EFFECT OF SUBSIDENCE ON RECHARGE AT ABANDONED COAL MINES GENERATING ACIDIC DRAINAGE: THE MAJESTIC MINE, ATHENS COUNTY, OHIO

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ABSTRACT

This paper addresses the relationship between the geology, hydrology, and transient variations in discharge and water chemistry of acidic water discharged by an abandoned underground coal mine: the Majestic Mine in Athens County, Ohio, a partially-flooded, downdip, drift mine. The Middle Kittanning (No. 6) Coal (Allegheny Series, Pennsylvanian System) was mined room-and-pillar until 1921. Loss of support from mine collapse has created large vertical subsidence fractures along the naturally occurring joints within the brittle sandstone overburden. The mine discharge hydrograph, temperature, and pH of the mine discharge indicate that the hydrology of the Majestic Mine can be explained in terms of pseudokarst hydrology. During rainfall events, water is preferentially recharged through the subsidence features. Increased pressure from the mine inflow is transmitted through the flooded workings, causing a rapid increase in discharge, and forcing older mine water out of the mine. A stream draining an overlying watershed is captured by one of the subsidence features, contributing 60 to 80% of the mine water outflow. During the summer, recharge to the mine is negligible because potential evapotranspiration is higher than precipitation. During late summer and fall months, when the mine pool is at its lowest elevation, atmospheric oxygen penetrates back into the mine workings, enhancing the oxidation reactions. During the increased discharge of the spring months, washing of the reaction products from the mine walls produces the highest metals concentrations and chemical loads.

INTRODUCTION

For almost a century, acid mine drainage (AMD) from abandoned coal mines has severely degraded many watersheds in southeastern Ohio. The 303 km^2 (117 mi^2) Monday Creek watershed is one of the most impacted (Figure 1). In this paper, we present the results of our studies at the abandoned Majestic Mine, Athens County, Ohio, one of the main contributors of AMD to Monday Creek. The results of this study are crucial in defining restoration strategies for the mine, and provide insight to other underground mine systems in the watershed and elsewhere in the Appalachian region of the United States.

The Majestic Mine was abandoned in 1921, and is currently discharging acidic waters from a discrete mine opening located on the northwest-facing toe of the Monday Creek Valley wall. The Middle Kittanning (No. 6) Coal of the Allegheny Series, Pennsylvanian System, was mined in a room-and-pillar fashion, with a thickness of approximately 2.0 to 2.3 m (6.5 to 7.5 feet). Part of the

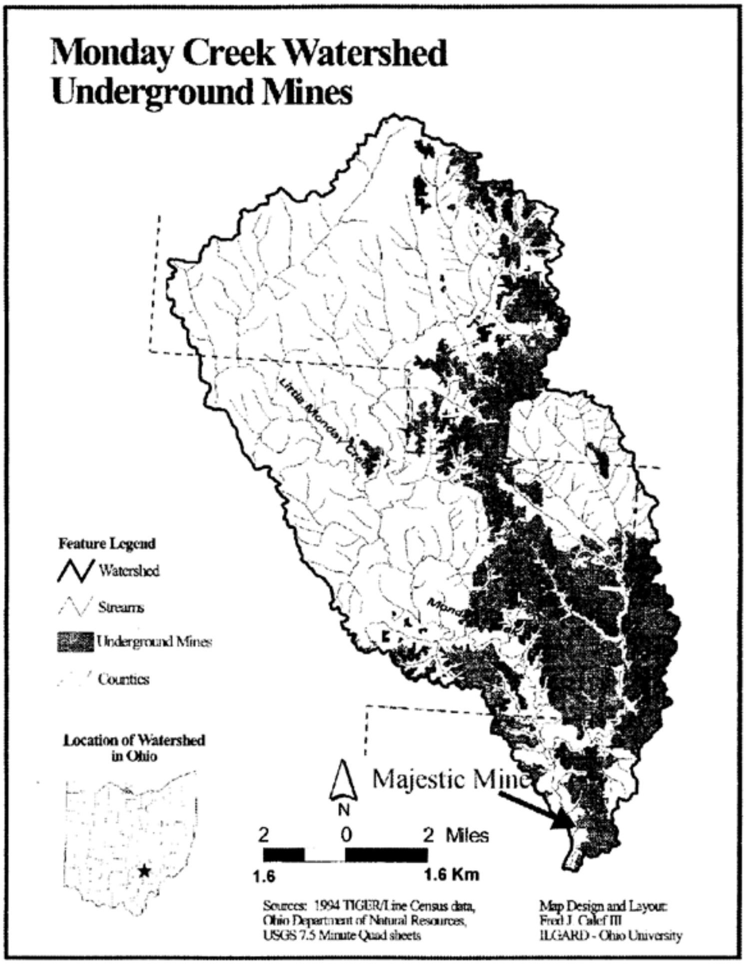


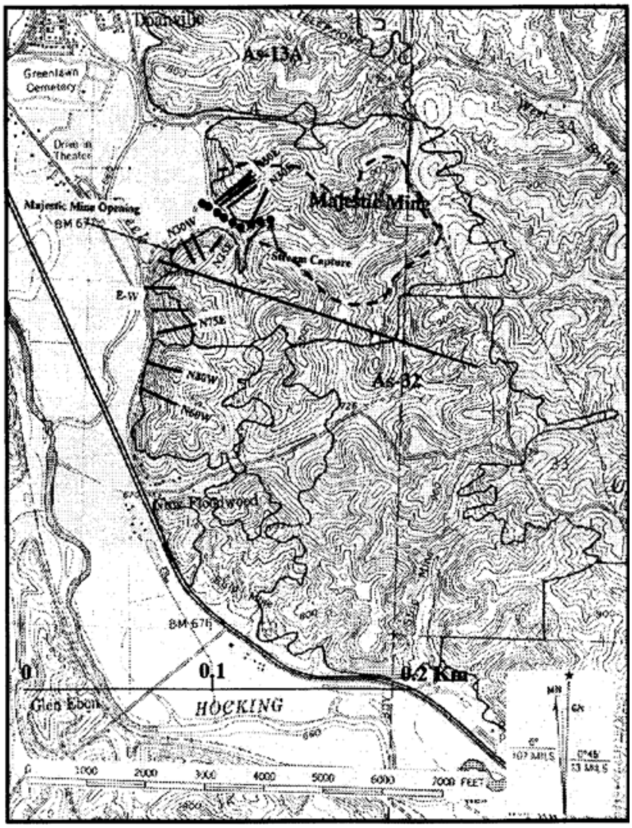
Figure 1. Extent of underground mining in the Monday Creek watershed (After Delong, 1980)

underground extent of the workings is above the Monday Creek drainage elevation of approximately 198 m (650 feet) above mean sea level, and encompasses about 1.26 km^2 (310 acres), in York Township (Figure 2). The elevation of the mine opening is about 204 m (668 feet) above sea level. Drift mining progressed down the dip of the coal seam, or "downhill" from the mine opening. A generalized structure contour map of the top of the Middle Kittanning (No. 6) Coal indicates a steady east-southeast dip of approximately 5.9 m per km (30 feet per mile) (Figure 3), with a large, unmined region adjacent to the mine to the east. This unmined region may act as a hydraulic barrier to downdip gravity drainage of water within the mine workings. The eastern and southeastern portions of the mine (Figure 3) have elevations lower than the elevation of Monday Creek (198 m or 650 feet), suggesting that about half of the mine is probably inundated. According to available surveyed underground mine maps, the Majestic Mine complex is directly connected with approximately 3.6 km^2 (880) acres of abandoned mines to the north-northwest. The mine complex to the northwest (As-13A in Figure 2) has an elevation higher than 198 m, suggesting that it is not completely flooded. This mine complex could be contributing AMD to the Majestic Mine discharge. In comparison, the mine complex to the south (downdip from the Majestic Mine) is not likely to be contributing AMD to the Majestic Mine discharge because it has an elevation lower than the elevation of Monday Creek and it is probably inundated.

GEOLOGICAL SETTING

Athens County is located within the Kanawha section of the Appalachian Plateau region in southeastern Ohio (Sturgeon et al., 1958). The topography is one of gently-dipping sedimentary rocks dissected into deep, narrow, v-shaped valleys and steep-sided, forested hills, commonly capped by resistant sandstone or limestone (Seaber, 1988). The main outcropping units in Athens County are around 300 million years old and are Pennsylvanian to Permian in age (Sturgeon et al., 1958). The average structural dip of the Pennsylvanian rocks in Athens County is gentle, and rock units typically appear flat-lying in outcrop. Based on measurements of two persistent rock units, the Ames Limestone and the Middle Kittanning (No.6) Coal, the Pennsylvanian rocks in southeast Ohio have a regional strike of N 17.5° E, and a regional dip of 5.9 m/km (30.75 feet/ mile) to the southeast (Sturgeon et al., 1958). There are two mutually perpendicular joint sets developed within the sedimentary rocks in southeast Ohio, trending northwest-southeast and northeast-southwest (Ver Steeg, 1944).

A maximum of 76 m (250 feet) of rock overlies the Majestic Mine complex, typically consisting of massive non-marine sandstone, and interbedded sandstone and shale of the Allegheny and Conemaugh Series, Pennsylvanian System. Thin limestones are also present within the overburden (Sturgeon et al., 1958). A strike normal geologic cross-section is provided in Figure 4 (see orientation in Figure 2). The cross-section was developed using measured sections from Sturgeon et al. (1958). Subsidence fractures overlying the Majestic Mine occur exclusively in the brittle sandstone overburden. The most obvious fractures are located within the Lower Freeport Sandstone (the Majestic Mine roof rock) above the mine opening along the hillsides (Figure 5). Fifteen subsidence fracture orientations were measured within the study area (see Figure 2). These subsidence fractures are subvertical-to-vertical, and generally form along or parallel to the pre-existing joint sets within the Lower Freeport Sandstone. The Lower Freeport Sandstone is about 9 m (30 feet) thick close to the Majestic Mine opening. A direct connection



N80W – fracture location and azimuth direction

● = sinkhole   – Captured Stream watershed

Figure 2. Extent of the Majestic Mine and adjacent underground mines (modified from U.S.G.S., 1995) and (Ohio Geological Survey, 1987). Bold black lines represent the boundaries of the mine workings. Subsidence features overlying the Majestic Mine are shown.

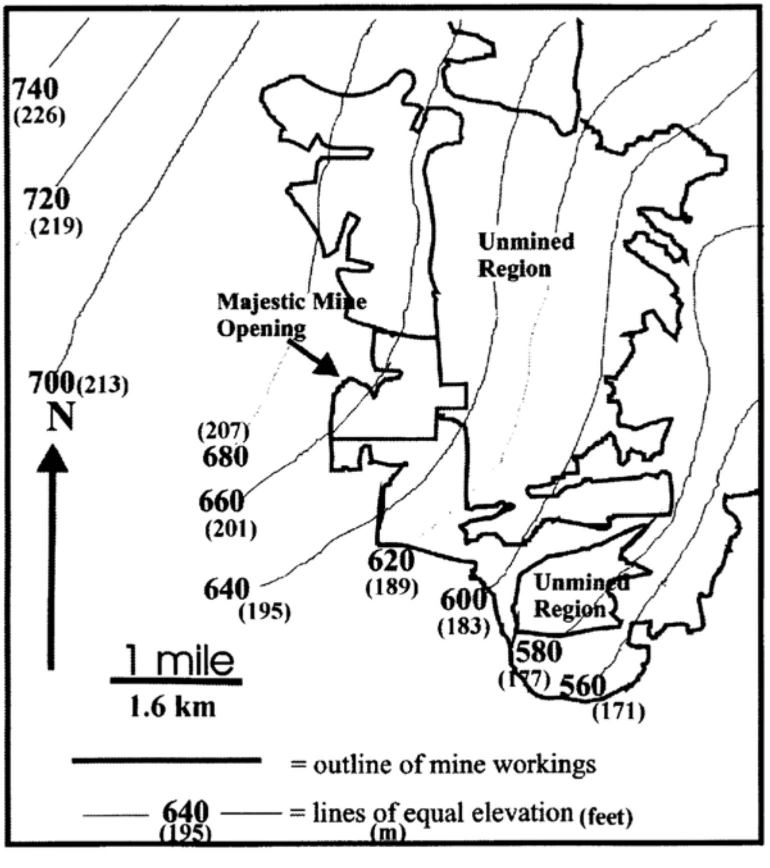
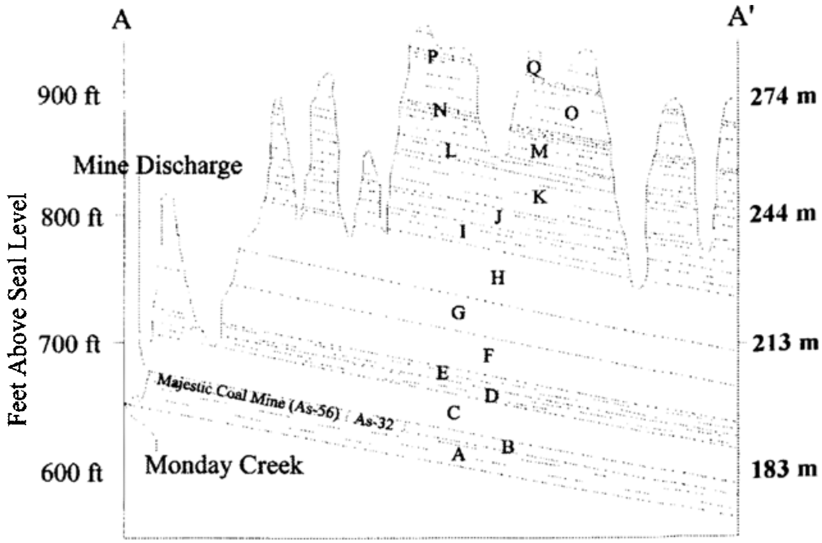


Figure 3. Structure contour map of the Middle Kittaning (No. 6) Coal (from Ohio Geological Survey non dated, 15-minute Athens Quadrangle).

of these fractures to the mine workings is suggested, as cool, moist mine air emanates from these fractures, forming water vapor during hot, humid days. Tracer tests to validate this observation were not performed. However, one of the collapse structures that captures an intermittent stream was monitored (flow versus time measurements) in order to understand the effect of the stream inflow on the mine discharge.



Note: Extent of Majestic Mine
from Surveyed Underground Mine Map

Horizontal Scale
2000 ft
610 m

A: Middle Kitanning Sandstone and Shale
B: Middle Kitanning Coal (No. 6)
C: Lower Freeport Sandstone
D: Lower Freeport Coal and Shale
E: Bolivar Sandstone and Clay (1.5' of limestone)
F: Upper Freeport Sandstone / some Shale (No. 7 coal at top)
G: Lower Mahoning Sandstone (1.5' of limestone)
H: Upper Mahoning Sandstone
I: Lower Brush Creek Sandstone and Shale
J: Upper/Lower Brush Creek Shale (0.5' of limestone)
K: Buffalo Sandstone and Shale w/ 3.5' of Cambridge Limeston
L: Anderson Cyclothem (clay/shale/coal)
M: Cow Run Sandstone and Shale
N: Ewing Limestone
O: Round Knob? Shale
P: Ames Limeston
Q: Gaysport S.S. And Shale

Figure 4. Strike-normal geologic cross-section alone line A - A' of Figure 2.

Figure 5. Photograph of a vertical subsidence fracture in the Lower Freeport Sandstone overlying Majestic Mine (rock hammer provides scale).

UNDERGROUND MINE HYDROLOGY

Natural and mine-subsidence related fractures are the most prevalent avenue of water inflow to underground mines in the Appalachian coal fields (Moebs and Clar, 1990). Fractures are most common in shallow rocks (within 61 m or 200 feet of the land surface) and tend to close with depth owing to the weight of the overburden rocks. Fractures within the overburden rocks act as reservoirs for ground water storage (released when tapped by the mine workings), and as conduits connecting water-bearing rocks or a surface water body to the mine workings (Schmidt, 1989).

After meteoric water enters the open mine workings, the flow system is dominated by downdip gravity drainage (Brant and Moulton, 1960). In the case of downdip drift mines such as the Majestic Mine, water that enters the mine workings will freely gravity drain until the downdip extent of the mine is reached. As the water cannot freely discharge, it will pool in the mine and may eventually flood the mine to the elevation of the mine opening, where it can then discharge into the local watershed (Brant and Moulton, 1960).

CLIMATE AND HYDROLOGY

Athens County has a continental climate with four distinct seasons. A moderately severe winter, with average monthly temperatures of a couple of °C (mid-30's °F) is in contrast to the warm, rainy weather in the spring and summer months, with average monthly temperatures in the 20's

°C (mid-70's °F) (Friel et al., 1984). The hydrology of the study area is driven by an average annual precipitation of about 102 cm (40 inches). Steep terrain, resistant bedrock, and silty soils account for the 28 cm (11 inches) of annual runoff in the area (Friel et al., 1984). The annual evapotranspiration rate is 69 cm (27 inches) per year (Schultz, 1978). Accounting for annual precipitation, runoff and evapotranspiration leaves 5 cm (2 inches) of annual recharge, or 5 percent of the average annual rainfall.

STUDY METHODOLOGY

The field work for this project consisted of the characterization of the Majestic Mine and its overlying watershed, field mapping of subsidence features and localized inflow points to the mine, measuring the mine discharge, measuring stream flows, and taking water samples and water quality field measurements. Field work began on March 26, 1996 and ended on March 4, 1997.

Discharge from the mine opening was measured using a permanent, fiberglass Parshall Flume installed by Woolpert Engineering for the United States Forest Service. Discharged water was stored in a small stilling pool and then routed through the flume. A plastic chart was mounted onto the side of the flume according to the manufacturer's specifications, which allowed for a direct observation of discharge in millions of gallons per day (MGD) (1 MGD = 43.82 l/s). The flume was able to accommodate all but the highest discharge observed during the study period. The overtopping and subsequent destruction of the flume during the March 1-2, 1997 flooding event ended the discharge data collection for the project.
Streamflow measurements were made using a United States Geological Survey pygmy-Price current meter and a measurement of the cross-sectional area of the stream using several subsections. The stream discharge for each subsection was calculated by multiplying the cross-sectional area by the stream velocity. The total stream discharge was then calculated by summing the discharge for each stream subsection.

Water samples were analyzed for total and dissolved parameters by two U.S. EPA-approved analytical laboratories. Water filtering was performed using a sterile 60 cc syringe with a sterile 0.45 micron filter attached to the tip. The syringe was rinsed with the sample water three times before filling the syringe and filtering the water into the sample bottle. The sample bottle and cap were rinsed with filtered water before taking the water sample. After filling the sample bottle, 4 to 5 drops of concentrated nitric acid were added, the cap was screwed on, and the bottle was gently inverted to disperse the nitric acid throughout the water sample.

Measured water quality field parameters included pH, temperature, specific conductance, and dissolved oxygen. Temperature and pH measurements were taken using a Cole-Parmer Digi-Sense pH meter. The pH meter was calibrated with a pH 4 and pH 7 standard solution prior to each measurement. A thermistor temperature sensor attached to the meter allowed direct temperature and temperature-compensated pH measurements. Specific conductance was measured using a factory-calibrated YSI Model 33 S-C-T meter. The specific conductance was measured in micromhos per centimeter. Dissolved oxygen was measured using a YSI Model 50B D.O. meter. Calibration was performed before each measurement, using the oxygen level of air as the calibration end point.

DISCUSSION OF RESULTS

Hydrology

An unnamed west-facing watershed overlying the Majestic Mine, hereafter referred to as the Captured Stream Watershed, has a basin area of 303 km^2 (117 acres or 0.18 mi^2). Captured Stream (Figure 2) flows until it reaches the valley floor, where it then disappears into a collapse structure at an elevation of 210 m (690 feet) in an area of very thin overburden, directly entering the underground mine workings. The downstream reach of Captured Stream is routed into a "fishhook" structure, in which a stream is blocked by an earthen berm and rerouted until the channel turns back on itself. These "fishhook" structures were used to create small water reservoirs for use in coal mining and coal washing (Wikle, personal communication, 1996).

Figure 6 is a duration curve of the Majestic Mine discharge for the period of March 26, 1996 to March 2, 1997. The duration curve indicates the percentage of time during the study period that a certain discharge rate was equaled or exceeded. The relatively gentle 0-50 percent segment for the Majestic Mine indicates continuous mine inflow from Captured Stream and collapse fractures during the winter and spring. The mine discharge recession from the 50-100 percent mark represents negligible recharge and elimination of the mine inflow sources during the dry summer and early fall. The high flows of the March 1997 flooding event are unusual as observed in the low probability values in Figure 6. The mine discharge steadily decreased during the summer and fall as water in overburden fractures percolated slowly into the mine. Porous inflow from the sandstone roof-rock probably provided inflow on a smaller scale.

The periodic inflow of water into the Majestic Mine caused an observable increase in the mine discharge following heavy rainfall events (Figure 7). However, this mine discharge increase was only observed in the late winter to early summer months, when antecedent soil moisture was high, runoff to Captured Stream was high, and evapotranspiration was relatively low. During a heavy rainfall event, Captured Stream provided water to the mine, as did recharge of rainwater through the larger fractures in the overburden rocks. The inflow of water from the Captured Stream and the collapse fractures resulted in a sharp peak in the mine discharge with an approximate 2-day lag time following a heavy rainfall event. The gradual recession of the mine discharge was the result of delayed fracture inflow to the mine and the release of excess storage within the mine workings. It should be noted that, even though there was a two-day lag time between a rainfall event and the mine flood peak, the mine discharge started to increase almost immediately after a heavy rainfall event, eventually reaching its peak after two days.

Due to the geometry of the mine, and since the mine is discharging water updip of the Middle Kittanning (No. 6) Coal, a conceptual model of the Majestic Mine is proposed that considers the mine partially-flooded. In this model, mine inflow in the partially-flooded mine workings to the northwest of the Majestic Mine opening moves downdip to the submerged regions of the mine workings (see Figure 3 for orientation of the mine workings in relation to the discharge point at the mine opening). During heavy rainfall, the mine inflow creates a hydraulic ram effect within the submerged mine workings, very similar to observations in karst hydrology (Bogli, 1980;

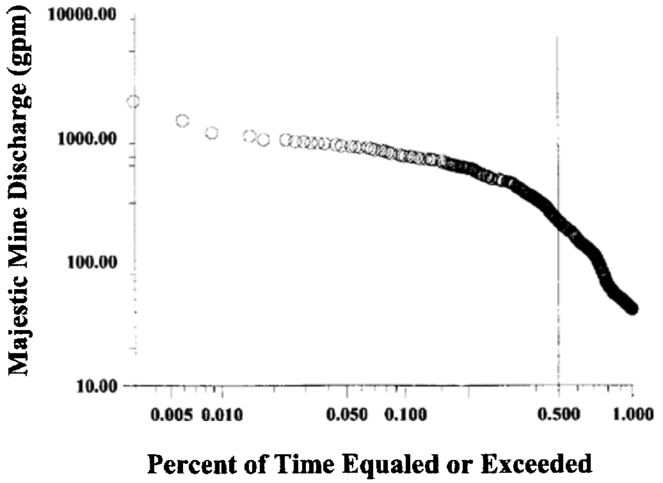


Figure 6. Duration curve of the Majestic Mine discharge, March 26, 1996 to March 3, 1997.

Jennings, 1985). The pressure wave from this hydraulic ram moves ahead of the mine inflow, causing a flood peak in the mine discharge before the actual inflow reaches the mine opening.

Hydrologic processes of the Majestic Mine could be considered in terms of pseudokarst hydrology. Springs in karst terrain respond to rainfall events depending on the proportion of direct stream capture and diffuse percolation through fractures (Figure 8). If stream capture inflow is dominant, the response of spring discharge is relatively fast, and the flood peak is sharp with a rapid recession. If diffuse percolation through fractures dominates the inflow to a cave system, the spring discharge response is delayed, the increase in spring discharge is subtle, and the recession of the flood peak is relatively slow. When a karst spring is fed by a combination of stream inflows and fracture percolation, the spring flow response is intermediate between these two cases (Jennings, 1985). In a study in the karstic Blue Waterholes at Cooleman Plain, New South Wales, flood waters from a captured stream took 24-48 hours to pass through 5 kilometers (straight-line distance) of the underground cave system before being discharged at a spring. The spring discharge, however, peaked earlier than 24-48 hours because the flooded section of the cave created a pressure wave by which increased water pressure from the stream inflow was transmitted through the flooded cave, causing an immediate increase in the spring discharge (Jennings, 1985).

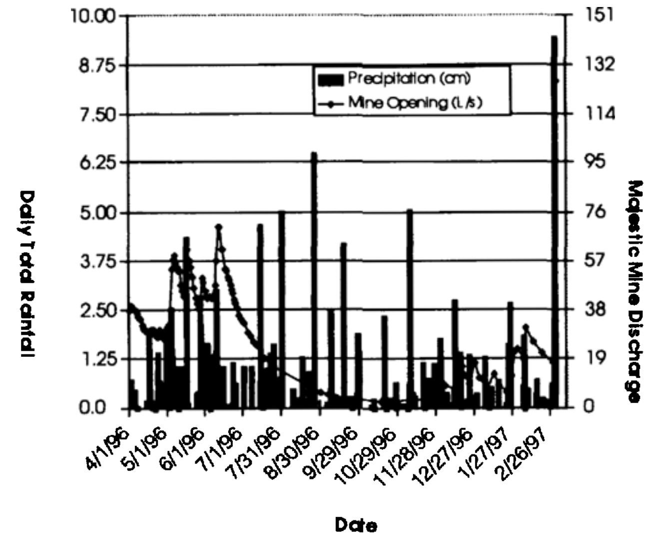


Figure 7. Majestic Mine hydrograph and daily rainfall. April 1, 1996 to March 1, 1997

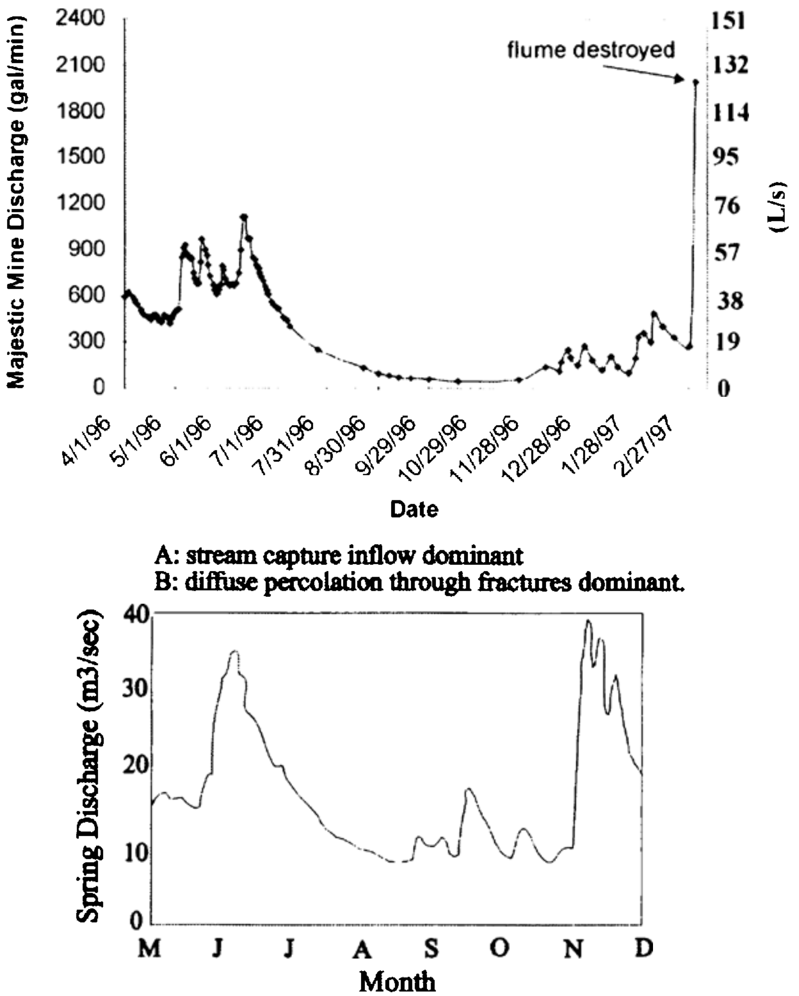


Figure 8 Comparison of the Majestic Mine hydrograph (upper Figure) with a karst spring (bottom). Karst hydrograph after Brogli (1980)

Monthly potential evapotranspiration was calculated for the study period using the Thornthwaite Method, which incorporates average monthly temperature and the latitude of the study area (Thornthwaite and Mather, Jr., 1957). The Thornthwaite equation is: $PE_m = 16N_m[10T_m/I]^a$, where PE_m is the monthly potential evapotranspiration (millimeters), N_m a monthly adjustment factor related to hours of daylight, $I = \Sigma[T_m/5]^{1.5}$ where T_m is average monthly temperature (Celcius degrees), and $a = 6.7e^{-7} I^3 \quad 7.7e^{-5}I^2 + 1.8e^{-2} I + 0.49$. Figure 9 indicates that during those months in which precipitation is greater than potential evapotranspiration (November through May), the mine discharge fluctuates with rainfall events as Captured Stream and recharge provides water inflow to the Majestic Mine. During those months in which the potential evapotranspiration is greater than the total monthly rainfall (June through October), the inflow sources are eliminated, and there is no relationship between rainfall events and the mine discharge.

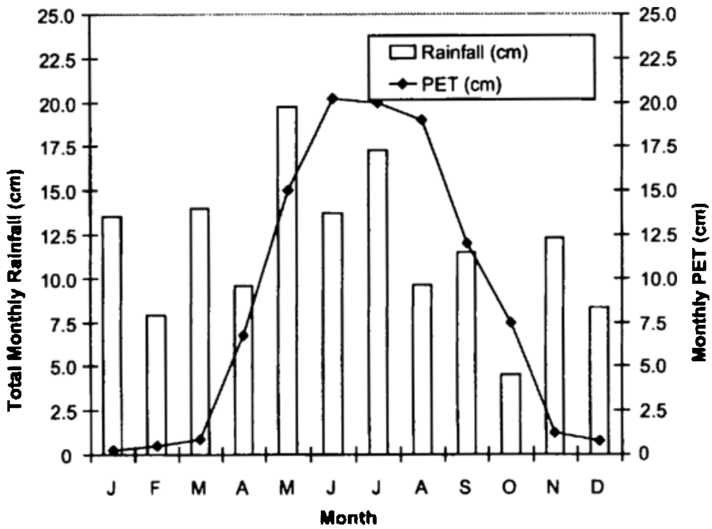


Figure 9. Calculated potential evapotranspiration and total monthly rainfall for the study area in 1996.

Figure 10 is the hydrograph for both Captured Stream and the mine opening for the time period of March 27, 1996 to October 15, 1996. The total volume of water discharged by Captured Stream and the mine opening during this time period was determined by integrating the discharge over time. The total volume of water inflow into the mine by Captured Stream during the study period was approximately 2.08×10^8 liters (5.5×10^7 gallons), while the total mine opening discharge was approximately 3.43×10^8 liters (9.04×10^7 gallons). Thus, the contribution of the mine inflow from Captured Stream was (2.08×10^8 liters/3.43×10^8 liters) = 61 percent of the total mine discharge. The assumption here is that water entering the mine from Captured Stream results in additional discharged water of equal volume at the mine opening. In other words, if one million gallons of water entered the mine from Captured Stream, then one million gallons of water would discharge from the mine opening in response to the Captured Stream inflow, in addition to water recharged from other fractures, diffuse infiltration, and groundwater recharge. A large portion of this additional flow is probably coming from the northwest mine complex.

The difference between the total mine discharge and the Captured Stream inflow for this time period was ($3.43 \times 10^8 - 2.08 \times 10^8$) liters = 1.35×10^8 liters (3.54×10^7 gallons). This represents mine inflow from recharge features overlying the mine complex. The total area of interconnected underground mine workings, including the Majestic Mine (1.22 km^2 or 300 acres), and the adjacent mines to the north-northwest (3.6 km^2 or 880 acres) has an approximate area of 4.8 km^2 (1180 acres). Using a contributing area of 4.8 km^2, this volume of water represents (1.35×10^8 l)(10^{-3} m^3/1 liter)(1 km^2/10^6 m^2)(1/4.8 km^2)(100 cm/1 m) = 2.8 cm or 1.1 inches. The total rainfall amount from March 27, 1996 to October 15, 1996 was 83.6 cm (32.9 inches). This recharge is 3.3 percent of the total rainfall observed during this time period, which is comparable to the established average annual recharge rate of 5 percent for the study area.

A similar analysis was made using the Captured Stream and mine discharge hydrographs resulting from a single storm event. The May 15, 1996 storm event was chosen for analysis, as Captured Stream was at baseflow conditions prior to the storm and returned to baseflow conditions following the storm. This storm also resulted in a distinct peak in the Majestic Mine discharge that was used in the analysis. Using the same calculation procedure and assumptions as above, the single storm analysis yielded an 80 percent contribution of the mine discharge from Captured Stream, with a 4.8 percent recharge rate overlying the mine complex.

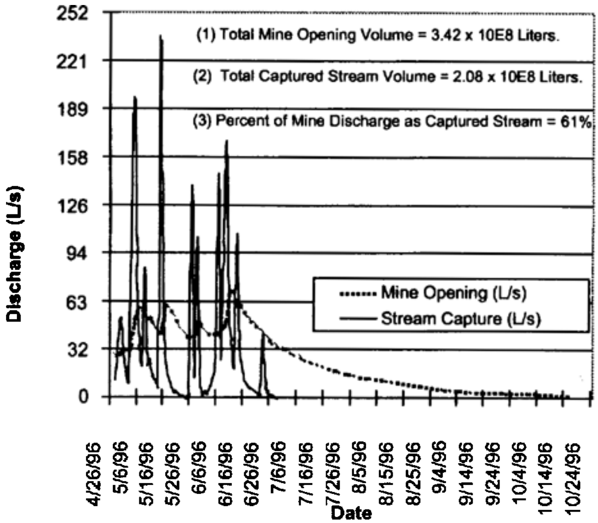


Figure 10. Hydrograph of the Majestic Mine discharge and Captured Stream, March 27 to October 15, 1996.

Water Chemistry

Figure 11 illustrates the seasonal variation in the dissolved oxygen of the Majestic Mine discharge at the mine opening. During those months in which the mine discharge was high, the dissolved oxygen concentration of the discharge fluctuated around 0.7 mg/L. During the recession of the mine discharge and the subsequent lowering of the mine pool, a greater area of mine workings was exposed to atmospheric oxygen, and the dissolved oxygen concentration of the mine discharge increased to a range of 1.25-1.80 mg/L. During this time of the year, Captured Stream is dry and does not contribute water to the Majestic Mine. Captured Stream ceased to discharge water into Majestic Mine in early July (Figure 10). Another possible explanation for the higher oxygen concentrations during the late summer and fall is a delayed elevation of dissolved oxygen produced by the input of oxygenated waters from Captured Stream during the spring and early summer. However, a residence time of the water of a couple of months should be needed in that case. This is unlikely given the fast hydraulic response observed in the mine discharge.

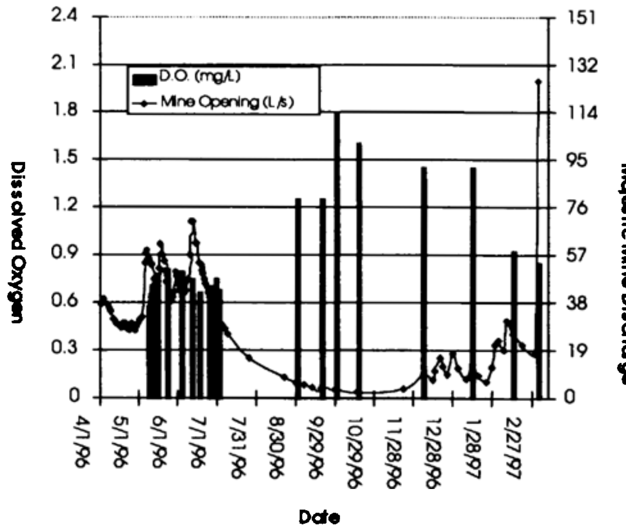


Figure 11. Dissolved oxygen concentrations and discharge versus time at the Majestic Mine opening.

The observed seasonal variations in the water chemistry of the Majestic Mine discharge supports the "spring flush" theory (Smith and Shumate, 1971; Johnson and Thorton, 1987), in which lower mine pool elevations in the dry summer months exposes a larger area of the mine workings to atmospheric oxygen, resulting in an increase in pyrite oxidation and the subsequent leaching of metals from rocks in contact with the acidic mine water. An increase in the mine pool elevation during the wet spring months acts to flush the oxidation products from the reaction sites and into the mine pool, resulting in an increase in acidity and metals concentrations of the mine discharge.

Figure 12 shows discharge and concentrations of iron (A), and aluminum (B) versus time. It shows that the Majestic Mine workings were flushed of oxidation products and leached metals at the onset of early spring snowmelt and rainfall. Acidity and metals concentrations decreased with time as the oxidation products formed during the summer were continuously released. The dissolved iron (140 mg/L - 88 mg/L), aluminum (2.8 mg/L - 0.86 mg/L), and acidity (272 mg/L - 174 mg/L) concentrations of the mine discharge all display a decreasing trend from March 1996 to October 1996. The concentrations of these parameters then increased as the flush occurred at the onset of increased mine discharge in December, 1996. During the March 1-2, 1996 flood event, the concentration of aluminum increased from 1.1 mg/L to 6.2 mg/L, while the concentrations of nickel, cobalt, and zinc increased from 42 to 56 mg/L, 80 to 110 mg/L, and 19 to 30 mg/L, respectively.

The flushing of reaction sites is probably why the pH of the mine discharge decreased from 4.7 to 3.9, and the trace metals increased during the March 1-2, 1996 flood event. At 126.3 l/s (2000 gallons per minute), the mine discharge during this event was the highest observed during the study period. The large inflow of water entering the mine created a pressure wave that caused an increase in the mine pool elevation within the partially-submerged regions. There were probably reaction sites in the mine complex that had not been flushed since the last discharge event of this magnitude. Therefore, these reaction sites had accumulated reaction products that were dissolved by the flooding waters, decreasing the pH and increasing the concentration of heavy metals.

The temperature of the Majestic Mine discharge was fairly constant during the study period, ranging from 11.1 to 11.6 °C (52.0 - 52.9 °F) (Figure 13). In comparison, most karst springs have a very constant temperature, generally just above the average annual air temperature of the catchment area (Bogli, 1980). The pH of the mine discharge was also fairly constant (Figure 13), fluctuating over a range of 4.24 to 4.86, with no discernible trends with mine discharge, except the flood of March 1-2, 1996. The temperature and pH data indicate that the residence time of the mine inflow was long enough for the inflow to come to thermal equilibrium with the mine temperature and homogenize with the mine pool waters before being discharged. This behavior for the mine temperature is consistent with the hydrologic model of the mine previously proposed. The volume of mine discharge following a rainfall event equals the total mine inflow volume, but is actually older, displaced water located near the mine opening.

The chemical loadings of the Majestic Mine were calculated by assuming that the change in chemical concentrations between two successive sampling events was linear. A line was fit through the chemical concentrations of successive sampling events, and the equation of the line was used to determine concentrations for each day between sampling events. The chemical concentration for each day was multiplied by the mine discharge for the corresponding day to calculate the contaminant loadings. Water concentrations probably do not change linearly with time between successive sampling events. However, given the limited number of samples, we need to interpolate between the known concentrations to calculate the loadings. Chemical loadings were calculated, in pounds and kg per day, of total iron, aluminum, zinc, nickel, and cobalt originating from the Majestic Mine from April 9, 1996 to March 2, 1997 (Table 1).

Table 1. Total Chemical Loadings from the Majestic Mine discharge, April 9, 1996 to March 2, 1997. Values in parenthesis are pounds.

	Iron-kg (lb)	**Sulfate-kg (lb)**	**Aluminum-kg (lb)**	**Zinc-kg (lb)**	**Nickel-kg (lb)**	**Cobalt-kg (lb)**
Total	54,752 (120,600)	415,455 (915,100)	1090 (2400)	52 (114)	22 (49)	12 (26)

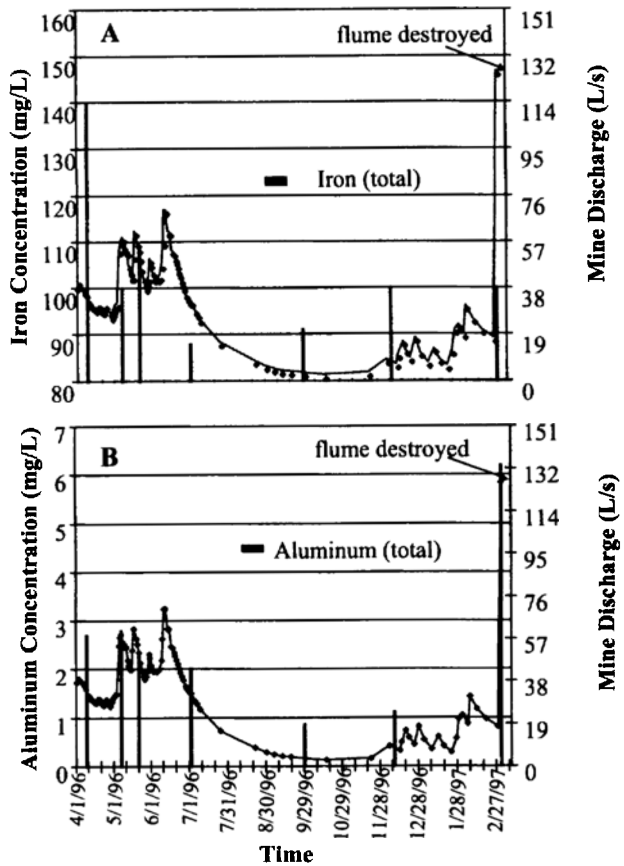


Figure 12. Water Discharge and A) total iron, and B) total aluminum concentrations versus time for the Majestic Mine discharge. Concentrations in mg/L.

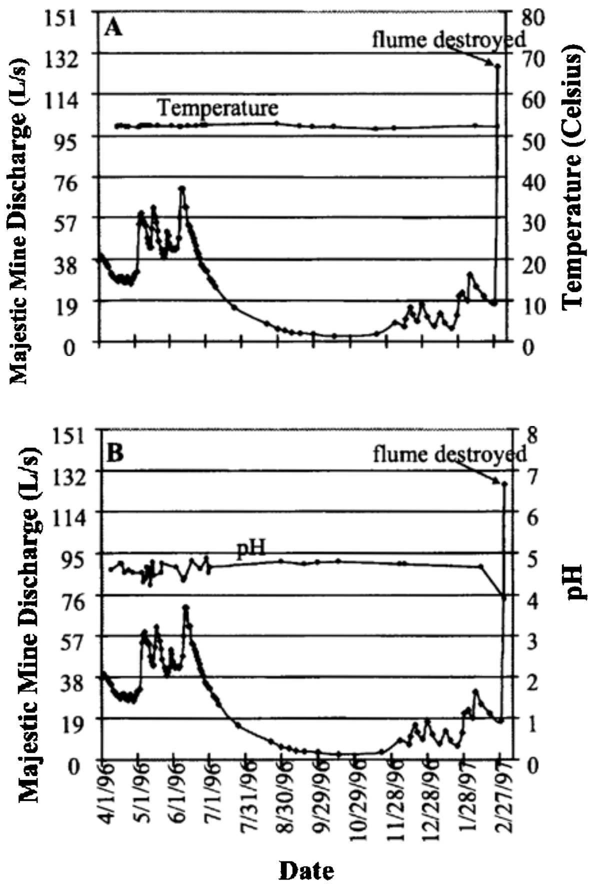


Figure 13. Water discharge and A) temperature, and B) pH versus time for the Majestic Mine.

The Majestic Mine discharge was the primary determinant of the chemical loadings, as the maximum seasonal variation in chemical concentrations showed a 7-fold increase (0.86 mg/L to 6.2 mg/L aluminum), while the mine discharge varied by a factor of 50 (2.5 l/s to 126.3 l/s). The greatest Majestic Mine loadings to Monday Creek during the study period occurred from April through June, when the mine discharge was high. Relatively small loadings occurred from July through November during low-flow conditions.

In the previous discussion, we have assumed that the waters discharged from Majestic Mine acquired their chemical composition from the oxidation reactions occurring at the walls of the mine. However, we have not considered the composition of the waters entering the mine from Captured Stream. Further research is needed to evaluate the contribution of any chemicals from external sources such as rock and soil weathering, or other AMD sources.

CONCLUSIONS

A careful examination of the geology, hydrology, and subsidence features of the study area, and monitoring of rainfall, mine discharge, and water chemistry for one year has allowed us to construct a conceptual model of the Majestic Mine:

1. Loss of support from mine collapse has resulted in large vertical to subhorizontal subsidence fractures along the naturally occurring joints and bedding planes within the sandstone roof-rock.

2. The Majestic Mine and the adjacent interconnected mine complexes to the northwest are partially flooded. The water discharged from the Majestic Mine opening originates as mine inflow from large collapse fractures, smaller, naturally-occurring fractures, and porous inflow from the sandstone roof-rock. Captured Stream, draining a 303 km^2 (117-acre) watershed, is routed directly into the mine workings in an area of thin overburden, and is a discrete inflow point to the Majestic Mine. Captured Stream supplies about 60-80 percent of the mine discharge.

3. A comparison of monthly total rainfall and monthly potential evapotranspiration revealed months of water surplus (November through May) and water deficit (June through October) within the study area. During those months of water surplus, the mine discharge responded to heavy rainfall events. During those months of water deficit, the mine discharge did not respond to heavy rainfall events. Due to evapotranspiration, the inflow to the Majestic Mine was eliminated during these months, and the mine discharge decreased exponentially.

4. The hydrology of the Majestic Mine can be explained in terms of pseudokarst hydrology. As with karst springs, the water temperature of the mine discharge was almost constant, ranging from 11.1 to 11.6 ^{o}C (52.0 F to 52.9 ^{o}F), and reflected the average annual air temperature of the study area. A pressure wave, similar to those observed in some karst systems, is proposed responsible for a rapid response of the mine discharge following a heavy rainfall. An almost immediate increase in mine discharge was observed following a recharge event, with the lag-time between a rainfall event and the corresponding flood peak of the mine discharge of about 2 days.

5. The seasonal variations in the water chemistry of the Majestic Mine discharge supports the "Spring Flush" theory. During months of high mine discharge in the winter and spring, the dissolved oxygen concentrations of the discharged water fluctuated around 0.7 mg/L. During months of low mine discharge in the summer and fall, the lowering of the mine pool exposed a greater area of the mine workings to atmospheric oxygen, and the dissolved oxygen concentrations at the mine opening ranged from 1.25 mg/L to 1.80 mg/L. During the low-

flow months, pyrite oxidation products and leached trace metals remained on the walls of the mine workings exposed to atmospheric oxygen. During the snowmelt and rainfall of early spring, the inflow to the mine caused the mine pool elevation to rise, and the oxidation products were flushed from the reaction sites. The concentrations of iron, aluminum, zinc, nickel, and cobalt decreased with time during the spring, summer, and fall. The concentrations then increased during the following winter and spring as the mine discharge increased, and reaction sites within the mine were again flushed of their oxidation products.

6. Except for the March 1-2, 1997 flood event, the pH of the mine discharge ranged from 4.24 to 4.86, with no discernible trends with discharge. The pH and temperature (11.1 to 11.6 °C) data indicate that the residence time of the water is long enough to allow thermal equilibrium within the mine and that the waters of the mine pool are probably well mixed prior to discharge.

7. The chemical loadings of the Majestic Mine discharge to Monday Creek, for the study period of April 9, 1996 to March 2, 1997, totaled about 54,752 kg (120,500 pounds) of iron, 415,455 kg (915,000 pounds) of sulfate, 1090 kg (2,400 pounds) of aluminum, 52 kg (114 pounds) of zinc, 22 kg (49 pounds) of nickel, and 12 kg (26 pounds) of cobalt.

This research has shown how important it is to carefully consider the geology, subsidence features, and extent of underground mining in investigating discharges from abandoned underground mines. It also demonstrates the need for monitoring of the discharge, chemical composition, and other field parameters (temperature, pH, dissolved oxygen, conductivity, etc.) over time, for at least one complete year. Conclusions based on a few measurements could lead to under or overestimation of the chemical loads and water discharge from the mines, and inappropriate remediation procedures.

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