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TECHNICAL ARTICLE

Hydrologic Impacts of Multiple Seam Underground and Surface Mining: A Northern Appalachia Example

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Abstract An underground mine complex overlain by extensive surface mining in north-central Pennsylvania is drained principally by one discrete discharge point at which the flow rate (median of 2,167 L/min) increased significantly (67%) above background (median of 1,317 L/min) during a 3 year period. The source of this major discharge rate increase and other unusual hydrologic characteristics were investigated. Subsequent to background monitoring, about 440 ha of surface mining and reclamation (85% of the recharge area) occurred on numerous seams overlying the underground mines, which induced 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 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 mine is the main storage unit for mine water. The Middle Kittanning mine behaves like a perched aquifer system because of the moderate vertical hydraulic conductivity (a median rate of 1.0×10^{-7} m/s) of the thin (mean of 11.7 m) clay-rich shale and siltstone interburden and local structural features. During periods of low recharge, pool levels decline to a point where most of the mine water flowing downward from the Middle Kittanning mine to the underlying Lower Kittanning mine is diffuse in nature. The discharge rate is consistently in a narrow range of 1,745–2,381 L/min about a median of 2,040 L/min. When surface infiltration rates are high, the mine pool levels rise, and a portion of the recharge from the Middle Kittanning mine to the lower seam mine is apparently more channelized, flowing through the backfill 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.

Keywords Infiltration rate · Interburden · Iron hydroxide · Mine pool · Recharge · Spoil · Underground mine sludge injection · Vertical hydraulic conductivity

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Introduction

In the United States, water that emanates from coal mines that closed before environmental regulations went into effect is typically only treated if government and/or citizen groups take on that responsibility. The Brandy Camp treatment facility was constructed by the Pennsylvania Department of Environmental Protection (PADEP) Bureau of Abandoned Mine Land Reclamation (BAMR) and a watershed association in southern Elk County to treat mine water emanating from the Elbon Mine, which closed in the 1930s. This study was performed at the request of, and in cooperation with, the Cambria County BAMR office (Ebensburg, PA). From this point forward, that mine discharge will be referred to as the Brandy Camp discharge. Untreated, the Brandy Camp discharge substantially degrades Brandy Camp Creek, which subsequently has a considerable impact on Toby Creek below their downstream confluence. BAMR operates the treatment plant at the Brandy Camp discharge, in combination with other treatment facilities, to improve the water quality of the entire Toby Creek watershed. Shortly after the treatment plant was operational, it was found to be significantly undersized. During high-flow conditions, the plant treats significantly less than 50% of the mine discharge; the remainder is bypassed.

We addressed two salient questions regarding the discharge and the associated mines. The first was why were the baseline (background) discharge measurements much lower than those recorded since the plant became operational? The second was whether the underground mines could potentially be used as locations for injection of iron sludge from the treatment plant and settling ponds. At present, this sludge is buried in nearby surface mines. Once the last of these surface mines is closed, a new disposal site and/or method will be necessary. Sludge injection areas within an underground mine 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 mine sections that receive the iron sludge will need to have adequately open entries to allow for movement of the sludge away from the injection point before it settles. In addition, it had to be determined that the iron hydroxide in the sludge would neither be dissolved nor resuspended and thus recycled back to the Brandy Camp discharge.

Background

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

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 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 thin-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 low dipping (generally, 2° or less). The southwest to northeast trending Shawmut Syncline bisects the drainage area. The synclinal axis lies just north of the Brandy Camp discharge. This structural setting in concert with the deeply-incised topography causes the Brandy Camp discharge to be the principal mine water relief point for the underground mines. The discharge emanates directly from the Elbon underground mine, which is in the Lower Kittanning Coal seam.

Like much of this region, most groundwater 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 groundwater regime is generally negligible. At shallow depths, generally less than 45–60 m, 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, with horizontal bedding-plane separations common approaching the valley bottoms (Wyrick and Borchers 1981). Groundwater flows from the hilltops and hillsides down toward the adjacent streams in a quasi stairstep manner.

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 and continued until the 1930s. Around the time of closure of the Elbon Mine Lower Kittanning mine, mining of 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.

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 were statistically significant. Pre-construction data include flows recorded during plant construction as well. Figure 2 indicates that the median flow rate after plant construction (3,617 L/min) was 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 that 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

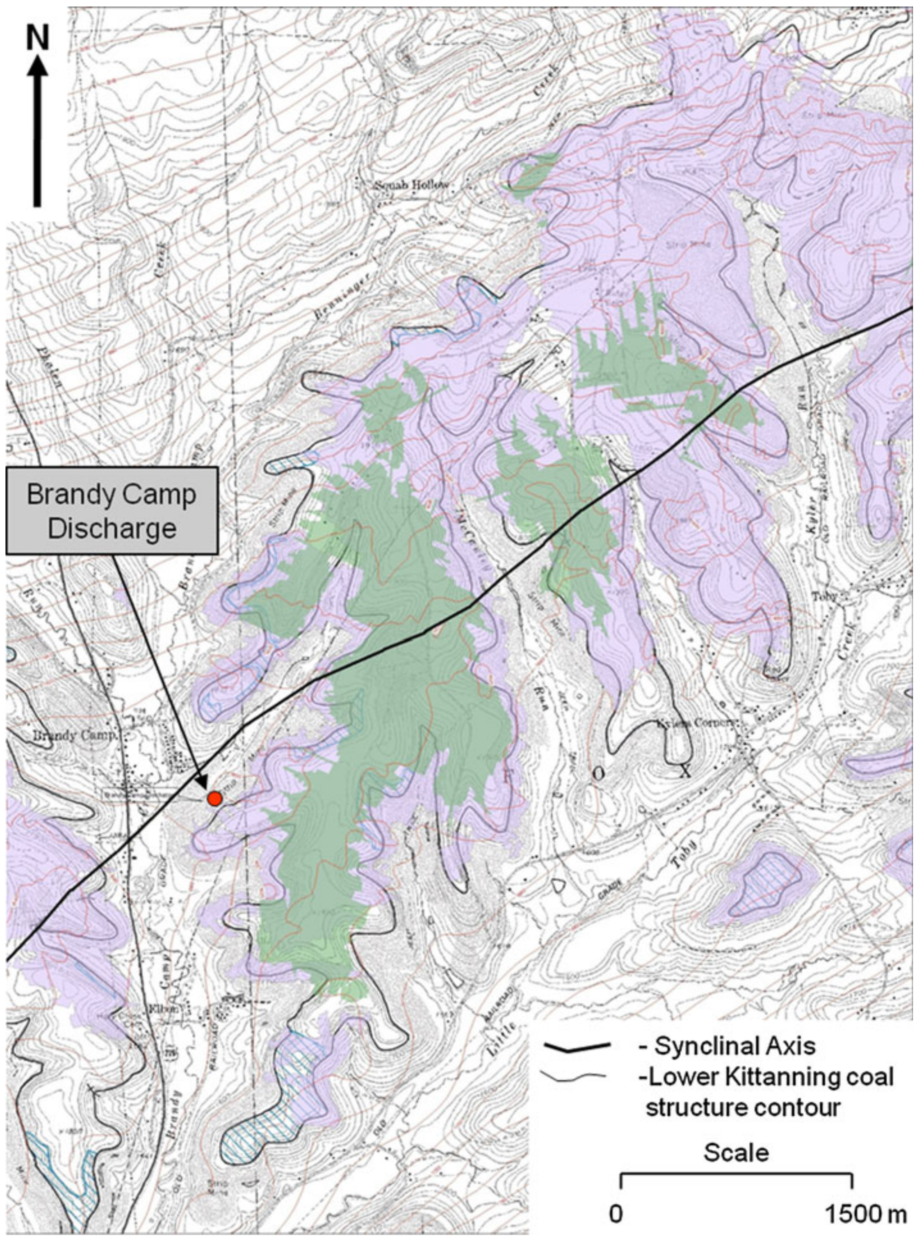

Fig. 1 Topographic map of the Brandy Camp discharge and surrounding area. Underground coal mining is shown for the Middle (*green*) and Lower Kittanning (*amethyst*) coals. Structure contours and synclinal axis are based on the bottom of the Lower Kittanning Coal. Map created by US Office of Surface Mining personnel from data provided by the PA Bureau of Topographic and Geologic Survey

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 also indicated that the distribution of the two data sets was significantly different ($p \leq 0.05$).

Several potential reasons for the pre-versus. post-plant construction flow disparity were postulated: (1) the pre-plant measurements were conducted improperly or the flow measuring device was faulty, (2) the post-construction measurements were incorrect, (3) the measurement point location changed substantially from background, (4) surface mining within the basin during this period impacted the recharge rates, or (5) 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

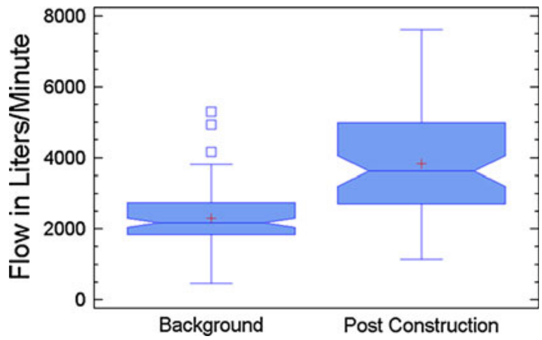

Fig. 2 Notched box-and-whisker plot illustrating the flow rate differences observed before and after construction of the treatment plant. The horizontal center line in each box is the median, while the box represents the first and third quartiles above and below the median, respectively. Vertical lines (*whiskers*) extend from the end of the box to the farthest point within 1.5 interquartile range. Values falling beyond the whiskers, but within 3 interquartile ranges (*suspected outliers*), are plotted as individual points (*squares*). The notch on the box sides represents an approximate 95% confidence interval about the median

on the flow measurements, given that no gain or loss of flow occurred between the two points. A review of the weirs indicates that they were constructed and functioning properly. Discussions with plant personnel indicate that they were reading and recording the discharge rates accurately.

Hydrologic Impacts of Surface Mining

During modern surface mining, surface and ground water flows are largely controlled. Surface water is collected and diverted to impoundments via ditches. The impoundments and ditches are engineered to prevent leakage of the water. They are designed to collect the runoff and hold it until effluent standards are reached; then the water is discharged into the nearest natural drainage way. Groundwater 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 recharge to underlying strata or deep mines as much as possible. 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. However, once the site is backfilled and revegetated, the ditches and ponds are removed. Thus, surface water is no longer collected 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 recharge the underlying units.

Previous Studies

Earlier studies of the impacts of surface mining and reclamation indicate that precipitation infiltration rates are frequently 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 4 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 infiltration rates of 1–2 cm/h, but within 4 years after reclamation, the infiltration rates of “some minesoils” approach the pre-mining 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 degree to which the material has been regraded or degree of surface roughness. Deane (1966) recorded infiltration rates of 10.2 and 23.6 cm/h for ungraded spoils and 1.5 and 2.3 cm/h for the same spoils after they had been regraded in Ohio and Illinois, respectively.

Other studies have indicated 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 due both to the higher recharge of the mine spoil and fact that spoil aquifers tend to have higher storage capacities than undisturbed strata.

The deforestation that precedes mining may be a major factor in the increased infiltration. Deforestation greatly reduces evapotranspiration and increases the amount of groundwater going into storage (Dickens et al. 1989; Douglass and Swank 1975; Lieberman and Hoover 1951). The increase in stream flow, previously noted, was due mainly to 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 increased 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 unmined watershed. For a complete 2 year period, total unit flow in liters per second per square kilometer 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 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 unmined watershed stopped flowing. They did, however, attribute some continued baseflow through the summer to the increased storage capacity of mine spoil. The substantially increased groundwater 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 may go dry during dry spells.

Wiley et al. (2001) observed that the 90% duration flow (percent of the time the flow is equaled or exceeded) of streams that originate at the toe of valley fills is 6–7 times greater than nearby streams draining unmined watersheds. Truax (1965) observed that at a time when mined watersheds in southwestern Indiana were yielding about 177 L/min/km^2 (September and October 1964), other nearby watersheds were dry. Curtis (1979) stated that spoil can store large quantities of water that eventually discharge as baseflow to the streams. He further states that they "function as reservoirs" of groundwater storage. Peak storm discharge rates show reductions commensurate with the area of the watershed disturbed.

Spoil is capable of storing much larger quantities of groundwater than 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 at nearly 20%, and likely approaches 25% 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 fractured strata are generally less than 1% (Mackay and Cherry 1989).

Influence of Surface Mining on the Brandy Camp Discharge

There has been a large amount of surface mining and subsequent reclamation within the recharge area for the Brandy Camp discharge from 1989 to 2002. The bulk of the surface mining was on coal seams overlying the Middle Kittanning coal. There was surface mining 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 characterization study. A positive correlation was observed between increased area affected by surface mining and a higher average flow rate at the Brandy Camp Discharge (Fig. 3). Given the difficulties in determining flow rate and inherent uncertainties common to natural data, the correlation here ($R^2 = 68.6\%$) is comparatively strong. The sample size is 14. Some data points are superimposed or close enough to other points to appear as one in Fig. 3.

When background monitoring for the discharge started in July of 1993, recent surface mining had affected about 40 ha, with 29 ha already reclaimed. Approximately 174 ha had been affected with 121 ha 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. 3). An additional 266 ha were surface mined and 318 ha were reclaimed subsequent to the background sampling, in 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. The possible impacts of precipitation and climatic conditions are discussed in more detail in a later section.

An aerial photo taken in October 1968 of the contributing area for the Brandy Camp discharge indicates that most of the land was heavily forested before mining. Initially, grasses were planted as a vegetative cover when the mines were reclaimed. This drastic change in

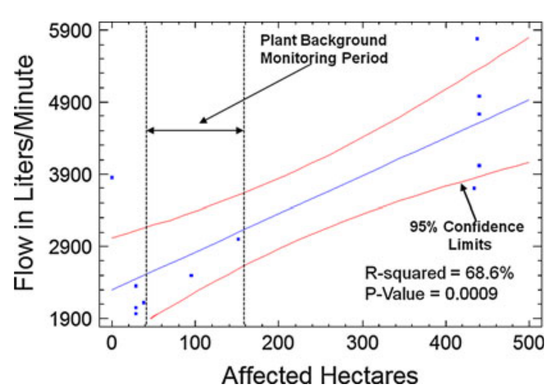

Fig. 3 Regression analysis illustrating the relationship of discharge rate to amount of drainage area affected by surface mining

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 mine sites (supplemental figures. 1 and 2). 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. The average percent of precipitation expressed at the Brandy Camp discharge from 2003 through 2009 was slightly more than 36% (Fig. 4), 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 2003–2009 time period. This earlier high recharge rate may be related to previous surface mining activities that occurred during the preceding years; however, the 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 ($\approx$7%) was likely caused by the considerable evapotranspiration occurring over the discharge recharge area at that time due to the heavy forest cover.

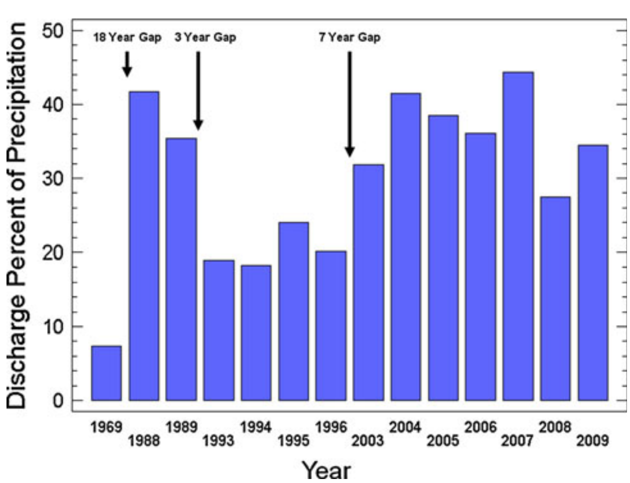

Fig. 4 Changes in the percentage of recharge from precipitation before and after construction of the treatment plant

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 that 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. 5). The annual precipitation data for the area is based on precipitation at the Ridgeway station, the closest National Oceanic and Atmospheric Administration recording site, which is approximately 12.1 km north of the center of the study area.

The precipitation amounts for 1993 through 1996 were well within two standard deviations of the mean of 110.2 cm/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 for the time period 2002–2006 were also well within the 95% confidence interval about the mean. This indicates that the higher discharge rates exhibited since the plant came on line are not due to periods of abnormally high precipitation. Additionally, there is no significant difference ($p \leq 0.05$) in the precipitation rates between the two time intervals.

Precipitation amount does influence the discharge rate. Since the bulk of recent surface mine reclamation was completed during the years 2003 through 2007, the discharge rate exhibits a weak positive correlation ($R^2 = 51.2$, with a p-value of 0.174) with precipitation. In contrast, 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

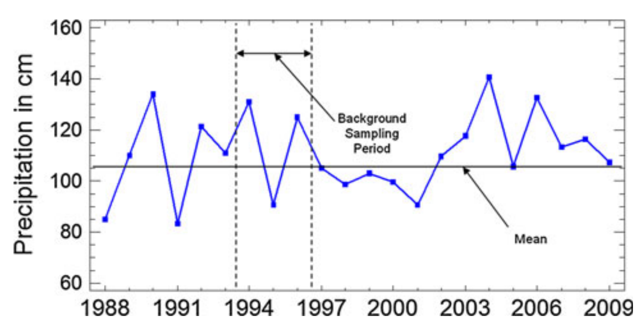

Fig. 5 Annual precipitation amounts from 1988 through 2006

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 cm 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 since much of the water was being bypassed from the plant through a non-gauged pipe and ditch system. This mine flushing event also raised the concentration of acidity, iron, sulfate, and other dissolved parameters.

There was a distinct change or break in the slope of the regression hydrograph at approximately the 5,725 L/min discharge rate (Fig. 6). This is directly attributable to a substantial change in the recharge rate to the Elbon Mine from the Shawmut Mine. The break in slope and the lower slope below the 5,725 L/min discharge rate indicates that the recharge from the Shawmut Mine was declining at a rate more consistent with diffuse flow vertically through fractures in the interburden, and regulated by the head within the Shawmut Mine. When the discharge rate was above the 5,725 L/min rate, the regression slope was considerably steeper, indicating that a substantial portion of the recharge was more direct and less restricted. The higher discharge rates appear to be caused when the mine water rises to a elevation where it spills over the buried surface mine highwalls down through the more transmissive spoil (Hawkins 1998) to the Lower Kittanning pit floor, flows down dip along the pit floor, and recharges 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 in the Shawmut Mine at the time of the flushing event and the total extent of surface mining on the Middle Kittanning is unclear. However, on Feb. 9, 2010, the flow rate briefly exceeded 5,725 L/min and the water elevation in the Shawmut Mine was 505.62 m above mean sea level, which indicates this may be the point above which the recharge characteristics become less restricted as spillover occurs and the rates greatly increase. The median flow rate quadrupled from 2,040 L/min during diffuse flow to 8,328 L/min, with overflow occurring through the spoil (Fig. 6).

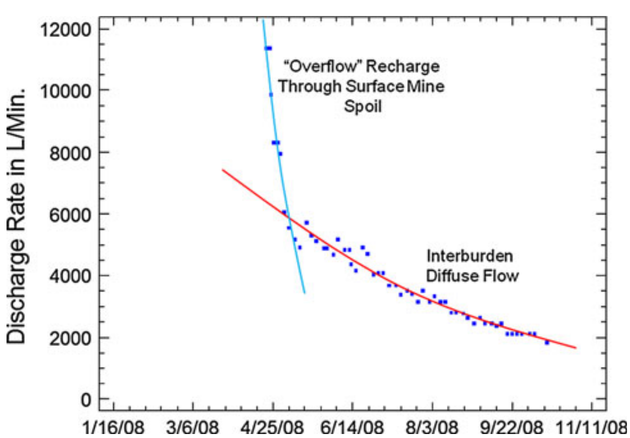

Fig. 6 Brandy Camp discharge rate from the spring of 2008, showing diffuse flow, and overflow discharge response

Hydrologic Characterization of the Underground Mine Workings

Physical Characteristics

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 was determining if there was ample storage capacity in the mines and if the connection between open entries was unrestricted enough 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 (at a minimum, tens of meters) from the injection point before the solids settle out. However, it is important that the flow system not allow the iron sludge to flow unimpeded back to the Brandy Camp discharge. Another concern was whether the quality of the water in the mine(s) was such that the iron would be dissolved and mobilized by low pH or reducing conditions in the mine pool. It is undesirable to treat iron reintroduced by sludge injection.

In the Appalachian Plateau, vertically stacked mines situated above the local drainage system are often hydrologically connected and tend to drain down to the lowest coal seam mined. They discharge laterally from a structural low point from that stratum (Booth 1986; Scales 1992). This scenario is not the case for the study area. The hydrologic regime within the study area is distinct because the mine pool is located in the Middle Kittanning Coal of the Shawmut Mine rather than in 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 diffuse fashion into the Elbon Mine. The mine water then 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. Monitoring over a period of 3 years with pressure transducers/data loggers indicates that the Shawmut mine pool varies in water elevation and aerial extent seasonally. Monitoring wells in 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 m, with a mean of 11.7 m. 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 9 m above the Lower Kittanning mine. Core samples and drilling records show that 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 groundwater flow through them (supplemental Figure. 3).

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 reducing vertical hydraulic conductivity and restricting groundwater movement.

The relatively low vertical hydraulic conductivity (Kv) of the strata is illustrated by the perched mine pool in the Middle Kittanning, which exists despite the relatively thin interburden. The Kv values were estimated using measured mine pool heads, 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} m/s, with a median of 1.0×10^{-7} m/s. These values are similar to 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 m thick glaciolacustrine clay unit in southwestern Ontario, Canada. While much lower values have been estimated for true aquitard units (e.g. 10^{-12}–10^{-15} m/s) (Eaton and Bradbury 2003; Kleeschulte and Seeger 2005), the interburden here has sufficiently low vertical hydraulic conductivity to support the perched mine pool system.

Drilling into the Shawmut Mine indicates that most of the workings encountered are open. The drilling targeted primarily main entries, which tend 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 m, with an average of 0.67 m thick. A few of the drill holes indicate that some collapse and nearly complete convergence has occurred, but the bulk of the entries that were intersected were close to the original full mine height. The voids averaged 1.9 m with a range of 0.8–2.7 m for main entries. This illustrates that at least the main entries are accessible and able to accept large quantities of iron sludge.

Previous Sludge Stability Studies

Factors that influence the stability of iron hydroxide sludge in general include the type of neutralizing agent used, age of the sludge, whether the sludge was aged while submerged in water or 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 sodium hydroxide (NaOH), calcium hydroxide ($Ca(OH)_2$), and calcium oxide (CaO) were more stable than that produced from sodium carbonate (Na_2CO_3). They further observed that sludge that was 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. 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.

Chemical Characteristics

The quality of the mine pool water in the Shawmut Mine is considerably better than what ultimately discharges at Brandy Camp. 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 was 5.9, with alkalinity concentrations ranging from 77 to 134 mg/L (as $CaCO_3$). Acidity concentrations range from 0 to 29 mg/L (as $CaCO_3$). Dissolved iron collected directly from the pool via monitoring wells was low, ranging from 0.03 to 0.24 mg/L.

The mine water at the Brandy Camp discharge for 2009 averaged 165 mg/L of net acidity and had a geometric average pH of 5.1. The pH of the Brandy Camp discharge has been slowing rising from approximately 3.0 in July 1988 to 4.6–5.4 at the present time. The mean for total iron was 69 mg/L. This water was treated with hydrated lime (calcium hydroxide) to increase the alkalinity and thus raise the pH. Prior to lime addition, minor aeration of the mine water allows some of the excess dissolved carbon dioxide to exsolve, which reduces the carbonic acid content. This decreases the amount of lime required to raise the pH of the water. The mine water is suboxic at the discharge point ($\approx$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 facilitate the oxidation of the ferrous iron. 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. The sludge yielded at the plant from the filter belt press or the settling ponds is expected to remain stable if injected into the Shawmut Mine.

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 groundwater 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, mainly white pine, returns 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 L/min for each hectare disturbed. Surface mining caused a significant increase in the total discharge rate, once several hundred hectares were disturbed. In all, a total of 440 ha were surface mined during the period of interest. The total recharge area for the mines that the Brandy Camp discharge drains is approximately 520 ha, so the surface mining during this period affected approximately 85% of the recharge area. This caused the median flow rate to increase by 67% at the Brandy Camp discharge.

Multiple regression analyses predicting the mean annual discharge rate (dependent variable) in L/min, based on the independent variables of percent of the recharge area affected and annual precipitation in centimeters, illustrates that these two variables provide a robust predictive model. An R^2 value of 88.5% with a *p*-value of 0.0002 was obtained for an equation for the fitted line (Eq. 1) to the 14 samples.

$$\text{Mean annual discharge rate} = -164.36 + (30.22 \times \text{A}) + (18.61 \times \text{P}) \quad (1)$$

where A = percentage of the recharge area affected and P = precipitation (cm).

Regression using either parameter alone gave much smaller R^2 values. Similar sites with a large percentage of the recharge area affected by additional surface mining can be expected to discharge groundwater at increased rates. The percentage of the 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 1 (or something similar) developed on a region-specific basis should be employed to predict future discharge rates. However, it is anticipated that site-specific conditions, such as greater overburden and interburden thicknesses, will also impact the equation.

The relatively low median Kv (1.0×10^{-7} m/s) of the thin (11.7 m) interburden between the Middle and Lower Kittanning coals supports a perched mine pool within the Middle Kittanning Shawmut Mine. The low Kv is directly related to the clay-rich strata of the interburden, which inhibits subsidence-induced fractures from extending from the Elbon Mine up to the Shawmut Mine.

The diffuse flow regime between the mines in concert with the quality of the mine water in the targeted Shawmut Mine should inhibit if not prevent the recycling of the iron hydroxide sludge into the Elbon Mine and back to the Brandy Camp discharge. Furthermore, the Shawmut Mine pool water is a geochemically suitable environment for the introduction of iron hydroxide sludge. Given the amount of available abandoned underground workings associated with the Shawmut mine and the present sludge production rate, there should be sufficient space for injection disposal for well over 100 years. It is anticipated that sludge production will diminish with time as the effluent iron and acidity concentrations likewise decrease, allowing the use of less lime. Therefore, disposal of iron hydroxide sludge into the Shawmut Mine by injection is a viable option.

Recommendations

In order to 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 these overlying areas 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 a good recommendation.

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. While additional drilling and evaluation of the mine workings is recommended to more accurately assess the degree of openness and free interconnection of the mine workings to refine the estimate of available storage, injection of iron sludge from the Brandy Camp treatment plant into the Shawmut underground mine is recommended.

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