EVALUATING OPTIONS FOR LARGE-SCALE WATERSHED REMEDIATION[1]

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Abstract: Monday Creek of the Hocking River has a 300 km^2 drainage basin in southeastern Ohio, and since the middle of the 19th century, extensive portions of the watershed have been subjected to underground and surface coal mining. A recent survey of the watershed has identified over 4,300 point sources of acid mine drainage which have rendered a number of stream reaches within the watershed sterile and unable to support diverse, aquatic life. In 2003, Dr. Stiles developed a model of those aspects of water quality related to Acid Mine Drainage (AMD) for the watershed using the TAMDL computer program developed at West Virginia University. The computer program TAMDL was designed to model stream water quality in watersheds affected by AMD and its treatment by simulating the evolution of stream pH, net acidity, and the concentrations of aluminum, iron, and manganese. The Monday Creek TAMDL model was then employed by the authors to develop a cost effective strategy for the treatment of AMD in the watershed. Since the close of this project, several passive and active treatment systems have been installed in the Monday Creek watershed. The objective of this new project was to recalibrate the TAMDL model created in 2003 for the new conditions in the watershed and use this recalibrated model to design a revised cost effective treatment strategy to bring the water quality conditions from their current level up to the remediation target conditions. The remediation target conditions for the Monday Creek watershed were those minimum and maximum pH levels and maximum aluminum and iron concentrations that would allow aquatic life to be reestablished in the main stem.

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Introduction

In 2003, the West Virginia Water Research Institute at West Virginia University designed an Acid Mine Drainage (AMD) treatment strategy for the Monday Creek, Ohio watershed using the Total Acid Mine Drainage Loading computer program (TAMDL). 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 main stem were used to calculate the level of treatment required in each Monday Creek sub-watershed affected by AMD. The level of required AMD treatment was employed to design passive and active AMD treatment systems for each affected sub-watershed (Ziemkiewicz, Stiles, and Kessinger, 2004).

Since the completion of the original Monday Creek project (Stiles and Ziemkiewicz, 2003) and (Ziemkiewicz, Stiles, and Kessinger, 2004), some active and passive AMD treatment systems have been constructed in the Monday Creek watershed. Some of these treatment systems were constructed to the specifications outlined in the final report of the earlier project. Other constructed systems were designed using water quality data collected since the completion of the earlier project.

Objectives

The objectives of the current research were to:

1. Recalibrate the Monday Creek TAMDL model with the constructed AMD treatment systems and the additional water quality data collected since the previous project.
2. Use the recalibrated TAMDL model to design two treatment scenarios for the watershed to achieve the treatment goals outlined by the previous project (Ziemkiewicz, Stiles, and Kessinger, 2004).
3. Recommend one of the two treatment scenarios based upon cost.

Methodology

TAMDL

The Total Acid Mine Drainage Loading computer program (TAMDL) was designed to simulate the evolution of stream water quality in watersheds affected by AMD and its treatment. TAMDL solves the following partial differential equation for the one-dimensional transport of a water quality constituent in a stream for each of the simulated constituents, except for proton activity (Ziemkiewicz, Stiles, and Kessinger, 2004).

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

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.

Equation (1) is solved for each sub-watershed in the model for all of the simulated water quality constituents except for proton activity. Proton activity is calculated from the net acidity, total acidity minus total alkalinity, using a net acidity-pH constitutive relationship.

AMD Treatment

Table 1 contains a list of the installed AMD treatment systems in the Monday Creek watershed. The doser for the Essex mine discharge in Sycamore Hollow was removed in July 2009, the Steel slag Leach Bed (SLB) downstream of the Shawnee Wastewater Treatment Plant was turned off in December 2008, and the Rock Run OLC was removed from service in June 2007, so a column in Table 1 entitled ‘off-line’ was added to indicate the date that those systems were intentionally withdrawn from service. The locations of the sub-watersheds listed in Table 1 are shown in Fig. 1.

Pebble quicklime dosers operate from on-site hydraulic power and add a fixed amount of calcium oxide to each volume of water that passes through the system. Therefore, the calcium oxide dosage rate can be expressed in with units of concentration, mg/L of CaO. Aquafix is a manufacturer of pebble quicklime dosers that have been used extensively in West Virginia and

Ohio (Skousen and Jenkins, 1993). Adding 0.56 kg of CaO to the stream adds an amount of alkalinity equivalent to 1.0 kg of $CaCO_3$ (Skousen, Hilton, and Faulkner, 1996).

Table 1. Summary of existing AMD treatment systems in the Monday Creek watershed. The data for these projects came from the Monday Creek Restoration Project (Schlater, 2009).

Sub-water.	Location	Type	Operation Timeline	Alk. Produced, kg/day $CaCO_3$ eq.
Big-4	BIG-440	LLB/OLC	09/01/2004 – present	16.6
Big-4	BIG-44	LLB/OLC	09/01/2004 – present	29.8
Big-4	BIG-49	OLC	09/01/2004 – present	92.9
Big-4	BIG-43B	OLC	09/01/2004 – present	3.58
Lost Run	LR-1W1	LLB/OLC	11/01/2006 – present	10.7
Lost Run	LR-1W2	LLB/OLC	11/01/2006 – present	7.08
Lost Run	LR-1W3	LLB/OLC	11/01/2006 – present	3.45
Lost Run	LR-1W5	LLB/OLC	11/01/2006 – present	18.2
Lost Run	LR-1W8	LLB/OLC	11/01/2006 – present	1.94
Lost Run	LR-1E	SLB	12/01/2007 – present	645.
Lost Run	4W3-4-5	SLB	12/01/2007 – present	199.
Sycamore	Essex	Doser	03/01/2006 – 07/01/2009	590.
Snake H.	ATC-07	LLB/OLC/SSB	01/01/2005 – present	5.17
Snake H.	ATC-01	OLC	01/01/2005 – present	-3.01
Snake H.	SNA-60	OLC	01/01/2005 – present	116.
Shawnee	WWTP	SLB	10/17/2008 – 12/01/2008	59.3
Jobs H.	JOB-13	Doser	07/01/2004 – present	292.
Jobs H.	JOB-4.2	LKD/OLC	08/01/2004 – present	30.9
Jobs H.	JOB-4.4	LKD/OLC	10/01/2004 – present	11.8
Rock Run	RR-24	OLC	10/01/2001 – present	0.00
Rock Run	RR-Upper Pipe	OLC	10/01/2001 – 06/01/2007	82.1

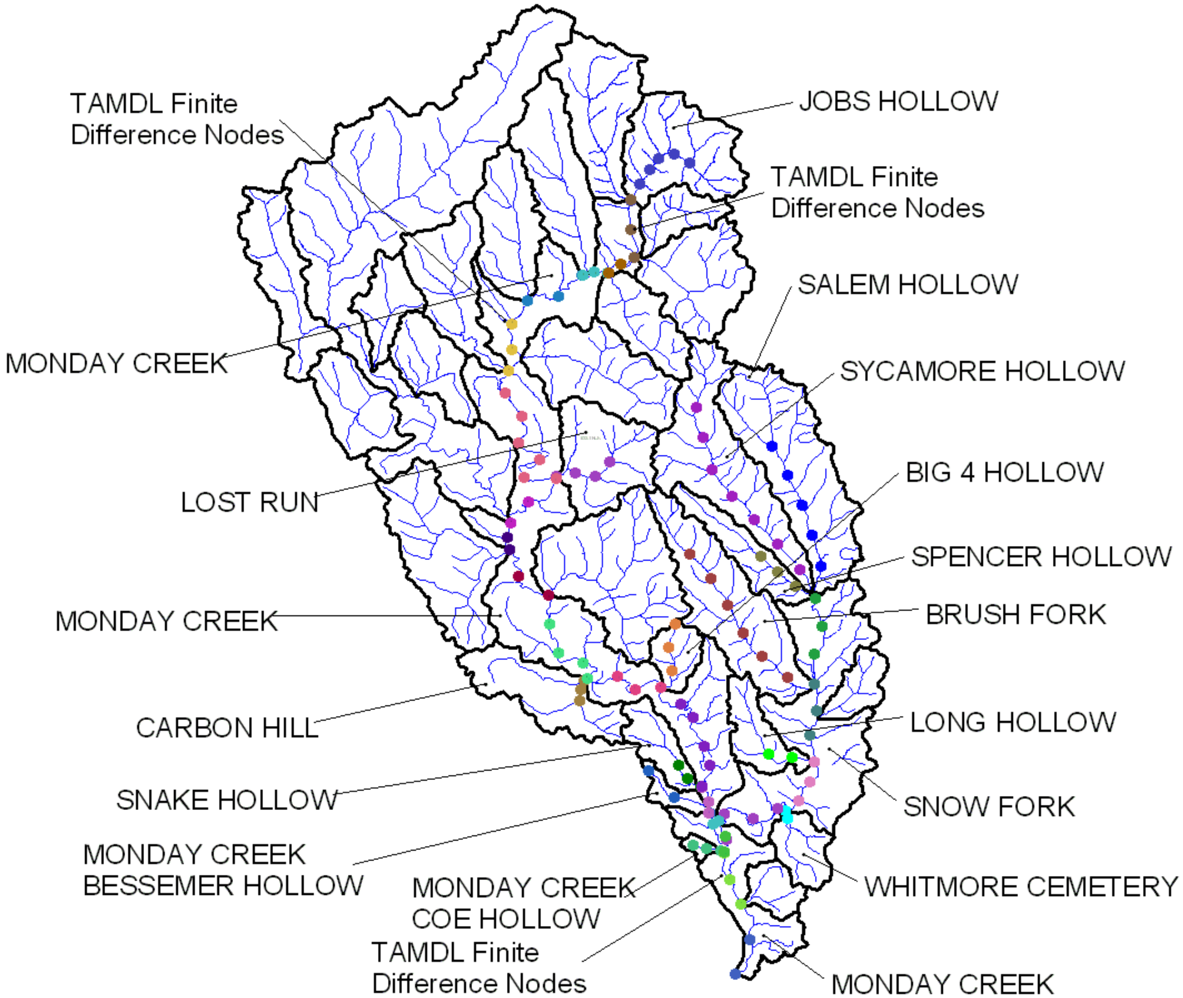

Figure 1. Map of the Monday Creek watershed and computational domain of the TAMDL model.

Open limestone channels (OLC) and limestone leach beds (LLB) operate by neutralizing a portion of the acidity in the water that flows through them. The examination of observed water quality data from samples collected by the Monday Creek Restoration Project (Schlater, 2009) upstream and downstream of constructed OLC and LLB systems in the watershed indicated that the median treatment factor was 68%. The OLC at ATC-01 in Snake Hollow was not working properly and the site actually produced more acidity after construction than before construction.

Model Calibration

Model calibration was accomplished by comparing the model results at water quality sample collection sites against the observed data collected and supplied by the Monday Creek Restoration Project (Schlater, 2009) and making adjustments to AMD loading rates from various sub-watersheds.

In order to have a simulation period during the period when the major AMD treatment systems were operation, it was decided to set up the calibration simulations to run from July 1, 2004 to August 30, 2009. While this simulation duration resulted in long run times, this simulation period allowed the investigators to include the majority of post-treatment water quality data into the calibration process.

Of the currently operating AMD treatment systems, the most important is the Jobs Hollow doser. According to the Monday Creek Restoration Project (Schlater, 2009), this doser is treating the discharge from the JOBS-13 mine seep with between 181 and 340 kg/day of pebble quicklime (CaO). Examination of the water quality data from samples collected immediately downstream of the doser indicated that the mean CaO being added per volume of water passing through the doser was 83.21 mg/L.

Figure 2 is a plot of the simulated and observed net acidity at the Monday Creek main stem station MC-127. Station MC-127 is 32.7 km upstream of the mouth of Monday Creek. While other stations were also employed in evaluating the calibration of the model, for space considerations, this paper will only show the results of the calibration model at station MC-127.

During the simulation period, the model demonstrated good calibration for net acidity at station MC-127. The maximum simulated net acidity levels were approximately 10 mg/L $CaCO_3$ equivalents higher than the maximum observed net acidity levels, and the minimum simulated net acidity levels were approximately 15 mg/L $CaCO_3$ equivalents lower than the minimum observed levels.

Figure 3 is a plot of the simulated and observed pH at the Monday Creek main stem station MC-127. While the maximum simulated and observed pH levels are close, the minimum simulated pH levels are approximately 1.5 standard units below the observed pH levels. This discrepancy in the apparent calibration of the TAMDL model's simulation of pH suggests that there may be problems with the observed pH data collected in the Monday Creek watershed.

Figure 4 is a plot of the simulated and observed Al concentrations at Monday Creek main stem stations MC-127. The simulated Al concentrations were approximately 0.5 mg/L less than the observed concentrations. While total dissolved concentrations work better when calibrating a TAMDL model, total Al concentration data was employed in the calibration of the model at the request of the Monday Creek Restoration Project.

Figure 5 is a plot of the simulated and observed iron concentrations at Monday Creek main stem stations MC-127. The maximum simulated Fe concentrations were approximately 0.5 mg/L less than the observed concentrations. The minimum simulated Fe concentrations were approximately 0.75 mg/L less than the observed concentrations. As with aluminum, total iron concentration data was employed in the calibration of the TAMDL model at the request of the Monday Creek Restoration Project. The samples with very high Fe concentrations that were collected near the start of the simulation probably included some sediment material in the water sample.

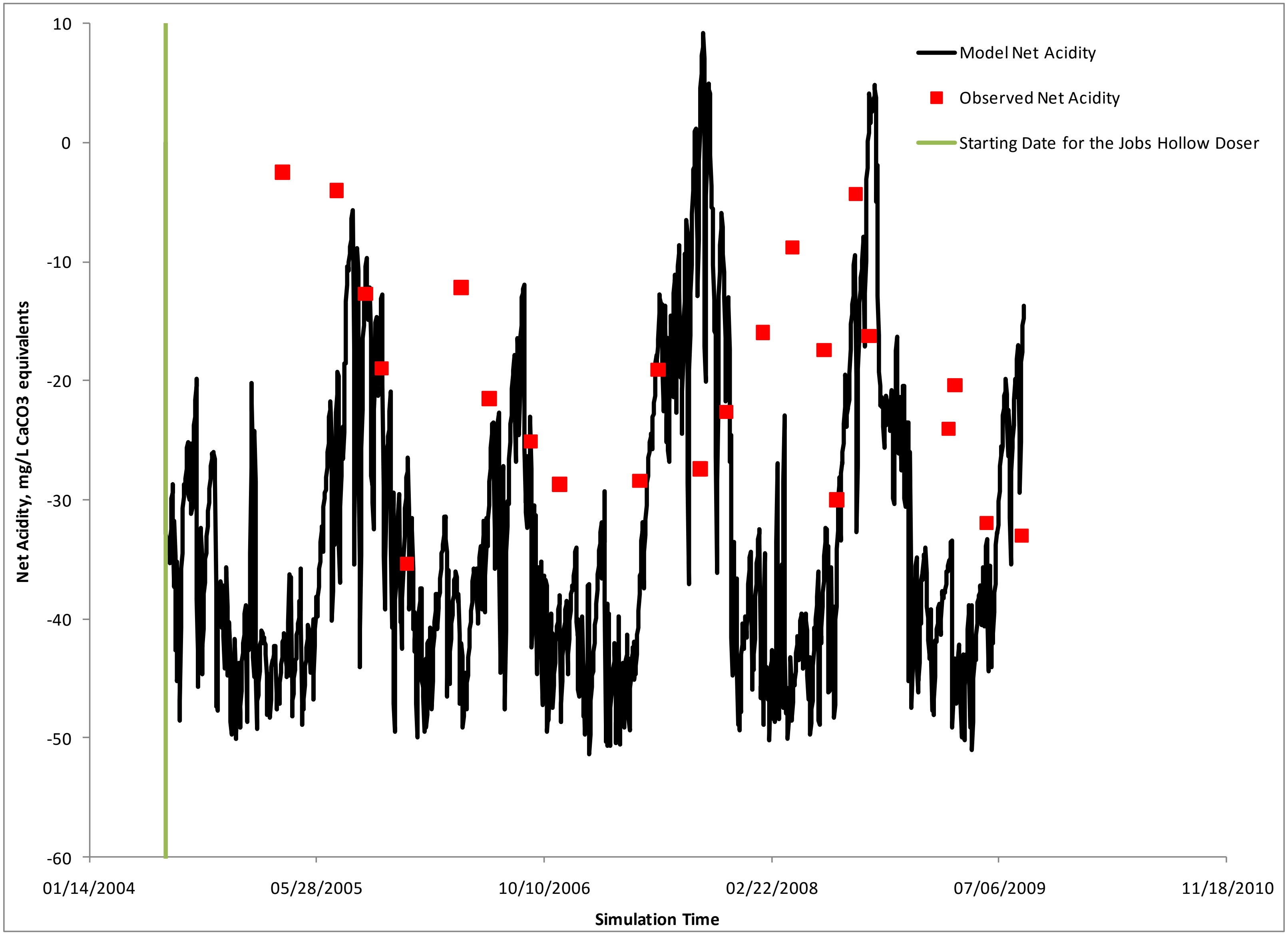

Figure 2. Simulated and observed net acidity at MC-127 from the calibrated Monday Creek model.

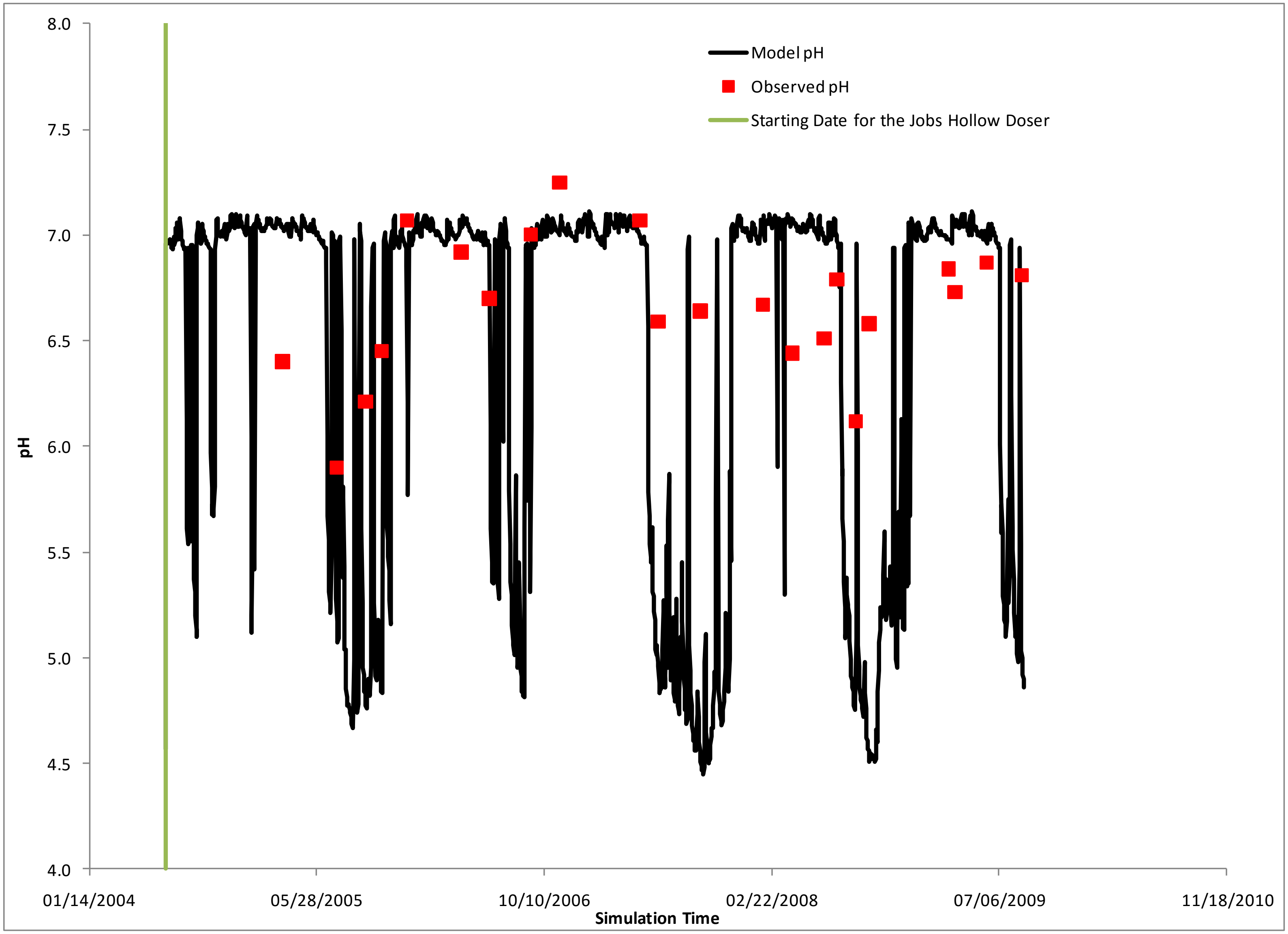

Figure 3. Simulated and observed pH at MC-127 from the calibrated Monday Creek model.

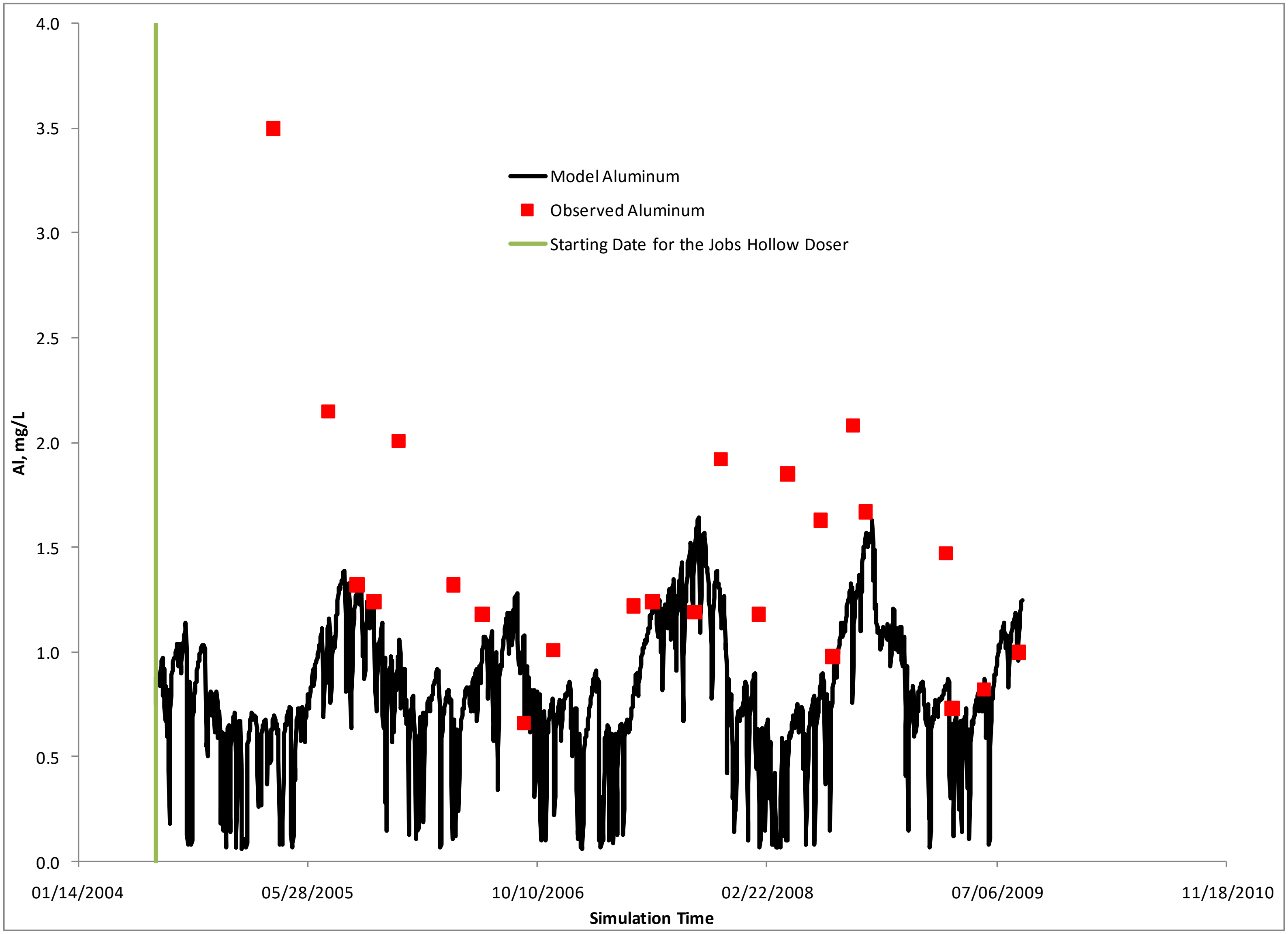

Figure 4. Simulated and observed aluminum at MC-127 from the calibrated Monday Creek model.

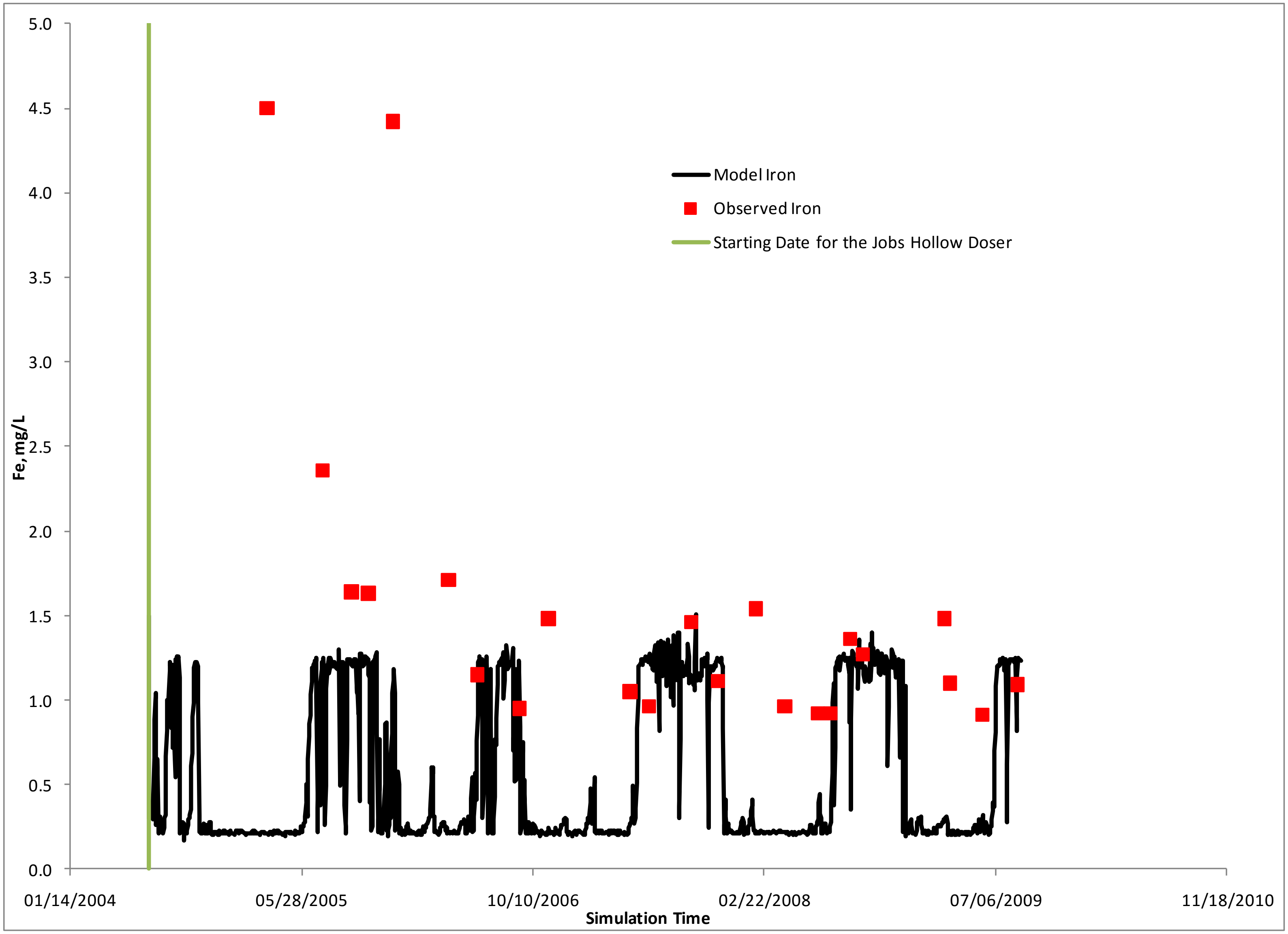

Figure 5. Simulated and observed iron at MC-127 from the calibrated Monday Creek model.

The quality of the calibration was judged by comparing the results of the model with the observed data. The correlation coefficient (R^2) between the observed and calculated stream net acidity, pH, aluminum, and iron are listed in Table 2.

Table 2. Correlation Coefficients (R^2) between observed and simulated constituents.

Constituent	R^2
Net Acidity	0.81
pH	0.49
Aluminum	0.82
Iron	0.68

Inspection of the observed data set during the calibration process resulted in the observation of several pH readings above 8.0 where the observed net acidity indicated near neutral conditions. These data points were removed from the calibration data set, but the investigators have serious doubts about the quality of the remaining pH data. Discussions with ODNR have indicated that there are probably quality control problems with the field and laboratory pH data obtained from sampled collected in the watershed (Borch, 2010).

The correlation coefficient for Al compared well with the coefficient observed with the TAMDL model constructed for the 2003 project. Aluminum concentrations are strongly dependent upon pH levels, so the relatively high correlation between model and observed Al concentrations suggests that the modeling and sampling problems with pH did not strongly affect the rest of the model.

The correlation coefficient for iron was less than the coefficient observed with the TAMDL model constructed for the 2003 project. Iron concentrations are strongly dependent upon the hydraulics of the stream segment being simulated. The low correlation coefficient for Fe suggests that the assumptions made in the TAMDL model about the hydraulics and hydrology of the Monday Creek watershed may have introduced significant error into the results of the model.

While no model can ever be said to be completely calibrated, the results shown in this report indicated that the model was adequately calibrated to be permit the formulation of AMD treatment strategies for the Monday Creek watershed.

Development of AMD Treatment Strategies

Treatment Goals. Table 3 lists the treatment goals for the Monday Creek main stem that were determined by the Ohio Department of Natural Resources (ODNR) (Stiles and Ziemkiewicz, 2003). To achieve the treatment goals for the watershed, the 5^{th} percentile of pH in the main stem should be greater than 6.75, the 95^{th} percentile of the aluminum concentrations should be less than 0.72 mg/L, and the 95^{th} percentile of the Fe concentrations should be less than 1.09 mg/L. The remediation endpoints were applied to that portion of the main stem below river km 31.4.

Table 3. Remediation Endpoints (RE) and Margins of Safety (MS) for the Remediation Simulation Models.

Constituent	RE	MS	RE + MS
pH	6.50 su	+0.25 su	6.75 su
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 is a plot of the 5^{th} percentile of simulated pH for the Monday Creek main stem after the activation of the Jobs Hollow doser. Figure 7 is a plot of the 95^{th} percentile of the simulated aluminum for the Monday Creek main stem after the activation of the doser. Figure 8 is a plot of the 95^{th} percentile of the simulated iron for the main stem after the activation of the doser. Figure 9 is a plot of the compliance of the simulated pH, Al, and Fe with the remediation endpoint levels. Only the main stem between river km 5.6 and river km 22.9 satisfied the treatment goal for pH. The entire main stem satisfied the treatment goal for Fe. None of the main stem satisfied the treatment goal for Al.

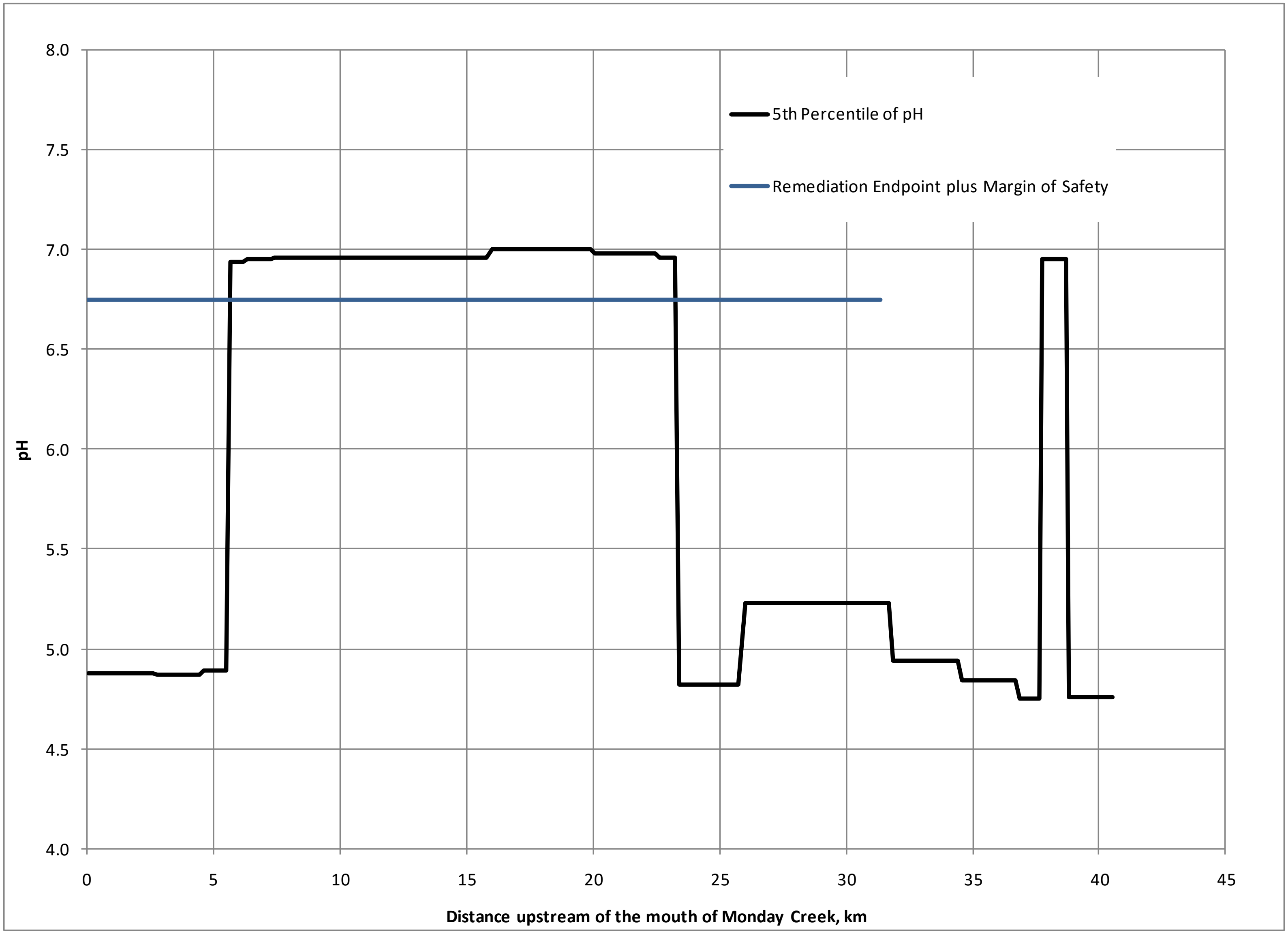

Figure 6. Plot of the 5th percentile of simulated pH for the Monday Creek main stem after the activation of the Jobs Hollow doser.

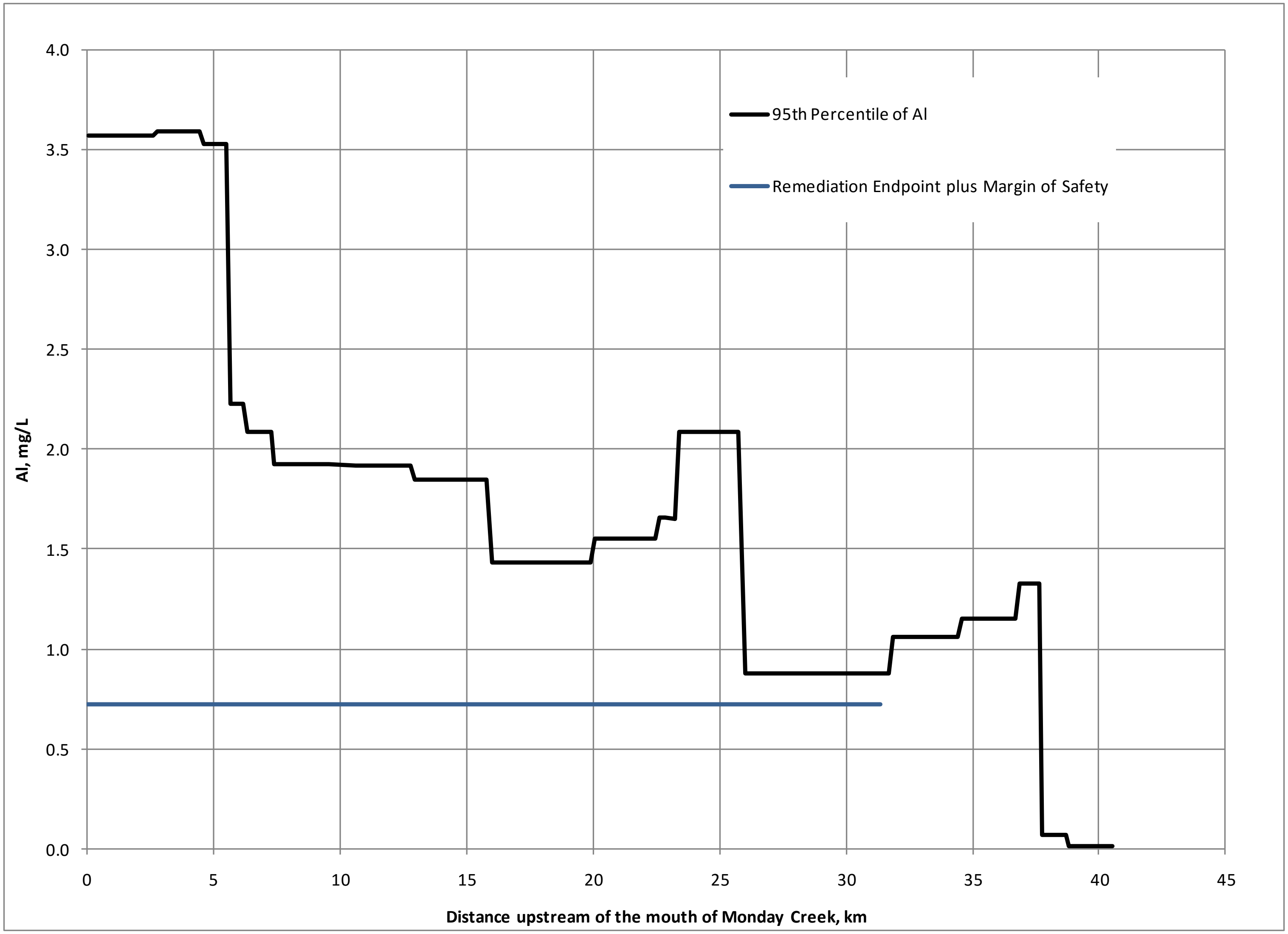

Figure 7. Plot of the 95th percentile of the simulated aluminum for the Monday Creek main stem after the activation of the Jobs Hollow doser.

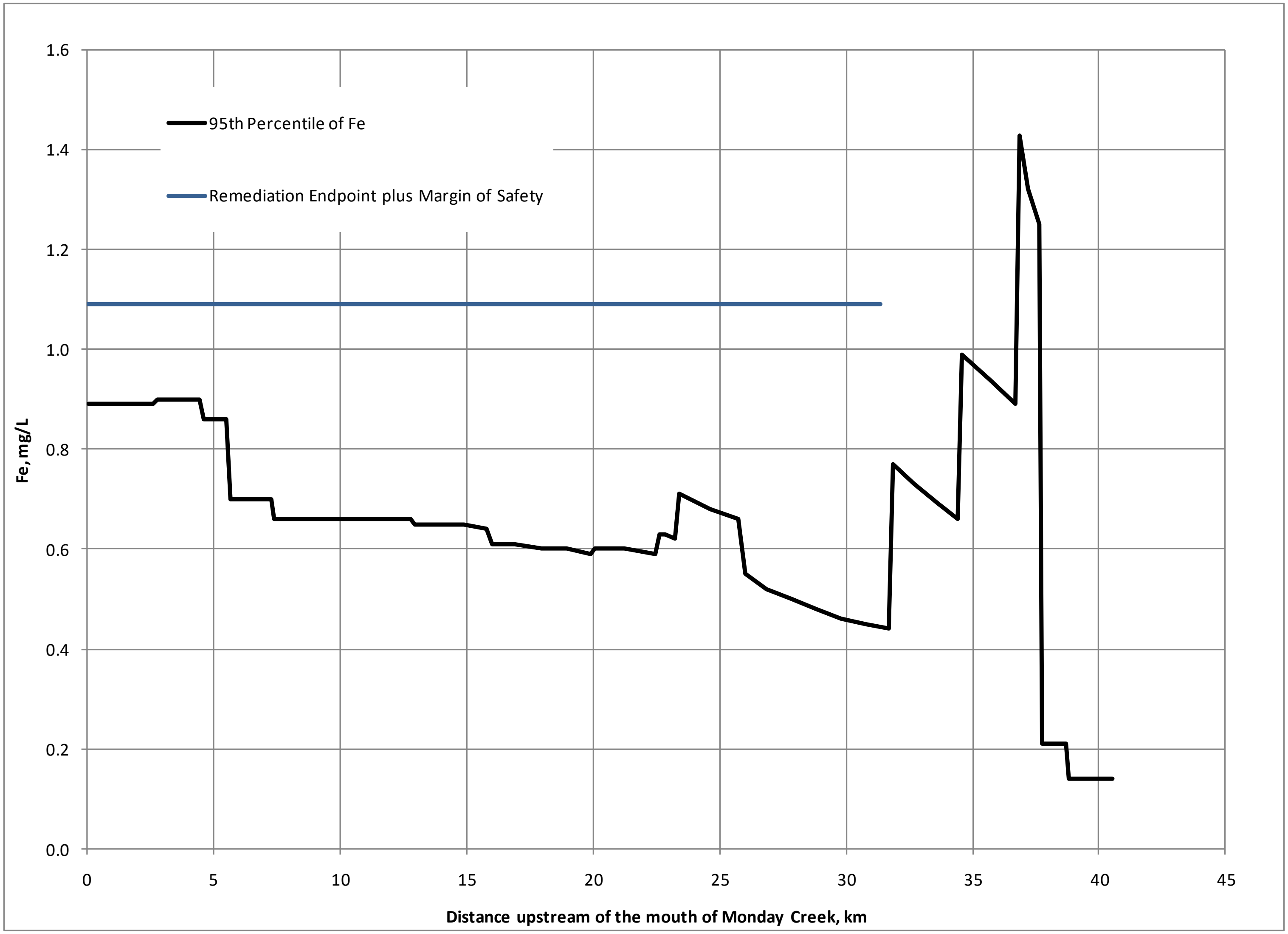

Figure 8. Plot of the 95th percentile of the simulated iron for the Monday Creek main stem after the activation of the Jobs Hollow doser.

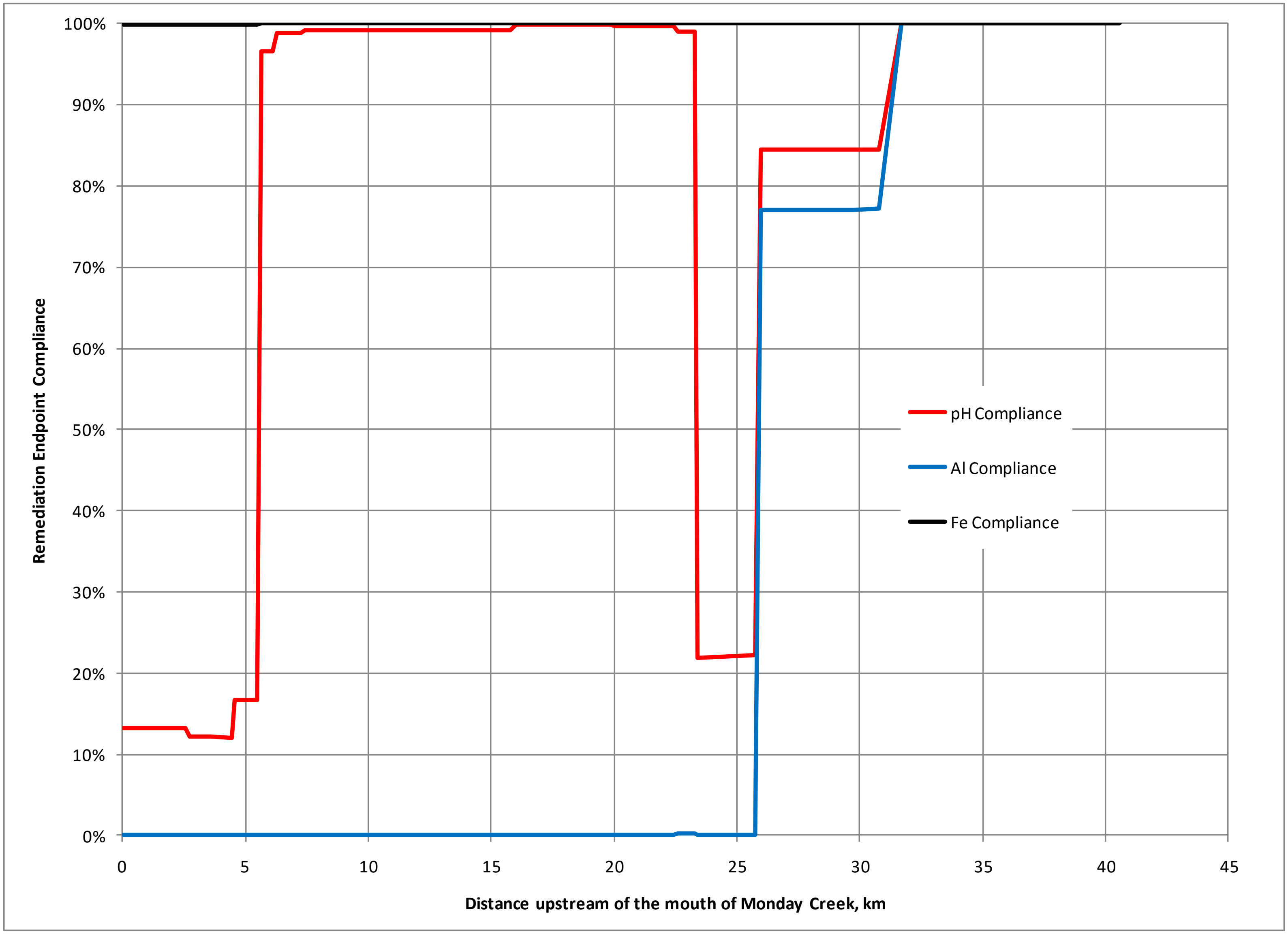

Figure 9. Plot of the compliance of the simulated pH, aluminum, and iron from the calibration model with the remediation endpoints.

Table 4 is a list of the mean loading rates for net acidity, iron, and aluminum for the Monday Creek sub-watersheds simulated by the Monday Creek TAMDL model. Salem Hollow, Sycamore Hollow, Spencer Hollow, Brush Fork, Long Hollow, and Whitmore Cemetery are tributaries of Snow Fork, which discharges into Monday Creek.

Table 4. Mean net acidity, iron, and aluminum loads from Monday Creek sub-watersheds.

Sub-watershed	Mean Net Acid Load, kg/day $CaCO_3$ eq.*	Mean Iron Load, kg/day	Mean Aluminum Load, kg/day
Jobs Hollow	25.71	30.24	30.16
Dixie Hollow	194.41	4.20	30.86
Shawnee Creek	-743.56	3.39	2.00
Ironpoint Cemetery	-299.30	1.37	0.81
Rock Run	267.25	38.61	24.53
Stone Church	-278.57	4.29	1.79
Salt Run	-328.59	3.69	1.48
Dans Run	-493.89	4.87	1.98
New Straitsville	-330.37	3.89	2.05
Lost Run	1071.73	43.65	146.97
Little Monday Creek	-4678.78	26.80	9.54
Kitchen Run	-836.81	6.86	2.45
Sand Run	-1041.22	16.70	3.04
Monkey Hollow	653.19	18.01	80.63
Big-4 Hollow	333.50	5.50	35.08
Snake Hollow	513.04	11.80	40.42
Bessemer Hollow	176.68	3.00	21.47
Snow Fork	3591.67	103.73	418.70
Coe Hollow	190.31	14.45	21.78
Happy Hollow	-161.34	2.59	0.47
Salem Hollow	134.19	17.72	9.35
Sycamore Hollow	690.81	21.11	51.74
Spencer Hollow	207.47	2.12	58.05
Brush Fork	1621.94	36.40	182.65
Long Hollow	223.20	6.07	31.06
Whitmore Cemetery	-18.30	4.08	0.73

*Negative loads indicate a net alkaline load from the sub-watershed.

Treatment Alternatives. Treatment alternatives consist of passive or active treatment systems placed within the various Monday Creek sub-watersheds with the objective of meeting the treatment goals for the Monday Creek main stem. The only active treatment system employed in the treatment alternatives investigated by this project was pebble quicklime dosing, and the only passive treatment systems employed in the investigated treatment alternatives were Open Limestone Channels (OLC), Limestone Leach Beds (LLB), and Slag Leach Beds (SLB). Treatment alternatives with these only types of systems were investigated by this project because these systems have been successfully employed in the Monday Creek watershed.

Treatment Alternative 1: Pebble Quicklime Dosing. This treatment alternative consists of adding dosers to the Brush Fork, Salem Hollow, Spencer Hollow, Sycamore Hollow, Dixie Hollow, Rock Run, Lost Run, and Monkey Hollow sub-watersheds. The design parameters for these dosers are listed in Table 5. With the except of the doser in the Lost Run sub-watershed, all of these dosers are to be operated at the same CaO dosage rate as the current Jobs Hollow doser is being operated. The CaO dosage rate for the Lost Run doser will need to be 100.8 mg/L. The dosage rates and doser locations were selected to meet the treatment goals with the lowest capital and O&M cost.

Table 5. Design parameters for the pebble quicklime dosers of Treatment Alterative 1.

Sub-watershed	Required Alkalinity, mg/L $CaCO_3$ equiv.	CaO Dosage Rate, mg/L
Jobs Hollow	148.59	83.21
Brush Fork	148.59	83.21
Salem Hollow	148.59	83.21
Spencer Hollow	148.59	83.21
Sycamore Hollow	148.59	83.21
Dixie Hollow	148.59	83.21
Rock Run	148.59	83.21
Lost Run	180.00	100.8
Monkey Hollow	148.59	83.21

Figure 10 is a plot of the 5th percentile of the simulated stream pH for the Monday Creek main stem with this treatment alternative, and Fig. 11 and 12 are plots of the 95th percentile of the simulated main stem Al and Fe, respectively. Figure 13 is a compliance plot for this treatment alternative. As indicated by these plots, the main stem Al concentration was the limiting factor in determining the treatment loads from the dosers.

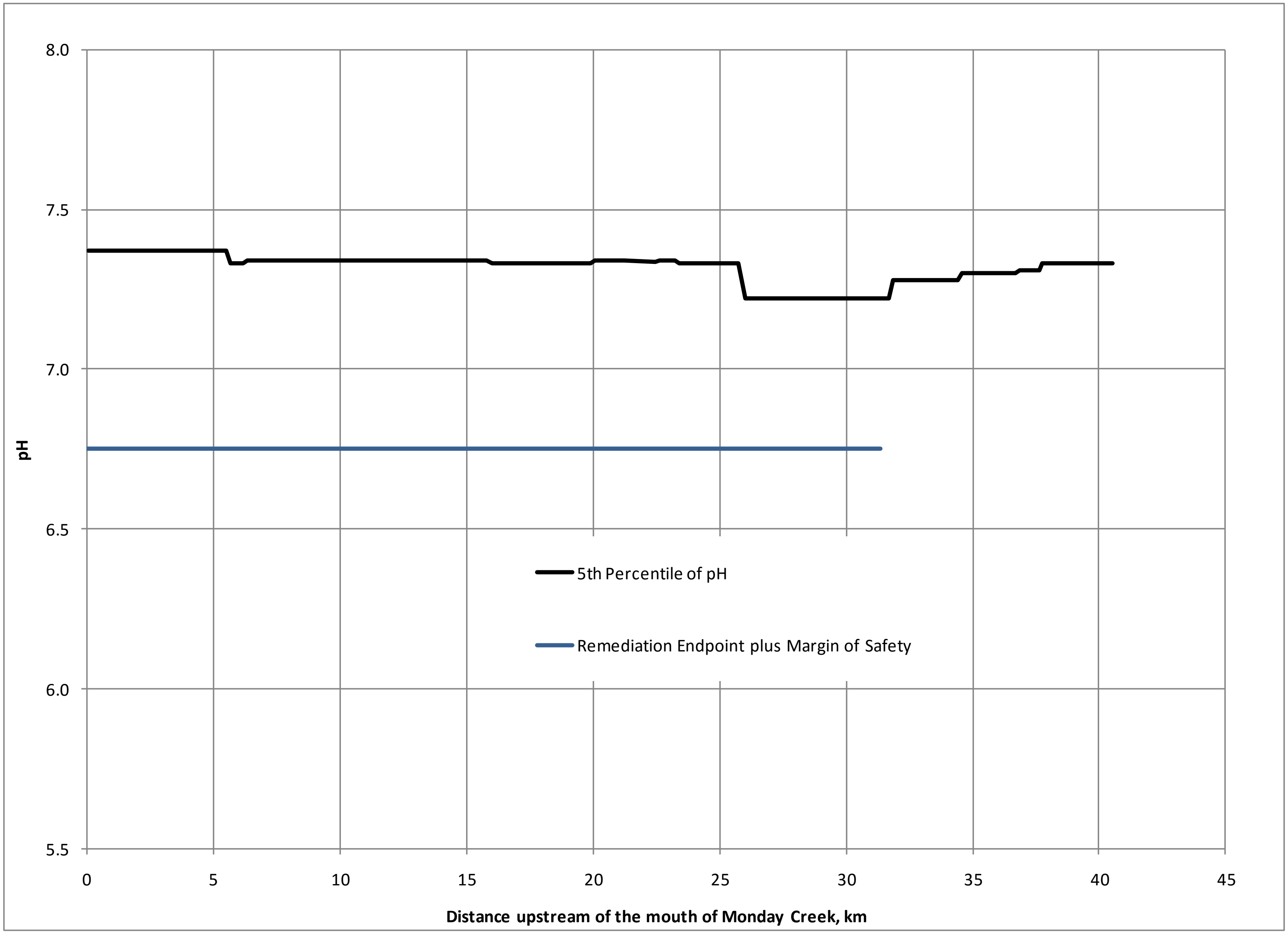

Figure 10. Plot of the 5th percentile of the simulated main stem pH with Treatment Alternative 1.

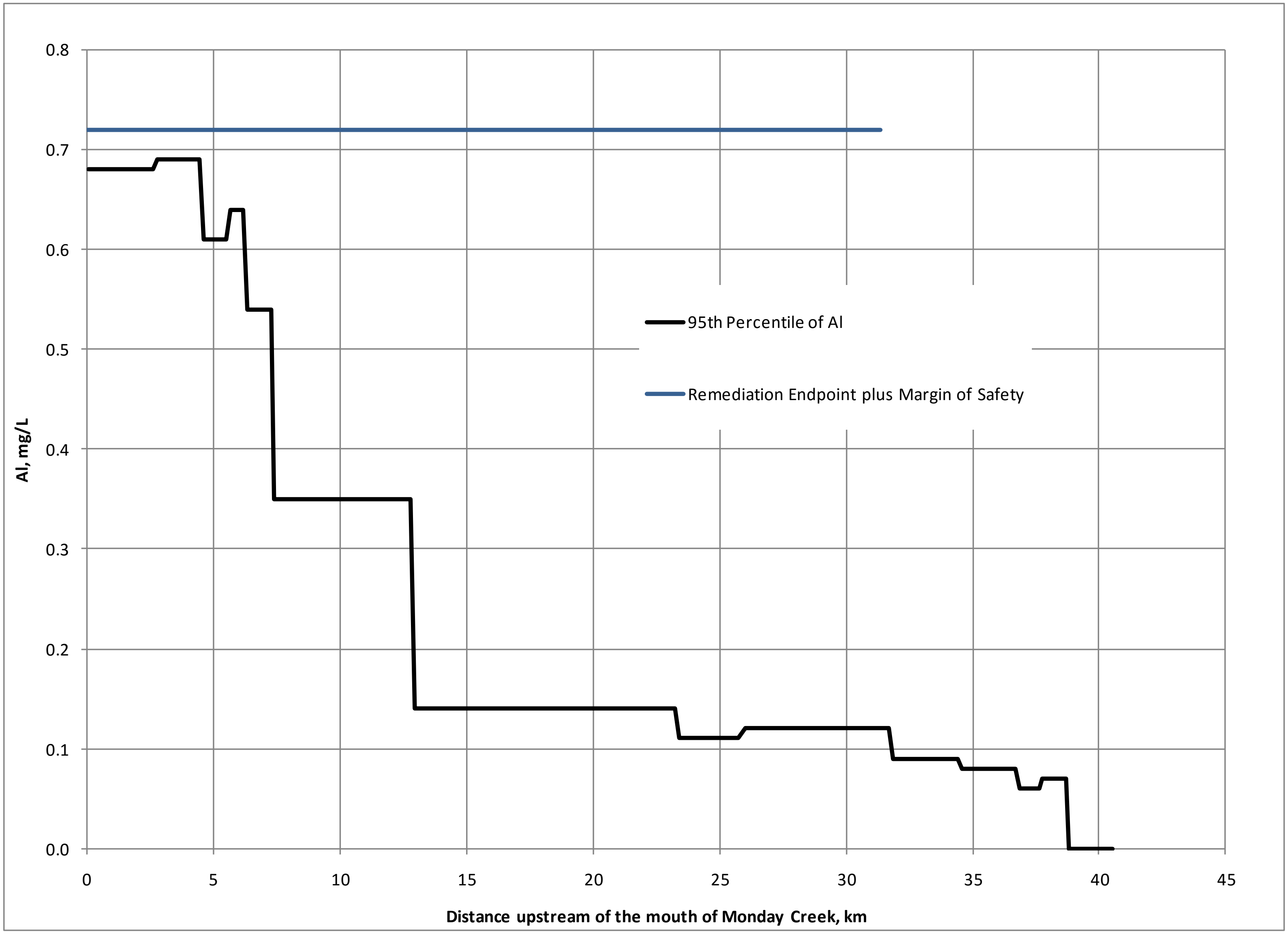

Figure 11. Plot of the 95th percentile of the simulated main stem aluminum with Treatment Alternative 1.

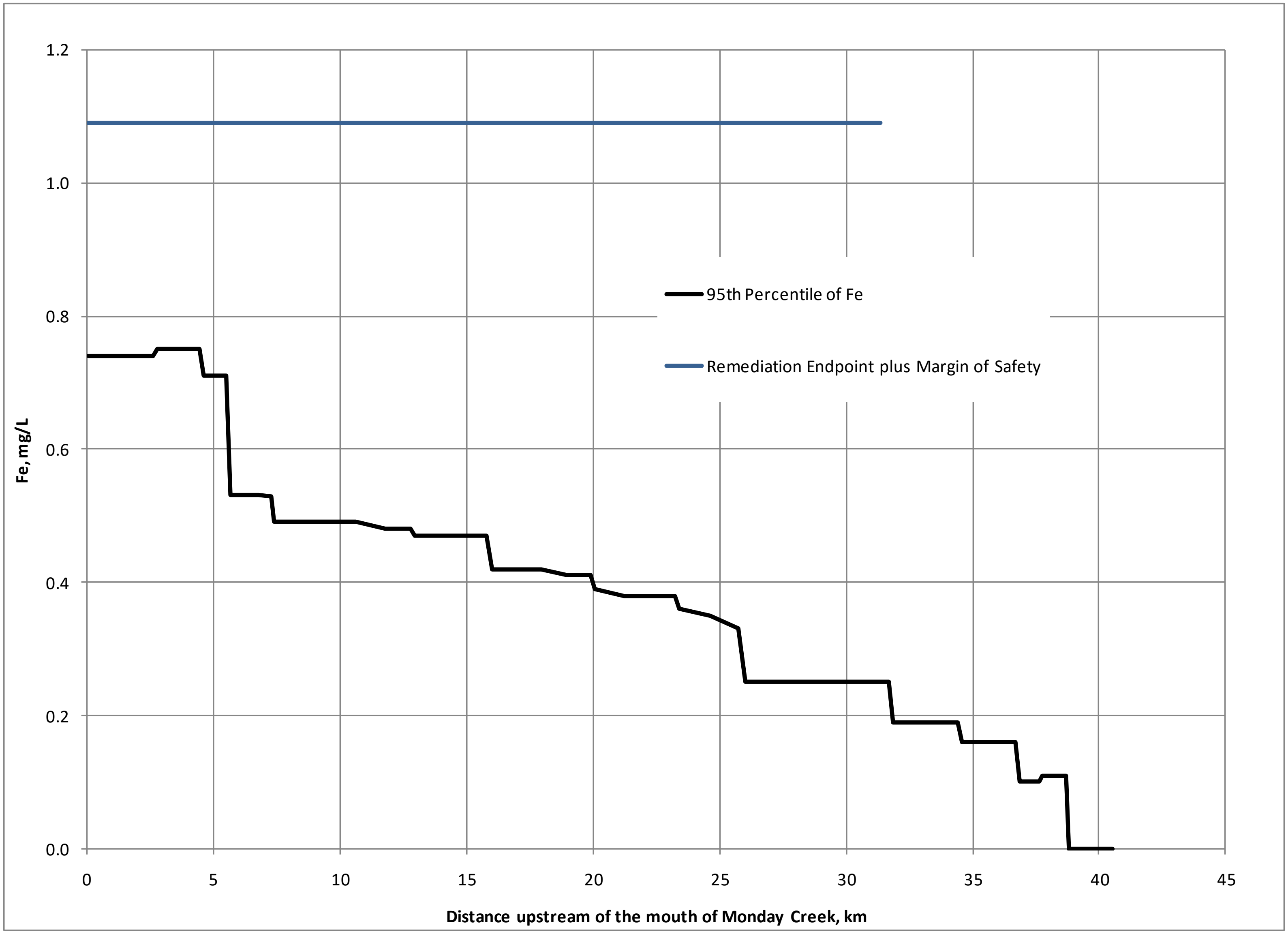

Figure 12. Plot of the 95th percentile of the simulated main stem iron with Treatment Alternative 1.

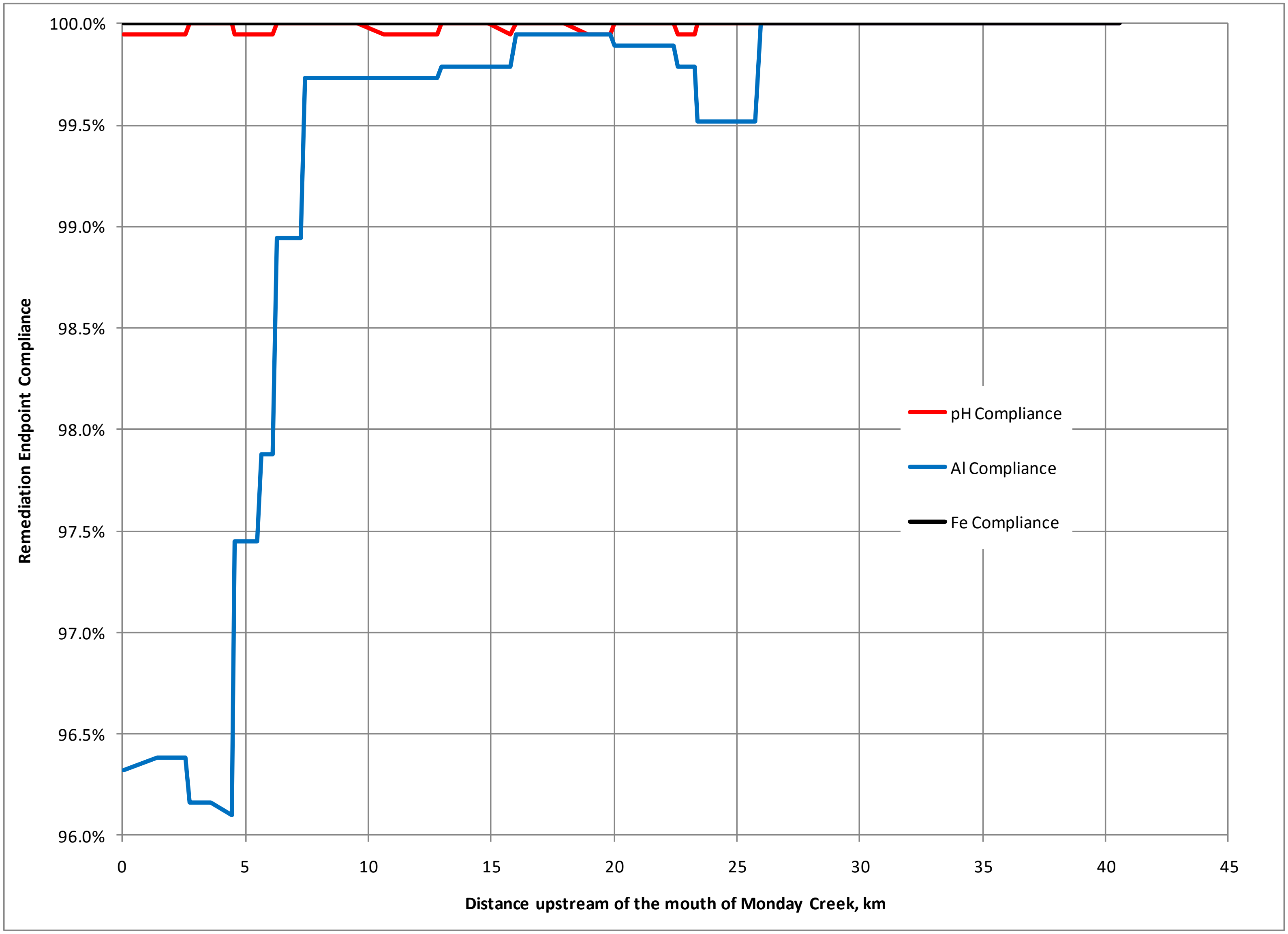

Figure 13. Compliance plot for the simulated pH, aluminum, and iron with Treatment Alternative 1.

Treatment Alternative 2: Pebble Quicklime Dosing and Passive Treatment Systems. This treatment alternative consists of both pebble quicklime dosing and passive treatment systems. New pebble quicklime dosers are placed in the Lost Run, Rock Run, Big Four Hollow, Monkey Hollow, and Brush Fork sub-watersheds. With the exception of the Brush Fork doser, all of the dosers for this treatment alternative will be operated with the same calcium oxide dosage rate as the current operation of the Jobs Hollow doser, 83.21 mg/L. The Brush Fork doser will use a calcium oxide dosage rate of 224 mg/L. The design parameters for the dosers are listed in Table 6. The dosage rates and doser locations in Table 6 were selected so as to meet the treatment goals with the minimum capital and O&M cost.

The design parameters for the passive treatment systems of this alternative are listed in Table 7 and 8. The LLB and OLC passive treatment systems designs, listed in Table 7, employed a treatment factor of 50%. The alkalinity released by the SLB systems, listed in Table 8, was assumed to be 500 mg/L $CaCO_3$ equivalents. The specifications of the passive treatment systems in Tables 7 and 8 were taken from the passive treatment systems designs prepared for the 2003 project (Stiles and Ziemkiewicz, 2003).

Figure 14 is a plot of the 5th percentile of the simulated stream pH for the main stem, and Figures 15 and 16 are plots of the 95th percentile of the simulated main stem Al and Fe, respectively. Figure 17 is a compliance plot for pH, Al, and Fe with this treatment alternative. As with the other alternative, the main stem Al concentration was the limiting factor in determining the treatment loads from the treatment systems.

Table 6. Design parameters for the pebble quicklime dosers of Treatment Alternative 2.

Sub-watershed	Required Alkalinity, mg/L $CaCO_3$ equiv.	CaO Dosage Rate, mg/L
Jobs Hollow	148.59	83.21
Lost Run	148.59	83.21
Rock Run	148.59	83.21
Big Four Hollow	148.59	83.21
Monkey Hollow	148.59	83.21
Brush Fork	400.00	224.0

Table 7. Design parameters for the LLB and OLC passive treatment systems of Treatment Alternative 2.

Sub-water.	Site	Type	Discharge, L/s	Net Acidity, mg/L	Req. Alk., kg/day $CaCO_3$ equiv.
Brush Fork	BR-MSBS	LLB	10.6	465.	288.
Brush Fork	BR-20	LLB/OLC	6.23	251.	91.9
Brush Fork	BR-21	LLB/OLC	0.54	164.	5.2
Brush Fork	BR-32A	LLB/OLC	10.3	384.	232.
Brush Fork	BR-4W	LLB/OLC	0.62	228.	8.2
Brush Fork	BR-5E50	LLB/OLC	0.45	141.	3.7
Brush Fork	BR-6WB	LLB/OLC	2.52	148.	21.9
Brush Fork	BR-6WC	LLB/OLC	2.26	132.	17.6
Brush Fork	BR-MS7	LLB/OLC	10.9	83.5	53.4
Brush Fork	BR-MS7C	LLB/OLC	18.2	90.1	96.1
Brush Fork	BR-MSSP1	LLB/OLC	3.94	85.4	19.9
Brush Fork	BR-MSSP2	LLB/OLC	7.50	141.	61.8
Brush Fork	BR-MSSP3	LLB/OLC	22.6	210.	279.
Brush Fork	BR-MSSP5	LLB/OLC	9.52	207.	116.
Brush Fork	MSSP7E	OLC	0.54	81.6	2.5
Dixie H.	DIX-14	OLC	3.15	220.	40.7
Dixie H.	DIX-98	OLC	3.85	205.	46.4
Jobs Hollow	JOB-7	OLC	1.72	35.3	3.5
Long Hollow	LON-93	LLB/OLC	16.9	178.	177.
Long Hollow	LON-94	LLB/OLC	7.25	142.	60.4
Long Hollow	LON-95	LLB/OLC	15.3	52.0	46.7
Long Hollow	S-27	LLB/OLC	43.9	52.0	134.
Monkey	FRT-1	LLB/OLC	2.26	78.5	10.4
Monkey	FRT-2	LLB/OLC	0.14	274.	2.2

Table 7. Design parameters for the LLB and OLC passive treatment systems of Treatment Alternative 2, continued.

Sub-water.	Site	Type	Discharge, L/s	Net Acidity, mg/L	Req. Alk., kg/day $CaCO_3$ equiv.
Monkey	FRT-3	LLB/OLC	0.06	340.	1.2
Monkey	FRT-4	LLB/OLC	0.08	455.	2.2
Monkey	FRT-5	LLB/OLC	1.85	181.	19.9
Monkey	FRT-5A	LLB/OLC	0.48	200.	5.7
Monkey	MNK-1	LLB/OLC	0.62	338.	12.4
Monkey	MNK-11	LLB/OLC	1.19	493.	34.5
Monkey	MNK-13	LLB/OLC	1.33	256.	20.1
Monkey	MNK-7A	LLB/OLC	0.16	609.	6.0
Monkey	MNK-8	LLB/OLC	0.38	465.	10.2
Snake H.	ATC-02	LLB/OLC	3.94	85.4	19.9
Snake H.	ATC-03	LLB/OLC	0.13	151.	1.2
Snake H.	ATC-04	LLB/OLC	0.45	141.	3.7
Snake H.	SNA-61	LLB/OLC	10.3	384.	232.
Snake H.	SNA-62	LLB/OLC	22.6	210.	279.
Snake H.	SNA-63	LLB/OLC	2.26	132.	17.6
Snake H.	SNA-64	LLB/OLC	7.50	141.	61.8

Table 8. Design parameters for the SLB passive treatment systems of Treatment Alternative 2.

Sub-water.	Site	Discharge, L/s	Required Alkalinity, kg/day $CaCO_3$ equiv.
Brush Fork	SMEMSBS	1.96	84.7
Brush Fork	MSSP7E	0.54	23.3
Brush Fork	BR-TOP	2.97	128.
Dixie Hollow	DIX-16	3.15	136.
Dixie Hollow	DIX-4	1.26	54.4
Jobs Hollow	JOB-10	4.79	207.
Jobs Hollow	JOB-5	1.72	74.3
Jobs Hollow	JOB-US	1.72	74.3
Long Hollow	LON-4	6.31	273.
Monkey H.	FRT-6	6.31	273.
Spencer H.	SPN	3.15	136.

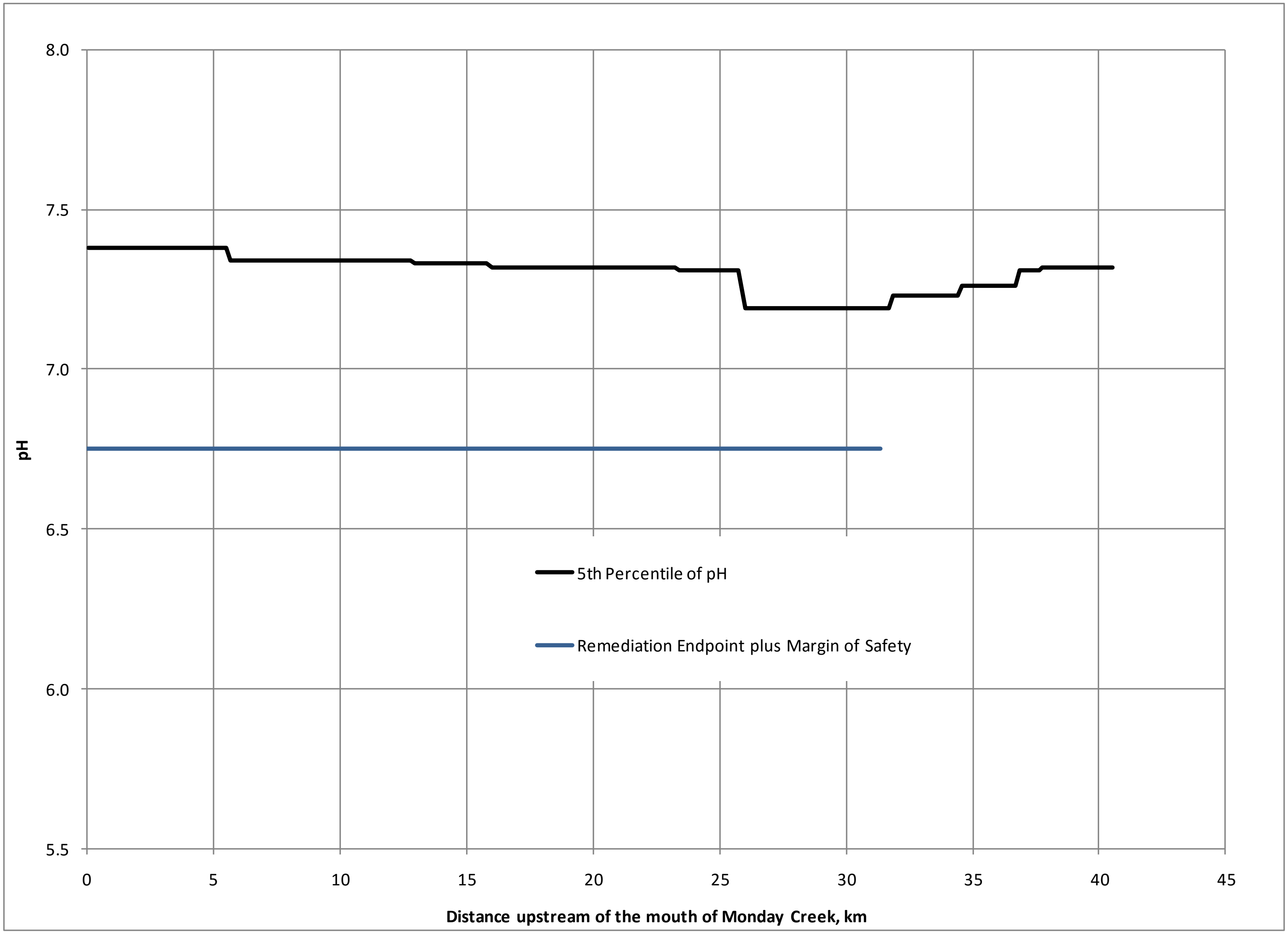

Figure 14. Plot of the 5th percentile of the simulated main stem pH with Treatment Alternative 2.

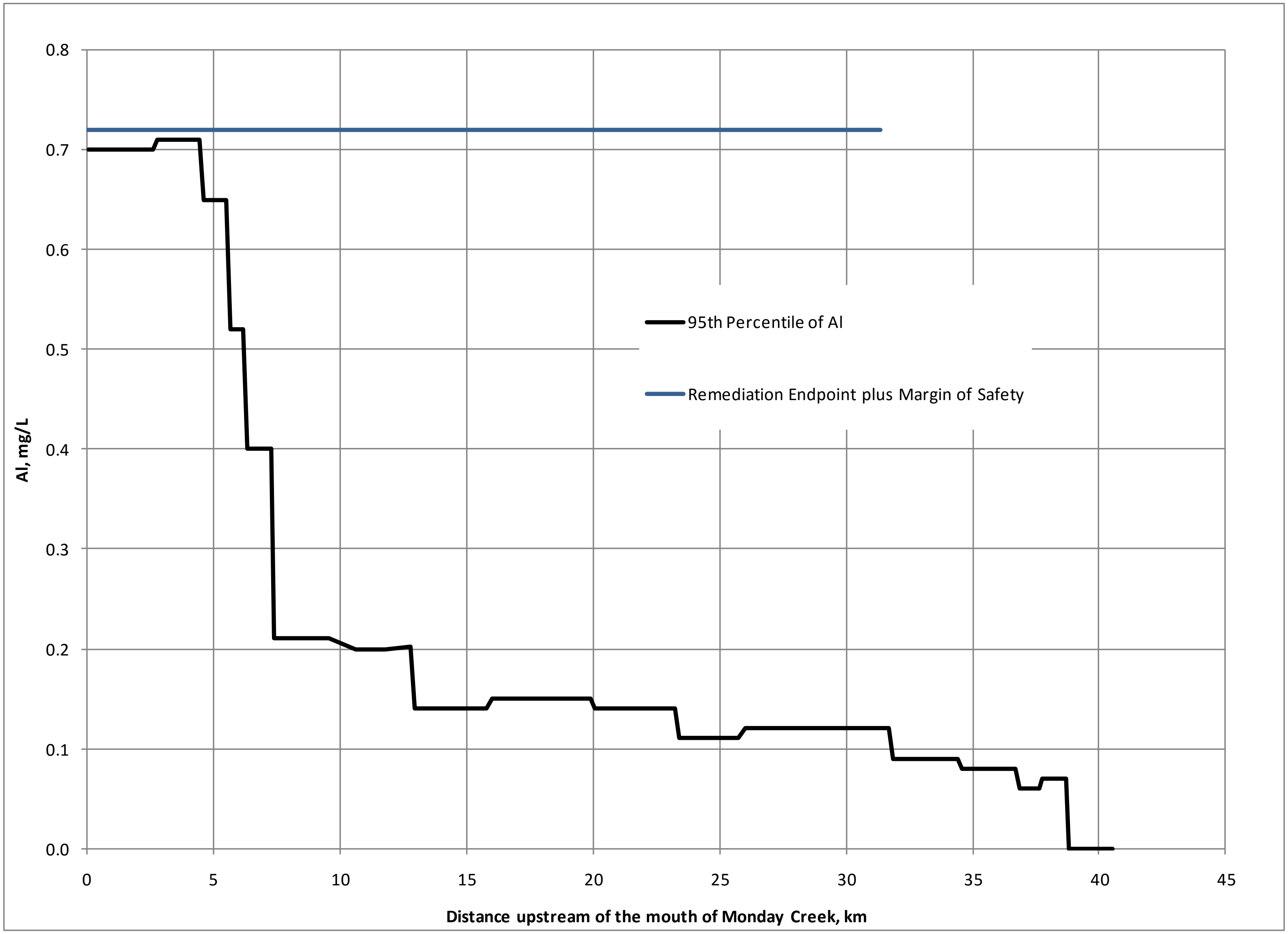

Figure 15. Plot of the 95th percentile of the simulated main stem aluminum with Treatment Alternative 2.

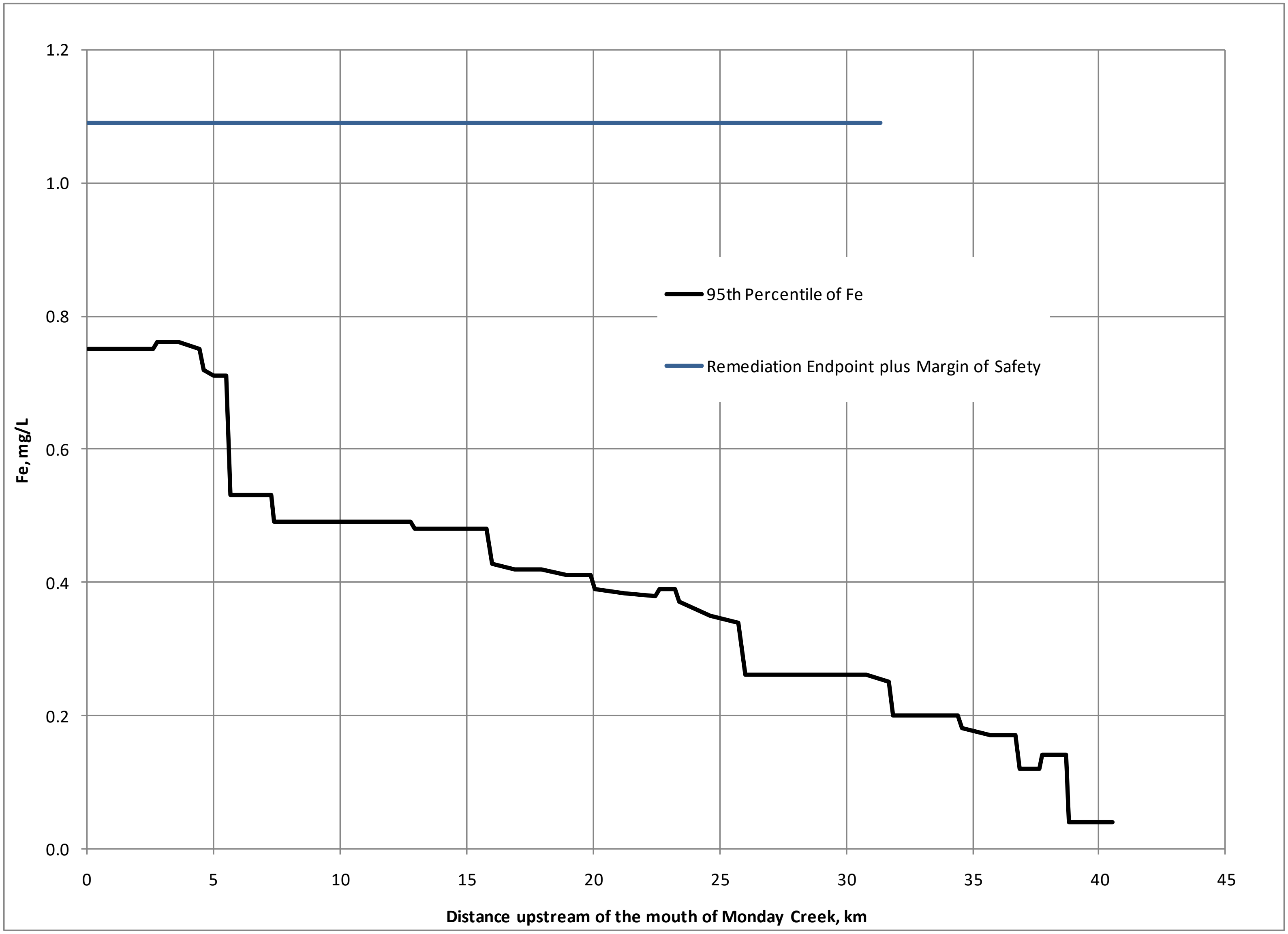

Figure 16. Plot of the 95th percentile of the simulated main stem iron with Treatment Alternative 2.

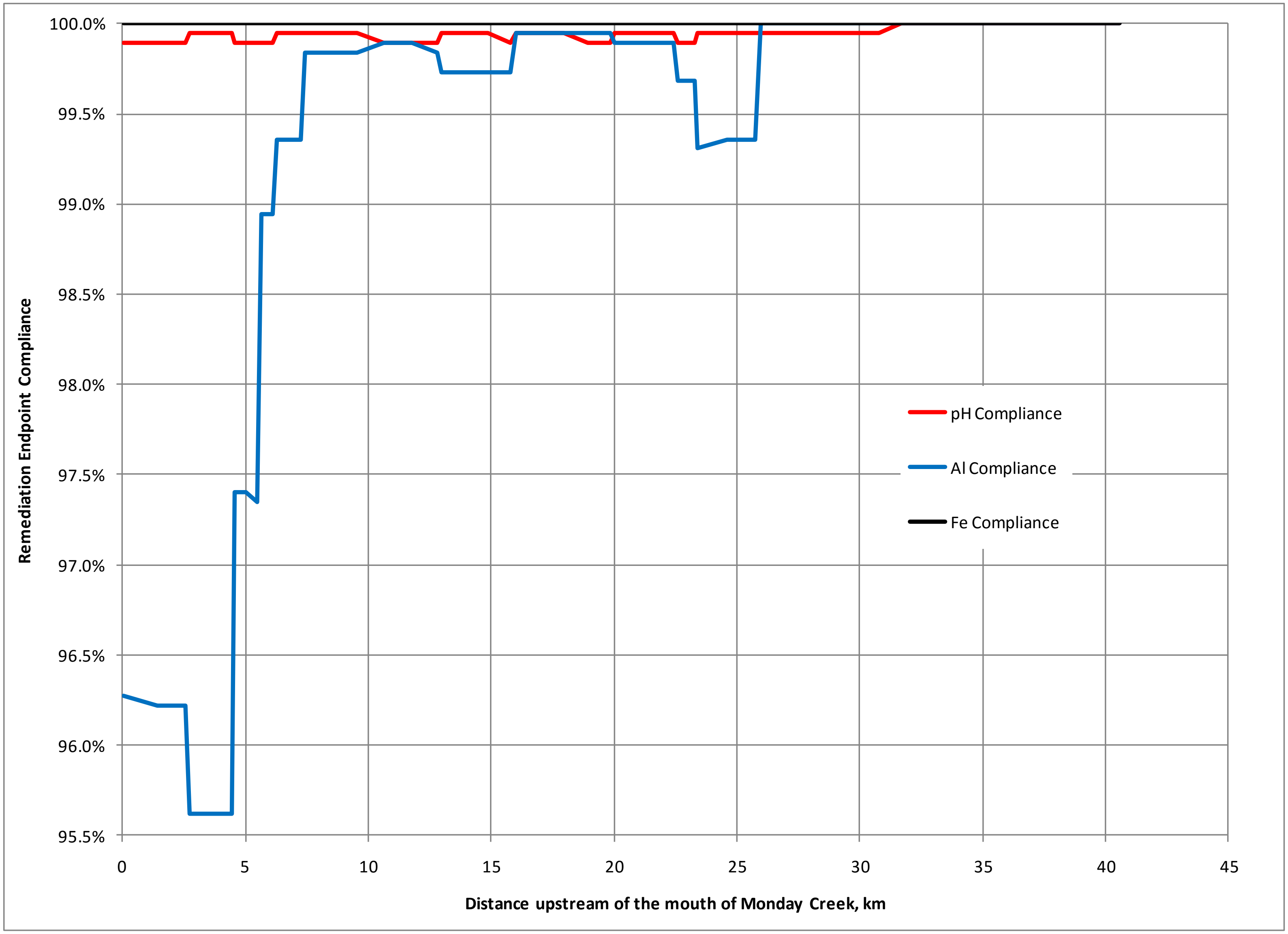

Figure 17. Compliance plot for the simulated pH, aluminum, and iron with Treatment Alternative 2.

Results

Cost for Treatment Alternative 1

Table 9 is a list of the cost assumptions for both Treatment Alternative 1 and Treatment Alternative 2.

Table 9. Unit cost assumptions for AMD treatment designs.

Item	Value	Units
Limestone Installed Unit Cost	$27.56	per tone
Steel Slag Installed Unit Cost	$27.56	per tonne
Excavation Unit Cost	$3.92	per m^3
Pebble Quicklime Unit Cost	$137.79	per tonne
Pebble Quicklime Doser Capital Cost	$150,000	per unit
Passive Treatment Systems O&M Cost	5%	of Capital Cost per year
Pebble Quicklime Dosers Maintenance Cost	$8,333	per doser per year

Table 10 shows the results of the cost calculations for Treatment Alternative 1. Alternative 1 employed one pebble quicklime doser for each sub-watershed listed in Table 10, so the capital cost for each sub-watershed was equal to the cost of one doser, $150,000. The Operation and Maintenance (O&M) cost of each doser was assumed to be equal to the cost of the consumed CaO plus the maintenance cost for the doser.

The total capital and O&M costs for Treatment Alternative 1 are $1,200,000 and $422,101 per year, respectively.

Table 10. Cost calculations of the pebble quicklime dosers for Alternative 1.

Sub-watershed	Capital Cost	CaO Required, tonne/yr	O&M Cost, per yr
Brush Fork	$150,000	429.21	$67,474
Salem Hollow	$150,000	494.68	$76,495
Spencer Hollow	$150,000	151.86	$29,258
Sycamore Hollow	$150,000	448.31	$70,105
Dixie Hollow	$150,000	297.36	$49,306
Rock Run	$150,000	181.87	$33,393
Lost Run	$150,000	321.66	$52,654
Monkey Hollow	$150,000	254.62	$43,417

Cost for Treatment Alternative 2

Table 11 shows the results of the cost calculations for the pebble quicklime dosers in the Treatment Alternative 2. The capital and O&M costs for these dosers were calculated in the same manner as the dosers in Treatment Alternative 1. Table 12 shows the design and cost calculations for the Limestone Leach Bed (LLB) systems in Treatment Alternative 2. These calculations assume that the O&M cost of the passive treatment systems is equal to the rebuilding of the systems every twenty years (Stiles and Ziemkiewicz, 2010). Table 13 shows the design and cost calculations for the Open Limestone Channel (OLC) systems in Treatment Alternative 2, and Table 14 shows the design and cost calculations for the Steel Slag Leach Bed (SLB) systems in Treatment Alternative 2 (Stiles and Ziemkiewicz, 2010).

Table 11. Cost calculations of the pebble quicklime dosers for Alternative 2.

Sub-watershed	Capital Cost	CaO Required, tonne/yr	O&M Cost, per yr
Lost Run	$150,000	266.0	$44,980
Rock Run	$150,000	182.2	$33,434
Big Four Hollow	$150,000	85.62	$20,130
Monkey Hollow	$150,000	255.0	$43,474
Brush Fork	$150,000	1157.	$167,796

Table 12. Cost calculations for LLB passive treatment systems for Alternative 2.

Sub-water.	Site	Capital Cost, $	O&M Cost, $/yr
Brush Fork	BR-MSBS	$10,263	$513
Brush Fork	BR-20	$6,059	$303
Brush Fork	BR-21	$523	$26
Brush Fork	BR-32A	$20,005	$1,000
Brush Fork	BR-4W	$603	$30
Brush Fork	BR-5E50	$438	$22
Brush Fork	BR-6WB	$2,451	$123
Brush Fork	BR-6WC	$2,203	$110
Brush Fork	BR-MS7	$5,301	$265
Brush Fork	BR-MS7C	$8,840	$442
Brush Fork	BR-MSSP1	$1,914	$96
Brush Fork	BR-MSSP2	$7,297	$365
Brush Fork	BR-MSSP3	$21,995	$1,100
Brush Fork	BR-MSSP5	$9,262	$463
Long Hollow	LON-93	$32,643	$1,632
Long Hollow	LON-94	$6,999	$350
Long Hollow	LON-95	$14,763	$738
Long Hollow	S-27	$21,188	$1,059
Monkey Hollow	FRT-1	$2,203	$110
Monkey Hollow	FRT-2	$69	$3
Monkey Hollow	FRT-3	$55	$3
Monkey Hollow	FRT-4	$160	$8
Monkey Hollow	FRT-5	$1,806	$90
Monkey Hollow	FRT-5A	$936	$47
Monkey Hollow	MNK-1	$604	$30
Monkey Hollow	MNK-11	$2,324	$116
Monkey Hollow	MNK-13	$1,292	$65
Monkey Hollow	MNK-7A	$160	$8

Table 12. Cost calculations for LLB passive treatment systems for Alternative 2, continued.

Sub-water.	Site	Capital Cost, $	O&M Cost, $/yr
Monkey Hollow	MNK-8	$367	$18
Snake Hollow	ATC-02	$192	$10
Snake Hollow	ATC-03	$131	$7
Snake Hollow	ATC-04	$476	$24
Snake Hollow	SNA-61	$2,680	$134
Snake Hollow	SNA-62	$1,090	$55
Snake Hollow	SNA-63	$1,994	$100
Snake Hollow	SNA-64	$463	$23

Table 13. Cost calculations for OLC passive treatment systems for Alternative 2.

Sub-water.	Site	Capital Cost, $	O&M Cost, $/yr
Brush	BR-20	$3,616	$181
Brush	BR-21	$2,628	$131
Brush	BR-32A	$3,998	$200
Brush	BR-4W	$993	$50
Brush	BR-5E50	$3,345	$167
Brush	BR-6WB	$3,973	$199
Brush	BR-6WC	$3,118	$156
Brush	BR-MS7	$3,352	$168
Brush	BR-MS7C	$3,403	$170
Brush	BR-MSSP1	$4,671	$234
Brush	BR-MSSP2	$7,385	$369
Brush	BR-MSSP3	$4,164	$208
Brush	BR-MSSP5	$3,853	$193
Brush	BR-MSSP7E	$4,051	$203
Dixie	DIX-14	$26,624	$1,331
Dixie	DIX-98	$32,056	$1,603

Table 13. Cost calculations for OLC passive treatment systems for Alternative 2, continued.

Sub-water.	Site	Capital Cost, $	O&M Cost, $/yr
Jobs	JOB-7	$48,411	$2,421
Long	LON-93	$1,330	$67
Long	LON-94	$1,002	$50
Long	LON-95	$8,588	$429
Long	S-27	$3,006	$150
Monkey	FRT-1	$11,318	$566
Monkey	FRT-2	$992	$50
Monkey	FRT-3	$464	$23
Monkey	FRT-4	$736	$37
Monkey	FRT-5	$11,389	$569
Monkey	FRT-5A	$2,905	$145
Monkey	MNK-1	$5,016	$251
Monkey	MNK-11	$20,728	$1,036
Monkey	MNK-13	$23,888	$1,194
Monkey	MNK-7A	$1,496	$75
Monkey	MNK-8	$2,692	$135
Snake	ATC-02	$1,014	$51
Snake	ATC-03	$627	$31
Snake	ATC-04	$2,159	$108
Snake	SNA-61	$12,662	$633
Snake	SNA-62	$6,652	$333
Snake	SNA-63	$10,139	$507
Snake	SNA-64	$2,382	$119

Table 14. Cost calculations for SLB passive treatment systems for Alternative 2.

Sub-water.	Site	Capital Cost, $	O&M Cost, $/yr
Brush Fork	SM-E-MSBS	$87,299	$4,365
Brush Fork	BR-MSSP7E	$23,976	$1,199
Brush Fork	BR-TOP	$132,500	$6,625
Dixie Hollow	DIX-16	$140,578	$7,029
Dixie Hollow	DIX-4	$15,909	$795
Jobs Hollow	JOB-10	$212,774	$10,639
Jobs Hollow	JOB-5	$76,548	$3,827
Jobs Hollow	JOB-US	$76,548	$3,827
Long Hollow	LON-4	$78,223	$3,911
Monkey Hollow	FRT-6	$281,156	$14,058
Spencer Hollow	SPN	$130,905	$6,545

The total capital and O&M costs for Treatment Alternative 2 are listed in Table 15 with the present cost calculated from the capital cost, O&M cost, assumed longevity, and assumed interest rate. While 7% annual interest rate would be more realistic (EPA, 2000), the Monday Creek Restoration Project requested that the investigators use a zero interest rate in comparing the alternatives.

Table 15. Cost summary of Treatment Alternatives 1 and 2.

Alt.	Type	Capital Cost	O&M Cost, 1/yr	n, yrs	Interest Rate, 1/yr	Present Cost
	Dosers	$1,200,000	$422,101	20	0%	$9,642,027
1	**Total**	**$1,200,000**	**$422,101**	**20**	**0%**	**$9,642,027**
	Dosers	$750,000	$309,814	20	0%	$6,946,273
	LLB's	$189,749	$9,487	20	0%	$379,498
	OLC's	$290,826	$14,541	20	0%	$581,652
	SLB's	$1,256,416	$62,821	20	0%	$2,512,832
2	**Total**	**$2,486,991**	**$396,663**	**20**	**0%**	**$10,420,255**

Conclusion

This project recalibrated the Monday Creek *TAMDL* model that was designed by the previous project for simulating the transport and reaction of those water quality constituents related to AMD within the Monday Creek watershed (Stiles and Ziemkiewicz, 2003). This recalibrated model was used to devise two treatment strategies for raising the quality of the Monday Creek main stem up to the remediation standards established by ODNR (Stiles and Ziemkiewicz, 2003). The first treatment strategy consists of using pebble quicklime dosing for selected sub-watersheds to raise the alkalinity of and precipitate metals from the streams flowing into the main stem. The second treatment strategy employed pebble quicklime dosing in fewer sub-watersheds along with LLB, OLC, and SLB passive treatment systems.

The capital cost of Treatment Alternative 1 was $1,200,000, and the O&M cost was $422,101 per year. The capital cost of Treatment Alternative 2 was $2,486,991 and the O&M cost was $396,663 per year. With a lifetime of 20 years and an interest rate of 0% per year, the present cost of Treatment Alternative 1 was $9,642,027, and the present of cost of Treatment Alternative 2 was $10,420,255.

While an interest rate of 0% was not realistic for commercial activity, the State and Federal agencies in charge of the remediation of the Monday Creek watershed can obtain funds for the remediation at a zero interest rate. On the basis of cost alone, Alternative 1 was the superior choice. However, there are aspects to watershed remediation that were beyond the scope of this project.

Acknowledgements

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