SAMPLING STRATEGIES FOR TMDL OF AMD-AFFECTED STREAMS[1]

Brian A. Dempsey[2], Benjaphon Paksuchon, Ratda Suhataikul, and Jon Dietz

Abstract. Water quality was monitored during March 1999 to May 2001 at 106 AMD stream sites, within eleven watersheds in Western Pennsylvania. Data were used to prepare Total Maximum Daily Load (TMDL) reports using a probabilistic model (@Risk) to determine the required percent removals of acidity and of total Al, Fe, and Mn in order to comply with water quality criteria at least 99% of the time. Water quality was measured as a function of stream stage during storm events for some sites. Sites were divided into five categories, based on pH and sulfate concentration. Category 1 (pH<3.5 and sulfate>50 mg/L) accounted for 17% of total sites. Removal of >90% of the current load of acidity and aluminum was required in all category 1 cases. The relative standard deviations for water quality parameters were low for category 1 sites. We recommend that TMDL water quality sampling be limited to four expeditions for these streams, to conserve resources and to speed the development of remediation efforts. Category 2 sites (3.5<pH<6.0 and sulfate>50 mg/L) required removal of lower percentages of metals, and we recommend more sites per stream mile and an early intensive survey to determine the important sources of contamination. Stream sites in Category 3 (3.5<pH<6.0 and sulfate<50 mg/L) required removal of acidity, but in most cases no removal of total metals was required. Stream sites in Category 4 (pH>6.0 and sulfate>50 mg/L) occasionally required removal of acidity and of metal loads. Stream sites in Category 5 (pH>6.0 and sulfate<50 mg/L) did not require removal of metals for compliance. For these three categories, we recommend: an early intensive stream survey; continuous monitoring of conductivity and pH at some sites to determine possible impacts during high water events; and measurement of dissolved or monomeric Al(III), Fe(II), and Mn(II) in addition to total metals.

Additional Key Words: AMD effects, water quality, modeling

[1] Paper was presented at the 2002 National Meeting of the American Society of Mining and Reclamation, Lexington KY, June 9-13, 2002. Published by ASMR, 3134 Montavesta Rd., Lexington, KY 40502.

[2] Brian A. Dempsey is Professor of Environmental Engineering, The Pennsylvania State University, University Park, PA 16802.
Benjaphon Paksuchon, Ratda Suhataikul, and Jon Dietz are Graduate Students, The Pennsylvania State University, University Park, PA 16802.

Proceedings America Society of Mining and Reclamation, 2002 pp 10-26
DOI: 10.21000/JASMR020100010
https://doi.org/10.21000/JASMR02010010

Background

Section 303(d) of the 1972 Clean Water Act requires that states develop lists of impaired waters that do not meet water quality standards even after installation of pollution control technology for point sources of pollution. The law requires that these jurisdictions establish priority ranking for waters on the lists and develop a total maximum daily load (TMDL) for these waters (Sears, 1998;U.S. EPA 814-D-99-001, 1999). TMDL was described in the EPA's guidance for water quality-based decisions (U.S. EPA 440/4-91-001, 1991) as:

$$TMDL = LC = WLA + LA + MOS \qquad \textbf{(1)}$$

where loading capacity (LC) is the greatest amount of pollutant loading that water can receive without violating the water quality standards, waste load allocation (WLA) is load that is allocated to existing or future point sources of pollution, load allocation (LA) is the portion of a receiving water's loading capacity that is attributed to an existing or future non-point sources of pollution or to natural background sources, and margin of safety (MOS) accounts for uncertainty in modeling and analysis. In essence, TMDL describes how much pollutant can enter a waterway before the water quality criterion is reached more than a prescribed percentage of the time (Christman, 1999).

To create a TMDL for a specific body of water, water samples are analyzed to identify types and concentrations of pollutants. EPA allows states to consider a wide range of pollutants, including toxins, nutrients, metals, pesticides, sediments, and less traditional concerns such as water temperature and flow. Often, states identify which pollutants should be evaluated, based on the source of pollution (e.g. agricultural activity, abandoned mine lands, conventional or industrial wastewater). The state determines what level of pollution in a body of water is acceptable. Then pollutant loads are determined for the upstream boundary from point sources (e.g. industrial municipal and waste water treatment facilities) and non-point sources (e.g. agricultural surface runoff and acid mine drainage).

In Pennsylvania, abandoned mines are the source of acidity and metals for many water bodies. Under the PA Title 25 chapter 93.5(b), at least a 99% level of protection is required, i.e. the concentrations of potentially toxic chemicals must be less than the water quality criteria 99%

of the time. Although only the dissolved metals are considered to be toxic, Pennsylvania has specified TMDL guidelines in terms of total metals, i.e. following a hot HCl/HNO_3 extraction. Dissolved metals are less than or equal to total metals, which provides an additional margin of safety. The Pennsylvania water quality criteria for stream waters affected by AMD are shown in Table 1.

Table 1. PA water quality criteria for streams affected by AMD (Bureau of District Mining Operations, 2000)

Parameter	**Criterion value (Cc)**
Aluminum	0.75 (mg/L as total)
Iron	1.50(mg/L as total)
Manganese	1.00(mg/L as total)
pH	6.0 - 9.0
Acidity	Equal or lower than average alkalinity

Probabilistic models using Monte Carlo simulation are frequently used to model water quality for TMDL (U.S. EPA 440/4-91-001, 1991). Probabilistic models for water quality data often use log-normal probability distributions of model inputs to calculate probability distributions of the model output. For AMD-affected waters, contaminants are typically considered to be conservative; therefore, the point of greatest contamination is the point closest to the source of pollution. This simplifies the modeling process.

Problem Statement

Implementation of the TMDL strategy requires stream monitoring to assess the nature, concentration, and variability of pollution. Resources are usually inadequate to perform intensive and long-term monitoring on every water body that is affected by AMD. EPA did not provide watershed specific guidelines for conducting stream sampling. Rather, EPA and PADEP negotiated a minimum number of samples that would be used to determine the pollutant loading on water bodies that are affected by AMD.

Since resources are limited, it is reasonable to ask whether all of the water bodies that are affected by AMD should be required to receive the same level of data collection. The severity of the pollution from AMD depends on the characteristics of the abandoned mines and of the stream. Therefore, application of the same sampling strategy for every watershed could be inadequate for some conditions and could be wasteful for other conditions. Several investigators have linked the severity of AMD problems to pH and sulfate concentration (Bencala et al., 1987; Herlihy et al., 1990; Gray 1996; Sams et al., 2000).

Scope of Study

This study was started in March 2000 in association with PADEP. Ten study areas in western Pennsylvania were selected. Preliminary surveys indicated that these streams were affected by AMD. Monitoring locations were selected by PADEP, and many were new sites that had not been previously sampled. Accurate flow measurements did not exist for any of the monitoring locations. Therefore, each site in this study was sampled multiple times, to include a range of seasons and flows. During each sampling trip, the stream flow was measured, and water samples were collected and subsequently analyzed. The parameters used in this study were pH, acidity (hot peroxide procedure), alkalinity, total suspended solids, sulfate, total aluminum, iron, and manganese. Aluminum, iron, manganese, acidity, and pH were target pollutants with respect to the water quality criteria.

Objective

The objectives for this study included:

- Conduct a sampling and analysis program to determine seasonal flow and water quality data for ten study areas (106 sample sites) in western Pennsylvania that were affected by AMD;
- Perform TMDL calculations to determine the percent removals of Al, Fe, Mn, and acidity that would be required to comply with water quality criteria at least 99% of the time;
- Critically evaluate the water chemistry data in order to categorize the AMD effects and then propose water-sampling strategies for each AMD category.

Results

Data for each sampling area were analyzed to obtain the percent metals and acidity removal that would be required to attain the in-stream water quality criteria. All of the water chemistry data were compiled and evaluated relative to pH and sulfate concentration.

Figure 1 shows acidity as a function of sulfate concentration. Sulfate was used as an indicator to assess AMD impact sulfate tends to be conservative in streams and is produced during the oxidation of pyrite. A vertical dashed line represents a sulfate cutoff concentration at 50 mg/L (Herlihy et al. 1990). When sulfate was less than 50 mg/L, acidity was negligible. When pH was less than 3.5, sulfate was high and acidity correlated well with sulfate concentration. When pH was greater than 6, acidity was low even for high sulfate concentrations.

Figure 2 shows Al concentrations as a function of sulfate concentration. Lines were inserted to represent the water quality criteria for Al at 0.75 mg/L (-0.12 in a log-scale) and the sulfate cutoff concentration (50 mg/L or 1.69 in a log-scale). The solid rectangular area on the lower left in Figure 2 showed that Al concentrations were lower than the Al criteria when sulfate concentrations were lower than 50 mg/L. When stream waters pH values were <3.5, Al concentrations were higher than the Al criteria and sulfate concentrations were higher than the Herlihy cutoff concentration for sulfate. When sulfate concentrations were higher than 50 mg/L and pH >6, Al concentrations were almost always above the criterion value. Conversely, Al concentrations were usually below the criterion value for sulfate above 50 mg/L and pH>6.0. High sulfate concentration by itself did not indicate that stream waters would contain Al concentrations higher than the Al criterion value.

Figure 3 shows Fe concentrations as a function of sulfate concentration. Lines were inserted to represent the water quality criteria for Fe at 1.5 mg/L (0.18 in log-scale), and the sulfate cutoff concentration (50 mg/L or 1.69 in a log-scale). Fe concentrations were lower than the Fe criteria whenever sulfate concentrations were lower than 50 mg/L. For pH<3.5, Fe concentrations exceeded the criteria except for one site. When sulfate concentrations were higher than 50 mg/L and pH was above 6, Fe concentrations were usually above the criterion value. Conversely, Fe concentrations were usually below the criterion value for sulfate above 50 mg/L and pH>6.0.

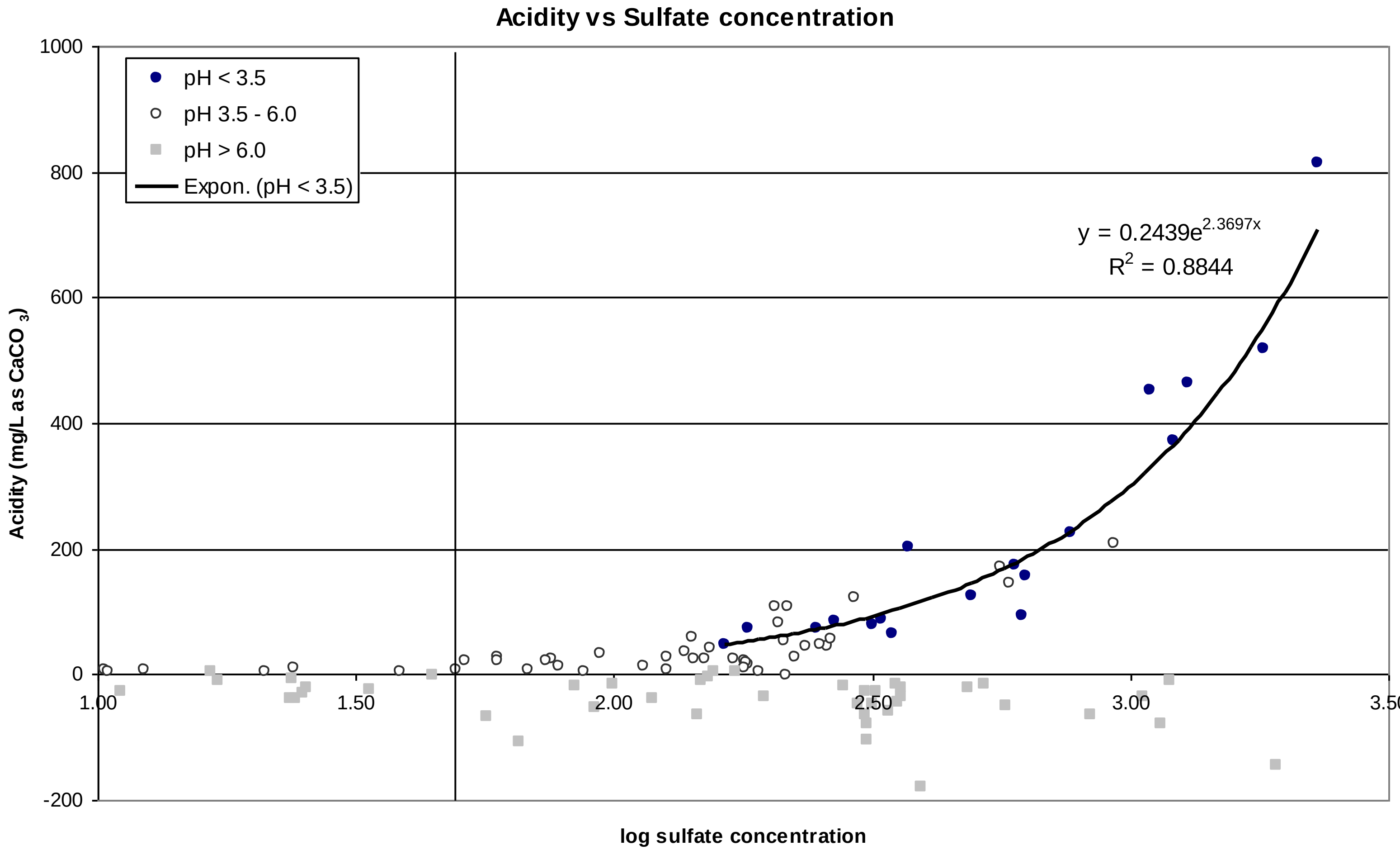

Figure 1. Acidity as a function of sulfate concentration.

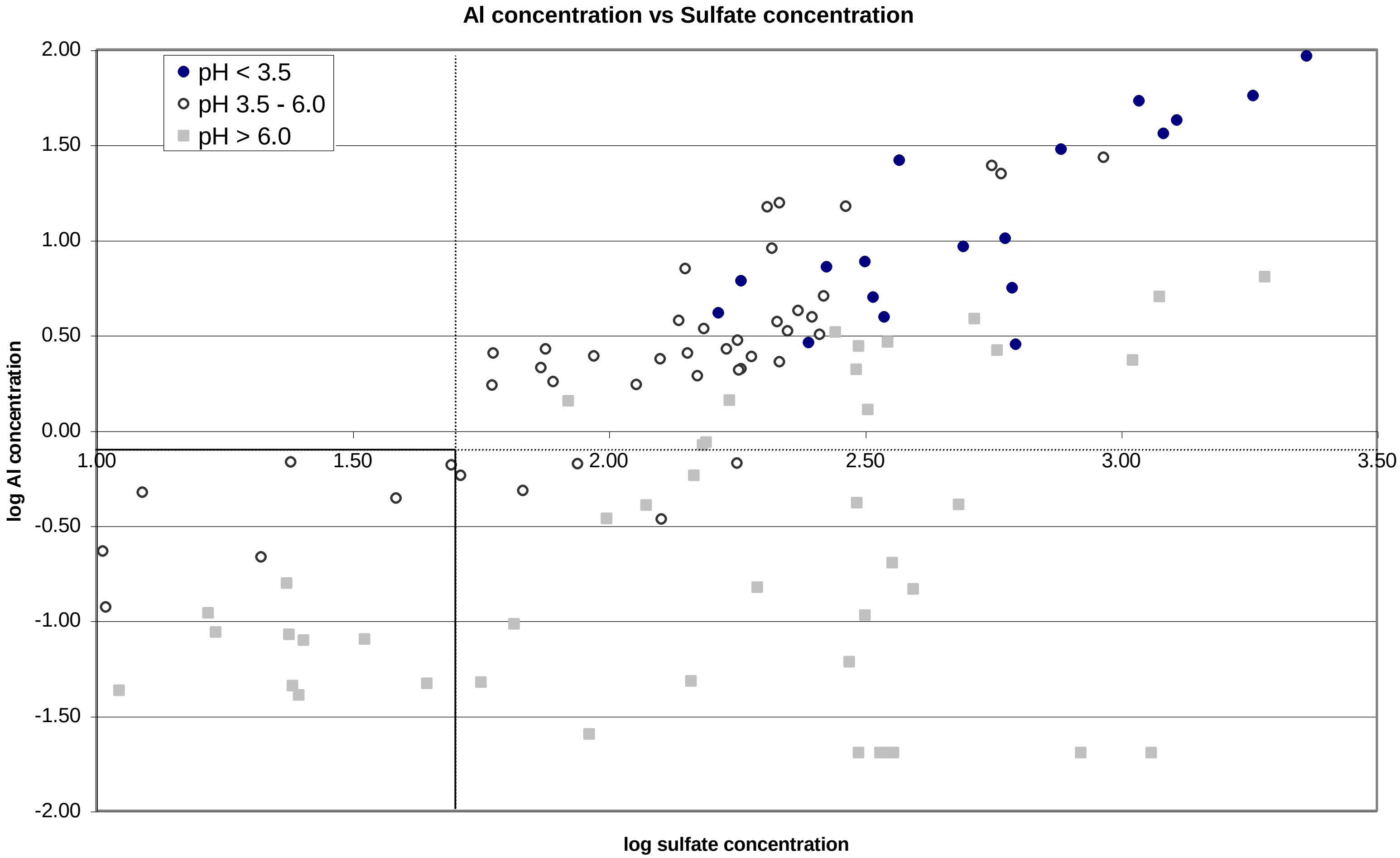

Figure 2. Al concentration as a function of sulfate concentration.

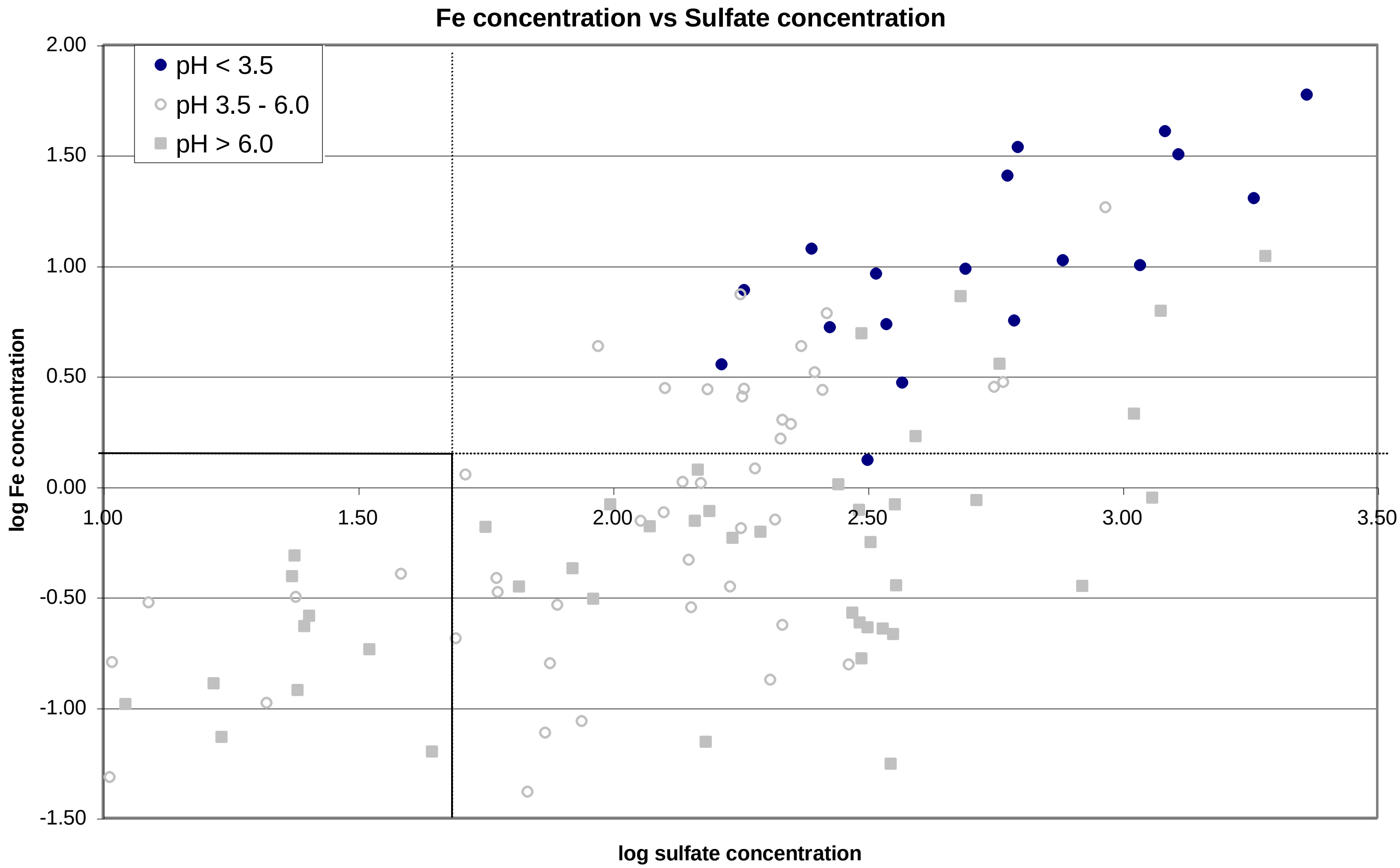

Figure 3. Fe concentration as a function of sulfate concentration.

Therefore, high sulfate concentration by itself did not indicate that stream waters would contain Fe concentrations higher than the Fe criterion value. Similar results were observed for Mn concentrations versus sulfate and pH as for the other metals.

Five categories of water were identified based on sulfate and pH (Figure 4). The categories included:

- Category 1 - strongly acidic water with strong AMD impact (pH<3.5);
- Category 2 - acidic water with AMD impact (3.5<pH<6 and sulfate>50mg/L);
- Category 3 - acidic water without serious AMD impact (3.5<pH<6 and sulfate<50mg/L);
- Category 4 - non-acidic water with AMD impact (pH>6 and sulfate>50mg/L);
- Category 5 - non-acidic water without serious AMD impact (pH>6 and sulfate<50mg/L).

Category 1 represents the most severe AMD impact. Our results showed that at pH<3.5, stream waters in this study always had sulfate concentration higher than the sulfate cutoff concentration of 50 mg/L suggested by Herlihy et al. (1990). Moreover, at pH <3.5, sulfate and pH had a strong correlation with correlation coefficient = -0.82. Every site with pH<3.5 had metal concentrations above the criteria values. Consequently, the observation that pH<3.5 was adequate to predict severe AMD impact.

Categories 3, and 5 represented the least AMD impact, i.e. when sulfate concentration was less than 50 mg/L. These waters contained net alkalinity or very little acidity. There was net alkalinity whenever pH was above 6, the PA water quality criterion. Metal concentrations were less than criteria whenever sulfate concentrations were less than 50 mg/L.

Summary and Recommendations

Based on monitoring and TMDL analysis, the 106 sampling sites were divided into five categories.

Strongly acidic waters with strong AMD impact (Category 1, Table 2) were defined entirely by low pH (pH<3.5). These waters always had extremely high sulfate concentrations and typically had high metal concentrations (see Table 2). These sites accounted for 17% of sites in this study. In addition to the consistently high acidity and metal concentrations, the metals are likely to be in the more toxic dissolved forms. It is proposed that 3 to 4 sampling expeditions during one year would be adequate to represent the water quality and to calculate the TMDL.

Table 2. Average and standard deviation values and the required percent removal of metals and acidity for Category 1 (strongly acidic waters with strong AMD impact).

Site	Average		Sulfate		Acidity		Al		Fe		Mn		% Removal			
	pH	Flow (gpm)	(mg/L)		(mg/L as $CaCO_3$)		(mg/L)		(mg/L)		(mg/L)		Acidity	Al	Fe	Mn
			ave	std	ave	std	ave	std	ave	std	ave	std				
149	2.73	5	2315	89	812	48	91.50	10.61	58.50	2.12	4.68	0.25	100	99	98	81
145	2.93	70	1819	455	516	73	56.67	3.79	20.00	1.00	3.60	0.56	100	99	93	80
21	2.97	320	1090	458	452	130	52.95	27.49	9.91	5.87	24.62	13.24	100	99	95	99
5	3.04	9	627	219	156	57	2.78	0.59	34.00	13.70	11.82	4.47	100	83	98	96
38	3.11	2897	598	319	175	96	10.09	4.82	25.19	13.24	12.50	7.26	100	97	98	97
141	3.14	1048	1217	594	370	88	35.75	6.50	40.00	14.65	3.61	0.54	100	99	98	80
143	3.14	14	1293	339	464	81	42.00	5.60	31.50	4.43	3.40	0.29	100	99	97	76
24	3.14	1063	496	223	124	20	9.13	1.65	9.58	1.38	11.32	3.29	100	94	89	95
56	3.15	832	318	137	79	23	7.58	3.64	1.30	0.36	1.31	0.40	100	96	37	60
7	3.26	419	616	395	93	27	5.51	3.40	5.57	4.13	6.82	4.97	100	96	93	96
23	3.26	188	372	143	202	36	25.83	3.66	2.92	2.34	7.82	3.58	100	98	87	95
64	3.31	2960	182	78	73	22	6.02	1.71	7.63	2.72	1.33	0.29	100	93	91	53
6	3.37	919	247	117	73	40	2.85	0.94	11.82	5.70	4.58	2.39	100	87	95	92
142	3.38	975	768	136	224	87	29.50	12.02	10.46	5.01	2.70	0.85	100	99	94	81
37	3.40	10513	330	320	86	93	4.93	4.55	9.10	7.51	7.25	6.32	100	97	96	97
9	3.43	2516	347	137	64	27	3.88	1.40	5.37	1.26	4.55	1.83	100	91	83	90
20	3.47	8297	268	128	83	37	7.11	1.90	5.18	2.25	5.76	2.81	100	94	88	93
67	3.50	4347	165	65	48	14	4.07	1.36	3.53	0.50	1.07	0.18	100	91	69	36

Acidic waters with AMD impact (Category 2, Table 3) were defined as having an average pH between 3.5-6.0 and sulfate greater than 50 mg/L and accounted for 35% of total sites. TMDL analyses showed that metals had to be removed at all sites in this category, to comply with water quality criteria. Al concentrations exceeded criteria at every site in this category. Removal of Fe was required at 25 of the 37 sites, and removal of Mn was required at 34 of the 37 sites. Standard deviations showed that water quality parameters fluctuated more than for category 1 waters. Therefore, at least 6 samples, spread over one year, should be taken for category 2 waters.

Table 3. Average and standard deviation values and the required percent removal of metals and acidity for Category 2 (acid waters with AMD impact).

Site	Average		Sulfate		Acidity		Al		Fe		Mn		% Removal			
	pH	Flow	(mg/L)		(mg/L as $CaCO_3$)		(mg/L)		(mg/L)		(mg/L)		Acidity	Al	Fe	Mn
		(gpm)	ave	std	ave	std	ave	std	ave	std	ave	std				
8	4.30	2377	52	24	21	18	0.57	0.32	1.12	0.62	0.60	0.38	99	54	53	47
28	3.84	183	60	11	26	3	1.70	0.76	0.38	0.33	0.74	0.34	100	82	7	47
17	4.30	79	60	55	22	4	2.52	0.31	0.33	0.67	0.77	0.17	100	78	44	21
58	4.71	1989	68	36	8	3	0.48	0.30	0.04	0.02	0.18	0.07	95	51	0	0
11	4.19	120	74	32	21	3	2.10	0.44	0.08	0.08	0.62	0.04	100	77	0	0
13	4.05	28	76	13	25	2	2.63	0.49	0.16	0.09	1.63	0.26	100	81	0	57
124	4.97	807	78	5	13	6	1.78	0.74	0.29	0.21	1.90	0.16	96	82	0	57
57	5.64	2604	87	45	4	3	0.66	0.28	0.09	0.04	0.18	0.04	82	52	0	0
69	3.83	1409	94	30	31	8	2.42	0.54	4.27	3.36	0.65	0.15	100	81	91	7
39	4.94	4798	114	51	13	9	1.72	0.44	0.69	0.13	0.89	0.15	85	75	0	23
62	3.86	646	127	52	27	4	2.34	0.40	0.76	0.17	1.77	0.25	100	78	0	60
63	5.81	1325	127	51	7	6	0.34	0.25	2.75	0.78	0.58	0.16	85	40	70	3
125	4.11	547	138	63	34	7	3.73	0.54	1.04	0.26	2.85	0.13	100	85	17	68
26	3.73	122	142	39	58	14	6.98	2.23	0.46	0.37	2.60	0.57	100	94	20	76
61	4.29	591	143	62	25	2	2.50	0.37	0.28	0.25	1.87	0.23	100	78	0	59
15	4.04	9918	150	75	24	7	1.90	0.41	1.02	0.43	1.99	0.73	100	75	37	76
22	3.62	6957	154	61	42	20	3.37	0.86	2.72	1.10	3.62	1.86	100	87	76	90
68	4.41	5050	171	101	23	11	2.64	1.92	0.35	0.14	0.62	0.28	100	92	0	34
54	4.33	948	179	98	20	17	0.66	0.53	7.32	5.65	0.37	0.26	100	72	95	25
121	5.35	1526	179	28	10	7	2.93	0.56	0.64	0.06	2.70	0.28	91	83	0	71
51	4.72	6094	180	88	17	11	2.04	1.64	2.52	1.70	0.59	0.26	100	91	83	30
53	4.68	6568	182	81	16	13	2.08	1.46	2.74	0.87	0.62	0.27	100	90	72	32
123	5.97	326	191	102	5	14	2.40	1.57	1.20	0.76	2.60	1.71	80	91	61	89
19	3.67	36	205	43	106	22	14.75	3.00	0.13	0.16	4.34	0.99	100	97	0	86
12	3.55	64	209	49	80	24	8.91	4.54	0.70	0.39	4.31	2.23	100	97	27	92
4	3.70	1779	214	84	54	32	3.66	1.93	1.63	0.89	2.75	1.50	100	93	69	88
33	5.92	23916	217	113	-1	15	2.26	1.31	1.98	0.51	3.13	1.76	68	89	57	89
3	3.51	90	217	27	106	12	15.48	1.56	0.23	0.14	4.00	0.35	100	96	0	80
50	4.30	7067	225	116	26	13	3.29	2.12	1.89	0.67	0.91	0.46	100	93	62	59
41	3.88	3238	236	97	45	18	4.18	1.33	4.27	0.79	2.35	0.40	100	91	77	71
36	3.87	12710	251	148	45	32	3.88	2.99	3.25	1.45	5.35	3.34	100	95	81	94
42	3.78	907	259	92	43	10	3.13	0.58	2.70	0.62	6.80	2.00	100	84	66	92
43	3.82	2230	264	88	57	26	5.00	1.58	6.00	1.86	1.35	0.44	100	92	87	63
18	3.95	42	292	48	121	32	14.78	7.36	0.16	0.20	5.01	2.39	100	98	0	92
147	3.76	213	563	124	169	94	24.30	13.14	2.79	4.55	3.55	1.03	100	99	92	85
146	3.90	357	586	115	144	66	21.93	10.00	2.94	2.73	3.20	0.61	100	99	89	80
144	3.61	138	931	431	208	133	26.83	15.22	18.16	25.14	3.10	0.82	100	99	99	82

Acidic waters without serious AMD impact (Category 3, Table 4) were defined as having pH 3.5 -6.0 and sulfate concentration less than 50 mg/L, and accounted for seven of the 106 sites in this study. These waters also contained lower metal concentrations than in categories 1 and 2. Acidity was still a problem for Category 3 sites. For this category, the sampling objectives should include analysis of water quality during storm events and identification of the major sources of contaminant loads. Water should be sampled seasonally, at least 6 times during a one-year period. Continuous monitoring of conductivity and pH (along with water level) should be used to make sure that more serious contaminant episodes do not escape attention. Also, metal speciation should be analyzed, to determine whether total metals are accurate representations of discharge chemistry or merely indicators of erosion from riparian zones.

Table 4. Average and standard deviation values and the required percent removal of metals and acidity for Category 3 (acidic waters without serious AMD impact).

Site	Average		Sulfate		Acidity		Al		Fe		Mn		% Removal			
	pH	Flow	(mg/L)		(mg/L as $CaCO_3$)		(mg/L)		(mg/L)		(mg/L)		Acidity	Al	Fe	Mn
		(gpm)	ave	std	ave	std	ave	std	ave	std	ave	std				
66	4.78	379	10	4	7	2	0.23	0.04	0.05	0.03	0.10	0.02	100	0	0	0
14	5.80	23	10	5	5	4	0.12	0.13	0.16	0.17	0.03	0.01	84	0	0	0
16	5.85	9896	12	4	6	2	0.47	0.47	0.30	0.59	0.18	0.16	83	67	43	0
27	5.08	2760	21	7	5	2	0.21	0.10	0.10	0.07	0.11	0.01	89	0	0	0
25	4.49	2436	24	9	11	3	0.67	0.35	0.31	0.22	0.39	0.25	100	59	0	21
133	5.20	250	39	52	4	3	0.44	0.31	0.40	0.38	0.08	0.04	90	52	16	0
59	4.95	531	50	31	8	3	0.65	0.58	0.20	0.14	0.85	0.55	92	72	0	65

Non-acidic water with AMD impact (Category 4, Table 5) had average pH between 6.0-8.0 (compliant with the criteria) but sulfate greater than 50 mg/L (indicating AMD impact). Category 4 accounted for 34 of the 106 sample sites. Metals might be precipitated at these pH values, and therefore less toxic or non-toxic for aquatic organisms (Gitelman, 1989; Sigel, 1986; Sigel and Sigel, 1988; Sigel and Sigel, 2000). For example, total Al was high enough to require removal in 8 of the 34 sites in Category 4, but $Al(OH)_{3[s]}$ precipitates rapidly at these pH values, whether or not oxygen is present in the water or not, and it is unlikely that dissolved or monomeric Al would exceed criteria values for any sites in this category. Similarly, Fe(II) is rapidly oxidized to Fe (III) and then precipitated as $Fe(OH)_{3\,[s]}$ when there is any oxygen in the stream and pH is greater than 7.0. For many of these waters, sulfate concentration was the only indicator that could be used to indicate an AMD impact. Water sampling strategies should deal with dissolved metal concentrations, to determine whether metals comply with the water quality criteria. Continuous monitoring of conductivity would be useful. At least 6 water samples over a one-year period are suggested for category 4 waters.

Table 5. Average and standard deviation values and the required percent removal of metals and acidity for Category 4 (non-acidic waters with AMD impact).

Site	Average		Sulfate		Acidity		Al		Fe		Mn		% Removal			
	pH	Flow	(mg/L)		(mg/L as $CaCO_3$)		(mg/L)		(mg/L)		(mg/L)		Acidity	Al	Fe	Mn
		(gpm)	ave	std	ave	std	ave	std	ave	std	ave	std				
148	7.38	7	57	9	-67	8	0.05	0.03	0.65	0.15	0.20	0.10	0	0	0	0
35	7.97	5423	66	46	-107	38	0.10	0.12	0.35	0.39	0.06	0.04	0	0	18	0
10	7.14	868	84	8	-19	16	1.41	1.02	0.42	0.51	0.71	0.09	0	86	35	0
103	7.42	932	92	54	-53	13	0.03	0.01	0.31	0.11	0.20	0.08	0	0	0	0
132	7.14	1677	100	60	-16	3	0.34	0.11	0.82	0.34	2.23	1.12	0	0	21	83
31	7.49	6322	119	77	-40	21	0.40	0.33	0.65	0.39	0.80	0.40	0	55	25	54
108	7.63	1822	146	27	-64	13	0.05	0.05	0.69	0.37	0.27	0.05	0	0	25	0
131	7.06	1836	148	65	-11	7	0.57	0.27	1.18	0.60	2.90	0.93	0	48	53	83
55	6.68	477	153	75	-4	6	0.82	0.32	0.07	0.04	1.39	0.30	32	59	0	55
34	6.12	6611	156	42	4	5	0.85	0.52	0.77	0.48	0.83	0.22	64	72	39	32
44	6.27	453	173	114	5	2	1.42	1.34	0.58	0.50	0.64	0.13	54	89	39	0
104	7.39	390	196	32	-37	12	0.15	0.14	0.62	0.66	0.25	0.14	25	0	54	0
164	7.34	215	279	101	-21	8	3.23	2.57	1.01	0.70	0.96	0.09	0	94	59	15
118	7.68	3227	297	46	-49	14	0.06	0.08	0.27	0.30	0.46	0.70	0	0	0	69
155	6.85	3362	306	135	-28	9	2.06	1.56	0.77	0.58	0.31	0.13	20	90	49	0
112	7.67	534	306	28	-65	7	0.41	0.67	0.24	0.20	0.57	0.39	0	75	0	48
153	7.57	6	309	149	-78	34	2.72	3.65	4.88	7.90	0.45	0.28	0	96	96	30
107	7.84	141	310	29	-106	9	0.02	0.00	0.17	0.12	0.11	0.07	0	0	0	0
115	7.65	2663	318	64	-47	14	0.11	0.17	0.23	0.25	0.42	0.37	0	0	0	46
156	7.45	3020	323	81	-29	8	1.27	0.39	0.55	0.13	0.28	0.11	10	69	0	0
117	7.65	1588	341	42	-61	16	0.02	0.00	0.23	0.26	0.15	0.16	0	0	0	0
154	7.22	44	353	77	-17	21	2.87	3.16	0.06	0.05	0.25	0.21	0	95	0	2
114	7.62	2153	356	55	-45	18	0.02	0.00	0.21	0.18	0.61	0.40	0	0	0	52
113	7.48	2045	360	42	-38	21	0.20	0.29	0.82	0.48	0.96	0.54	0	45	41	66
111	7.34	1195	362	92	-23	5	0.02	0.00	0.35	0.08	1.48	0.71	0	0	0	74
105	7.59	10	396	66	-180	16	0.15	0.25	1.67	1.78	1.63	0.68	0	32	83	74
162	7.11	211	485	123	-23	8	0.40	0.54	7.18	2.50	3.05	1.03	0	72	90	84
152	6.84	999	520	106	-17	14	3.81	0.72	0.86	0.13	0.71	0.09	0	87	0	0
151	6.98	435	577	108	-50	25	2.60	0.29	3.55	2.65	1.06	0.19	0	78	89	37
167	7.62	2162	840	260	-65	4	0.02	0.00	0.35	0.26	1.04	0.58	0	0	0	66
165	6.89	1643	1059	483	-37	71	2.31	4.46	2.11	3.14	3.40	3.97	50	96	89	95
163	7.58	1502	1151	323	-80	18	0.02	0.00	0.88	0.72	2.09	0.72	0	0	59	77
166	6.33	407	1194	335	-11	58	4.98	4.14	6.16	5.21	4.97	3.37	80	96	94	94
161	7.12	410	1917	304	-146	28	6.31	2.77	10.93	5.44	6.40	0.62	0	95	95	87

Non-acidic water without serious AMD impact (Category 5, Table 6) accounted for 9% of the total sites in this study. These waters had neutral pH, low sulfate, low metal concentration, and low acidity, although there was a record of abandoned mines in these areas. TMDL analyses indicated that neither metals nor acidity would have to be removed, in order to comply with criteria (except for site #1). Conductivity and pH should be monitored continuously at these sites, to investigate the effects of extreme water levels. TMDL reports for these streams could result in a change of regulatory category, from "non-attainment" of water quality criteria to "attained" status. In order to be confident in making this change, at least 6 samples should be collected from these streams.

Table 6. Average and standard deviation values and the required percent removal of metals and acidity for Category 5 (non-acid waters without serious AMD impact).

Site	Average		Sulfate		Acidity		Al		Fe		Mn		% Removal			
	pH	Flow	(mg/L)		(mg/L as $CaCO_3$)		(mg/L)		(mg/L)		(mg/L)		Acidity	Al	Fe	Mn
		(gpm)	ave	std	ave	std	ave	std	ave	std	ave	std				
134	7.53	1146	11	7	-29	4	0.04	0.03	0.10	0.11	0.02	0.01	0	0	0	0
1	6.49	6004	17	15	5	4	0.11	0.10	0.13	0.04	0.06	0.06	76	0	0	0
2	6.73	35	17	7	-11	6	0.09	0.10	0.07	0.05	0.06	0.05	0	0	0	0
102	7.32	57	24	9	-38	13	0.16	0.11	0.39	0.25	0.25	0.23	0	0	0	0
65	7.00	683	24	8	-9	9	0.08	0.06	0.48	0.22	0.24	0.11	0	0	0	0
32	7.61	14722	24	12	-38	25	0.05	0.06	0.12	0.10	0.03	0.01	0	0	0	0
122	7.35	62	25	2	-30	10	0.04	0.03	0.23	0.15	0.06	0.04	0	0	0	0
101	7.29	560	26	3	-22	11	0.08	0.06	0.26	0.17	0.03	0.01	0	0	0	0
52	7.41	197	34	21	-24	7	0.08	0.08	0.18	0.15	0.04	0.02	0	0	0	0
60	6.61	38	44	42	-3	4	0.05	0.05	0.06	0.05	0.03	0.01	0	0	0	0

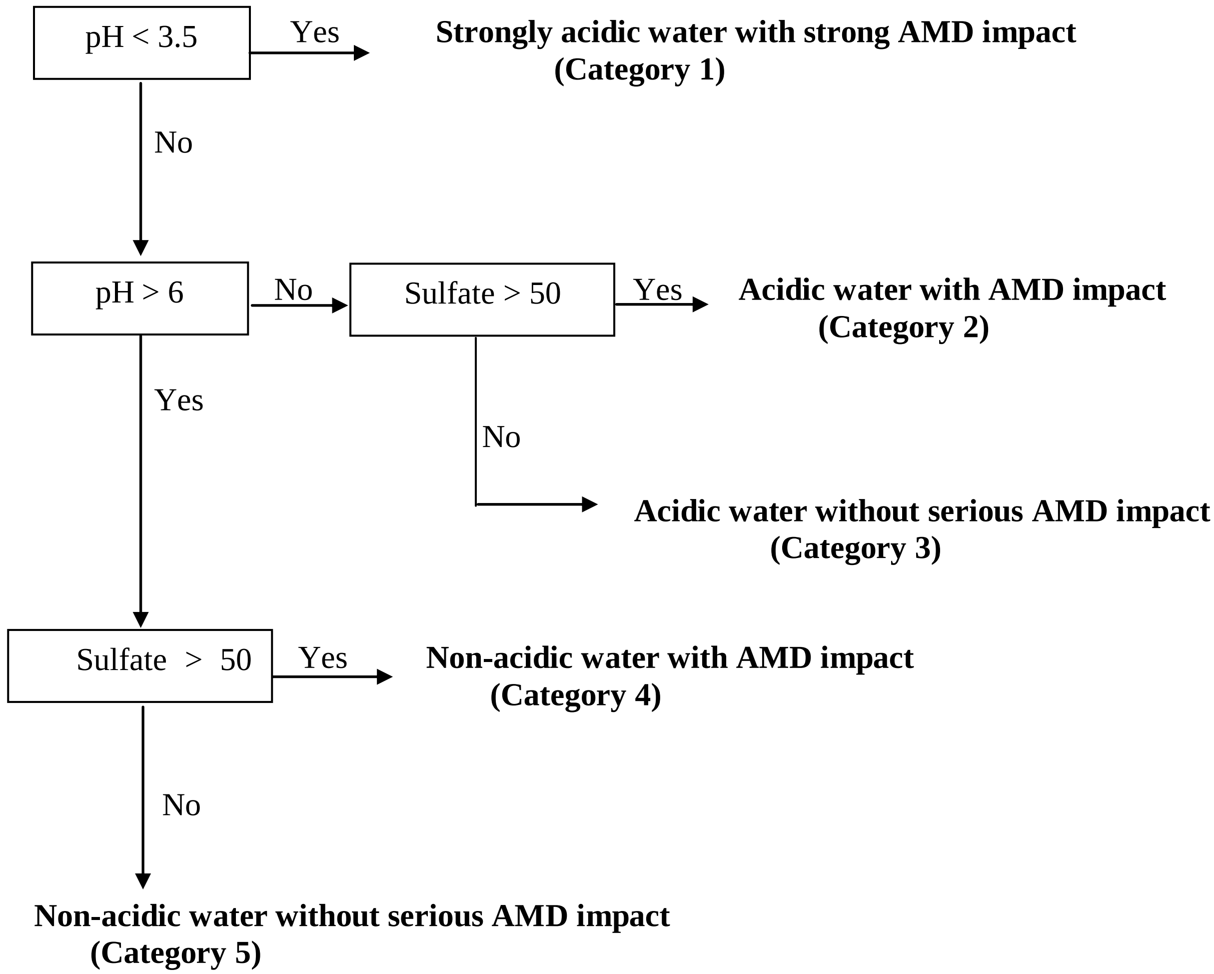

Figure 4. Categories of AMD impacts based on pH and sulfate concentration.

Citations

Bencala, K.E., McKnight, D.M., and Zellweger, G.W. 1987. Evaluation of natural tracers in an acidic and metal-rich stream, Water Resources Research, 23(5):827-836. http://dx.doi.org/10.1029/WR023i005p00827.

Bureau of District Mining Operations, PADEP. October 2000. *McKee Run Watershed TMDL for Acid Mine Drainage Affected Segments.*

Christman, J.N. 1999. Total Maximum Daily Loads (TMDL), *Environmental Regulation and Permitting*, 8(4):5-38.

Gitelman, H.J. 1989. *Aluminum and health: A critical review*, Marcel Dekker, Inc, New York, 294 pp.

Gray, N.F. 1996. Field assessment of acid mine drainage contamination in surface and ground water, Environmental Geology, 27:358-361. http://dx.doi.org/10.1007/BF00766705.

Herlihy, A.T., Kaufmann, P.R., Mitch, M.E., and Brown, D.D. 1990. Regional estimates of acid mine drainage impact on streams in the Mid-Atlantic and southeastern United States, Water, Air, and Soil Pollution, 50:91-107. http://dx.doi.org/10.1007/BF00284786.

Sams, J.I., and Beer, K.M. 2000. Effects of coal-mine drainage on stream water quality in the Allegheny and Monongahela River basins-sulfate transport and trends, U.S. Geological Survey, Water-Resources Investigations Report 99-4208, 17 pp.

Sears, E.B. 1998. Rebirth of EPA's TMDL program, *Environmental Regulation and Permitting*, 8(1):85-94.

Sigel, A., and Sigel, H. 2000. Manganese and its role in biology processes, *Metal ions in biology systems,* Marcel Dekker, Inc, New York, page 37, 761 pp.

Sigel, H. 1986. Concepts on metal toxicity, *Metal ions in biology systems*, Marcel Dekker, Inc, New York, page 20, 386 pp.

Sigel, H., and Sigel, A. 1988. Aluminum and its role in biology, *Metal ions in biology systems*, Marcel Dekker, Inc, New York, page 24, 424 pp.

U.S. Environmental Protection Agency. 1991. *Guidance for water quality-based decisions: The TMDL process*, EPA 440/4-91-001, Washington D.C.

U.S. Environmental Protection Agency. 1999. *Draft guidance for water quality-based decisions: The TMDL process second edition,* EPA 841-D-99-001, Washington D.C.