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HYDROLOGIC ANALYSIS OF DISCHARGE SUSTAINABILITY FROM AN ABANDONED UNDERGROUND COAL MINE[1]

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ABSTRACT: Discharge from flooded abandoned subsurface coal mines is considered a potential source for water supplies where other acceptable water sources are not available. The objective of this study was to develop procedures for determining sustainability of mine-water discharge using rainfall and discharge data for a case study site. The study site is located in southwest Virginia where Late Paleozoic sequences of sandstone, coal, and shale predominate. A rain gauge and a flow rate monitoring system were installed at the site and data were collected for a period of 100 days. The recording period corresponded with one of the driest periods in recent years and, therefore, provided valuable information regarding the flow sustainability during baseflow conditions. From available data on underground mining patterns, geology, and ground water flow regimes, it was determined that a coal mine aquifer exhibits hydraulic characteristics very similar to the extremely heterogeneous systems observed in karst aquifers, and the mine discharge is analogous to springflow. Thus, techniques commonly used in karst-water systems and springflow analysis were used to develop rainfall/mine-discharge relationships. Springflow recession analysis was performed on five rainfall recessions and the coefficient for each recession was compared and interpreted in light of known geologic information. It was found that the recession coefficients described the mine discharge adequately and the mine aquifer response to a rainfall pulse was very similar to the response from certain types of karst aquifers. A cross-correlation analysis was performed to verify the results of the recession analysis and to develop a "black box" statistical model for discharge data. The correlation analysis proved the validity of springflow recession analysis for mine discharge. The recorded data length was not adequate to create a statistical model, however, but a procedure was proposed for a statistical model that could be used with large flow records. For the study site, the mine discharge was found to be sustainable for a prolonged period of time.
(KEY TERMS: springflow; mine-discharge; karst systems; correlation analysis.)

INTRODUCTION

In southwestern Virginia, adequate sources of water supplies for small rural communities are difficult to find due to natural surface water and ground water conditions as well as past mining activities. Many communities in this region are often located beyond the services of public water supplies. Consequently, alternative sources of water must be utilized. These sources include private wells, water hauling, water-collection devices such as cisterns, and abandoned mine aquifers. Logically, it would seem that wells tapping groundwater supplies would be the most feasible source of potable water, and approximately 77 percent of the residents in this region obtain their water resources by this means (Ross *et al.*, 1996). However, because of the high cost of drilling and because adequate quantities are usually limited to thin coal-bearing seams, the risk and cost factors associated with drilling make it a less favorable option. Additionally, many shallow wells yield poor quality water. A water testing survey conducted within the coal counties of Virginia indicated that 62 percent of all ground water samples collected tested positive for coliform and 21 percent for fecal coliform (Ross *et al.*, 1996). Consequently, alternative sources of water should be considered.

One alternative source of drinking water evaluated in this study is abandoned coal mine drainage. Hobba (1981) found that in West Virginia, 82,000 people and numerous commercial establishments obtained their water from abandoned coal mine aquifers. Of particular concern is the quality of water originating from

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abandoned mines (Scott and Hays, 1975). The quality of water is largely governed by (1) the source water quality, (2) the throughflow rate, and (3) the presence of calcium carbonate. That is, if the quality of water entering the mine is good (e.g., recharge from precipitation) and the quantity of inflow and outflow through the mine is large and rapid so to limit dissolution and ion exchange, and if enough carbonate rock is available to neutralize the acidity of the water from the coal, then the quality tends to be comparable to ground water conditions in other regions of the state. Thus, if the quality of outflow is acceptable, the main issues then become quantity and sustainability.

The study site evaluated for water quality, quantity, and sustainability is located at the Screaming Eagle Mine in the community of Duty, in Dickenson County, one of seven "coal counties" in southwestern Virginia (Figure 1). The primary objective of this study was to assess the sustainability of the water yield from a mine portal using hydrologic analyses. In other words, evaluation of sustainability is accomplished by correlating spatial and temporal relationships between precipitation (or recharge) and discharge rates from the mine.

HYDROGEOLOGY IN THE VICINITY OF THE MINE

The study area is located in the southern Appalachian Plateau physiographic province, referred to as the Cumberland Plateau. This region is characterized by generally flat-lying or gently folded shallow nonmarine and marginal marine consolidated sedimentary rocks of Middle Pennsylvanian age comprised primarily of sequences of sandstone, coal, and shale (Harlow and LeCain, 1991). The study area lies west of major thrust faulting and compressional tectonic features are limited to gently dipping anticlinal folds. The Sourwood Mountain anticline forms a hydrogeologic divide and lies about 0.5 km east of the mine discharge site [the mine portal is a 0.3 m diameter (12-inch) pipe that discharges from the mine through the wall of the hillside and is the focus of this study] and dips at an angle of about 5° toward the west-southwest (toward the portal). Fracturing associated with thrust faulting occurs more than 5 km east of the study area; hence, fracture permeability is probably more limited in this region.

Weathering and erosion of the less resistant rocks has created an area of high relief and steep topography. Throughout the region, ridge tops are often 200-340 m above the valley floor. Ground water levels are assumed to represent a subdued reflection of the surface topography. Hence, springs and seeps can often be observed in the sides of the steep valley walls, particularly above the shale units. Vertical flow is restricted by continuous shale layers that underlie the coal seams. Hence, downward percolating water tends to saturate the coal layers overlying the shale, in some locations as perched ground water. Within the study area the Tiller coal seam (5 m in thickness) represented the major mineable unit and, where it has

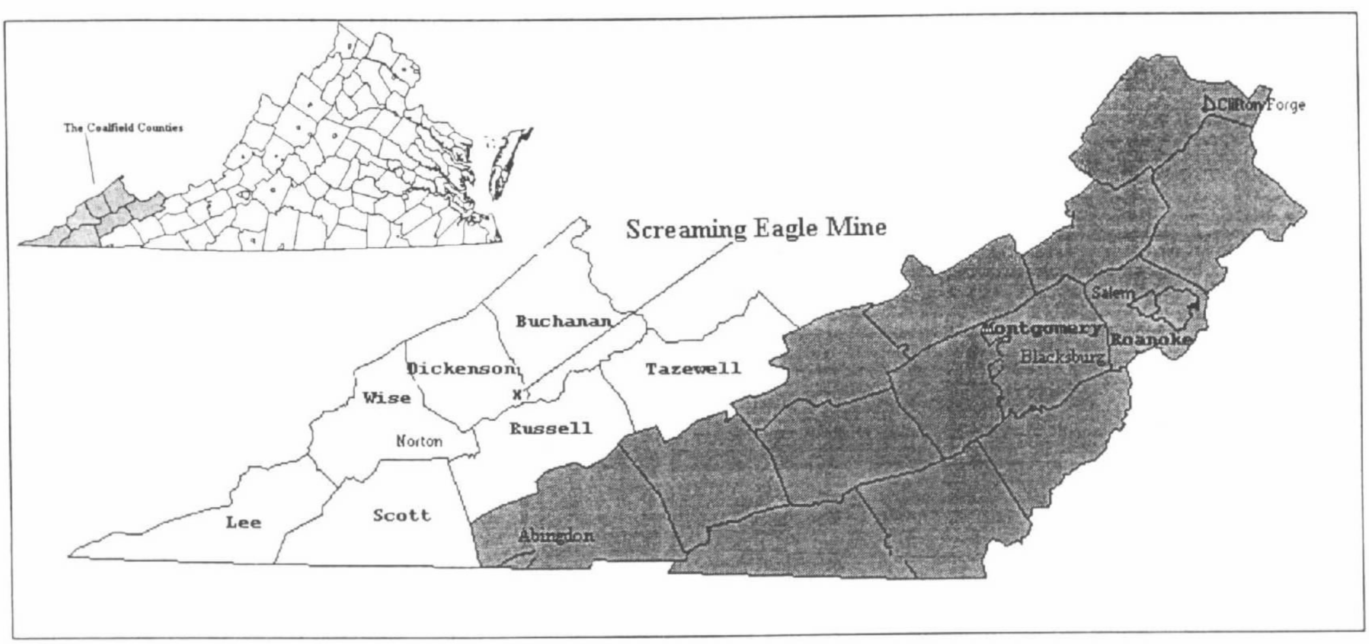

Figure 1. Location of Study Area.

not been mined, has an average transmissivity much greater than either the overlying sandstone or underlying shale units (Table 1).

TABLE 1. Transmissivities Estimated From Packer-Test Data (modified from Harlow and LeCain (1991).

	50th Percentile Values* in m²/day		
Depth (meters)	**Coal**	**Sandstone**	**Shale**
0-30	0.1	0.075	0.0001
30-60	0.07	0.0001	< 0.0001
60-100	0.01	< 0.0001	0.0001
> 100	0.007	< 0.0001	< 0.0001
All Tests	0.01	< 0.0001	<< 0.0001

*50th percentile values indicate 50 percent of the values measured were at or below this transmissivity value.

Mining operations at the site utilized both surface and underground methods beginning in 1951, with surface mining operations continuing until 1996. The thinner and shallower coal seams were surface mined (R. Jones, 1998, oral communication, Pittston Coal Company, Dante, Virginia), while the deeper and thicker Tiller coal seam was mined for about nine years using a technique called *room* and *pillar mining* (Buchanan and Brenkley, 1994). This technique removes as much as 90 percent of the available coal by drilling a series of underground passageways that intersect at 90° angles, leaving behind square pillars composed of unmined coal as permanent roof supports. During active mining much of the ground water was discharged from the mine through the mine portal and is represented by the approximate downdip extent of the mining operation (only about 1.6 ha of mine extend downdip of the portal discharge point). Once the mining activities had advanced to where no additional coal could be extracted, many of the coal pillars used to prevent ceiling collapse were removed. Over time it is believed that much of the ceiling has collapsed filling the mine cavity with coal and sandstone rubble (Scott and Hays, 1975; Hobba, 1981). This rubble represents a zone of high porosity and permeability for horizontal ground water flow (Figure 2). An area of approximately 4 km² upgradient of the portal (and within the recharge area of the portal) was mined using this technique. Currently the rubble region below the portal is likely to be fully saturated, while the rubble region upgradient of the portal may be fully to partially saturated.

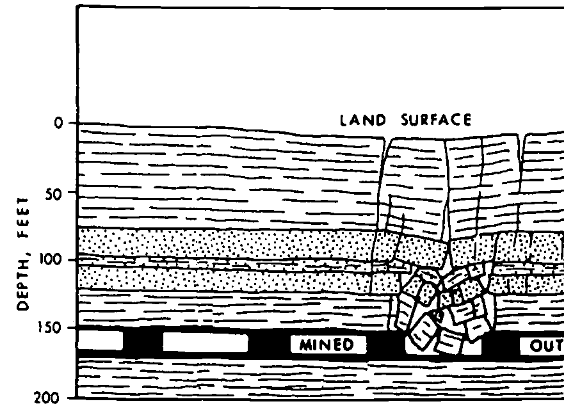

Figure 2. Effect of Mine Roof Collapse Resulting From Room and Pillar Mining.

METHODS OF MEASUREMENTS AND ANALYSIS

No well information was available to assess hydraulic gradients or water-level changes within the mine associated with rainfall events; hence, springflow recession was used to evaluate the flow characteristics of the mine water. To collect springflow (mine discharge) data, a Doppler velocity meter was installed in a 380 mm diameter pipe located in an artificially dammed pond below the discharge portal and connected to a data logger. The discharge velocity was measured continuously for a period of 100 days beginning in August 1998. The discharge rate was computed using velocity readings and pipe characteristics (Anderson, 1999). Rainfall data for the same period were measured by a rain gauge installed nearby. Rainfall and discharge data for the study period are shown in Figure 3. Several short intervals (two or three days) of data are missing due to problems associated either with the malfunctioning of the velocity meter caused by clogging or by a data logger with a low battery. Linear interpolations were used to fill in for missing data. The flow rates shown in Figure 3 are believed to be approximately 3 L/s higher than true flow rates due to losses associated with leakage through the artificial dam and evaporation. Discharge variations due to temperature changes that affected the velocity meter were evident but were insignificant.

ANALYSIS OF SPRINGFLOW

In order to assess discharge rates associated with recharge events, proper characterization of the mechanisms influencing the rate and time of discharge

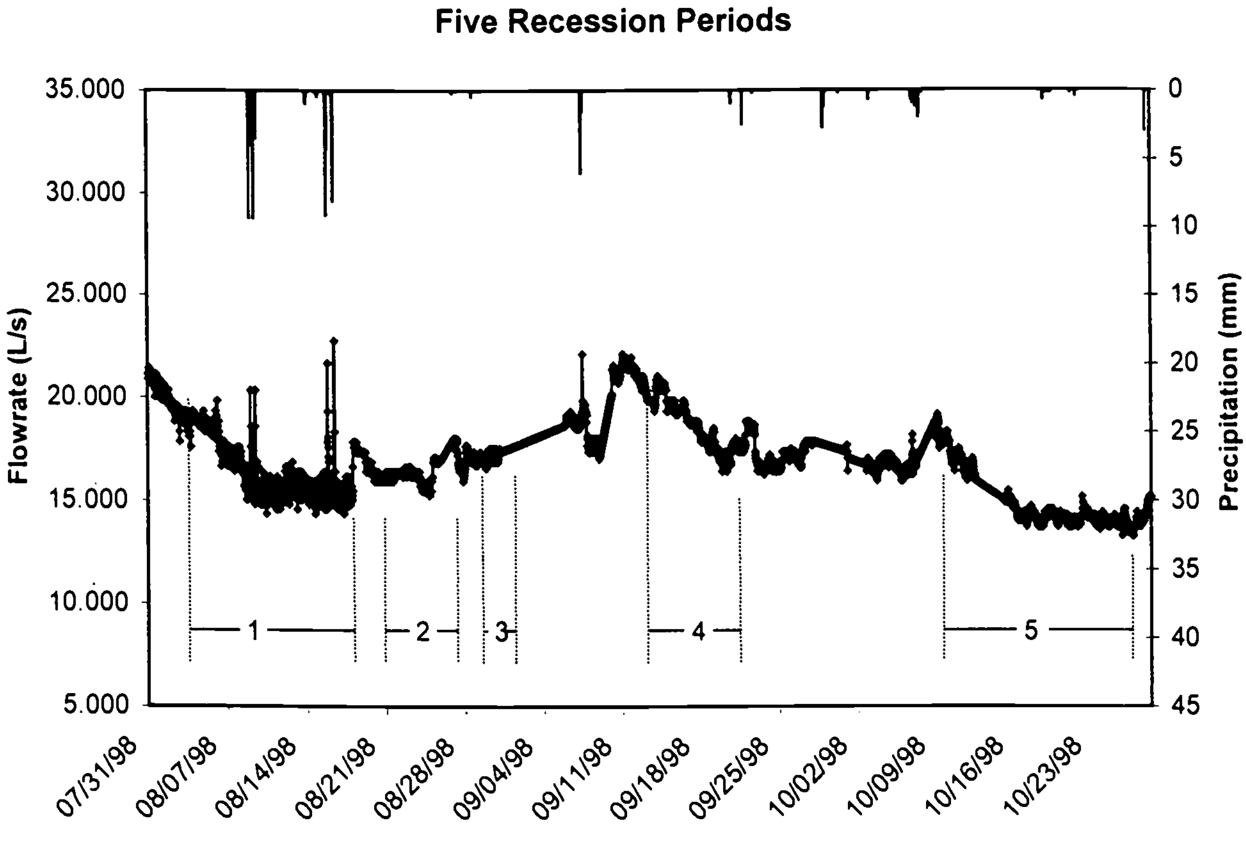

Figure 3. Hydrograph and Precipitation Data Showing Recession periods (numbered).

from rainfall events is necessary. Because of the suspected cavern and possible rubble zones within the mine workings, it is believed that the hydraulics of the mine network behaves similar to a karst system where diffuse, or conduit (free flow), conditions are present (Ford and Williams, 1989; White, 1969, 1977, 1989). It is believed that the portion of the mine near the portal may be a partially open cavern with free-flow conditions. Water may pool within the cavern below the discharge portal. Recharge is believed to be supplied to the mine by way of diffuse flow through the overlying disturbed rubble zones or through fractures within the sandstone unit. Some of the mine passageways may be filled with collapsed overlying sandstone; but, in general, recharge is considered to enter the cavern from above and then flow over the underlying shale toward the mine portal. Figure 4 is a depiction of the expected flow regime.

Analysis of the recession coefficient, α, in the classical springflow equation of Maillet (1905), can possibly lead to a determination of which flow types dominate the system. In addition, springflow analysis can provide an estimate of the amount of water stored in the saturated zone upgradient of the mine portal. This value is valuable for determining the sustainable baseflow (portion contributed from ground water) from the system. Maillet's equation is expressed as

$$Q_t = Q_o e^{-\alpha(t-t_o)} \tag{1}$$

where Q_t is the flow at time t, Q_o is the flow at the beginning of the recession, t_o is the time at the beginning of the recession, and t is the time since the beginning of the recession. The recession coefficient α represents the ability of the aquifer to release water and is a function of the transmissivity and specific yield of the system. A large α on the order of 10^{-2} days^{-1} indicates rapid drainage with high hydraulic conductivity. A value of 10^{-3} days^{-1} generally indicates a system with lower conductivities and less rapid flow (Kresic, 1997). Several recession coefficients are often fit to a single recession curve, indicating multiple types of flow conditions influencing discharge from the system. The recession coefficient can be thought of as the ratio of the discharge to the dynamic volume. The dynamic volume represents the quantity of water present in the aquifer above the level of the discharge point at a particular instant in time. Therefore, by monitoring the discharge rate, the dynamic volume can be estimated once the recession coefficient is

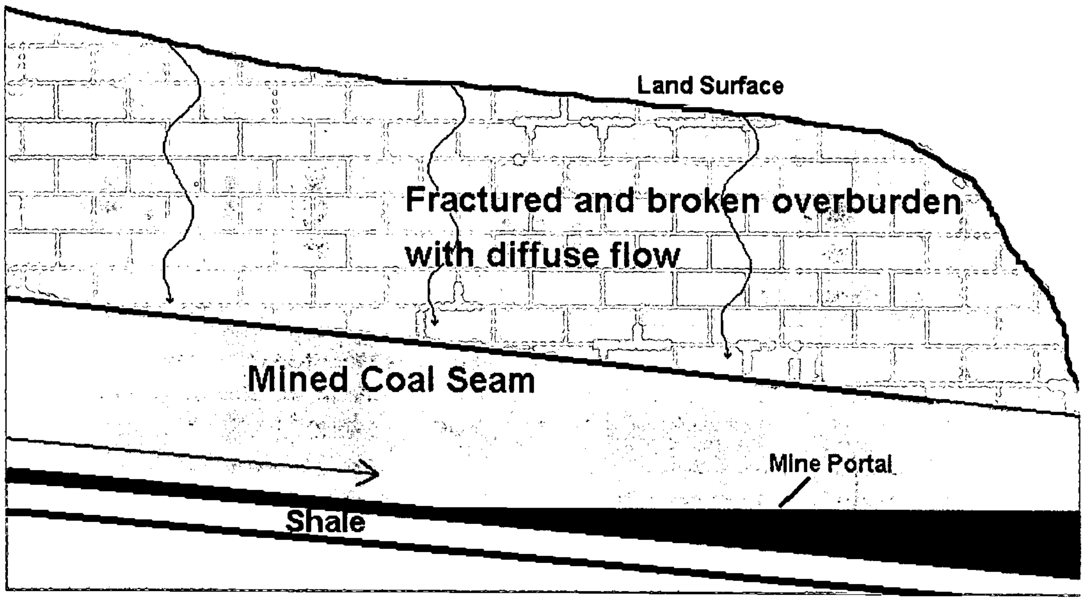

Figure 4. Conceptualized Flow System Within the Mine Aquifer System.

calculated for a particular time during the recession interval. Generally, the later the time the smaller the recession coefficient and the more the system is dominated by diffuse-type flow.

To further analyze the relationship between rainfall events and discharge from the mine portal, a cross-correlation time-series analysis was performed to evaluate the significance in the two series (rainfall and discharge) for a number of different time intervals.

Results of Recession Analysis

Four significant rainfall events and one smaller event are correlated with subsequent increases in springflow and are shown in Figure 3 with the corresponding recession curves (numbered). The time lags from the rainfall event to the corresponding increase in flow are generally about eight days. In all but the first event (July 31), it appears that each rainfall event produces a quick discharge response followed by a later more significant, increase in flow. This is believed to be the result of early conduit flow followed by a later pulse of diffuse flow. The largest peak in flow (Sept. 12) was probably associated with two large rainfall events in the middle of August. The nearly coincident spikes in flow immediately after each rainfall event are more than likely from surface-water runoff or responses to the rain events and are ignored in this analysis. In the following analysis it is assumed that no significant rainfall events occurred during the period of the recessions.

Using Equation (1) recession coefficients were computed for all five recessions. Table 2 is a summary of the recession analysis and lists the computed recession coefficients for all five recessions. The computed α values reflect the type of flow conditions present within the system. The average computed value of α_1 is 0.033 days^{-1} (the average does not include the 0.099 days^{-1} value representing the abbreviated one day recession) and indicates a condition of rapid drainage from well-interconnected pore spaces. This may indicate that the mine passages may have been at least partially filled with collapsed overburden (as expected) as the average is too small for purely open or free flow conditions. The calculated average value for α_2 is about 0.005 days^{-1}. This value reflects a more diffuse flow condition (Kresic, 1997) where water drains from small pores or fractures into the mine toward the discharge portal.

To use the Maillet equation (Equation 1), values of Q_o and Q_t (Q at a specific time) need to be estimated. The values of Q_t are selected on the hydrograph curve at the end of the current recession just prior to the increased flow from a new rain event. Values of Q_o are more difficult to quantify and are chosen at the beginning of the recession. However, because of the large oscillations in the data, the exact location of this parameter was difficult to pinpoint. Choosing Q_o from the hydrograph 30 minutes before or after the actual start of the recession often resulted in large variations in the calculated value of α. The initial flow rate was estimated from the first recession. Each successive predicted flow rate was calculated using Equation (1) with the previously calculated α (a previous

TABLE 2. Summary of Recession Characteristics.

Recession Number	Recession Start	Recession End	Recession Length (days)	Q_o for α_1 (L/s)	Q_t for α_1 (L/t)	α_1 (days^{-1})	R^2 Value for α_1	Q_o for α_2 (L/s)	Q_t for α_2 (L/t)	α_2 (days^{-1})	R^2 Value for α_2
1	7/31/98	8/15/98	15.38	20.88	15.94	0.0298	0.84	15.94	15.26	0.0069	0.94
2	8/19/98	8/21/98	2.81	17.84	15.94	0.0400	0.84				
3	8/27/98	8/28/98	0.92	17.67	16.40	0.0990	0.77				
4	9/8/98	9/21/98	9.25	21.94	16.72	0.0292	0.89				
5	10/7/98	10/27/98	17.75	18.00	14.29	0.0316	0.90	14.29	13.72	0.0040	0.02

recession). The predicted flow rate curve is referred to as the recession trend. A multiple regression was performed on the recession trend and flow rate record in order to smooth the flow record and more accurately obtain the parameter values. An optimal value for the initial discharge rate, Q_o, was determined by maximizing the R^2 value between the recession trend and measured flow rate. In all but the fifth recession, where a precipitation event probably affected the recession curve, the α-based recession equations fit the flow data extremely well. Two α values were computed in the first and fifth recessions. The first recession coefficient fits the early-time hydrograph data and the second fits the later-time hydrograph data. Figure 5 shows an example of one such set of computations for a portion of the hydrograph curve from October 10 to October 26.

Another analysis to characterize discharge response was developed by White (1988). In this analysis, the ratio of the largest recorded flow, Q_m, over the estimated baseflow, Q_b, is determined for each recession. The average ratio of Q_m/Q_b for the five recessions in this analysis yielded a value of 1.16, which according to White, represents a slow response spring. This tends to agree with the results of the analysis using Equation (1).

Estimating Diffuse and Conduit Volumes and Sustainability

Rainfall and discharge data were collected for this study during the late summer and fall of 1998. Total measured rainfall during the period of record was about one-fourth the average amount and is advantageous for estimating discharge sustainability from the mine portal and for estimating baseflow. Baseflow conditions were assumed at the start of each recession record. The estimated dynamic volume (the quantity of water estimated upgradient of the mine portal that

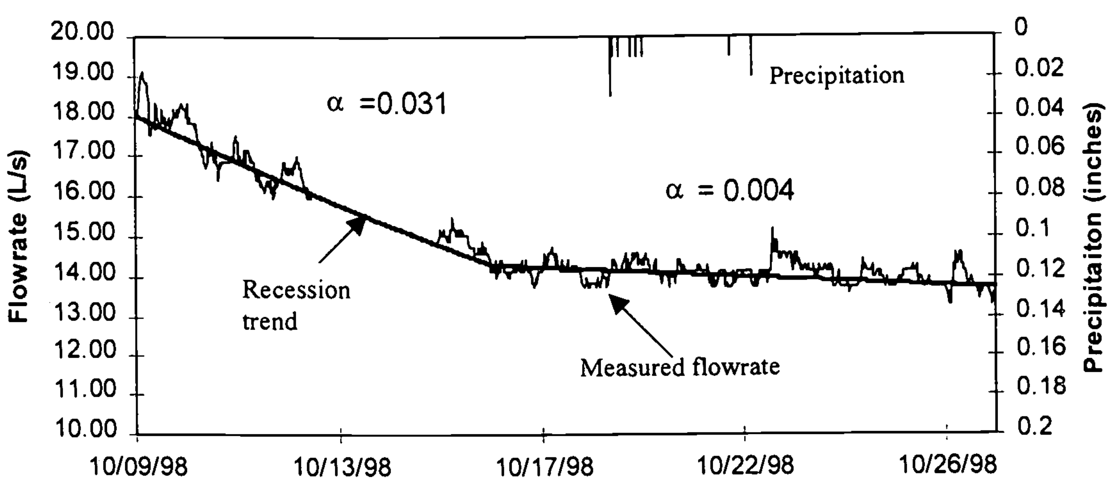

Figure 5. Recession Constants Calculated From Recession Trend for Recession 5.

potentially can discharge from the portal) for each recession is shown in Table 3. The initial dynamic volume provides an estimate of the total ground water available to the system and is equal to the measured discharge, Q_o, divided by the recession coefficient, α. From the recession coefficients, the proportion of flow originating from conduit (α_1) and diffuse flow (α_2) can be estimated. The initial volume is calculated at the beginning of the recession, whereas the change in dynamic volume is calculated from the portion of the recession curve beginning at the peak flow rate and ending at the end of the recession curve (Q_o/α-Q_t/α).

Recession coefficients estimated from the first part of the recession curves are large and probably represent more rapid flow through open or partly open conduits within overlying rubble zones and within the mine cavity. The volume of conduit and diffuse flow (Table 3) is the estimated quantity of water discharged through either conduit or diffuse channels from a single rain event. The total estimated volumes closely match the total measured volume in each of the five recession periods. Only in recession 1, where some additional surface flow may have resulted in increased measured volume, was the difference more than one percent.

Results from the multi-segmented recession curves (recessions 1 and 5) reveal that although much of the change in dynamic volume occurs in conduits, the estimated volume discharging through the portal as conduit flow is small. This is probably due to a large percentage of the conduit volume having to travel through lower permeable collapse zones within the mine before reaching the discharge portal.

Recession curves were also used to estimate the volume of water discharged through the portal as a result of a single rainfall event. Recession coefficients were calculated for a series of rain events that occurred in late July and early August 1998. An average recession value of 0.0055 days^{-1} was obtained. Table 4 lists the pertinent information obtained from these recession curves. The calculated percentage of rainfall discharged from the portal (about 30 percent) is equivalent to the estimated percentage of rainfall that recharges the aquifer systems on average in this region of the country (LeGrand, 1988). The volume of water added to the system per millimeter rainfall depth can be used to estimate discharge sustainability. The Virginia Department of Health requires that the design demand for a potable water source never exceed the lowest flow rate at a given site over the previous 30-year period. Although discharge records are not available for this 30-year period, rainfall records are. The rainfall quantity for the driest of the previous 40 years of record is 345 mm, or about one-fourth the yearly average. Using the recession coefficients from monitored rain and discharge events, this would result in an average yield of 264 m^3/mm of rainfall, or a sustainable yield of 2.85 L/s. This value is about half the estimate (6.0 L/s) from current base-flow conditions.

Evaluation of Discharge Using Time Series Analysis

The purpose of the time series analysis was to predict the occurrence of future outflows based on rainfall events. That is, what is the likely time lag between a precipitation event and the corresponding increase in discharge? If it can be shown that the correlations are high between rainfall observations in

TABLE 3. Calculated Dynamic Water Volume in Mine Aquifer for All Recorded Recessions.

Recession	Flow Type	Initial Dynamic Volume (m^3)	Change in Dynamic Volume (m^3)	Volume From Each Flow Type (m^3)	Total Estimated Volume (m^3)	Total Measured Volume (m^3)
1	Conduit	60,440	14,294	803	22,247	23,074
	Diffuse	198,920	8,534	21,444		
2	Conduit	38,559	4,100	4,244	4,244	4,214
3	Conduit	18,771	1,349	1,380	1,380	1,373
4	Conduit	64,903	15,458	14,493	15,493	15,635
5	Conduit	49,210	10,128	995	22,719	22,877
	Diffuse	307,474	12,403	21,724		

TABLE 4. Volume of Flow Produced From Significant Rainfall Events.

Volume	Total Rainfall (mm)	Volume Added to Flow (m^3)	Volume Per Millimeter of Rainfall (m3/mm)	Percent of Rainfall Discharged
V_1	71	20,279	283	33
V_2	61	14,899	241	28

one time period and the discharge observations of a different time period, then the analysis can be used to predict when and how discharge rates will be affected. The cross-correlation function establishes a relation between corresponding observations as the time lag is increased and can identify any systematic variation that occurs between the two data series. The Statistical Analysis System (SAS Institute, 1993) was used for the statistical time-series analysis described herein.

Stationarity is a prerequisite for applying time series analyses to two series of data. Rainfall data are stationary; that is, they have instantaneous mean values and autocorrelation parameters that do not vary over time. The discharge data, however, are nonstationary. The discharge data were made stationary by taking the difference between two adjacent values in the data set. Thus, instead of using the absolute flow rates, the changes in flow rate from one time interval to the next were selected.

Because the objective was to determine the relation between rainfall and discharge, it is important that the autocorrelation present in either of the two series (rainfall and discharge) not interfere with the analysis. The rainfall data do exhibit some autocorrelation up to lags of 10 hours. A first-order autoregressive model was fit to the rainfall data to obtain a set of residuals. The discharge data set was applied to the same model and the resulting residuals were cross-correlated with the rainfall residuals to eliminate autocorrelations that may have been present in the data (a process referred to as prewhitening). Figure 6 shows the cross correlations for 30-minute time intervals. Horizontal standard error bands are included. Three distinct zones of correlation at about seven days (336 lags), 10 days (480 lags), and 17 days (819 lags) rise above the upper error band. Correlations were also made with time intervals of one hour and one day. Figure 7 shows the relation between the correlations for different time intervals. For correlations to be considered significant, the values must rise above at least one standard deviation from zero; thus, observations at 10, 17, and 25 days, respectively, show considerable correlation depending on the time interval used. The observations created for the one-day interval reveal correlations over much greater lengths of time than those created for shorter time intervals. The longer lag time indicates that the quick flow responses (less than a day) to a rainfall event will be eliminated because they were evaluated using an

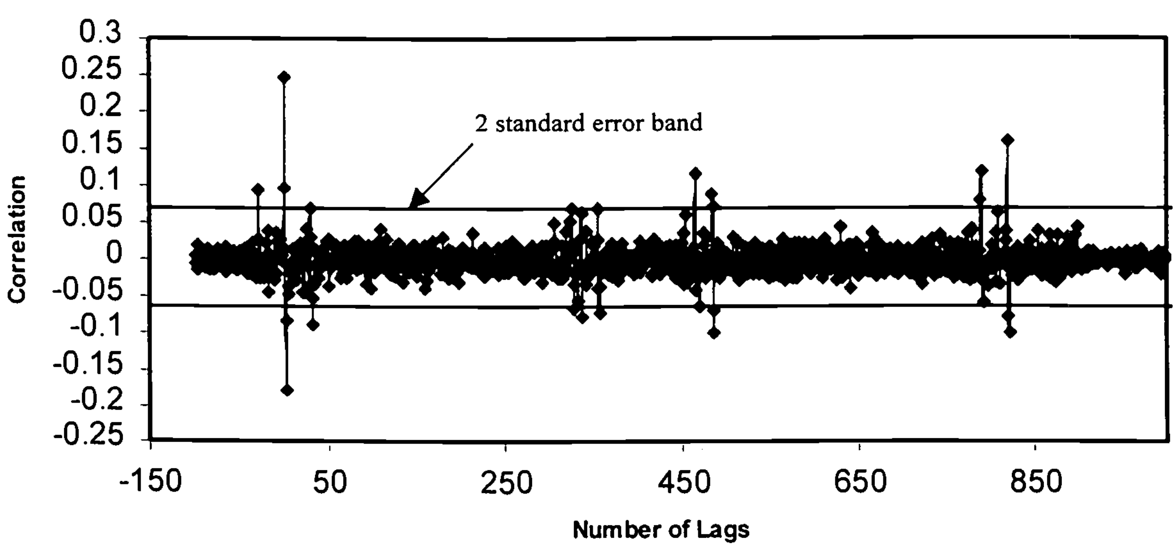

Figure 6. Cross-Correlation Data Obtained From 30-Minute Time Intervals.

average flow rate over an entire day. Hence, using the one-day interval in the correlation analysis allowed for better evaluation of long-term trends in the data. Significant correlations for the one-day intervals were found after 17, 25, and 32 days, respectively. However, the last two lags obtained may be of questionable reliability because they occur at values greater than 25 percent of the record length.

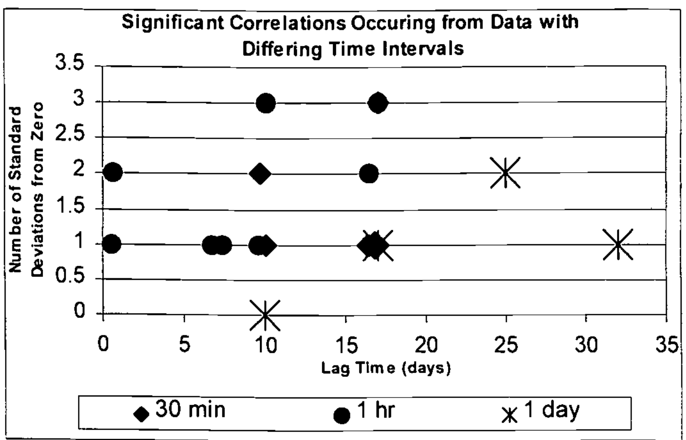

Figure 7. Correlations Produced From Time Series for 30-Minute, One-Hour, and One-Day Time Intervals, Respectively.

The next phase in the analysis was to develop a higher order autoregressive model to fit the discharge data. The autoregressive model would use patterns in the rainfall data to estimate mine discharge rates. The rainfall time lags that correlate with changes in flow rate are the chief parameters in the model. A significance test was used to determine which lags had significant correlation. That is, which rainfall occurrences affect discharge? For example, small amounts of rain after a dry period may simply replenish soil moisture and never affect the discharge rates.

Efforts to develop a reliable model using 30-minute time intervals resulted in poor correlation with observed flows. It is likely that too much random fluctuation occurs at short intervals that cannot be explained simply by rainfall patterns. Hence, it was determined that one-day time intervals should be used. Lags with significant correlations for daily flows were found to be at 17, 25, 26, and 32 days, respectively. Using these values as parameters, the resulting calibrated model can be expressed as:

$$Q\,(L/s) = -.24039 + .01327r_0 + .007394r_{25} + .00523r_{26} - .00425r_{32} \qquad (2)$$

where r_x is the rainfall in hundredths of an inch and x represents the lag time. Figure 8 shows how the predicted model fits with the observed discharge rates. Although the model matches much better than the 30-minute or one-hour models, it still misses some trends, most notably those changes in flow immediately after a rainfall event. This indicates that the natural system responds more quickly than the model. Indeed, the significant lags used in the model preclude such determination. The model presented is likely to be most accurate for assessing long-term trends in flow associated with droughts and wet periods, and not the changes in flow associated with individual rain events. More data and perhaps more variables are needed to properly assess short-term trends in discharge rates. For example, it would be beneficial to include the thickness of the unsaturated zone and the antecedent soil moisture conditions to more accurately predict discharges associated with individual rain events. However, the model does seem to indicate that a large portion of the discharge response occurs several weeks after a rainfall event, similar to the 14-day estimate obtained from evaluating the change in iron concentration (discussed in the following section) following a change in discharge. This seems to imply that much of the flow through the mine is diffuse in nature. Indeed, earlier results from the recession analysis indicate that much of the outflow from the mine portal originates from diffuse type aquifer conditions.

WATER QUALITY CONSIDERATIONS

Although a sustainable discharge rate is vitally important in assessing the viability of the mine discharge as a potential water supply, the water quality discharging from the mine is of equal importance. If the water discharging from the portal can be shown not to be influenced by potential contaminants on the land surface and if the discharge water meets EPA drinking water standards, then the discharge water does not require costly filtering. A comprehensive analysis of water quality for drinking water standards identified the water as acceptable for water supplies can be found in Younos *et al.* (1999).

In addition to evaluating the quality of the mine discharge, chemical analyses can help to determine the time difference between a given rain event and the associated discharge from the mine portal if the chemical signature of the precipitation water is different than the discharge water. If the chemistries are different a throughput rate can be estimated. This is one of the parameters necessary for assessing long-

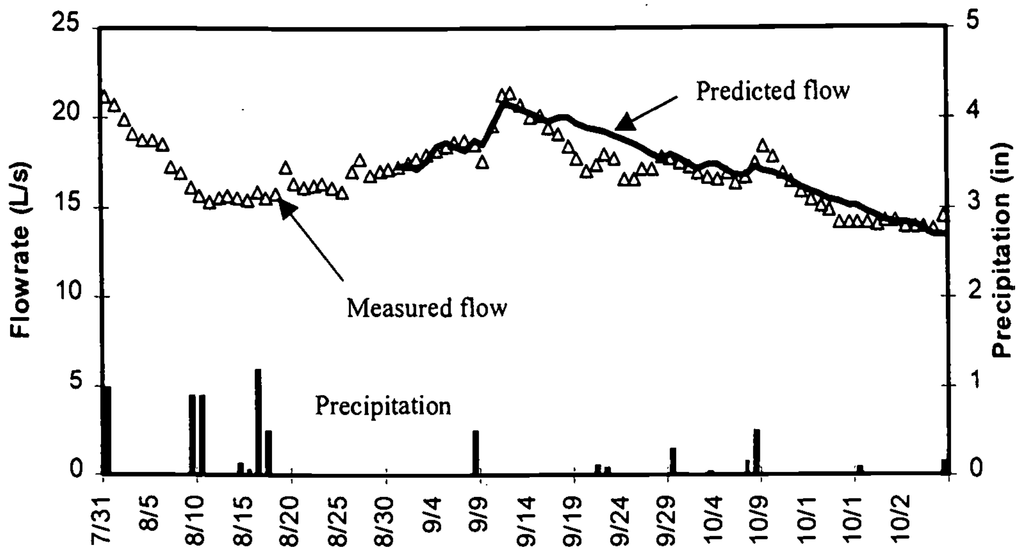

Figure 8. Predicted Flow Rates From Model Results Compared With Measured Flow Rates for One-Day Time Intervals.

term water quality and viability as a potable source of water for municipal use.

Periodic grab samples were obtained from the discharge portal from July through December 1998. Samples were analyzed for magnesium, calcium, sulfate and iron concentrations, pH, and total dissolved solids (TDS). In general, it can be assumed that concentration variations that inversely mimic the changes in flow rate represent rapid throughflow associated with rainfall events, while concentration variations that are nearly constant over time suggest a discharge having a high percentage of ground water (baseflow) with longer residence times.

Discharge from the mine is slightly basic, with pH values typically just below eight. These values drop to nearly seven during increased flow from rainfall. Magnesium (Figure 9A), sulfate (Figure 9B), and calcium (Figure 9C) concentrations do not change significantly as a result of recharge from rainfall events. Although some variations did occur, the most notable was the general increase in concentration of these constituents as the season became drier. In other words, increased concentrations of these three ions is associated with an increased percentage of discharge originating from ground water as opposed to precipitation generated flow. Iron, on the other hand, shows an inverse relation to discharge (Figure 10). Recharge water has no iron and the small concentrations that are measured in the samples likely originate from within the mined coal seam. Recharge associated with rainfall dilutes the discharge with respect to iron. It appears that the lag between increased flow and decreased iron concentrations is about 14 days. This indicates that the pressure increase associated with a recharge event occurs about two weeks prior to the active flushing of recharge water from the mine cavity. Iron concentrations are well below the standards set by the EPA for drinking water and will not likely pose a water-quality problem even during long dry spells.

CONCLUSIONS

Availability of potable sources of water is a major concern in southwestern Virginia where many residents live far from municipal water supplies and water wells often produce meager quantities of ground water and are costly to install. Discharge from an underground abandoned coal mine – the Screaming Eagle Mine – is being considered as an alternative source of water for residents living in the town of Duty in Dickenson County, Virginia.This report describes the quantification of the sustainability of flow from the discharge portal emanating from the mine cavity. No well data were available for the study. Hence, springflow recession and time-series analyses were used to evaluate the sustainability of the discharge. Discharge from the mine is believed to behave much like springflow from karst regions because of the extent to which the main coal seam has been mined and the possible overburden collapse deposits that may at least partially fill the mine cavity.

Rainfall and discharge data were measured during one of the driest periods in recent years, providing useful information for assessing the sustainability of the system during baseflow conditions. Calculation of

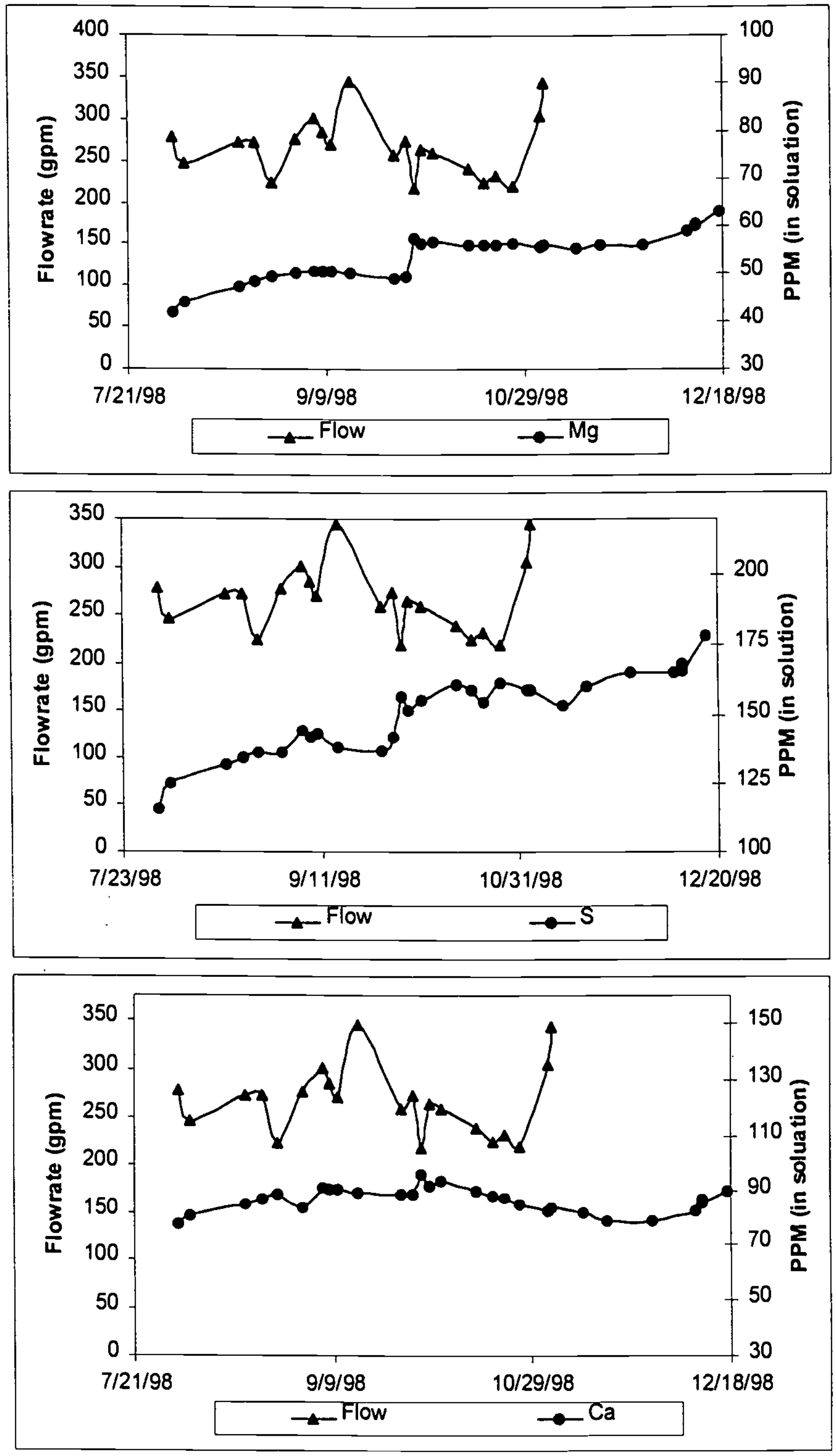

Figure 9. Relation of Spring Flow Concentrations in Parts Per Million of A. Magnesium, B. Sulfate, and C. Calcium.

recession coefficients from springflow recession analysis provide good correlation between estimated and measured flows, and the indication is that much of the flow discharged from the portal lags about 14 days behind the associated rainfall event. Current baseflow yields a sustainable discharge rate of 6.0 L/s. Evaluation of past rainfall records suggests that during the driest conditions baseflow will yield a rate of 2.85 L/s. If an average household uses 800 L/day, then the discharge portal will currently provide enough water for 650 households and can support as many as 310 households during even the driest conditions. The quality of the discharge is generally good and meets EPA drinking water standards.

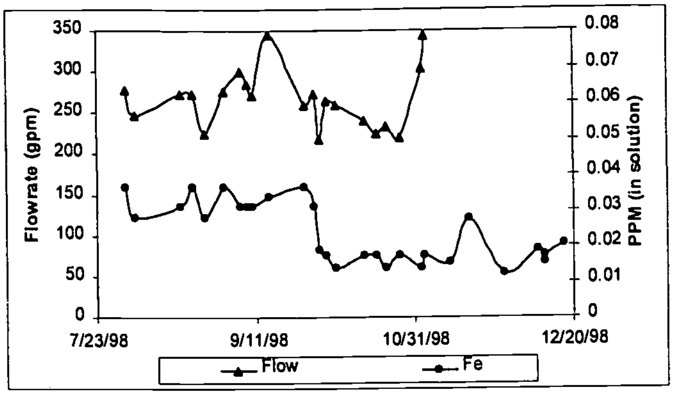

Figure 10. Relation of Spring Flow to Iron Concentration in Parts Per Million.

A cross-correlation analysis was performed in an attempt to fit a "black box" model to the flow data as well as to verify the results of the springflow recession analysis by correlating rainfall and discharge. Thirty-minute and one-hour time intervals did not produce regression models that adequately fit the data. This is likely due to unaccounted for system parameters, such as thickness of the unsaturated zone and antecedent soil moisture conditions. However, one-day time intervals did produce a regression model that adequately matched the discharge data. This time-series analysis indicates that the major discharge response occurs several weeks after the rainfall event and implies that much of the flow through the system is diffuse in nature.

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