HYDROLOGIC MODELING OF COAL-MINE IMPACTS AND ASSOCIATED REMEDIATION ALTERNATIVES FOR THE NANTICOKE CREEK WATERSHED[1]

by

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Abstract. The Nanticoke Creek watershed (Luzerne County, Pennsylvania) has been heavily impacted by both surface and deep coal mining. Currently, almost all of the flow in the creek including both of its tributaries (Espy Run and Lueder's Creek) disappear underground into the abandoned Truesale-Bliss (T-B) underground mine workings. The water flows out of the mines at the Askam Borehole as acid mine drainage (AMD) which comprises virtually all of the flow in the lower reaches of Nanticoke Creek. Outflow from this borehole ranges from approximately 8,500 m^3/day (2.2 MGD) to 52,000 m^3/day (14 MGD). Wetland treatment systems are being constructed to treat portions of the water that flows from the mine and efforts to restore surface flow in Nanticoke Creek are underway. As less water enters the minepool, less AMD will need to be treated. We present the water-balance model used specifically to estimate the behavior of the minepool in response to various reclamation alternatives. Standard hydrologic models either are too complicated or they do not accurately simulate the interaction between the minepool and surface streams at the level of detail required by this study. The water-balance model accounts for rainfall, snowmelt, soil storage, evapotranspiration, minepool storage and the hydraulics of the borehole. Given historical climatic data, the model was able to approximate observed discharges from the Askam Borehole.

Additional key words: reclamation, water-balance model, abandoned mines, remediation, stream flow restoration

Introduction

Background

Most acid mine drainage (AMD) remediation projects involve treatment at the source while another option involves preventing or limiting the formation of AMD by preventing "clean" surface water from contacting pyrite-bearing rock. Within the latter option is stream restoration defined here as: The modification of the hydrology of a mine-altered watershed to prevent or limit the conveyance of stream flow to underground mine workings for the purpose of preventing or limiting the production of acid mine drainage.

Streamflow can enter underground mine workings at discrete points, such as open mine shafts, or along reaches of mine-impacted streams where losses occur by rapid infiltration through disturbed and highly permeable channel bottoms, such as in strip mined areas. Alleviating this problem by means of stream restoration might involve "lining" lengths of existing stream channel with impervious material, re-channeling lengths of stream around water loss areas or sealing off of shafts and sink holes.

Success of stream restoration projects depends on a careful evaluation of each alternative based on a thorough understanding of existing hydrologic conditions. A water-balance model, used to quantify the hydrologic impact of stream restoration, can be an important tool for assessing the effectiveness of remediation alternatives. This paper describes a procedure for developing and utilizing a water-balance model to evaluate AMD remediation alternatives for the coal-mine impact-

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[1] Paper presented at the 1997 National Meeting of the American Society of Surface Mining and Reclamation, Austin, Texas, May 10-15, 1997.

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Proceedings America Society of Mining and Reclamation, 1997 pp 49-59
DOI: 10.21000/JASMR97010049

https://doi.org/10.21000/JASMR98010049

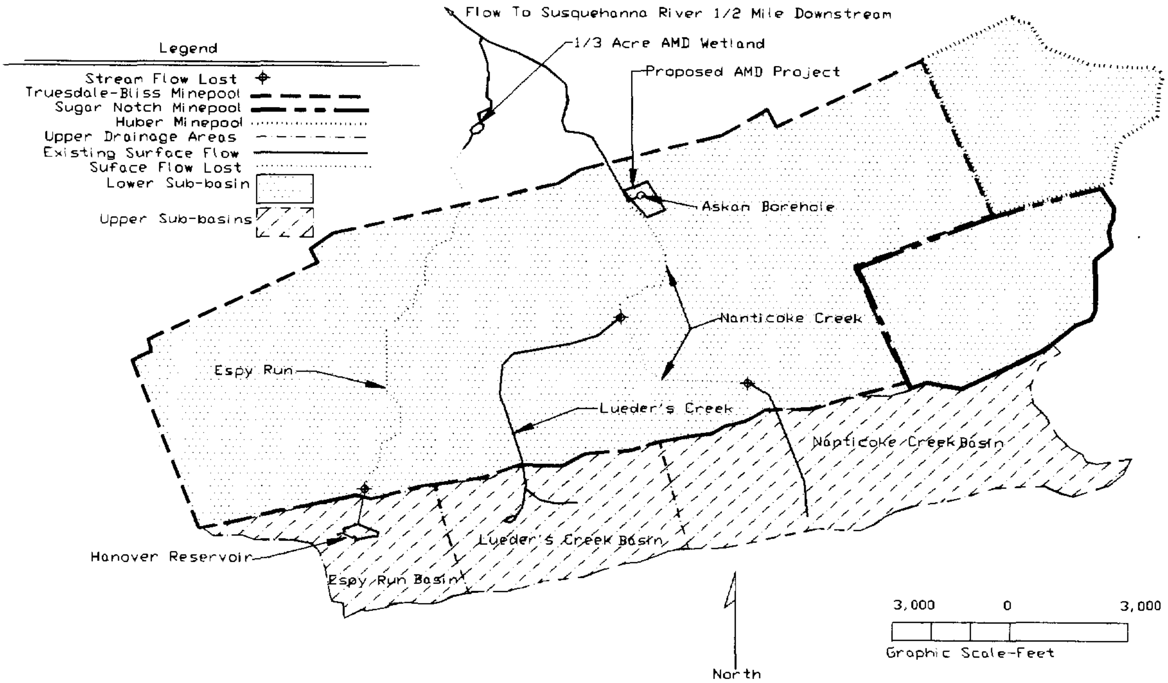

Figure 1: Map Of Nanticoke Creek Watershed

ed Nanticoke Creek watershed (Luzerne County, PA). The work was performed under the auspices of Wilkes University for the Earth Conservancy, a major landowner in the area which is planning AMD remediation projects in the Nanticoke Creek watershed involving AMD treatment and stream restoration.

Historical Perspective

The Nanticoke Creek watershed is located in the Northern Field of the anthracite coal-mining region of Northeastern Pennsylvania. During the past century, the watershed has undergone extensive surface and sub-surface mining. As a result, nearly all of the flows from Nanticoke Creek and its tributaries, Espy Run and Leuder's Creek, disappear into the abandoned Truesdale-Bliss (T-B) underground mine workings (Figure 1). Deep mining, along with associated pumping operations, ended in the 1960's.

Watershed and T-B Minepool Characteristics

The portion of the Nanticoke Creek watershed that has a hydrologic influence on the T-B minepool has an approximate area of 24 km^2 (9.3 mi^2), and the area of the watershed influenced by mining is approximately 18 km^2 (7 mi^2). For the purpose of this study, the watershed was divided into four sub-basins as shown on Figure 1. There are three "upper sub-basins" above the extent of mining operations (i.e., upper reaches of Espy Run, Lueder's Creek and Nanticoke Creek) with a heavily mine-impacted "lower sub-basin". Most of the three upper sub-basins (25% of the watershed) are located above an elevation of approximately 305 m (1,000 ft) MSL, with the lower basin below this elevation. Also, the upper sub-basins are geographically located above the extent of mining activities and underlying all the upper sub-basins is relatively impervious bedrock. It was therefore concluded (based on field observations) that all precipitation that falls on the upper sub-basins is transported to the lower sub-basin exclusively as streamflow, where it is subsequently lost in stripping pits or mine shafts.

The minepool also receives water by direct ground-water infiltration in the lower sub-basin.

The AMD flows from the mine workings and into the Nanticoke Creek channel through a 30-inch (0.8 m) diameter, pressure-relief well called the Askam Borehole (Figure 2). The borehole was installed in the 1970's by the PA Department Of Environmental Resources (currently the PA Department Of Environmental Protection) to alleviate flooding caused by high minepool levels, principally caused by absence of deep-mine pumping (PA DER Scarlift Report, 1975). The Askam Borehole is the primary point of AMD discharge to Nanticoke Creek from the T-B mine workings. The T-B workings also have hydraulic connections (by barrier pillar breaches) to the neighboring Sugar Notch and Huber mine complexes. Average borehole discharge is approximately 38,000 m^3/day (10 MGD). For most of the year, except during major precipitation and snowmelt events, the only source of water for the lower reaches of Nanticoke Creek is AMD flowing from the Askam Borehole. This suggests that a large percentage of the precipitation that falls on this watershed discharges from the Askam Borehole as AMD. Borehole discharges measured in 1973-74 ranged from about 8,500 m^3/day (2.2 MGD) to 52,000 m^3/day (14 MGD) (PA DER 1975). Flow measurements made by the authors during 1995-96 ranged from approximately 7,000 m^3/day (1.8 MGD) to 170,000 m^3/day (45 MGD).

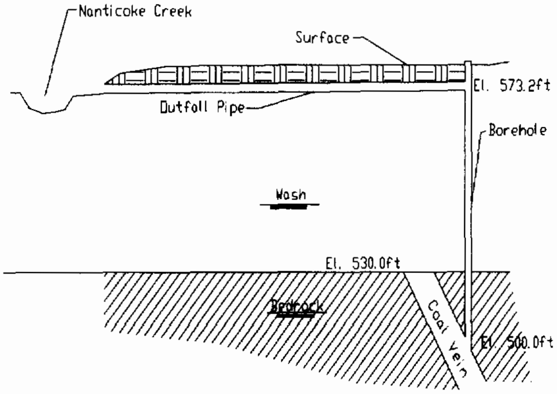

Figure 2: Section Through Askam Outfall.

Inflow into the T-B mine workings of approximately 4,500 m^3/day (1.2 MGD) is required to overcome leakage of water from the T-B minepool to adjacent minepools with lower water levels, while maintaining the T-B water level at the "rim" (elev. 174.8 m, 573.2 ft) of the borehole (PA DER, 1975). During prolonged dry periods, as in the drought of 1995, flow from the borehole ceases.

Overview

The model calculations are described below in Model Logic, the model calibration results are presented in Model Calibration, and Remediation Simulations describes how three remediation alternatives were modeled. Lastly, the results of this study are summarized in the Conclusion.

Model Logic

Model

The model was calibrated using historical climatic data for 1995-96 with corresponding borehole-discharge measurements and mine-pool level measurements. The calibrated model was verified with corresponding historical climatic and borehole-discharge data from 1973-74. The model was then used to predict the impacts of several stream-channel restoration alternatives on the magnitude of flow from the Askam Borehole.

Model Parameters and Input Data

The model quantified rainfall, snowmelt, soil storage, evapotranspiration, minepool storage, minepool leakage and the hydraulics of the Askam Borehole. Subscript i was used to denote the model timesteps, the units of which are in days.

Model calibration was based on historical climatic data for June, 1995 through November, 1996, recorded at the National Weather Service (NWS) first-order weather station located at the Wilkes-Barre/Scranton International Airport, approximately 23 km (14 miles) north of the study area, along with borehole discharge and minepool water-level data (measured by the authors). To verify the calibrated model, NWS climatic data for June, 1973 through August, 1974 were used with corresponding borehole-discharge data taken from the Scarlift Report (PA DER 1975).

Precipitation

The daily volume of rainfall (R_i) and snowfall (Sw_i) were calculated by multiplying the daily water equivalent of precipitation (m/day) by the watershed area (m^2).

Snowmelt and Snowcover

Snowmelt was modeled by the *Temperature-Index Approach* (Maidment, 1993), as follows.

Melt Temperature. The melt temperature, $T_{(melt)i}$, was assigned based on the logic in equation 1. This temperature was used to calculate the melt-water depth for a given day. The $T_{(melt)i}$ was taken as 0 °C when the daily maximum temperature was equal to or below 0 °C in equation 1a. For days when the minimum temperature was above 0 °C, the average temperature was used as the $T_{(melt)i}$, as shown in equation 1b. One-half the maximum temperature was used when the minimum temperature was less than 0 °C and the maximum temperature was greater than 0 °C in equation 1c.

$$T_{(melt)i} = 0, \text{ If } T_{(max)i} \leq 0 \qquad (1a)$$

$$T_{(melt)i} = T_{(ave)i}, \text{ If } T_{(min)i} > 0 \qquad (1b)$$

$$T_{(melt)i} = 1/2 \times T_{(max)i}, \text{ If } T_{(min)i} < 0 \text{ and } T_{(max)i} > 0 \qquad (1c)$$

where, $T_{(melt)i}$= temperature used equation 2 to calculate daily snowmelt (°C)
$T_{(min)i}$ = minimum daily temperature (°C)
$T_{(max)i}$ = maximum daily temperature (°C)
$T_{(ave)i}$ = average daily temperature (°C)

Zero Melt. As calculated below in equation 2a, on days with $T_{(melt)i}$ equal to 0 °C, no melt occurred.

$$M_i = 0, \text{ If } T_{(melt)i} = 0 \qquad (2a)$$

where, M_i = water transported to upper soil from melting snow (m^3/day)

Melt Without Rainfall. On days with no rain and $T_{(melt)i}$ above 0 °C, snowmelt was found by equation 2b. The snowmelt coefficient C_{melt}, is directly related to snowpack density (Maidment, 1993) and a snowmelt coefficient of 0.0018 m/°C•day was used assuming a constant snow density.

$$M_i = C_{melt} \times T_{(melt)i} \times A_{total}, \text{ If } R_i = 0 \text{ and } SC_i > M_i, \text{ else } M_i = SC_i \qquad (2b)$$

where, M_i = water transported to upper soil from melting snow (m^3/day)
C_{melt} = snowmelt coefficient (m/°C•day)
A_{total} = Area of Nanticoke Creek watershed (m^2)
SC_i = water equivalent of snowcover (m^3/day)
R_i = daily volume of rainfall (m^3/day)

Melt With Rainfall. On days with rain and $T_{(melt)i}$ above 0 °C, M_i was determined by equation 2c (Maidment, 1993).

$$M_i = (0.74 + 0.007 \times LP_i) \times T_{(melt)i} \times A_{total}, \text{ If } R_i > 0 \text{ and } SC_i > M_i, \text{ else } M_i = SC_i \qquad (2c)$$

where, LP_i = daily liquid precipitation (m)
SC_i = water equivalent of snowcover (m^3/day)

On days when the calculated snowmelt exceeded the snowcover, snowmelt was equal to the remaining snowcover for equations 2b and 2c.

Snowcover. Daily snowcover was equal to the liquid equivalent of the previous day's snowfall minus snowmelt plus the snowcover (equation 3a). If this value was less than zero, snowcover was zero as shown in equation 3b.

$$SC_i = Sw_{i-1} - M_{i-1} + SC_{i-1}, \text{ If } (Sw_{i-1} - M_{i-1} + SC_{i-1}) > 0 \qquad (3a)$$

$$SC_i = 0, \text{ If } (Sw_{i-1} - M_{i-1} + SC_{i-1}) < 0 \qquad (3b)$$

where, Sw_i = snowfall (m^3/day)

Evapotranspiration

Evapotranspiration was calculated for the entire watershed by equation 4 (Maidment, 1993).

$$E_i = C_{evap} \times (PanEvap_i) \times A_{total} \qquad (4)$$

where, E_i = evapotranspiration (m^3/day)
C_{evap} = evaporation coefficient
$PanEvap_i$ = daily pan evaporation (m/day)

The evapotransporation coefficient value, C_{evap}, determined by trial-and-error adjustments, was found to be (0.7). Pan evaporation data for April 1995 to October 1995, and May 1996 to September 1996, was obtained from the nearest weather observation station with the available data at the Francis E. Walter Dam (U.S. Army Corps of Engineers), approximately 20 km (12.5 miles) south and east of the study area. Because pan evaporation data were not available for November 1995 through April 1996, the pan evaporation value assigned for this time period was the minimum pan evaporation value that was measured (1,500 m^3/day).

Upper Sub-basin Storages and Outflows

Equation 6 was used to calculate the amount of water transferred to the lower sub-basin from each upper sub-basin based on the amount of water available in the upper soil layers of each upper sub-basin (equation 5). Subscript x, used in equations 5 and 6, is generalized for the upper sub-basins, where x represents either of the following subscripts: E for Espy Run, Lu for Lueder's Creek, and Nu for Nanticoke Creek. The quantity of water in the upper soil layer of each sub-basin (equation 5) was found using the following quantities from the previous day: rain plus snowmelt minus evapotransporation, and sub-basin outflow plus the upper soil storage. The sub-basin water-release coefficients were used as calibration parameters.

$$S_{x(i)} = S_{x(i-1)} - O_{x(i-1)} + (R_{i-1} + M_{i-1} - E_{i-1}) \times A_x/A_{total} \qquad (5)$$

$$O_{x(i)} = C_x \times S_{x(i)} \qquad (6)$$

where, $S_{x(i)}$ = water stored in upper soil of upper sub-basin x, (m^3)
$S_{x(i-1)}$ = previous day's upper soil storage for sub-basin x (m^3)
$O_{x(i)}$ = water transferred from $S_{x(i)}$ to lower sub-basin, (m^3/day)
A_x = area of sub-basin x, (km^2)
C_x = fraction of water released from sub-basin x to lower sub-basin

Lower Sub-basin Soil Storage and Outflow

The model calculated minepool inflow (equation 7) based on the amount of water available for release from the soil storage in the lower sub-basin soil storage (equation 8). The soil storage in the lower sub-basin was calculated similar to equation 5, except for additional inflows received from the upper sub-basins.

$$I_i = C_{Lo} \times S_{Lo(i)} \qquad (7)$$

$$S_{Lo(i)} = S_{Lo(i-1)} - I_{i-1} - Ro_i + (R_{i-1} + M_{i-1} - E_{i-1}) \times A_{Lo}/A_{total} + \Sigma\, O_{x(i-1)} \qquad (8)$$

where, $S_{Lo(i)}$ = upper soil storage for lower sub-basin (m^3)
$S_{Lo(i-1)}$ = previous day's upper soil storage for lower sub-basin (m^3)
I_{i-1} = water transferred from $S_{Lo(i-1)}$ to the minepool on previous day (m^3/day)
RO_i = surface runoff (m^3/day)
A_{Lo} = area of lower sub-basin (km^2)
$\Sigma\, O_{x(i-1)}$ = total water input to the lower sub-basin from the upper sub-basins on the previous day (m^3/day)

Runoff

Only a fraction of precipitation left the study area as runoff, and the majority of this runoff seemed to occur from a small area during and shortly after precipitation events. This was simulated by allowing runoff to occur, over the portion of the watershed where runoff was observed, only on days with precipitation using equations 9a and 9b.

$$RO_i = 0, \text{ If } R_i = 0 \qquad (9a)$$

$$RO_i = C_{RO} \times R_i \times A_{RO}/A_{total}, \quad \text{If } R_i > 0 \qquad (9b)$$

where, RO_i = daily runoff that leaves the watershed (m^3/day)
A_{RO} = portion of watershed where runoff occurs (km^2)
C_{RO} = runoff coefficient

Leakage

Minepool leakage was calculated in equation 10 by taking a percentage of the water stored from the previous day and adding it to a base leakage of 4,500 m^3/day.

$$L_i = 4{,}500 + C_{leak} \times S_{i-1} \qquad (10)$$

where, L_i = daily leakage from minepool, (m^3/day)
C_{leak} = leakage coefficient
S_{i-1} = minepool storage on previous day (m^3)

Leakage was directly related to the minepool water level, which was calculated directly from minepool storage (equation 13). As storage increases, the minepool water level increases, thereby increasing the driving force for leakage.

Borehole Hydraulics

Minepool water levels and borehole discharges were measured periodically over an eight-month period and these data were used to develop an equation for borehole discharge as a function of minepool water level. The following equation was used to solve for a and b by regression analysis:

$$O_i = a h_i^b \text{, If } h_i > 0 \text{, else If } h_i < 0,$$

$$O_i = 0 \qquad (11)$$

where, O_i = borehole discharge at timestep i (m^3/day)
h_i = water level above borehole rim at time i (m)
a = hydraulic coefficient of borehole (41,500)
b = exponent that relates the potential energy at the minepool water surface (h_i) to the magnitude of the borehole discharge (1.34)

Since most of the flow measurements were made during average and low-flow periods, the development of equation 11 was biased toward these flows. With exponent $b > 1$ in equation 11, the model projections contain the assumption that the borehole consistently behaves (in hydraulic terms) more like a weir[3]. However, at higher flows, the borehole may behave more like an orifice[4] with a value for $b < 1$ (Linsley et. al., 1992). Therefore, equation 11 was expected give the most accurate projections for borehole discharge for average and low flows.

Minepool Water-balance

The minepool water-balance (Figure 3) is stated as: Inflow (I_i) minus outflow (O_i) minus leakage (L_i) is equal to the change in volume of water stored for a given day ($\Delta S_i/\Delta t$), and is shown in the following equations:

$$I_i - O_i - L_i = \Delta S_i/\Delta t \text{, and} \qquad (12)$$

$$\Delta S_i = S_i - S_{i-1} \qquad (13)$$

where, ΔS_i = change in storage (m^3)
S_i = minepool storage above borehole rim (m^3)
S_{i-1} = minepool storage above borehole rim for the previous day (m^3)

Minepool Water Level

The minepool water level h_i was calculated by the following:

$$h_i = S_{i-1}/(A_{mine} \times C_{void}) \qquad (14)$$

where, A_{mine} = minepool area (km^2)
C_{void} = storativity or % void space in sub-surface above elevation 174.8 m (573.2 ft) in mined area

Model Calibration and Verification

Procedure

The calibration procedure consisted of varying the sub-basin water release coefficients C_B, C_{Lu}, C_{Nu} and C_{Lo}, pan evaporation coefficient C_{evap}, leakage coefficient C_{leak}, runoff coefficient C_{RO}, and the storativity C_{void}, until the predicted borehole discharges agreed reasonably well with the measured borehole discharges.

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[3] Weir flow area changes with changes in flow.

[4] Orifice flow area remains constant with changes in flow tending to restrict higher flows.

The calibration process began by determining the "hierarchy of sensitivity" of each of the coefficients, as they related to the borehole discharge, by changing each coefficient individually while observing the relative changes in the model output. The model was most sensitive to changes in the storativity, C_{void}, and therefore, was the first parameter to be adjusted. The C_{void} was adjusted until the predicted borehole discharges were as in as close agreement as possible with the measured borehole discharges.

The calibration process then proceeded using the remaining coefficients, as follows. Foremost among these was C_{Lo}, which was used in the calibration procedure next because it appears in the calculation of minepool inflow (equation 7) which directly impacts the minepool mass balance (Figure 3). Since evapotranspiration was found to be a rather significant water loss mechanism in the watershed, C_{evap} was adjusted next. The water-release coefficients of each sub-basin were then adjusted, since they had a direct effect on the lower sub-basin storage. The leakage coefficient C_{leak}, followed in the calibration sequence, because it had a direct, although minimal, affect on the minepool balance when compared to the other terms of equation 13 (based on findings of the PA DER Scarlift Report). The final calibration parameter was the runoff coefficient. This term was found to be the least significant for two reasons, based on the following observations of the authors. First, runoff (i.e., water lost from the watershed as runoff) occurred in a very small area of the lower sub-basin. Second, this runoff process seemed to occur only for a very short time during and shortly after precipitation events and/or rapid snowmelt periods.

The model was then verified using the 1973-74 data set. Evapotranspiration data were not available for this time period and this was compensated for by assigning a constant value for evapotranspiration (arithmetic mean of evapotranspiration data from the 1995-96) for this time period.

Results

The model was determined to be calibrated when it produced results shown on Figures 4, 5 and 6. That is, to the extent of the accuracy of the borehole discharge measurements and the inherent lack of complexity in the model,

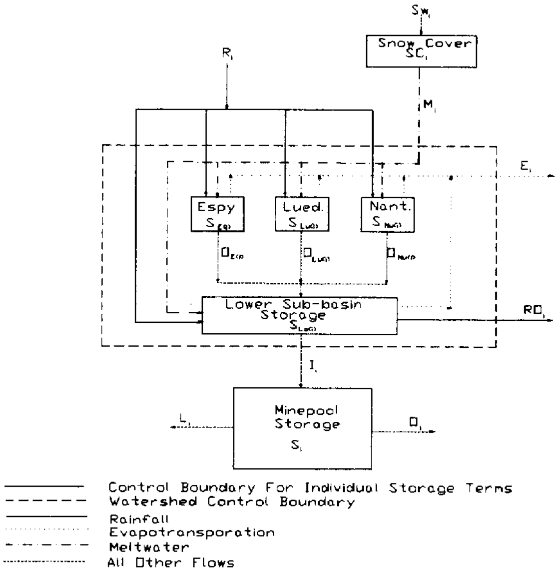

Figure 3: Nanticoke Creek Watershed Water Balance.

Figures 4 and 5 show that the model projections did reflect the trends shown in the measurements. In Figure 6, the relation between corresponding predicted and measured borehole discharges should generate a straight line for 100% agreement. However, Figure 6 shows that the model tends to overpredict borehole discharge. Also evident is that the model tends to overpredict by greater amounts for discharges exceeding 30,000 m^3/day.

One explanation for the tendency of the model to overpredict borehole discharge at higher flows might be the basis of the borehole discharge equation (equation 11). Since the assumption was made that the borehole behaved constantly like a weir with $b > 1$, the model overpredicted borehole discharge during high flow periods if "orifice conditions" existed during high-flow periods. That is, during high flow periods the borehole most likely behaved like an orifice with $b < 1$. With $b < 1$ during high-flow periods would have given more accurate predictions for borehole discharge.

In any case, the tendency of the model to overpredict borehole discharges will result in conservative simulation results, including all estimates of remediation alternatives. Any

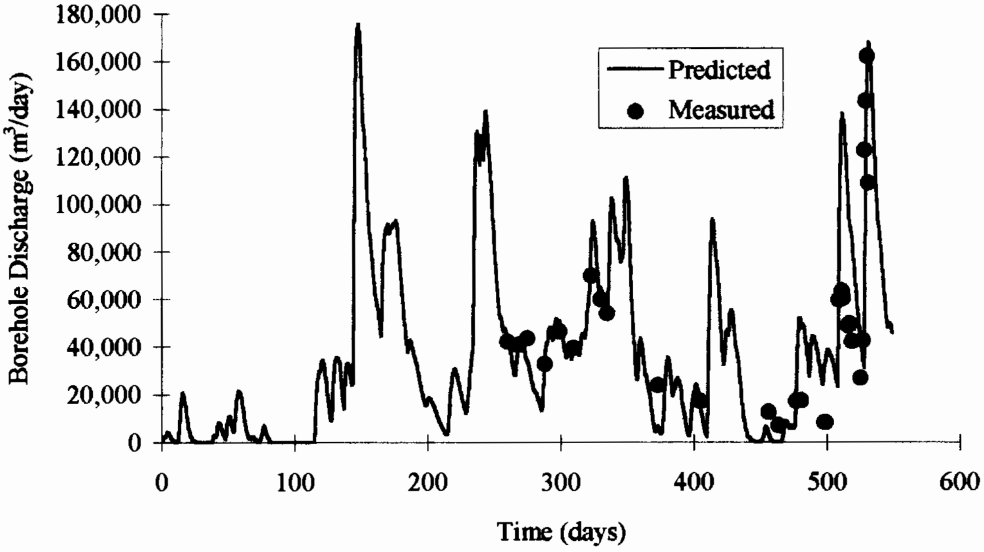

Figure 4: Calibration With 1995-1996 Data.

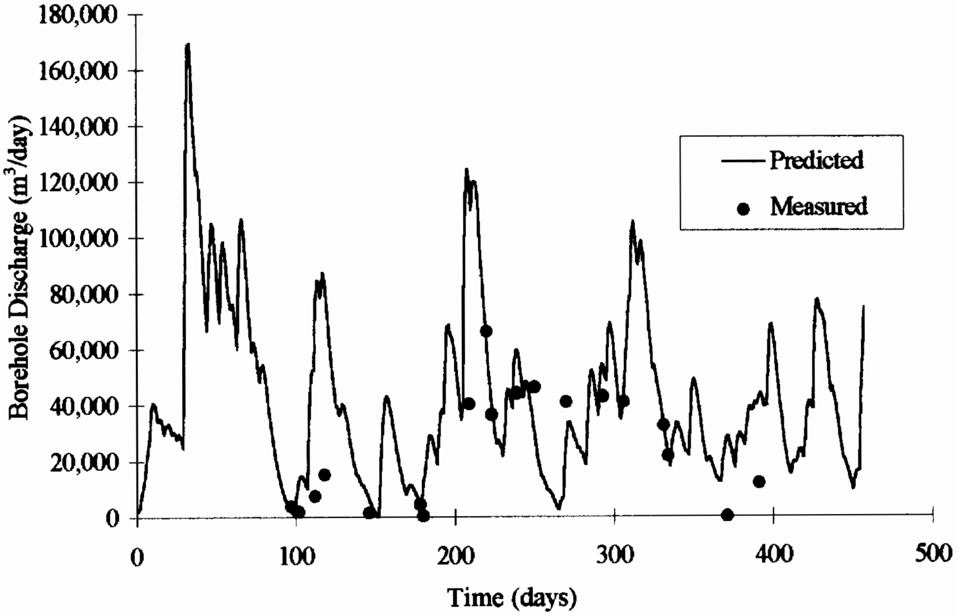

Figure 5: Verification With 1973-1974 Data.

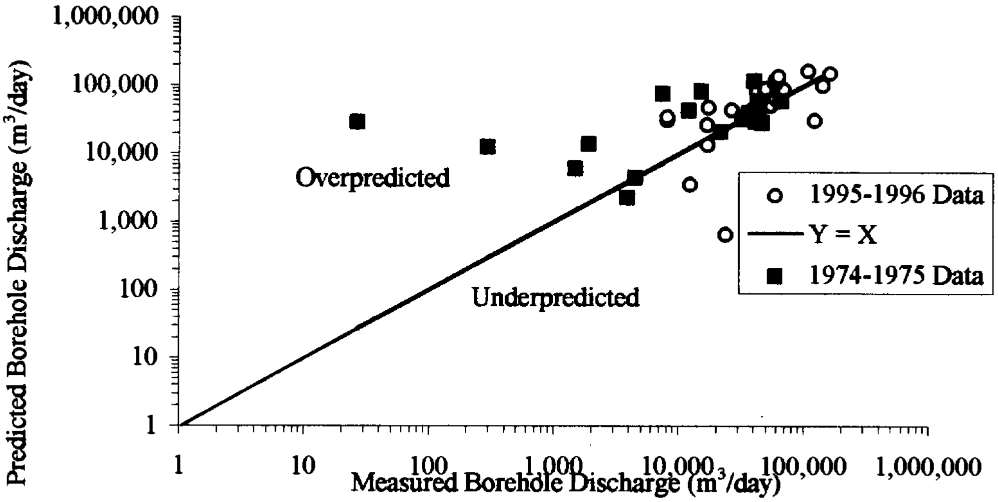

Figure 6: Correspondence of Predicted Vs. Measured Borehole Discharges.

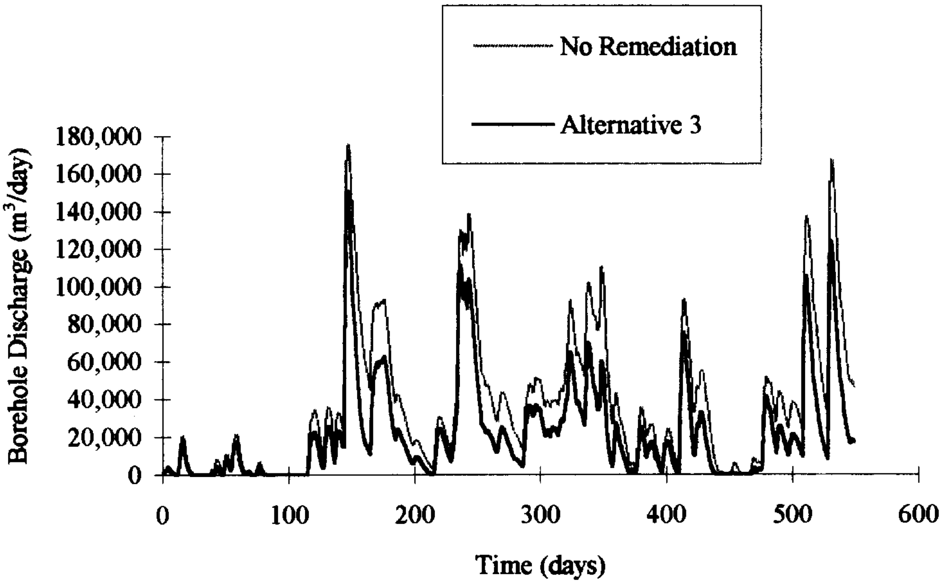

Figure 7: Comparison of Remediation Alternative With Existing Conditions Using 1995-1996 Data.

remediation alternatives implemented should be more effective than indicated by the model prediction.

Remediation Simulations

Three stream-channel restoration alternatives were simulated using the input data from 1995-96. Each simulation demonstrated the cumulative effects of removing surface water inputs to the lower sub-basin from the three upper sub-basins, which thereby decrease soil storage in the lower sub-basin, resulting in corresponding decreases in inflow to the minepool. Alternative 1 involved channel restoration of only Espy Run, Alternative 2 channel restoration was simulated for both Espy Run and Lueder's Creek; for Alternative 3 channel restoration was simulated for Espy Run, Lueder's Creek and Nanticoke Creek. Alternative 3 is plotted on Figure 7, along with the simulation of no remediation as projected for comparison purposes. Simulations of Alternatives 1 and 2 were not included on Figure 7, since they had relatively minimal effects on the borehole discharge when compared with Alternative 3.

Figure 8 shows the probability (vertical axis) of discharges occurring that are less than any discharge taken from the horizontal. Three sets of data points are shown. The points designated as "Measured" show the measured borehole discharges. The points associated with "No Remediation (model)" show the simulated discharges with no remediation. The points represented by "Remediation (model)" are the results of simulating Alternative 3.

The authors were interested in illustrating the effectiveness of Alternative 3 for the median discharge. The median discharge corresponds to the 50% probability on the vertical axis of Figure 8. From Figure 8, if we draw a horizontal line from the vertical axis at 50% to the "Measured" line, the discharge measurements show that a median discharges of 45,000 m^3/day (8,256 gpm) can be expected. Extending the horizontal line over to the "No Remediation" line shows that the model predicts that with no remediation, a median discharge of approximately 35,000 m^3/day (6,400 gpm) can be expected. Likewise where the horizontal line intersects the "Remediation" line, the model predicts a median discharge of 20,000 m^3/day (3,700 gpm) for Alternative 3. A comparison of "No Remediation" and "Remediation" shows a 43% reduction of the median discharge from the Askam borehole for Alternative 3. A comparison between "Remediation" and "Measured" shows a 56% decrease in the median discharge for Alternative 3.

Conclusion

A water-balance model was developed to asses the hydrologic impacts of several AMD remediation alternatives specifically involving stream channel restoration. The results show that stream restoration of Espy Run, Lueder's Creek and the upper reach of Nanticoke Creek can reduce median discharge from the Askam borehole. A comparison of simulations, generated by a conservative model, with and without remediation suggest a reduction in median discharge of 43%. Comparing remediation simulations and "real world" borehole discharge data demonstrates a possible reduction in median discharge of 56%.

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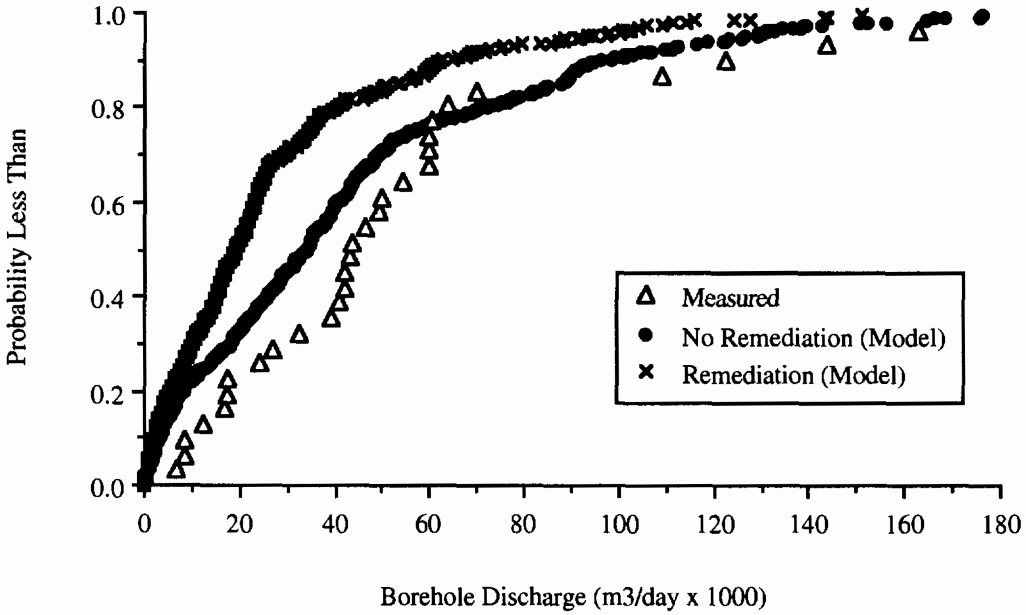

Figure 8: Borehole Discharge Probabilities for Measured Discharges, No Remediation, and Remediation Alternative 3.