NORTH FORK WATERSHED ASSESSMENT AND RESTORATION PLAN

JEFFERSON COUNTY, PENNSYLVANIA

FINAL REPORT

NORTH FORK WATERSHED ASSOCIATION

In Cooperation with

THE JEFFERSON COUNTY CONSERVATION DISTRICT

A PADEP Growing Greener Project

North Fork Watershed Assessment and Restoration Plan

FINAL REPORT

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February 10, 2006

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TABLE OF CONTENTS

Page

Appendices (Under Separate Cover)

EXECUTIVE SUMMARY

The North Fork watershed, located in Jefferson County, Pennsylvania, is adversely impacted to varying degrees by atmospheric acid deposition, or acid rain. Under a Pennsylvania Growing Greener Grant, a study was conducted by the North Fork Watershed Association in cooperation with the Jefferson County Conservation District to identify acidification problem areas and quantify potential alkaline addition requirements to restore impacted reaches. The study consisted of an in-stream water quality and flow monitoring program conducted at 25 sample points for 11 collection runs, and sampling of soils at 16 headwaters sites to determine calcium/aluminum ratios as an indication of soil acidification.

Results show that acidification impacts are concentrated in two problem areas, located in the northwest and northeast portions of the watershed. Degree of acidification is correlated to exposed bedrock geology, with lower (older) units having low inherent alkalinity being responsible in part for excess acidity. Tributaries with headwaters in higher (younger) sediments are generally net alkaline. Although not assessed as part of this study, tannin (bog) acidity may also be a portion of the overall acidification problem. An assessment was made of the extent of acidification, types of acidification present (negligible, sustainable, episodic, and chronic), degree of acidity loading and alkaline deficiency in each stream, and of potential downstream effects of alkaline addition activities. Episodically and chronically acidified streams are most in need of alkaline addition.

A review was conducted of potentially applicable alkaline addition technologies, grouped into direct addition methods (limestone sand dosing, lake liming, high flow buffer channels, land application liming, and road surface liming) and controlled addition methods (limestone diversion wells, limestone rotary drums and basket wheels, vertical flow wetlands, and pebble quicklime systems). Applicability and cost comparisons were made between the addition methods, and conceptual alternatives for primary and supplemental alkaline addition were suggested for each stream.

A progressive restoration plan was developed to provide a suggested sequence of progressively achievable alkaline addition projects resulting in measurable environmental benefits. The total cost of implementing the progressive restoration plan for the North Fork watershed is estimated between $1.0 and $6.5 million depending on the types of alkaline addition applied, with an approximately $500,000 needed to maintain the restoration projects over a 15 year projection period.

INTRODUCTION

The North Fork of Redbank Creek is a freestone stream located in Jefferson County, Pennsylvania. The surrounding region of the Appalachian Plateau has been impacted by atmospheric acid deposition (acid rain) for decades, resulting in stream impairment and soil acidification. As shown by Figure 1, the North Fork watershed is situated within the zone of lowest rainfall pH within the state. Bedrock in this region is largely deficient in neutralizing alkalinity, leaving watersheds susceptible to long-term acidification and water quality degradation. Watersheds in the vicinity of the North Fork have shown depleted or extirpated fish populations because of this effect. Historic sampling indicates that portions of the North Fork and its tributaries are acidified, but a systematic assessment of water quality and flows was not previously available to quantify these impacts.

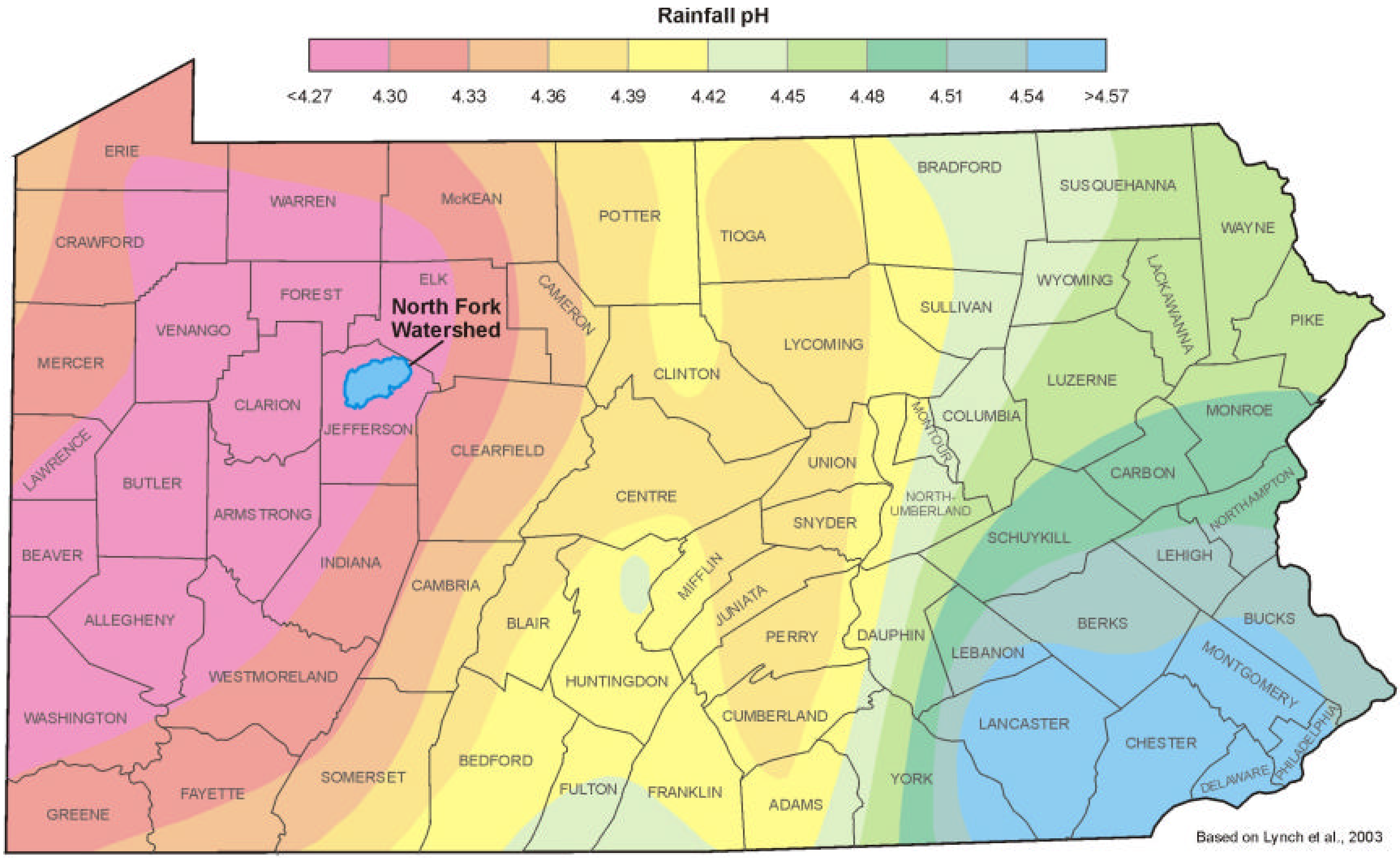
To determine existing stream conditions and identify areas where acid abatement activities might be beneficial, a watershed-scale assessment has been undertaken by the North Fork Watershed Association (NFWA) using a Pennsylvania Growing Greener Grant sponsored by the Jefferson County Conservation District (JCCD). A monitoring program consisting of 25 in-stream sample points was conducted for 11 sample rounds between June 2004 and August 2005. Soil samples were also collected at 16 locations throughout the watershed to determine acidification conditions in soils.

The monitoring results were analyzed to determine types of stream acidification impacts (negligible, sustainable, episodic, or chronic), influence of soils and bedrock geology, degree of alkaline deficiency in adversely affected streams, and potential effects of acid abatement. Conceptual alkaline addition options were reviewed to address adversely impacted streams, and a progressive restoration plan was developed with a suggested course of acid abatement activities in the North Fork watershed. This report summarizes the results of this study and provides recommendations for future work in support of the restoration plan.

North Fork Watershed Facts

Drainage Basin:	**Allegheny/Ohio River**
Subbasin:	**W17C – Redbank Creek**
Drainage Area:	» **100 square miles**
State Game Lands:	**32.5 square miles**
Stream Reach:	**700+ miles**
Classification:	**High Quality – Exceptional Value**

Figure 1 – Project Location and Average Annual Rainfall pH for Pennsylvania (2003)



METHODS

An in-stream water quality and flow monitoring program was established for 25 sample points on the main stem of the North Fork and selected tributaries. These points were located at the sites of historic sampling conducted by the NFWA and use the same sample point designations. Sampling was conducted at intervals of approximately 6 weeks between June 2004 and August 2005, yielding 11 sample rounds. An additional one-round soil sampling program was conducted on May 15, 2005 at 16 points located in headwaters settings. Figure 2 shows the sample point locations for the two monitoring programs relative to the North Fork watershed and local landmarks, and the following summarizes the methodologies applied.

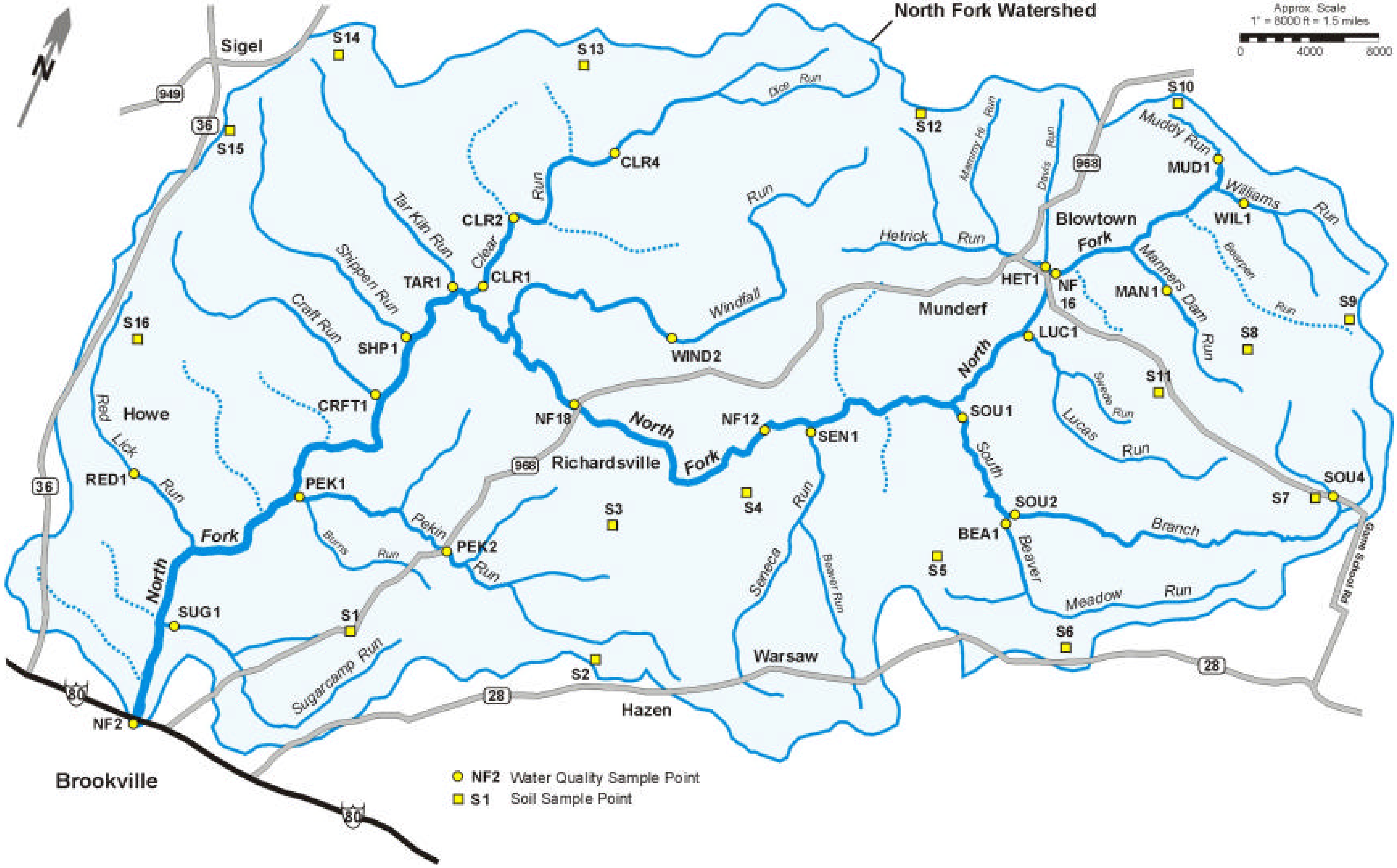
Water Sampling

Water samples were collected using the grab method with sample bottles provided by Analytical Services, Inc. laboratory of Brockway, Pennsylvania. Field parameters measured at the time of sampling included flow, temperature, pH, and conductivity. Samples were transported in coolers for delivery to Analytical Services, where laboratory parameters were analyzed except for acid neutralization capacity, which was analyzed by the Penn State Environmental Resources Research Institute Laboratory. Table 1 provides a summary of the sample parameters and analysis methods used for the water monitoring program.

Table 1 –Water Quality Monitoring Parameters

Parameters	Units	Analysis Method
Field		
Flow	gallons/minute (gpm)	Cross-Sectional Velocity
pH	standard units (SU)	pH Meter
Temperature	degrees Centigrade (C^o)	Thermometer
Conductivity	microsiemens (*u*ohms/cm)	Conductivity Meter
Laboratory		
pH	standard units (SU)	EPA-150.1
Conductivity	microsiemens (*u*ohms/cm)	EPA-120.1
Acid Neutralization Capacity (ANC)	milliequivalents/liter (meq/L)	ERRI
Acidity	milligrams/liter (mg/L)	EPA-305.1
Alkalinity	milligrams/liter (mg/L)	EPA-310.1
Aluminum	milligrams/liter (mg/L)	EPA-200.7

Figure 2 – Water and Soils Monitoring Program Map



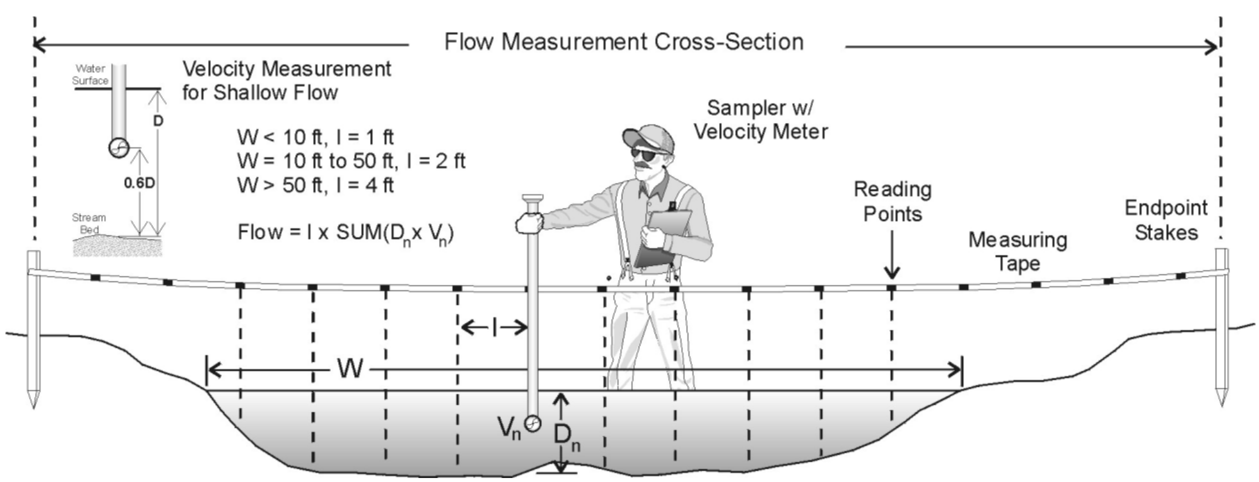
Field sampling was conducted by NFWA members with oversight and assistance from the JCCC and training from Water's Edge Hydrology. Flow measurements were taken by the cross-sectional velocity method (Figure 3) using a velocity meter at permanently marked stream sections. Raw data from the in-stream monitoring program are contained in Appendix A, with field flow data sheets contained in Appendix B, and representative photographs of the sample locations contained in Appendix C.

For some sample points, high flows or other site conditions prevented direct flow measurements on one or more dates. To estimate flows for these occasions, relationships were developed comparing known measured flows at the monitoring points to flows recorded on the same dates for Mahoning Creek at Punxsutawney (USGS Gaging Station 03034000). Mahoning Creek is directly adjacent to Redbank Creek, and its gaging station has a 158 square mile drainage area that is comparable to the 100 square miles contained in the North Fork. Flows at the North Fork sample points were found to be linearly related to those in Mahoning Creek, in most cases with R^2 values greater than 0.9. Where these relationships were used to estimate flows, the flow values in Appendix A are shown in italics.

Soil Sampling

Soil samples were collected from 16 sites selected to represent conditions in the general headwaters of the North Fork and its tributaries. Samples were collected by NFWA members under the technical supervision of Water's Edge Hydrology, and analyzed by the Penn State Agricultural Analytical Services Laboratory for aluminum stress test and other standard soil condition parameters. At each site, samples were taken from three separate locations by removing the organic horizon and collecting a portion of the exposed mineral soil. Care was taken not to include organic matter or soils containing roots greater than 1 mm in diameter. Complete results from the soil analyses are contained in Appendix D.

Figure 3 – Cross-Sectional Velocity Flow Measurement Method



RESULTS AND ANALYSES

Results from the water quality monitoring and soil sampling programs were analyzed to assess four primary considerations within the North Fork watershed: (1) the extent and degree of acidification impacts, (2) the relationship of soil and bedrock conditions to acidification, (3) the temporal nature of acidification and degree of alkaline deficiency in impacted streams, and (4) the water quality improvements that could be realized if the existing alkaline deficiencies were corrected. The following provides background information for understanding acidification effects, and a summary of these four evaluations as they relate to development of acid abatement strategies and a progressive restoration plan for the watershed.

Acidity, Alkalinity, pH, and ANC

Water is composed of hydrogen and oxygen in the formula H_2O. Water naturally breaks down to some extent into positively charged hydrogen ions (H^+) and negatively charged hydroxide ions (OH^-). The measurement of pH is the negative logarithm of the concentration of hydrogen ions, meaning that as the H^+ concentration goes up, the pH goes down. In the desirable pH range for fish, 6 to 9 standard units (SU), the concentrations of H^+ and OH^- are fairly equal. When the H^+ concentration begins to significantly exceed that of OH^-, water is considered to be acidic, and the pH measurement is lower. Acid mine drainage typically has a pH around 3 SU, and some colas are as low as 2 SU.

$$\mathbf{H_2O \text{ Þ } H^+ + OH^-}$$

$$\mathbf{pH = - Log[H^+]}$$

Alkalinity is the chemical opposite of acidity. Alkaline materials generate an excess of OH^- ions, which neutralize H^+ ions by reforming water. The most familiar alkaline material is limestone ($CaCO_3$). When limestone dissolves in water, it neutralizes acidity by the following reactions:

$$\mathbf{CaCO_3 + H_2O \text{ Þ } Ca^{2+} + HCO_3^- + OH^-}$$

$$\mathbf{OH^- + H^+ \text{ Þ } H_2O}$$

Both acidity and alkalinity are measured as the equivalent concentration as limestone, reported as milligrams of $CaCO_3$ per liter (mg/L). When the acidity concentration is greater than the alkalinity concentration, water is considered to be net acidic, and in the opposite case the water is net alkaline. A net acidity is a measure of the mass of limestone that would need to be added to bring water to a neutral state, or its *alkaline deficiency*. This measure is used in determining alkaline addition rates for stream restoration projects.

Another measure of relative acidity is acid neutralization capacity (ANC). This has the units of milliequivalents of $CaCO_3$ per liter (meq/L) and can be thought of as the ability of water to resist changes in pH resulting from the addition of acid. ANC is a good measure for assessing the health of a stream for supporting fish populations. A positive ANC normally represents survivable conditions for fish, while a negative ANC indicates unhealthy conditions. Water can be slightly net acidic and still have a positive ANC, so correcting an alkaline deficiency in a stream should produce the desirable positive ANC condition.

Extent of Acidification

Results from the in-stream monitoring program were analyzed to develop average and high flow water quality and quantity conditions in the North Fork watershed. Average values were determined as the arithmetic average of the raw sampling data. For a common level of comparison between streams, high flow conditions were established as being the 95% confidence interval (CI) flow for each data set. High flow loadings of ANC, net acidity, and aluminum were predicted for the 95% CI flows by linear regression of the loadings calculated for the individual sample dates in each data set. Concentrations of these parameters were then calculated for the 95% CI flows by dividing the loading predictions by the 95% CI flow and a conversion factor. A prediction was also made of the pH for the 95% CI flows based on a project-specific relationship developed between laboratory pH and ANC.

Average and high flow conditions determined from this analysis are summarized in Table 2, with N indicating the number of flow measurements for each sample point between June 2004 and August 2005. Observed ranges of pH and ANC are shown by sample point on Figures 4 and 5, respectively. Figures 6 and 7 graphically illustrate the average and high flow conditions. On the latter two figures, the conditions of individual streams or reach segments have been ranked from very good to severe using qualitative categories based on pH and ANC. These categories are summarized in Table 3 with comments relative to their implications for fish populations. Where no sampling data are available, some stream conditions have been inferred from upstream and downstream information.

On Figures 6 and 7, it is apparent that acidification impacts are concentrated in two primary problem zones: (1) a northwest area extending from Craft Run through Shippen Run and Tar Kiln Run to the headwaters of Clear Run, and (2) a northeast area extending from South Branch through Lucas Run, Manners Dam Run, and Williams Run to the headwaters of Muddy Run. These areas typically show fair to very poor quality under average flow conditions, and poor to severe quality under high flow conditions. Drainage from the northeast zone appears to cause impairment in the main stem of the North Fork as well, with fair to poor quality interpreted to extend downstream to the vicinity of Seneca Run. Although Clear Run is adversely impacted under high flow conditions, the drainage from the northwest zone does not appear to significantly impact the lower reaches of the North Fork.

Despite the observed impacts in some of its tributaries, the North Fork is typically of very good quality under average conditions, with a slight reduction to good quality under high flow conditions. This is likely due to a number of tributaries having good to very good quality under all flow conditions, including Sugarcamp Run, Red Lick Run, Pekin Run, Windfall Run, and Seneca Run. Given the conditions observed in the main stem and the mouth of the North Fork, the watershed as a whole appears to have sufficient excess alkalinity to offset localized deficiencies in the northeast and northwest problem areas.

Table 2 – Summary of In-Stream Monitoring Data for Average and High Flows

Sample Point	Values of Interest	Flow gpm	pH SU	Cond. mg/L	ANC mg/L	Alk.	Acid.	Net Acid	Al mg/L	N
NF2	Average	135816	6.45	63	209	10	3	-7	0.042	11
	High Flow Prediction	314653	5.92		74			-2	0.067	
SUG1	Average	2808	6.47	93	230	10	3	-7	0.055	9
	High Flow Prediction	8267	6.24		138			-7	0.089	
RED1	Average	3241	6.33	91	168	7	3	-4	0.026	11
	High Flow Prediction	8894	6.13		112			-3	0.055	
PEK1	Average	15498	6.47	74	262	12	4	-8	0.059	9
	High Flow Prediction	42945	6.02		92			-2	0.057	
PEK2	Average	9765	6.39	62	134	8	4	-4	0.040	11
	High Flow Prediction	31489	5.87		65			0	0.111	
CRFT1	Average	5915	5.95	41	24	3	3	1	0.039	11
	High Flow Prediction	16903	5.37		9			2	0.065	
SHP1	Average	4379	5.15	32	2	1	4	3	0.054	11
	High Flow Prediction	11368	5.11		-8			4	0.113	
TAR1	Average	5934	4.87	30	-6	1	5	4	0.082	11
	High Flow Prediction	17584	4.97		-14			4	0.164	
CLR1	Average	18217	6.05	34	121	5	3	-2	0.035	11
	High Flow Prediction	52889	5.35		8			2	0.087	
CLR2	Average	14720	6.20	36	140	6	4	-2	0.031	11
	High Flow Prediction	44266	5.50		20			2	0.088	
CLR4	Average	8180	5.87	27	66	3	4	1	0.047	11
	High Flow Prediction	29606	5.08		-9			3	0.140	
WIND2	Average	4950	6.20	47	232	6	5	-2	0.062	11
	High Flow Prediction	16359	5.80		54			0	0.071	
NF18	Average	47782	6.35	56	248	10	3	-7	0.069	11
	High Flow Prediction	124574	5.83		59			-2	0.123	
NF12	Average	30388	6.27	53	201	9	4	-5	0.054	11
	High Flow Prediction	75820	5.82		58			1	0.089	
SEN1	Average	4810	6.35	62	158	8	4	-4	0.041	11
	High Flow Prediction	13117	5.86		63			1	0.062	
SOU1	Average	12946	5.47	39	61	2	4	2	0.111	11
	High Flow Prediction	36046	5.35		8			3	0.169	
BEA1	Average	4239	6.34	52	160	8	4	-4	0.058	8
	High Flow Prediction	12118	6.09		104			-3	0.079	
SOU2	Average	11414	4.69	35	-12	1	6	5	0.191	9
	High Flow Prediction	32906	3.89		-36			7	0.295	
SOU4	Average	1613	4.58	41	-20	1	7	6	0.199	11
	High Flow Prediction	4848	4.13		-33			8	0.309	
LUC1	Average	5433	4.63	38	-13	0	6	5	0.129	11
	High Flow Prediction	14842	4.79		-21			5	0.081	
HET1	Average	6558	6.23	54	228	11	3	-7	0.057	11
	High Flow Prediction	18338	5.63		33			1	0.112	
NF16	Average	11839	5.27	34	84	2	5	3	0.108	11
	High Flow Prediction	29549	5.12		-7			4	0.160	
MAN1	Average	2607	4.71	35	-10	1	6	5	0.162	11
	High Flow Prediction	6299	4.66		-24			6	0.256	
WIL1	Average	1549	4.49	28	-15	0	7	6	0.224	11
	High Flow Prediction	3707	4.47		-29			7	0.357	
MUD2	Average	1154	5.18	41	44	2	6	5	0.084	11
	High Flow Prediction	3513	5.08		-9			5	0.141	

Table 3 – Summary of Relative Water Quality Rankings

Ranking	Criteria	Comments
Very Good	pH > 6.0 SU ANC > 100 meq/L	No significant acidification impacts, should support healthy fish populations.
Good	pH > 5.5 SU ANC 25 to 100 meq/L	Possible minor impacts, but suitable for fish during short-term storm acidification effects.
Fair	pH > 5 SU ANC 5 to 25 meq/L	Maintaining a positive ANC, but pH trending towards the low end of sustainability for fish.
Poor	pH > 4.5 SU ANC –10 to 5 meq/L	Usual negative ANC and reduced pH, poor to no buffering, reduced populations with few tolerant fish.
Very Poor	pH > 4 SU ANC –10 to –25 meq/L	Consistently negative ANC, likely not supportive of any significant fish populations.
Severe	pH > 3 SU ANC < -25 meq/L	Consistent and highly negative ANC, likely no fish populations and restricted benthic populations.

Influence of Soils and Geology

Figure 8 shows the exposed bedrock geology of the North Fork watershed relative to average water quality conditions, with soil sample locations shown for reference. The lowermost exposed units are Mississippian in age, trending upward through the Pennsylvanian Pocono Group and Allegheny Group. These sediments were deposited over millions of years by rivers draining from mountain-building events to the east. Progressive erosion of these historic mountains led to a fining-upward sequence from coarse sands and pebbles in the lower exposed units to finer fluvial sediments and shallow terrestrial deposits in the upper units. The lower sediments tend to be silicious and devoid of alkalinity, while the upper units of the Allegheny Group contain alkaline zones and local thin limestone beds in association with cyclical coal measures. Because of this stratigraphic sequence, the highest topography in the watershed tends to contain the greatest amount of inherent alkalinity.

Water quality in the North Fork watershed appears to be fairly well correlated to stratigraphy. Tributaries with headwaters within the alkaline Allegheny Group tend to be alkaline, while those with headwaters in the lower units tend to be acidified. This trend is also evident in the soil sample data. Composite results from the soil sampling program are shown in Table 4 and summarized on Figure 8 by their aluminum stress test results (ratio of calcium to aluminum, or Ca:Al). Those with a Ca:Al ratio less than 1 show evidence of acidified conditions, and those with higher ratios show progressively more alkaline conditions. This comparison of soils and geology is supportive of the supposition that some tributaries in the North Fork watershed contain excess alkalinity and have a degree of buffering protection against atmospheric acidification. The northeast and northwest problem areas have tributaries with headwaters mostly rooted in lower sedimentary units.

Figure 4 – Observed Ranges of pH for North Fork Sample Points

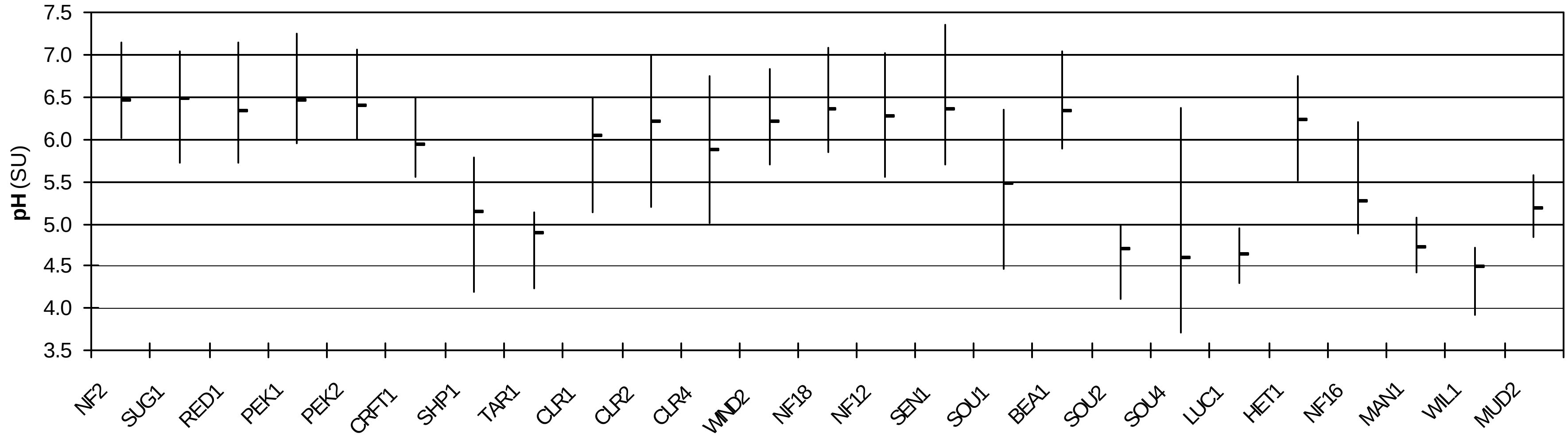


Figure 5 – Observed Ranges of ANC for North Fork Sample Points

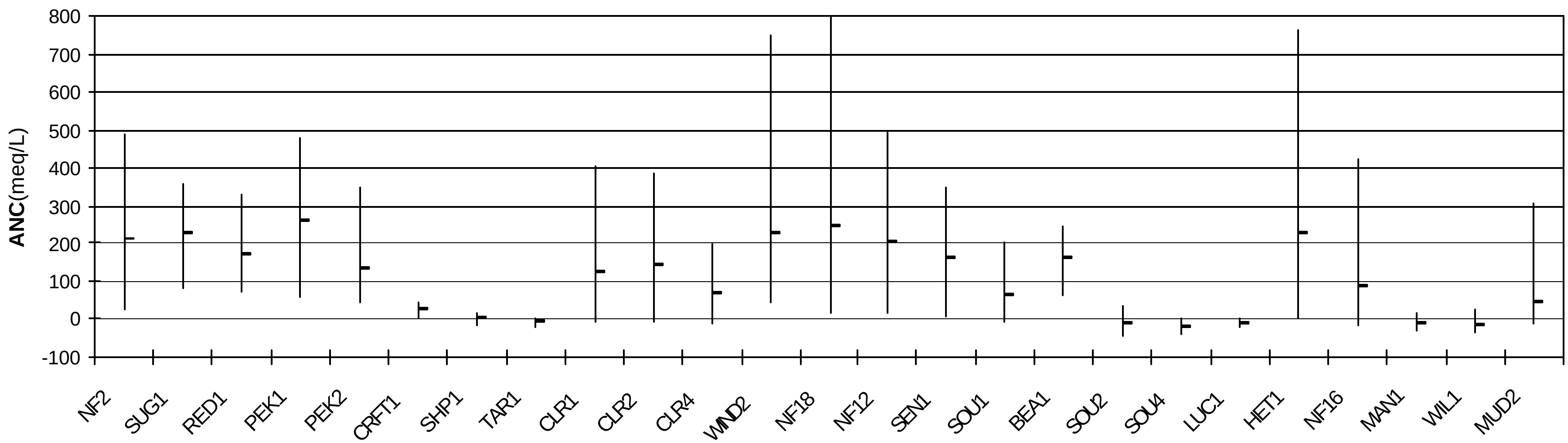


Figure 6 – North Fork Watershed Average Water Quality Conditions

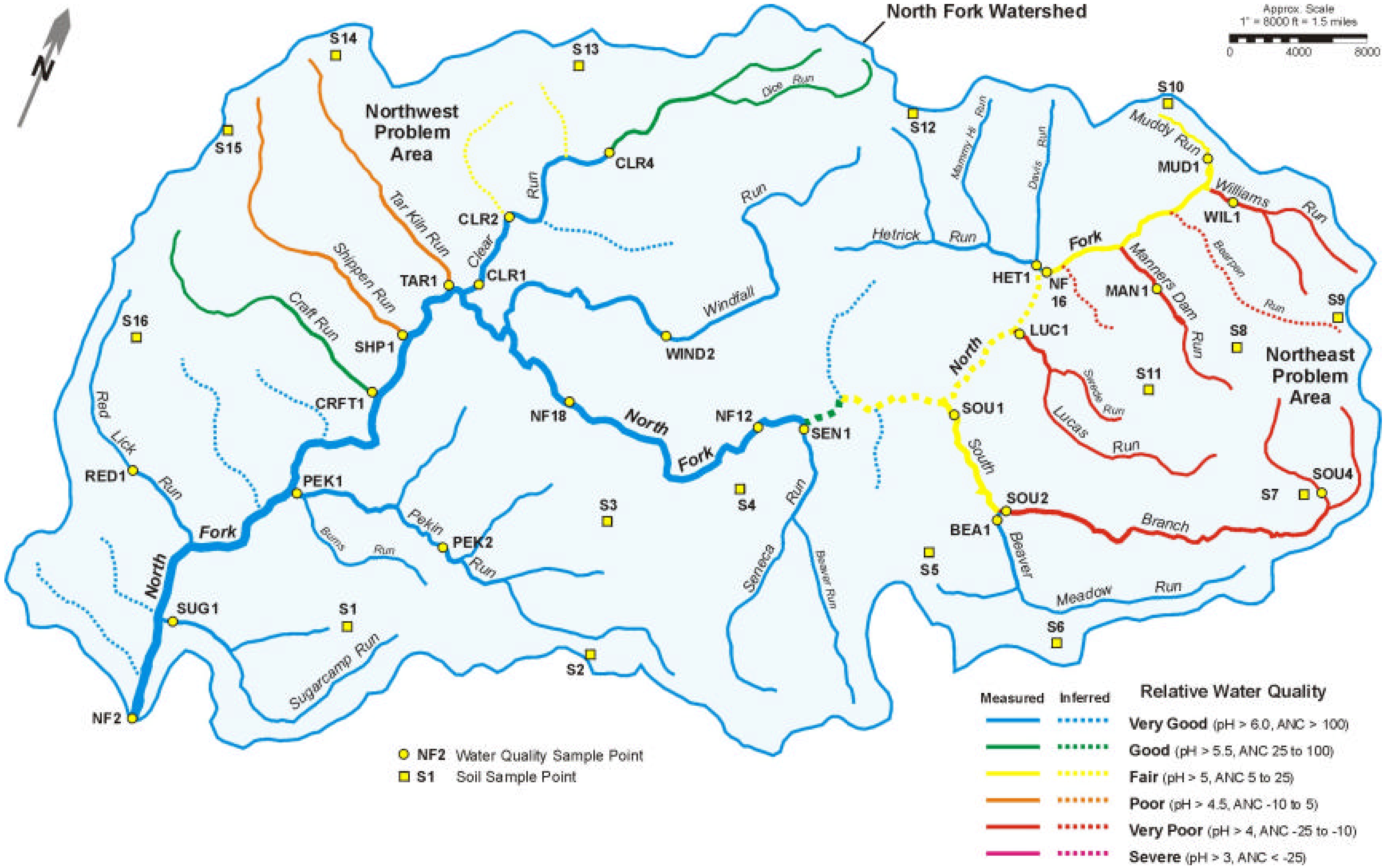


Figure 7 – North Fork Watershed High Flow Water Quality Conditions

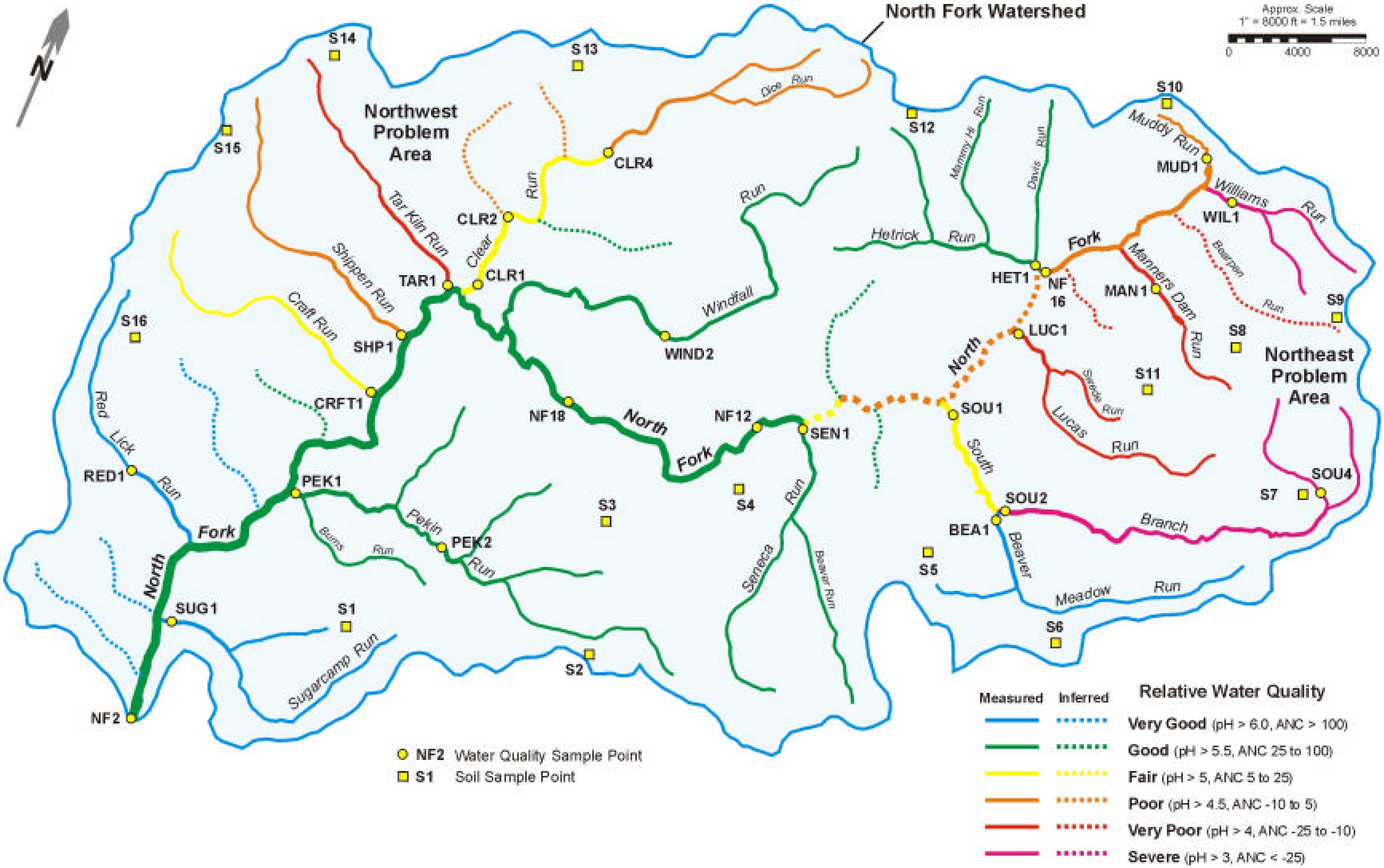


Figure 8 – North Fork Watershed Regional Geology and Soil Quality Map (Average Flow Conditions)

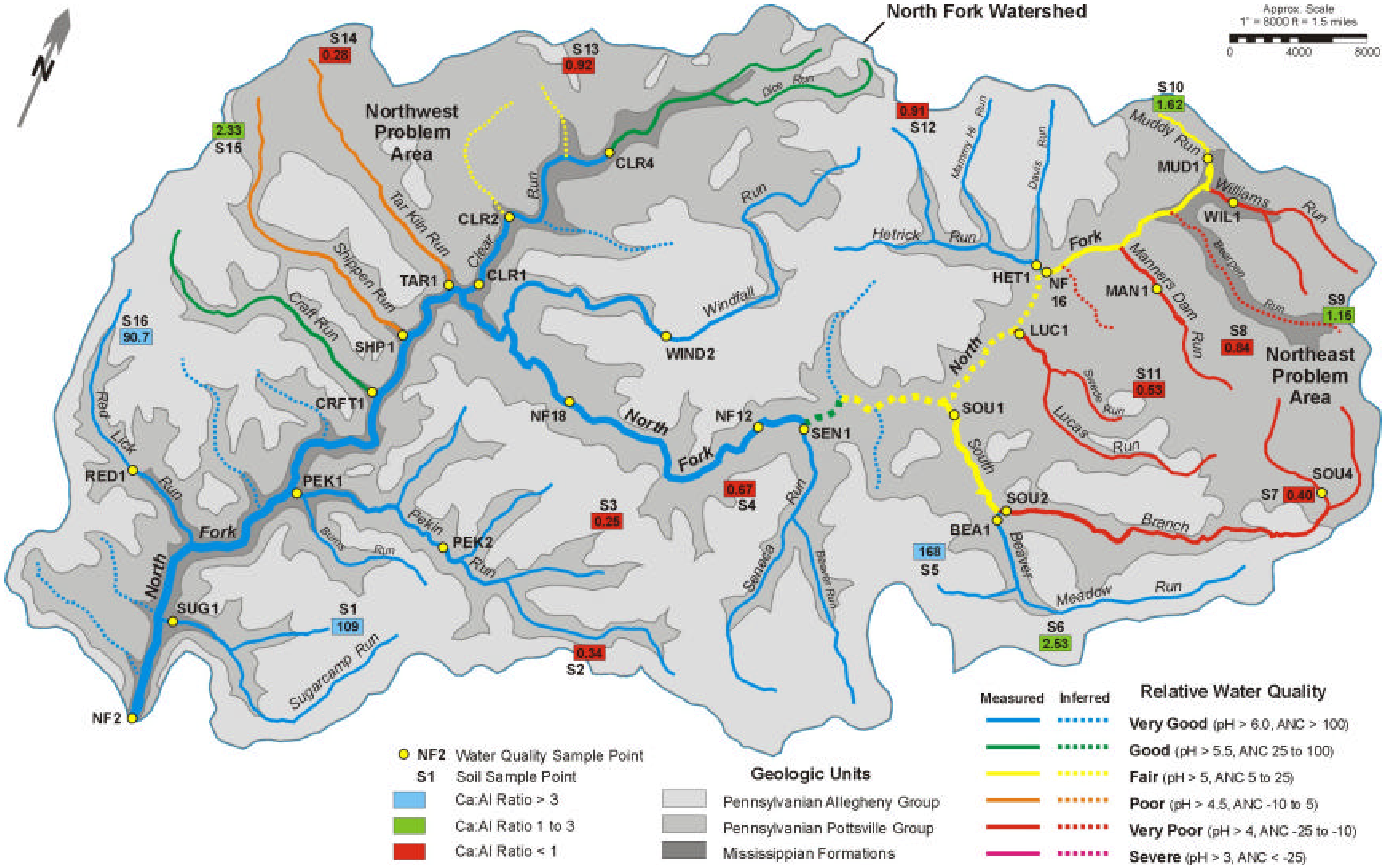


Table 4 – Summary of Soil Sampling Data

Sample Site	Serial #	Sample ID	Ca:Al Ratio	Avg. Ca:Al Ratio	Location - Watershed
1	18031	S04-36933	136.76	108.69	N 41?11.824? W 79?02.149?
	18032	S04-36940	91.07		Sugarcamp
	18033	S04-36936	98.25		
2	18034	S04-36921	0.37	0.34	N 41?12.472? W 78?59.081?
	18035	S04-36917	0.24		Pekin Run
	18036	S04-36928	0.42		
3	18037	S04-36931	0.31	0.25	N 41?13.775? W 78?59.508?
	18038	S04-36935	0.17		Pekin Run
	18039	S04-36932	0.27		
4	18040	S04-36927	0.36	0.67	N 41?14.612? W 78?58.085?
	18041	S04-36930	0.21		North Fork
	18042	S04-36939	1.43		
5	18043	S04-36937	354.52	168.21	N 41?14.772? W 78?55.473?
	18044	S04-36942	121.71		Seneca Run
	18045	S04-36926	28.41		
6	18046	S04-36922	2.76	2.53	N 41? 14.426? W 78?53.468?
	18047	S04-36918	2.98		Beaver Meadow Run
	18048	S04-36946	1.85		
7	18049	S04-36924	0.41	0.40	N 41?16.750? W 78?51.157?
	18050	S04-36919	0.37		South Branch
	18051	S04-36929	0.42		
8	18052	S04-36934	1.83	0.84	N 41?17.800? W 78?52.731?
	18053	S04-36925	0.34		Manners Dam Run
	18054	S04-36943	0.34		
9	18055	S04-36920	0.34	1.15	N 41?18.435? W 78?51.643?
	18056	S04-36952	1.74		Williams Run
	18057	S04-36953	1.37		
10	18058	S04-36923	0.75	1.62	N 41?19.742? W 78?54.787?
	18059	S04-36947	1.71		Muddy Run
	18060	S04-36938	2.39		
11	18061	S04-36951	0.58	0.53	N 41?17.038? W 78?53.611?
	18062	S04-36950	0.32		Lucas Run
	18063	S04-36941	0.68		
12	18064	S04-36954	0.24	0.91	N 41?18.707? W 78?57.885?
	18065	S04-36955	1.30		Hetrick Run
	18066	S04-36945	1.20		
13	18067	S04-36916	0.26	0.92	N 41?17.840? W 79?02.177?
	18068	S04-36913	2.39		Clear Run
	18069	S04-36912	0.12		
14	18070	S04-36948	0.30	0.28	N 41?17.004? W 79?05.239?
	18071	S04-36915	0.28		Tar Kiln Run
	18072	S04-36911	0.26		
15	18073	S04-36906	5.23	2.33	N 41?15.899? W 79?06.199?
	18074	S04-36909	1.23		Shippen Run
	18075	S04-36910	0.53		
16	18076	S04-36908	14.02	90.72	N 41?13.668? W 79?06.240?
	18077	S04-36907	204.99		Lick Run
	18078	S04-36949	53.14		

Quantification of Impacts

The degree of impact to a stream from acid deposition depends largely on the inherent alkalinity of its baseflow. If a stream has very alkaline baseflow, it may be capable of neutralizing all the acid rain runoff from a storm event and still retain a positive ANC. If less alkaline baseflow is present, a stream may exhibit reduced or negative ANC during acidified runoff events. In the worst case, a stream may not have sufficient alkalinity to overcome acid inputs at any flow condition, and will have a consistently negative ANC.

To evaluate the North Fork watershed, these degrees of acidification have been grouped into four basic categories: negligible, sustainable, episodic, and chronic. The characteristics of these categories and their implications regarding needs for alkaline addition are summarized in Table 5. Figure 9 shows examples of these categories through the relationship of flow and ANC.

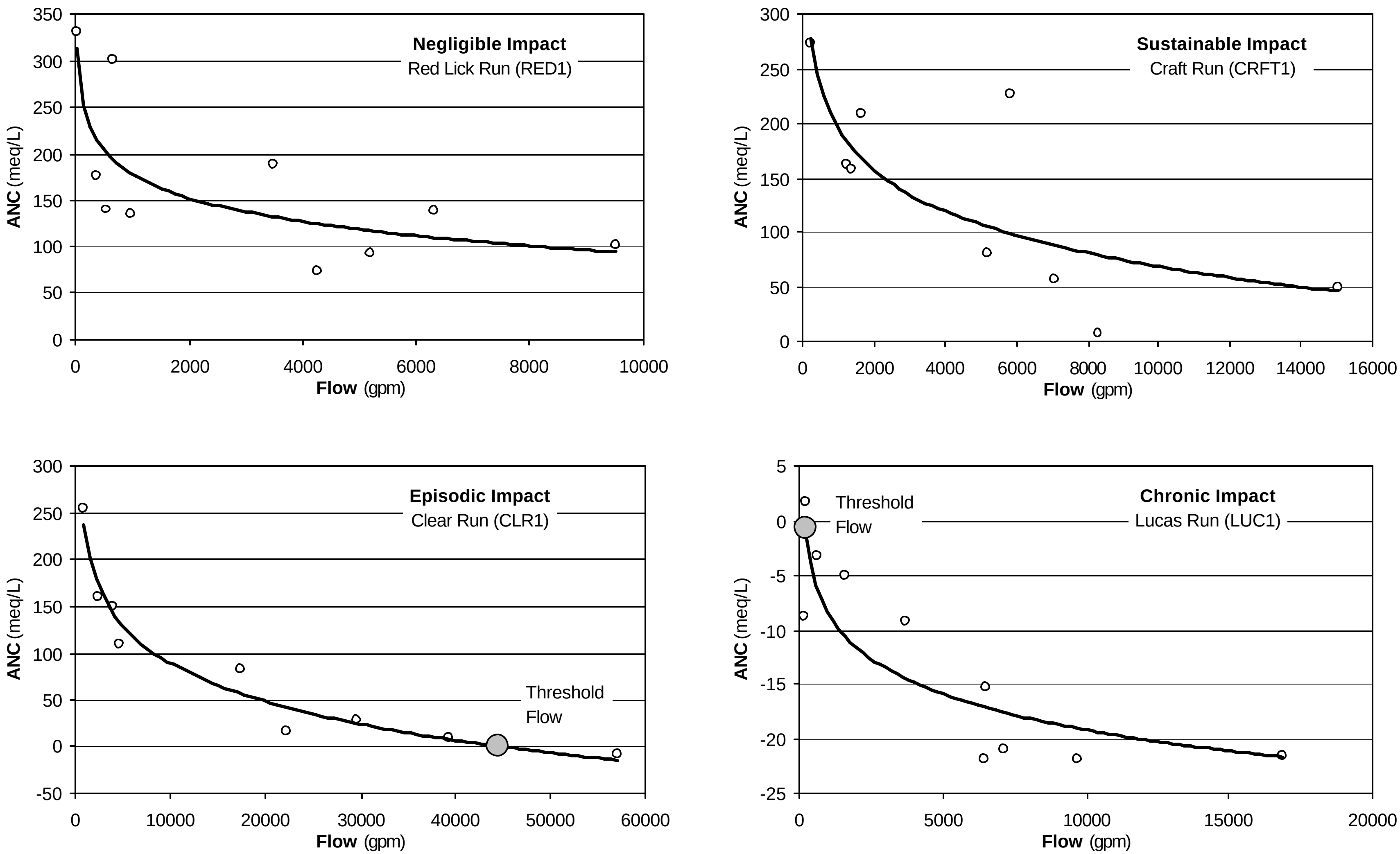
Figure 9 also illustrates the concept of "threshold flow," or the level of flow in a stream at which the baseflow alkalinity is predicted to be exceeded by runoff acidity, and the ANC to become negative. Chronically acidified streams have threshold flows at the low end of the observed range and usually require a method of continuous alkaline addition. In episodically acidified streams, the threshold flow occurs higher in the observed range, and alkaline addition may only be needed at flows above this threshold. Streams with negligible or sustainable impacts generally do not have threshold flows within any reasonable projection of flow. These streams may still benefit from alkaline addition, but do not require it to be based on any flow criteria.

Table 6 provides a summary of acidification conditions and a quantification of alkaline addition requirements for each sample point in the monitoring program. These factors can be used in selecting and sizing the appropriate alkaline addition method for each stream. The following is an explanation of each factor in Table 6 as it relates to this evaluation process:

Table 5 – Summary of Stream Acidification Categories

Category	Characteristics	Alkaline Addition Requirement
Negligible	Some decline in ANC at high flows, but no negative values observed.	No alkaline addition currently required.
Sustainable	Reduced ANC compared to negligible impact streams, but ANC not negative or only negative at highest flows.	Alkaline addition would be beneficial, but current water quality should support fish.
Episodic	Positive ANC at lower flows, but negative ANC at high flows; threshold flow occurs above average flow.	Alkaline addition required during higher flows for sustainable fish populations.
Chronic	ANC always or nearly always negative; threshold flow occurs below average flow.	Alkaline addition required for all flows for sustainable fish populations.

Figure 9 – Examples of Acidification Conditions



- Alkaline addition requirements are based on the net acidity of a stream, expressed as the equivalent concentration as $CaCO_3$ (limestone). The first two columns of Table 6 show the net acidity of the sample points for average and high flow conditions. A negative net acidity indicates excess alkalinity, or conditions not requiring alkaline addition

- In the next three columns, the Alkaline Deficiency represents the amount of alkaline material (as limestone) needed to neutralize excess acidity under three conditions that relate to selection of an alkaline addition method, as follows:

    - The Annual Deficiency is the tons of alkalinity that would be required to neutralize the observed acidity excess over the course of a year (determined as the sum of the excess acidity loadings observed for a point during the monitoring program projected over 365 days), related to annual operating costs of an alkaline addition system.

    - The Daily Deficiency is the average daily alkaline addition rate that would be required to neutralize the stream under average flow conditions, representing the normal operating design rate for an alkaline addition system.

    - The Peak Deficiency is the alkaline addition rate that would be required to neutralize the flow under the predicted high flow (95% CI) acidity loading, representing the value that an alkaline addition system would have to meet or exceed at its maximum design delivery rate.

- The Flow Condition columns provide a comparison of where the Threshold Flow occurs in a stream relative to the average and high flow values. Flow-triggered alkaline addition systems could be applied where the Threshold Flow is reasonably greater than the average flow.

- The Acidification Condition indicates the general acidification condition of a stream based on the relationship of the Threshold Flow to the average flow (chronically acidified if less than the average, episodically acidified if between the average and high flow, sustainable if near or greater than the high flow, and negligible if always greater than the high flow).

Table 6 – Quantification of Acidification Conditions in North Fork Sample Points

Sample Point	Net Acidity		Alkaline Deficiency			Flow Condition			Acidification Condition
	Average mg/L	High Flow mg/L	Annual tons/year	Daily lbs/day	High Flow lbs/day	Average gpm	Threshold gpm	High Flow gpm	
NF1	-7	-2	102	559	0	135816	466141	314653	Sustainable
SUG1	-7	-7	0	0	0	2808	43403	8267	Negligible
RED1	-4	-3	0	0	0	3241	115375	8894	Negligible
PEK1	-8	-2	0	0	0	15498	151164	42945	Negligible
PEK2	-4	0	12	64	152	9765	105849	31489	Sustainable
CRFT1	1	2	15	84	318	5915	32835	16903	Sustainable
SHP1	3	4	29	160	503	4379	4063	11368	Chronic
TAR1	4	4	51	277	936	5934	261	17584	Chronic
CLR1	-2	2	65	354	1496	18217	37616	52889	Episodic
CLR2	-2	2	44	243	990	14720	108818	44266	Episodic
CLR4	1	3	36	197	1098	8180	14984	29606	Episodic
WIND2	-2	0	2	10	0	4950	25086	16359	Negligible
NF18	-7	-2	29	161	0	47782	146663	124574	Sustainable
NF12	-5	1	97	531	733	30388	100211	75820	Sustainable
SEN1	-4	1	18	98	143	4810	31849	13117	Sustainable
SOU1	2	3	75	412	1334	12946	31262	36046	Episodic
BEA1	-4	-3	0	0	0	4239	91349	12118	Negligible
SOU2	5	7	155	852	2693	11414	1574	32906	Chronic
SOU4	6	8	23	127	467	1613	27	4848	Chronic
LUC1	5	5	57	310	977	5433	170	14842	Chronic
HET1	-7	1	13	73	198	6558	13501	18338	Episodic
NF16	3	4	84	458	1330	11839	13350	29549	Episodic
MAN1	5	6	31	167	467	2607	667	6299	Chronic
WIL1	6	7	21	114	321	1549	301	3707	Chronic
MUD2	5	5	10	57	211	1154	1182	3513	Episodic

Analysis of Abatement Results

If the alkaline deficiencies measured at the mouth of a given tributary are neutralized, the stream will presumably achieve acceptable water quality in its full reach downstream of the point at which the alkaline addition is applied. There are several mid-stream points in the monitoring program that measure combined flows from one or more upstream points, namely NF18, NF12, and NF16 on the North Fork, CLR1 on Clear Run, and SOU1 on the South Branch. It is desirable to evaluate whether upstream acid abatement will produce satisfactory improvements in these points as well.

Table 7 provides a comparison of the alkaline deficiencies measured at the mid-stream points to the sum of the known alkaline deficiencies in points upstream. If the total upstream deficiencies are greater than those at the mid-stream point of interest, then their neutralization will most likely produce satisfactory results at the mid-stream point. Conversely, if the deficiency at the mid-stream point is greater than the sum of the upstream points, there are other deficiencies present that have not been accounted for in the current monitoring program. In this case, either additional monitoring is needed to identify the unknown deficiencies, or abatement of the known upstream sources will have to produce an excess of alkalinity to compensate for them.

Based on this analysis, two potential problem areas are evident. The alkaline deficiency measured at NF16 is greater than the measured upstream points by a sufficient margin to indicate that Muddy Run, Williams Run, and Manner Dam Run are not the sole sources of acidity above NF16. Bearden Run and several small unnamed tributaries present upstream from NF16 may be the sources of this deficiency. Additional water monitoring may be warranted on these streams for development of further alkaline addition plans to fully address the deficiency at NF16. Clear Run also shows an increasing alkaline deficiency downstream to CLR1. There are likewise several small unnamed tributaries on the northwest side of Clear Run that may be worth investigating further, although excess alkaline addition could be applied in the upper portions of Clear Run sufficient to overcome the deficiency observed at its mouth.

Other than these two problem areas, it appears that alkaline addition in the monitored tributaries should be sufficient to overcome observed deficiencies in the mid-stream points. Where the neutralized upstream deficiencies are greater than the downstream deficiencies, it can be anticipated that excess alkalinity will be available to further improve pH and ANC conditions in already good quality downstream reaches.

Table 7 – Comparison of Upstream Alkaline Deficiencies to Mid-Stream Sample Points

Mid-Stream Point	Upstream Point(s)	Alkaline Deficiency	
		Average Flow (lbs/day)	High Flow (lbs/day)
NF16	MUD2	57	211
	WIL1	114	321
	MAN1	167	467
	Totals	338	999
	Less	458	1330
	Difference	-120	-330
NF12	NF16	458	1330
	HET1	73	198
	LUC1	310	977
	SOU1	412	1334
	SEN1	98	143
	Totals	1352	3982
	Less	531	733
	Difference	820	3249
NF18	NF12	531	733
	Less	161	0
	Difference	371	733
SOU1	SOU2	852	2693
	BEA1	0	0
	Totals	852	2693
	Less	412	1334
	Difference	440	1358
CLR1	CLR2	243	990
	Less	354	1496
	Difference	-111	-506

CONCEPTUAL ALKALINE ADDITION METHODS

The North Fork watershed is impacted by upwind industrial acidity sources. Portions of the watershed have little or no inherent bedrock alkalinity to neutralize this acid influx. Although regulation of acid-producing sources is occurring, the adverse effects on local waters and soils are expected to persist for the foreseeable future. As such, the only immediate solution to restore the impacted portions of the watershed is to add alkalinity until the upwind acidity sources can be ameliorated.

Limestone is the alkaline material of choice for stream restoration projects. The calcium ion (Ca^{2+}) released by dissolving limestone is naturally occurring in most waters and is benign to fish. Many streams in Pennsylvania are buffered by limestone bedrock, whereas the North Fork watershed has only a small amount contained in the highest bedrock units. Stronger neutralizing chemicals, including caustic soda (NaOH) and ammonia (NH_3), are used in severe cases of acid mine drainage, but these can introduce less beneficial cations to streams and may involve special handling precautions due to their reactive properties. Limestone and limestone-related products would be the most practical form of alkaline addition for the North Fork watershed.

There are a number of methods for applying alkalinity to a stream or watershed, each with different advantages and limitations. These can be generally grouped into the categories of *direct addition*, where limestone is applied in bulk for long-term neutralization, and *controlled addition*, in which alkaline material is delivered at known rates depending neutralization needs at a given time. This section provides a summary of several of the common addition methods in these categories that would be applicable to the North Fork watershed. A comparison of these methods is then made to the alkaline addition needs of the impacted tributaries identified by this study to allow conceptual selection of the most effective technologies.

A number of the methods discussed are currently undergoing detailed evaluation as part of the Growing Greener Round 4 Mosquito Creek project. More detailed technical guidelines will be available in the final report for this project, to be published in early 2006.

Direct Addition Methods

In direct addition, limestone is applied in bulk to points within a watershed where it can benefit streams through gradual dissolution. This approach has the benefit of requiring essentially no supervision or maintenance between application efforts, and the costs of application can be addressed as discrete events rather than a continuous expense. Direct application is also fairly low in cost per unit of alkalinity delivered. However, this approach is fairly imprecise with regards to amount of alkalinity delivered in response to changing water quality and flow conditions, and a large percentage of the material applied may be depleted during periods when it is not needed. Direct addition cannot be adjusted to meet the needs of extreme acidification events and has a lower reliability for maintaining restoration goals. Short-term labor requirements can also be high for the individual application events. The following summarizes several forms of direct alkaline addition that have been applied to acid rain impacts.

Limestone Sand Dosing

The simplest form of direct alkaline addition is in-stream limestone sand dosing. This involves periodically dumping a quantity of limestone sand in a stream channel or on the banks where high flows will wash it away. While imprecise as far as addition quantity versus momentary need, this method does appear effective over a broad range of flows because higher flows tend to mobilize the sand and increase its rate of dissolution by contact and abrasion. Figure 10 provides an example of a recent limestone sand dosing project on Gifford Run in the Mosquito Creek watershed.

Figure 10 – Example of Limestone Sand Dosing

Several formulae have been developed for determining the required limestone sand dosing rate, based variously on watershed area and stream pH (see Schmidt & Sharpe, 2002, for a complete summary). The Mosquito Creek studies involving limestone sand dosing in Gifford Run indicate that the Clayton Formula appears to best describe an effective addition rate for streams with a similar regional and geological setting as the North Fork. The calculations for this formula are given below. The applied stream pH should be the lowest, or high flow, pH for adequate dosing.

The results of the Clayton Formula indicate the annual addition rate in tons of limestone per year, and it is recommended that this value be doubled for the first year of application. It appears more effective to dose several points along a stream to prevent excessive sedimentation at a single point and limit aesthetic impacts. Gifford Run is dosed annually at two points and shows a positive ANC and acceptable pH downstream to its confluence with Mosquito Creek.

Clayton Formula for Limestone Sand Dosing

$$\text{Limestone Sand Applied (tons/yr)} = 132 \times \text{Watershed Area (acres)} \times [\text{Stream pH (SU)}]^{-5.69}$$

Limestone sand dosing is best suited to relatively small streams with low to moderate acidification impacts. It requires a dumping access point, such as a bridge abutment, but no other appreciable capital investment. Depending on the site conditions, it may be necessary to use a small loader or skid steer for spreading. The preferred limestone sand material corresponds to an AASHTO No. 10 aggregate size, which is typically available for about $20 per ton.

There are some concerns that long-term dosing can degrade streambeds by clogging cobbly bottoms with finer-grained sand, reducing the quality of habitat for benthic macroinvertebrates. Work is underway as part of the Mosquito Creek project to develop "off-line" addition methods that use limestone sand to generate alkalinity without placing the sand in the natural stream channel. However, results will not be available from these projects until construction and monitoring are completed, and for the time being limestone sand dosing is still an inexpensive and successful approach. Watershed interest groups and volunteer labor can readily accomplish limestone sand dosing. Although permitting has not been required for this activity to date, coordination and permissions are needed with the regulatory agencies before adding any materials to a stream.

Lake Liming

Lake liming and other forms of riparian lime addition for acid abatement are widely used in Norway and Sweden, and have also shown favorable results in North America. The concept is to spread fine limestone material by air or by boat to open water bodies, creating a large reservoir of alkaline water that is progressively flushed out to neutralize downstream reaches. Figure 11 shows an aerial liming operation that was recently conducted in the headwaters of Beaver Run in the Mosquito Creek watershed.

The rule-of-thumb approach to lake liming is 2 tons of limestone per acre of surface area. This application rate proved effective in maintaining alkaline conditions in the Beaver Run lake for approximately one year, and the effect would likely have been longer if not for several excessively large storm events during this period. The duration of alkaline improvement depends on a number of factors, including the storage capacity of the water body relative to flow-through volume, stratification of water layers, and degree of turnover and presence of "dead water" pockets. It will be necessary to monitor results and adjust the application rate over time to determine the most effective addition rate and replenishment cycle.

Figure 11 – Example of Aerial Lake Liming

Surface application by boat is less expensive than aerial liming, but requires that the water body be accessible to towed equipment and lime delivery. A typical surface operation consists of a specially equipped application boat and a delivery barge to shuttle limestone from the shore. A work crew of 4 to 6 individuals is required to operate the boats and move material. A modest operation can lime about 10 acres of open water per day. With boat rental and labor, application costs are approximately $200 per acre, plus about $70 per ton for bagged pulverized limestone. The application boats are specialized equipment that may not be commonly available. For long-term projects, it may be more economical for a watershed interest group to purchase and equip a boat (on the order of $20,000), rather than contract these services.

Aerial liming requires a specially equipped airplane or helicopter, but can reach inaccessible water bodies. This approach was necessary on Beaver Run because the lake is located in the Quehanna Wild Area and off limits to ground equipment. Aerial application costs about $1,000 per acre, assuming that an airstrip is available within about 10 miles. A free flowing pelletized lime works better for aerial application, costing approximately $100 per ton. Properly equipped aircraft are probably less commonly available than application boats.

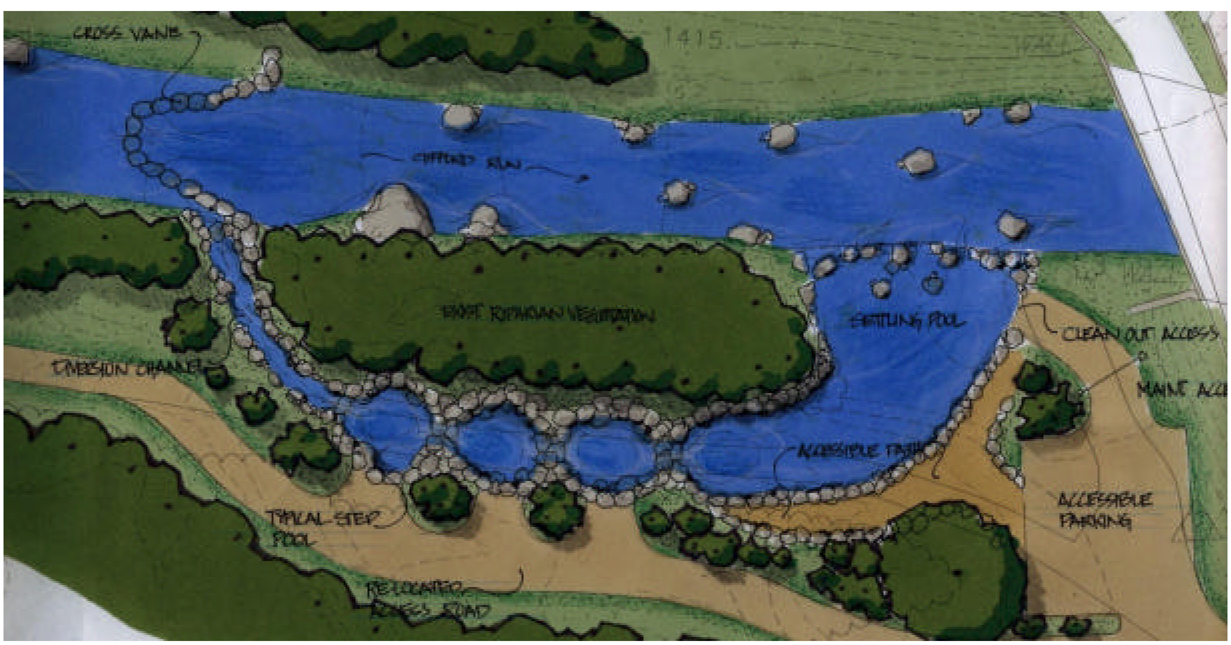
There are few large open water bodies in the North Fork watershed, so lake liming is of limited utility. The two most applicable locations are Manners Dam and the open water area at the confluence of Muddy Run and Williams Run. Manners Dam is accessible by road, but the Muddy Run area may require access by off-road vehicles and consequently higher equipment transport and material delivery costs.

<u>High Flow Buffer Channels</u>

High flow buffer channels (HFBCs) are an innovative concept intended to address two concerns involved with direct alkaline addition to water: the placing of fine materials in natural stream channels, and the wasting of limestone by dissolution during low flow periods in episodically acidified streams. As shown by Figure 12, the concept is to create a “stream beside a stream” in which limestone sand can be placed. An in-stream structure, such as a cross vane, is designed to direct flow into the HFBC only during runoff events that exceed the threshold flow for negative ANC. Diverted waters flowing through the HFBC acquire alkalinity from migrating limestone sand in a series of step pools, much as with sand dosing in a natural channel. In this plan, however, a settling pool traps the sand, preventing contamination of the natural stream channel. The settling pool also serves as a temporary alkaline refuge for fish during acid runoff events. The only anticipated maintenance for HFBCs after construction is periodic recycling of limestone sand from the settling pool back to the step pools using a loader, and replenishing the sand by truck delivery as it dissolves.

Two HFBC demonstration projects have been designed for the Mosquito Creek project, with one currently funded for construction in 2006. Final design, performance, and cost criteria will be established based on the results from these projects. In the interim, HFBCs are applicable for conceptual planning of improvements on sustainable and episodically impacted streams. Implementation costs are estimated at about $150,000 per unit, with annual maintenance costs being equivalent to that of limestone sand dosing thereafter.

Figure 12 – Conceptual High Flow Buffer Channel Plan



Land Application Liming

Limestone need not be applied straight to water to provide an alkaline benefit. Direct application to upland surfaces, riparian corridors, and wetlands can neutralize acid rain by contact with surface storm runoff and by improving the neutralization capacity of soils. Because the alkaline material is not in continuous contact with water, the actual benefits to streams may not be immediately observed, but the effects may last considerably longer than other direct application methods. This is also to some degree an "on demand" addition approach, since neutralization occurs for acid rain as it reaches the surface and before entering streams.

There are as yet no established criteria for land application liming rates to treat acid rain runoff. Several Penn State projects in the Mosquito Creek watershed used 2 tons per acre, equivalent to the normal lake liming rate, but some projects use rates up to 4 tons per acre. Water quality results from the Penn State projects will be available in the final Mosquito Creek report and may influence future recommendations for addition rates. The type of lime product applied depends on the nature of the spreading equipment used. Pelletized lime is available for about $20 per ton, and agricultural limestone can be obtained for about $30 per ton.

The methods and costs of land application liming vary depending on the type of surface cover in the application area. Open fields present the easiest areas and can be limed using common agricultural equipment, such as a tractor and an agricultural lime spreader. With volunteer labor and equipment, this type of liming can be conducted for essentially the cost of materials. Local landowners also can be encouraged to start or expand agricultural or landscape liming on their properties.

Scrubland and forests require more specialized equipment to navigate between obstacles. For the Mosquito Creek projects, Penn State purchased and outfitted a log skidder with a liming hopper, the "Regenerator" shown by Figure 13. The "Regenerator" is currently a unique piece of equipment, but is available for rent for restoration projects in the central Pennsylvania region. The operation also involves a dedicated loader to fill the hopper from on-site stockpiles. Basic costs are $1,000 for mobilization, $29 per hour for the skidder, $25 per hour for the operator, $200 per day for the loader, and the cost of limestone delivered. On projects greater than 100 acres, this equates to a per-acre cost on the order of $150 to $200 for 2 to 4 tons per acre of application. For more information on using the "Regenerator," please contact Dr. William Sharpe at the Penn State College of Agricultural Sciences.

Some areas may not be accessible for practical ground application of lime, such as dense forests, steep slopes, sensitive riparian corridors, and wetlands. If direct application is required for these areas, the only solution may be aerial liming using methods much as described for lake liming. The costs of aerial land application will be essentially the same as for aerial lake liming, or about $1,000 per acre for application and $100 per ton for materials.

Figure 13 – The Penn State "Regenerator" Lime Application Skidder

Limestone Road Surfacing

Recent studies indicate that use of limestone for unpaved road surfacing may provide a significant alkaline benefit to acidified watersheds. Field measurements show that acid rain is directly neutralized by contact with limestone road surfaces, and acidified flows from surrounding areas are improved by draining into roadside limestone ditches. Vehicle travel and grading operations provide abrasive action to keep the reactive surfaces of the limestone particles fresh, and during drier periods the limestone dust can migrate to neutralize surrounding soils. Although the surface area of roads is usually a very small percentage of a given watershed, they often affect a significant portion of the total overland flow along their lengths. As such, limestone road surfacing may be an effective way of concentrating the benefits of land application liming on the most accessible portions of a watershed.

Costs of limestone road surfacing depend greatly on the nature of the road, including width, thickness of cover, and coarseness of the aggregate applied. Roadside ditch designs also require site-specific planning for water handling capacity. Basic AASTHO No. 10 limestone road cover is available for about $20 per ton. Riprap for constructing roadside ditches costs about $35 per ton. Unless volunteer labor and equipment are available, additional costs will be incurred for the actual installation of the material. The lowest cost projects will be those where limestone can be used in place of another type of surfacing material for already planned road maintenance.

Work is still ongoing to quantify the effects of limestone road surfacing in terms such as alkalinity generation per unit area surfaced. This is a component of the Mosquito Creek final project report, which includes an evaluation of a surfacing and open limestone channel project on Lost Run Road in the Moshannon State Forest. Pending results of these studies, it is believed that limestone surfacing is a worthwhile investment as part of an overall watershed restoration plan. Although higher in material costs compared to non-alkaline shale or sandstone gravel, limestone is more durable and attractive as a surfacing material. A watershed interest group need not directly fund limestone surfacing projects; a modest investment in educational outreach could yield a beneficial change in surfacing practices among the stakeholders managing roads within the watershed.

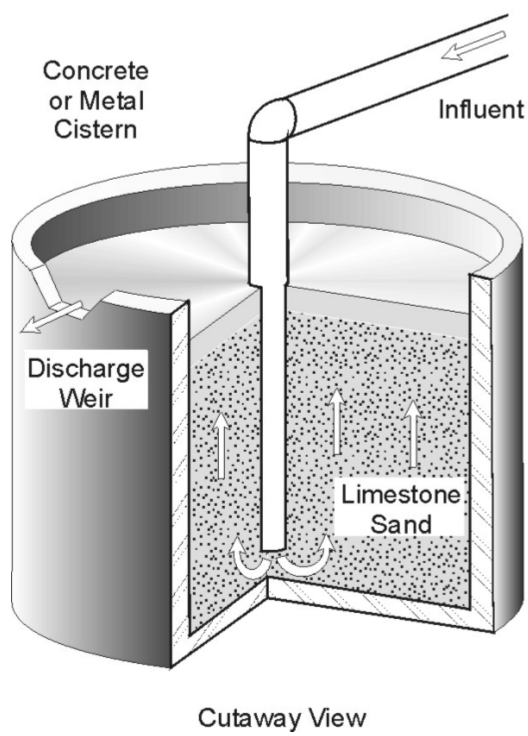
Controlled Addition Methods

In controlled addition, alkaline material is added to a stream at a rate controlled by a mechanical or hydraulic device. The delivery rate can be established by design or through field adjustments to more precisely meet the needs of a stream than direct addition methods, limiting material wastage. Controlled addition devices also allow a degree of self-adjustment to changing flows to better compensate for high-acidity runoff events. They typically require more operational and maintenance involvement than direct addition methods, and can have significant initial construction costs to install the addition devices. They also consume material on a continuous basis and require more frequent replenishment. The following summarizes several controlled addition methods that may be applicable on the scale of needs within the North Fork watershed.

Limestone Diversion Wells

Limestone diversion wells originated in Norway and Sweden as methods for treating acid rain, and they were adopted for mine drainage treatment in the United States during the 1990s. A diversion well (Figure 14) typically consists of a 4 to 6 foot circular concrete culvert section or metal cistern set on end at 6 to 9 feet in depth and filled with crushed limestone. A central pipe introduces flow to the bottom of the well under a hydraulic head slightly greater than the discharge elevation of the culvert section, causing the limestone particles to become fluidized like quicksand. Continuous agitation in the fluidized bed prevents armoring of the limestone and maximizes its contact with the influent water. Hydraulic head may be developed by damming and diversion of a portion of a stream flow to the well (hence the name "diversion well").

Figure 14 – Typical Diversion Well



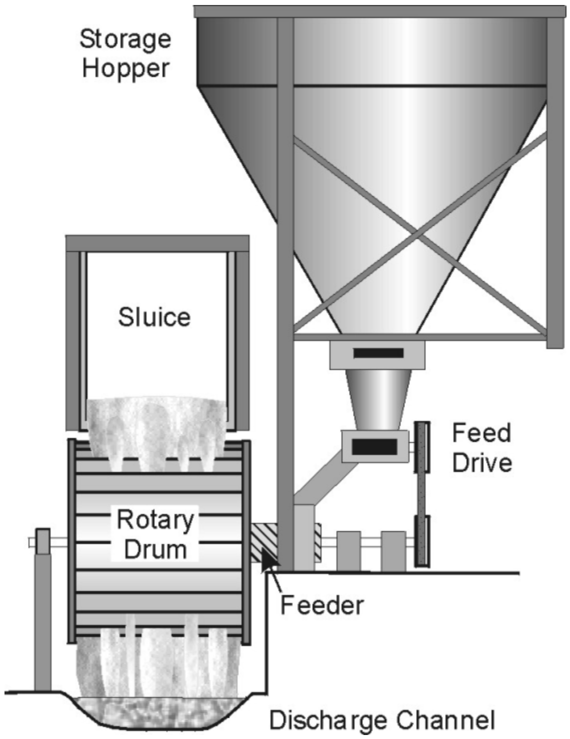
There have been numerous applications of diversion wells in the Appalachian states since their introduction, but there are as yet no specific criteria for their design or determining their performance results. A typical diversion well will cause a pH increase of 1 to 2 units in the water passing through it, along with some release of alkalinity. The amount of alkaline increase has not been adequately modeled to allow sizing of diversion wells to meet specific alkaline deficiency needs. At their current state of development, diversion wells are best suited for improvements to sustainable streams where an unspecified headwaters alkaline addition would be beneficial.

Diversion wells require frequent replenishment of limestone lost to dissolution and washout, sometimes on a weekly basis. One project on Swatara Creek in Pennsylvania reported two diversion wells consuming approximately one ton of limestone per week, although the flow and influent acidity loading were not provided. Ready truck access is necessary to maintain diversion wells at this rate of consumption. Sizing of a diversion well requires careful regulation of hydraulic head pressures to keep the limestone sand in motion without sweeping it out of the well. This can be approximated using fluidized bed mechanics, with the minimum fluidizing velocity and terminal velocity setting the lower and upper flow thresholds, respectively, for a given well configuration. Assistance from experienced persons is recommended in designing and installing diversion wells to assure proper performance.

<ins>Limestone Rotary Drums & Basket Wheels</ins>

Limestone rotary drums and basket wheels seek to overcome armoring and material loss problems by enclosing limestone aggregate in a rotary wheel, usually consisting of a drum with slots, perforations, or external screening (Figure 15). Typical installations are powered by water diverted from the stream and directed to a sluiceway. In the bottom of the sluice are openings located directly above each drum. As water falls through the openings in the sluice, blades attached to the exteriors of the drums initiate their rotation, as in a waterwheel. Crushed limestone is either manually loaded into each drum or automatically fed to the drums through a reciprocating feeder at the bottom of a hopper. Volume through the sluiceway determines the speed at which the drums rotate, the amount of aggregate supplied to the drum, and, ultimately, the amount of neutralization supplied to the stream. The grinding of the limestone aggregate within the drum liberates fine limestone powder and retards formation of aluminum armoring. Water enters the drum from the sluiceway through small holes in its exterior, and exits through the bottom through the same holes, mixing with and carrying away the limestone fines. Output of the produced fines is controlled by aggregate size and rotation rate of the drums, with various screens and meshes used to control the discharge size of the fines. Several drums can be operated in series, with increased flow increasing the number of drums in operation, or multiple drums may be operated in parallel for large flows.

Figure 15 – Typical Rotary Drum (Hopper Type)



Limestone rotary drums and basket wheels are typically custom-built facilities and can vary greatly in size and complexity. Self-feeding types require the most mechanical complexity and may need frequent inspection. The Toby Creek project in Pennsylvania is such a large-scale example and includes water-powered limestone crushers to prepare bulk limestone for delivery to the rotary drums. Smaller types, true basket wheels, are based on simple mesh cylinders or perforated drums. These non-fed systems require that the wheel be periodically stopped and opened to replenish the limestone content.

There are no specific design criteria for limestone rotary drums and basket wheels. Each must be sized to provide an acceptable balance of limestone containment volume relative to the motive energy of the influent flow. Too large a drum will not rotate, and too small a basket wheel will exhaust its limestone rapidly in a high-volume flow, requiring frequent maintenance. Large-scale rotary drums and self-feeding systems can involve complex engineering design. Assistance from experienced persons is recommended in designing and installing rotary drums and basket wheels to assure proper performance.

<u>Vertical Flow Wetlands</u>

Vertical flow wetlands (VFWs) are a technology that was originally developed for treatment of acid mine drainage, but recent applications in the Mosquito Creek watershed indicate that they may be effective for acid rain as well. VFWs consist of deep basins filled with a basal layer of limestone aggregate topped by a bed of spent mushroom compost. Water diverted from a stream is introduced into the top of the basin and migrates down through the two layers, acquiring excess alkalinity before being returned to the stream through an underdrain system. Although the mechanism is not certain, the compost bed appears to enhance the alkalinity production and reduce armoring of the limestone from metals precipitates. Figure 16 shows a typical section of a VFW, and Figure 17 shows a completed unit.

Figure 16 – Typical Vertical Flow Wetland Section

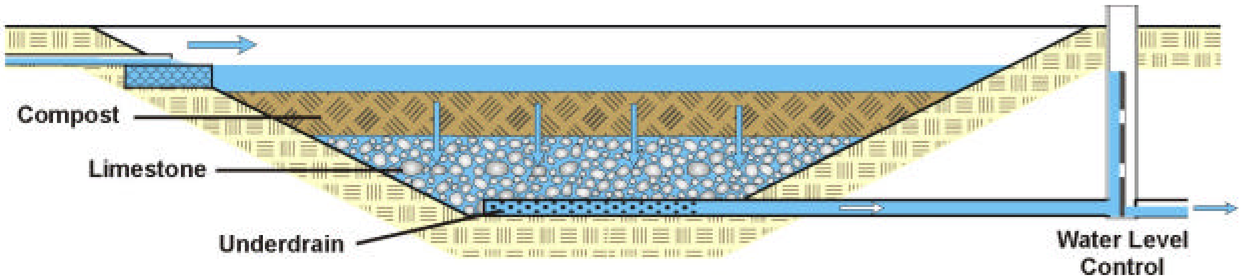


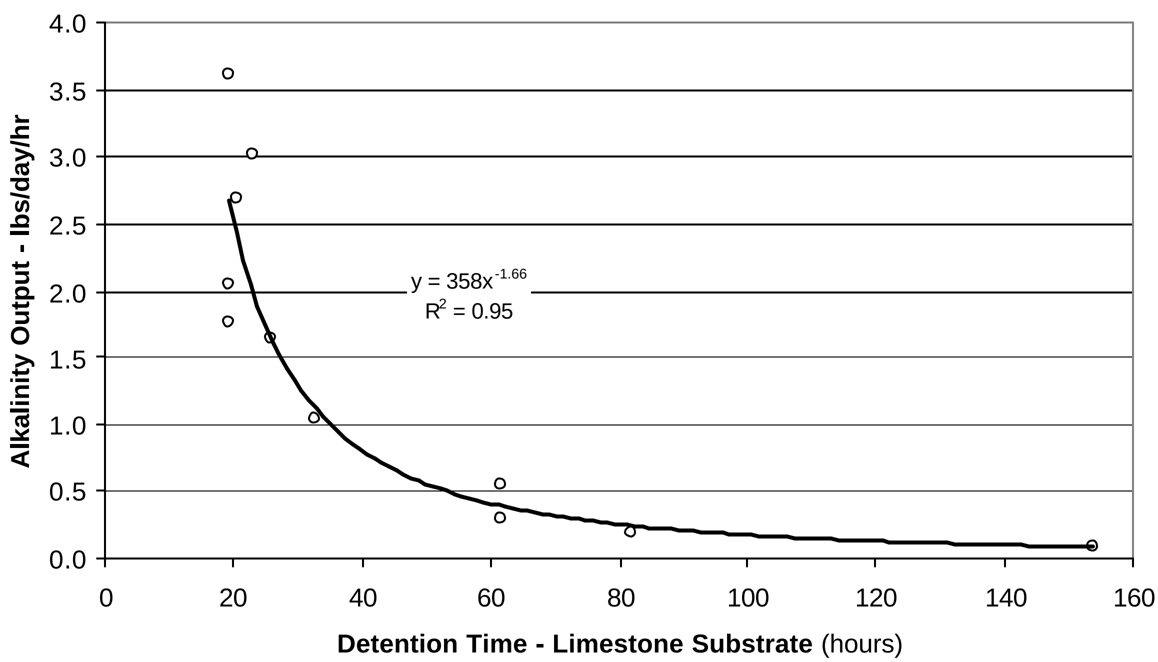
Figure 17 – Example of a Completed Vertical Flow Wetland

The advantage of VFWs is that they provide a large reservoir of limestone and require little maintenance and no material replenishment after construction. They are essentially a hybrid between bulk limestone application and controlled addition. As a continuous source of alkalinity, VFWs are best suited to chronically acidified streams. They are also appropriate where maintenance labor is very limited or where restoration funding requires a one-time investment without provision for ongoing replacement of alkaline materials.

Sizing criteria have been established for VFWs for use in treatment of acid mine drainage, but are still under development for low-level acid abatement applications such as acid rain runoff. Based on the Mosquito Creek projects, VFWs produce fairly reliable discharge alkalinity concentrations of about 50 mg/L at 24 hours detention in the limestone substrate. Much of the alkalinity generation occurs within the first few hours of contact with the limestone, so although discharge alkalinity concentration diminishes with shorter detention times, the actual discharge alkalinity loading is higher for detention times less than 24 hours. This is illustrated in Figure 18, which shows results from the Mosquito Creek projects plotted in terms of pounds of alkalinity per day per hour of detention time within a VFW.

There are insufficient data at this time to extrapolate the alkalinity loading discharges from VFWs much below 24 hours detention time. As experimental projects, the flow rates through the Mosquito Creek VFWs were limited by orifice-based influent structures to a detention time equivalent of 20 hours, averaging about 24 hours. Since the discharge alkalinity loading increases with influent flow, it is reasonable to assume that future VFWs can be constructed with a variable influent control structure that delivers addition alkalinity at higher flows.

Figure 18 – VFW Alkalinity Output as a Function of Detention Time



For conceptual design purposes, it can be assumed that a VFW constructed for 24 hours detention at average flows can meet high flow alkaline addition requirements using a variable influent control. The approximate construction cost for VFWs is $3,000 per pound per day of discharge alkalinity at 24 hours detention time. As a relatively new technology, the ultimate functional life of a VFW is not known, but at observed alkalinity generation rates is probably on the order of several decades. The one-time construction cost can then be spread over many years for comparison to systems that require periodic replenishment, in addition to any savings from reductions in labor requirements.

VFWs are fairly substantial earthwork structures and require an engineering design for stability and appropriate hydraulic sizing. Depending on site topography, they will occupy approximately 1 acre per 50 pounds per day of alkalinity output capacity. The inlet and outfall structures will normally require stream encroachment permits, and earth disturbance and NPDES permits may also be required depending on the project size. For these reasons, VFW designs are generally contracted to an engineering firm. Base costs for design and permitting will normally be about $50,000.

VFWs using mushroom compost beds tend to generate a discoloration in the discharge water and reduce dissolved oxygen content for a short distance downstream. More recent VFW designs have used vegetated wetland outfall channels to polish the system effluent. In a variation of the VFW concept, two demonstrations of vertical flow limestone beds (VFLBs) are planned for the Mosquito Creek project at a future date. These are essentially VFWs without the compost bed, using straight limestone sand and aggregate in a downflow configuration. Although the compost bed appears to be required to maintain alkalinity generation in acid mine drainage treatment settings, it may not be as necessary in "clean water" applications such as acid rain runoff. If results from these projects are favorable, it is anticipated that VFLBs will replace VFWs as the design standard for acid rain remediation. Removal of compost and outfall wetland channels will reduce construction costs to some extent compared to VFWs, but the overall implementation costs and applicability are expected to be about the same, so the term "VFW" is used to represent both in comparisons to other technologies.

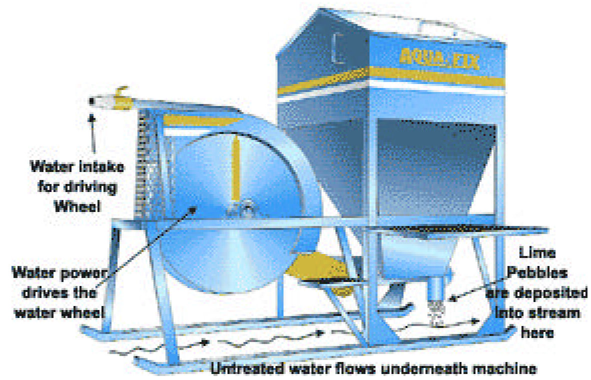
<u>Pebble Quicklime Addition Units</u>

In recent years, an effective alkaline addition system has been developed using pelletized pebble quicklime (CaO). This material is much more soluble than limestone, allowing more controlled delivery and neutralization results. The Aqua-Fix addition unit, manufactured by Aqua-Fix Systems, Inc. in West Virginia, combines a substantial reagent storage capacity with a simple, low maintenance rotary delivery unit driven by waterpower. Figure 19 provides a schematic of the Aquafix mechanism, along with several site examples.

The Aquafix system is scalable for differing addition requirements based on its constructed storage capacity, either as an integral hopper or an overhead silo unit. For conceptual sizing, it is recommended that the lime storage capacity be at least sufficient to operate between inspections at the highest design delivery rate, such that the system will not be depleted by a major storm event. The units should be inspected at least weekly to check for mechanical problems and add fresh material as needed. Pebble lime is available in 50 pound bags for hopper-based systems (about $160 per ton at the plant) or in bulk for silo-based systems (about $120 per ton delivered).

For silo systems, there is little difference in construction cost between a small silo and a large silo. The standard delivery truck size is about 20 to 25 tons, and for single site applications a 25 ton silo is just as economical in the long run in terms of cost and effort as a smaller silo. With multiple systems operating in one watershed, it may be possible to arrange for a scheduled bulk delivery to all the systems using smaller and somewhat less expensive silos. The savings of bulk delivery over bagged pebble lime also makes operation of multiple local systems more economical than single-project applications.

Figure 19 – Examples of Aquafix Pebble Quicklime Addition Systems



System Schematic

1 Ton Hopper Unit

35 Ton Silo with Equipment House

75 Ton Silo with Equipment House

Images courtesy of Aquafix Systems, Inc.

The driving water flow for the waterwheel mechanism is taken from a diversion upstream of the addition site. Motion begins with essentially zero head, so the waterwheel need not be placed very far downstream from the diversion point. Although mechanical losses occur within the system, the water powered delivery rate is fairly linear with increasing head. This allows the systems to provide an addition feed scaled to increasing flow.

The flow depth (head at the diversion point) in most natural streams is about twice the average flow depth under 95% CI flow conditions. The 95% CI flow is also fairly consistent at about three times the average flow volume. As such, it can be expected that approximate twice the driving head will be available for the mechanism to treat about three times the average flow. For conceptual sizing purposes, it is recommended that the pebble lime systems be calibrated to deliver the required alkaline addition rate at the design high flow, recognizing that in some cases the average flow loading will be the controlling factor.

Aquafix systems will require site-specific designs for hydraulic calibration of addition rates, diversion structures, building foundations and storage structure supports, and the chemical mixing zone. For small systems, this work may be within the means of watershed interest groups, but professional assistance is recommended for silo system designs. Construction of the diversion and outfall structures will usually require a stream encroachment permit. The disturbance footprint of this type of system is relatively small and may not require an additional earth disturbance permit.

Comparison of Addition Methods

Of the streams assessed by this study, 11 show levels of acid impairment that would benefit from alkaline addition. Although not sampled in the monitoring program, Bearden Run in the northeast problem area is also included as a stream that will likely need to be addressed at some point in the future. Each of these streams has differing levels of alkaline addition needs and specific characteristics that will affect the selection of an appropriate addition method.

Table 8 summarizes the conceptual applicability of the reviewed methods to the impaired streams. The methods are categorized as either being applicable as the primary addition technology, useful as a supplement to the selected primary technology, excessive with regards to the needs of the stream, or not applicable given the stream acidification type or characteristics. An alternative is denoted for each in bold as being the method suggested for first consideration for a stream. A qualitative assessment of the relative implementation costs and operation and maintenance (O&M) costs or labor is also provided for comparison of the alternatives.

Determining the actual costs of each addition method is more complicated. Some methods, such as diversion wells and rotary drums, have no established sizing criteria. Others, including the land application methods, depend on a detailed assessment of the practical extent of application. Of the reviewed technologies, four have fairly well known construction and O&M cost factors: pebble quicklime (Aquafix systems), limestone sand dosing, lake liming, and vertical flow wetlands.

Table 8 – Conceptual Applicability Comparison of Alkaline Addition Methods

Impaired Stream	**Acidification Condition**	**Alkaline Addition Methods**							
		Direct Addition				Controlled Addition			
		Limestone Sand Dosing	Lake Liming (boat)	High Flow Buffer Channels	Land Application Liming	Diversion Wells	Rotary Drums or Baskets	Vertical Flow Wetlands	Pebble Quicklime Units
Craft Run	Sustainable	**A** (L/L)	NA	A (H/L)	S (U/0)	A (M/H)	A (M/H)	X (H/N)	X (M/H)
Shippen Run	Chronic	S (L/L)	NA	NA	S (U/0)	S (M/H)	S (M/H)	A (H/N)	**A** (M/H)
Tar Kiln Run	Chronic	S (L/L)	NA	NA	S (U/0)	S (M/H)	S (M/H)	A (H/N)	**A** (M/H)
Clear Run	Episodic	S (L/L)	NA	S (H/L)	S (U/0)	S (M/H)	S (M/H)	A (H/N)	**A** (M/H)
Seneca Run	Sustainable	**A** (L/L)	NA	A (H/L)	S (U/0)	A (M/H)	A (M/H)	X (H/N)	X (M/H)
South Fork	Chronic	S (L/L)	NA	NA	S (U/0)	S (M/H)	S (M/H)	A (H/N)	**A** (M/H)
Lucas Run	Chronic	S (L/L)	NA	NA	S (U/0)	S (M/H)	S (M/H)	A (H/N)	**A** (M/H)
Hetrick Run	Episodic	**A** (L/L)	NA	A (H/L)	S (U/0)	A (M/H)	A (M/H)	X (H/N)	X (M/H)
Manners Dam Run	Chronic	S (L/L)	**A** (L/L)	NA	S (U/0)	S (M/H)	S (M/H)	A (H/N)	A (M/H)
Bearden Run	Chronic	S (L/L)	NA	NA	S (U/0)	S (M/H)	S (M/H)	A (H/N)	**A** (M/H)
Williams Run	Chronic	S (L/L)	NA	NA	S (U/0)	S (M/H)	S (M/H)	A (H/N)	**A** (M/H)
Muddy Run	Episodic	S (L/L)	**A** (M/M)	S (H/L)	S (U/0)	S (M/H)	S (M/H)	A (H/N)	A (M/H)

Applicability	(Implementation Cost/O&M Cost or Labor)
A - Applicable Alternative	L - Low
S - Supplementary Project	M - Moderate
X - Excessive for Needs	H - High
NA - Not Applicable	U - Undetermined
Bold - Suggested Alternative	N - None

Due to their relatively small construction size, standardized design practices, and controlled material delivery rates, pebble quicklime systems provide the most consistent method on which to develop a baseline comparison cost for alkaline addition. Pebble quicklime systems can be designed to meet the addition needs of any of the impaired streams, although they may not always be the most practical alternative. Table 9 provides a comparison of the estimated costs for pebble quicklime addition and the next most applicable method for each stream out of limestone sand dosing, lake liming, or vertical flow wetlands. (Bearden Run is not included in this table because no monitoring data are available to size the alternatives.) Cost factors are broken down by capital construction (implementation) costs, annual O&M costs, and the 15-year present value of the alternatives equating to the approximate operational life of a vertical flow wetland. An estimate of annual labor hours is also included, but not factored into the costs. The following are other specific assumptions applied in developing Table 9:

- The storage capacity of the Aquafix units has been scaled to provide at least 7 days of delivery at the high flow addition requirement, assuming that weekly inspections and refilling will be available.

- Bulk delivery is assumed for pebble quicklime between multiple systems at $120 per ton. If bagged pebble quicklime is used for individual systems, the unit cost will be higher.

- The addition rate of the pebble lime systems is calibrated to meet the high flow alkaline addition requirement, or twice the average addition requirement, whichever is greater, based on twice the head driving force being available under high flow conditions as for average conditions.

- Limestone sand dosing is considered to be applicable for streams with sustainable or mildly episodic acidification and annual dosing quantities of 50 tons or less. The capital cost for dosing is double the material requirement for the first year, without costs of access development.

- Lake liming is considered appropriate for Manners Dam Run and the Muddy Run impoundment. Surface liming by boat is probably feasible for both sites, although the Muddy Run impoundment may require use of off-road vehicles for access.

- VFWs are assumed as the appropriate passive alternative for all other impacted tributaries, with construction costs based on delivery of the average alkalinity requirement at 24 hours detention time.

- All labor is assumed to be voluntary or included in the delivery cost of materials. If this is not the case, labor should be factored into the annual operation costs at the local prevailing wage for semi-skilled labor.

Table 9 – Conceptual Cost Comparison of Selected Addition Methods

Tributary Sizing Sample Point	Baseline Alternative (Pebble Quicklime)					Comparative Alternative					Stream Reach Improved (miles)
	Pebble Lime (tons/yr)	Capital Construction Cost	Annual O&M Cost	15 Year Present Value	Annual Labor (hours)	Lime-stone (tons/yr)	Capital Construction Cost	Annual O&M Cost	15 Year Present Value	Annual Labor (hours)	
Craft Run	1 ton Hopper Unit					In-Stream Dosing					2.2
CRFT1	22	$20,000	$1,457	$35,119	73	20	$1,284	$892	$10,543	16	
Shippen Run	1 ton Hopper Unit					Vertical Flow Wetland(s)					2.1
SHP1	34	$20,000	$2,303	$43,904	86	NA	$530,785	NA	$530,785	26	
Tar Kiln Run	25 ton Silo Unit					Vertical Flow Wetland(s)					1.6
TAR1	64	$95,000	$4,288	$139,505	115	NA	$881,993	NA	$881,993	26	
Clear Run	25 ton Silo Unit					Vertical Flow Wetland(s)					5.4
CLR1	102	$95,000	$6,849	$166,091	153	NA	$1,110,916	NA	$1,110,916	26	
Seneca Run	500 lb Hopper Unit					In-Stream Dosing					2.6
SEN1	10	$12,000	$675	$19,004	62	34	$1,845	$1,173	$14,016	16	
South Branch	25 ton Silo Unit					Vertical Flow Wetland(s)					6.7
SOU2	183	$95,000	$12,328	$222,961	235	NA	$2,604,961	NA	$2,604,961	26	
Lucas Run	25 ton Silo Unit					Vertical Flow Wetland(s)					2.0
LUC1	67	$95,000	$4,473	$141,432	118	NA	$978,894	NA	$978,894	26	
Hetrick Run	1 ton Hopper Unit					In-Stream Dosing					1.5
HET1	14	$20,000	$908	$29,426	65	24	$1,453	$976	$11,588	16	
Manners Dam Run	1 ton Hopper Unit					Lake Liming (Boat Application)					0.8
MAN1	32	$20,000	$2,139	$42,199	83	26	NA	$5,352	$55,552	Contractor	
Williams Run	1 ton Hopper Unit					Vertical Flow Wetland(s)					0.9
WIL1	22	$20,000	$1,469	$35,246	73	NA	$391,491	NA	$391,491	26	
Muddy Run	1 ton Hopper Unit					Lake Liming (Boat Application)					0.1
MUD2	14	$20,000	$967	$30,041	66	7	NA	$2,146	$22,273	Contractor	
TOTALS:	563	$512,000	$37,855	$904,927	1,129	109	$6,503,622	$10,539	$6,613,011	204	26

Based on this comparison, limestone sand dosing and lake liming are comparable in cost to pebble quicklime addition. Vertical flow wetlands prove to be considerably more expensive than pebble quicklime when labor is not a cost factor. However, pebble quicklime systems require funding for ongoing maintenance and material purchase, whereas vertical flow wetlands do not. In grant request situations where maintenance and material costs will not be funded (typical with Growing Greener grants), vertical flow wetlands may be the preferred alternative despite higher implementation costs.

Beyond this conceptual screening, selection of an appropriate alkaline addition method can depend on a number of factors other than cost and basic technical compatibility with stream flow and quality. These may include available construction area, access constraints for application sites, and availability and degree of skill of maintenance labor. Each stream proposed for restoration should be thoroughly evaluated by field reconnaissance and examination of available application sites before committing to any addition method.

For controlled addition methods, the flow at the addition point must be a sufficient proportion of the downstream flow of the treated reach such that the amount of alkaline material added to neutralize the downstream reach does not rise to an excessive in-stream concentration at the addition point. (Excessively high alkalinity and pH can be as detrimental as high acidity.) As such, it is seldom possible to position a single alkaline addition system to treat an entire affected stream, and portions of the headwaters usually do not receive the benefits of treatment. The point of placement for a controlled addition system will depend on the individual flow characteristics and addition requirements of the stream, but a position within the upper 20% of the perennial reach is typically a reasonable estimate. As such, these types of projects may require supplementary addition activities in the headwaters to completely restore the stream reach. These may include either the other applicable technologies or the supplementary methods identified in Table 8.

A final important consideration for the feasibility of an addition method is the need for permitting and other types of permissions. Projects involving placement of structures (including intakes and discharges) in a stream will require stream encroachment permitting. Any earth disturbance activity in wetlands will also require an encroachment permit. Project planning should be coordinated with local, state, and federal regulatory agencies to assess potential permitting requirements and other permissions before proceeding beyond the conceptual planning stage.

PROGRESSIVE RESTORATION PLAN

In general, the North Fork watershed would benefit to some degree from any form of alkaline addition described in the previous section. However, the most immediate results would be achieved by concentrating efforts in streams that can be most readily restored to good quality conditions given currently available resources. Once alkaline addition projects are established and demonstrated for these streams, the gained experience can be applied to justify new addition projects on other streams having greater acidification impacts and more difficult treatment requirements. Each new project adds more alkalinity to the watershed and increases the cumulative downstream benefit until the goal of complete restoration is achieved. This sequencing of projects towards an ultimate restoration goal is known as a *progressive restoration plan*.

The scope of restoration within the North Fork watershed will depend on the resources and goals of the NFWA and other stakeholders. The progressive restoration plan presented here is a suggested sequence of activities that can produce fairly immediate benefits, allow the stakeholders to gain experience in implementing alkaline addition projects, and provide justification for funding of future projects. The actual sequence of projects can be modified to fit the capabilities and priorities of the stakeholders, but it is recommended that the following basic guidelines be applied to assure that the selected projects are meaningful:

- Alkaline addition projects must be **sufficient** in size to neutralize the net acidity of the stream on an average annual and maximum loading basis (alkaline deficiency in Table 6).

- Addition projects must be **sustainable**, meaning in most cases that more alkaline material must be added on a regular basis to maintain the treatment results, and that provision is needed for long-term funding and maintenance.

- Addition projects should be documented to **support** requests for future funding of new projects, including pre- and post-addition water quality monitoring and records of materials and project costs.

- Addition projects should **supplement** existing good quality reaches or extend the results of previous projects, meaning that it is usually better to treat a bad stream feeding a good stream than a bad stream feeding another bad stream.

- Addition projects should **satisfy** a socioeconomic need, such as improving an accessible fishery on public lands.

The NFWA has already expressed an interest in conducting a lake liming project on Manners Dam Run. This would be an excellent location to gain experience with this technology due to the relatively small size of Manner Dam and its ease of access. While the restored reach would not be connected to other quality reaches due to the acidification of the North Fork main stem in this location, the project would be of a sustainable scale for the watershed group.

The next suggested efforts would be on Craft Run, Seneca Run, and Hetrick Run. These streams currently have sustainable or mildly episodic acidification, and would benefit immediately from relatively modest additions of alkalinity. This could consist of limestone sand dosing, high flow buffer channels, or diversion wells. This would provide the NFWA with experience in other addition technologies and improve water quality in many miles of stream at low cost. These streams can be addressed in their order of importance to the group rather than simultaneously. Their headwaters would also be good starting points to demonstrate land limestone application and limestone road surfacing to supplement limestone sand dosing.

Projects beyond these initial activities will depend on the priorities of the NFWA and availability of funds and labor. Figure 20 provides a qualitative assessment of the relative level of alkaline addition effort that may be required to restore the impacted tributaries based on their estimated annual alkaline deficiencies. If total stream miles restored were the only goal of the progressive restoration plan, it would make sense to treat these streams in an ascending order of addition effort. However, a piecemeal approach would tend to leave some restored streams isolated until the higher impact areas were also restored. Restoration of Muddy Run, for example, would leave a small, isolated headwaters tributary with no connection to other good aquatic habitat for many miles downstream.

Figure 21 provides a suggested alternative course of activities based on the general guidelines for meaningful projects presented in this section. After Craft Run, Seneca Run, and Hetrick Run, the northwest problem area would provide the next best opportunities for discrete, meaningful projects on Shippen Run, Tar Kiln Run, and Clear Run. These streams can be addressed individually as resources become available and will be interconnected by the existing good quality of the North Fork main stem as they are restored. The northeast problem area presents a more difficult prospect because the North Fork itself is acidified. The suggested course of action here is to restore the impacted tributaries in a downstream to upstream order, starting with the South Branch. It is anticipated that concurrent improvements will occur in the North Fork and interconnect these streams as they are restored in this sequence. However, given the high degree of acidification in the South Branch, it may prove more practical to address other tributaries in the northeast problem area first. The ultimate course of restoration activities in the watershed will depend on the desires of the NFWA and other stakeholders relative to available funds and labor.

Concurrent with and in support of restoration efforts, the NFWA can pursue general alkaline addition efforts throughout the watershed. Examples may include educational outreach to promote alkaline addition by landowners, working with municipal and state agencies to promote limestone road surfacing, and other public outreach programs to solicit additional funding and volunteer contributions.

Prior to designing any alkaline addition activities, further monitoring should be conducted on the target streams to determine final application siting locations and sizing requirements. At the minimum, monitoring should be conducted upstream and downstream of candidate application sites to assure adequate flow quantities. Long-term monitoring programs should also be established to document progressing restoration achievements as justification for additional funding.

Figure 20 – Relative Degrees of Alkaline Addition Effort for North Fork Tributaries

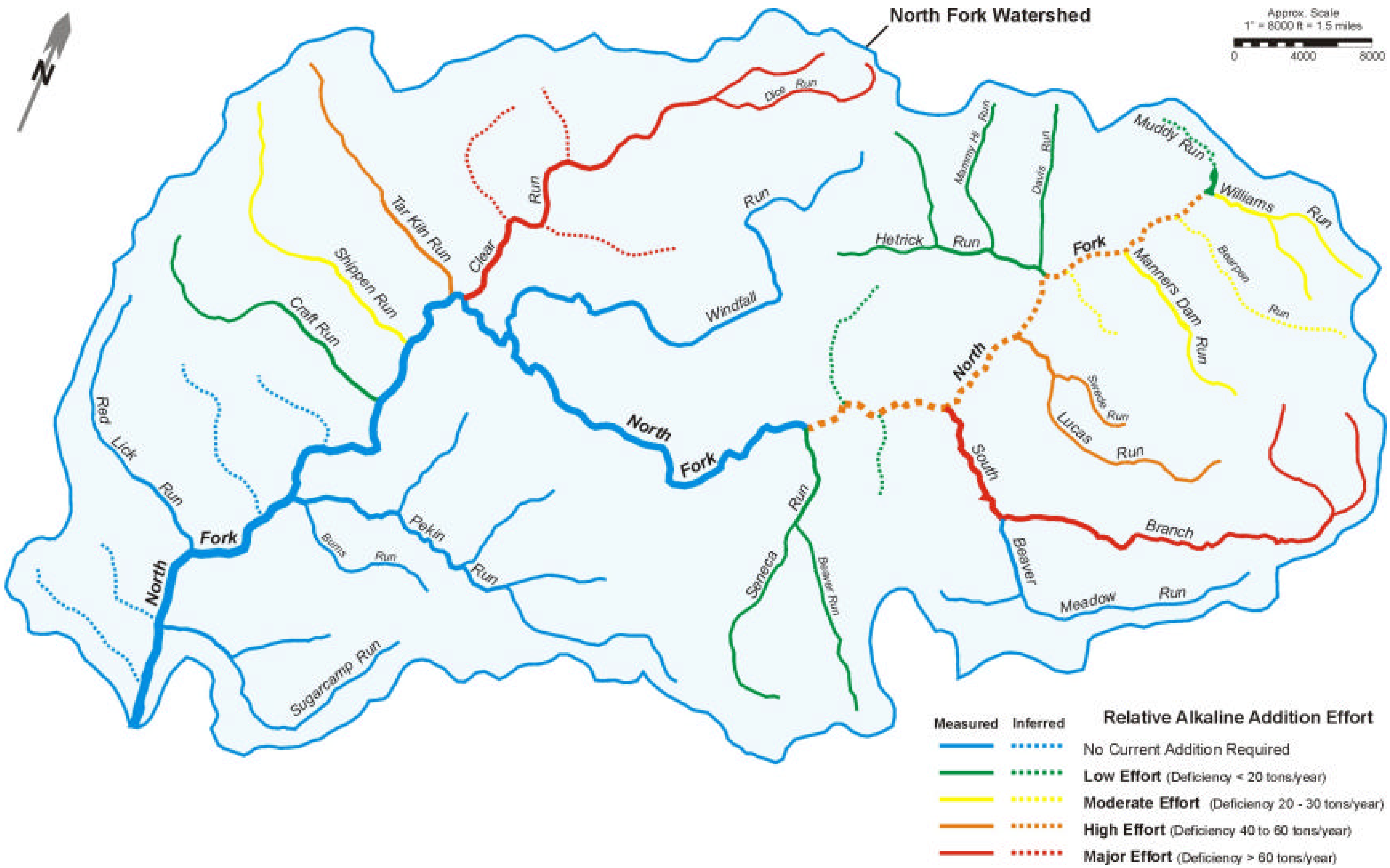


Figure 21 – Suggested North Fork Watershed Progressive Restoration Plan

Suggested Order of Stream Projects	⇒ Increasing Level of Effort ⇒			
	Phase 1 Initial Demonstration	**Phase 2** Rapid Restoration	**Phase 3** Northwest Problem Area	**Phase 4** Northeast Problem Area
	Potentially Applicable Addition Technologies			
Manners Dam Run	*Lake Liming*			
Craft Run		*Limestone Sand Dosing, High Flow Buffer Channels, or Diversion Wells*		
Seneca Run				
Hetrick Run				
Shippen Run			*Pebble Quicklime or Vertical Flow Wetlands with other methods supplementing*	
Tar Kiln Run				
Clear Run				
South Branch				*Pebble Quicklime or Vertical Flow Wetlands with other methods supplementing*
Lucas Run				
Bearden Run				
Williams Run				
Muddy Run				*Lake Liming*
Throughout	*Land Application Liming, Limestone Road Surfacing, and Supporting Public Outreach*			

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this assessment, the North Fork watershed is an excellent candidate for remediation of acid rain impacts. The acidified areas are localized in fairly discrete tributary subwatersheds, and the majority of the watershed has good water quality. Alkaline addition can be implemented for a reasonable cost and show immediate and substantial reach restoration gains in several mildly impacted tributaries. Several other moderately impacted streams are present in the northwest portion of the watershed that, while requiring greater effort, can be restored on an individual basis with immediate interconnection through the good quality North Fork main stem. Only one region of systemic acidification is present in the northeast portion of the watershed that will require a substantial effort to restore. This water quality configuration presents a reasonable succession of alkaline addition activities through which the NFWA can gain implementation and funding experience while achieving a fairly steady progression of restoration milestones.

The overall implementation cost of restoring the North Fork watershed is estimated to range from \$500,000 to \$6.5 million depending on the alkaline addition methods applied. Long-term costs of maintaining water quality will likely be on the order of \$50,000 per year. It is unlikely that this level of funding will be immediately available from grants and donations. The most important considerations for the NFWA at this point are to establish short-term priorities and implement relatively low cost and high benefit projects. Demonstration of success, resolve, and a working relationship among stakeholders are major factors in justifying funding of more substantial restoration projects. For the near future, it is recommended that the NFWA undertake the following activities:

- Continue monitoring the sample points for pH to develop a long-term database of basic water quality for comparison to improvements resulting from alkaline addition projects.
- Develop an educational outreach program to inform local landowners of the benefits of using limestone in land application, road surfacing, ditch lining, and bank stabilization projects.
- Proceed with currently planned lake liming activities on Manners Dam Run using remaining funds from this study project grant, and by applying for additional funds if needed.
- Develop a desired prioritization of streams for restoration based on local wishes, considering factors such as recreational value, accessibility, aesthetics, and landowner interest.
- Seek funding and implement one or more alkaline addition projects for Craft Run, Seneca Run, and Hetrick Run depending on their priority order in the desired list.

- Prepare a practical, long-term prioritization of remaining streams by comparing the desired list to the levels of restoration effort presented in this study for individual streams.

- Review the long-term prioritization list with the PADEP for input regarding the best candidate projects and avenues for funding.

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