Hectares Filled per Year of Solids	Hectares Filled per Year of Total Sludge
10	110	0.11	4.50
15	165	0.07	3.00
20	220	0.06	2.24
25	275	0.04	1.80
30	330	0.04	1.50
35	385	0.03	1.28
40	440	0.03	1.12
45	495	0.02	1.00
50	550	0.02	0.90
55	605	0.02	0.82
60	660	0.02	0.75

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 0.03 and 1.28 hectares per year. Given the propensity of iron hydroxide to settle out of solution at extremely slow flow rates of mine water within underground mines, the sludge in-filling rate will be closer to the 0.03 hectares per year and in any event should be well below a hectare per year.

Based on the void-filling calculations and experience with sludge injection at other mines in the region, the injection holes should last several years before a replacement is required. The need for future injection 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 degree of propagation that can be anticipated.

Discussion and Conclusions

Substantial increases in infiltration rates in overlying reclaimed surface mined areas have caused a significant increase in the mean 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 decreases evapotranspiration which facilitates increased infiltration rates. As tree cover, mainly white pine, increases over time, the infiltration rates will likely decrease and may eventually return to near pre-surface mining levels.

Analysis of the area affected by surface mining with respect to the average annual discharge rate indicates that the flow rate increases approximately 1.2 liters per minute for each hectare disturbed. While this does not appear to be a significant amount compared to the total discharge rate, once several hundred hectares were disturbed, the overall flow rate exhibited a substantial increase.

Use of multiple regression analyses to predict the mean annual discharge rate (dependent variable) based on the independent variables of percent of the recharge area affected and annual precipitation, illustrates that the impact of those two variables is much stronger than either parameter individually. An R-squared value of 88.5% with a P-value of 0.0002 was obtained for an equation for the fitted line (Equation 2).

$$\text{Mean annual discharge rate} = -164.363 + (30.2203 \times A) + (18.611 \times P) \qquad (2)$$

Where: A = percentage of the recharge area affected and P = precipitation centimeters

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 area to be disturbed and the annual precipitation need to be factored into forecasted 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 1 or something similar developed on a region-specific basis should be employed to predict future discharge rates.

The moderately low vertical hydraulic conductivity (median of 1.0×10^{-7} m/s) of the thin interburden (average of 11.7 m) 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 openly connecting the Elbon Mine to 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. The rate of mine void filling from the iron sludge is calculated to be well less than one hectare 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. Injection of the iron sludge which has excess alkalinity will reduce the acidity of the mine water decreasing the amount of lime needed to raise the pH thus, further reducing the sludge volumes with time.

Recommendations

In order to reduce the amount of mine water that ultimately must be treated, the recharge rate needs to be reduced for the overlying areas that contribute to the mine. Reforestation of the 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 is also recommended.

A drilling program has been conducted in the potential sludge injection area to determine the true nature of the mine workings in the Middle Kittanning Shawmut Mine. The large scale sludge injection test was successful on all accounts. Therefore, injection of iron sludge from the Brandy Camp treatment plant into the Shawmut underground mine is recommended.

Acknowledgements

The authors wish 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 aid with this study. Appreciation goes out to Clifford Dodge of the Pennsylvania Geological Survey for graciously sharing mine maps and his own work for this project and 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. The suggestions and comments of the three anonymous reviewers did much to improve the paper and where greatly appreciated.

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