THE PARTITIONING OF FLOW COMPONENTS OF ACIDIC SEEPS FROM SURFACE COAL MINES AND THE IDENTIFICATION OF ACID-PRODUCING HORIZONS WITHIN THE BACKFILL[1]

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Abstract.--Two surface coal mine backfills in Upshur County, W.V. were monitored for 3 years to determine the relationship between the hydrology and the mine drainage quality. The recharge of the ground water system was determined by analyzing the response of the water table to precipitation events. Recharge occurs in two ways either by rapid recharge by runoff draining into highly permeable randomly oriented channels during times of high intensity - short duration rain events or regional downward migrating wetting fronts occurring during low intensity - long duration rains and spring thawing events. In the former case,water movement through the unsaturated zone was found to be from 12 to 30 ft/day. Seep flow is comprised of shallow subsurface lateral flow (interflow) and deep ground water discharge (baseflow). Using regression analyses, water table elevations were correlated with baseflow and subsequently used to estimate the baseflow component of the total flow of the acidic seeps. Accordingly, total flow minus baseflow represents the interflow component of the seep. With these flow relationships, variations in seep chemistry were correlated with various flow components to identify the sources of acidity within the backfill. At one mine, interflow did not correlate with acid concentration, whereas at the second mine, interflow was negatively correlated with acidity. Therefore, runoff draining into the permeable channels of the vadose zone, flowing as interflow in the backfill, does not appear to be a major acid contributor. Instead most of the acidity is produced by low-intensity long-duration generated wetting fronts (spring recharge events), infiltrating the system at field capacity. This creates a reservoir of acidic water that sustains the acid mine drainage seeps for the remainder of the water year.

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INTRODUCTION

Water is a crucial factor in the production of acid mine drainage, not only in the oxidation of pyrite but as a medium to transport the reaction products, including acidity and sulfate, to a discharge point. Previous studies of the relationship between ground water flow in backfills and acid mine drainage quality include Collier et al. (1970), Oertel and Hood (1983), Ladwig and Campion (1985), Lusardi and Erickson (1985), and Erickson and Ladwig (1986). The current study differs from the above studies in that it was designed to delineate the interflow and baseflow contributions to seep discharge, determine the relationship between the location of the flow path in the backfill and the resultant seep quality, and identify the acid-producing horizons within the backfill. This information can provide the basis for the design and development of in-situ acid mine drainage abatement strategies.

METHODOLOGY

Data Collection

Two reclaimed surface coal mines in Upshur County, W.V. were selected for detailed hydrogeochemical analysis (fig. 1). The Eight Acre site is a small, unlined, northwestern portion of a larger 15 ha refuse pile which has been almost completely covered with a 20 mil PVC plastic liner. A high-volume acidic seep emerges from the northwestern toe of the Eight Acre site. The Forty Acre Well site is a northwest-southeast oriented strip bounded to the north by a highwall. Acidic drainages are found at the western edge of this site.

Beginning in the spring of 1985, alkaline recharge trenches were installed on the Forty Acre Well site to mitigate acid seeps through alkalinity additions (Caruccio, et al., 1984). Treatments were through the construction of permeable trenches that contained sodium carbonate briquettes and crushed limestone (designed to intercept and divert chemically modified surface runoff into the backfill), and covering the surface of the mine with a veneer of crushed limestone.

Thirteen observation wells were installed on the two sites between 1983 and 1985 (10 on the Forty Acre site and 3 on the Eight Acre site). The 4 and 6-inch (10-and 15-cm) diameter cased (but not grouted) wells fully penetrate the spoil and are screened along a 10 ft (3-m) interval at the bottom of the wells. Water levels in these wells were measured on a weekly basis at the Forty Acre Well site and daily at the Eight Acre site.

During the time frame of this study seep discharge was measured daily at seeps 6 and 7A which emanate from the Eight Acre site and the Forty Acre Well site, respectively. Flows are routed through 1-foot long, 8-inch-diameter, PVC pipes located as close to the seeps as possible. Discharge is measured using an 8-inch-(20-cm) diameter V-notch weir.

Precipitation has been monitored on a daily basis at the site since 1981, using a 4-inch (10-cm) diameter all-weather rain gauge.

Water samples have been collected from seeps 6 and 7A on a weekly basis since 1983 and 1985, respectively. These samples are analyzed for temperature, pH, specific conductance, acidity, alkalinity, and sulfate at the Environmental Hydrogeology Laboratory at the University of South Carolina.

Data Analysis

Seep flow is comprised of shallow subsurface flow (interflow) and deep subsurface flow (baseflow). Interflow is further defined as the ground water flow that occurs in the unsaturated zone, while baseflow is the ground water flowing in the saturated zone below the water table.

To separate the total seep flow into its constituent components of baseflow and interflow, it was necessary to predict the baseflow components of the total flow. Using Darcy's law and relating the seep discharge to a function of the head, the baseflow component of the total seep discharge is directly proportional to the water table elevation measured in a well.

At the Eight Acre site, the partitioning of seep 6 into its flow components was accomplished through multiple linear regression, to examine the relationship between the discharge of seep 6 (during periods of little or no interflow input) and the water table elevation, as measured in wells 6, 6A, and 6B.

During the calibration of the regression model, discrete sets of observations were used to remove the influence that interflow might exert on the seep flow. Seep flow data were discarded if they were measured within 6 days of a precipitation event of 0.25 inch (0.64 cm) or greater. Additionally, because snowmelt might contribute interflow for a much longer period after the precipitation occurred, all observations were discarded when 2 inches (5 cm) or more of snow was on the ground.

Once calibrated, the regression model can be used to predict the baseflow discharge by substituting the estimated regression coefficients and intercept (as determined during the calibration process) and using the water table elevations measured in the wells.

The seep flow from the Forty Acre Well site was analyzed in a fashion

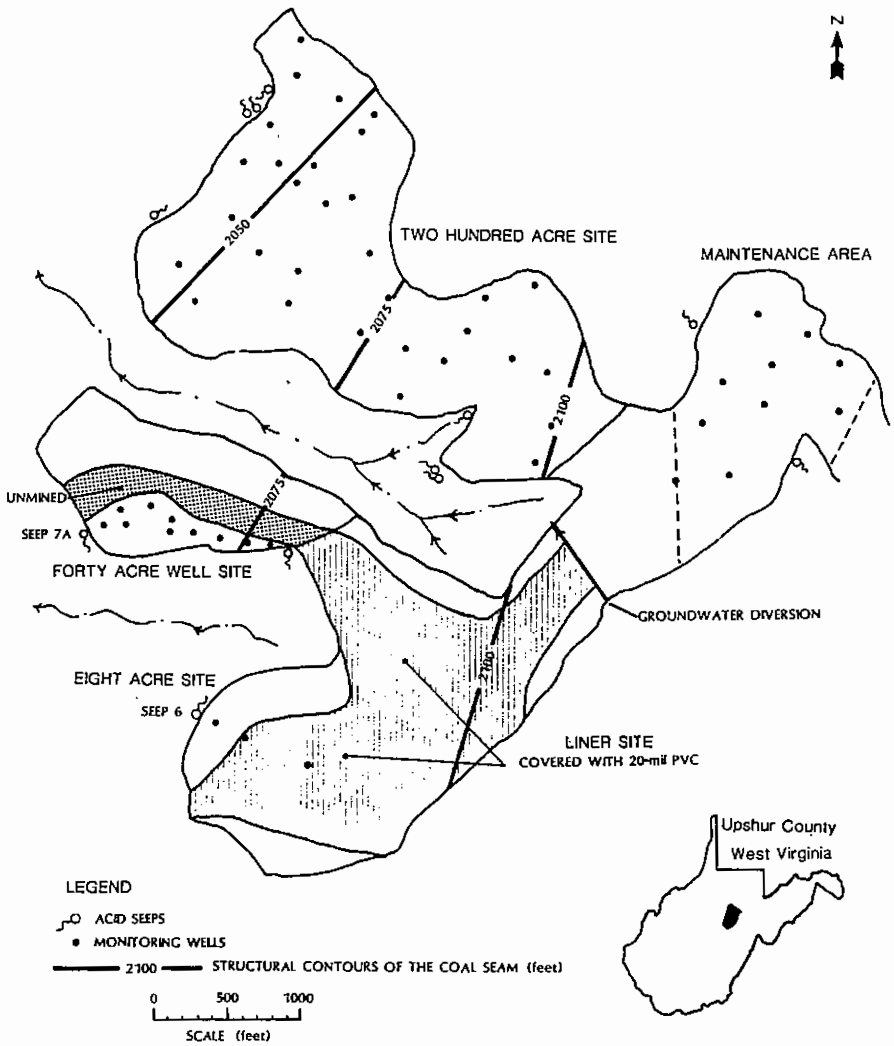

Figure 1. Map of mine sites used in this study and their location.

similar to that used for the Eight Acre site. Because the water levels in the wells at the Forty Acre Site are highly correlated with each other (see fig. 2), a single well was selected for use in the regression analysis of water elevation and seep discharge. Well 14 was selected because it had the highest r-square (r^2) value of any well when used as the regressor variable.

Seep flow and water level observations used to calibrate the Forty Acre Well site regression model were selected using the same criteria as those used for the Eight Acre Site.

Once the baseflow contribution to the total seep flow has been determined, and assuming that other contributions to seep flow, specifically overland flow and direct input from precipitation, are negligible, subtracting the predicted baseflow from the observed total seep flow yields the interflow.

Having separated seep flow into its baseflow and interflow components, seep chemistry can now be correlated with the magnitude of each flow component to determine sources of acidity in the backfill. However, an important consideration should be recognized in this type of analysis. The total flow of the seep is an aggregate of ground water flow components whose origins are spatially and temporally distributed throughout the backfill. Correlation normally only evaluates the relationship between two variables without regard for temporal separation. While the effects of some variables are immediate, such as the transfer of the pressure head through the saturated zone due to a change in the elevation of the water table, the effects of other variables are delayed, such as the mass transfer of ground water from its place of infiltration through the mine-spoil to the seep. A time series analysis called cross-correlation, which creates a series of correlations comparing the effect of one variable with the delayed impact on another variable (the unit of delay time is called the lag or lag time), was used to circumvent this problem. Correlations are conventionally calculated from 0 to n/4 lags, where n is the total number of lags in the time series (Davis 1986).

RESULTS

Water Table Response to Precipitation

By comparing the well hydrographs with the precipitation data, the response time between a precipitation event and water table recharge in the vicinity of a well can be established. In addition, due to the excellent data coverage for the wells at the Eight Acre site, cross-correlation can be used to determine the response time between precipitation and changes in water level elevations.

The hydrograph of well 6 (fig. 3) shows the water table responding to precipitation events of about 1 inch or greater with a moderate increase in water elevation. Cross-correlation analysis indicates that well 6 responds in as little as 1 day and as long as 5 days, with a mean of 2 days. The unsaturated thickness of the spoil at well 6 is approximately 60 ft (18 m). Therefore, the water that recharges the water table moves with an average downward velocity of 30 ft/day (9 m/day) through the backfill.

The hydrograph of well 6A (fig. 3) reveals a dramatic change in the response character of the well which occurred around March 1985, at which time post-holes spiked with caustic soda (NaOH) were constructed at the Eight Acre site to intercept flow channels, that feed Seep 6A. Prior to March 1985, well 6A responded to precipitation in a manner similar to that of well 6 though with a slightly greater intensity and a faster response time. After March 1985 well 6A exhibited a flashy character, responding immediately and strongly to precipitation events of 1 inch (2.5 cm) or greater. Statistical analysis indicates that well 6A has a minimum response time of less than 1 day and a maximum response time of 1 day with a mean of less than 0.5 day. The unsaturated thickness of the spoil at well 6A is about 15 ft (4.6 m). Water recharging this area has an average downward velocity of greater than 30 ft/day (9 m/day) through the backfill.

The results from cross-correlation analysis of precipitation and the water elevation in well 6B show a consistent response time of 5 days. The mine-spoil unsaturated thickness at well 6B is approximately 90 ft (27 m). If water is recharging vertically through the backfill in the vicinity of well 6B, then it has a downward velocity of 18 ft/day (5.5 m/day). However, the mine-spoil around well 6B is at the edge of a plastic liner installed to inhibit infiltration. There are several possible causes for the change in the water table as observed at well 6B: 1) the liner may be leaking, 2) channelized flow paths may direct the water laterally through the unsaturated zone from the unlined portions of the mine, 3) ground water may be moving through the saturated zone downslope (with respect to the mine-floor) or a combination of (2) and (3).

At the Forty Acre Well site all wells display similar responses to precipitation events, albeit with varying magnitudes (fig. 2). Response times appear to be on the order of a few days.

Collier et al. (1970) have also observed well responses to precipitation events within 24 hours at a mine-spoil in Beaver Creek Basin, KY indicating that recharge is capable of moving rapidly through the unsaturated zone.

Relationship Between Baseflow and Water Table

Using regression analysis, a strong predictive relationship (adjusted r^2 = 0.89 and a p-value (or probability) = 0.001) was established between baseflow and water levels in the observation wells at the Eight Acre site. The baseflow hydrograph predicted for seep 6 and the total seep discharge hydrograph compare favorably (fig. 4). Subtracting the baseflow from the total seep discharge yields the predicted interflow hydrograph which is also presented in figure 4. Significant interflow events appear to be correlated with the precipitation record, suggesting that the regression model is working properly.

At the Forty Acre Well site an equally strong predictive relationship (adjusted r^2 = 0.89, p-value = 0.001) exists between baseflow and the water level in observation well 14.

For the period following April 1985, at which time induced alkaline recharge zones were introduced at the Forty Acre site, the predicted baseflow hydrograph for seep 7A agrees favorably with the total seep discharge (fig. 5). Prior to April 1985 the predicted baseflow is consistently greater than the observed total discharge. The model was calibrated using data following the treatment, suggesting that the hydrology of the site has been substantially modified by the reclamation efforts.

Flow Components and Seep Chemistry

The cross-correlation analysis of baseflow and acidity for the Eight Acre site shows that at zero lag time acidity is negatively correlated (-0.57) with baseflow. The correlation becomes progressively more positive with increasing lag time, reaching a peak

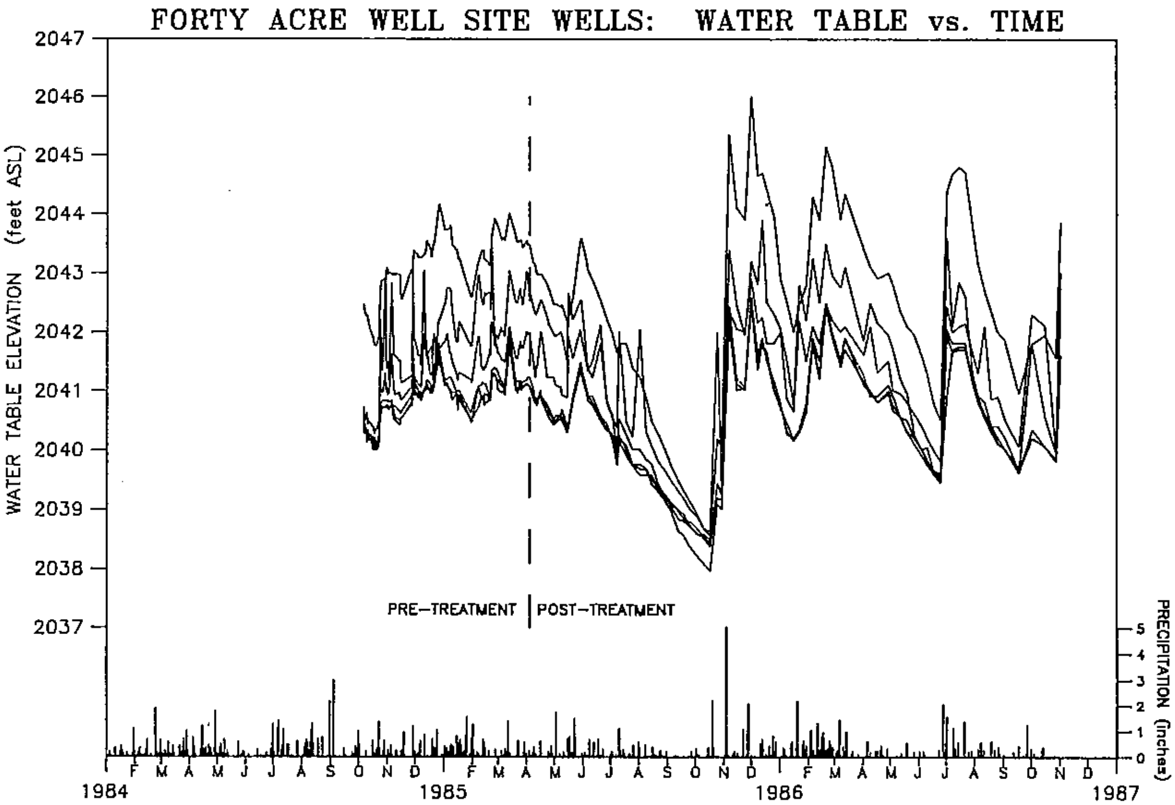

Figure 2. Water table elevations versus time and precipitation data for Forty Acre Well site.

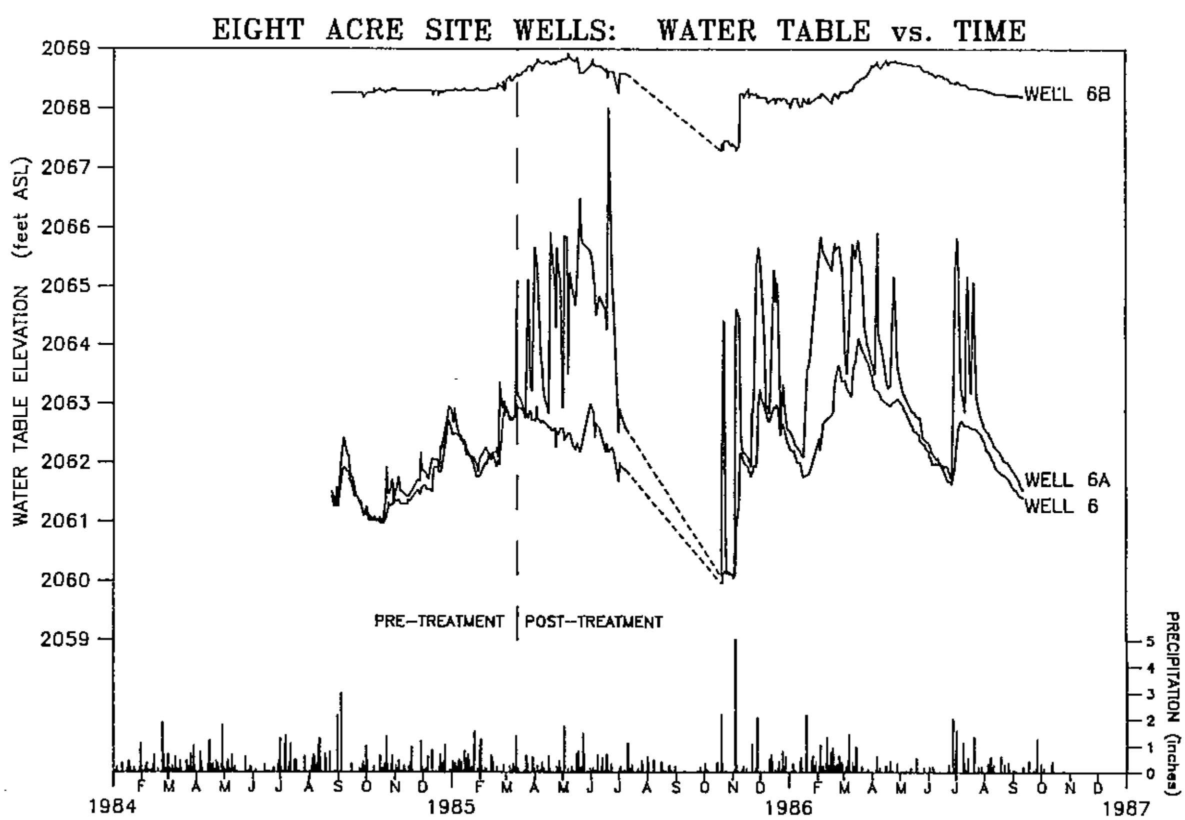

Figure 3. Water table elevations versus time and precipitation data for Eight Acre Well site.

correlation of +0.60 with a lag time of 20 weeks.

The initial inverse relationship may be the result of three effects. The first is that an increase in baseflow is usually preceded by an increase in interflow. As described below, interflow is negatively correlated with acidity and may mask the impact of baseflow. A second alternative is that the baseflow, which arrives at the seep earliest, is from meteoric waters which have infiltrated the backfill in the vicinity of the seep. The thickness of the mine-spoil through which these waters pass is relatively thin as compared with most of the Eight Acre site. Additionally, this particular part of the mine-spoil is adjacent to the outslope, which has more oxygen available to circulate and react with the acid-producing material. Therefore, the infiltrating water comes into contact with a thinner sequence of overburden material that may already be leached of its acid production potential. The third possibility is that the installation of post-holes treated with sodium hydroxide, centered around the seep, is reducing the acid production in the vicinity of the seep or neutralizing acidity.

At the Eight Acre site the strong positive correlation between baseflow and acidity which peaks at a lag of 20 weeks may represent the arrival of water that has percolated through the spoil up-gradient from the seep and flowed laterally below the water table. In this area the spoil is thicker and the oxygen circulation may be more restricted than in the spoil near the seep. These factors could prolong the acid-producing potential of this portion of the backfill and increase the acidity of the water relative to the water that passes through a thinner portion of the spoil.

A weak negative correlation (-0.26) exists between interflow and acidity at zero lag time. Though the correlation becomes slightly more negative (-0.33) over the next two lag periods, interflow is expected to have diminished by the end of the first week. The results show that interflow serves to dilute seep acidity.

Acidity to sulfate ratios, when compared with baseflow, indicate slightly higher acidity to sulfate values with increasing lag time. This may be due to a difference in the pyrite oxidation reactions.

Acidity to sulfate ratios display an inverse relationship with interflow (-0.43 at 1 week). This may indicate that some neutralization of acidity is occurring, possibly due to treatment interaction.

At the Forty Acre Well site, cross-correlation analysis shows a very weak relationship between baseflow and acidity. Initially, the correlation is negative (-0.19 at zero lag time). After 3 weeks there is a slightly positive correlation (+0.20), and at 11 weeks there is another negative peak (-0.24). The early negative correlation may be the result of causes similar to those of the Eight Acre site. The overall subdued character of the relationship between baseflow and acidity may be due either to the character of the ground water flow within the mine site or to treatment effects which will be discussed below.

There is no apparent correlation between interflow and acidity from zero lag time up to 20 lags (weeks).

At zero lag time, sulfate is negatively correlated (-0.43) with baseflow. The correlation becomes more positive and reaches a peak (+0.47) near a lag of 16 weeks. This is similar to what was observed at the Eight Acre site. Here too, the local baseflow may pass through a thin column of spoil which may be depleted of its acid production potential. The baseflow originating from more distant parts of the mine may have a higher acidity because of traversing a thicker and more reactive spoil.

There is no apparent correlation between interflow and sulfate. This suggests that the observation that acidity is not correlated with interflow is due to the lack of acid production in the unsaturated zone through which the interflow moves, rather than neutralization of the acidity.

The acidity to sulfate ratio exhibits a slight positive correlation (+0.29), with baseflow peaking at 3 weeks followed by a moderate negative correlation which reaches a peak at 13 weeks (-0.56). The inverse relationship may indicate neutralization of acidity in ground water within the backfill due to the impact of treatments or an alteration of the chemical reactions controlling the oxidation of pyrite and its reaction products.

There is no apparent correlation between acidity to sulfate ratio and interflow. There is no evidence to suggest that the interflow water quality is being modified by neutralization or an alteration of the oxidation reactions of pyrite.

CONCLUSIONS

During high-intensity, short-duration precipitation events, runoff recharges the water table by flowing through highly permeable channels in the backfill. This occurs quickly as demonstrated by the rapid response of the water table to a precipitation event (manifested by the rise of the water elevation in observation wells). Under these conditions, the rate of water movement through the unsaturated zone is from 10 to 30 ft/day (3 to 9

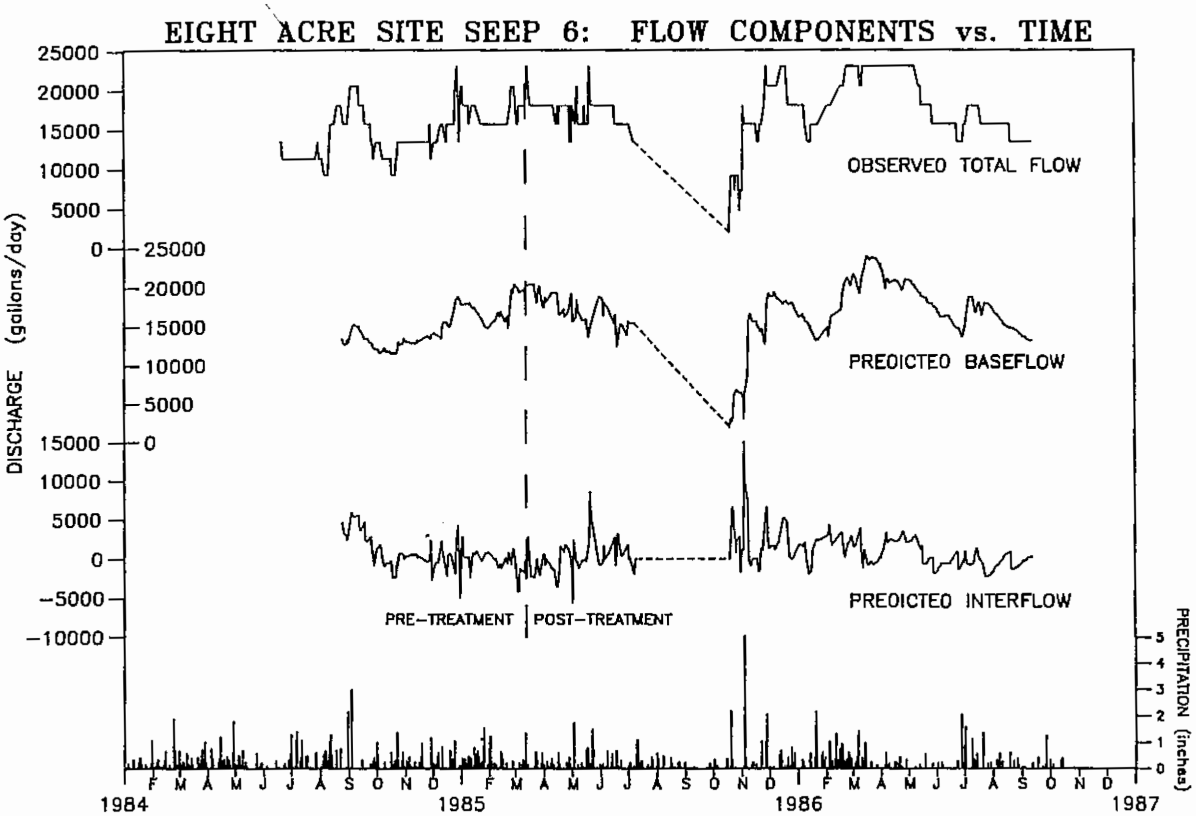

Figure 4. Flow hydrographs of total flow, predicted base flow and predicted interflow for Seep 6, Eight Acre Site.

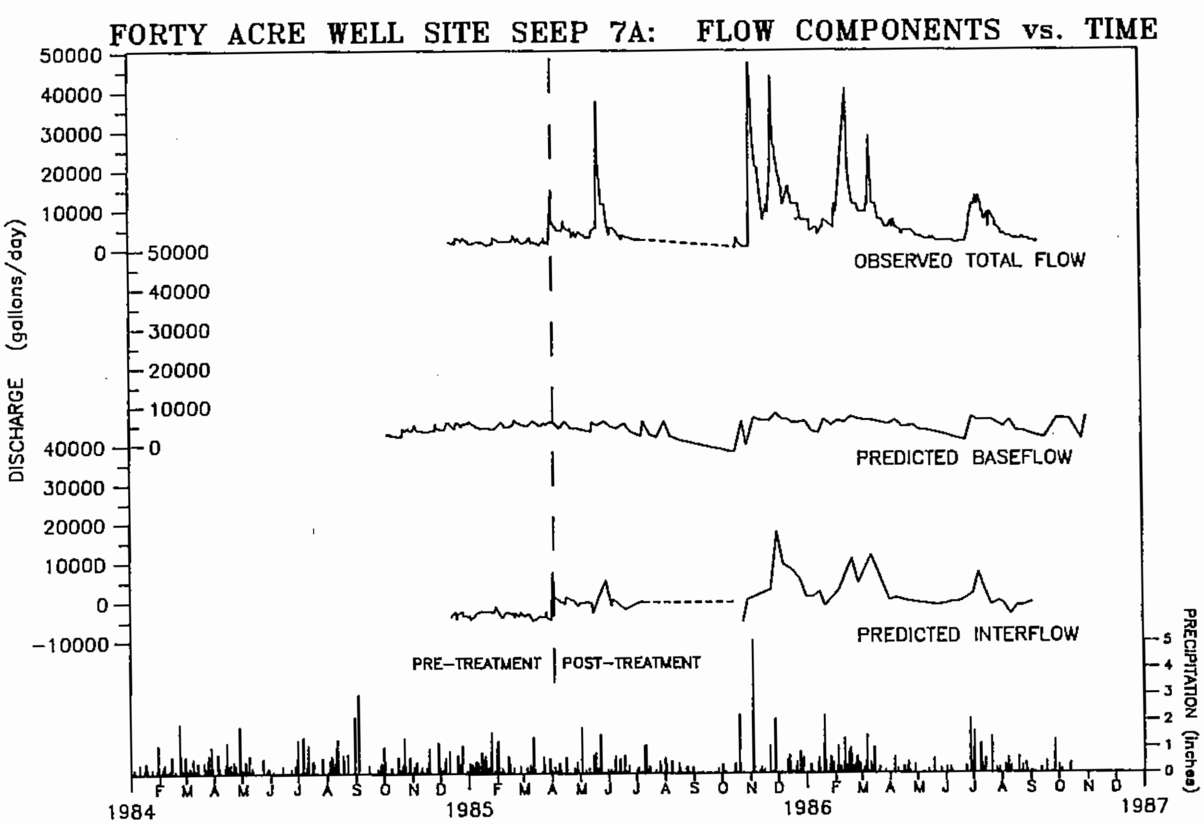

Figure 5. Flow hydrographs of total flow, predicted base flow and predicted interflow for Seep 7A, Forty Acre Site.

m/day). The speed at which the water table is recharged reflects very high hydraulic conductivity and/or channelized flow.

Further analysis of the data show the installation of induced alkaline recharge zones at both the Eight Acre and Forty Acre Well sites to have successfully modified the hydrology of the backfill.

The plastic liner covering a major portion of the Eight Acre site is not completely effective in preventing recharge of the backfill by meteoric waters due either to unlined portions of the backfill, leaks in the liner, of lateral flow.

Regression analysis was successfully used to correlate water table elevations with baseflow (sustained by deep ground water regimes) and to predict the baseflow component of the total flow. Having successfully estimated the baseflow component, it was possible to quantify the interflow (shallow lateral flow) component of a seep.

The baseflow at both the Eight Acre and Forty Acre sites promptly displays a negative correlation with acidity. This indicates that the interflow component of baseflow, which arrives at a seep first, has less acidity because it flowed through a smaller thickness of spoil and which may be leached clean of its acid-producing potential.

At both the Eight Acre and Forty Acre sites baseflow exhibits a delayed positive correlation with acidity. This suggests that baseflow, sustained by ground water from deeper parts within the mine-spoil has a higher acidity, possibly due to the greater thickness of spoil through which recharge must pass and/or a greater acid-producing potential of the spoil material. Under these conditions recharge to the backfill is by the occasional areally distributed, vertically infiltrating wetting fronts, generated by low-intensity, long-duration rains or spring thaws. Here, the entire backfill becomes saturated and a larger volume of rock material is leached.

At the Forty Acre Site interflow did not correlate with acid concentration. At the Eight Acre site interflow is negatively correlated with acidity. Therefore, the vadose zone of the backfill, through which interflow moves, does not appear to be a major acid contributor. This suggests that the acidity of the seep is sustained by a large acid reservoir, occasionally replenished by long-term vertically infiltrating waters (recharge events occurring at field capacity saturation) that commonly develop during the spring thaw.

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