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A PROCESS FOR DEVELOPING AND EVALUATING DESIGN OPTIONS FOR LARGE-SCALE WATERSHED REMEDIATION[1]

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Abstract. The U.S. Army Corps of Engineers, in partnership with the Ohio Department of Natural Resources (ODNR), Division of Mines and Reclamation, is conducting a study to evaluate the applicability of various restoration solutions to the overall degradation of the ecosystem of the Monday Creek Watershed in southeastern Ohio. Extensive portions of the watershed have been subjected to underground and surface mining since the mid-1800s and a number of stream reaches in the watershed are sterile and unable to support diverse, aquatic life due to acid mine drainage. In addition to the Corps and the ODNR, seven other federal, state and local agencies are actively involved in the project including West Virginia University (WVU). WVU's primary role in the project was to develop and use a computer model called the Total Acid Mine Drainage Loading (TAMDL) model to simulate the evolution of stream water quality affected by acid mine drainage. WVU then used the data from the model to design passive and active treatment structures to meet the remediation goals. The objectives of this paper are to explain how the model works, its strengths and weaknesses, and its results.

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Introduction

The Monday Creek watershed of the Hocking River basin study area encompasses 116 square miles in southeastern Ohio. Extensive portions of the watershed have been subjected to underground and surface mining of coal. Severe acid mine drainage problems occur and erosion from disturbed land areas have accelerated sedimentation and deposition of materials in over 100 miles of streams of the area. A number of stream reaches are essentially sterile and unable to support diverse, aquatic life. Over 40% of the watershed is on U.S. Forest Service land. In addition to the USFS, other agencies involved include the Ohio Department of Natural Resources, which is the non-Federal sponsor, the Ohio EPA, Ohio University, the U.S. Department of Energy's National Energy Technology Laboratory, West Virginia University, and the Monday Creek Watershed Group. The reconnaissance phase was completed in April 2000. The Feasibility Study began in 2002 and will be completed later this year. The Corps has identified over 4,300 point sources of acid mine drainage within the Monday Creek Watershed including deep mine seeps, gob pile leachate, subsidence features, spoil blocks and stream captures.

To assist with plan formulation, West Virginia University has recently developed a water quality computer model, the "Total Acid Mine Drainage Loading (TAMDL) Model," for determining the effects of acid mine drainage on streams. The model can simulate the hydrology of the watershed as well as the improvements to water chemistry due to restoration activities. Environmental restoration activities under study include wetland creation, plugging stream captures, filling subsidences, constructing limestone leach beds and open limestone channels and active treatment of acid mine drainage.

Project Purpose

The basic goal of this research project was to design a cost effective Acid Mine Drainage (AMD) treatment strategy for the Monday Creek, Ohio watershed. This treatment strategy was designed by first developing a Total Acid Mine Drainage Loading (*TAMDL*) model of the watershed. The computer program *TAMDL* was designed to simulate the evolution of stream water quality in watersheds affected by AMD and its treatment. The watershed's *TAMDL* model and the remediation endpoints for the mainstem were used to calculate the level of treatment required in each Monday Creek subwatershed affected by AMD. The level of required AMD treatment was employed to design passive and active AMD treatment structures for each affected subwatershed. The feasibility of the designed structures was tested by incorporating them into the Monday Creek model and comparing the simulated stream pH, aluminum, and iron concentrations against the corresponding remediation endpoints. Because the original design did not result in the satisfaction of the pH, aluminum, and iron remediation endpoints, the design was adjusted until the remediation endpoints were satisfied.

Methodology

Governing Equation

The following partial differential equation is the governing equation for the one-dimensional transport of a water quality constituent in a stream and is solved by *TAMDL* for each of the simulated constituents, except for proton activity.

$$\frac{\partial C_i}{\partial t} = \mu \frac{\partial^2 C_i}{\partial x^2} - V \frac{\partial C_i}{\partial x} + L_i + S_i \qquad (1)$$

Where: C_i = Simulated concentrations of the constituents.

L_i = Model node loading terms for each of the constituents.

S_i = Net chemical and physical reaction source (sink) terms.

μ = Hydrodynamic dispersion.

V = Mean stream velocity.

Because the hydrodynamic dispersion and mean stream velocity must remain uniform throughout the computational domain, the watershed must be divided into small sub-watersheds before using the computer program. The spatial coordinate, x, proceeds from the head of the sub-watershed and follows the stream channel to the mouth.

The governing equation is solved using net acidity rather than pH. Net acidity is defined as the total acidity minus the total alkalinity. Total acidity consists of the acidity caused by metal ion hydrolysis and the acidity caused by proton activity. In typical mine drainage, metal ions, rather than protons, constitute the major component of acidity. Therefore, *TAMDL* estimates pH through its relationship with net acidity by subtracting the effect of the metal ions.

If the stream chemistry was simulated with proton activity instead of net acidity, then it would be necessary to also simulate dissolved carbon dioxide, bicarbonate ion, carbonic acid, and total sulfate in addition to the other constituents. While this would be more pleasing theoretically, each of the additional parameters would require the estimation of boundary and initial conditions, which would degrade overall simulation precision. When the transport of acidity by the stream is simulated with net acidity instead of proton activity, then a constitutive relationship is required to calculate the pH from the net acidity.

Net Acidity – pH Constitutive Relationship

The parameter pH must be calculated by the model because water quality standards invariably use pH instead of net acidity and the kinetic rates of ferrous iron, aluminum and manganese oxidation and/or precipitation depend heavily upon pH. Because defining the nature of the net acidity – pH constitutive relationship is a part of the modeling process, the computer program *TAMDL* allows the user to specify the relationship with paired series of net acidity and pH data.

Ferric Iron Sedimentation

TAMDL assumes that all ferric iron above the pH-dependent ferric iron solubility limit has combined with dissolved oxygen to form ferric hydroxide. The computer program also assumes all of the ferric hydroxide in the stream clings to sediment particles, which leave the computational domain by flowing through the downstream boundary or by sedimentation. The rate at which ferric iron leaves the model domain via sedimentation is assumed to follow Stokes Law. This assumption is valid when the particle Reynolds number is less than unity (Roberson and Crowe 1980). Given the size of sediment particles most likely to carry ferric hydroxide of 1×10^{-6} meters, this assumption is realistic.

Because this process is not dependent upon the precise concentration of suspended solids, the simulation of the erosion, transport, and deposition of sediment was not required. Since *TAMDL* is often employed to simulate watersheds, like Monday Creek, where very little information on stream hydraulics is available, sediment transport is not simulated and the re-suspension of ferric iron-containing sediment particles must be neglected. Because the computer program can be easily modified to use the results of a sophisticated hydraulics model, the incorporation of a suspended sediment constituent and ferric iron re-suspension into the model would not be difficult.

Manganese Oxidation and Precipitation

The formulation used by *TAMDL* to calculate the kinetic rate of manganese oxidation and precipitation was obtained from Stumm and Morgan (1981). When the stream's dissolved oxygen concentration is less than 0.01 mg/L, manganese oxidation and reduction are neglected.

$$\mathrm{Mn}^{2+} + \mathrm{H_2O} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{MnO_2} + 2\mathrm{H}^{+} \qquad (2)$$

The kinetic rate for the progress of manganese oxidation and precipitation is calculated by the program using the following formula.

$$S'_{\mathrm{Mn}} = \frac{-a_{\mathrm{Mn}} C_{\mathrm{Mn}} C_{\mathrm{DO}} C_{\mathrm{Fe3+}}}{[H^{+}]^{2}} \exp\left(\frac{-E_{\mathrm{Mn}}}{RT}\right) \qquad (3)$$

Where:

S'_{Mn} = Manganese kinetic rate, mg/L/day.

E_{Mn} = Empirical rate constant, kJ/mole.

= 107.987 kJ/mole.

a_{Mn} = Empirical rate multiplier specified by user, $L^4/(mg^4\text{-day})$.

R = Universal gas constant, kJ/mole/K.

= 8.314×10^{-3} kJ/mole/K.

T = Stream water temperature, K.

C_{Mn} = Manganese concentration, mg/L.

C_{DO} = Dissolved oxygen concentration, mg/L.

$C_{\mathrm{Fe3+}}$ = Ferric iron concentration, mg/L.

The array containing the net rate of production (consumption) for each of the constituents, S_i is calculated by taking the algebraic sum of the kinetic rates for each chemical and physical reaction being modeled. Because manganese oxidation consumes oxygen, equation (2) is used to calculate the corresponding decline in dissolved oxygen concentration. The effect of this reaction's proton production on the pH and net acidity is calculated with equation (2) and the net acidity – pH constitutive relationship.

Aluminum Precipitation

The chemical reaction for aluminum precipitation is similar to the equation for manganese oxidation and precipitation except for the absence of oxidation because aluminum has only a single oxidation state.

$$\mathrm{Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+} \tag{4}$$

$$S'_{\mathrm{Al}} = \frac{-a_{\mathrm{Al}} C_{\mathrm{Al}} A_{\mathrm{Al}}}{[\mathrm{H}^+]^3} \exp\left(\frac{-E_{\mathrm{Al}}}{RT}\right) \tag{5}$$

Where: S'_{Al} = Aluminum precipitation kinetic rate, mg/L/day.

a_{Al} = Empirical rate constant specified by the user, dimensionless.

C_{Al} = Aluminum concentration, mg/L.

A_{Al} = Empirical rate multiplier, mole^3/L^3/day.

= 3160 mole^3/L^3/day.

E_{Al} = Empirical rate constant, kJ/mole.

= 58.2 kJ/mole.

Like for manganese precipitation and oxidation, the effect of this reaction's production of protons on the pH and the net acidity is calculated with the chemical equation (4) and the net acidity – pH constitutive relationship.

If the user specifies a negative value for the dimensionless empirical rate constant, the program does not evaluate equation (5), but does not allow the aluminum concentration to be greater than the solubility limit under equilibrium conditions, which is calculated with equation (6).

$$C_{\text{Al-equ}} = \exp\left(35.071 - 6.9078\,\text{pH}\right) \tag{6}$$

Where: $C_{\text{Al-equ}}$ = Solubility limit for aluminum, mg/L.

Ferrous Iron Oxidation

Ferrous iron oxidation can be simulated by *TAMDL* with the following chemical reaction, when the stream's dissolved oxygen concentration is greater than 0.01 mg/L.

$$\text{Fe}^{2+} + \frac{1}{4}\text{O}_2 + \frac{5}{2}\text{H}_2\text{O} \rightarrow \text{Fe(OH)}_3 + 2\text{H}^+ \tag{7}$$

The rate of ferrous iron oxidation is calculated by the program with the formulation presented by Kirby, Thomas, Southam, and Donald (1998). This formulation has a biotic term as well as an abiotic term to account for the oxidation of ferrous iron by *T. ferrooxidans* bacteria.

$$S'_{\text{Fe2+}} = -\frac{U_{\text{DO}} A_a C_{\text{Fe2+}} C_{\text{DO}}}{[\text{H}^+]^2} \exp\left(\frac{-E_a}{RT}\right) - U_{\text{DO}} A_b C_{\text{Fe2+}} C_{\text{DO}} C_{\text{TF}}\, [\text{H}^+] \exp\left(\frac{-E_b}{RT}\right) \tag{8}$$

Where: $S'_{\text{Fe2+}}$ = Ferrous iron oxidation kinetic rate, mg/L/day.

U_{DO} = Unit conversion constant, g-moles O_2 / mg O_2.

= $3.125117192 \times 10^{-5}$ g-moles O_2 / mg O_2.

A_a = Empirical abiotic oxidation rate multiplier, mole/L/day.

= 3.456×10^{10} mole/L/day.

E_a = Empirical abiotic rate constant, kJ/mole.

= 96 kJ/mole.

$C_{\text{Fe2+}}$ = Ferrous iron concentration, mg/L.

C_{TF} = Dry biomass concentration of *T. ferrooxidans* bacteria, mg/L.

A_b = Empirical biotic rate constant, mole/L/day.

= 8.8128 x 10^{13} mole/L/day.

E_b = Empirical biotic rate constant, kJ/mole.

= 58.77 kJ/mole.

All of the empirical rate constants in equation (8) were determined from the analysis of field data (Kirby, Thomas, Southam and Donald, 1998). Because the results of Kirby, Thomas, Southam, and Donald (1998) suggest that the dry biomass concentration of *T. ferrooxidans* bacteria is difficult to measure accurately, it can be used as a model calibration parameter. Simulating ferrous oxidation requires that the user have information about the speciation of iron in the stream. Because this data was not available for streams in the Monday Creek watershed, the Monday Creek *TAMDL* model assumed that all of the iron was in the ferric oxidation state.

Other Reactions

Because the kinetic rates of manganese oxidation and precipitation, aluminum precipitation and ferrous iron oxidation depend upon the stream temperature and the dissolved oxygen concentration, it is necessary that *TAMDL* simulate these water quality constituents as well. With dissolved oxygen, the user has the option of directing the program to assume that saturated conditions are always present or calculate the dissolved oxygen concentration from stream reaeration and organic material decay. In this case, it was assumed that the streams were saturated with dissolved oxygen because dissolved oxygen was not measured. Diurnal fluctuations in dissolved oxygen concentration are normally caused by diurnal changes in stream temperature. Because the model did not simulate stream temperature, diurnal flucuations in dissolved oxygen could not be simulated. Therefore, a zeroth order sediment oxygen demand formulation from the lake model *CE-QUAL-W2* (Cole and Buchak, 1995) was adapted for use in *TAMDL*. Stream reaeration is calculated with the O'Conner and Dobbins (1958) formulation. Because stream temperature is not absolutely crucial to the modeling of streams affected by acid mine drainage, the simplified formulation used by the program assumes that the amount of heat transferred between the stream and the atmosphere is directly proportional to the difference in temperature and wind speed and inversely proportional to the depth of the stream.

Boundary and Initial Conditions

Upstream of the computational domain for each simulation, the user specifies the boundary temperature and concentrations. The specified upstream boundary temperature and concentrations may vary with simulation time. Normally, the upstream boundary condition is calculated from the results of the model for the upstream sub-watershed. If there is no upstream sub-watershed, the upstream boundary condition must be implied from the results of water quality sampling.

At the downstream end of each computational domain, *TAMDL* assumes that the spatial gradient of the temperature and concentration is zero. Downstream boundary conditions are required because of the dispersion (second derivative) term in governing equations. If there is no flow through the computational domain, *TAMDL* automatically applies the downstream boundary condition to the upstream boundary, and the concentrations specified for the upstream boundary are ignored.

The program also requires that the initial temperature and concentration be specified for each node. Initial conditions are not very important when one desires a steady state solution. When one is simulating a transient problem, the precise selection of initial conditions may have an important effect on the results calculated in the early portion of the simulation. Realistic initial conditions can be generated by simulating water quality conditions for a period prior to the desired simulation period.

Numerical Algorithm

In order to make efficient use of computational resources, the selection of an appropriate numerical algorithm is very important. In the planning stages of *TAMDL*, it was decided that the selected algorithm should be both explicit and at least second order accurate in both time and space. One well-tested algorithm that satisfies this requirement is the explicit MacCormack predictor – corrector method described by Anderson, Tannehill, and Pletcher (1984). Because this finite difference algorithm is normally applied to the solution of the advection – dispersion equation, the loading and chemical reaction terms in the governing equation must be solved analytically or with a numerical technique for first order ordinary differential equations.

Since the equations describing the kinetic rates of the aforementioned reactions are both complex and non-linear, it was decided that both the loading and reaction terms should be solved numerically. First order ordinary differential equations are commonly solved with one of the Runge-Kutta methods (Boyce and DiPrima, 1977). In order to simplify the program's source code, it was decided that intermediate time steps to solve the chemical reaction terms would not be employed. Therefore, to achieve the desirable accuracy, it was decided to use the fourth order Runge-Kutta method to solve the contributions of these terms.

Source Loads

The source loads applied to finite difference model nodes are represented in *TAMDL*'s governing partial differential equation, equation (1), by the array L_i. The program allows one to specify thermal, alkaline, acid, ferrous iron, ferric iron, manganese, aluminum and dissolved oxygen loads with this array. The operation of passive acid mine drainage treatment systems can also be simulated for specified model nodes. Because the production of alkalinity by passive acid mine drainage treatment systems depends upon the stream's acidity, the source load terms can be non-linear and the fourth order Runge-Kutta method is also used to calculate the contribution of these terms.

Hydrology

Because the advection term in the governing partial differential equation, equation (1), contains the mean flow velocity of the stream, V, the mean velocity must be known for all portions of the computational domain throughout the simulation period. The current formulation of the explicit MacCormack predictor – corrector method requires that the stream velocity and the hydrodynamic dispersion be uniform throughout the computational domain. Therefore, to account for changes in the stream hydraulics, the watershed must be divided into many small sub-watersheds.

Strengths and Weaknesses of TAMDL

The basic strength of the *TAMDL* computer program is that it solves the differential equation governing the transport, loading and reaction of AMD-related water quality constituents, equation (1). This equation requires that the user specify the stream's discharge flow rate, Q, throughout the simulation period and rating tables for the depth, h, flow area, A, wetted perimeter, *P*, and top width, *T*. Ideally, one would use a hydrologic simulation program to determine these parameters before executing the *TAMDL* computer program.

Unfortunately, those streams affected by AMD tend to be small and the information required to run a sophisticated hydrologic simulation program is not available. In those situations, the user is required to estimate the discharge flow rate for a particular stream segment from the drainage area of the stream segment and discharge flow rate data collected at a nearby stream gage. The rating tables for the stream segment are then estimated from measurements of the stream channel geometry and educated guesses about the Manning's n value for the stream. This was the approach used for Monday Creek.

Model Development

The development of the Monday Creek *TAMDL* was a cooperative effort between the U.S. Army Corps of Engineers, Huntington District and West Virginia University (WVU). WVU submitted to the Huntington District a series of locations along Monday Creek and its tributaries. The Huntington District contracted a surveyor to measure the cross section of the stream at those locations and calculated the drainage area and rating tables for the stream cross sectional area, top width and wetted perimeter at those sites. This information was used by the computer program to calculate the stream hydraulics during the simulation period.

With the hydrologic model results provided by the Huntington District, WVU determined that the mainstem of Monday Creek needed to be divided into seventeen sections and that Snow Fork needed to be divided into three sections. The other Monday Creek subwatersheds needed no further division. When this was completed, the computational domain for the Monday Creek *TAMDL* model was devised and is shown in Fig. 1.

Because the computer program *TAMDL* calculates stream pH from net acidity, an empirical constitutive relationship between the two variables was required. The empirical relationship derived for the Monday Creek watershed is shown in Fig. 2 and 3. Fig. 2 is a plot of the constitutive relationship with observed pH and net acidity data. Fig. 3 is a plot of the observed pH versus the pH calculated by the empirical net acidity – pH constitutive relationship and the observed net acidity arranged to facilitate the evaluation of the empirical relationship. Daily stream flow data was employed so diurnal fluctuations in the model's dependent variables (pH, net acidity, iron, aluminum and manganese) would be impossible to simulate accurately.

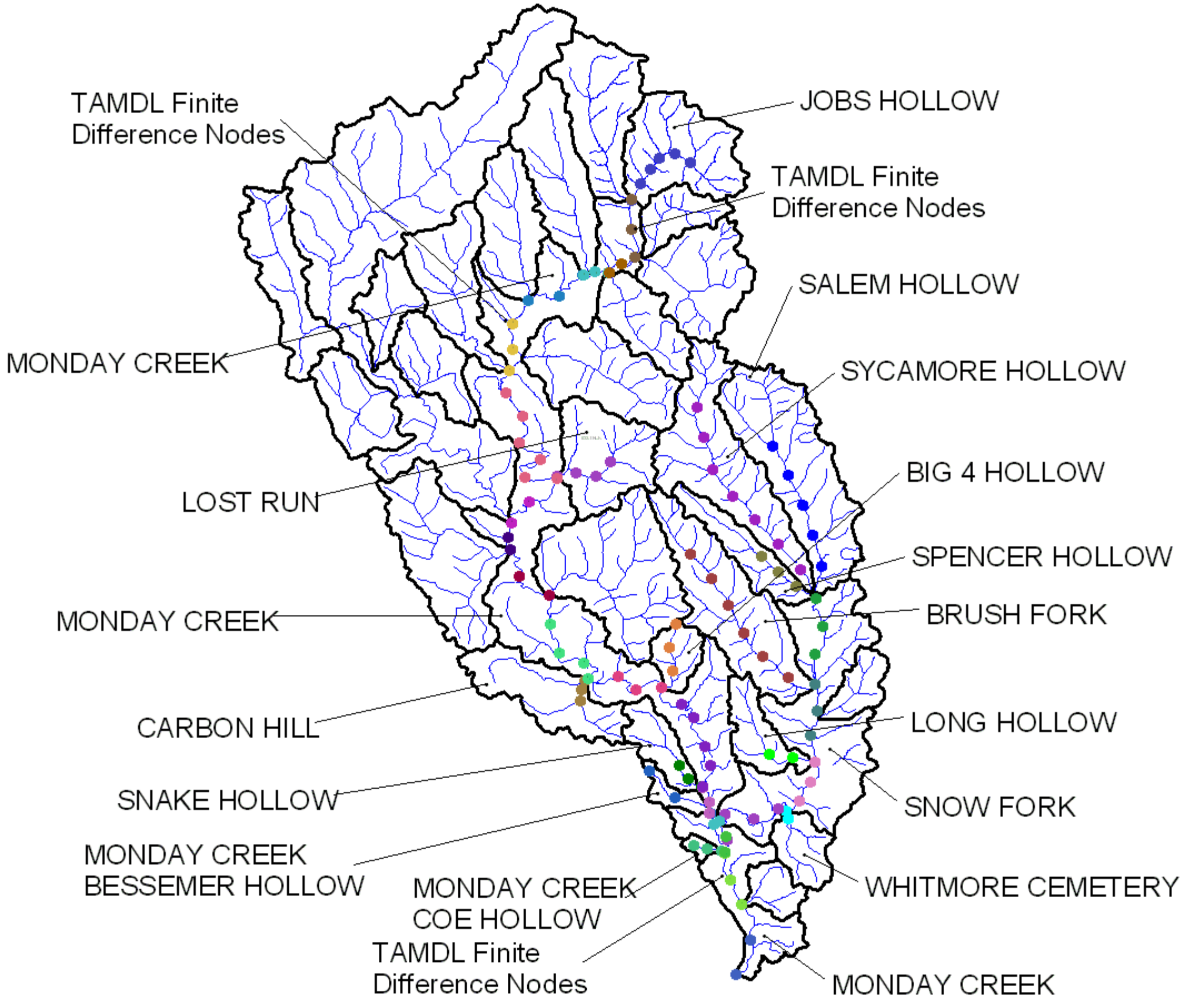

Figure 1. Computational Domain of the Monday Creek *TAMDL* model.

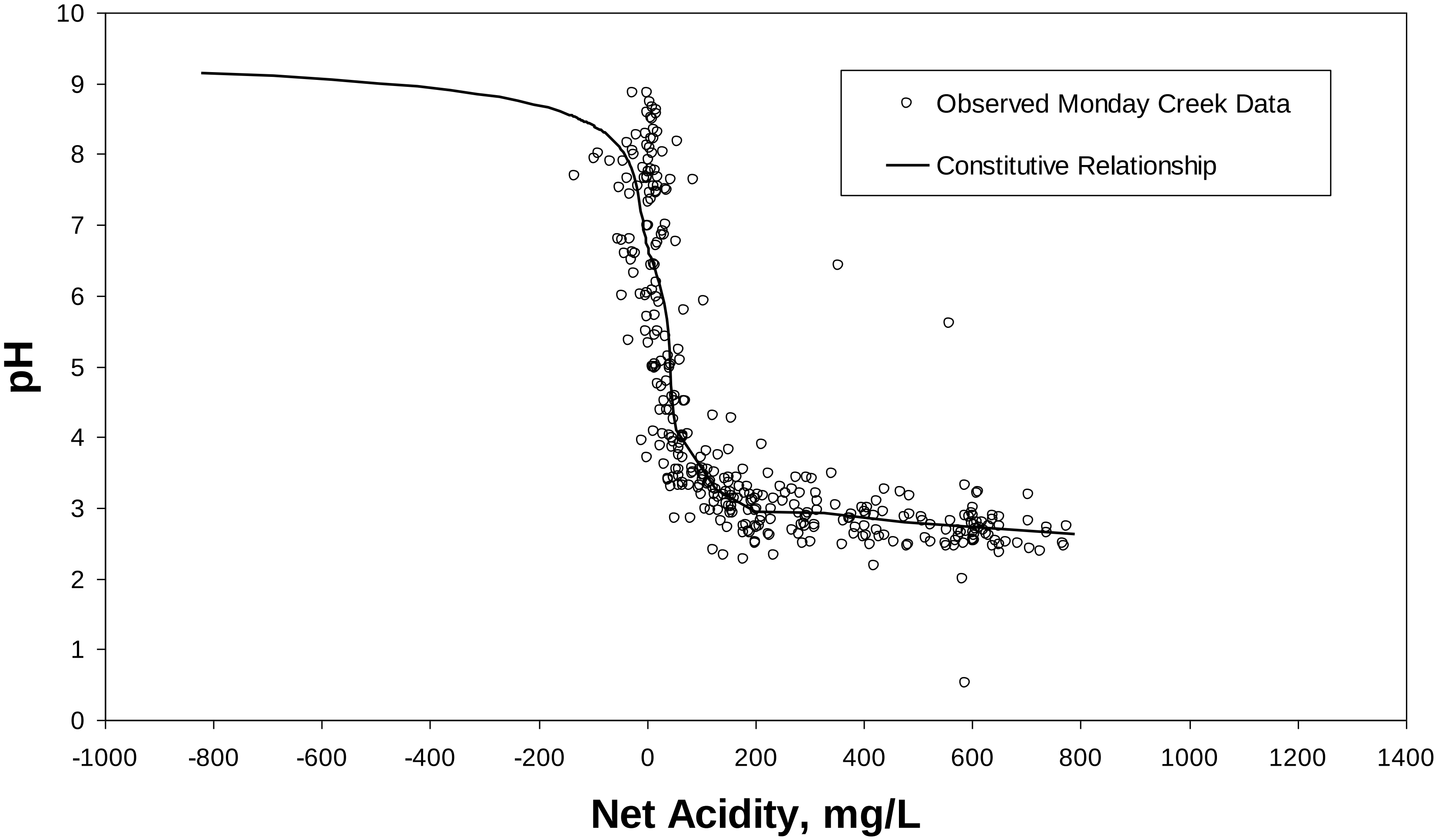

Figure 2. Comparison of Empirical Net Acidity – pH Constitutive Relationship with Observed Data.

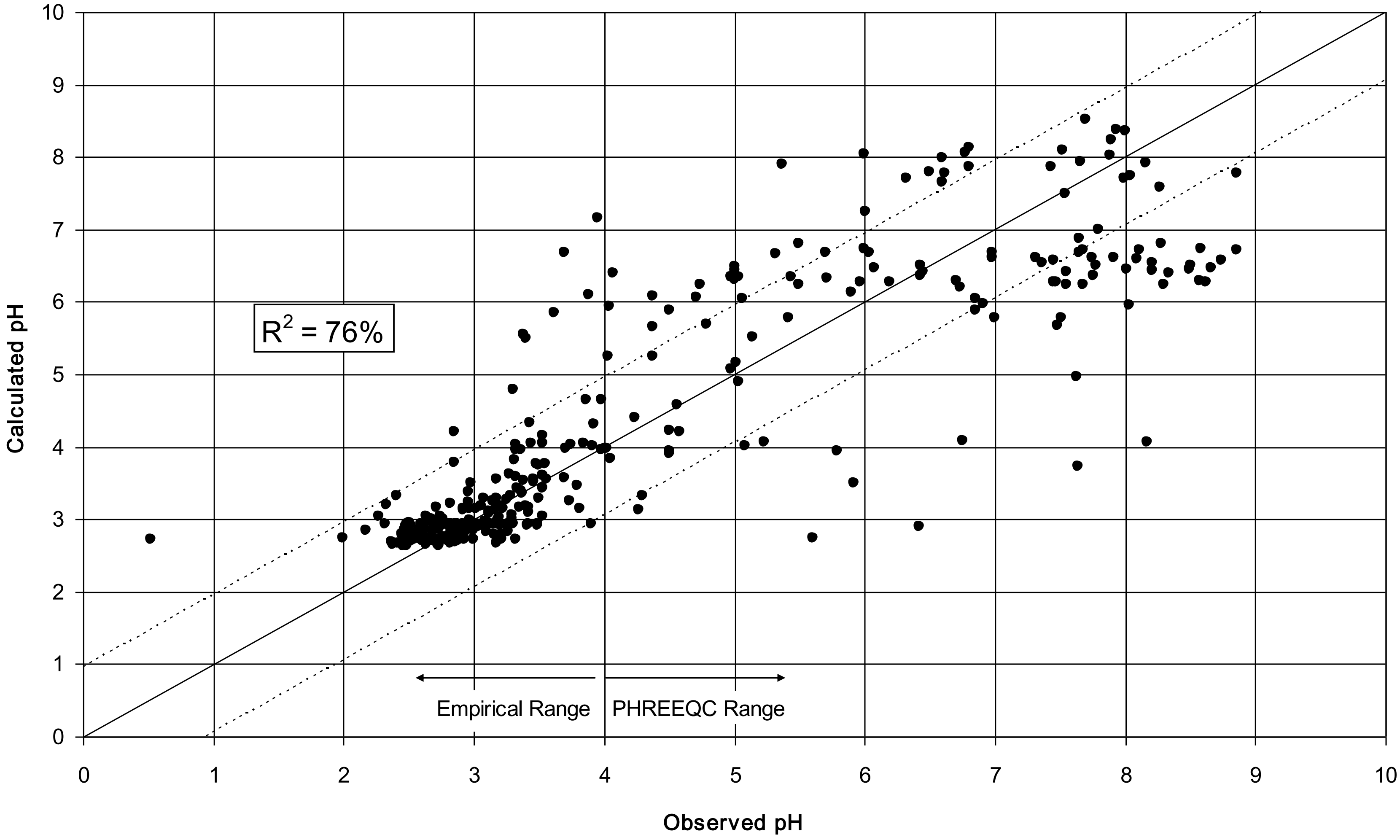

Figure 3. Comparison of Empirical Net Acidity – pH Constitutive Relationship with Observed Data.

Diurnal pH fluctuations are caused by the metabolism of aquatic life, and since TAMDL does not have the capability to simulate the metabolism of aquatic life it also cannot simulate diurnal pH fluctuations.

Because *TAMDL* calculates in-stream pH and metals concentrations by simulating the stream transport process, the net acidity and metals concentrations or loading rates in the water entering the computation domain from the upstream ends must be specified in some manner. Since these concentrations or loading rates must be specified continuously throughout the simulation, regression equations were derived for these locations. It was empirically observed that regression equations of the following form best replicated observed concentrations.

$$C \cong C_{\text{model}} = aQ^{b} \tag{9}$$

Where:
C = Observed constituent concentrations, mg/L.
C_{model} = Estimated constituent concentrations, mg/L.
Q = Stream discharge flow rate, m^3/s.
a, b = Empirical regression coefficients.

The discharge flow rate, Q, in equation (9) is the same as what was used by the Monday Creek TAMDL model for that stream segment. This data was calculated by adjusting the discharge flow rate measured at the USGS gage at Doanville, OH by the drainage area of the stream segment. Stream or seep loading rates can be specified with a formula virtually identical to equation (9).

$$L \cong L_{\text{model}} = 86.4\,(a)\,Q^{b+1} \tag{10}$$

Where:
L = Observed constituent loading rates, kg/day.
L_{model} = Estimated constituent loading rates, kg/day.

The empirical coefficients in equations (9) and (10) were calculated for the net acidity, iron, manganese, and aluminum entering the Monday Creek TAMDL model's computational domain. The empirical coefficients for the manganese and aluminum entering the model's computational domain via stream JS-8 in the Jobs Hollow subwatershed are shown in Fig. 4 and 5. Fig. 4 and 5 also contain plots that compare the results of the regression equations with the observed concentrations.

Fig. 4 and 5 show the observed manganese and aluminum concentrations at various levels of stream discharge flow rate. With one exception, all of these samples were collected when the stream discharge flow rate was more than 0.1 m^3/s. Since the 75th percentile of the stream discharge flow rate data is less than 0.1 m^3/s, the collected stream samples appear to reflect the normal variation in stream flow at the site. The plots show the change in estimated concentration at stream discharge flow rates as high as 0.5 m^3/s.

Model Calibration

Model calibration was accomplished by comparing the model results at water quality sample collection sites against the observed data. The quality of the calibration was judged by calculating the correlation coefficients (R^2) between the observed data and the model's results. These correlation coefficients for the calibration model are listed in Table 1. All of the correlations are greater than 62%. Given the complexity of AMD chemistry, simplifying assumptions made by the *TAMDL* computer program, and sampling error, these correlations are fairly good.

In order to verify the calibration of the model, a verification model run was executed and the results compared against observed data collected after the end of the calibration model run. The correlation coefficients (R^2) for the verification model run are also listed in Table 1. Since these coefficients were not less than the coefficients for the calibration model run, we concluded that the quality of the model calibration is accurately reflected in the correlation coefficients for the calibration model run.

The observed data used to calculate the correlation coefficients listed in Table 1 and the observed data shown in the time series plots in this report were filtered by comparing the titrated and estimated total acidity values. The estimated total acidity values were calculated by summing the proton and metal acidities. Those samples with a difference between the estimated total acidity and the titrated total acidity greater than 50% were removed from the analysis.

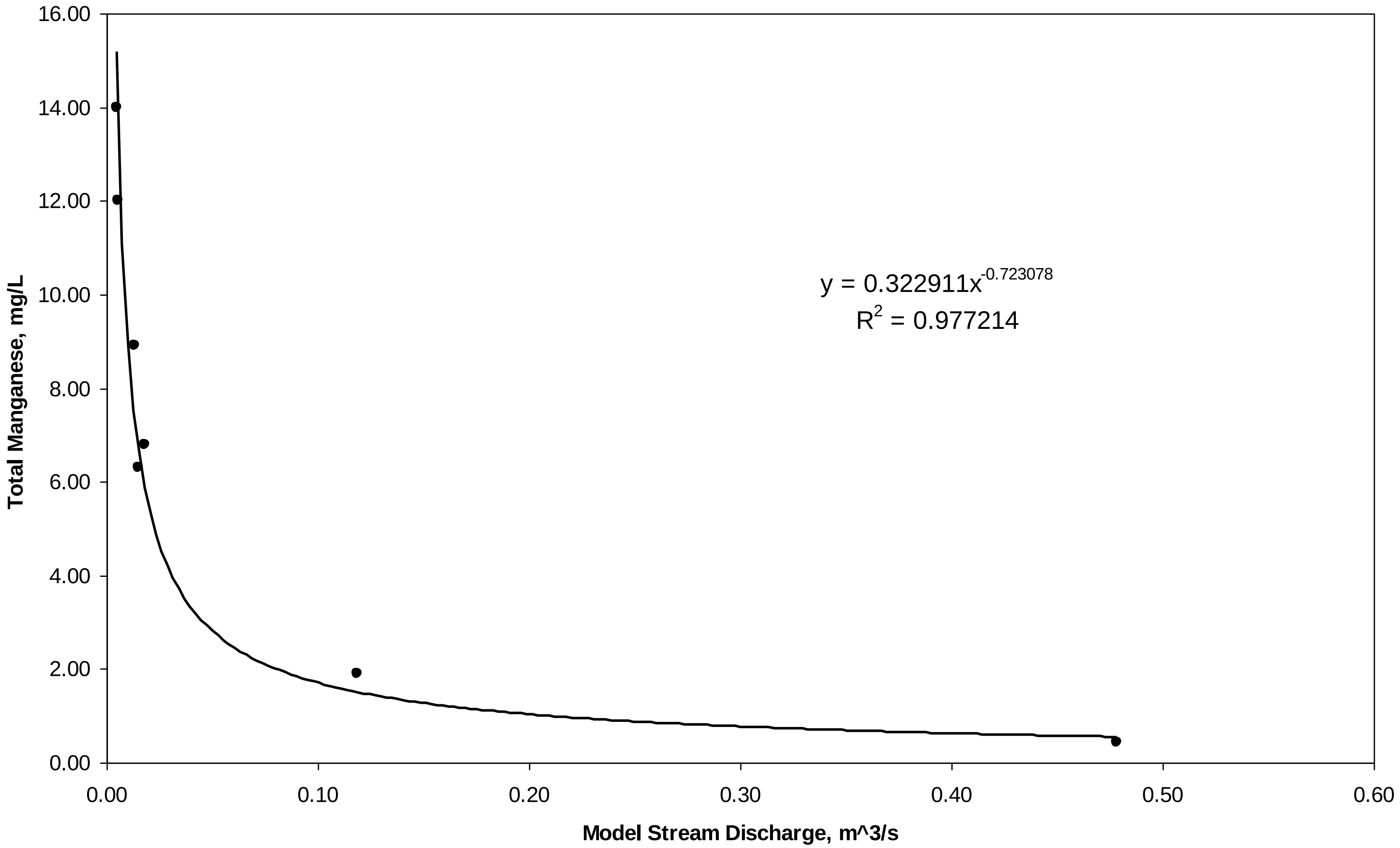

Figure 4. Regression Formula for Manganese at Stream Station JS-8 in the Jobs Hollow Subwatershed.

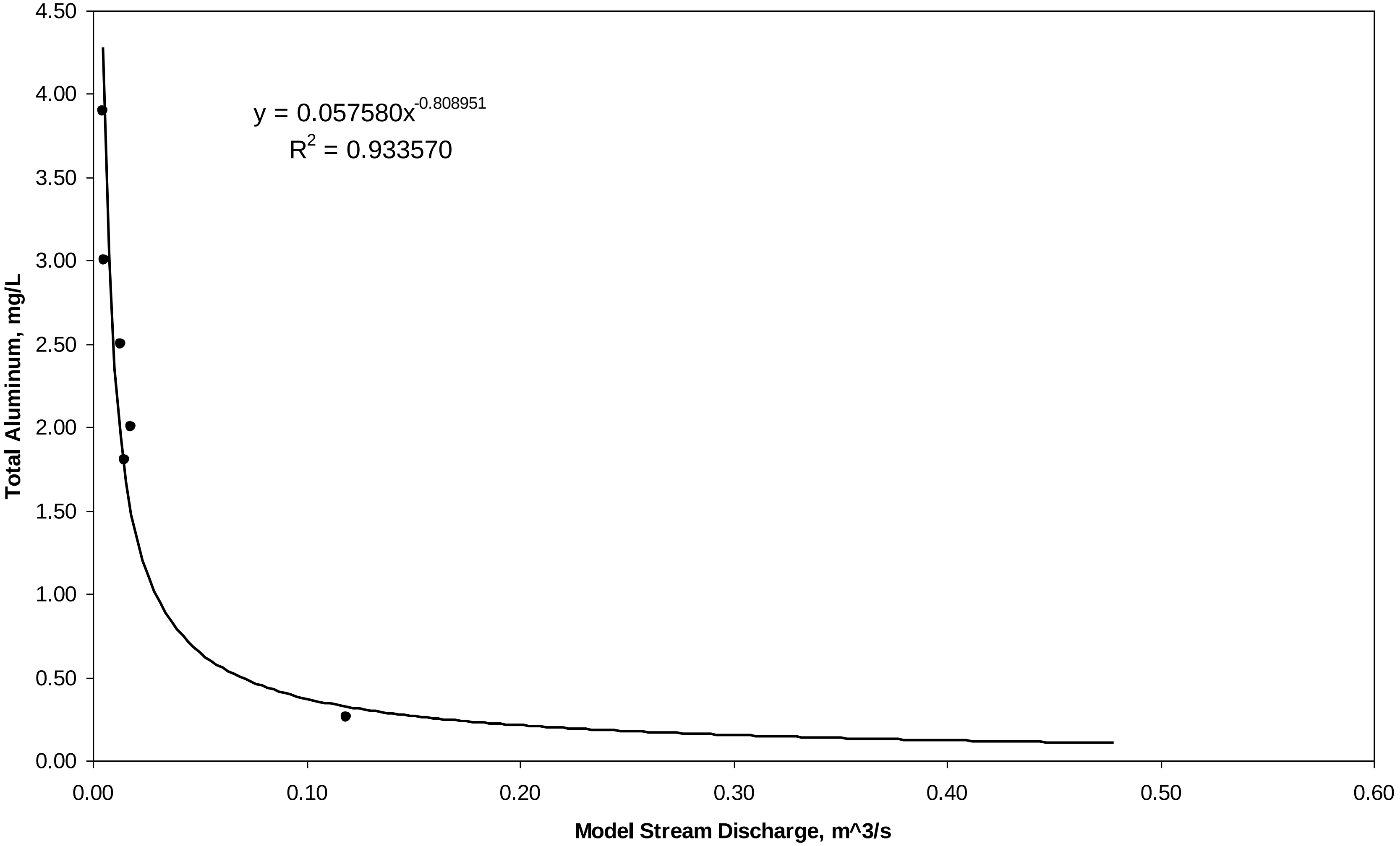

Figure 5. Regression Formula for Aluminum at Stream Station JS-8 in the Jobs Hollow Subwatershed.

Table 1. List of correlation coefficients of the water quality constituents calculated during model runs versus observations.

Water Quality Constituent	Calibration Model Run Correlation Coefficient, R^2	Verification Model Run Correlation Coefficient, R^2
Stream Discharge Flow Rate	73%	86%
Stream pH	65%	70%
Total Iron Concentration	77%	81%
Total Aluminum Concentration	63%	70%

Fig. 6, 7, and 8 are time series plots of the aluminum concentrations calculated by the calibration model at station JS-107-MC on Snow Fork and stations JS-153-MC and JS-151-MC on the Monday Creek mainstem, respectively. Most of the observed concentrations are replicated rather closely by the model, but there are a few low concentrations not replicated at station JS-107-MC, shown in Fig. 6. The low concentrations not replicated at station JS-107-MC may be a consequence of errors in the stream hydrology of Snow Fork. Snow Fork and its tributaries are above abandoned mines which are probably modifying the Snow Fork stream hydrograph in ways that cannot be replicated by any existing hydrologic model.

Because of the error associated with the Monday Creek *TAMDL* model, margins of safety will have to be specified for the remediation endpoints before the model is employed in the design of AMD treatment strategies. Since no water quality model is free of error, this outcome is expected. Table 2 lists the remediation endpoints and the margins of safety for pH, iron, and aluminum. The margin of safety for pH was 0.25 standard units, which is approximately 25% of the range in the 5th percentile of mainstem stream pH in the treatment model. The margins of safety for iron and aluminum were greater than 25% of the remediation endpoint.

Table 2. Remediation Endpoints and Margins of Safety for the Remediation Simulation Models.

Water Quality Constituent	Remediation Endpoint	Margin of Safety	Remediation Endpoint plus Margin of Safety
pH	6.82 standard units	+0.25 standard units	7.07 standard units
Aluminum	1.12 mg/L	-0.4 mg/L	0.72 mg/L
Iron	1.49 mg/L	-0.4 mg/L	1.09 mg/L

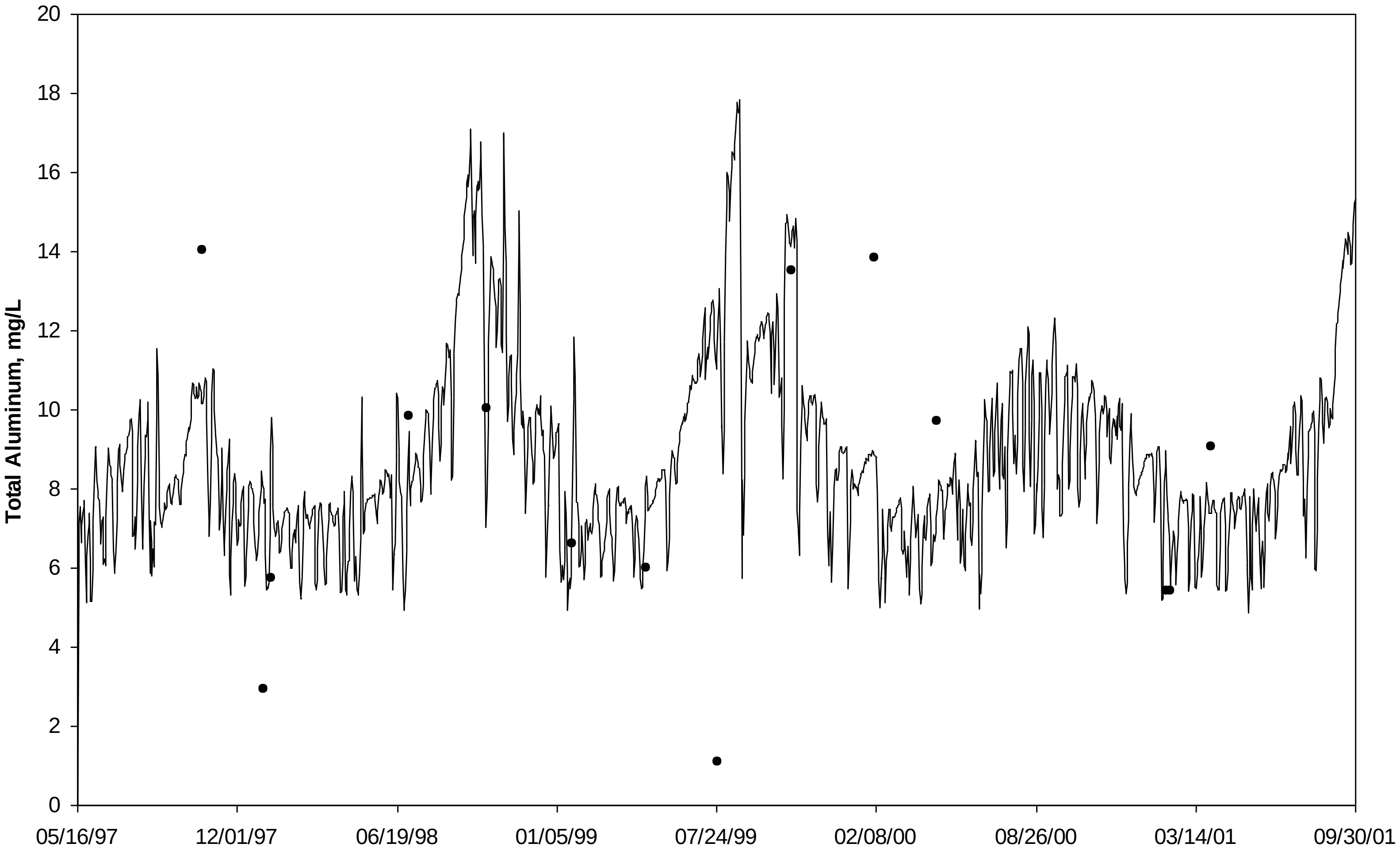

Figure 6. Simulated and Observed Aluminum Concentrations at Station JS-107-MC on Snow Fork of Monday Creek.

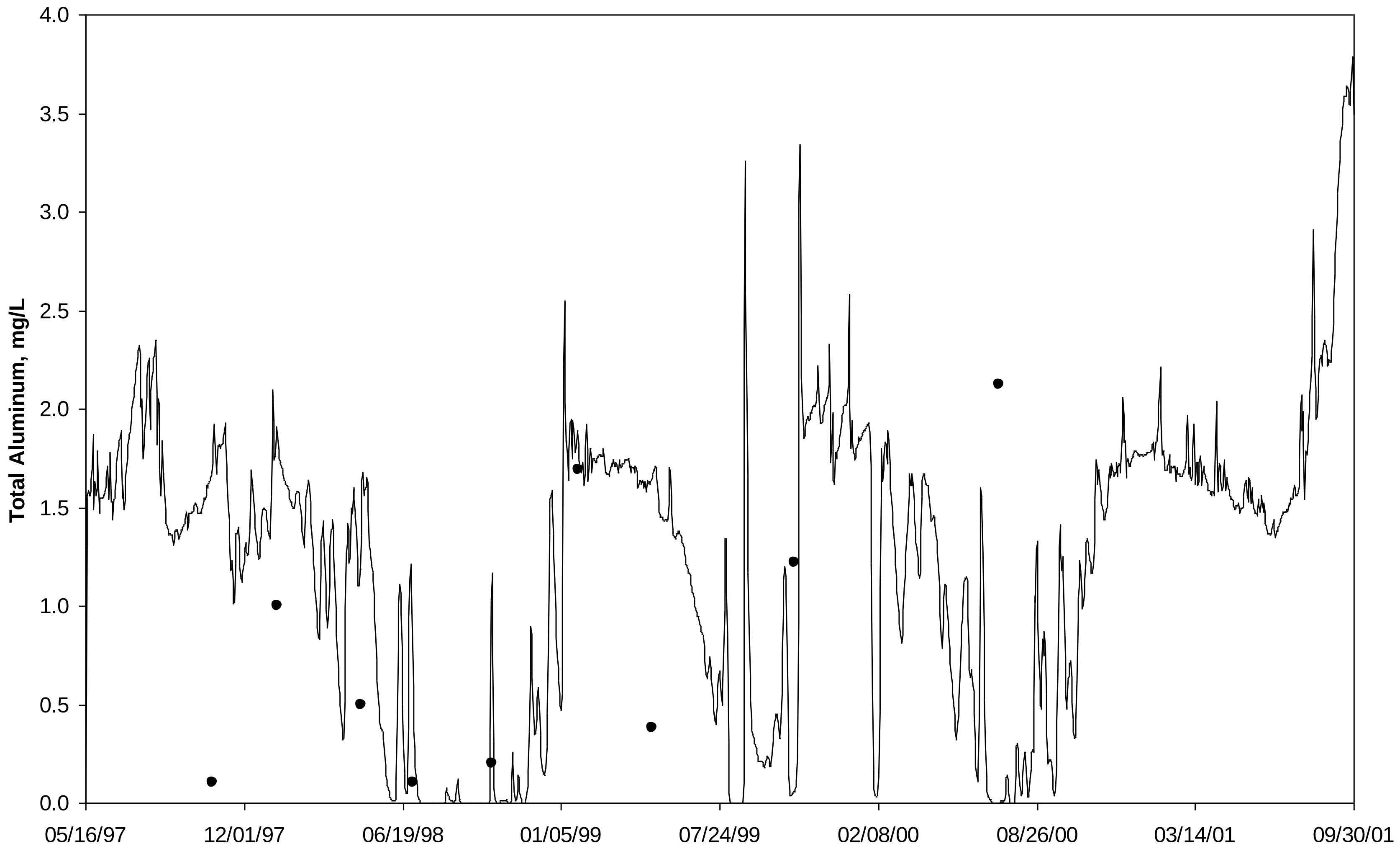

Figure 7. Simulated and Observed Aluminum Concentrations at Station JS-153-MC in Monday Creek.

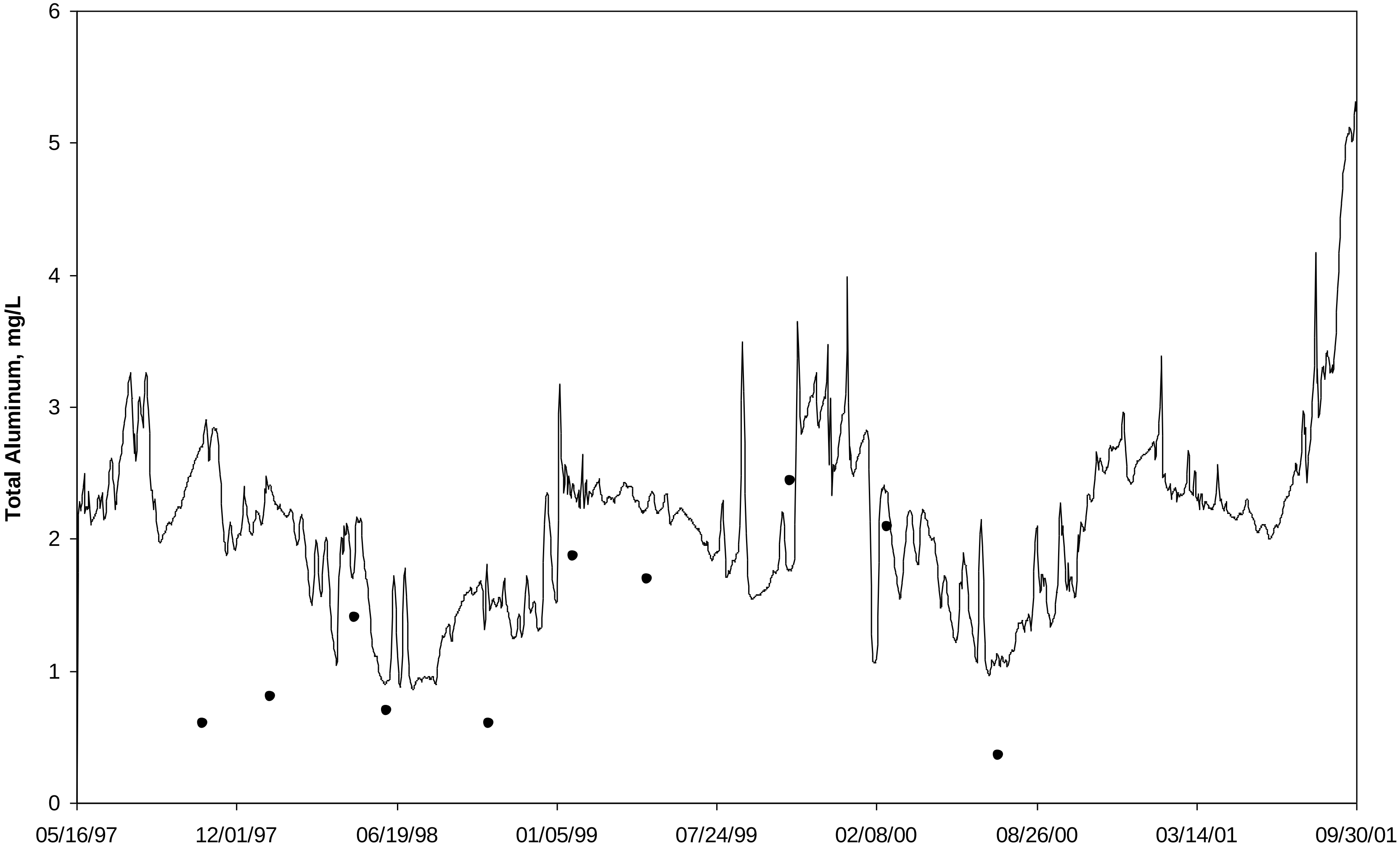

Figure 8. Simulated and Observed Aluminum Concentrations at Station JS-151-MC in Monday Creek.

While the quality of the calibration of the model is less than desirable, we believe that the Monday Creek *TAMDL* model should be employed in the development of AMD treatment strategies, with the aforementioned margins of safety, because of sampling error. Additional collected data would have allowed more complete quality assurance and quality control of the calibration data. Error in stream pH measurements can be introduced by debris plugging the probe's reference junction, improper probe calibration, or carelessness in measurement. Error in total metal concentration measurements can be introduced by the collection of bottom sediment in the stream water or procedural errors made by the laboratory.

Development of AMD Treatment Strategies

The first step in designing an AMD treatment strategy for the Monday Creek watershed is deciding the final goal of the remediation process. This goal was expressed by the Huntington District in terms of remediation endpoints, which are listed in Table 2. Because all models have some error associated with their results, margins of safety for each of the parameters are included in Table 2. The endpoints listed in Table 2 express the minimum allowable 5th percentile for stream pH and the maximum allowable 95th percentile for aluminum and iron concentration and were enforced for the entire length of the Monday Creek mainstem.

Fig. 9, 10 and 11 show the simulated 5th percentile of stream pH, the 95th percentile of aluminum concentration and the 95th percentile of iron concentration, respectively, before and after AMD load reductions in various subwatersheds. The load reductions in each of the Monday Creek subwatershed required to achieve the improvements shown in Fig. 9, 10 and 11 are shown in Table 3.

Originally, the remediation endpoint margin of safety for the 5th percentile of the mainstem stream pH was 0.2 standard units; this was increased to 0.25 standard units as the result of a flow parametric study that was conducted to determine the variability of the calculated results with changes in the stream discharge flow rate. With the margin of safety for the pH remediation endpoint increased to 0.25, the minimum 5th percentile for mainstem stream pH remained above the remediation endpoint for changes in the discharge flow rate as large as 30%.

Because the stream discharge hydrographs employed in the Monday Creek *TAMDL* model had an accuracy of approximately 30%, this result, shown in Fig. 12, was deemed acceptable.

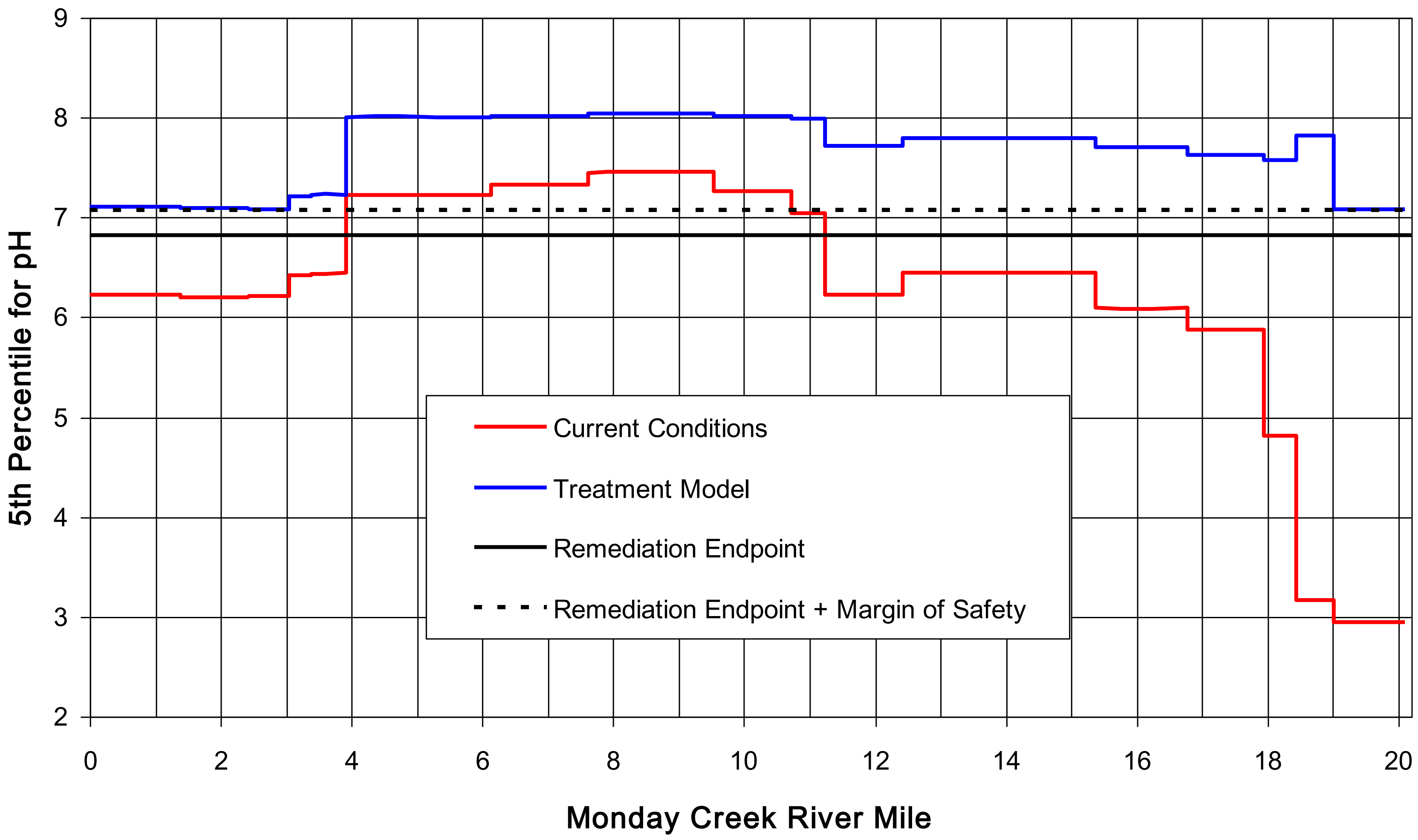

Figure 9. Simulated Pre- and Post-Treatment 5th Percentile of Stream pH for Monday Creek Mainstem.

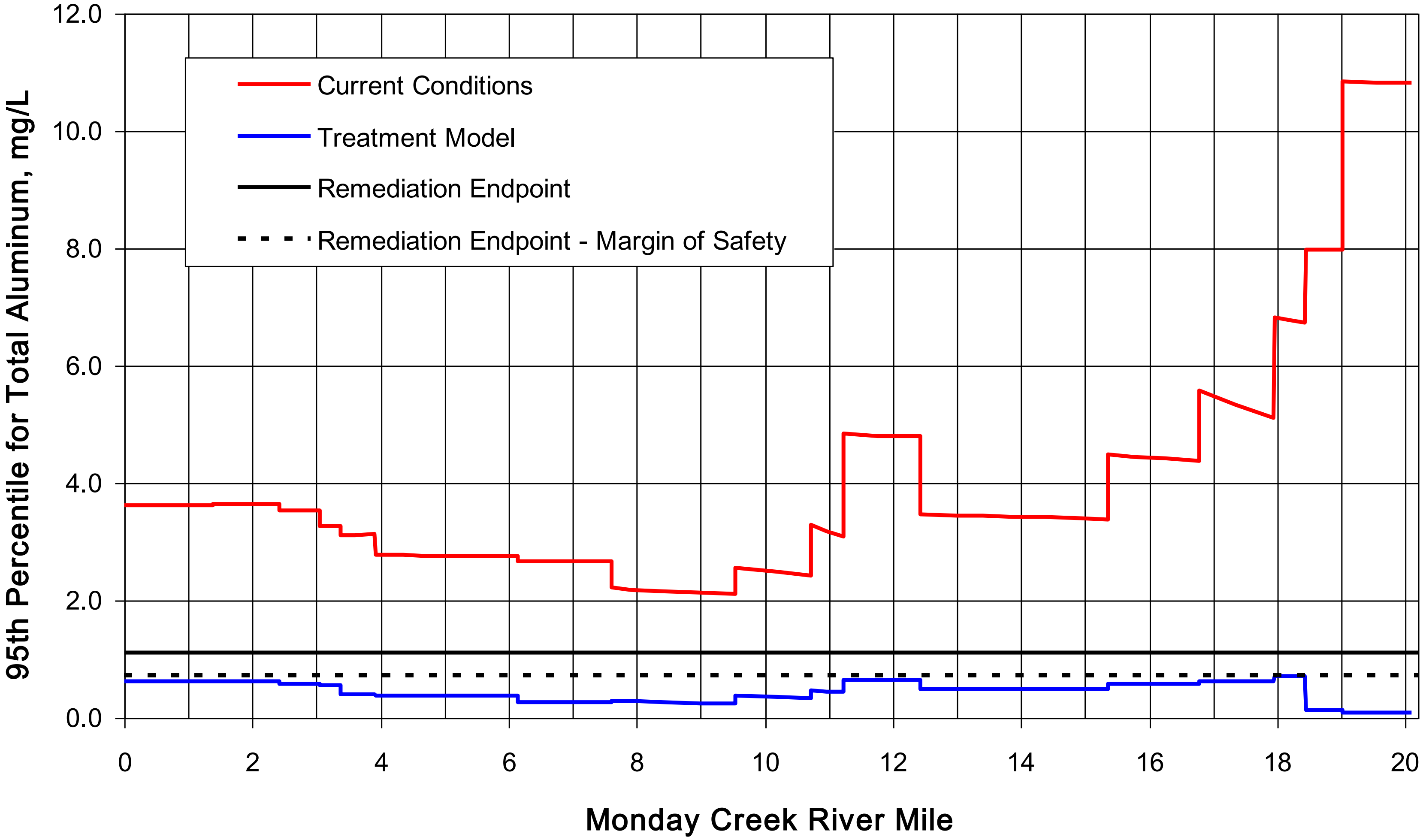

Figure 10. Simulated Pre- and Post-Treatment 95th Percentile of Aluminum Concentration for Monday Creek Mainstem.

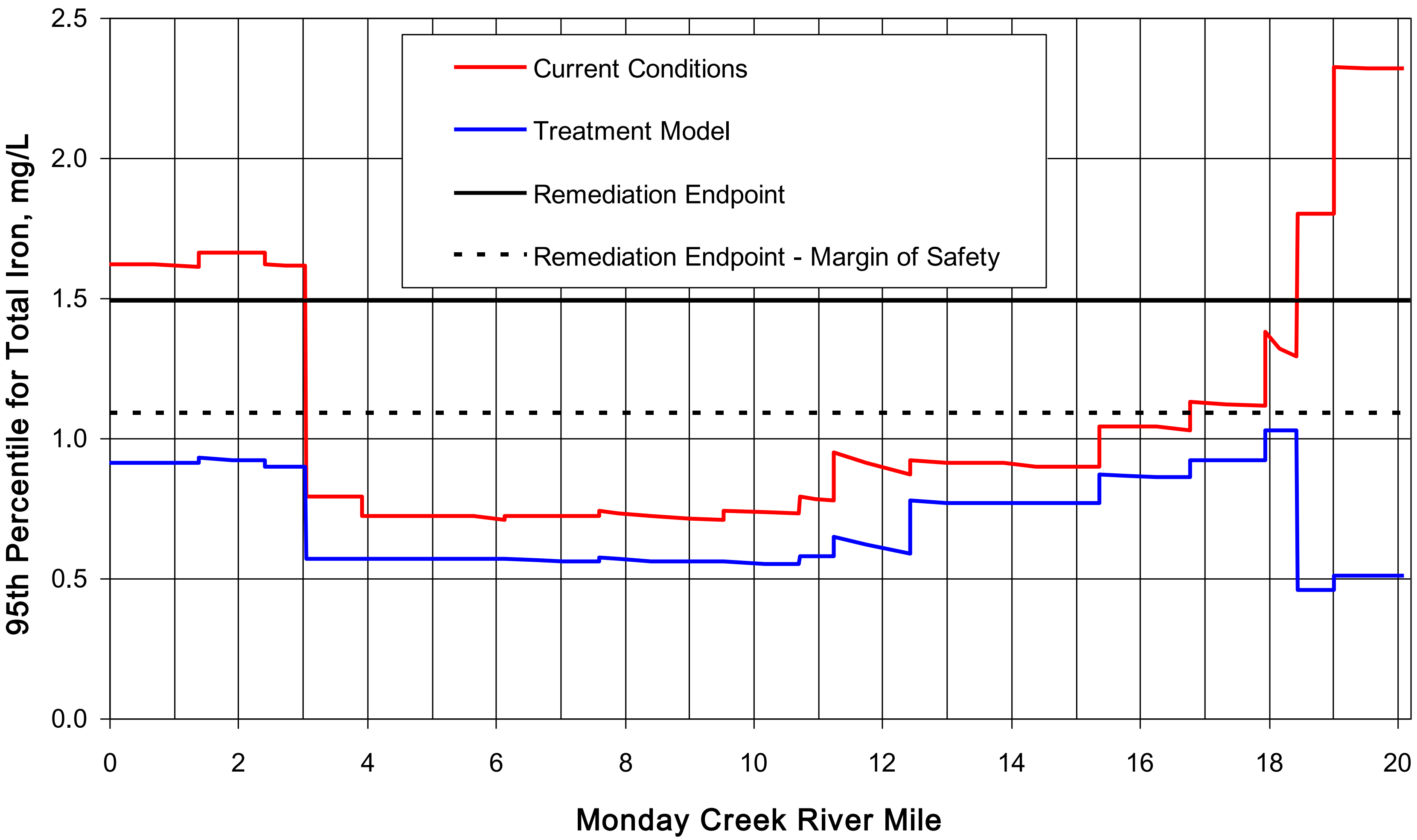

Figure 11. Simulated Pre- and Post-Treatment 95th Percentile of Iron Concentration for Monday Creek Mainstem.

Table 3. Minimum Required Load Reductions in each Monday Creek Subwatershed.

Subwatershed	Mean Net Acidity Load Reduction	Mean Fe Load Reduction	Mean Al Load Reduction
Jobs Hollow	123%	90%	99%
Dixey Hollow	178%	0%	97%
Shawnee Creek	0%	0%	0%
Ironpoint Cemetery	0%	0%	0%
Rock Run	0%	50%	0%
Stone Church	0%	0%	0%
Salt Run	0%	0%	0%
Dans Run	0%	0%	0%
New Straitsville	0%	0%	0%
Lost Run	90%	96%	90%
Little Monday Creek	0%	0%	0%
Kitchen Run	0%	0%	0%
Sand Run	0%	0%	0%
Monkey Hollow	28%	0%	90%
Big-4 Hollow	0%	0%	0%
Snake Hollow	90%	90%	90%
Bessemer Hollow	0%	0%	0%
Snow Fork	98%	53%	88%
Coe Hollow	54%	51%	50%
Happy Hollow	0%	0%	0%
Salem Hollow (of Snow Fork)	331%	50%	90%
Sycamore Hollow (of Snow Fork)	90%	78%	90%
Spencer Hollow (of Snow Fork)	91%	8%	99%
Brush Fork (of Snow Fork)	90%	52%	90%
Long Hollow (of Snow Fork)	90%	51%	90%
Whitmore Cem. (of Snow Fork)	296%	50%	0%
Orbiston (of Snow Fork)	0%	50%	50%

Fig. 13 and 14 show the results of the flow parametric study for aluminum and iron, respectively, and indicate that the discharge flow rate would have to change by approximately 50% in order for the 95th percentile of the aluminum and iron concentrations to be greater than the remediation endpoints.

Design of AMD Treatment Structures

Traditional techniques for the design of active and passive AMD treatment structures were used to develop treatment systems for all of the subwatersheds listed in Table 3 with required reductions in AMD load. The unit cost assumptions made in the cost estimates for these structures are listed in Table 4. With the exception of the stream subsidence closures, the designed treatment structures are summarized in Table 5 and displayed schematically in Fig. 15. AMD treatment designs for the Monday Creek watershed include: a lime kiln dust doser, low head dams, limestone leach beds, open limestone channels, slag leach beds, aerobic wetlands, and stream subsidence closures. The details of these designs are shown in Tables 6 through 12.

The treatment efficiency in Tables 6, 8, 9, 10 and 12 is the average cost of the acid removed from the stream over the course of the treatment structure's service life and was calculated with the following formula.

$$E_T = \frac{C}{\Delta L\,(T)} \tag{11}$$

Where:

E_T = Treatment efficiency of the treatment structure, \$/ton.

C = Estimated cost of the treatment structure, \$.

ΔL = Acid load removed by the treatment structure, tons/yr.

T = Service life of treatment structure, yrs.

The mean treatment efficiency in Table 5 is the average treatment efficiency for the treatment structures in that subwatershed. No mean treatment efficiency is given for the Rock Run subwatershed because the structures in that subwatershed are not treating acidity.

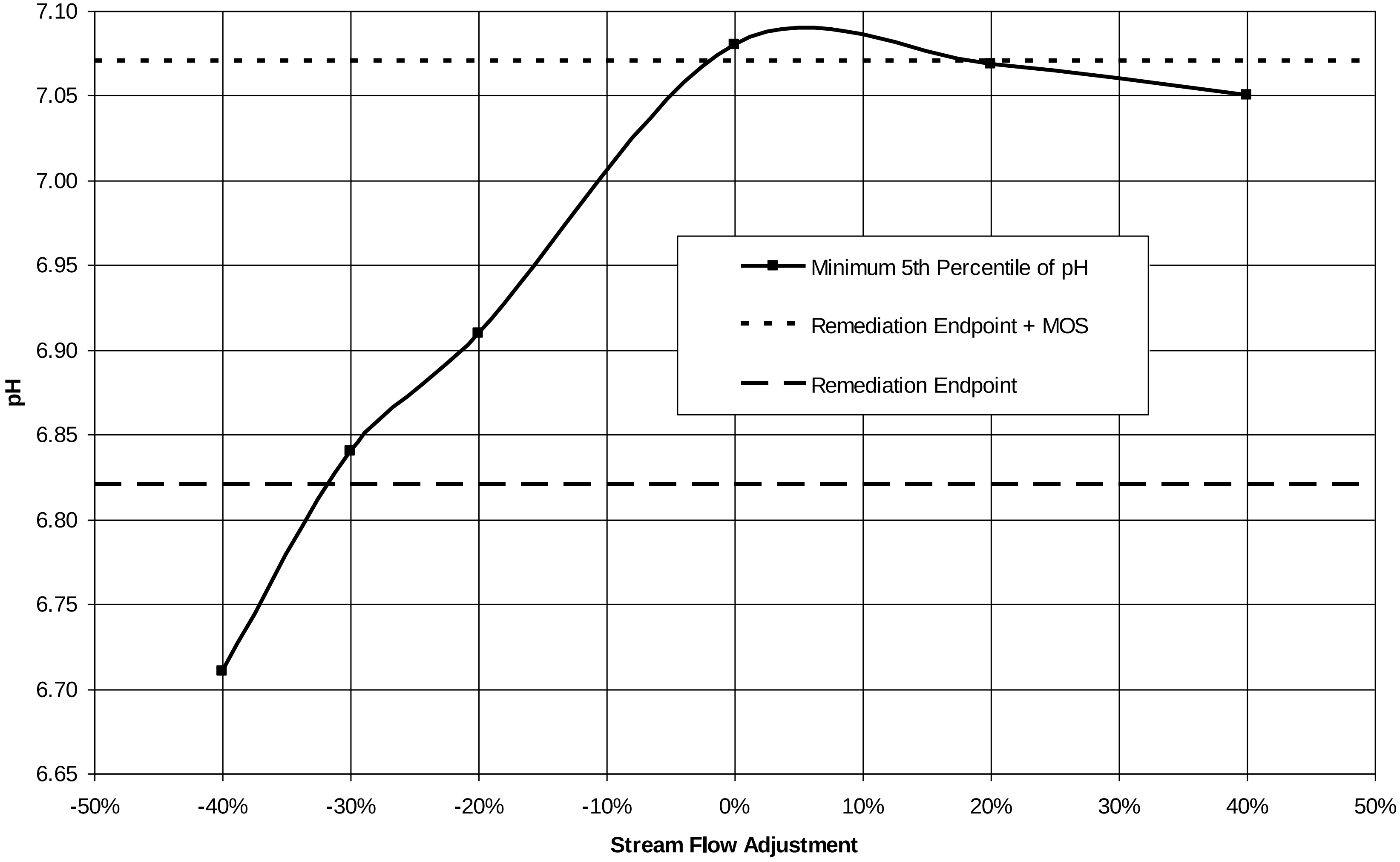

Figure 12. Minimum 5th Percentile Mainstem Stream pH calculated by Parametric Study Simulations.

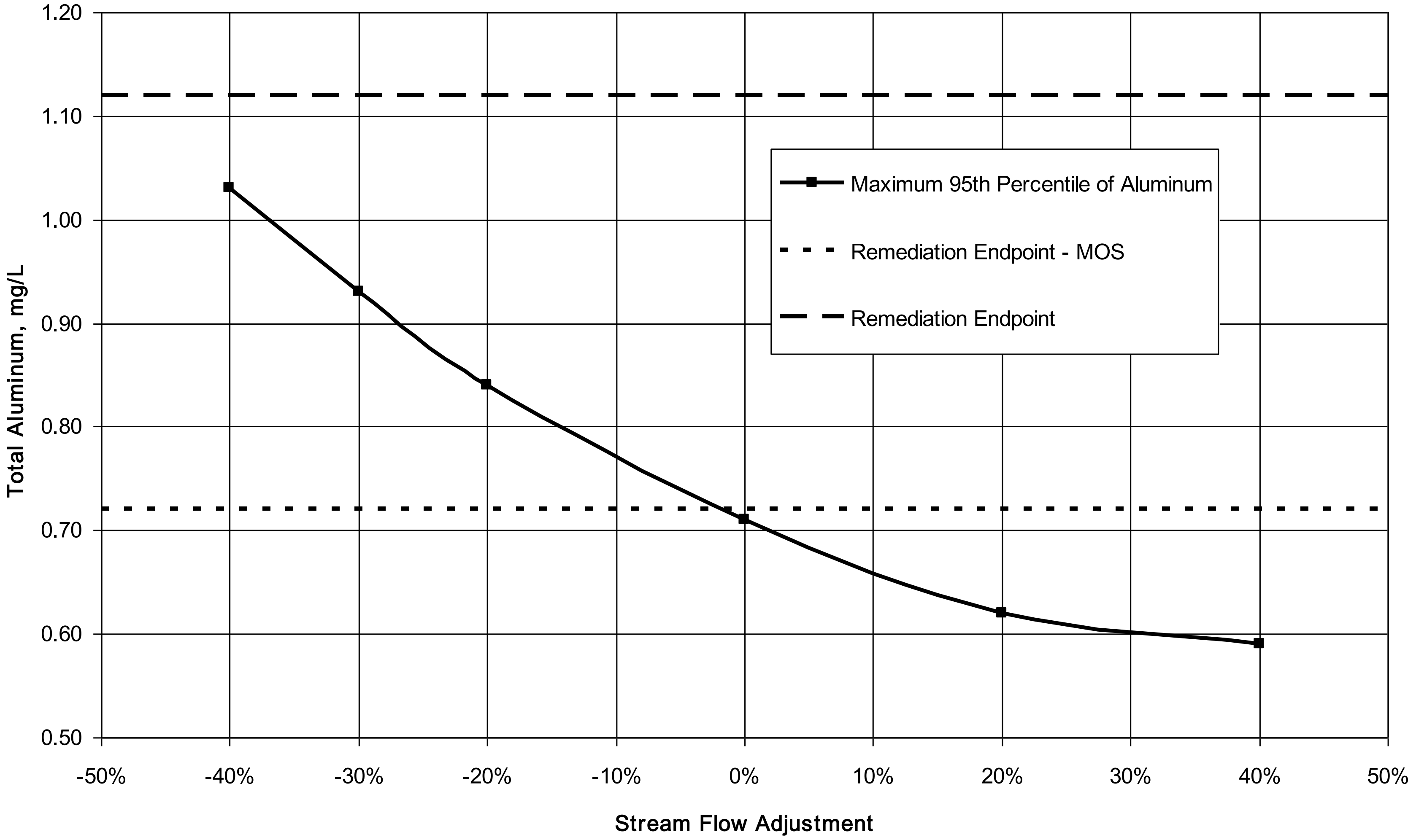

Figure 13. Maximum 95th Percentile Mainstem Aluminum Concentration calculated by Parametric Study Simulations.

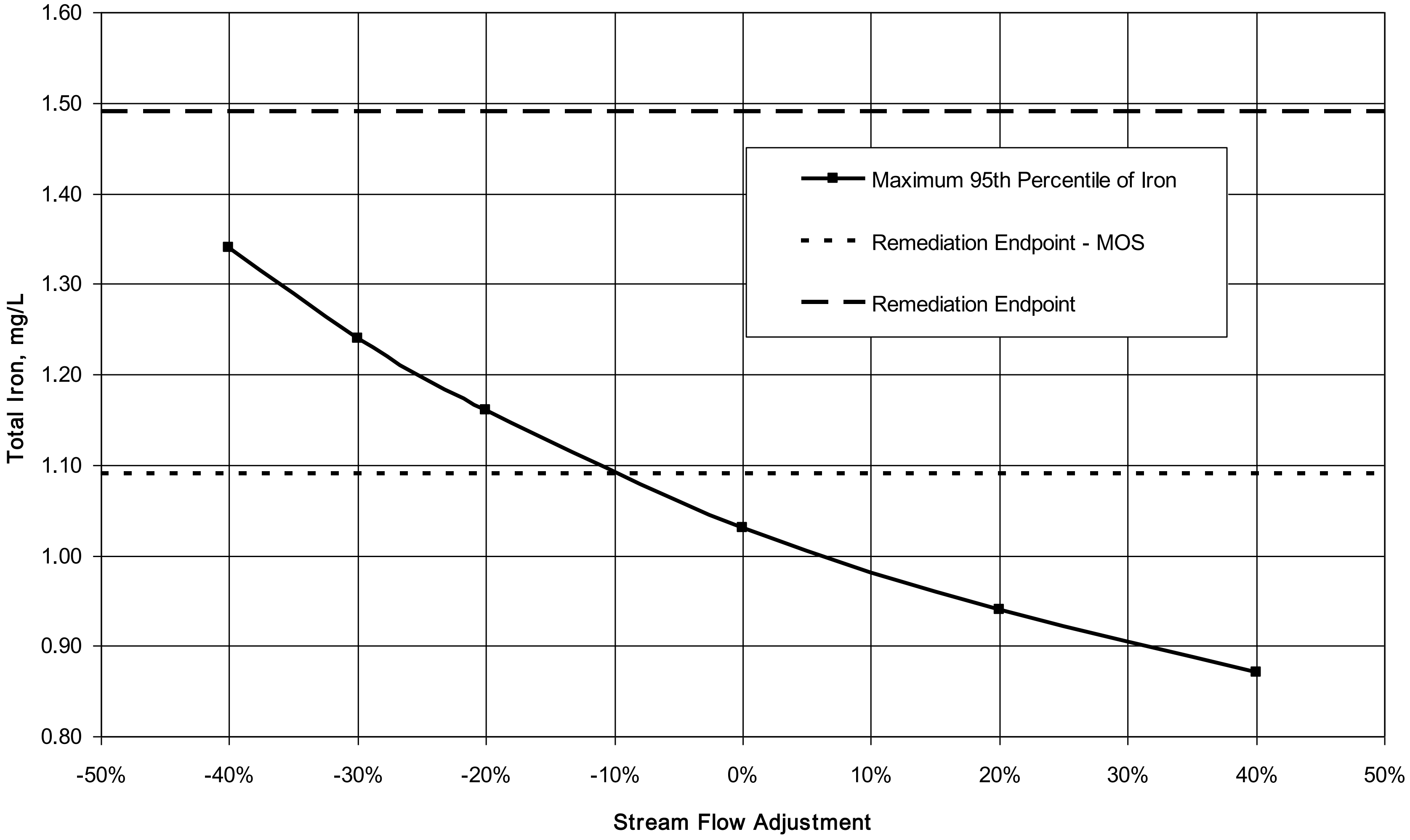

Figure 14. Maximum 95th Percentile Mainstem Iron Concentration Calculated by Parametric Study Simulations.

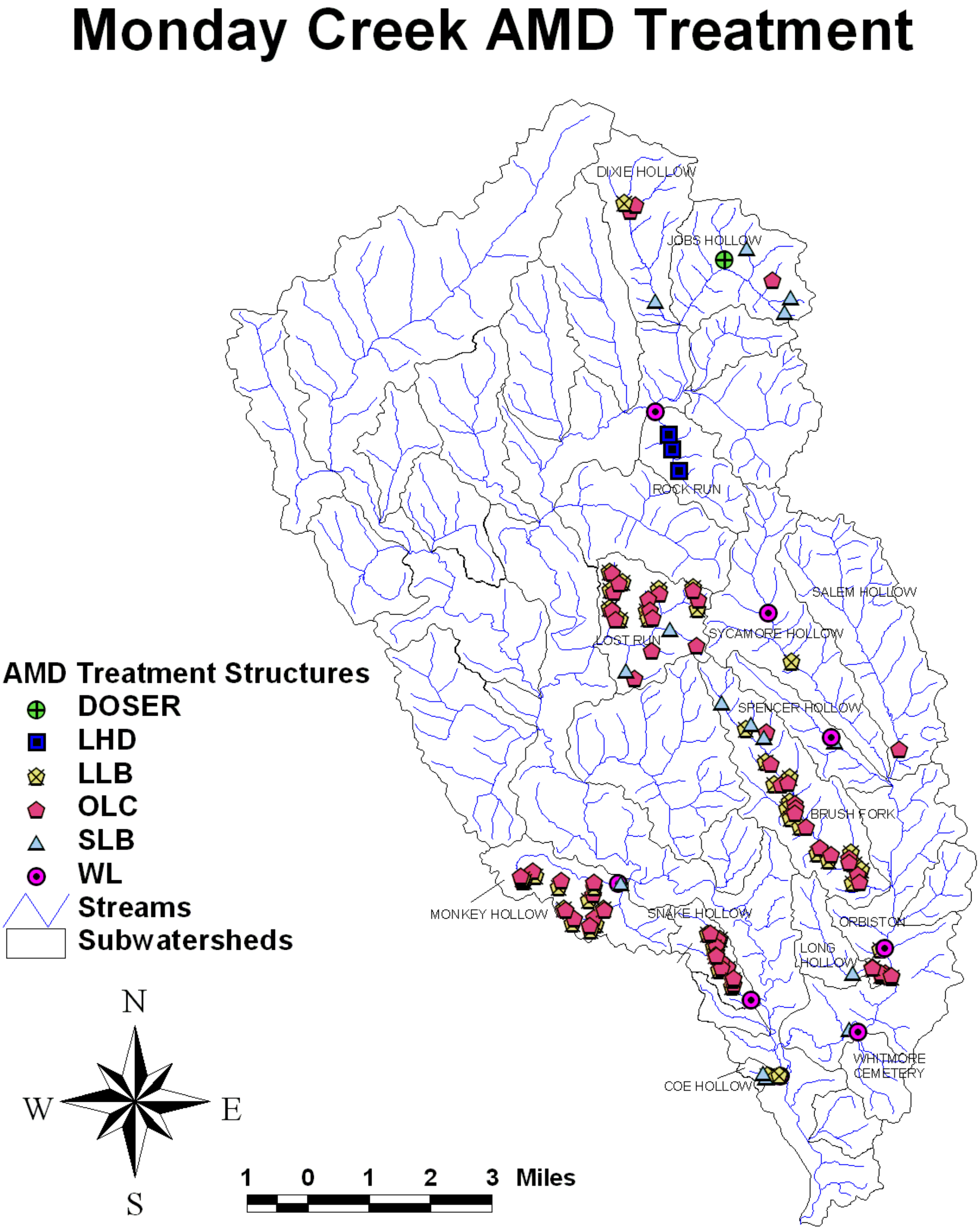

Figure 15. Designed AMD Treatment Structures for the Monday Creek Watershed.

Table 4. Unit Cost Assumptions for AMD Treatment Designs.

Item	Unit Cost	Units
Limestone (installed)	$25.00	Per Ton
Steel Slag (installed)	$25.00	Per Ton
Excavation	$3.00	Per Cubic Yard
Lime Kiln Dust	$25.50	Per Ton
Lime Kiln Dust Doser	$60,000.00	Per Unit
Stream Channel Restoration	$43.78	Per Foot

Feasibility Testing of Designed AMD Treatment Strategies

In order to test the feasibility of the designed AMD treatment structures, the action of the treatment structures was directly simulated by the Monday Creek *TAMDL* model. With the structures designed for Jobs Hollow, none of the designs required later modification. In order to satisfy the remediation endpoints for the upper portion of the Monday Creek mainstem, the mean alkalinity load from the OLC and SLB in Jobs Hollow had to be increased from 247 tons per year to 547 tons per year. Table 8 reflects this change in the design.

Conclusions

This project developed the Monday Creek *TAMDL* model for simulating the transport and reaction of those water quality constituents related to AMD within the Monday Creek watershed. This model was used to calculate the required load reductions from each of the Monday Creek and Snow Fork subwatersheds in order to satisfy the remediation endpoints specified by the Huntington District. No water quality model is free from error, and the Monday Creek *TAMDL* model is no exception. To ameliorate the effect of this error on the calculation of the required amount of AMD treatment, margins of safety were adopted for the remediation endpoints. These margins of safety were designed to force the model to over-estimate the amount of AMD treatment needed to satisfy the remediation endpoints to ensure that modeling errors do not result in substandard water quality conditions after the proposed treatment structures have been constructed.

These required reductions in AMD load were used to develop an AMD treatment strategy that will bring the mainstem of Monday Creek back into compliance with the remediation endpoints specified by the Huntington District. This strategy consists of a lime kiln dust doser, low head dams, limestone leach beds, open limestone channels, slag leach beds, aerobic wetlands, and stream subsidence closures. The ultimate feasibility of this treatment strategy was tested by directly simulating the actions of the designed structures in the Monday Creek *TAMDL* model. The results of these simulations led to an increase in the designed capacity of the treatment structures to be placed within Jobs Hollow.

Overall, the strategy provided by this project appears to provide a near optimal set of designs for treating AMD. In the strategy's current form, it will treat approximately 54,100 tons of acid at an estimated cost of $6,000,000. This total includes $1,570,000 for stream subsidence closures and $4,430,000 for conventional passive and active AMD treatment.

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Table 5. Summary of Monday Creek AMD Treatment Designs, excluding Stream Subsidence Closures.

Subwatershed	Excavation, yd^3	Limestone, tons	Steel Slag, tons	Estimated Cost	Acid Load Removed, tpy	Mean Treatment Efficiency, $/ton
Jobs Hollow	9,122	1,851	13,626	$527,647	681	$44.62
Dixie Hollow	2,208	2,881	636	$93,395	82	$47.15
Rock Run	42,554	24	0	$128,262	0	Not Applicable
Lost Run	24,718	40,277	5,863	$1,227,659	610	$58.24
Monkey Hollow	10,446	3,378	10,472	$377,599	183	$180.33
Snake Hollow	43,263	3,825	0	$225,423	162	$80.83
Coe Hollow	561	387	301	$18,886	91	$50.29
Salem Hollow	1,959	2,673	0	$72,703	67	$49.12
Sycamore Hollow	132,413	3,454	0	$483,578	106	$138.41
Spencer Hollow	5,358	0	5,236	$137,305	55	$402.01
Brush Fork	10,519	5,397	9,080	$393,480	580	$86.98
Long Hollow	5,047	3,206	3,129	$167,740	245	$57.52
Whitmore Cemetery	14,272	0	12,567	$356,987	132	$435.50
Orbiston	70,196	394	0	$220,428	42	$587.86
Total	372,636	67,747	60,910	$4,431,092	3,036	$81.91

Table 6. Monday Creek Lime Kiln Dust Doser Design (DOSER).

Subwatershed	Site	Treatment Unit	Q, gpm	Total Acidity, mg/L	Acid Load, tpy	Estimated Cost	Acid Load Removed, tpy	Service Life, years	Treatment Efficiency, $/ton
Jobs Hollow	DOSER	DOSER	2237.45	34.87	104.64	$113,366	104.64	20.00	$54.17

Table 7. Monday Creek Low Head Dam Designs (LHD).

Subwatershed	Site	Treatment Unit	Q, gpm	Total Acidity, mg/L	Acid Load, tpy	L, ft	W, ft	H, ft	Excavation, yd^3	Limestone, tons	Estimated Cost	Service Life, years
Rock Run	RR-1	LHD-1	815.00	2.71	48.54	6.2	10.0	5.0	7.04	7.99	$221	15.00
Rock Run	RR-2	LHD-2	815.00	2.71	48.54	6.2	10.0	5.0	7.04	7.99	$221	15.00
Rock Run	RR-3	LHD-3	815.00	2.71	48.54	6.2	10.0	5.0	7.04	7.99	$221	15.00

Table 8. Monday Creek Limestone Leach Bed Designs (LLB).

Subwatershed	Site	Treatment Unit	Q, gpm	Total Acidity, mg/L	Acid Load, tpy	L, ft	W, ft	H, ft	Excavation, yd^3	Limestone, tons	Estimated Cost	Acid Load Removed, tpy	Treatment Efficiency, $/ton
Sycamore	RM-2.5	LLB	782.4	65.0	111.6	181.6	75.0	6.0	3532.0	3453.6	$96,935	105.9	$27.74
Orbiston	302+304	LLB 1	96.3	395.9	41.8	116.4	20.0	4.0	431.2	393.5	$11,132	41.7	$29.69
Dixie	DIX-16	LLB 1	50.0	-75.0	-8.3	75.0	40.0	5.0	666.7	672.2	$18,806	8.3	$27.99
Lost Run	LR-1W	LLB 1W1	1065.1	72.6	170.1	112.7	25.0	4.0	521.7	505.0	$14,190	23.5	$30.13
Lost Run	LR-1W	LLB 1W2	1065.1	72.6	170.1	112.7	25.0	4.0	521.7	505.0	$14,190	23.5	$30.13
Lost Run	LR-1W	LLB 1W3	1065.1	72.6	170.1	112.7	25.0	4.0	521.7	505.0	$14,190	23.5	$30.13
Lost Run	LR-1W	LLB 1W4	1065.1	72.6	170.1	112.7	25.0	4.0	521.7	505.0	$14,190	23.5	$30.13
Lost Run	LR-1W	LLB 1W5	1065.1	72.6	170.1	112.7	25.0	4.0	521.7	505.0	$14,190	23.5	$30.13
Lost Run	LR-2W	LLB 2W1	86.0	237.6	45.0	56.3	50.0	4.0	521.7	505.0	$14,190	8.4	$29.67
Lost Run	LR-2W	LLB 2W2	86.0	237.6	45.0	56.3	50.0	4.0	521.7	505.0	$14,190	7.1	$29.99
Lost Run	LR-3W	LLB 3W1	94.3	390.2	80.9	22.5	25.0	4.0	104.3	101.0	$2,838	3.3	$30.33
Lost Run	LR-MS	LLB 4E1	13.3	183.3	5.4	22.5	25.0	4.0	104.3	101.0	$2,838	1.8	$30.03
Lost Run	LR-4W	LLB 4W1	128.9	390.2	110.6	112.7	50.0	4.0	1043.4	1010.0	$28,380	55.0	$30.38
Coe	A SEEP	LLB-A	58.2	230.0	29.5	23.5	20.0	3.0	69.6	63.1	$1,787	14.6	$30.51
Coe	B SEEP	LLB-B	66.0	285.0	41.4	26.6	20.0	3.0	78.9	71.6	$2,026	20.6	$32.83
Coe	D TRIB	LLB-D	84.3	302.0	56.0	25.5	20.0	4.0	94.3	91.3	$2,566	27.8	$30.76
Brush Fork	MSBS	LLB1	167.3	465.3	171.2	89.9	30.0	3.0	399.5	362.6	$10,263	85.1	$30.17
Monkey	FRT-3	LLB1	0.9	340.0	0.7	2.9	5.0	3.0	2.1	1.9	$55	0.3	$33.03
Snake	ATC-03	LLB1	2.1	151.0	0.7	6.9	5.0	3.0	5.1	4.6	$131	0.4	$37.18
Long	LON-93	LLB1	268.0	178.0	104.9	216.0	30.0	4.0	1200.1	1161.7	$32,643	52.1	$62.62
Brush Fork	32A	LLB10	163.0	384.0	137.7	262.8	20.0	3.0	778.8	706.7	$20,005	68.4	$29.24
Monkey	FRT-5	LLB10	29.4	181.0	11.7	26.4	18.0	3.0	70.3	63.8	$1,806	5.8	$31.01
Snake	SNA-61	LLB10	163.0	384.0	137.7	39.1	18.0	3.0	104.3	94.7	$2,680	8.8	$30.35
Brush Fork	MS7C	LLB11	288.1	90.1	57.1	116.2	20.0	3.0	344.2	312.3	$8,840	28.4	$31.16
Monkey	FRT-1	LLB11	35.9	78.5	6.2	32.2	18.0	3.0	85.8	77.8	$2,203	3.1	$29.80
Brush Fork	MS7	LLB12	172.8	83.5	31.7	69.7	20.0	3.0	206.4	187.3	$5,301	15.8	$30.57
Brush Fork	21	LLB13	8.5	164.0	3.1	6.9	20.0	3.0	20.4	18.5	$523	1.5	$31.12
Brush Fork	20	LLB14	98.7	251.0	54.5	79.6	20.0	3.0	235.9	214.0	$6,059	27.1	$31.96
Brush Fork	MSSP1	LLB2	62.4	85.4	11.7	25.1	20.0	3.0	74.5	67.6	$1,914	5.8	$29.88
Monkey	FRT-4	LLB2	1.3	455.0	1.3	8.4	5.0	3.0	6.2	5.6	$160	0.7	$59.56
Snake	ATC-02	LLB2	62.4	85.4	11.7	8.4	6.0	3.0	7.5	6.8	$192	0.6	$29.65
Long	LON-94	LLB2	114.9	142.0	35.9	46.3	30.0	4.0	257.3	249.1	$6,999	17.8	$30.19
Brush Fork	MSSP2	LLB3	118.9	140.5	36.7	95.9	20.0	3.0	284.1	257.8	$7,297	18.3	$30.75
Monkey	MNK-7A	LLB3	2.6	609.0	3.5	8.4	5.0	3.0	6.2	5.6	$160	1.7	$30.73
Snake	SNA-64	LLB3	118.9	140.5	36.7	20.3	6.0	3.0	18.0	16.3	$463	1.5	$31.90
Long	LON-95	LLB3	242.4	52.0	27.7	97.7	30.0	4.0	542.8	525.4	$14,763	13.8	$29.77
Brush Fork	5E50	LLB4	7.1	141.0	2.2	5.8	20.0	3.0	17.0	15.5	$438	1.1	$30.63
Monkey	FRT-2	LLB4	2.2	274.0	1.4	3.6	5.0	3.0	2.7	2.4	$69	0.7	$14.64
Snake	ATC-04	LLB4	7.1	141.0	2.2	12.5	10.0	3.0	18.5	16.8	$476	1.1	$44.84
Long	S-27	LLB4	695.7	52.0	79.6	210.3	20.0	4.0	779.0	754.0	$21,188	39.5	$29.77
Brush Fork	MSSP3	LLB5	358.5	210.4	165.9	289.0	20.0	3.0	856.2	777.0	$21,995	82.4	$29.65
Monkey	MNK-8	LLB5	6.0	465.3	6.1	8.0	12.0	3.0	14.3	13.0	$367	3.0	$30.17
Snake	SNA-62	LLB5	358.5	210.4	165.9	28.6	10.0	3.0	42.4	38.5	$1,090	5.4	$20.25
Brush Fork	6WB	LLB6	39.9	148.0	13.0	32.2	20.0	3.0	95.4	86.6	$2,451	6.5	$29.18

Subwatershed	Site	Treatment Unit	Q, gpm	Total Acidity, mg/L	Acid Load, tpy	L, ft	W, ft	H, ft	Excavation, yd^3	Limestone, tons	Estimated Cost	Acid Load Removed, tpy	Treatment Efficiency, $/ton
Monkey	FRT-5A	LLB6	7.6	200.0	3.4	12.3	20.0	3.0	36.5	33.1	$936	1.7	$29.55
Snake	ATC-01	LLB6	39.9	148.0	13.0	44.3	20.0	3.0	131.2	119.0	$3,370	13.7	$12.33
Brush Fork	6WC	LLB7	35.9	132.0	10.4	28.9	20.0	3.0	85.8	77.8	$2,203	5.2	$30.38
Monkey	MNK-1	LLB7	9.8	337.9	7.3	10.6	15.0	3.0	23.5	21.3	$604	3.6	$27.69
Snake	SNA-63	LLB7	35.9	132.0	10.4	34.9	15.0	3.0	77.6	70.4	$1,994	8.2	$24.30
Brush Fork	MSSP5	LLB8	150.9	206.9	68.7	121.7	20.0	3.0	360.5	327.2	$9,262	34.1	$30.16
Monkey	MNK-11	LLB8	18.9	493.0	20.5	30.5	20.0	3.0	90.5	82.1	$2,324	10.2	$28.47
Snake	SNA-60	LLB8	150.9	206.9	68.7	58.6	20.0	3.0	173.7	157.6	$4,461	34.2	$6.52
Brush Fork	4W	LLB9	9.8	228.0	4.9	7.9	20.0	3.0	23.5	21.3	$603	2.4	$30.78
Monkey	MNK-13	LLB9	21.1	256.2	11.9	22.6	15.0	3.0	50.3	45.6	$1,292	5.9	$31.31
Snake	ATC-07	LLB9	9.8	228.0	4.9	40.2	15.0	3.0	89.3	81.1	$2,294	8.0	$28.80

Table 9. Monday Creek Open Limestone Channel Designs (OLC).

Subwatershed	Site	Treatment Unit	Q, gpm	Total Acidity, mg/L	Acid Load, tpy	L, ft	W, ft	H, ft	A, deg	F, Ft	Limestone, tons	Excavation, yd^3	Estimated Cost	Acid Load Removed, tpy	Treatment Efficiency, $/ton
Lost Run	LR-1E	OLC 1E1	530.4	17.5	20.4	3838.0	6.0	2.0	153	2.0	5868.1	2558.7	$154,378	21.4	$30.31
Lost Run	LR-1W	OLC 1W1	1065.1	72.6	170.1	1023.0	6.0	2.0	153	2.0	1564.1	682.0	$41,147	15.0	$78.38
Lost Run	LR-1W	OLC 1W2	1065.1	72.6	170.1	1023.0	6.0	2.0	153	2.0	1564.1	682.0	$41,147	15.0	$78.38
Lost Run	LR-1W	OLC 1W3	1065.1	72.6	170.1	1023.0	6.0	2.0	153	2.0	1564.1	682.0	$41,147	15.0	$78.38
Lost Run	LR-1W	OLC 1W4	1065.1	72.6	170.1	1023.0	6.0	2.0	153	2.0	1564.1	682.0	$41,147	15.0	$78.38
Lost Run	LR-1W	OLC 1W5	1065.1	72.6	170.1	1023.0	6.0	2.0	153	2.0	1564.1	682.0	$41,147	15.0	$78.38
Lost Run	LR-2E	OLC 2E1	160.2	22.6	8.0	1140.0	8.0	2.0	153	2.0	1947.4	1013.3	$51,724	7.8	$67.38
Lost Run	LR-2W	OLC 2W1	86.0	237.6	45.0	712.5	5.0	1.5	153	1.5	636.7	329.9	$16,907	8.4	$74.64
Lost Run	LR-2W	OLC 2W2	86.0	237.6	45.0	944.1	5.0	1.5	153	1.5	843.7	437.1	$22,404	7.0	$75.76
Lost Run	LR-2W	OLC 2W3	86.0	237.6	45.0	1397.9	6.0	2.0	153	2.0	2137.3	932.0	$56,230	10.2	$79.64
Lost Run	LR-3E	OLC 3E1	227.6	160.7	80.5	4025.6	8.0	2.5	153	2.5	9842.4	4174.7	$258,585	79.7	$75.43
Lost Run	LR-3W	OLC 3W1	94.3	390.2	80.9	2431.7	8.0	2.0	153	2.0	4153.9	2161.5	$110,331	77.3	$67.92
Lost Run	LR-4W	OLC 4W1	128.9	390.2	110.6	1277.4	8.0	2.0	153	2.0	2182.1	1135.5	$57,958	49.5	$68.90
Lost Run	LR-MS	OLC MS1	13.3	183.3	5.4	57.5	8.0	2.0	153	2.0	98.2	51.1	$2,609	3.4	$64.54
Brush Fork	MSSP7E	OLC1	8.5	81.6	1.5	653.4	4.0	0.5	153	1.0	144.6	145.2	$4,051	1.5	$72.64
Monkey	FRT-3	OLC1	0.9	170.0	0.3	40.1	4.0	1.0	153	1.0	17.1	11.9	$464	0.3	$69.75
Salem Hollow	87+89	OLC1	86.2	357.0	67.7	1102.2	16.0	2.0	153	2.0	2673.0	1959.4	$72,703	67.3	$49.12
Snake Hollow	ATC-03	OLC1	2.1	75.5	0.4	101.2	4.0	0.5	153	1.0	22.4	22.5	$627	0.3	$72.88
Dixie Hollow	DIX-14	OLC1	50.0	220.0	24.2	586.8	8.0	2.0	153	2.0	1002.4	521.6	$26,624	24.0	$65.22
Long Hollow	LON-93	OLC1	268.0	89.0	52.5	214.5	4.0	0.5	153	1.0	47.5	47.7	$1,330	2.4	$70.72
Brush Fork	BR-32A	OLC10	163.0	384.0	137.7	155.6	6.0	1.5	153	1.5	149.6	86.5	$3,998	15.0	$66.59
Monkey	FRT-5	OLC10	29.4	90.5	5.9	384.7	8.0	1.5	153	1.5	421.4	285.0	$11,389	5.8	$57.98
Snake Hollow	SNA-61	OLC10	163.0	92.5	33.2	492.9	6.0	1.5	153	1.5	473.6	273.8	$12,662	8.4	$68.68
Brush Fork	MS7C	OLC11	288.1	90.1	57.1	132.5	6.0	1.5	153	1.5	127.3	73.6	$3,403	3.2	$66.68
Monkey	FRT-1	OLC11	35.9	39.3	3.1	382.3	8.0	1.5	153	1.5	418.7	283.2	$11,318	3.0	$58.72
Brush Fork	BR-MS7	OLC12	172.8	83.5	31.7	141.2	5.0	1.5	153	1.5	126.2	65.4	$3,352	2.6	$72.92
Brush Fork	BR-21	OLC13	8.5	164.0	3.1	110.7	5.0	1.5	153	1.5	99.0	51.3	$2,628	1.4	$76.04
Brush Fork	BR-20	OLC14	98.7	251.0	54.5	152.4	5.0	1.5	153	1.5	136.2	70.5	$3,616	7.7	$78.41
Brush Fork	MSSP1	OLC2	62.4	85.4	11.7	103.0	8.0	2.0	153	2.0	175.9	91.5	$4,671	3.1	$68.38
Monkey	FRT-4	OLC2	1.3	227.5	0.7	63.6	4.0	1.0	153	1.0	27.2	18.8	$736	0.7	$68.74
Snake Hollow	ATC-02	OLC2	62.4	94.7	13.0	42.7	5.0	1.5	153	1.5	38.2	19.8	$1,014	0.6	$74.89
Dixie Hollow	DIX-98	OLC2	61.0	205.0	27.5	706.5	8.0	2.0	153	2.0	1206.9	628.0	$32,056	27.3	$41.95
Long Hollow	LON-94	OLC2	114.9	71.0	17.9	22.1	8.0	2.0	153	2.0	37.7	19.6	$1,002	1.5	$66.25
Brush Fork	MSSP2	OLC3	118.9	140.5	36.7	162.8	8.0	2.0	153	2.0	278.0	144.7	$7,385	45.7	$80.84
Monkey	MNK-7A	OLC3	2.6	304.5	1.7	129.4	4.0	1.0	153	1.0	55.3	38.3	$1,496	1.7	$66.53
Snake Hollow	SNA-64	OLC3	118.9	88.0	23.0	100.4	5.0	1.5	153	1.5	89.7	46.5	$2,382	1.4	$75.46
Long Hollow	LON-95	OLC3	242.4	26.0	13.9	290.1	8.0	1.5	153	1.5	317.7	214.9	$8,588	5.8	$43.20
Brush Fork	BR-5E50	OLC4	7.1	141.0	2.2	141.0	5.0	1.5	153	1.5	126.0	65.3	$3,345	1.1	$75.02
Monkey	FRT-2	OLC4	2.2	137.0	0.7	76.9	5.0	1.0	153	1.0	36.3	28.5	$992	0.7	$61.78
Snake Hollow	ATC-04	OLC4	7.1	62.6	1.0	91.0	5.0	1.5	153	1.5	81.3	42.1	$2,159	1.0	$76.00
Long Hollow	S-27	OLC4	695.7	26.0	39.8	126.7	5.0	1.5	153	1.5	113.2	58.6	$3,006	1.5	$75.77
Brush Fork	MSSP3	OLC5	358.5	210.4	165.9	162.1	6.0	1.5	153	1.5	155.8	90.1	$4,164	11.9	$49.85
Monkey	MNK-8	OLC5	6.0	232.6	3.1	188.9	6.0	1.0	153	1.0	97.6	84.0	$2,692	3.0	$55.44
Snake Hollow	SNA-62	OLC5	358.5	115.5	91.1	258.9	6.0	1.5	153	1.5	248.8	143.9	$6,652	5.2	$67.77
Brush Fork	BR-6WB	OLC6	39.9	148.0	13.0	167.4	5.0	1.5	153	1.5	149.6	77.5	$3,973	3.9	$73.63

Subwatershed	Site	Treatment Unit	Q, gpm	Total Acidity, mg/L	Acid Load, tpy	L, ft	W, ft	H, ft	A, deg	F, Ft	Limestone, tons	Excavation, yd^3	Estimated Cost	Acid Load Removed, tpy	Treatment Efficiency, $/ton
Monkey	FRT-5A	OLC6	7.6	100.0	1.7	203.9	6.0	1.0	153	1.0	105.3	90.6	$2,905	1.7	$56.58
Snake Hollow	ATC-01	OLC6	39.9	227.7	20.0	405.6	6.0	1.5	153	1.5	389.7	225.3	$10,419	13.4	$64.75
Brush Fork	BR-6WC	OLC7	35.9	132.0	10.4	131.4	5.0	1.5	153	1.5	117.4	60.8	$3,118	2.8	$73.35
Monkey	MNK-1	OLC7	9.8	169.0	3.7	195.3	6.0	1.5	153	1.5	187.6	108.5	$5,016	3.6	$69.19
Snake Hollow	SNA-63	OLC7	35.9	115.5	9.1	394.7	6.0	1.5	153	1.5	379.2	219.3	$10,139	7.9	$67.77
Brush Fork	MSSP5	OLC8	150.9	206.9	68.7	150.0	6.0	1.5	153	1.5	144.1	83.3	$3,853	1.6	$345.13
Monkey	MNK-11	OLC8	18.9	246.5	10.3	806.9	6.0	1.5	153	1.5	775.3	448.3	$20,728	10.2	$67.77
Snake Hollow	SNA-60	OLC8	150.9	430.5	143.0	852.9	12.0	1.5	153	1.5	1163.6	947.7	$31,932	34.2	$49.08
Brush Fork	BR-4W	OLC9	9.8	228.0	4.9	143.4	5.0	0.5	153	1.0	34.9	39.8	$993	1.6	$69.17
Monkey	MNK-13	OLC9	21.1	128.1	5.9	806.9	8.0	1.5	153	1.5	883.8	597.7	$23,888	5.9	$156.54
Snake Hollow	ATC-07	OLC9	9.8	97.5	2.1	644.4	6.0	1.0	153	1.0	333.0	286.4	$9,183	7.6	$55.05
Jobs Hollow	JOB-7	OLC7	27.3	35.3	2.1	1200.0	4.0	3.0	153	1.0	1851.1	711.1	$48,411	2.1	$79.50

Table 10. Monday Creek Slag Leach Bed Designs (SLB).

Subwatershed	Site	Treatment Unit	Q, gpm	Total Acidity, mg/L	Acid Load, tpy	L, ft	W, ft	H, ft	Excavation, yd^3	Steel Slag, tons	Estimated Cost	Acid Load Removed, tpy	Treatment Efficiency, $/ton
Whitmore C.	WC	SLB	120.0	0.0	0.0	204.4	204.4	4.0	7738.2	12566.9	$337,387	132.0	$411.59
Spencer H.	SPN	SLB	50.0	42.0	4.6	132.0	132.0	4.0	3224.3	5236.2	$130,905	55.0	$383.27
Lost Run	LR-1E	SLB-1E1	530.4	17.5	20.4	118.0	118.0	4.0	2578.5	4187.5	$112,423	55.0	$157.24
Lost Run	LR-3E	SLB-3E1	227.6	160.7	80.5	74.6	74.6	4.0	1031.8	1675.6	$44,985	22.0	$157.29
Coe Hollow	SOUTH-TRIB	SLB-1	4.3	0.0	0.0	25.0	20.0	4.0	92.6	150.4	$4,037	4.8	$136.27
Coe Hollow	UP-MAIN	SLB-2	20.8	0.0	0.0	25.0	20.0	4.0	92.6	150.4	$4,037	22.9	$28.39
Brush Fork	BR-TOP	SLB1	47.1	8.9	0.9	128.1	128.1	4.0	3039.0	4935.3	$132,500	51.8	$411.59
Monkey Hollow	FRT-6	SLB1	100.0	27.3	6.0	186.6	186.6	4.0	6448.5	10472.4	$281,156	110.0	$411.59
Dixie Hollow	DIX-4	SLB1	20.0	0.0	0.0	46.0	46.0	4.0	391.9	636.4	$15,909	22.0	$116.45
Long Hollow	LON-4	SLB1	100.0	-500.0	-110.0	102.0	102.0	4.0	1926.7	3128.9	$78,223	110.0	$114.51
Brush Fork	SM-E-MSBS	SLB2	31.1	0.0	0.0	104.0	104.0	4.0	2002.3	3251.7	$87,299	34.2	$411.59
Brush Fork	BR-MSSP7E	SLB3	8.5	81.6	1.5	54.5	54.5	4.0	549.9	893.1	$23,976	9.4	$411.59
Jobs Hollow	JOB-US	SLBUS	27.3	4.6	0.3	97.5	97.5	4.0	1759.7	2850.8	$76,548	120.1	$40.10
Jobs Hollow	JOB-10	SLB10	75.9	12.8	2.1	162.5	162.5	4.0	4891.4	7924.0	$212,774	333.8	$40.10
Jobs Hollow	JOB-5	SLB5	27.3	5.8	0.4	97.5	97.5	4.0	1759.7	2850.8	$76,548	120.1	$40.10

Table 11. Monday Creek Aerobic Wetland Designs (WL).

Subwatershed	Site	Treatment Unit	Q, gpm	L, ft	W, ft	H, ft	Excavation, yd^3	Limestone, tons	Estimated Cost
Whitmore C.	WC	WL	120.0	210.0	210.0	4.0	6533.3	0.0	$19,600
Spencer H.	SPN	WL	50.0	120.0	120.0	4.0	2133.3	0.0	$6,400
Rock Run	MOUTH	WL	815.0	1740.0	660.0	1.0	42533.3	0.0	$127,600
Sycamore H.	RM-3.4	WL	782.4	1077.0	1077.0	3.0	128881.0	0.0	$386,643
Orbiston	302+304	WL 1	96.3	792.4	792.4	3.0	69765.1	0.0	$209,295
Coe Hollow	MAINSTEM	WL COE	99.9	60.0	15.0	4.0	133.3	161.3	$4,433
Monkey H.	FRT-6	WL1	100.0	104.4	104.4	3.0	1614.7	0.0	$4,844
Snake Hollow	US SNA-65	WL1	494.0	522.0	522.0	3.0	40368.0	0.0	$121,104

Table 12. Monday Creek Subsidence Closure Designs.

Subwatershed	Acid Load Removed, tpy	Capture Area, acres	Restored Stream Length, feet	Estimated Cost	Estimated Service Life, years	Treatment Efficiency, $/ton
Brush Fork	130.73	1,275.29	14,268	$624,653	30	$159.28
Coe Hollow	26.03	75.11	2,847	$124,642	30	$159.64
Lost Run	106.09	578.32	14,134	$618,787	30	$194.43
Monkey Hollow	35.87	319.70	4,551	$199,243	30	$185.16
Total	298.72	2,248.42	35,800	$1,567,325	30	$174.89