**Mosquito Creek Watershed Assessment**
**And Restoration Plan**

# ASSESSMENT OF APPLIED TECHNOLOGIES FOR ACID ABATEMENT

# FINAL REPORT

**Pennsylvania Growing Greener Program**

**Project No. ME 352934**

**June 2006**

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# ABSTRACT

The 90 square mile Mosquito Creek watershed, located in north-central Pennsylvania, is moderately to severely impacted by acid deposition (acid rain), reducing or eliminating wild trout populations in most reaches. Since 2000, the Pennsylvania Growing Greener Grants Program has funded a series of projects sponsored by the Mosquito Creek Sportsmen's Association to determine the level of alkaline addition needed to restore these fisheries and to demonstrate and evaluate alkaline addition technologies. Between 2001 and 2005, an in-stream monitoring program was conducted for 15 points on tributaries and the main stem (13 rounds), with parameters of flow, pH, alkalinity, acidity, ANC, and aluminum. A complimentary program by the Pennsylvania State University (PSU) sampled 7 additional in-stream points. Results were used to determine alkaline deficiencies before and after alkaline addition projects, and for average and high flow conditions, including evaluation of acidification response to flow under the categories of sustainable, episodic, and chronic. Results showed that the watershed is impacted throughout, with the most severe acidification occurring in the northern headwaters around Pebble Run and Beaver Run. The total alkaline deficiency for the watershed was estimated at 150 tons per year. Applied technologies included three vertical flow wetlands (VFWs), in-stream limestone sand dosing, lake liming, limestone road surfacing and runoff channels, and forest liming by PSU under a separate Grant. Designs and permits were prepared for two high flow buffer channels (HFBCs) and two vertical flow limestone beds (VFLBs), with one HFBC currently funded for construction. Completed projects were monitored to develop alkalinity output rates, design criteria, and costs of for application. Typical costs per pound of alkalinity generation were found to be \$0.75 for VFWs, \$0.01 for sand dosing, \$0.10 to \$0.30 for lake liming, and \$0.05 for road and forest liming. A benefit/cost analysis was prepared using a progressive restoration plan divided into four implementation phases. Costs were based on alkaline deficiencies and the addition costs determined for the technologies. Benefits were estimated as returns on direct recreational use losses and community willingness-to-pay. Full restoration of the watershed is estimated to cost approximately \$3.4 million over 15 years, for an annualized cost of \$229,000, or \$5,400 per mile per year for 42 miles of potential improvements. Expected returns range from \$1.2 million per year for recreational use to \$6.1 million per year for total community willingness-to-pay. It was concluded that restoration is technically feasible and economically beneficial for the Mosquito Creek watershed, and it is recommended that planned projects and the remainder of the progressive restoration plan be implemented.

# EXECUTIVE SUMMARY

Mosquito Creek, located in north-central Pennsylvania, is moderately to severely impacted by acid deposition (acid rain) throughout its 90 square mile watershed. Wild trout have been extirpated from all but a few residual pockets, and stocking is possible only on a 4 mile reach of Gifford Run where annual limestone sand dosing is applied. Since 2000, the Pennsylvania Growing Greener Program has funded a series of assessments and restoration projects for Mosquito Creek, with the goals being to determine the level of alkaline addition needed to restore viable fisheries in impacted streams, and to demonstrate and evaluate alkaline addition technologies capable of meeting this need. Activities have been sponsored by the Mosquito Creek Sportsmen's Association (MCSA), a local group of concerned citizens seeking to return the stream to its pre-impact conditions. This report presents the findings of the water quality and technology assessments, and proposes a progressive restoration plan for the watershed.

Assessment activities have included in-stream monitoring by the MCSA on 15 sample points to characterize and quantify alkaline deficiencies in major tributaries and the main stem of Mosquito Creek. The study area included the reaches above Grimes Run, which is impacted by a different source of acidity from acid mine drainage (AMD). Primary monitoring parameters included flow, pH, acidity, alkalinity, acid neutralization capacity (ANC), and aluminum. Additional in-stream monitoring was conducted by the Pennsylvania State University (PSU) on 7 sample points under separate Grants. Results were used to determine the alkaline deficiencies in pounds per day (lbs/day) and tons per year (tons/yr) present at each sample point, presented as conditions before and after existing alkaline addition projects. These conditions were also assessed under average and high (95% confidence interval) flow conditions. Relative water quality was summarized by categories ranging from very good to very poor based on ANC and pH levels, and interpreted survivability for fish populations. Relationships between ANC and flow were developed to correlate acidification to runoff events, with acidification conditions classified as sustainable (consistently positive ANC), episodic (negative ANC with increasing flow), or chronic (consistently negative ANC). The report details monitoring and assessment methodologies that would be applicable to acid deposition studies in other watersheds.

Assessments of pre-addition conditions indicate that the most severe acidification occurs in the vicinity of Pebble Run and Beaver Run, located in the northern headwaters of Mosquito Creek. Poor to very poor conditions persist downstream to approximately Panther Run. Streams in this area are very chronically acidified and are not believed to support any significant fish populations. The lower reaches, including Gifford Run, Twelvemile Run, and Cole Run, show very poor conditions under high flows, with milder acidification and more episodic conditions under average flows. The areas of greatest impact appear to correlate with exposures of quartz pebble conglomerates of the lower Pennsylvanian Pottsville formation. Pre-addition alkaline deficiencies as mass loadings (pounds per day) are interpreted to be greatest in the main stem between Beaver Run and Meeker Run, and between Gifford Run and the end of the study area at Grimes Run. Post-addition conditions differ from pre-addition conditions only for the tributaries affected by existing alkaline addition projects, as discussed for the individual technologies in the remainder of this section.

Constructed alkaline addition demonstration projects included vertical flow wetlands (VFWs), lake liming, alkaline road runoff channels (ARRCs), and a limestone sand dosing ford. A round of limestone sand dosing was also funded for the MCSA in continuation of their ongoing treatment activities for Gifford Run. Two new technologies, vertical flow limestone beds (VFLBs) and high flow buffer channels (HFBCs), were designed and permitted, but have not yet been constructed. Performance monitoring was conducted for the constructed and ongoing projects to determine alkalinity generation rates and assess costs per pound of alkalinity produced. Under a separate Grant, PSU conducted and monitored forest liming as another alkaline addition technology. The following summarizes the nature and results of these projects:

- **Vertical Flow Wetlands** consist of open water basins containing basal beds of limestone aggregate covered by spent mushroom compost, with water diverted from a stream passing downward through the beds to acquire alkalinity before return via an underdrain to neutralize the main stream flow. They were originally developed for AMD and were adapted by this project for acid runoff setting. VFWs were constructed on each of the Ardell tributary (2001), Duck Marsh tributary (2003), and Pebble Run (2003) sites. A standardized design was developed for the latter two systems that is applicable to other acidified watersheds on a loading-demand basis. Alkalinity output was found to be optimized by 18 hours detention in the limestone bed, with a sizing nomogram presented in the report. Results indicate that positive ANC has been restored in 1.6 miles of the Ardell tributary and 1.7 miles of the Duck Marsh tributary. The Pebble Run system generates positive ANC for some distance downstream; however, the stream is larger and more acidic than the first two applications, and it is interpreted that a second VFW will be needed to fully restore Pebble Run to the Mosquito Creek confluence. The standard design VFW will likely cost about $200,000 to construct at today's construction rates and occupies about 1 acre, with alkalinity generation rates of about 50 lbs/day (9 tons/yr) equating to $0.75 per pound.

- **Vertical Flow Limestone Beds** are essentially VFWs without the compost bed, which is recommended for systems treating high-metals AMD, but may not be needed for "clean water" applications such as acid runoff. VFLBs were designed and permitted for the headwaters of Lost Run and Deserter Run, but have not yet been funded for construction. These systems are intended to restore 1.8 miles of Lost Run and 1.6 miles of Deserter Run, and support other restoration projects for Gifford Run. It is anticipated that VFLBs will have a lower construction cost (about $175,000), with a comparable alkalinity output to VFWs.

- **In-stream Limestone Sand Dosing** is simply the addition of loose limestone sand (typically AASHTO No. 10) into a stream channel to neutralize acidity. The MCSA has been placing limestone sand in Gifford Run downstream of the Merrill Road and Lost Run Road bridges for a number of years in support of their annual trout stocking program. The results have been good quality, mildly episodic acidification conditions between Merrill Road and Lost Run Road, and very good quality, sustainable conditions downstream to Mosquito Creek. The dosing rate in tons appears to correspond reasonably well with the annual alkalinity generation in the stream. Four methods of estimating dosing requirements are presented in the report for use in other first-time applications. The $20 per ton for delivered limestone sand in this project equates to about $0.01 per pound of added alkalinity. There are concerns, however, that long-term dosing may degrade the streambed habitat with fines, and technologies such as VFWs, VFLBs, and HFBCs are being applied in an effort to eventually replace the practice.

- **Lake Liming** is the spreading of fine limestone over an open water body to create a large reservoir of alkaline water to gradually neutralize runoff flows, with the added benefit of improving large areas of open water fisheries. As a cooperative research project with the PA DCNR Bureau of Forestry, Moshannon State Forest, aerial liming was applied at a rate of 2 tons per acre to the 25 acre lake at the head of Beaver Run in May 2004. Monitoring showed that alkaline conditions were maintained in the lake until at least April 2005, and likely would have continued longer if not for unusually high precipitation during this period. The highest ANC at the mouth of Beaver Run was also recorded after lake liming. Aerial liming at this rate costs about $1,200 per acre, or $0.30 per pound of alkaline addition. Lime can also be applied by boat, which is more labor intensive, but costs less at about $270 per acre or $0.10 per pound. Boat liming could not be used in this case because the site is located within the Quehanna Wild Area, where mechanical access restrictions apply.

- **High Flow Buffer Channels** are basically a constructed "stream beside a stream" in which limestone sand can be placed to neutralize flows by normal migration action, but in which the sand is trapped at the discharge end by a settling pool that also serves as an alkaline refuge for fish. An in-stream vane structure diverts a portion of high flows into the HFBC to neutralize episodic acidification during storm events, while smaller portions of average flows infiltrate through the inlet to maintain baseflow conditions. This approach prevents streambed impacts in the natural channel and minimizes wastage of material through unneeded dissolution at low flows. HFBCs were designed and permitted immediately upstream of Lost Run Road and downstream from Merrill Road, with the Lost Run Road system funded for construction in 2007. Construction costs per unit are anticipated at about $90,000, with annual maintenance costs and alkalinity generation rates comparable to in-stream limestone sand dosing thereafter.

- **Road Liming** is a collection of practices using limestone in surfacing and construction for passive alkalinity generation in runoff affected by roads. It was observed during the study that acidified runoff gained approximately 1 unit of pH when encountering existing limestone-surfaced roads in the watershed. A cooperative research project was undertaken with the Moshannon State Forest in 2003 to construct an ARRC along Lost Run Road near Meeker Run. Sampling from the ARRC discharge showed an alkalinity of about 20 mg/L and pH of 7.6 SU. Limestone road surfacing can be used in place of other types of loose surfacing during routine maintenance for essentially the additional cost of material. Construction costs for ARRCs will vary by the size and length of the channel, but are estimated at approximately $0.05 per pound of alkalinity output. In a third road project, a limestone sand dosing ford was designed by the PA Game Commission and constructed across Mosquito Creek at Ardell Dam Road in 2001. The concept was to contain coarse limestone in gabion walls as a driving surface, with limestone sand filling the voids for alkalinity generation and dosing by washout during high flow events. The project was completed for $20,000, but results were ambiguous due to the upstream alkalinity generation from VFWs at Ardell and the Duck Marshes.

- **Forest Liming** and other forms of catchment liming involve spreading fine limestone over terrestrial areas to neutralize runoff and reduce soil acidity. In 2003, forest liming was conducted and assessed by PSU in the headwaters of two unnamed tributaries to Gifford Run at Merrill Road. A specially equipped log skidder with a lime spreader was purchased by PSU for this purpose. The application rate was 2 tons per acre of dolomitic AASHTO No. 10 limestone sand. The receiving tributaries were monitored in 2004 and 2005, but observed improvements could not be definitively linked to the liming operation. Other forest liming studies have documented improvements, but full results may not be realized for a number of years due to the slow migration time of alkalinity from upland areas. Costs of forest liming can very considerably depending on the difficulty of spreading access, but in this case equated to about $270 per acre, or $0.05 per pound of added alkalinity.

- **Other Technologies**, including diversion wells, limestone basket wheels and rotary drums, and pebble quicklime addition, were not applied in this study, but summary assessments are provided in the report for reference. These technologies all have higher operation and maintenance requirements than the applied technologies, and may not be as suitable for remote site applications such as Mosquito Creek.

At the conclusion of the watershed and technology assessments, a benefit/cost analysis was performed for the existing projects and future projects that might be required to fully restore the Mosquito Creek watershed. Benefits were assessed in two ways. The minimum benefit was assumed to be the direct losses to recreational fishing income, estimated by the Pennsylvania Fish & Boat Commission at $23,400 per mile per year in 1995 ($28,000 in 2000 dollars). The maximum return was taken to be the community willingness-to-pay (WTP) based on a study by PSU for nearby Clearfield Creek in 2000. The PSU study related WTP to the variables of reach length restored and travel time from home, with values ranging from $32 per household per year for 1 mile at 5 minutes, to $29 per household per year for 20 miles at 30 minutes. The 2000 census was used to estimate that approximately 70,000 households are present within 30 minutes of the watershed, with this figure broken down into 5, 10, 20, and 30 minute categories for comparison to 1, 5, 10, and 20 miles of restoration.

To quantify the costs of restoration, a progressive restoration plan was developed to outline the incremental treatment steps necessary to address the remaining alkalinity deficiencies identified in the watershed, with the sequence intended to create connected improvements in order of the most accessible fisheries. The plan was divided into four phases: Phase 1 – Gifford Run, Phase 2 – Mosquito Creek Headwaters, Phase 3 – Mosquito Creek Middle Reaches, and Phase 4 – Mosquito Creek Lower Reaches. Phases 1 and 2 are separate restoration areas with independent costs. Phase 3 depends on completion of Phase 2, and Phase 4 depends on completion of both Phases 1 and 3. Costs of restoration were estimated assuming mostly use of VFWs as being the best documented technology for cost and reliability of alkalinity output. A 15-year project period was applied as being the assumed life expectancy of a VFW. As the highest-cost technology, VFWs are considered to be a conservative estimate for the overall project. The following summarizes the scope of these phases and their associated costs and benefits:

- **Phase 1 – Gifford Run:** This stream has value for its existing fisheries and would provide the most immediate return for further alkaline addition. Existing limestone sand dosing will be maintained by the MCSA until HFBCs are completed at Lost Run Road and Merrill Road, and VFLBs are completed on Lost Run and Deserter Run, at which time the practice can be discontinued. The equivalent of two more VFWs will be needed in the Gifford Run headwaters to address acidity upstream of Merrill Road. The 15-year cost of this phase is estimated at $1 million for construction and maintenance, with an annualized value of $68,000 compared to an annual return range of $300,000 in recreational losses to $1.4 million in community WTP. Restoration costs equate to around $6,400 per mile per year, with about 11 connected stream miles restored.

- **Phase 2 – Mosquito Creek Headwaters:** This area is easily accessible and has already received a substantial investment in alkaline addition. Its restoration will likely be required before significant midstream improvements can occur in Mosquito Creek. Existing projects include VFWs on the Ardell tributary, Duck Marsh tributary, and Pebble Run, the limestone sand dosing ford at Ardell Dam Road, and Beaver Run lake liming. It is estimated that the equivalent of two more VFWs will be needed in the Mosquito Creek headwaters above the Duck Marsh tributary, one more on Pebble Run, and one on Beaver Run to provide main stem connectivity extending downstream to approximately McNerney Run. The 15-year cost of this phase will be about $1.6 million, or $100,000 per year compared to annual returns of $290,000 for recreation to $1.4 million for WTP. Costs per mile per year equates to approximately $9,800, with 10 miles restored.

- **Phase 3 – Mosquito Creek Middle Reaches:** Much of this area is reasonably accessible to foot travel, although Panther Run is fairly remote. No alkaline addition has been performed to date. McNerney Run, Meeker Run, and Panther Run will each require the equivalent of one headwaters VFW. The interpreted main stem acidity loading above Meeker Run is the equivalent of 3 VFWs, but only one accessible flowing tributary is present in this segment upstream to McNerney Run. It is proposed to construct one VFW at this site, and to use limestone sand dosing at Lost Run Road below Meeker Run to make up the deficiency difference. Cumulative improvements from Phase 2 and upstream Phase 3 projects may allow the later use of HFBCs in this area. The 15-year project cost of $2.4 million includes the upstream Phase 2 cost. The annual cost of $163,000 compares to annual returns of $630,000 for recreation to $2.9 million for WTP. Assuming improvements extending to Twelvemile Run, the cumulative restoration for Phases 2 and 3 is about 23 miles at $7,200 per mile per year.

- **Phase 4 – Mosquito Creek Lower Reaches:** This area, including Twelvemile Run and Cole Run, is the least accessible in the watershed. Improvements to the Mosquito Creek main stem are already observed from the Gifford Run sand dosing, and will certainly increase if Phases 1 – 3 are implemented, so Phase 4 is considered the lowest priority. Twelvemile Run and Cole Run will require the equivalent of 2 and 3 VFWs in their headwaters, respectively. These activities would cost about $1 million independent of the previous phases. In combination with Phases 1 – 3, the total 15-year cost to restore Mosquito Creek to the confluence with Grimes Run would be approximately $3.4 million. Compared to the annualized cost of $229,000, annual returns are $1.2 million for recreational losses to $6.1 million in community WTP. The cumulative restoration length for Phases 1 – 4 would be about 42 stream miles, equating to $5,400 per mile per year.

The overall conclusion of this study is that restoration of Mosquito Creek by alkaline addition is technically feasible and economically beneficial. Predicted restoration costs are consistently below both the estimated annual losses to recreational fishing and annual community willingness-to-pay for all implementation phases. The cost per mile per year is considerably less than that for many AMD-impacted watersheds in the region. Mosquito Creek is one of the least developed watersheds remaining in Pennsylvania, yet has easy access from Interstate 80, and over 70 percent is contained within public lands. It is considered to be well worth additional investment to complete the progressive restoration plan, with specific recommendations for initial implementation as follows:

- The remaining HFBC at Merrill Road and VLFBs on Lost Run and Deserter Run should be funded for construction using the existing designs before the secured permits expire in 2010.

- A design and permitting phase should be funded to develop remaining required alkaline addition projects in the headwaters of Gifford Run above Merrill Road.

- A design and permitting phase should be funded to develop remaining required alkaline addition projects for the upper Mosquito Creek headwaters, lower Pebble Run, and Beaver Run.

- A means of perpetual funding should be secured for lake liming in the Beaver Run headwaters to allow reestablishment of fisheries in that water body; a combined effort for the Duck Marshes could be considered.

- Alkaline addition requirements and conceptual project approaches for the Phase 3 area should be reevaluated after completion of Phase 2 to account for actual water quality improvements in the middle reaches; likewise Phase 4 should be reevaluated after completion of Phase 3.

- Sampling budgets should be included in future funding efforts to continue the in-stream monitoring program (April and October rounds at minimum) to develop long-term trends and document the effects of alkaline addition activities. Performance monitoring should be included with each new alkaline addition project to increase the available database and permit more efficient implementation of future projects.

# APPENDIX A

## WATER MONITORING DATA

MOSQUITO CREEK ASSESSMENT OF APPLIED
TECHNOLOGIES FOR ACID ABATEMENT

# APPENDIX B

# EXAMPLE RESEARCH STUDY PLAN

MOSQUITO CREEK ASSESSMENT OF APPLIED
TECHNOLOGIES FOR ACID ABATEMENT

# APPENDIX C

## GROWING GREENER GOALS AND ACCOMPLISHMENT FORMS

MOSQUITO CREEK ASSESSMENT OF APPLIED
TECHNOLOGIES FOR ACID ABATEMENT

# 1

# INTRODUCTION

Since 2000, the Mosquito Creek Sportsmen's Association (MCSA) and other stakeholders have been conducting a series of assessment and demonstration projects to identify methods to reduce atmospheric acid deposition (acid rain) impacts in the Mosquito Creek watershed, located in north-central Pennsylvania. This work has been funded by a series of Pennsylvania Growing Greener Grants administered through the Department of Environmental Protection (PADEP), with complimentary studies by the Pennsylvania State University (PSU) under concurrent Grants. The primary goals of these projects have been:

- To determine the nature and degree of acidification impacts in Mosquito Creek and its major tributaries.
- To design and implement innovative new technologies for passive acidity reduction by alkaline addition.
- To monitor alkaline addition projects and develop performance criteria for implementation in other watersheds.
- To evaluate the costs of these technologies and their economic benefits for restoration.
- To develop a progressive restoration plan for the Mosquito Creek watershed.

Assessment activities have included five years of in-stream monitoring on Mosquito Creek and its tributaries to evaluate acidification conditions and quantify the amount of alkaline addition required for restoration. Seven passive alkaline addition technologies have been evaluated, with five applied to the watershed and monitored for performance. Three of these technologies are new approaches to the problem of acid deposition abatement. This report provides a summary of the project findings and recommendations for the application of these technologies in other watersheds suffering similar acid impairment.

This section provides a description of the Mosquito Creek watershed, the scope of Grant-funded activities, and an overview of the chemistry and characteristics of acid deposition. A reference summary of acid/base chemistry is included at the end of the section for readers not familiar with the general concepts.

# THE MOSQUITO CREEK WATERSHED

As shown by Figure 1-1, the Mosquito Creek watershed covers portions of Clearfield, Elk, and Cameron Counties, Pennsylvania. It is a tributary to the West Branch of the Susquehanna River to the south, and shares boundaries with Trout Run to the west and Sinnemahoning Creek and Bennett Branch to the north. The area is predominantly forested and home to an abundance of game species and other wildlife, including the Pennsylvania elk herd. Located only a few miles off Interstate 80, it has superb access via a network of improved forest roads and hiking trails. Over 70 percent of the watershed is contained in State Game Lands and the Moshannon State Forest, making it ideal for outdoor recreation. It is one of the few remaining large, undeveloped areas in Pennsylvania with such habitat conditions and accessibility.

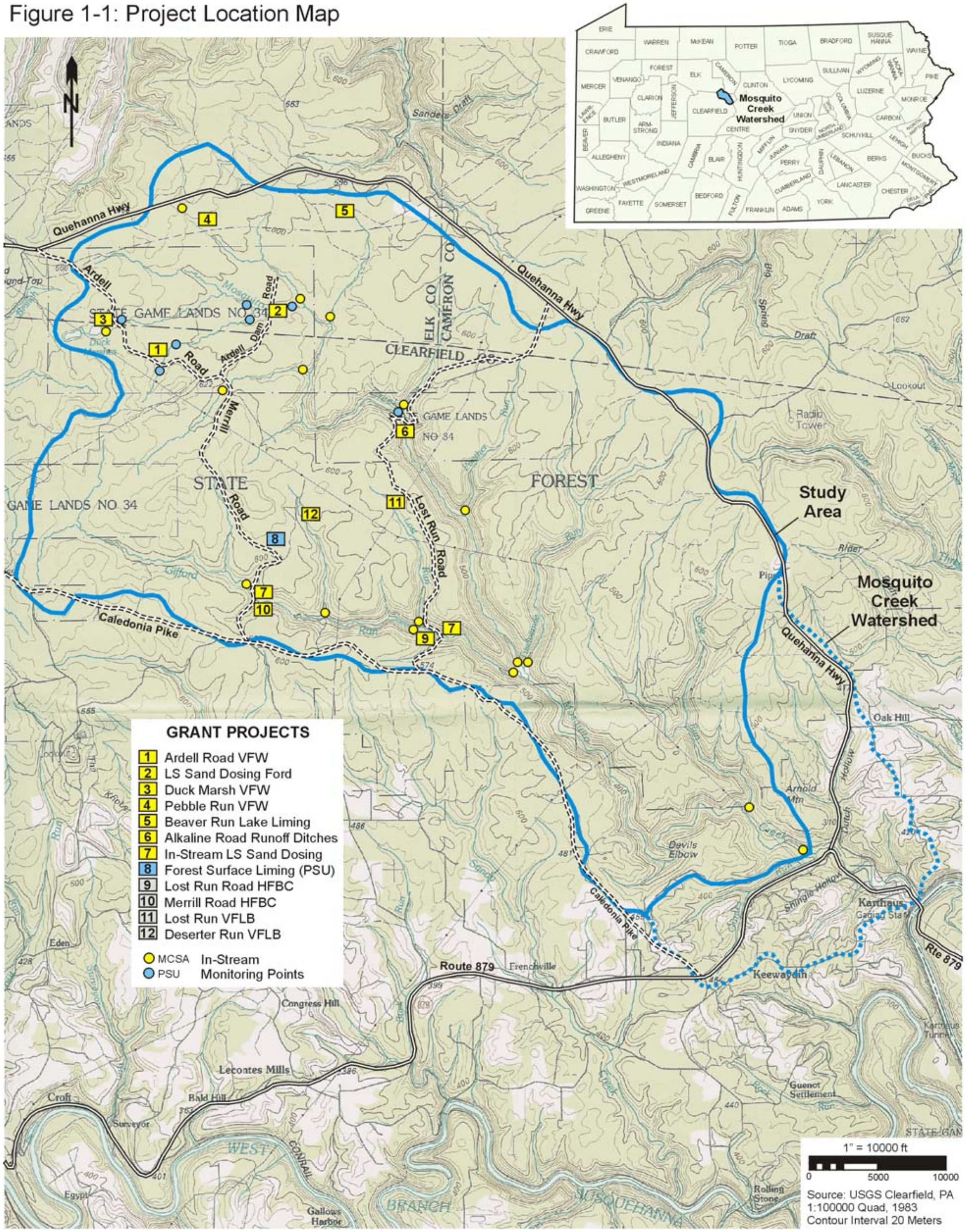
## Mosquito Creek Watershed Facts

| | |
|---|---|
| Drainage Basin: | Susquehanna River |
| Subbasin: | 8D – Mosquito Creek |
| Drainage Area: | ≈ 90 square miles |
| Stream Reach: | 50+ miles |
| Classification: | High Quality – Exceptional Value |

Despite these amenities, the recreational and environmental value of Mosquito Creek is limited by the impacts of acid deposition. Once a premier wild and stocked trout fishery, decades of acidification have decimated populations and entirely eliminated fish from most tributaries. Conditions had become so poor by the early 1980s that the Pennsylvania Fish & Boat Commission ceased stocking the stream due to fish mortality. Isolated reaches still contain limited populations of native brook trout tolerant to low pH conditions. In the lower reaches of Gifford Run where the MCSA has conducted in-stream limestone sand dosing, and in Mosquito Creek below the confluence of Gifford Run, a combination of native and stocked fishery exists.

Although regulation of upwind sources is believed to be reducing the acid load reaching the watershed, existing acidification effects are expected to continue into the foreseeable future. The area is underlain by sandstone and shale bedrock with little inherent buffering capacity, and soil acidification is a very long-term problem. By use of passive alkaline addition technologies, the MCSA is seeking to make up for this buffering deficit until source reduction can restore a sustainable natural condition.

Figure 1-1: Project Location Map



## SCOPE OF GRANT-FUNDED ACTIVITIES

As of 2006, the Pennsylvania Growing Greener Program has funded assessment and demonstration projects for Mosquito Creek in six of the first seven Grant rounds. This support has allowed establishment of one of the most comprehensive and diverse acid deposition abatement programs in the state. Table 1-1 provides a summary of the individual Grant activities, and Figure 1-2 shows the locations of these projects within the watershed study area.

At the time of this report, construction and monitoring of the Round 1 and 3 vertical flow wetlands (VFWs) has been completed. The watershed-scale in-stream monitoring program established under Round 2 has been continued through subsequent Grants and was completed in 2005. Construction of the first high flow buffer channel (HFBC) designed under Round 5 is planned for 2006 under a Round 7 Grant. This report represents the conclusion of the Round 4 assessment activities, including development of a final progressive restoration plan. It is anticipated that future funding will be sought to construct the remainder of the Round 5 project designs, and to implement the ongoing recommendations of the progressive restoration plan.

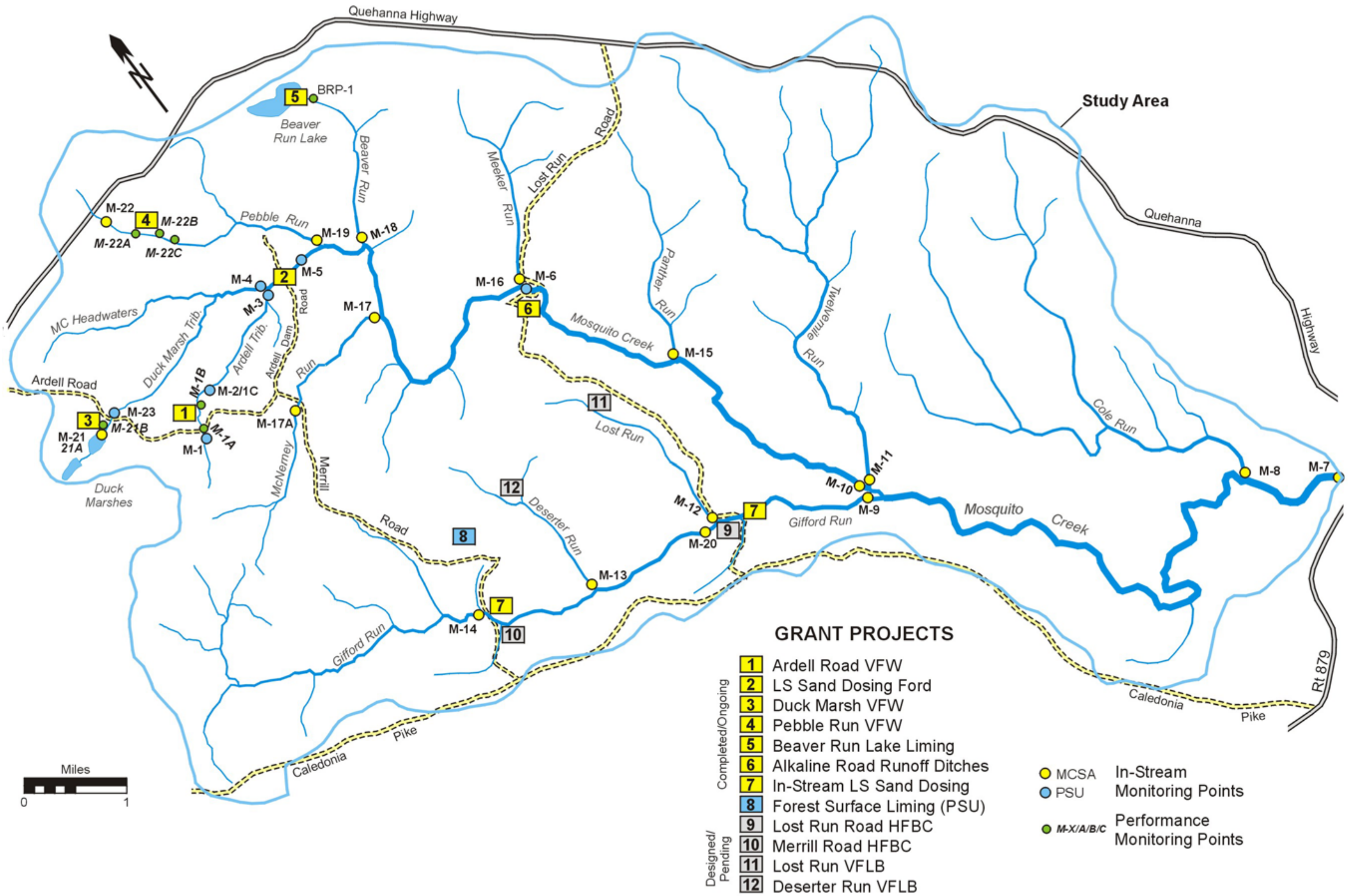
As concerned citizens, the MCSA has pursued these efforts on a voluntary basis to restore the Mosquito Creek fisheries as a valuable socioeconomic component of their community. Development of local recreational resources is particularly important as ecotourism represents one of the major potential economic opportunities in the region. Along with the MCSA, the following participants are acknowledged for their contributions to and support of these projects:

- Pennsylvania Department of Environmental Protection
- Pennsylvania DCNR Bureau of Forestry
- Pennsylvania Game Commission
- Pennsylvania Fish & Boat Commission
- Pennsylvania Department of Corrections Quehanna Boot Camp
- Wood Duck Chapter Trout Unlimited
- Canaan Valley Institute
- Clearfield County Conservation District
- USDA Natural Resource Conservation Service
- Penn State University Institutes of the Environment
- Water’s Edge Hydrology, Inc.
- Gannett Fleming, Inc.

Table 1-1: Summary of Mosquito Creek Growing Greener Grant Projects

| Grant | Project Scope | Results/Benefits |
|---|---|---|
| **Round 1** | *Phase 1 – Atmospheric Acidification Abatement Demonstration Projects:* Design and construction of a vertical flow wetland (VFW) to generate alkalinity in the Ardell tributary, and an experimental limestone sand dosing stream ford on the main stem. PSU monitored in-stream results under concurrent Grant. | Demonstrated that VFWs are applicable to acid deposition impacts. Water quality improvements extend 1.6 miles downstream to the confluence with Mosquito Creek, and the formerly acidified Ardell tributary now appears capable of supporting fish populations. Provided monitoring results for design of future VFW systems. |
| **Round 2** | *Phase 2 – Watershed-Scale Assessment for Acidification Abatement:* In-stream water quality and flow monitoring at 15 permanent stations on major tributaries and the main stem of Mosquito Creek, and evaluation of the results to develop a preliminary progressive restoration plan. | Provided data to characterize water quality throughout the watershed and identify the primary areas of acidification. Concurrent flow measurements allowed evaluation of episodic acidification patterns. Allowed planning of future treatment efforts to produce measurable results. |
| **Round 3** | *Phase 3 – Progressive Restoration Plan Implementation:* Design and construction of two VFWs on the Duck Marsh tributary and Pebble Run to evaluate the mutually supportive main stem effects of treating adjacent tributaries. Also funded continuation of the Phase 2 monitoring program. Surface liming conducted in headwaters areas by PSU under concurrent Grant. | Resulted in substantial improvements in the Duck Marsh Tributary, and measurable improvements in the Mosquito Creek main stem and the mouth of Pebble Run. Standardized design and performance expectations developed for VFWs. Remainder from construction budget used to fund aerial lake liming on Beaver Run and road runoff buffering channels on Lost Run Road. |
| **Round 4** | *Phase 4 – Assessment of Applied Technologies for Acid Abatement:* Preparation of a comprehensive report on the findings of the previous Grant projects and assessment of the effectiveness of the applied technologies. | Resulted in this report to provide technology transfer for the Mosquito Creek Grant activities, including cost effectiveness of the various technologies and implementation guidelines for other watersheds impacted by acid deposition. |
| **Round 5** | *Phase 5 - Design of Offline Limestone Sand Application Systems:* Design and permitting of two new alkaline addition technologies at four sites: high flow buffer channels (HFBCs) on Gifford Run, and vertical flow limestone beds (VFLBs) on Lost Run and Deserter Run | These systems will demonstrate new approaches to using limestone sand for stream buffering without the sedimentation problems associated with direct in-stream application. HFBCs are specific to episodically acidified streams, while VFLBs provide continuous treatment. |
| **Round 7** | *Phase 7 – Off-Line Alkaline Addition Demonstration Projects:* Construction and construction supervision for the Round 5 HFBC and VFLB designs. | Grant amount was sufficient to allow construction of the Lost Run Road HFBC to begin in 2006. Additional funding will be needed to construct the remaining Round 5 designs. |

Figure 1-2: Scope of Grant-Funded Activities



# OVERVIEW OF ACID DEPOSITION

Acid deposition, commonly known as "acid rain," occurs when volatile compounds such as sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_x$) are released to the air and react with atmospheric moisture to form dilute sulfuric ($H_2SO_4$) and nitric ($HNO_3$) acids. Acid is returned to the ground as rain and snow, where it reduces the pH of soils and streams and can damage aquatic habitats. Some watersheds contain sufficient inherent alkalinity to neutralize the excess acidity and are not significantly impacted. Others, like Mosquito Creek, are poorly buffered and exhibit poor water quality, and are unable to sustain a viable aquatic ecosystem. Figure 1-3 illustrates this basic process.

As shown by Figure 1-4, acid deposition is a widespread problem in the Mid-Atlantic and New England states, particularly in the Appalachian highlands. Northwestern Pennsylvania, including the Mosquito Creek watershed, receives rainfall with some of the lowest pH in the nation. The primary sources of acidity affecting Pennsylvania are electric power generation and other industrial discharges upwind in the Great Lakes region and Ohio River Valley. The Clean Air Act Amendments of 1990 require that 1980 $SO_2$ emission levels from electric power plants be cut in half by the year 2010, and an increasing trend in rainfall pH has been observed since emission controls were enacted. However, damage to soils and the buffering capacity of watersheds by acidification is a long-term impact that is not readily corrected by eliminating the source alone. In many watersheds, alkaline addition activities will be necessary until such time as a sustainable buffering capacity and rainfall acidity level can be restored.

Figure 1-3: Acid Rain Formation, Deposition, and Neutralization

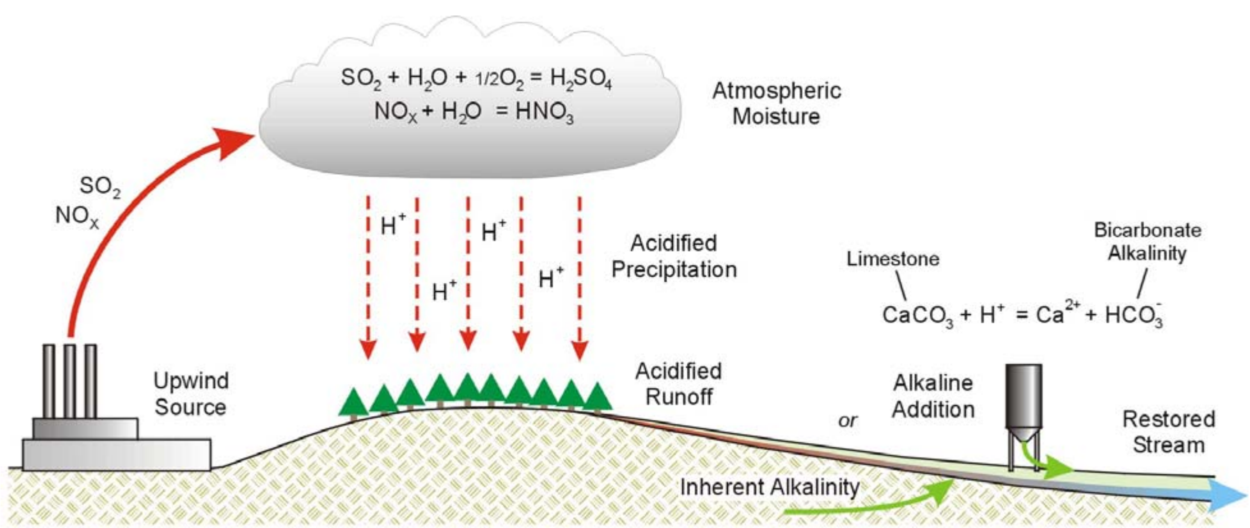
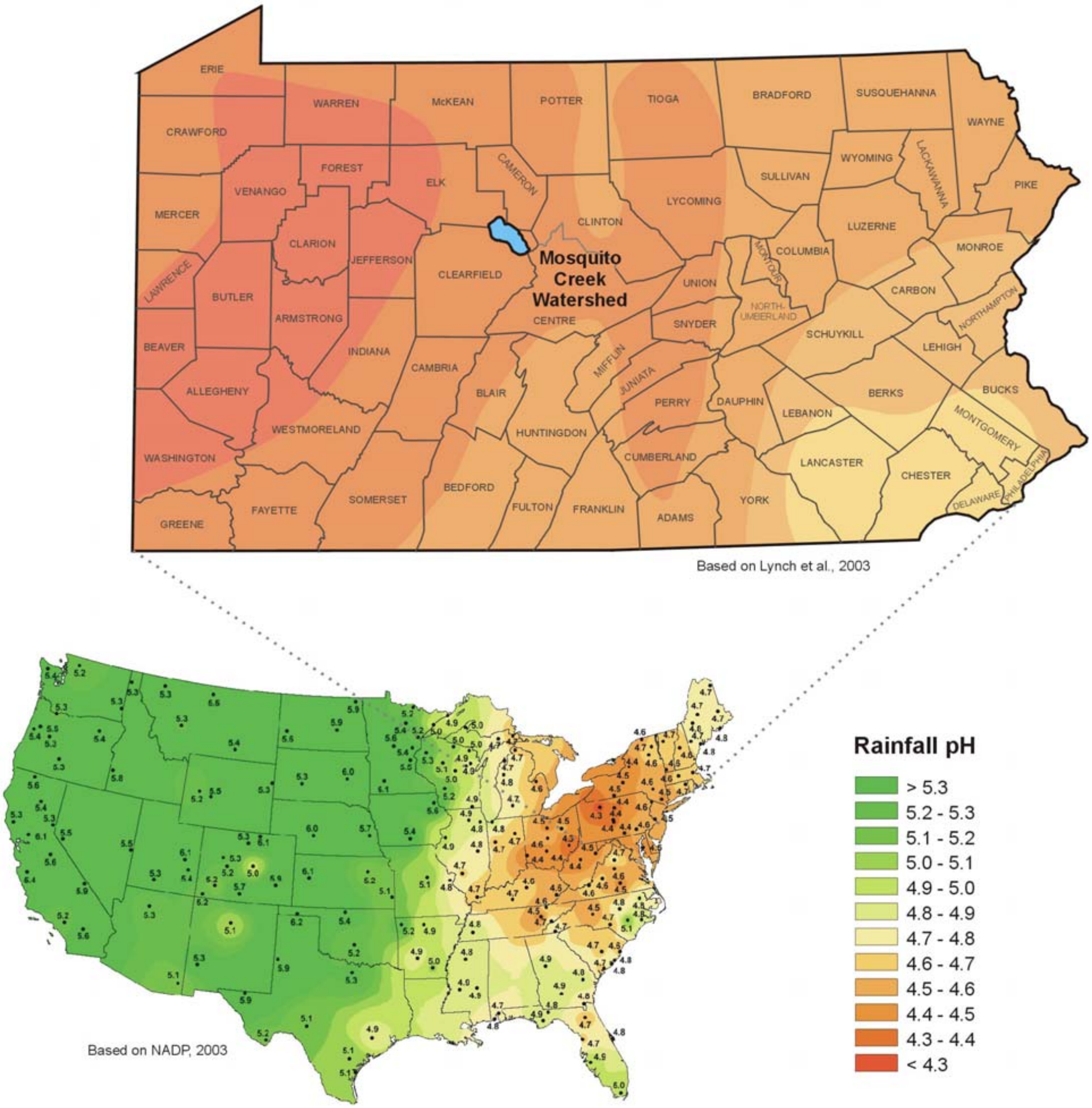


Figure 1-4: National and Pennsylvania Rainfall pH, 2003

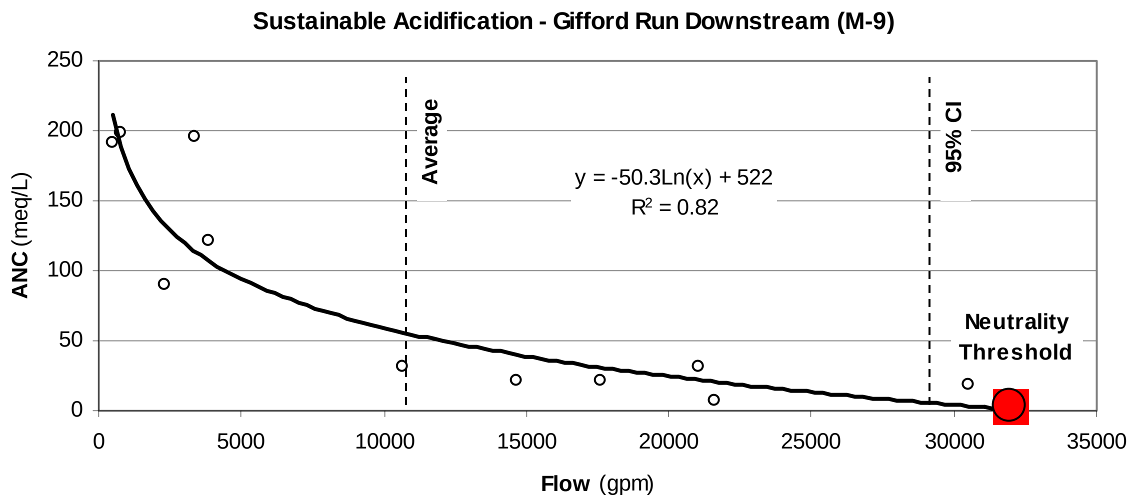


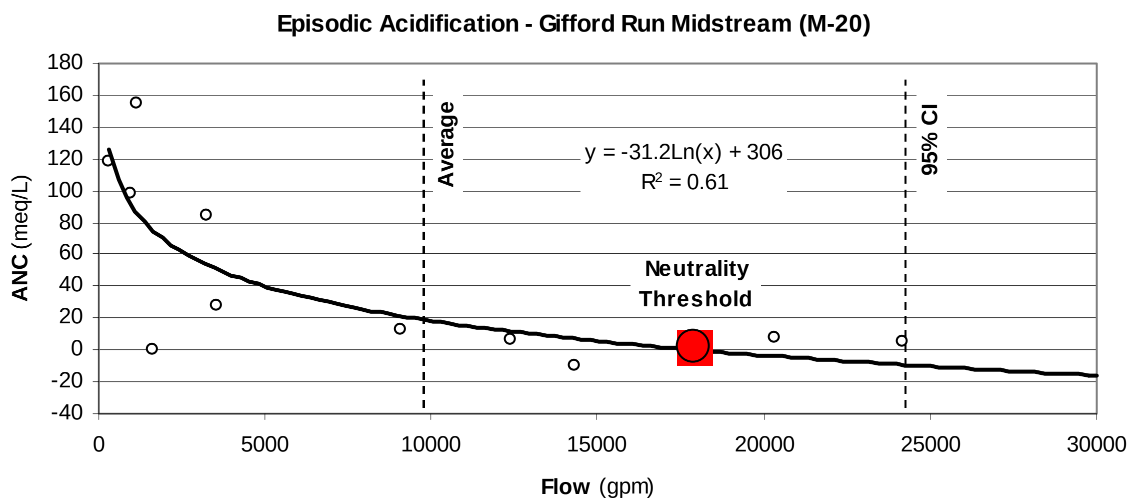
The three basic categories of acid deposition impacts used in this study are *sustainable, episodic,* and *chronic* depending on where acidification begins to occur in a stream's flow range from baseflow to storm flow. Sustainable streams contain sufficient alkalinity to neutralize the acid deposition loading and maintain acceptable water quality for fish populations under all or all but extremely high flow conditions. In episodically acidified streams, the neutralization capacity of alkaline baseflow can be overwhelmed during acidic storm flow or snow melt events, resulting in acidic conditions during moderate to high flows. If the acid deposition loading greatly exceeds the baseflow alkalinity, a stream will be chronically acidified and show poor water quality under most or all flow conditions.

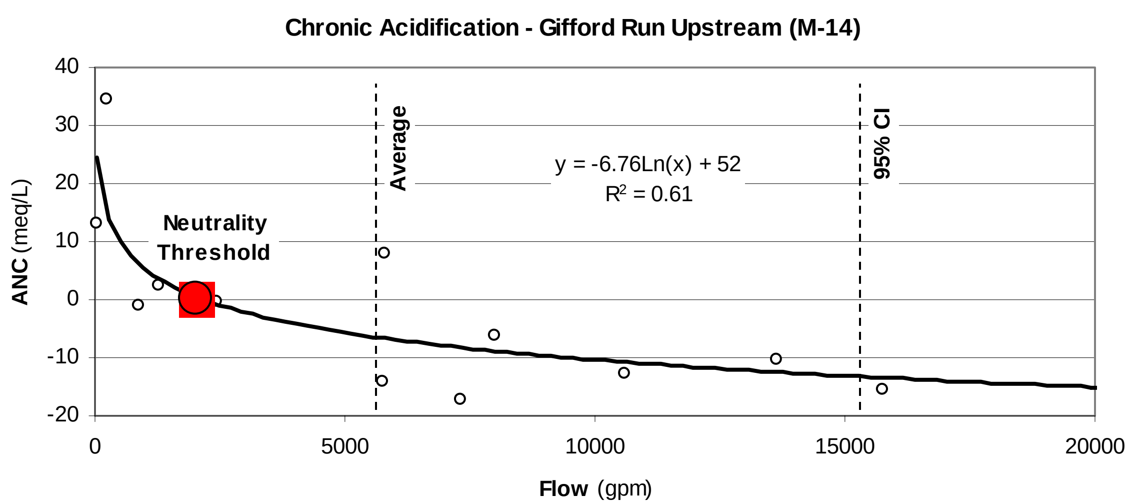
In Gifford Run, a tributary to Mosquito Creek, in-stream limestone sand dosing by the MCSA has resulted in all three categories being present, trending from sustainable conditions in the lower reaches to chronic impacts in the headwaters. Figure 1-5 illustrates these categories in Gifford Run using plots of acid neutralization capacity (ANC) versus flow. ANC is the primary measure of stream health relative to acidification used in this study. A positive ANC represents a buffered, net alkaline condition where the stream pH will normally remain in the circumneutral range and sustain fish populations. A negative ANC indicates an acidified condition, where the pH can drop to levels harmful or fatal to aquatic life. Between these extremes, studies have concluded that episodic acidification (periodic negative ANC) can be both a short-term and long-term detriment to fish populations. While some fish can survive these events by taking refuge in alkaline tributaries or microhabitats, this is not sufficient to maintain the potential population densities that would be implied by the water quality during baseflow periods. Historic data show such a long-term population decline in Mosquito Creek.

The "Neutrality Threshold" indicated on Figure 1-5 is the predicted flow volume above which the stream will reach a negative ANC and become acidic. It is the flows above this threshold that require some form of alkaline addition to maintain stream health. For this study, streams with a neutrality threshold below the average flow are considered chronically acidified. A threshold above the 95% confidence interval (CI) flow is assumed to represent sustainable conditions. Threshold values between the average and 95% CI flows are considered indication of episodic acidification.

Figure 1-5: Examples of Acidification Categories



# REFERENCE: ACID/BASE CHEMISTRY

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 exceed that of $OH^-$ to a higher degree, 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.

$$\mathbf{H_2O \leftrightarrows H^+ + OH^-}$$

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

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

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

$$\mathbf{OH^- + H^+ \rightarrow H_2O}$$

---

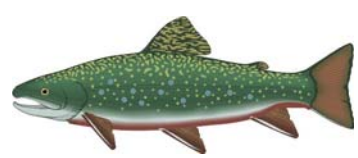
$$\mathbf{CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^-}$$

The product is the alkaline bicarbonate ion ($HCO_3^-$) and dissolved calcium, both of which are benign to aquatic species.

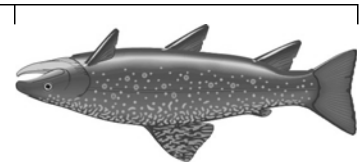
Both acidity and alkalinity are measured as the equivalent concentration as limestone, reported as milligrams of $CaCO_3$ per liter (mg/L). When the acidity concentration is greater than the alkalinity concentration, water is considered to be net acidic, and in the opposite case the water is net alkaline. Net acidity is essentially 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 a desirable positive ANC condition.

**Alk. > Acid.**
**$6 < pH < 9$**
**ANC > 0**



**Acid. > Alk.**
**$pH < 6$**
**ANC < 0**



# 2

# STUDY PLAN

It was recognized in the late 1970s that the Mosquito Creek watershed was suffering from acidification impacts. As shown by Figure 2-1, the pH of the stream had dropped from 6.5 SU in the 1960s to about 4 SU by the early 1980s. Prior to the Growing Greener Grants, however, there were insufficient resources to conduct a systematic assessment of the watershed to determine the nature and extent of the problem. To collect essential information for future restoration plans, the Round 2 Grant established a watershed-scale in-stream monitoring program that was continued in later Grants from 2001 to 2005.

Concurrent with the in-stream program, performance monitoring was conducted for the alkaline addition projects funded under other Grants. The goal of these studies was to quantify the alkalinity output capacity of each technology for use in determining their relative efficiencies and benefit/cost ratios for future restoration applications.

This section presents the methodologies employed for the in-stream and performance monitoring programs, with general guidelines for establishing comparable programs for other watersheds impaired by acid deposition. Locations of the sample points for both programs are shown on Figure 2-2. Recommended sampling parameters and flow measurement techniques are provided at the end of the section for reference.

Figure 2-1: Mosquito Creek pH vs. Time

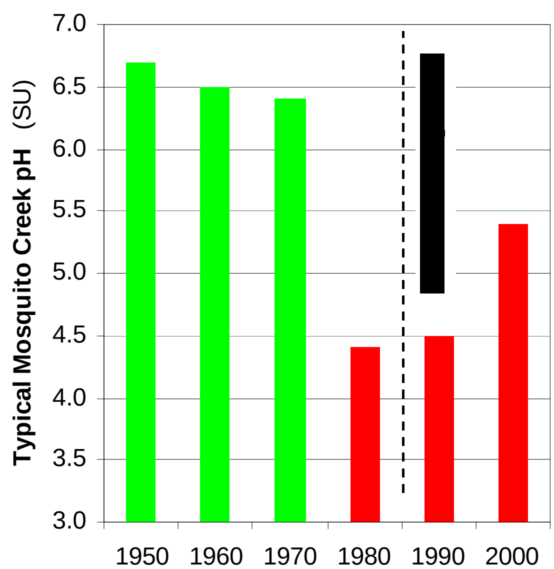
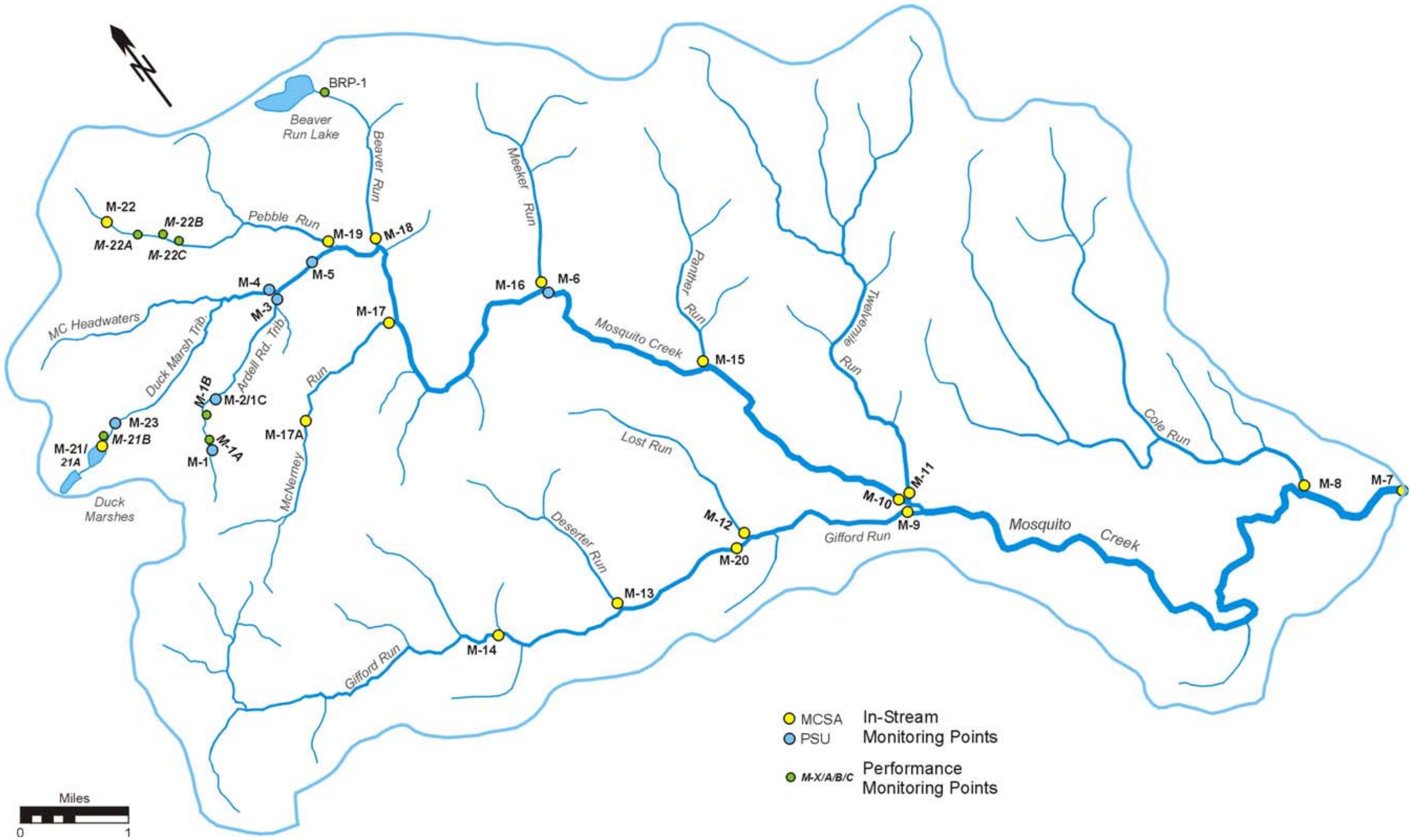


Figure 2-2: Monitoring Program Sample Point Locations



## IN-STREAM MONITORING PROGRAM

The Mosquito Creek in-stream monitoring program consisted of 15 sample points maintained by the MCSA at the mouths of the major tributaries and on representative sections of the main stem. An additional 7 sample points were operated by PSU under separate Grants. The overall goal was to better define the general acidity sources in the watershed, with the following specific objectives for the program:

- To establish permanent sampling locations for consistent comparisons with future results.
- To collect accurate flow measurements with chemistry samples to allow calculation of contaminant loadings.
- To monitor over a broad range of seasonal conditions to identify episodic and chronic acidification.
- To determine the degree of alkaline addition required to restore individual tributaries and the main stem.
- To provide a historic baseline for future restoration results.

The MCSA in-stream monitoring began in October 2001 and continued until April 2005, with a total of 13 rounds collected at frequencies ranging from monthly to biennially. The PSU program ran from November 2001 to May 2005, with up to 32 samples collected per point. As summarized in Table 2-1, sample parameters varied between the two programs due to their different research intents, but overlapped on the key parameters of pH, ANC, and aluminum.

Table 2-1: Sampling Parameters for MCSA and PSU In-Stream Programs

| Parameter | MCSA | PSU |
|---|---|---|
| *Field* | | |
| Flow | ● | |
| pH | ● | |
| Temperature | ● | |
| Conductivity | ● | ● |
| *Laboratory* | | |
| Acidity | ○ | |
| Alkalinity | ○ | |
| ANC | ● | ● |
| pH | ● | ● |
| Aluminum | ● | ● |
| Calcium | ○ | ● |
| Chloride | | ○ |
| Chem. Ox. Demand | ○ | |
| Dis. Org. Carbon | | ○ |
| Iron | ○ | ○ |
| Magnesium | | ○ |
| Nitrate | | ○ |
| Ortho-Phosphate | | ○ |
| Potassium | | ○ |
| Sodium | | ○ |
| Sulfate | | ○ |

● - Sampled throughout program
○ - Sampled for part of program

## Sample Point Selection

Round 2 funding for the MCSA in-stream program was sufficient to establish 15 sample points. These were arrayed within the watershed to sample Mosquito Creek at the downstream end of the study area, the mouths of all named tributaries, several midstream points of interest on Mosquito Creek and Gifford Run, and two upstream points of interest at the Duck Marshes and on Pebble Run. The PSU in-stream program focused on assessing the effects of the Ardell and Duck Marsh VFWs on stream water quality, with sample point locations selected more specific to headwaters areas affected by these systems.

The sample point pattern developed for this acid deposition study is summarized by Figure 2-2 and Table 2-2 based on four categories in their typical order of importance: culmination, confluence, midstream, and upstream. All or some of these may be used depending on the nature of the watershed and the study intent. The basic goals were to identify the major sources of acidification, quantify alkaline deficiencies for development of restoration plans, and document pre-existing conditions upstream and downstream of planned restoration reaches. Three basic guidelines for locating points are as follows from Figure 2-2:

- A study needs a culmination point (A) representing the lowermost extent of interest for assessment and restoration planning.
- For any downstream point of interest, the upstream points should provide a sum of the major upstream flow/loading sources (B + C + D = A, E + F = C).
- Any reach planned for restoration requires a downstream point and, if flows occur above the planned alkaline addition site, an upstream point (H to E, G to F, E + F to C).

Figure 2-2: Schematic Sample Point Pattern for Acid Deposition Studies

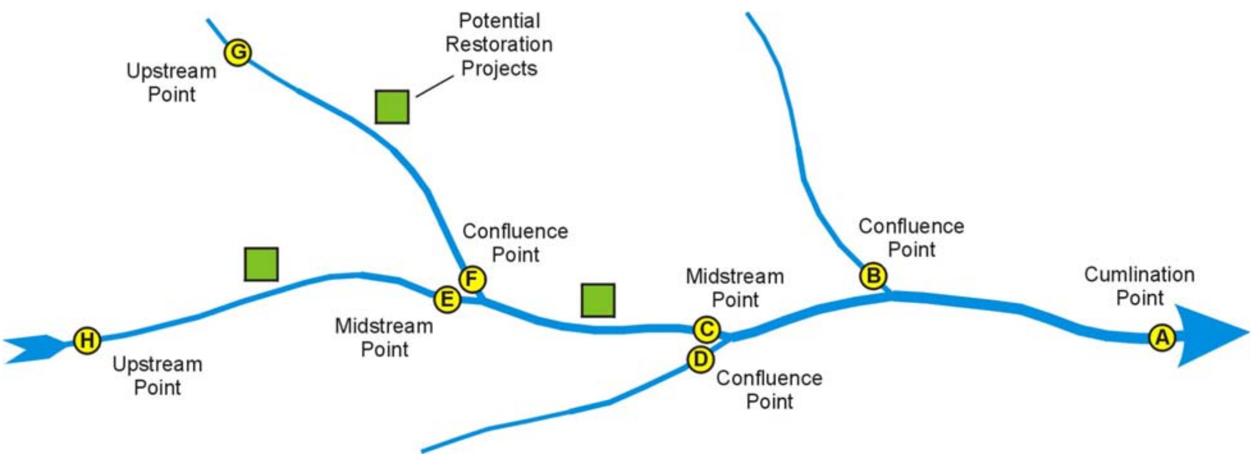


Table 2-2: General Categories of Sample Points for Acid Deposition Studies

| Point Type | Criteria | Representative Study Samples | Study Rationale |
|---|---|---|---|
| Culmination | A downstream point representing the combined drainage from all upstream sample points, usually the lowermost limit of study or restoration objectives. | M-7<br>(M-9 for Gifford Run) | Established on Mosquito Creek main stem above the confluence with Grimes Run, which contains acid mine drainage not representative of acid deposition impacts and is the limit of restoration planning. |
| Confluence | Mouths of major tributaries to compartmentalize a watershed for identification of primary acidity sources. | M-3, M-4, M-8, M-9, M-11, M-12, M-13, M-15, M-16, M-17, M-18, M-19 | Established by MCSA on all named tributaries to Mosquito Creek above M-7. PSU monitored Ardell tributary and Mosquito Creek headwaters at M-3 and M-4. |
| Midstream | Intermediate points to characterize long reaches of main stem, preferably immediately upstream of a confluence point or below alkaline addition projects. | M-2, M-5, M-6, M-10, M-20, M-23 | M-20 established to assess in-stream limestone sand dosing on Gifford Run at Merrill Road, M-2 for VFW on Ardell tributary. M-6 and M-10 represent intermediate points on main stem Mosquito Creek. |
| Upstream | Points to characterize water entering from upstream of the study area, above planned restoration projects, or the upstream limit of a main stem reach. | M-1, M-14, M-21, M-22 | Established to represent untreated conditions in headwaters above VFWs on Ardell Tributary, Duck Marsh Tributary, and Pebble Run, and the headwaters of Gifford Run. |

**MONITORING PERIOD**

The MCSA in-stream program was initially planned for one year of monthly sampling. After the first six rounds, it was decided to increase the monitoring frequency to a quarterly interval to provide a longer-term data set. At the end of the Round 2 funding, a Round 3 supplement allowed continuation of biennial sampling for the spring (high flow) and fall (low flow) periods for the remainder of the study.

The duration and frequency of monitoring programs in other watersheds will depend on the sampling budget and availability of sampling personnel. At the minimum, 6 sample rounds are recommended over a broad range of flow conditions for evaluation of episodic acidification, and 12 sample rounds for establishment of design criteria for alkaline addition projects. An in-stream monitoring program could thus be conducted monthly for a full year, every other month for two years, or quarterly for three years. Monitoring over several years is recommended to give a representation of climatic as well as seasonal variation. For projects requiring a rapid turnaround of data, it is also possible to collect sufficient samples at a bi-monthly interval over six months spanning high and low flow periods. Table 2-3 summarizes the suggested sampling schedules for these scenarios.

**EXTRAPOLATION**

Some desired sample points might not be practically accessible due to remoteness, ownership, or safety issues. In these cases, it may be necessary to extrapolate water quality and flow data rather than to attempt direct long-term sampling. In the MCSA program, access to the mouth of McNerney Run involved a hike of several hours, and it was recognized that this would be a burden on volunteer samplers, particularly during periods of heavy snow cover. To develop an extrapolation method, two sample points were established for McNerney Run, M-17 at the confluence with Mosquito Creek and M-17A along Merrill Road at approximately the midpoint of the tributary.

Table 2-3: Recommended Schedules for Various Sampling Interval Options

| Schedule | One Year | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | J | | F | | M | | A | | M | | J | | J | | A | | S | | O | | N | | D | |
| Bi-Monthly 1 | ● | ● | ● | ● | | | | | | | | | | | | | ● | ● | ● | ● | ● | ● | ● | ● |
| Bi-Monthly 2 | | | | | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | ● | | | | | | | | |
| Monthly | ● | | ● | | ● | | ● | | ● | | ● | | ● | | ● | | ● | | ● | | ● | | ● | |
| Two Month | | | ● | | | | ● | | | | ● | | | | ● | | | | ● | | | | ● | |
| Quarterly | ● | | | | | | ● | | | | | | ● | | | | | | ● | | | | | |
| Biennially | | | | | | | ● | | | | | | | | | | | | ● | | | | | |

After five concurrent sample rounds at both points, correlations were made between the flows and chemical concentrations of the two data sets. As shown by Figures 2-3 and 2-4, conditions at M-17A were found to predict those at M-17 with a high degree of confidence. M-17 was subsequently sampled only when volunteers were available to hike to the stream mouth, and its data set was extrapolated from M-17A on other sample dates. This approach requires sufficient initial samples at both points to assure that a reasonable relationship exists, with three being the minimum number recommended.

Figure 2-3: Comparison of M-17 to M-17A Flows in McNerney Run

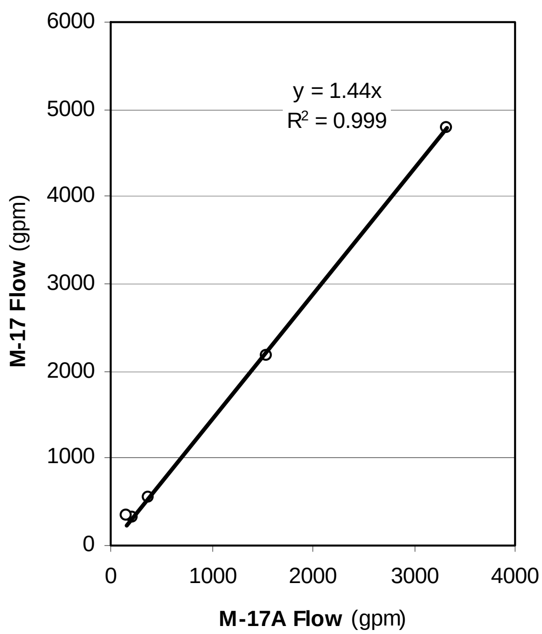
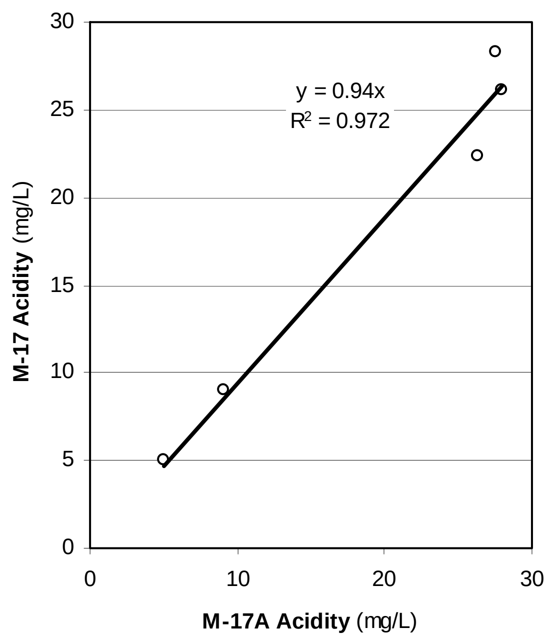



Figure 2-4: Comparison of M-17 to M-17A Acidity in McNerney Run



## PERFORMANCE MONITORING PROGRAM

Performance monitoring was conducted on alkaline addition projects implemented during the Grant phases. The purpose was to document alkalinity generation rates to establish design criteria and determine cost effectiveness for these technologies. Sampling parameters were flow, pH, alkalinity, acidity, ANC, and aluminum. The methods applied varied somewhat for each technology, as follows:

### VERTICAL FLOW WETLANDS

Influent to the VFWs was collected by grab sample at the upstream takeoff point, with total stream flow measured by weir methods at the associated check dams. Effluent was sampled at the stream return point where it discharged through an H-flume for flow measurement. Ten samples were collected from the Ardell system between September 2002 and April 2005, and seven samples were obtained from each of the Duck Marsh and Pebble Run systems between November 2003 and April 2005. In-stream effects on Pebble Run were monitored at sample point M-19. Those for the Ardell and Duck Marsh tributaries were monitored by PSU at sample points M-3 and M-23, respectively, although flows were not taken at these points.

### LIMESTONE SAND DOSING

Effects of the ongoing dosing project by the MCSA in Gifford Run were monitored as part of the in-stream program, with M-14 located upstream of the dosing site on Merrill Road, M-20 upstream of the dosing site on Lost Run Road, and M-9 representing downstream conditions at the confluence with Mosquito Creek. To avoid spike readings, sampling was not tied to specific dosing dates, which generally occurred in late March or early April.

### BEAVER RUN LAKE LIMING

Discharge from the Beaver Run lake was monitored at sample point BRP-1 before and after liming, with a total of 17 samples collected. Flows and effects on Beaver Run were monitored downstream as part of the in-stream program at sample point M-18.

### ALKALINE ROAD RUNOFF DITCHES

Monitoring of the runoff ditches proved problematic because of the need to be present during a significant rainfall event. One sample was collected in April 2004 shortly after ditch construction, but a flow measurement could not be obtained. The ditches were dry on other project sample dates.

### LIMESTONE SAND DOSING FORD

Sampling in the ford area was conducted by PSU, with sample points M-3 and M-4 upstream of the ford, and M-5 downstream. Flows were not measured at these points, so performance was estimated qualitatively based on water chemistry after construction of the ford in October 2001.

## SAMPLING PARAMETERS

Table 2-4 provides a summary of the sampling parameters that were determined through the Mosquito Creek monitoring programs to be most useful for acid deposition studies. Reporting units, standard analysis methods, typical costs, and relative importance to in-stream and performance monitoring are included for reference.

Flow is the field parameter of greatest importance since flow measurement concurrent with a water sample is essential in evaluating the degree of acidification and level of effort needed to restore alkaline conditions in a stream. Flow and field measurements are taken at the time of sampling and should be recorded along with the sample point identification, date, time, weather conditions, and name of the sampler(s). Flow measurement methods are discussed in detail at the end of this section. Temperature, pH, and conductivity are standard field parameters and can be measured with relatively inexpensive separate or combined field instruments. For this study, combined Hanna Instruments Model HI9812 pH/conductivity units were purchased for the MCSA through the Grant and used in conjunction with field thermometers.

Of the laboratory parameters, the acid/base parameters pH, ANC, alkalinity, and acidity are most important to acid deposition studies. For in-stream samples, pH and ANC provide the best measures of stream health. Alkalinity and acidity can have very low concentrations in weakly acidified streams, and may be difficult to interpret from an alkaline deficiency standpoint. For the Mosquito Creek assessment, ANC was found to be the most reliable measure of buffering capacity and potential alkaline addition requirements. Alkalinity and acidity as mass concentrations can be approximated from ANC in equivalents as follows:

<u>If ANC is positive:</u>

Alkalinity (mg/L) = ANC (meq/L) / 20

<u>If ANC is negative:</u>

Acidity (mg/L) = -ANC (meq/L) / 20

In performance studies of alkaline addition projects, alkalinity discharge levels are usually sufficiently high to warrant measurement. System discharges will often contain no acidity, so this parameter can be excluded from performance monitoring if not present and savings are needed.

Sampling for metals and other parameters may be included in monitoring programs if these are believed to be harmful factors in a given watershed. Aluminum is often the most toxic metal found in acidified Pennsylvania streams, and screening for this parameter may be worthwhile at least in initial sample rounds. Calcium is sometimes used as a surrogate for alkalinity when tracing the extent of influence from an alkaline addition project, since it may stay in solution after direct alkalinity has been exhausted in acidity neutralization.

Table 2-4: Summary of Important Sampling Parameters for Acid Deposition Studies

| Parameter | Units | Analysis Method | Cost | Importance to Study | |
|---|---|---|---|---|---|
| | | | | In-Stream | Performance |
| *Field Parameters* | | | | | |
| Flow | gpm | Velocity Meter | $300 - $2,500 Purchase | ●●●●● Required | ●●●●● Required |
| pH | SU | pH Meter | $150 - $400 Purchase | ●●●● Recommended | ●●●● Recommended |
| Temperature | F$^o$ or C$^o$ | Thermometer | $10 - $20 Purchase | ●●● Recommended | ●●● Recommended |
| Conductivity | *u*ohms/cm | Conductivity Meter | $40 - $150 Purchase | ●● Optional | ●● Optional |
| *Laboratory Parameters* | | | | | |
| pH | SU | EPA-150.1 | $5.00/sample | ●●●● Recommended | ●●●● Recommended |
| ANC | meq/L | Lab Specific | $16.50/sample | ●●●●● Required | ●●●● Recommended |
| Acidity (Cold) | mg/L | EPA-305.1 | $8.50/sample | ●●●● Recommended | ●●●● Recommended |
| Alkalinity | mg/L | EPA-310.1 | $8.50/sample | ●●●● Recommended | ●●●●● Required |
| Aluminum | mg/L | EPA-200.7 | $10.00/sample | ●●● Optional | ●● Optional |
| Calcium | mg/L | Consult Current References | $10.00/sample | ● Optional | ● Optional |

# FLOW MEASUREMENTS

As introduced in Section 1, the primary measure of acid impairment in a stream is its alkaline deficiency, or the mass of alkalinity that would have to be added to neutralize the acidified flow. This mass, or *loading*, is the product of the deficiency concentration and the flow volume, often expressed as pounds per day (lbs/day). Determination of the acidity loading (or loading of any other parameter of interest) at a give time requires the simultaneous collection of a chemical water sample and a flow volume measurement.

There are a number of flow measurement techniques available, with several of the more common methods summarized by Figure 2-5 The following provides a brief summary of each method.

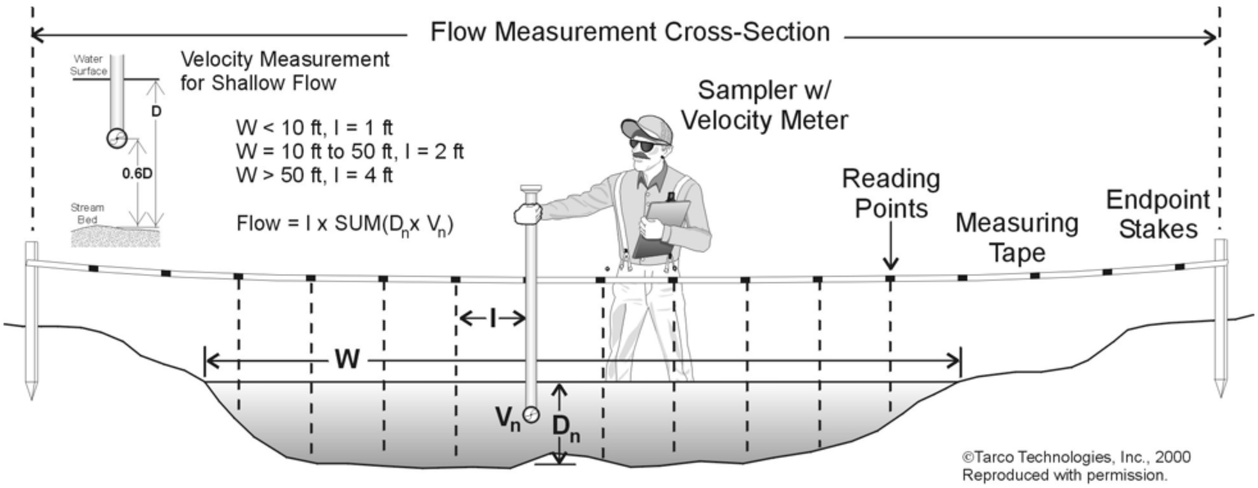
### CROSS-SECTIONAL VELOCITY

The cross-sectional velocity method was used to compute flows for all MCSA in-stream samples. Digital velocity meters with an instantaneous velocity reading accuracy of 0.5 ft/s, and an averaged velocity reading accuracy of 0.1 ft/s were used for this study.

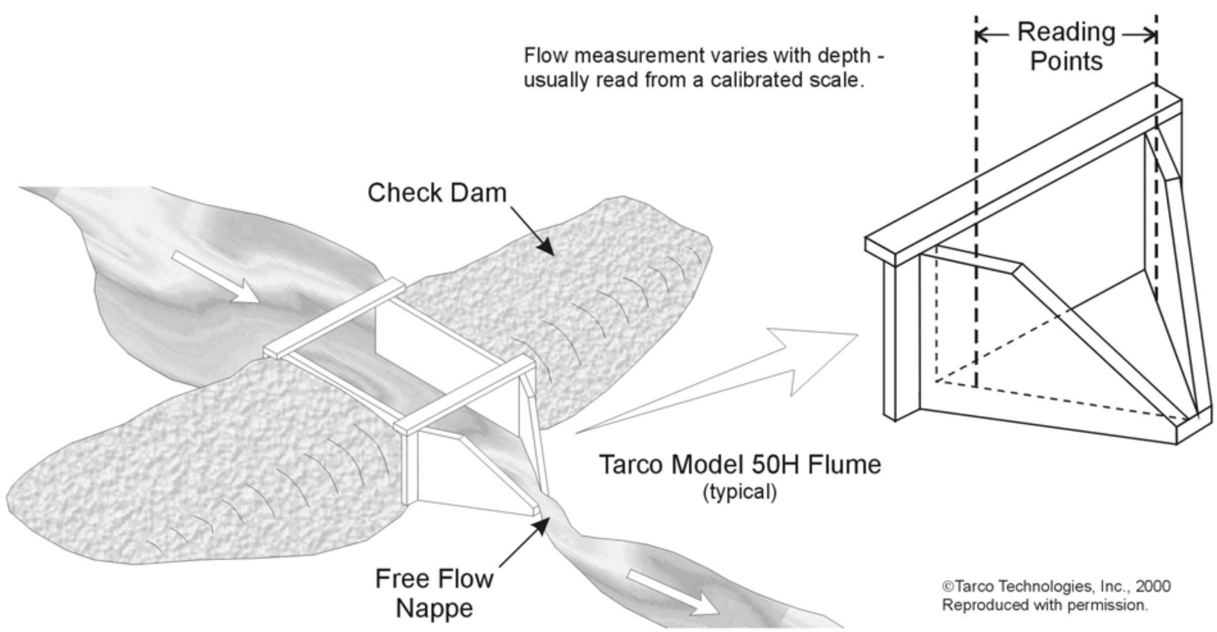
For the in-stream samples, it was desired to establish permanent cross-section stations that would be simple and convenient for volunteer samplers to use. The selected approach was to drive rebar stakes on either side of the stream perpendicular to flow. Hooks were attached to the rebars at equal elevation across the stream using a line level. Thereafter, a measuring tape could hooked level across the stream to provide incremental velocity reading points. When the stations were first established, the height of the tape above the stream bottom was also measured to develop a cross section profile for the channel. Figure 2-6 shows a completed cross-section of this configuration, and Figure 2-7 shows the taking of a velocity and depth reading at a tape increment.

To improve measurement accuracy in small streams, different measurement increments were used for different stream sizes depending on their width. For streams of less than 10 feet in width, measurements were taken every 1 foot across the channel; for streams of 10 feet to 50 feet in width, measurements were taken every 2 feet; and for streams greater than 50 feet in width, measurements were taken every 4 feet. The total flow volume for the cross section was then determined by multiplying the incremental section areas by their respective flow velocity readings.

Figure 2-5: Summary of Basic Flow Measurement Methods

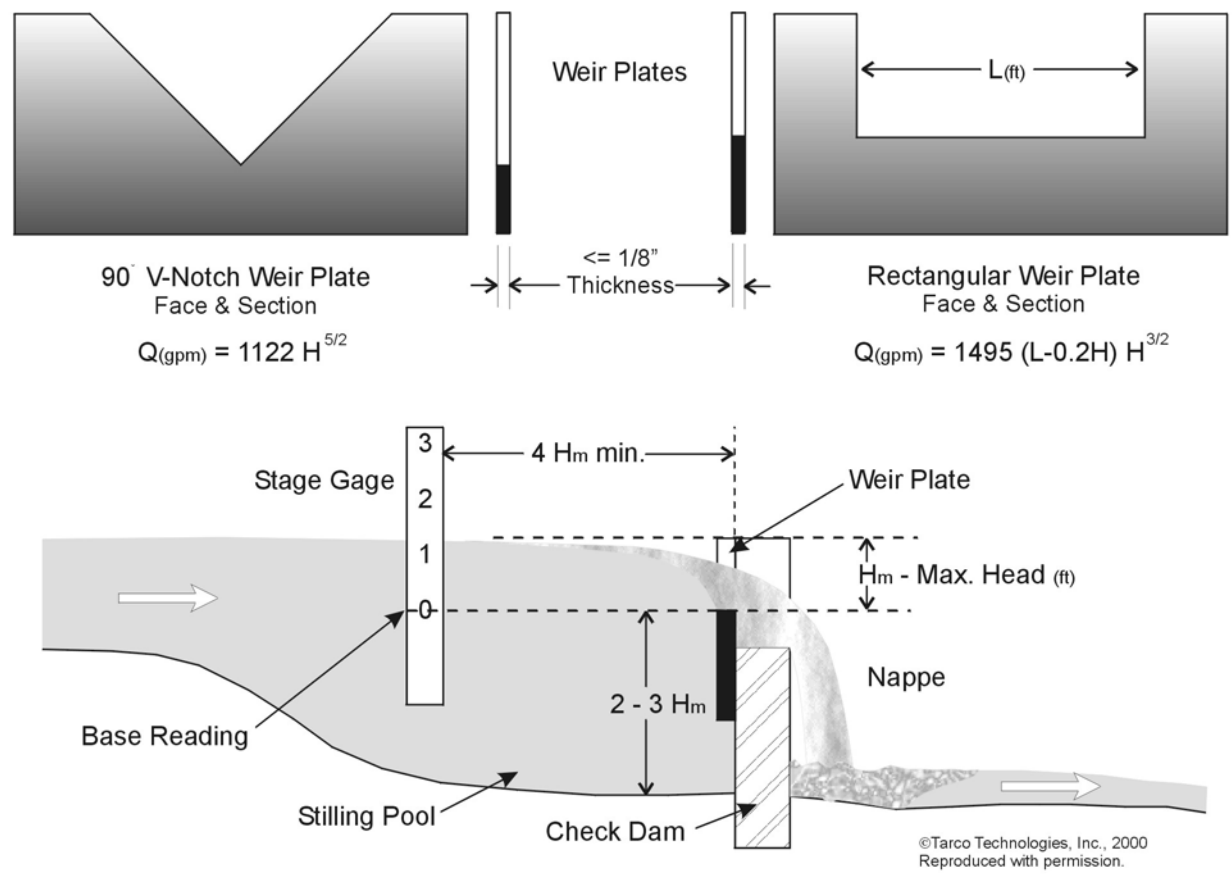



**Cross-Sectional Velocity Flow Measurement**

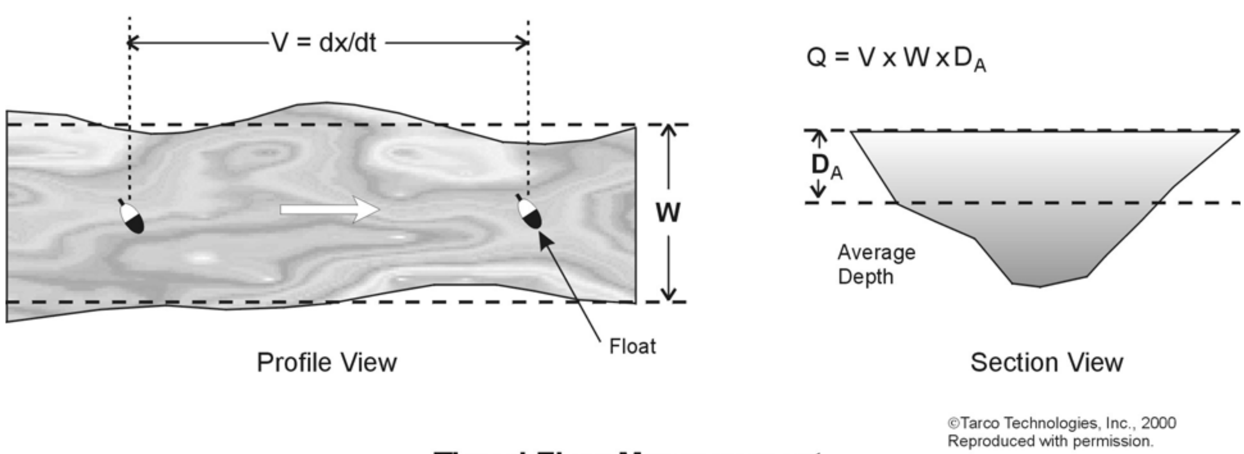



**H-Flume Flow Measurement**

Figure 2-5: Summary of Basic Flow Measurement Methods (Continued)




**Weir Plate Flow Measurement**




**Timed Flow Measurement**

Figure 2-6: Completed Cross-Section

Figure 2-7: Taking Flow Measurements

### H-FLUMES

H-flumes were used in the performance monitoring program as permanent flow measurement installations on the three project VFWs. These devices provide very good accuracy over a wide range of low to moderate channelized flows, with various sizes ranging from 140 gpm to 1600 gpm capacity, and can be used in parallel for larger flows. Commercial models come with integral stage gages and direct-read flow volume gages for convenience of field readings. They provide accurate readings with a fairly low drop at the nappe for use in low-gradient channels, and can be used in temporary installations.

### WEIRS

Weirs are best suited to permanent installations and are scaleable to accommodate low to large flows. The two basic types are rectangular weirs, best for larger flows, and V-notched weirs, which provide greater accuracy at low flows. V-notch weirs can be made at different angles than 90 degrees depending on the accuracy needs of the flow measurement. Weirs require an upstream stilling pool of the dimensions shown on Figure 2-5 and a greater drop at the nappe than H-flumes, and as such are not as suitable for low-gradient channels. They also do not provide direct flow readings without field calculations using the appropriate weir formula.

**TIMED MEASUREMENTS**

This approach involves simply multiplying the cross-sectional area of a channel by the velocity of an object floating in the flow. It is at best an approximation of flow and should not be used for detailed studies, or only in cases where another method is unavailable or unaffordable. A floating object will typically move down the path of maximum velocity. Velocity can be estimated by using partially filled plastic bottles or other floating objects and noting the time required for the objects to travel a measured distance.

$$\text{Velocity} = \frac{\text{Distance Traveled (dx)}}{\text{Time of Travel (dt)}}$$

Since velocities in open channels tend to zero at the sides and bottom, this results in over-estimation of the flow volume. Correction factors depend on channel roughness and are difficult to determine, but a generic correction factor of 0.6 is suggested.

# 3

# WATERSHED ASSESSMENT

The first major goal at Mosquito Creek was to characterize the nature of acidification impacts to allow planning and implementation of effective acid abatement efforts. The monitoring programs conducted by the MCSA and PSU have created one of the most detailed long-term records of acid deposition impacts in the central Pennsylvania region. This section provides a reduction of this work into an overview of the Mosquito Creek watershed with the following intended outcomes:

- To present the results from the monitoring programs at comparable condition scenarios between individual sample points.
- To compare the relative water quality of individual subwatersheds.
- To evaluate the influence of bedrock geology on water quality.
- To quantify alkaline deficiency levels at monitored points.
- To establish as background the conditions before existing alkaline addition projects.
- To propose minimum restoration goals and determine further alkaline addition requirements to meet them.

# DATA SUMMARY AND ANALYSIS

Results from the MCSA in-stream monitoring program (sample points M-7 thru M-22) were analyzed to develop average and high flow water quality and quantity conditions in the Mosquito Creek watershed, with results summarized in Table 3-1. A similar analysis was performed for the PSU in-stream monitoring program (sample points M-1 thru M-6, and M-23), as summarized in Table 3-2. The value N in these tables represents the number of observations or synthesized data records for each sample point. Complete data sets are contained in Appendix A.

Where applicable in Tables 3-1 and 3-2, conditions are presented before (pre-) and after (post-) alkaline addition for sample points influenced by existing acid abatement projects in the watershed. A number of analyses and assumptions were necessary to reduce the results of the two monitoring programs to comparable terms, and to synthesize pre-addition conditions for streams affected by alkaline addition prior to the start of monitoring. The following discusses these analyses and the implications of the results.

For both measured and synthesized data sets, average values were determined as the arithmetic average of the data. To provide a common level of comparison between streams, high flow conditions were established as being the 95% confidence interval (CI) flow for each data set, roughly equating to a 1 in 20 chance of a flow of that magnitude being observed on a given sample date. The 95% CI flow was approximated as the average flow plus the standard deviation of the data set multiplied by the 95% factor of the Students T-distribution for the appropriate degrees of freedom. In past applications, the 95% CI flow has been found to be an effective maximum design value for balancing performance confidence and implementation costs in acid abatement restoration projects.

Relationships between parameter concentrations and flow were established graphically and used to predict concentrations at the 95% CI flow, as shown by the example in Figure 3-1. In all cases the best-fit relationship was found to be a logarithmic function. 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.

On sample dates when flows could not be obtained for the MCSA monitoring program, flows were calculated based on runoff relationships to M-14, which was sampled on all dates. Flows were not measured as part of the PSU monitoring program, so a direct analysis of parameter concentration relationships could not be conducted. However, it was determined that average and 95% CI flows are strongly correlated to subwatershed area for individual sample points, as shown by Figure 3-2. The average and high flow values in Table 3-2 are derived from these relationships. As with the measured MCSA data, average parameter concentrations are assumed to occur simultaneously with the average flows in this Table 3-2.

## Table 3-1: Average and High Flow Conditions for MCSA In-Stream Monitoring

| Sample Point | | Flow Condition | Flow gpm | pH SU | Acid. mg/L | Alk. mg/L | ANC meq/L | Al mg/L | Fe mg/L | Ca mg/L | N |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Parameters | | | | | | | | |
| M-7 | Pre-Add. | Average | 63931 | 5.21 | 14.67 | 0.24 | -4.61 | 0.112 | 0.057 | 1.267 | 13 |
| | | High Flow | 146362 | 5.10 | 17.76 | 0.00 | -7.53 | 0.159 | 0.046 | 2.137 | |
| | Post-Add. | Average | 63931 | 5.42 | 30.69 | 1.78 | 5.00 | 0.072 | 0.033 | 1.788 | 13 |
| | | High Flow | 146362 | 5.30 | 15.81 | 0.00 | -2.27 | 0.111 | 0.043 | 2.081 | |
| M-8 | | Average | 9188 | 5.29 | 31.75 | 0.52 | -3.66 | 0.088 | 0.019 | 1.557 | 12 |
| | | High Flow | 24546 | 4.99 | 38.17 | 0.00 | -10.54 | 0.133 | 0.024 | 1.884 | |
| M-9 | Pre-Add. | Average | 11987 | 5.21 | 11.51 | 0.25 | -4.78 | 0.104 | 0.091 | 1.295 | 13 |
| | | High Flow | 30051 | 4.71 | 21.34 | 0.00 | -18.04 | 0.118 | 0.106 | 1.494 | |
| | Post-Add. | Average | 11987 | 6.22 | 7.41 | 5.85 | 80.24 | 0.035 | 0.064 | 2.348 | 13 |
| | | High Flow | 30051 | 5.51 | 9.04 | 0.62 | 7.36 | 0.061 | 0.027 | 1.615 | |
| M-10 | | Average | 25650 | 5.32 | 10.15 | 0.21 | -4.48 | 0.115 | 0.062 | 1.540 | 13 |
| | | High Flow | 60340 | 5.00 | 10.15 | 0.00 | -10.27 | 0.130 | 0.062 | 1.826 | |
| M-11 | | Average | 6416 | 5.31 | 11.69 | 0.46 | -3.02 | 0.111 | 0.026 | 1.683 | 13 |
| | | High Flow | 16113 | 4.82 | 13.37 | 0.00 | -14.90 | 0.150 | 0.038 | 1.895 | |
| M-12 | | Average | 1616 | 5.26 | 9.33 | 0.51 | -1.54 | 0.109 | 0.020 | 1.540 | 13 |
| | | High Flow | 4305 | 4.69 | 17.54 | 0.00 | -18.52 | 0.128 | 0.025 | 1.687 | |
| M-13 | | Average | 2143 | 4.87 | 15.57 | 0.00 | -15.88 | 0.125 | 0.023 | 1.310 | 13 |
| | | High Flow | 5873 | 4.77 | 19.18 | 0.00 | -16.29 | 0.145 | 0.028 | 1.264 | |
| M-14 | | Average | 6464 | 5.17 | 11.02 | 0.27 | -2.85 | 0.100 | 0.125 | 1.243 | 13 |
| | | High Flow | 16040 | 4.84 | 14.47 | 0.00 | -14.38 | 0.113 | 0.125 | 1.555 | |
| M-15 | | Average | 1595 | 5.08 | 11.40 | 0.09 | -7.44 | 0.145 | 0.046 | 1.58 | 13 |
| | | High Flow | 3250 | 4.95 | 24.74 | 0.00 | -11.50 | 0.150 | 0.065 | 2.41 | |
| M-16 | | Average | 2072 | 5.06 | 11.40 | 0.09 | -8.27 | 0.151 | 0.046 | 0.000 | 13 |
| | | High Flow | 4221 | 4.91 | 11.40 | 0.00 | -12.51 | 0.157 | 0.042 | 1.151 | |
| M-17 | | Average | 2085 | 5.06 | 15.88 | 0.00 | -8.87 | 0.091 | 0.096 | 1.280 | 11 |
| | | High Flow | 5456 | 4.78 | 14.36 | 0.00 | -16.09 | 0.103 | 0.000 | 1.328 | |
| M-17A | | Average | 1602 | 5.06 | 15.96 | 0.21 | -6.19 | 0.097 | 0.164 | 1.243 | 13 |
| | | High Flow | 4364 | 4.81 | 12.35 | 0.00 | -15.21 | 0.101 | 0.149 | 1.474 | |
| M-18 | Pre-Add. | Average | 1681 | 4.46 | 21.20 | 0.00 | -40.48 | 0.293 | 0.115 | 1.250 | 11 |
| | | High Flow | 3889 | 3.94 | 20.39 | 0.00 | -38.34 | 0.295 | 0.113 | 1.250 | |
| | Post-Add. | Average | 1681 | 4.74 | 15.10 | 0.00 | -25.35 | 0.163 | | 0.945 | 2 |
| | | High Flow | 3889 | 4.11 | | | -33.80 | 0.195 | | 0.950 | |
| M-19 | Pre-Add. | Average | 2099 | 4.36 | 22.00 | 0.00 | -51.13 | 0.330 | 0.110 | 1.340 | 9 |
| | | High Flow | 5060 | 3.55 | 20.81 | 0.00 | -48.83 | 0.345 | 0.113 | 0.000 | |
| | Post-Add. | Average | 2099 | 4.88 | 9.34 | 0.47 | -18.39 | 0.222 | | 1.633 | 4 |
| | | High Flow | 5060 | 5.37 | | | -0.42 | 0.420 | | 2.825 | |
| M-20 | Pre-Add. | Average | 9605 | 5.19 | 11.91 | 0.22 | -5.19 | 0.104 | 0.101 | 1.255 | 13 |
| | | High Flow | 24643 | 4.86 | 21.66 | 0.00 | -13.97 | 0.116 | 0.199 | 1.467 | |
| | Post-Add. | Average | 9605 | 5.85 | 10.10 | 2.59 | 40.78 | 0.052 | 0.051 | 1.960 | 13 |
| | | High Flow | 24643 | 5.32 | 11.49 | 0.00 | -1.78 | 0.073 | 0.048 | 1.551 | |
| M-21 | | Average | 313 | 5.11 | 16.34 | 0.68 | -2.78 | 0.095 | 0.290 | 1.338 | 8 |
| | | High Flow | 1093 | 4.53 | 16.72 | 0.00 | -22.81 | 0.097 | 0.290 | 1.124 | |
| M-22 | | Average | 271 | 4.77 | 19.16 | 0.15 | -22.31 | 0.321 | 0.058 | 1.428 | 7 |
| | | High Flow | 749 | 4.44 | 19.30 | 0.00 | -24.98 | 0.376 | 0.271 | 1.835 | |

Table 3-2: Average and High Flow Conditions for PSU In-Stream Monitoring

| Sample Point | | Flow Condition | Flow gpm | pH SU | Acid. mg/L | Alk. mg/L | ANC meq/L | Al mg/L | Fe mg/L | Ca mg/L | N |
|---|---|---|---|---|---|---|---|---|---|---|---|
| M-1 | | Average | *378* | 5.03 | NA | NA | -12.35 | 0.135 | 0.017 | 0.840 | 32 |
| | | High Flow | *959* | 4.37 | NA | NA | -26.30 | 0.670 | 0.038 | 0.282 | |
| M-2 | Pre-Add. | Average | *506* | 5.17 | NA | NA | -5.19 | 0.163 | 0.003 | 1.002 | 9 |
| | | High Flow | *1283* | 4.93 | NA | NA | -17.44 | 0.078 | 0.003 | 0.328 | |
| | Post-Add. | Average | *506* | 6.42 | NA | NA | 254.87 | 0.386 | 0.199 | 3.985 | 23 |
| | | High Flow | *1283* | 5.57 | NA | NA | -7.03 | 0.115 | NA | 1.730 | |
| M-3 | Pre-Add. | Average | *1305* | 4.75 | NA | NA | -22.26 | 0.113 | 0.013 | 0.468 | 9 |
| | | High Flow | *3313* | 4.75 | NA | NA | -28.02 | 0.083 | 0.032 | 0.302 | |
| | Post-Add. | Average | *1305* | 5.80 | NA | NA | 24.10 | 0.132 | 0.343 | 1.455 | 23 |
| | | High Flow | *3313* | 4.85 | NA | NA | -16.00 | 0.105 | NA | 1.320 | |
| M-4 | Pre-Add. | Average | *2937* | 4.72 | NA | NA | -24.66 | 0.217 | 0.083 | 0.832 | 25 |
| | | High Flow | *7454* | 4.71 | NA | NA | -27.51 | 0.093 | 0.224 | 0.337 | |
| | Post-Add. | Average | *2937* | 4.80 | NA | NA | -23.86 | 0.181 | NA | 1.477 | 7 |
| | | High Flow | *7454* | 4.71 | NA | NA | -24.20 | 0.160 | NA | 1.300 | |
| M-5 | Pre-Add. | Average | *4623* | 4.71 | NA | NA | -22.86 | 0.128 | 0.049 | 0.527 | 9 |
| | | High Flow | *11733* | 4.70 | NA | NA | -27.49 | 0.111 | 0.133 | 0.318 | |
| | Post-Add. | Average | *4623* | 4.94 | NA | NA | -12.63 | 0.176 | 0.167 | 1.157 | 23 |
| | | High Flow | *11733* | 4.77 | NA | NA | -21.90 | 0.135 | NA | 1.280 | |
| M-6 | Pre-Add. | Average | *18429* | 4.79 | NA | NA | -18.86 | 0.136 | 0.013 | 0.638 | 9 |
| | | High Flow | *46772* | 4.67 | NA | NA | -26.81 | 0.126 | 0.034 | 0.399 | |
| | Post-Add. | Average | *18429* | 4.85 | NA | NA | -16.12 | 0.191 | 0.090 | 1.180 | 23 |
| | | High Flow | *46772* | 4.49 | NA | NA | -23.50 | 0.210 | NA | 1.480 | |
| M-23 | Pre-Add. | Average | *513* | 4.76 | NA | NA | -20.50 | 0.137 | NA | 1.158 | 5 |
| | | High Flow | *1301* | 4.56 | NA | NA | -32.70 | 0.070 | NA | 1.150 | |
| | Post-Add. | Average | *513* | 6.12 | NA | NA | 80.46 | 0.080 | NA | 3.740 | 8 |
| | | High Flow | *1301* | 5.65 | NA | NA | 26.40 | 0.100 | NA | 1.830 | |

NA – Not Analyzed

Figure 3-1: Graphical Prediction of Parameter Concentration by Flow Relationship

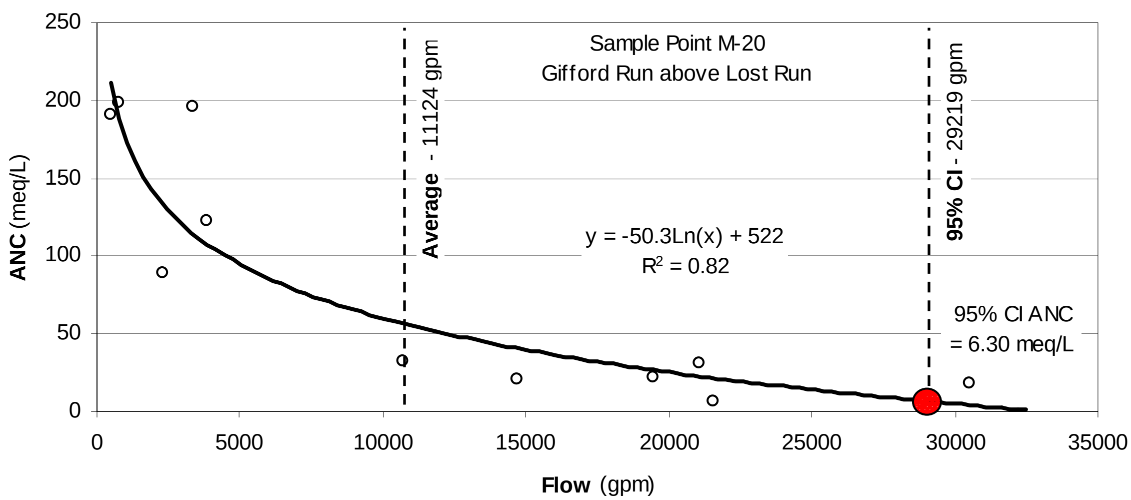
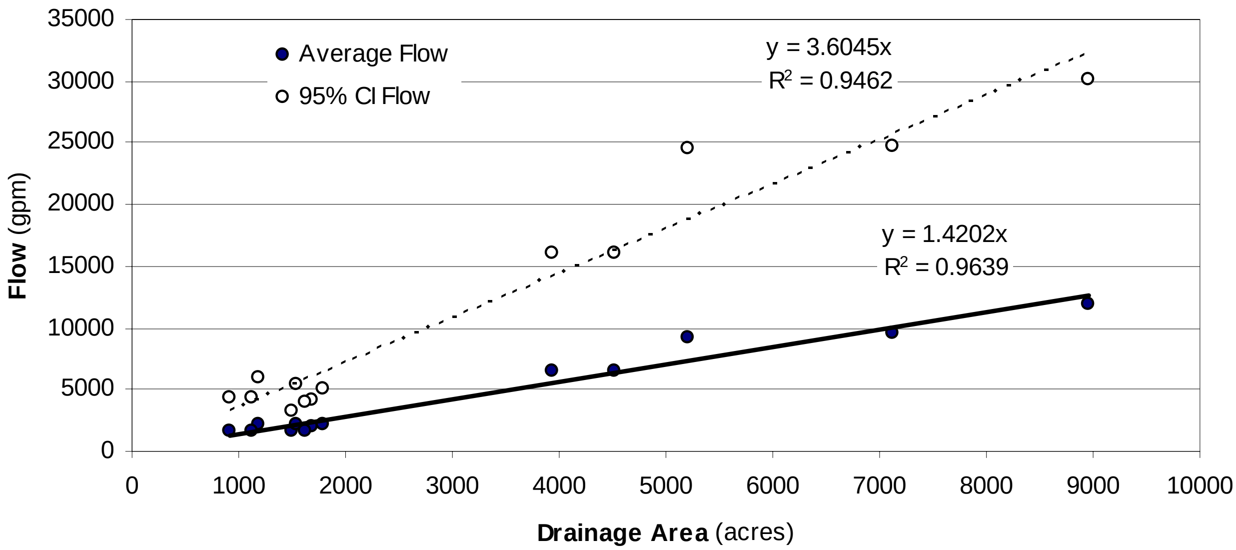


Figure 3-2: Relationships of Average and High Flows to Subwatershed Area




To estimate when high flow conditions had occurred, flow readings from the USGS Driftwood Branch gaging station were compared to the PSU sampling dates, and a 95% CI flow was established for the USGS data set. A pre- and post-addition sample date was then selected from the PSU data sets that best correlated to the 95% CI flow for Driftwood Branch, assuming that flow peaks of similar statistic levels would occur in adjacent watersheds on the same day. Parameter values from these dates were then used for the high flow values in Table 3-2.

In-stream limestone sand dosing has been conducted on Gifford Run for considerably longer than the monitoring program, so no results from M-9 or M-20 represent untreated conditions. For M-20, pre-addition water quality was estimated by combining the parameter loadings for M-13 and M-14 for each sample date and dividing the result by their combined flows to establish an untreated parameter concentration for M-20. The flows measured at M-20 were retained as being unchanged regardless of treatment. Pre-addition M-9 conditions were similarly modeled using M-12 and the predicted pre-addition M-20 conditions as untreated surrogates. As will be discussed in later sections, these hypothetical results predict the amount of limestone sand added to Gifford Run fairly well, and are believed to represent pre-addition conditions with reasonable accuracy.

Pre-study conditions in M-7 were modeled somewhat differently, with the untreated ANC being calculated by subtracting the estimated alkaline loading addition from the Gifford Run limestone sand dosing. Remaining parameters for M-7 were modeled on the same loading basis as M-9 and M-20, using M-8, M-10, M-11, and pre-addition M-9 predictions as upstream surrogates.

## WATER QUALITY EVALUATION

Based on results from the in-stream monitoring programs, Figures 3-3 and 3-4 have been prepared to show the predicted water quality conditions within the Mosquito Creek watershed under four scenarios:

- Average flows before the existing alkaline addition projects
- High flows (95% CI) before the existing alkaline addition projects
- Average flows after current alkaline addition
- High flows after current alkaline addition

To illustrate the degree of acidification in individual subwatersheds, water quality conditions have been ranked in semi-quantitative categories from very good to very poor based on pH and ANC levels. Table 3-3 summarizes these categories with comments relative to their implications for fish populations. Where no sampling data are available, some stream conditions have been inferred from adjacent information. For spatial understanding of conditions, subwatersheds are given uniform representative shadings based on the results from their associated sample points; however, local variation most likely occurs within their sub-tributary reaches.

Table 3-3: Relative Water Quality Categories (Specific to Mosquito Creek Watershed)

| Category | Criteria | Comments |
|---|---|---|
| Very Good | pH > 6.0 SU<br>ANC > 20 meq/L | No significant acidification impacts; fish should experience no notable stress. |
| Good | pH > 5.5 SU<br>ANC 5 to 20 meq/L | Minor levels of acidification usually occurring at high flows. Fish may experience short-term stress, but not suffer significant health impacts. |
| Fair | pH > 5.0 SU<br>ANC -5 to 5 meq/L | A poorly buffered condition subject to more serious impact from additional acidity. Fish are persistently stressed, and mortality may occur. |
| Poor | pH > 4.5 SU<br>ANC -20 to -5 meq/L | Acidified condition with no buffering capacity. Fish mortality likely and benthic populations may be significantly reduced. |
| Very Poor | pH < 4.5 SU<br>ANC < -20 meq/L | Chronically acidified condition, likely with no surviving fish and severely reduced or eliminated benthic populations. |

Figure 3-3: Pre- and Post-Addition Average Water Quality in Mosquito Creek

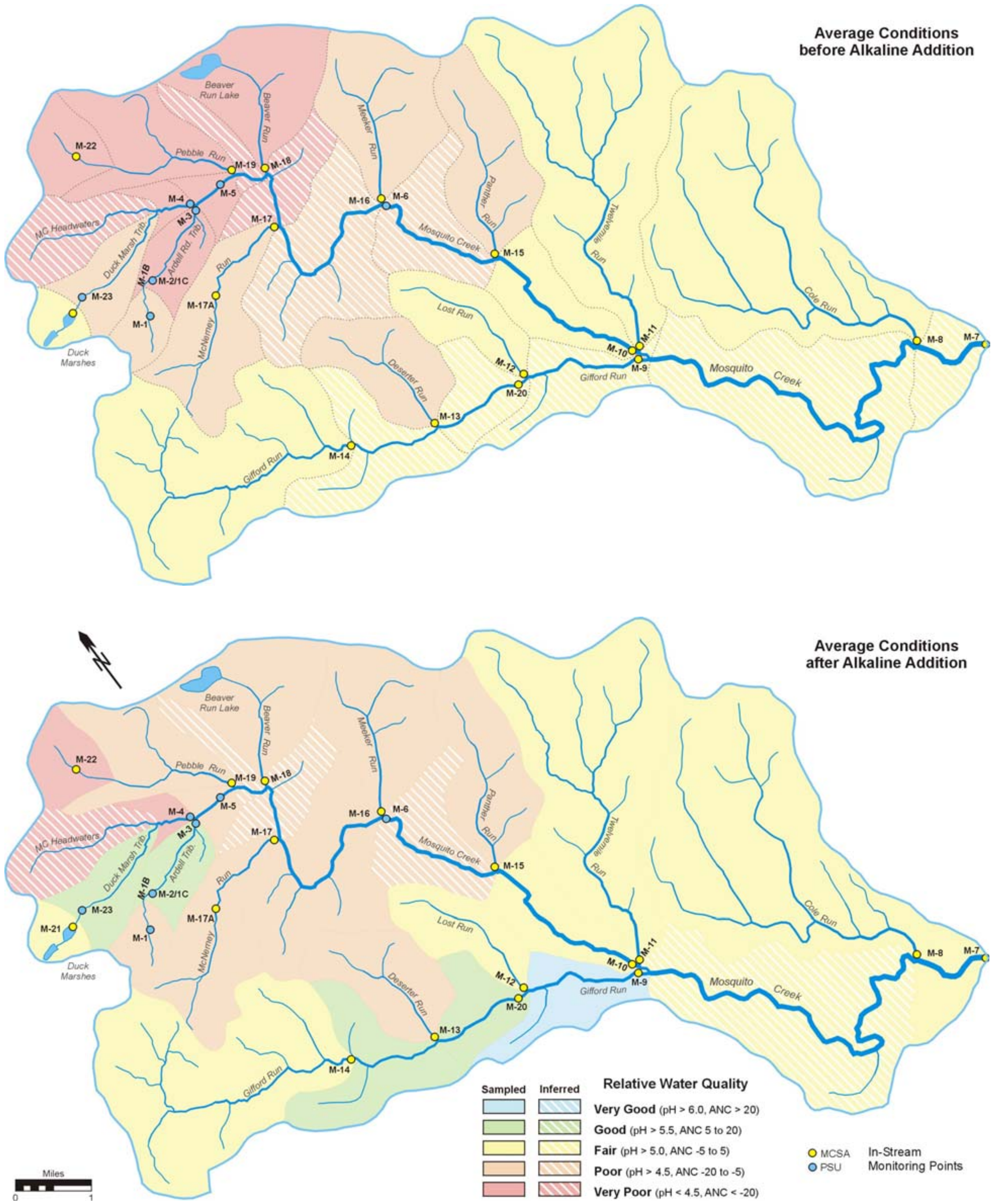
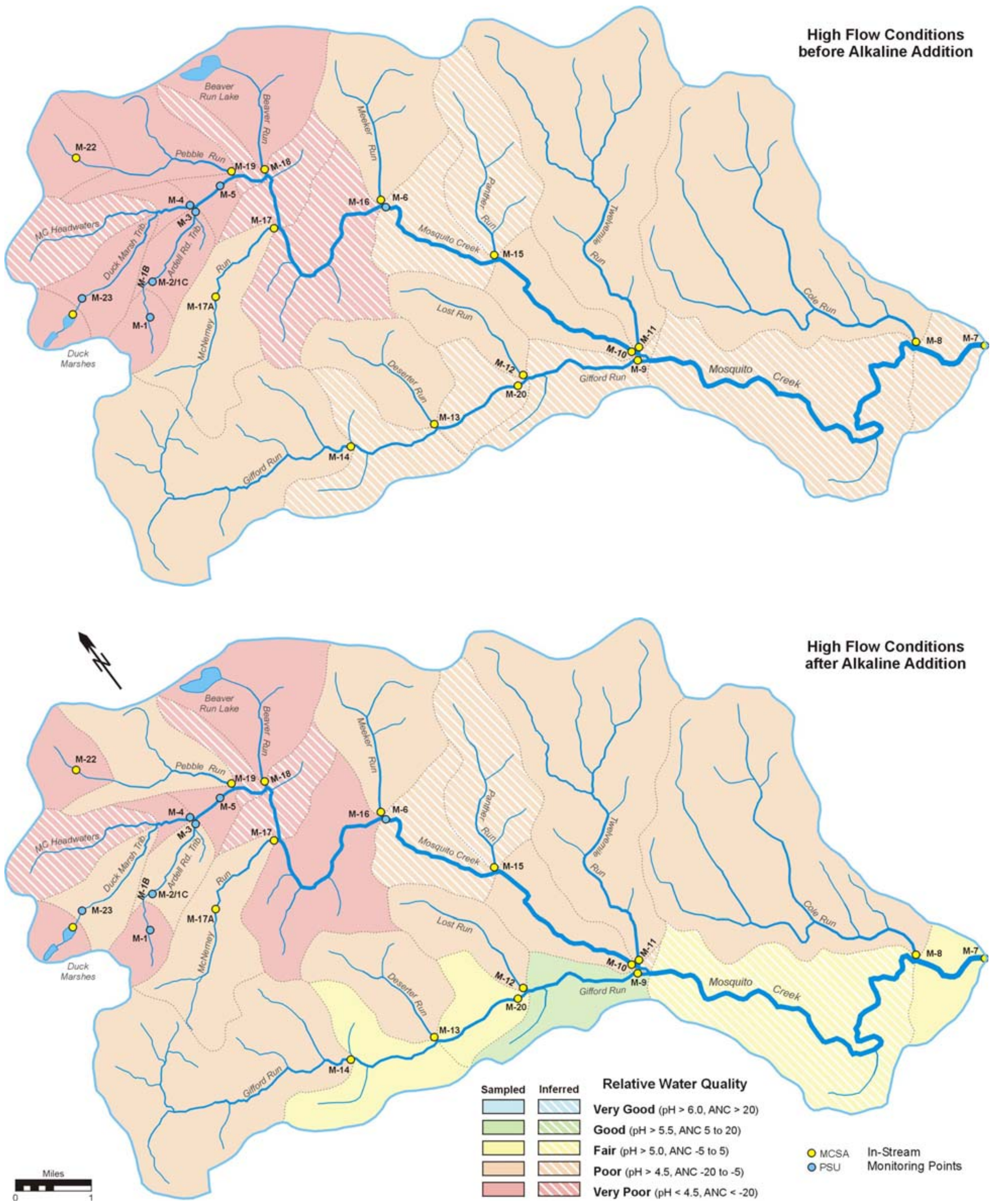


Figure 3-4: Pre- and Post-Addition High Flow Water Quality in Mosquito Creek



As these maps show, the most severe acidification occurs in the northern portion of the watershed around Pebble Run and Beaver Run. These streams and the Mosquito Creek headwaters (M-4) did not show a positive ANC under any conditions prior to alkaline addition. At high flows, very poor water quality extends as far downstream on the main stem as Meeker Run and possibly to Panther Run, and includes the Ardell and Duck Marsh tributaries.

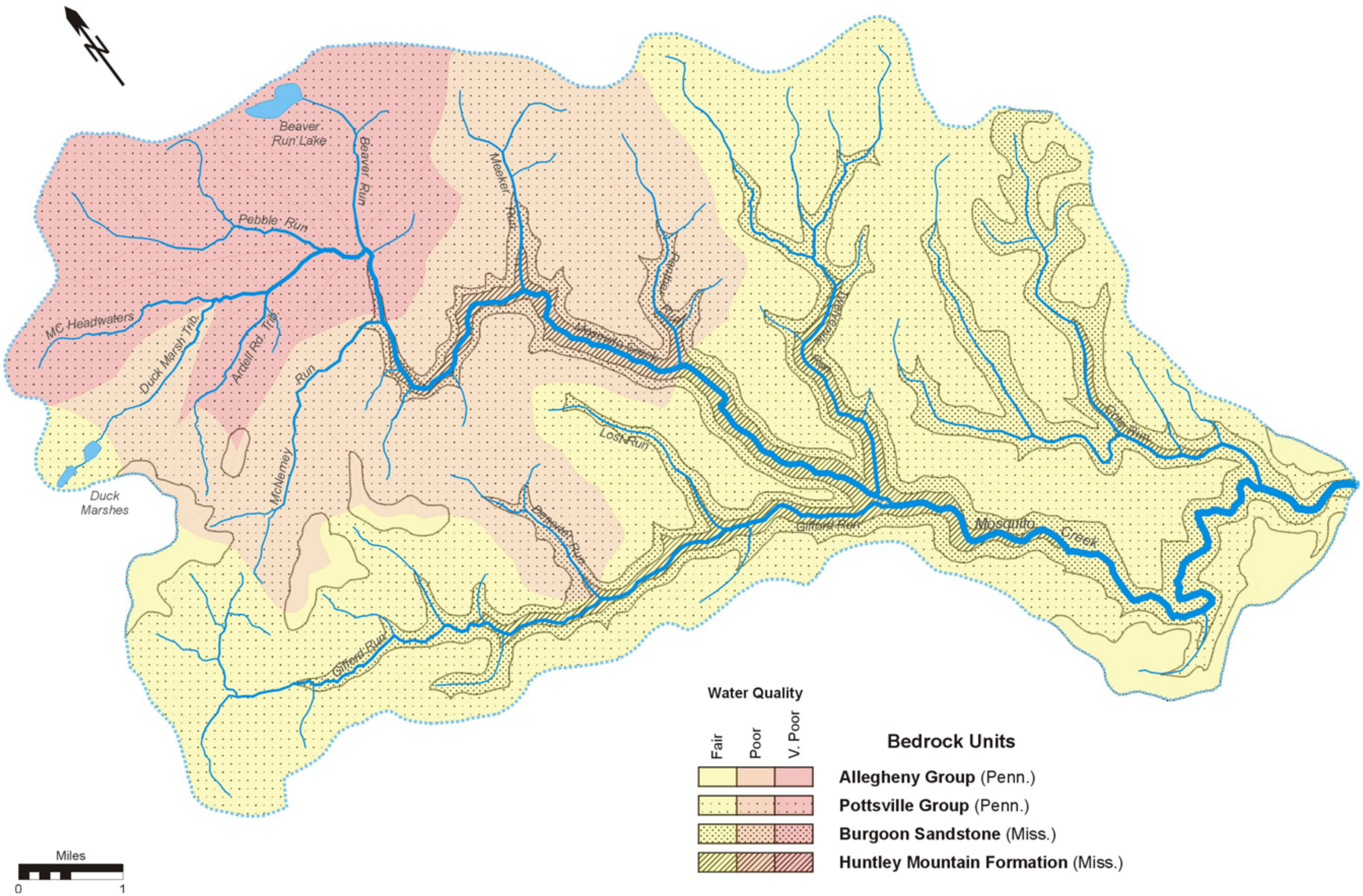
Water quality generally improves trending east and south along the main stem and into the Gifford Run drainage. Under average pre-addition conditions, poor quality extends from McNerney Run to Meeker Run and possibly Panther Run on the main stem. Deserter Run is the only poor quality tributary in the Gifford Run subwatershed on average. The remainder of the Mosquito Creek drainage either shows fair quality or is predicted to have possessed fair quality prior to alkaline addition. At high flows, however, poor quality extends downstream to sample point M-7.

Figure 3-5 provides a comparison between average pre-addition water quality and bedrock geology. Exposed units trend upward from the Mississippian Huntley Mountain Formation and Burgoon Sandstone in the deeper southern valleys to the Pennsylvania Pottsville Group on the northern highlands and headwaters areas, with several remnant knobs of the Allegheny Group at the highest elevations. The severe acidification in Pebble Run and Beaver Run occurs in association with the basal conglomerate member of the Pottsville Group, with large cliffs and boulders of quartz pebble conglomerate exposed throughout these subwatersheds.

Soils derived from quartz-rich parent materials are expected to have a low natural buffering capacity due to the high silica content. The Burgoon and Huntley Mountain strata contain a greater percentage of shale and siltstone, and are described as having calcareous interbeds. It is presumed that the streams with significant reaches rooted in these units are benefiting somewhat from this inherent alkalinity, although the quantity is not sufficient to fully overcome the influx of acid deposition.

The effects of existing alkaline addition projects are readily apparent on Figures 3-3 and 3-4. Limestone sand dosing in Gifford Run produces good to very good quality under average conditions, with good to fair quality at high flows. This addition appears to maintain fair quality in the Mosquito Creek main stem below Gifford Run as well. Under average conditions, the Ardell and Duck Marsh tributaries show significant improvements to the good category from the VFW installations, while the VFW on Pebble Run and lake liming on Beaver Run have elevated these streams to the poor category from very poor conditions. The mutual effects of the headwaters projects are inferred to produce improvements to poor conditions from previous average conditions of very poor downstream past the mouth of Beaver Run. The individual and cumulative effects of these projects related to design considerations are discussed in Section 4.

Figure 3-5: Comparison of Average Pre-Addition Water Quality to Bedrock Geology



## CHARACTERISTICS OF ACIDIFICATION

Table 3-4 summarizes the characteristics of acidification in the Mosquito Creek watershed in terms of alkaline deficiency and temporal nature (sustainable, episodic, or chronic) for the major sampling points in the in-stream monitoring programs. Alkaline deficiency is expressed as pounds per day of calcium carbonate ($CaCO_3$) derived by converting measured ANC into its approximate equivalent value as alkalinity (ANC in meq/L x 0.05 = alkalinity in mg/L). Negative values indicate an alkaline excess. Values are given for average and high flow (95% CI) conditions, and for pre- and post-alkaline addition for applicable points. As discussed in Section 1, streams with neutrality thresholds above the 95% CI flow are assumed to be sustainable, those with neutrality thresholds between the average and high flows to be episodic, and remaining streams to be chronically acidified.

The spatial nature of acidification is illustrated by Figures 3-6 and 3-7, which show alkaline deficiency or excess as a function of line weight for average and high flow conditions before and after existing alkaline addition. By this analysis, a major source of acid export is concentrated in the northern headwaters region between Pebble Run and Meeker Run, with some attenuation occurring between Meeker Run and Gifford Run. Pre-addition Mosquito Creek is interpreted to again gain acidity trending downstream from Gifford Run. Although the influence is uncertain, the attenuation zone between Meeker Run and Gifford Run corresponds to the deepest incision of the watershed into the Huntley Mountain formation, possibly exposing alkaline strata.

The effects of the existing alkaline addition projects are most evident under average conditions on Figure 3-6. Alkaline excesses from Gifford Run are carried through to the terminal sample point at M-7, counteracting acidity sources above M-10. The alkaline excesses from the headwaters projects also moderate acidity in the upper main stem, although the effects are not interpreted to be significant much below Beaver Run. Under high flow conditions, the Gifford Run export reduces the deficiency in the lower main stem to a third of its estimated pre-addition condition.

Figure 3-8 provides additional characterization of acidification by comparing observed ranges of pH and ANC before and after alkaline addition, as applicable. Sustainable and episodic streams receiving alkaline addition show broader ranges of these parameters than those chronically acidified. Post-addition improvements are readily apparent for Gifford Run (M-9 and M-20), the Ardell tributary (M-3), and the Duck Marshes (M-23), and are discernable for Beaver Run (M-18), Pebble Run (M-19), the Mosquito Creek headwaters (M-5), and the terminal watershed sample at M-7.

Table 3-4: Summary of Alkaline Deficiencies and Acidification Conditions

| Sample Points | | Alkaline Deficiency: Average lbs/day | Alkaline Deficiency: High Flow lbs/day | Flow Condition: Average gpm | Flow Condition: Neutral. Threshold gpm | Flow Condition: High Flow gpm | Acidification Condition |
|---|---|---|---|---|---|---|---|
| M-3 | Ardell Trib. DS - Pre | 17 | 56 | 1305 | 0 | 3313 | Chronic |
| | Ardell Trib. DS - Post | -19 | 32 | 1305 | 2082 | 3313 | Episodic |
| M-4 | MC Headwaters - Pre | 43 | 123 | 2937 | 0 | 7454 | Chronic |
| | MC Headwaters - Post | 42 | 108 | 2937 | 0 | 7454 | Chronic |
| M-5 | MC at Ardell Dam - Pre | 63 | 193 | 4623 | 0 | 11733 | Chronic |
| | MC at Ardell Dam - Post | 35 | 154 | 4623 | 192 | 11733 | Chronic |
| M-6 | MC below Meeker - Pre | 208 | 752 | 18429 | 0 | 46772 | Chronic |
| | MC below Meeker - Post | 178 | 659 | 18429 | 0 | 46772 | Chronic |
| M-7 | Mosquito Creek DS - Pre | 177 | 661 | 63931 | 6702 | 146362 | Chronic |
| | Mosquito Creek DS - Post | -192 | 199 | 63931 | 100757 | 146362 | Episodic |
| M-8 | Cole Run | 20 | 155 | 9188 | 2434 | 24546 | Chronic |
| M-9 | Gifford Run DS - Pre | 34 | 325 | 11987 | 3838 | 30051 | Chronic |
| | Gifford Run DS - Post | -577 | -133 | 11987 | 34899 | 30051 | Sustainable |
| M-10 | Mosquito Creek MS | 69 | 372 | 25650 | 6023 | 60340 | Chronic |
| M-11 | Twelvemile Run | 12 | 144 | 6416 | 2608 | 16113 | Chronic |
| M-12 | Lost Run | 1 | 48 | 1616 | 716 | 4305 | Chronic |
| M-13 | Deserter Run | 20 | 57 | 2143 | 0 | 5873 | Chronic |
| M-14 | Gifford Run US | 11 | 138 | 6464 | 2050 | 16040 | Chronic |
| M-15 | Panther Run | 7 | 22 | 63931 | 153 | 3250 | Chronic |
| M-16 | Meeker Run | 10 | 32 | 2072 | 175 | 4221 | Chronic |
| M-17 | McNerney Run | 11 | 53 | 2085 | 122 | 5456 | Chronic |
| M-18 | Beaver Run - Pre | 41 | 89 | 1681 | 0 | 3889 | Chronic |
| | Beaver Run - Post | 26 | 79 | 1681 | 0 | 3889 | Chronic |
| M-19 | Pebble Run - Pre | 64 | 148 | 2099 | 0 | 5060 | Chronic |
| | Pebble Run - Post | 23 | 1 | 2099 | 0 | 5060 | Chronic |
| M-20 | Gifford Run MS - Pre | 30 | 206 | 9605 | 1551 | 24643 | Chronic |
| | Gifford Run MS - Post | -235 | 26 | 9605 | 22967 | 24643 | Episodic |
| M-23 | Duck Marsh Trib. - Pre | 17 | 69 | 1388 | 0 | 3522 | Chronic |
| | Duck Marsh Trib. - Post | -8 | 48 | 1388 | 2206 | 3522 | Episodic |

Values for M-23 are projected to the confluence with Mosquito Creek

Negative values indicate alkaline excess.

Figure 3-6: Acidity Loading Trends in Mosquito Creek – Average Flow Conditions

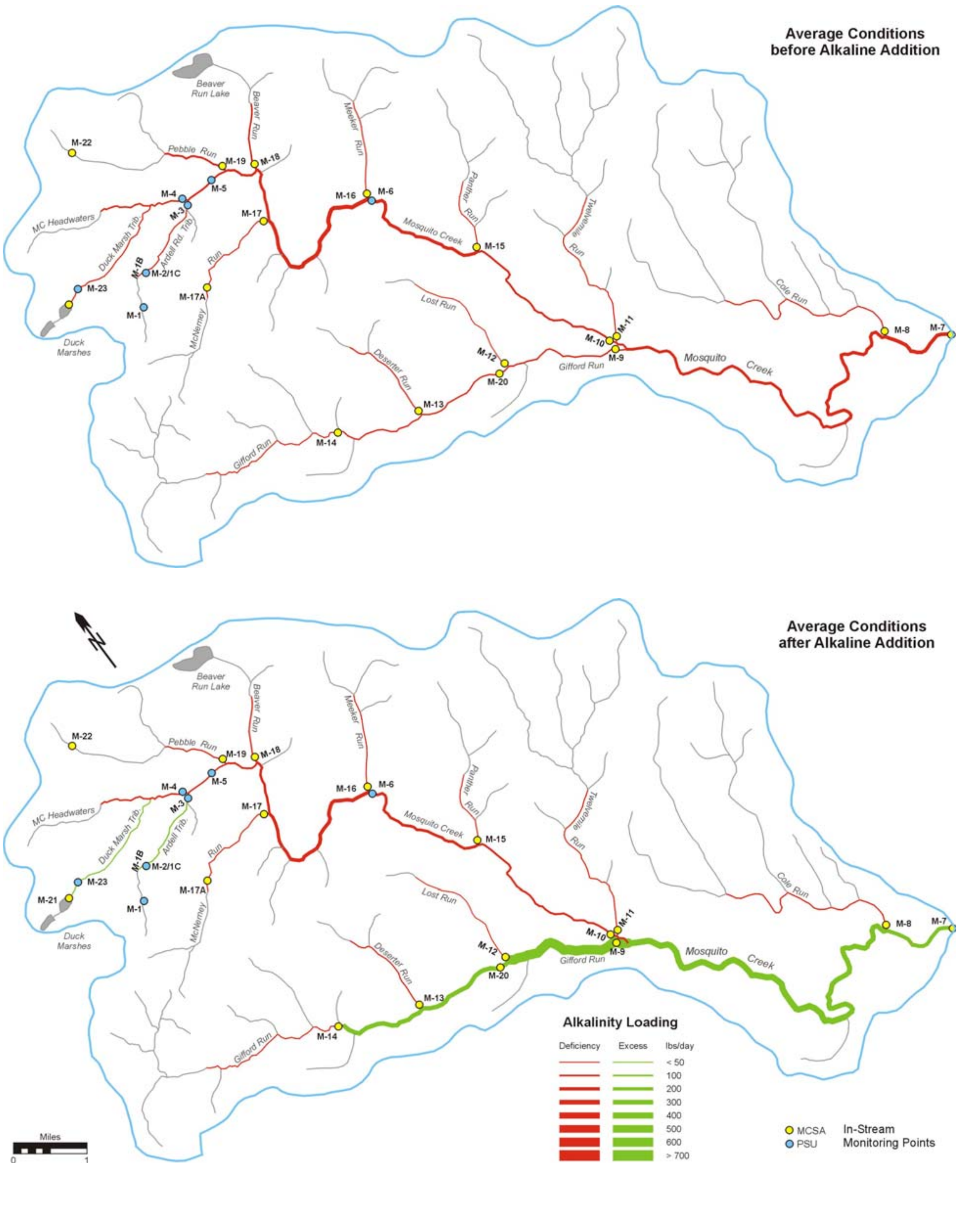


Figure 3-7: Acidity Loading Trends in Mosquito Creek – High Flow Conditions

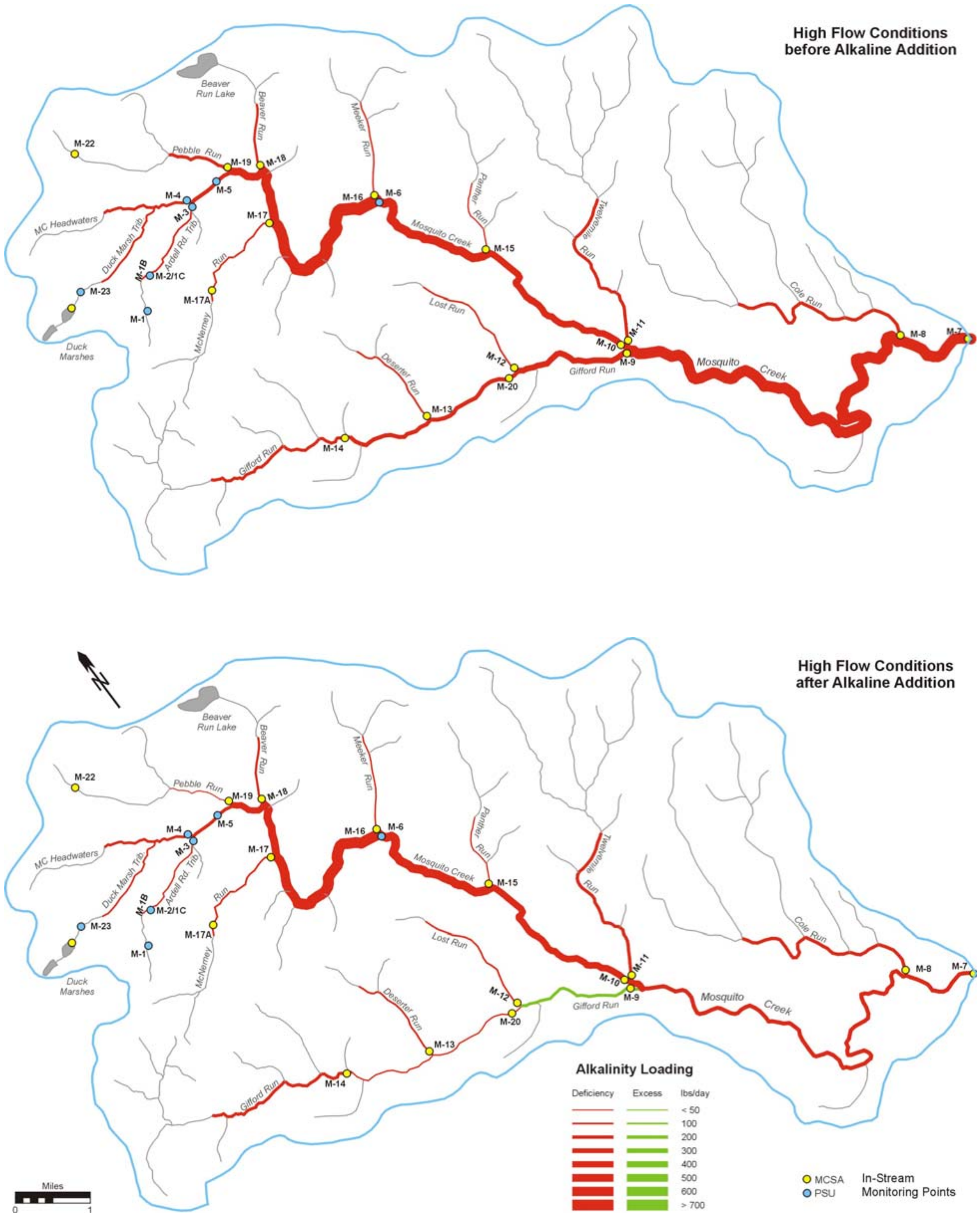
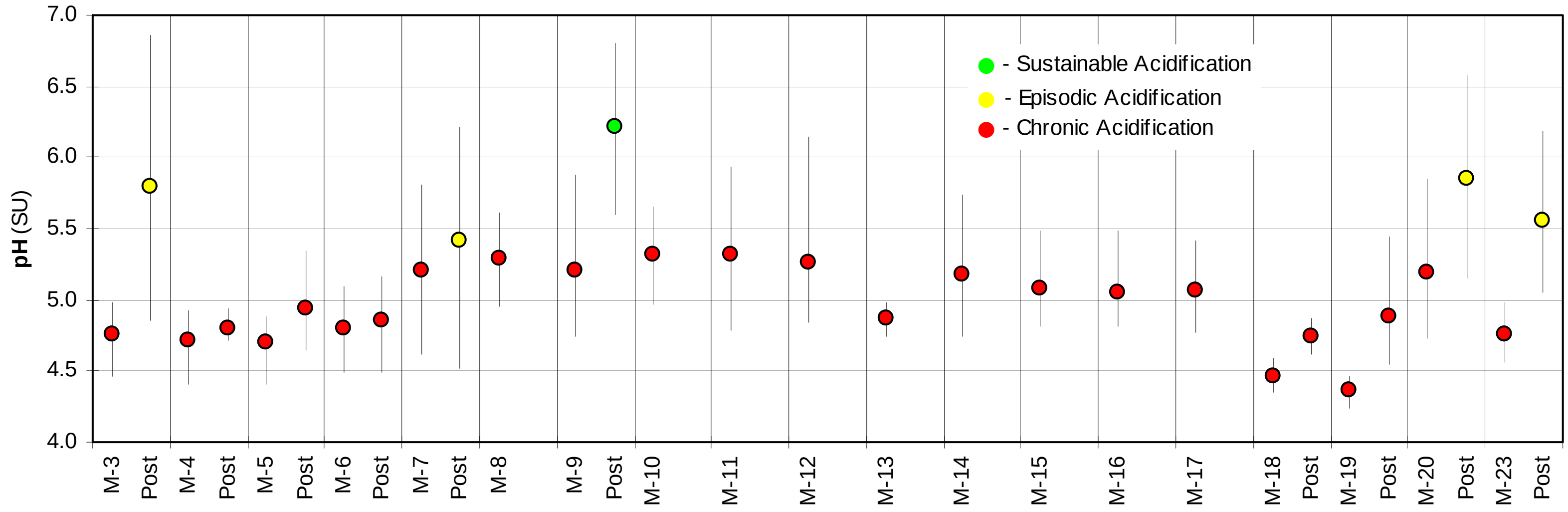
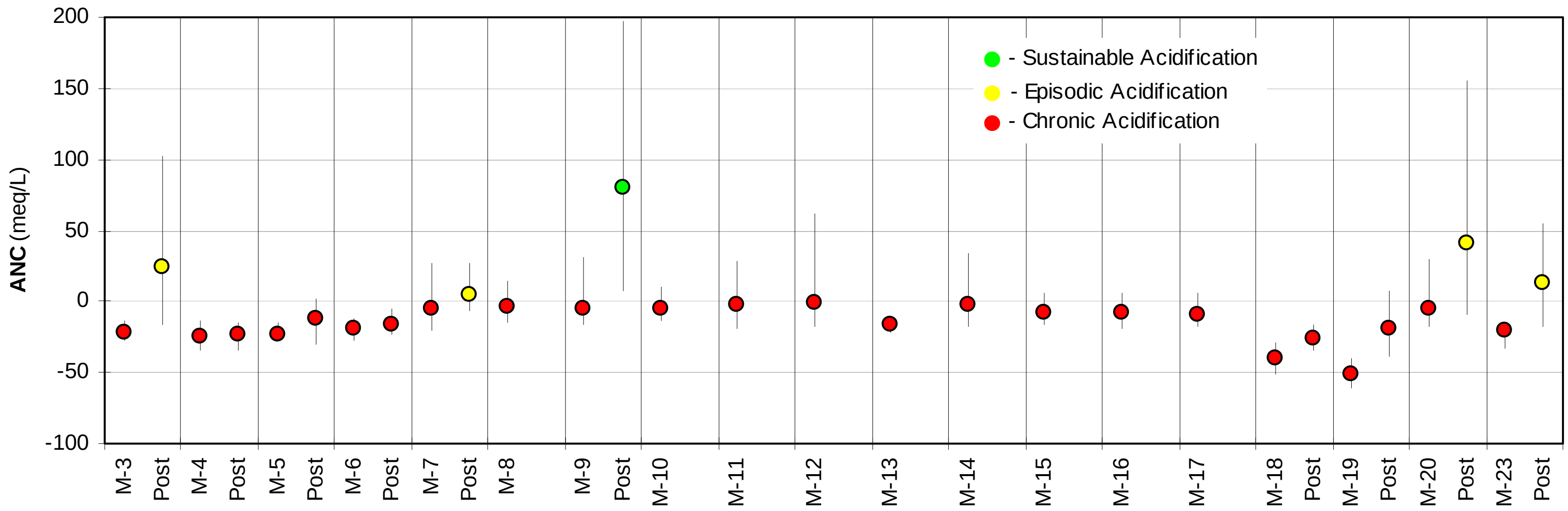


Figure 3-8: Ranges of pH and ANC Pre- and Post- Alkaline Addition



## ALKALINE ADDITION REQUIREMENTS

The alkaline deficiencies presented in Table 3-4 represent the changes required to reach a zero ANC, which is a neutral condition from an analytic standpoint and used for uniform comparison of relative deficiency levels between streams. This is not, however, a desirable condition for sustainable fish populations, since zero-ANC waters have no buffering capacity and equate to a pH of about 5.4 SU in this study. It is observed from the limestone sand dosing activities on Gifford Run that the reach between M-14 and M-20 is capable of sustaining fish under water quality conditions ranging from good to fair by the Table 3-3 categories. From this, it is proposed that the <u>minimum</u> restoration goals in the Mosquito Creek watershed should be an ANC of 20 meq/L under average flow conditions and 5 meq/L under high flow conditions. This equates to a pH range of about 5.8 SU on average, with a minimum of about 5.5 SU. Table 3-5 provides a comparison of this target range to the observed pH and ANC equivalent short-term survivability ranges of fish species living in waters acidified by mine drainage. These ranges may guide future adjustments to restoration goals if reintroduction is desired for more sensitive species.

Table 3-6 provides a summary of the predicted alkaline addition requirements to meet the proposed restoration goals at each of the major sample points in Table 3-4. Values are given for pre-addition conditions as a measure of accomplishments to date and potential long-term requirements in the treated streams, and for existing conditions to estimate future restoration requirements with existing addition projects. Average values would represent the normal daily feed rate of an addition system, with high flow values being the typical design maximum feed rate. Average and high flow alkaline addition requirements are presented as pounds per day as $CaCO_3$; actual addition rates will depend on the purity and type of alkaline addition material selected. Annual figures are also provided as an estimate of the yearly addition commitment. Determination of actual addition requirements will be discussed for specific technologies in Section 4.

In conclusion, Figure 3-9 shows a cumulative loading chart of alkaline addition required to meet minimum restoration goals throughout the major tributaries of the Mosquito Creek watershed. This analysis assumes that acidity reductions propagate downstream as alkalinity is added to upstream points, as is observed for the effect of the Gifford Run addition on downstream Mosquito Creek. A corollary to this observation is that headwaters alkaline addition is generally more effective than treating a downstream reach while upstream acidity sources remain untreated. Ultimately, downstream-progressing, long-term restoration will likely require a <u>minimum</u> of about 150 tons per year of alkaline addition as $CaCO_3$ (roughly 150 tons per year of high-quality limestone).

Table 3-5: Observed Survival Ranges of Fish Species in Mine Drainage Waters

| Species | Survival Range | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH (SU) | 4.5 | 4.6 | 4.7 | 4.8 | 4.9 | 5.0 | 5.1 | 5.2 | 5.3 | 5.4 | 5.5 | 5.6 | 5.7 | 5.8 | 5.9 | 6.0 | 6.1 | 6.2 | 6.3 | 6.4 | 6.5 |
| ANC Eq. (meq/L) | -31 | -26 | -22 | -18 | -14 | -11 | -8 | -5 | -2 | 1 | 7 | 13 | 19 | 25 | 32 | 40 | 48 | 56 | 66 | 77 | 90 |
| Ohio Lamprey | | | | | | | | | | | | | | | | | | | | | |
| Chain Pickerel | | | | | | | | | | | | | | | | | | | | | |
| Golden Shiner | | | | | | | | | | | | | | | | | | | | | |
| White Sucker | | | | | | | | | | | | | | | | | | | | | |
| Brown Bullhead | | | | | | | | | | | | | | | | | | | | | |
| Pumpkinseed | | | | | | | | | | | | | | | | | | | | | |
| Creek Chubsucker | | | | | | | | | | | | | | | | | | | | | |
| Largemouth Bass | | | | | | | | | | | | | | | | | | | | | |
| Brook Trout | | | | | | | | | | | | | | | | | | | | | |
| Creek Chub | | | | | | | | | | | | | | | | | | | | | |
| Yellow Perch | | | | | | | | | | | | | | | | | | | | | |
| Bluntnose Minnow | | | | | | | | | | | | | | | | | | | | | |
| Blacknose Dace | | | | | | | | | | | | | | | | | | | | | |
| Brown Trout | | | | | | | | | | | | | | | | | | | | | |
| Longnose Dace | | | | | | | | | | | | | | | | | | | | | |
| Margined Madtom | | | | | | | | | | | | | | | | | | | | | |
| Tessellated Darter | | | | | | | | | | | | | | | | | | | | | |
| Slimy Sculpin | | | | | | | | | | | | | | | | | | | | | |
| Stoneroller | | | | | | | | | | | | | | | | | | | | | |
| Silverjaw Minnow | | | | | | | | | | | | | | | | | | | | | |
| River Chub | | | | | | | | | | | | | | | | | | | | | |
| Common Shiner | | | | | | | | | | | | | | | | | | | | | |
| Silver Shiner | | | | | | | | | | | | | | | | | | | | | |
| Rosyface Shiner | | | | | | | | | | | | | | | | | | | | | |
| Mimic Shiner | | | | | | | | | | | | | | | | | | | | | |
| Northern Hogsucker | | | | | | | | | | | | | | | | | | | | | |
| Rock Bass | | | | | | | | | | | | | | | | | | | | | |
| Smallmouth Bass | | | | | | | | | | | | | | | | | | | | | |
| Greenside Darter | | | | | | | | | | | | | | | | | | | | | |
| Fantail Darter | | | | | | | | | | | | | | | | | | | | | |
| Johnny Darter | | | | | | | | | | | | | | | | | | | | | |
| Banded Darter | | | | | | | | | | | | | | | | | | | | | |
| Blackside Darter | | | | | | | | | | | | | | | | | | | | | |
| Cutlips Minnow | | | | | | | | | | | | | | | | | | | | | |
| Fallfish | | | | | | | | | | | | | | | | | | | | | |
| Redbreast Sunfish | | | | | | | | | | | | | | | | | | | | | |
| Rainbow Darter | | | | | | | | | | | | | | | | | | | | | |
| Variegated Darter | | | | | | | | | | | | | | | | | | | | | |
| Mottled Sculpin | | | | | | | | | | | | | | | | | | | | | |
| Redside Dace | | | | | | | | | | | | | | | | | | | | | |
| Spotfin Shiner | | | | | | | | | | | | | | | | | | | | | |
| Spottail Shiner | | | | | | | | | | | | | | | | | | | | | |
| Pearle Dace | | | | | | | | | | | | | | | | | | | | | |
| Green Sunfish | | | | | | | | | | | | | | | | | | | | | |

**Target Range**

**Minimum Proposed Restoration Goal**

Based on Earl & Callaghan, referencing Cooper & Wagner, 1973

Table 3-6: Alkaline Addition Requirements to Meet Minimum Restoration Goals

| Sample Points | | Pre-Addition Requirement 20 meq/L ANC Ave., 5 meq/L High Flow | | | Existing Requirement 20 meq/L ANC Ave., 5 meq/L High Flow | | |
|---|---|---|---|---|---|---|---|
| | | Average lbs/day | High Flow lbs/day | Annual tons/yr | Average lbs/day | High Flow lbs/day | Annual tons/yr |
| M-3 | Ardell Trib. | 33 | 66 | 6 | 0 | 42 | 0.4 |
| M-4 | MC Headwaters | 79 | 145 | 14 | 77 | 130 | 14 |
| M-5 | MC at Ardell Dam | 119 | 229 | 22 | 90 | 145 | 17 |
| M-6 | MC below Meeker | 429 | 892 | 78 | 399 | 799 | 73 |
| M-7 | Mosquito Creek DS | 943 | 1100 | 172 | 575 | 638 | 105 |
| M-8 | Cole Run | Currently Untreated | | | 130 | 229 | 24 |
| M-9 | Gifford Run DS | 178 | 415 | 32 | 0 | 0 | 0 |
| M-10 | Mosquito Creek MS | Currently Untreated | | | 376 | 552 | 69 |
| M-11 | Twelvemile Run | Currently Untreated | | | 89 | 192 | 16 |
| M-12 | Lost Run | Currently Untreated | | | 21 | 61 | 4 |
| M-13 | Deserter Run | Currently Untreated | | | 46 | 75 | 8 |
| M-14 | Gifford Run US | Currently Untreated | | | 89 | 186 | 16 |
| M-15 | Panther Run | Currently Untreated | | | 26 | 32 | 5 |
| M-16 | Meeker Run | Currently Untreated | | | 35 | 44 | 6 |
| M-17 | McNerney Run | Currently Untreated | | | 36 | 69 | 7 |
| M-18 | Beaver Run | 61 | 101 | 11 | 46 | 90 | 8 |
| M-19 | Pebble Run | 90 | 163 | 16 | 48 | 16 | 9 |
| M-20 | Gifford Run MS | 145 | 280 | 26 | 0 | 100 | 1 |
| M-23 | Duck Marsh Trib | 34 | 80 | 6 | 3 | 33 | 0.5 |

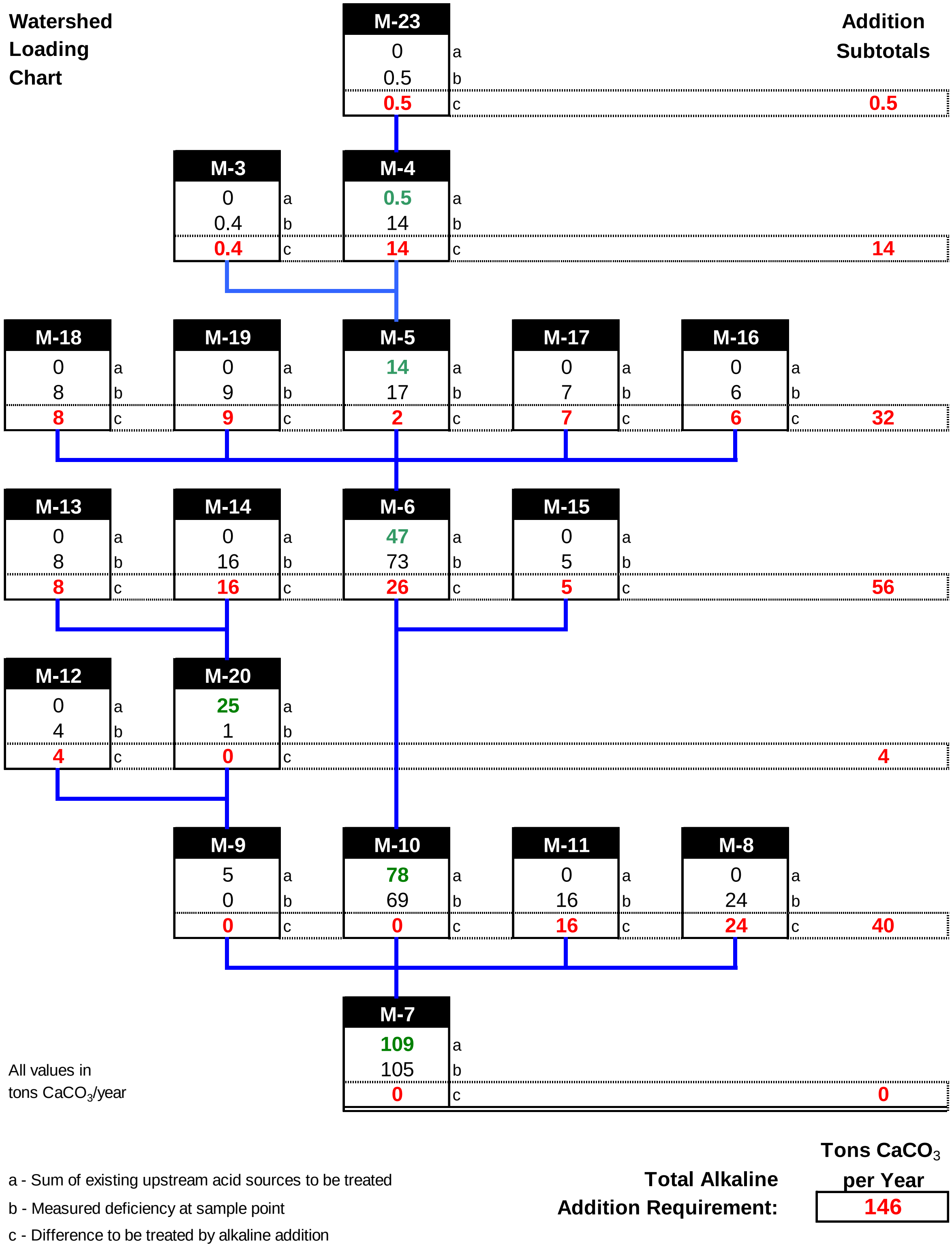
[1]Alkalinity equivalent as pure $CaCO_3$

[2]Average daily addition rate

[3]Typical design maximum addition rate

[4]Annual material consumption as $CaCO_3$ based on average rate. Where average rate is zero, annual rate assumes the high flow rate at 1 day in 20.

Figure 3-9: Estimated Annual Cumulative Alkaline Addition Required to Meet Minimum Goals



# 4

# TECHNOLOGY ASSESSMENT

Over the course of the Mosquito Creek projects, seven alkaline addition technologies were applied and/or assessed: vertical flow wetlands (VFWs), vertical flow limestone beds (VFLBs), in-stream limestone sand dosing, lake liming, high flow buffer channels (HFBCs), limestone road addition, and forest liming. Of these, VFWs, VFLBs, and HFBCs are new applications to acid deposition abatement. This section provides a summary of the individual technologies, their design and implementation approaches, treatment results, and approximate costs as developed from the project studies and documentation from other sites. Several other common forms of alkaline addition have been applied in the United States, including diversion wells, rotary drums and basket wheels, and pebble quicklime addition units. Although not assessed by this study, a summary is included for each at the end of this section. Table 4-1 provides a comparison of these technologies by applicability to acidification condition, approximate cost per pound of alkalinity added, relative construction and operation and maintenance (O&M) costs and effort, and advantages and limitations.

All of these technologies except pebble quicklime addition involve application of various forms of limestone ($CaCO_3$), which is generally less expensive and easier to handle than other common neutralizing agents, such as caustic soda (NaOH) or ammonia ($NH_3$). It is believed that limestone is the most environmentally benign neutralizing agent for stream restoration because it generates only naturally occurring calcium ions as a byproduct.

Wherever referenced, limestone used for restoration projects should be specified as *high calcium limestone* having a $CaCO_3$ content of 90% or greater. Products with a lesser $CaCO_3$ content have not proven as effective in past applications. The alkalinity deficiencies presented in Section 3 represent deficiencies as pure $CaCO_3$. The actual mass of impure limestone that needs to dissolve to correct a deficiency is greater than the mass of the deficiency. As shown by the equation below, this mass is determined by dividing the mass of alkalinity required by the purity of the limestone product in percent.

$$\text{Limestone Required (lbs)} = \text{Alkalinity Required (lbs)} / \text{Limestone Purity } (CaCO_3\ \%)$$

## Table 4-1: Summary of Assessed and Other Alkaline Addition Technologies

| **Technology** | **Applicable Acidification Conditions** | **Approx. Alkalinity Addition Cost** ($/lb) | **Relative Costs & Effort** | | **Advantages** | **Limitations** |
|---|---|---|---|---|---|---|
| | | | Construct. | O & M | | |
| Vertical Flow Systems | | | | | | |
| Vertical Flow Wetlands | Chronic to Mod. Episodic | ≈ $0.75 | ● | ⊗ | Large alkalinity reservoir, very low maintenance, one-time expenditure. | Relatively high capital cost, long-term performance not known, compost discoloration. |
| Vertical Flow Limestone Beds | Chronic to Mod. Episodic | * | ● | ⊗ | May not require compost or wetland outfall channels, less expensive than VFWs. | Performance untested, may be subject to substrate armoring. |
| In-Stream Limestone Sand Dosing | Episodic to Mildly Chronic | ≈ $0.01 | ⊗ | ○ | Very simple, low cost, little or no capital investment. | May degrade streambed, effectiveness variable, dosage difficult to estimate. |
| Lake Liming | Episodic to Mildly Chronic | ≈ $0.10 – $0.30 | ⊗ | ◉ | Creates large alkaline water reservoir, may restore lacustrine fisheries. | Relatively high application cost, must be re-applied ever 1 to 2 years. |
| High Flow Buffer Channels | Sustainable to Mod. Episodic | * | ● | ○ | Saves limestone for when needed in episodic events, prevents streambed degradation. | Performance untested, requires suitable floodplain construction site. |
| Road Liming | | | | | | |
| Limestone Road Surfacing | Sustainable to Mildly Episodic | ≈ $0.01 – $0.05 | ◉ | ⊗ | Can be incorporated with existing surfacing programs, no new earth disturbance. | Limited intercept area for runoff, net alkaline output relatively small. |
| Alkaline Road Runoff Channels | Sustainable to Mildly Episodic | ≈ $0.05 | ◉ | ⊗ | Can be used to stabilize existing ditches, intercepts surrounding land runoff. | Requires ditch reconstruction, only generates alkalinity during storm flows. |
| Limestone Sand Dosing Fords | Sustainable to Mildly Episodic | ** | ◉ | ○ | Can be used to reconstruct existing crossings, simple maintenance. | Limited alkaline generation capacity, subject to washout and algal growth. |

Table 4-1: Summary of Assessed and Other Alkaline Addition Technologies (Continued)

| Technology | Applicable Acidification Conditions | Approx. Alkalinity Addition Cost ($/lb) | Relative Costs & Effort | | Advantages | Limitations |
|---|---|---|---|---|---|---|
| | | | Construct. | O & M | | |
| Forest Liming | Sustainable to Mildly Episodic | ≈ $0.05 – $0.30 | ● | ⊗ | Long-term improvements to soil condition, runoff neutralization, and vegetative cover. | Can be difficult to apply with high initial cost, improvements not immediate. |
| Other Common Technologies*** | | | | | | |
| Diversion Wells | Episodic to Mildly Chronic | ** | **O** | ● | Simple to construct, proven in existing applications, unskilled maintenance. | High frequency of maintenance, no current criteria for alkalinity output. |
| Rotary Drums & Basket Wheels | Episodic to Mildly Chronic | ** | **O** | ● | Allows a degree of dosage control and response to flow changes. | High frequency of maintenance, mechanical systems can malfunction. |
| Pebble Quicklime | Chronic to Mod. Episodic | ≈ $0.05 – $0.10 | **O** | ● | Rapid neutralization and controllable dosage, small construction footprint. | Frequent maintenance and skill in quicklime handling required, higher material cost. |

*Technology not yet applied.
**Varies considerably depending on site conditions.
***Not assessed by Mosquito Creek study

⊗ Little or no cost or effort  **O** Moderate cost or effort
O Low cost or effort  ● High cost or effort

# VERTICAL FLOW WETLANDS

As shown by Figure 4-1, VFWs consist of deep basins filled with a basal layer of limestone aggregate topped by a bed of spent mushroom compost. Water diverted from an acidified source or stream is introduced into the top of the basin and migrates down through the two layers, acquiring alkalinity through sulfate reduction and limestone dissolution before discharging through an underdrain system to neutralize the source or stream. VFWs were originally developed to treat acid mine drainage based on observations that use of compost in conjunction with limestone improved alkalinity generation and reduced armoring by metals precipitates compared to use of limestone alone. The advantage of VFWs is that they provide a large reservoir of limestone and require little maintenance and no material replenishment for many years after construction. They are particularly effective where operational labor is limited or where restoration funding requires a one-time investment without provision for ongoing material replacement.

A primary goal of the Round 1 Grant for Mosquito Creek was to evaluate whether VFWs would also be effective for streams impacted by atmospheric deposition. Under this Grant, a VFW demonstration project was constructed in 2001 on the Ardell tributary (Figure 4-2) using existing design criteria from mine drainage systems. Subsequent monitoring showed that this VFW created a positive ANC for 1.6 miles downstream to the confluence with Mosquito Creek, leading to funding and construction of two more VFWs on the Duck Marsh tributary (Figure 4-3) and Pebble Run (Figure 4-4) in 2003. Influent and effluent monitoring was conducted on all three systems through 2005.

The experience gained from the initial Ardell system led to a standardized, scalable VFW design that was applied for identically sized systems at the Duck Marsh tributary and Pebble Run. Figure 4-5 summarizes the basic components of this design as seen during the construction phase.

Figure 4-1: Schematic Section of a Vertical Flow Wetland

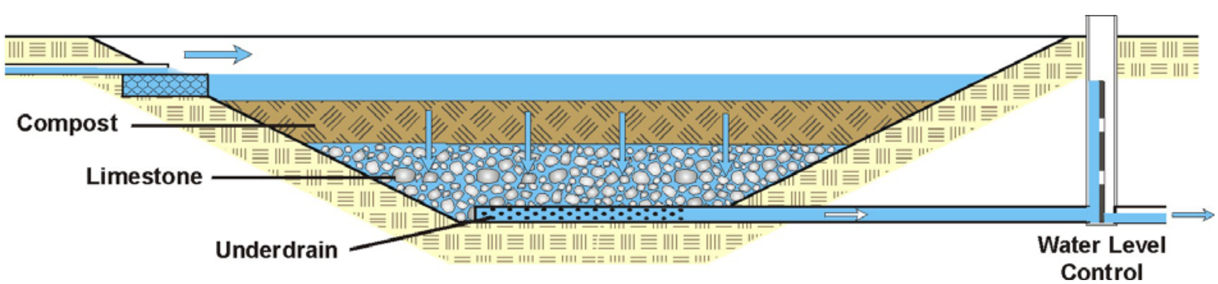


Figure 4-2: Ardell Tributary Vertical Flow Wetland

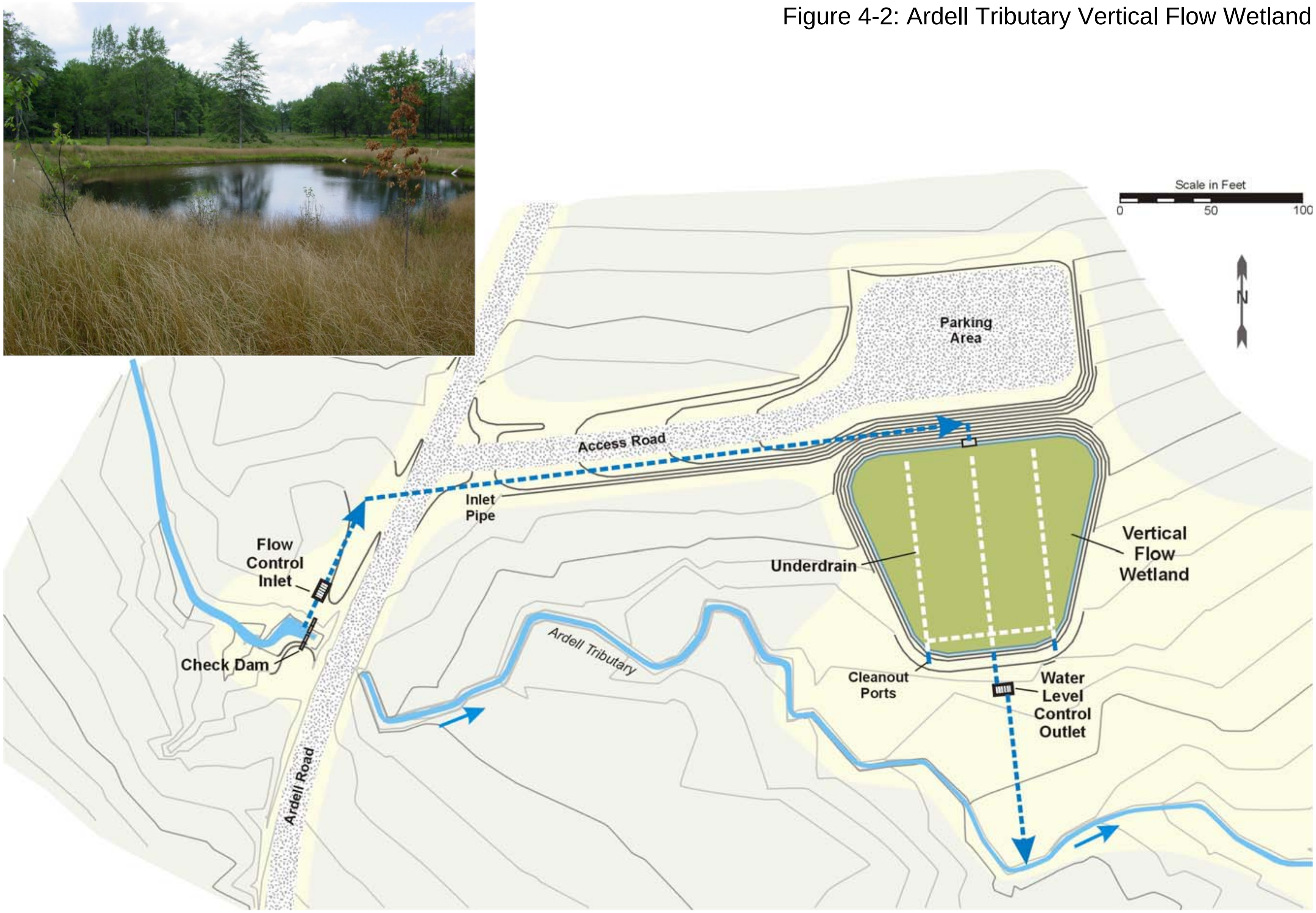


Figure 4-3: Duck Marsh Tributary Vertical Flow Wetland

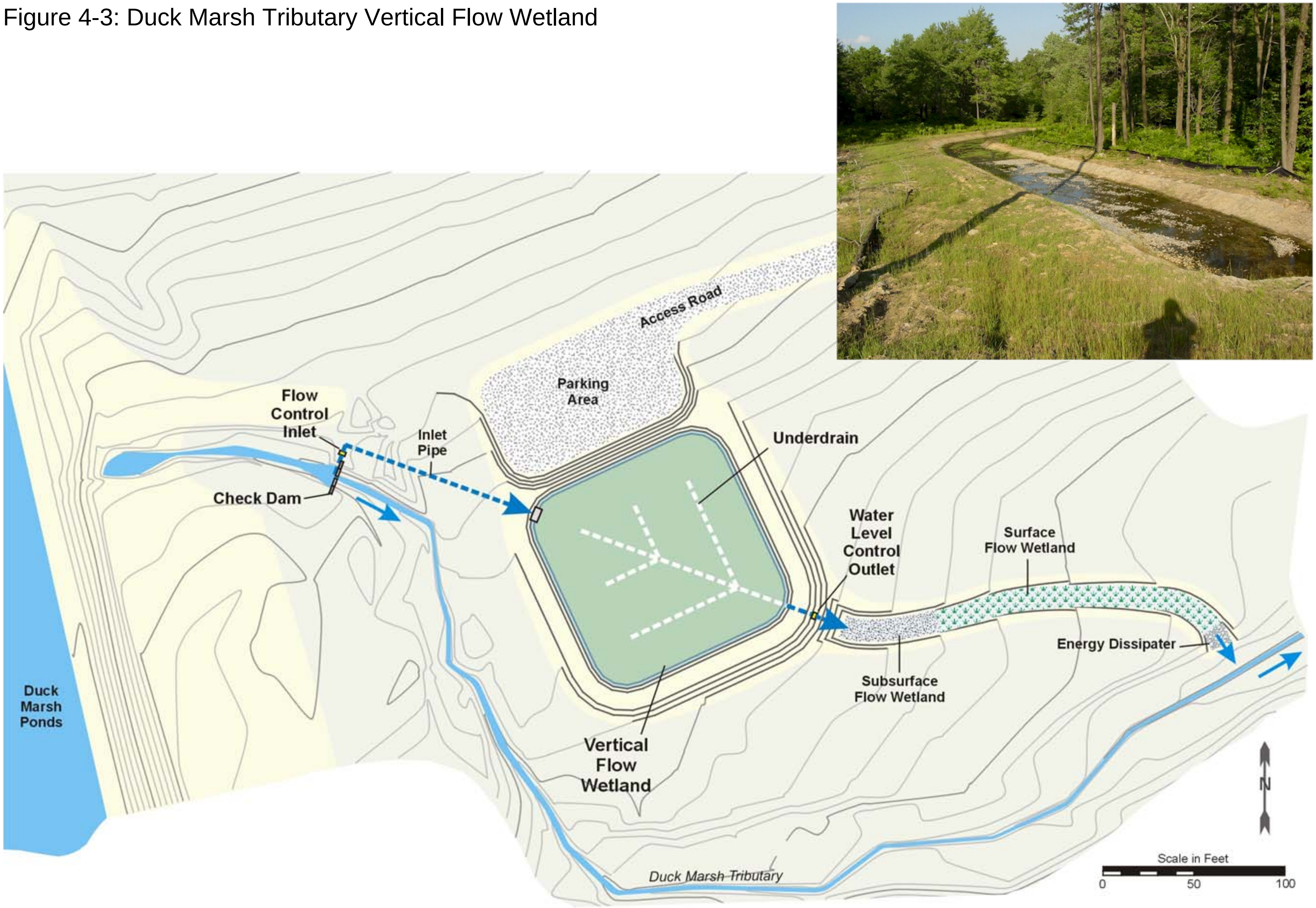


Figure 4-4: Pebble Run Vertical Flow Wetland

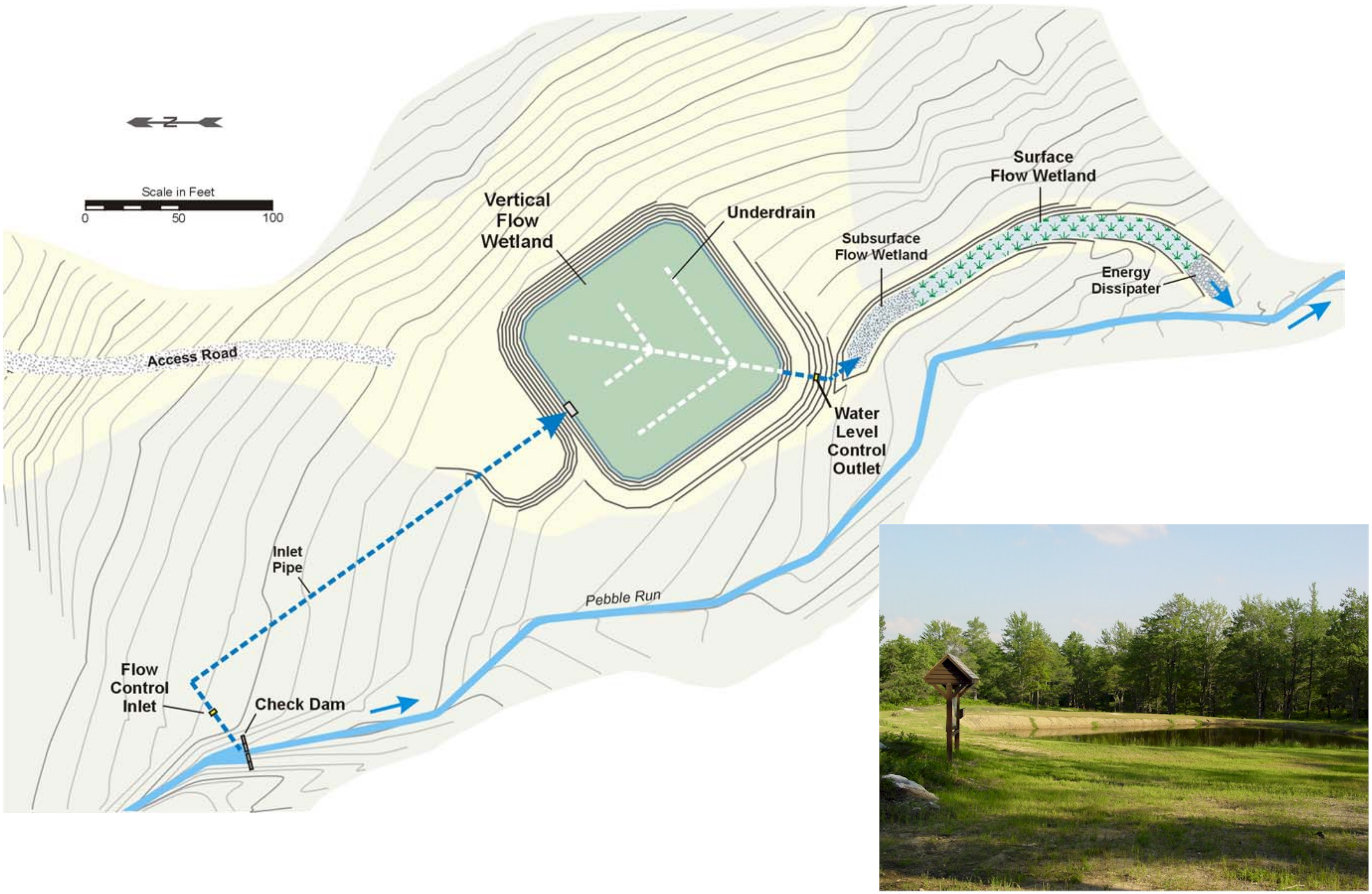


Figure 4-5: Basic Components of a Vertical Flow Wetland for Acid Deposition Treatment

Influent water is diverted to an inlet pipe by a staged check dam.

An in-line water level control with an orifice allows baseflow to enter the pipe, but limits high flows to prevent damage to the VFW.

An underdrain of perforated pipes is placed on the lined floor of the VFW cell.

A 3-foot bed of limestone aggregate is spread on top of the underdrain.

An 18-inch blended compost and limestone sand substrate is spread on top of the limestone bed.

The underdrain discharges through an in-line water level control, entering a wetland channel for discharge polishing.

A fundamental feature of the standard VFW plan is the controlled inlet structure, which is designed to admit baseflow from a stream while limiting high flow events that could damage the cell. A stepped-weir check dam is placed across the stream with a baseflow notch measuring 6 inches square, and a high flow crest with a width as needed to carry the design storm event. An inlet pipe is installed along the upstream side of the dam with the centerline of the pipe level with the bottom of the baseflow notch. A 6-inch pipe is adequate for the range of flows that can be handled by a practical VFW cell sizing. An inverted elbow is placed on the end of the pipe to exclude leaves and debris.

The level inlet pipe is connected to an in-line water level control manufactured by Agri Drain Corporation. This control features removable PVC stop logs set in brackets. A round hole is drilled in one of the stop logs and set center-to-centerline with the inlet pipe to act as an orifice, hydraulically limiting inlet flows even with relatively large head increases at the dam structure. A 3-inch orifice was found to divert the first 20 gpm of stream baseflow, with high flow passage of 80 gpm and maximum storm flow passage of 100 gpm. The inlet pipe then drains to the VFW cell across the top of a gabion basket to dissipate flow energy.

For substrates, the initial Ardell system used 4 feet of limestone and 2 feet of compost, with 24 hours detention in the limestone, typical of mine drainage VFWs at the time. Performance results indicated that less substrate was actually needed, and the Duck Marsh and Pebble Run VFWs used 3 feet of limestone and 1.5 feet of compost for more economical construction. In the later systems, the compost substrate was also blended with limestone sand at three parts compost to one of sand to improve alkalinity generation.

The underdrain pattern was altered for the Duck Marsh and Pebble Run systems from the rectangular underdrain pattern typical of mine drainage VFWs to a crows-foot pattern to improve spreading of downflow through the square cell shape. The underdrain is connected to another Agri Drain in-line water level control at the cell outlet, which is initially set to provide a minimum standing water level of 1 foot above the compost, and can be adjusted later to account for settling and gradual decreases in hydraulic conductivity. The cell is lined using a medium density polyethylene (MDPE) liner up to the design water level to prevent leakage, with a perimeter liner anchor extending to the freeboard elevation and covered with topsoil to allow revegetation to the waterline.

A final addition to the Duck Marsh and Pebble Run systems was a wetland outfall channel to remove organic matter and discoloration that can leach from the compost for several years after construction. The upper part of the channel is a subsurface flow wetland containing limestone aggregate, and the lower part is a surface flow wetland with a topsoil substrate. The aerobic wetlands also serve an important secondary function to dissipate hydrogen sulfide gas ($H_2S$) that is generated in the VFWs, reducing potential adverse effects on downstream biota in the effluent mixing zone. The channel discharges to the stream via a native stone energy dissipater and a flow monitoring Tarco H-flume.

Discharge monitoring results from the three VFW systems are summarized by Table 4-2, with raw data contained in Appendix A. As shown by Figure 4-6, discharge alkalinity from these VFWs is primarily a function of detention time in the limestone substrate, as has also been observed in VFWs for mine drainage treatment. The trend is asymptotic at greater detention times as the limestone approaches dissolution equilibrium in the VFW environment. Alkalinity diminishes more rapidly as detention times fall below about 24 hours. The minimum detention times observed for the Duck Marsh and Pebble Run VFWs were 18 hours.

Although longer detention times create higher discharge alkalinities, they also imply lower flow rates through a fixed volume of substrate. Actual alkalinity output as a mass loading is a function of both the flow volume and the concentration, so reducing flows to increase detention time can also reduce output loadings. Figure 4-7 illustrates this relationship with plots of predicted alkalinity output (pounds per day) versus input flow for several example limestone bed volumes in cubic yards (CY). Due to the logarithmic nature of the discharge alkalinity concentration function in Figure 4-6, alkalinity loading output reaches a peak at moderate flows for a given bed volume before diminishing again at higher flows. This is most apparent for the 500 CY example, but will occur for all bed volumes at sufficiently high flows.

Table 4-2: Summary of Discharge Characteristics for the Mosquito Creek VFWs

| **VFW System** | **Discharge Performance Parameters** | | | |
|---|---|---|---|---|
| | Flow (gpm) | pH (SU) | Alkalinity (mg/L) | ANC (meq/L) |
| Ardell Tributary | | | | |
| Average | 67 ± 18 | 7.71 ± 0.24 | 51.71 ± 12.80 | 973 ± 334 |
| Minimum | 40 | 7.36 | 35.50 | 593 |
| Maximum | 82 | 8.17 | 51.71 | 1517 |
| Duck Marsh Tributary | | | | |
| Average | 46 ± 38 | 7.70 ± 0.42 | 59.10 ± 31.07 | 1202 ± 697 |
| Minimum | 1 | 7.14 | 35.50 | 468 |
| Maximum | 80 | 8.21 | 125.00 | 2638 |
| Pebble Run | | | | |
| Average | 30 ± 29 | 7.44 ± 0.19 | 95.27 ± 26.66 | 1999 ± 570 |
| Minimum | 9 | 7.13 | 61.10 | 1173 |
| Maximum | 80 | 7.66 | 121.00 | 2617 |

Figure 4-6: Relationship of Discharge Alkalinity to Detention Time in VFWs

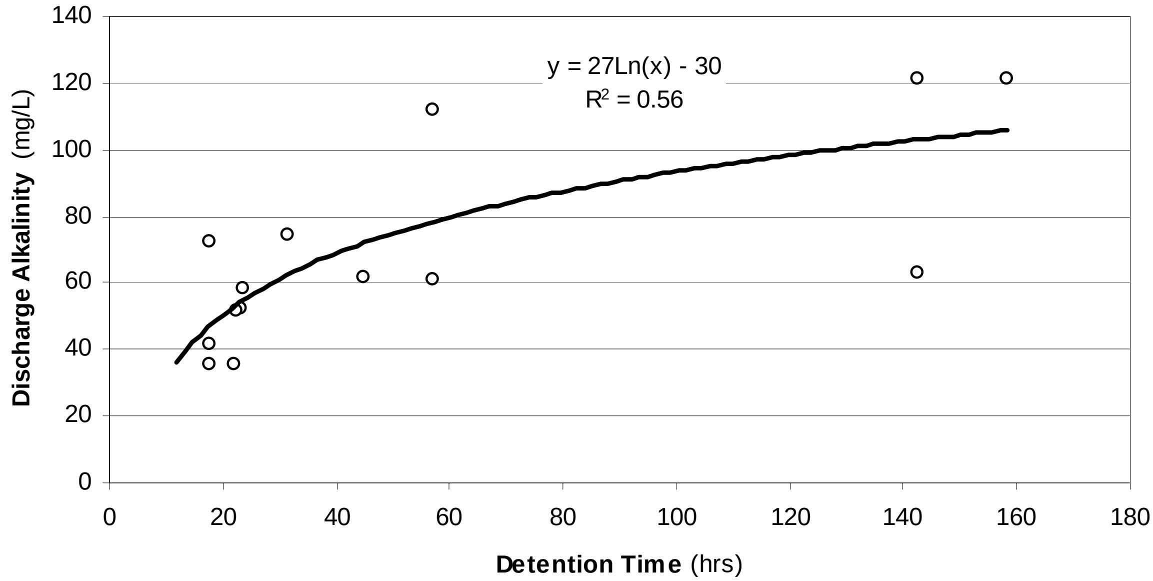
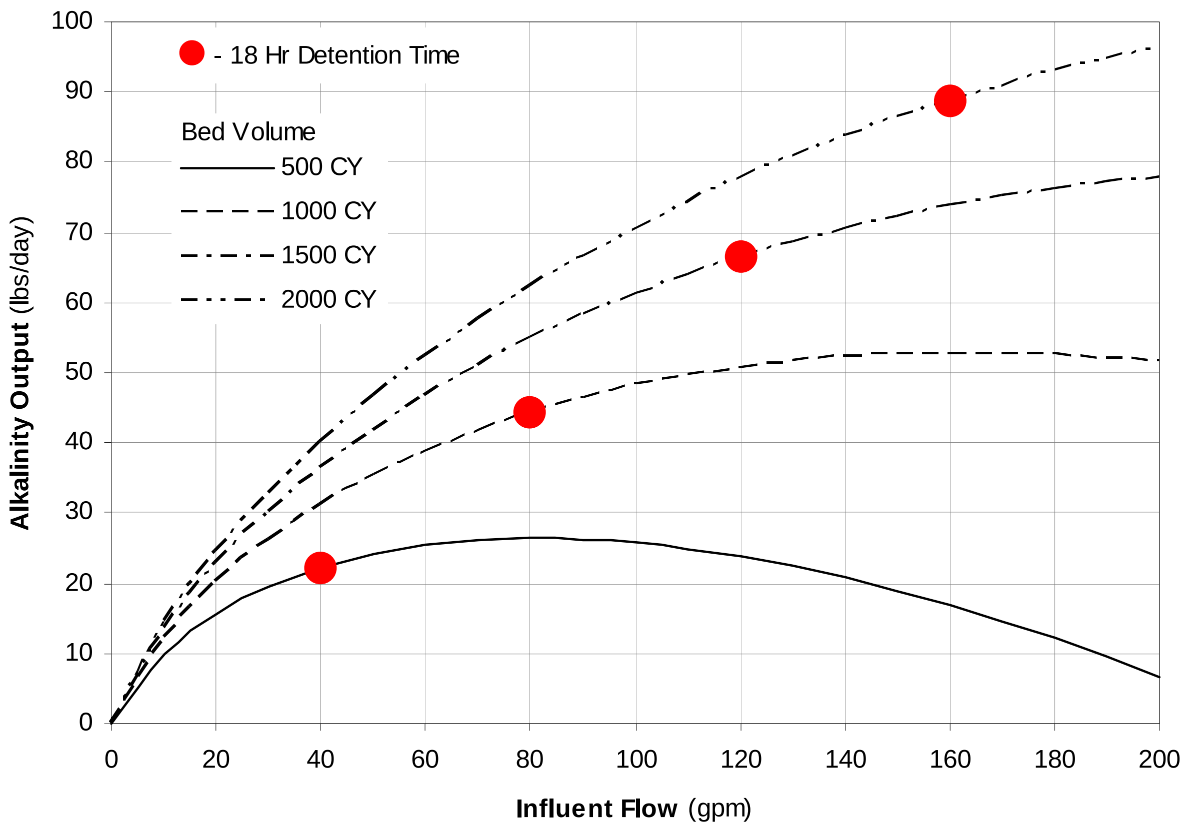



Figure 4-7: Relationship of Alkalinity Output, Influent Flow, and Bed Volume in VFWs



By this analysis, an 18 hour detention time appears to provide the most efficient alkalinity output rate for a VFW. Lesser detention times are not currently recommended because they are not documented by existing data, and are predicted to have diminishing and potentially negative returns. Figure 4-7 serves essentially as a nomogram to estimate the 18 hour detention limestone bed volume for a desired average alkalinity output rate, and for estimating the input flow volume required to achieve that rate. With limestone bed volumes of 1,060 CY each, the Duck Marsh and Pebble Run VFWs are appropriately sized for 18 hours detention at high flows of 80 gpm. Average output alkalinity for these systems at 80 gpm is about 48 lbs/day, correlating well with the Figure 4-7 prediction. Individual observations at 80 gpm, however, vary from 34 lbs/day to 70 lbs/day. Because of the potential for daily output variability, a design margin of error is advisable until more performance data become available.

Depending on access development and other site-specific project factors, a VFW with a similar size to the Duck Marsh or Pebble Run systems will currently cost about $200,000. This equates to a capital cost of about $4,000 per pound per day of alkalinity generation capacity. The actual longevity of VFWs in acid deposition settings is not yet known, but at the observed output rates, these systems each hypothetically contain over 100 years of consumable material. Assuming a more conservative operational life of 15 years without major maintenance, the $4,000 per pound per day capital cost equates to about $0.75 per pound of alkalinity output. The bed volume range shown on Figure 4-7 is probably the practical construction limit for VFWs. Systems smaller than 500 CY will have higher per-pound costs because of fixed construction costs, such as inlet structures, and those greater than 2,000 CY will occupy several acres and be more difficult to construct and maintain. For projects requiring greater alkalinity output, the required bed volume can be divided among multiple cells.

VFWs are fairly substantial earthwork structures and require an engineering design for stability and hydraulic sizing. The inlet and outfall structures will normally require stream encroachment permits, and earth disturbance and National Pollution Discharge Elimination System (NPDES) permits may also be required depending on the project size. For these reasons, VFW designs are usually contracted to a specialized design firm. Base costs for design and permitting will normally be about $35,000 per site.

In a variation of the VFW concept, two demonstrations of vertical flow limestone beds (VFLBs) were designed and permitted for Lost Run (Figure 4-8) and Deserter Run (Figure 4-9), to be funded for construction at a later date. VFLBs are simply VFWs without the compost bed. Although compost appears to be required to maintain alkalinity generation for AMD treatment, it may not be as necessary in “clean water” applications such as acid rain runoff. If results from these future projects are favorable, VFLBs may be used in place of VFWs for acid deposition, saving the costs of compost and outfall polishing wetlands.

Figure 4-8: Lost Run Vertical Flow Limestone Bed Construction Plan

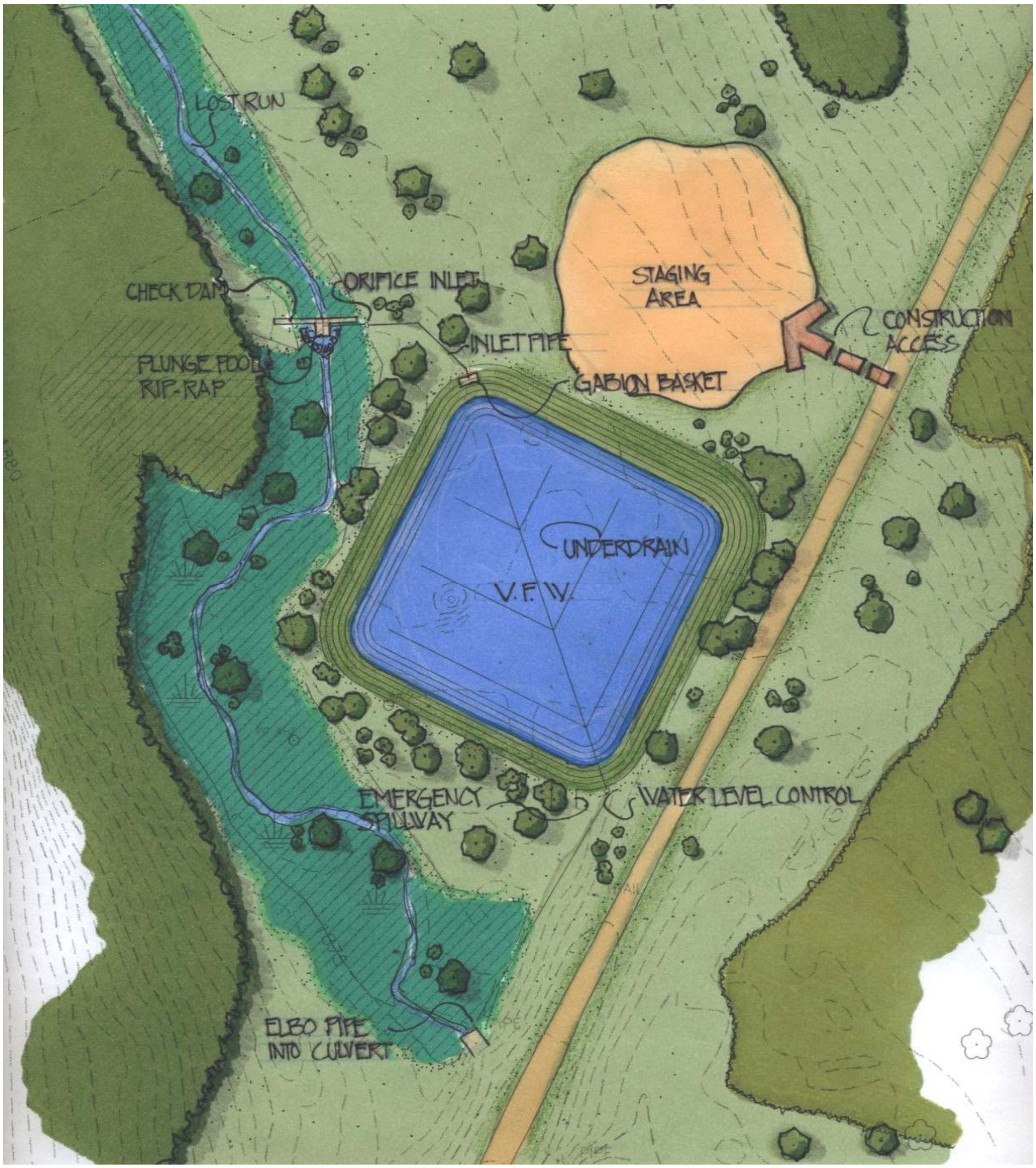
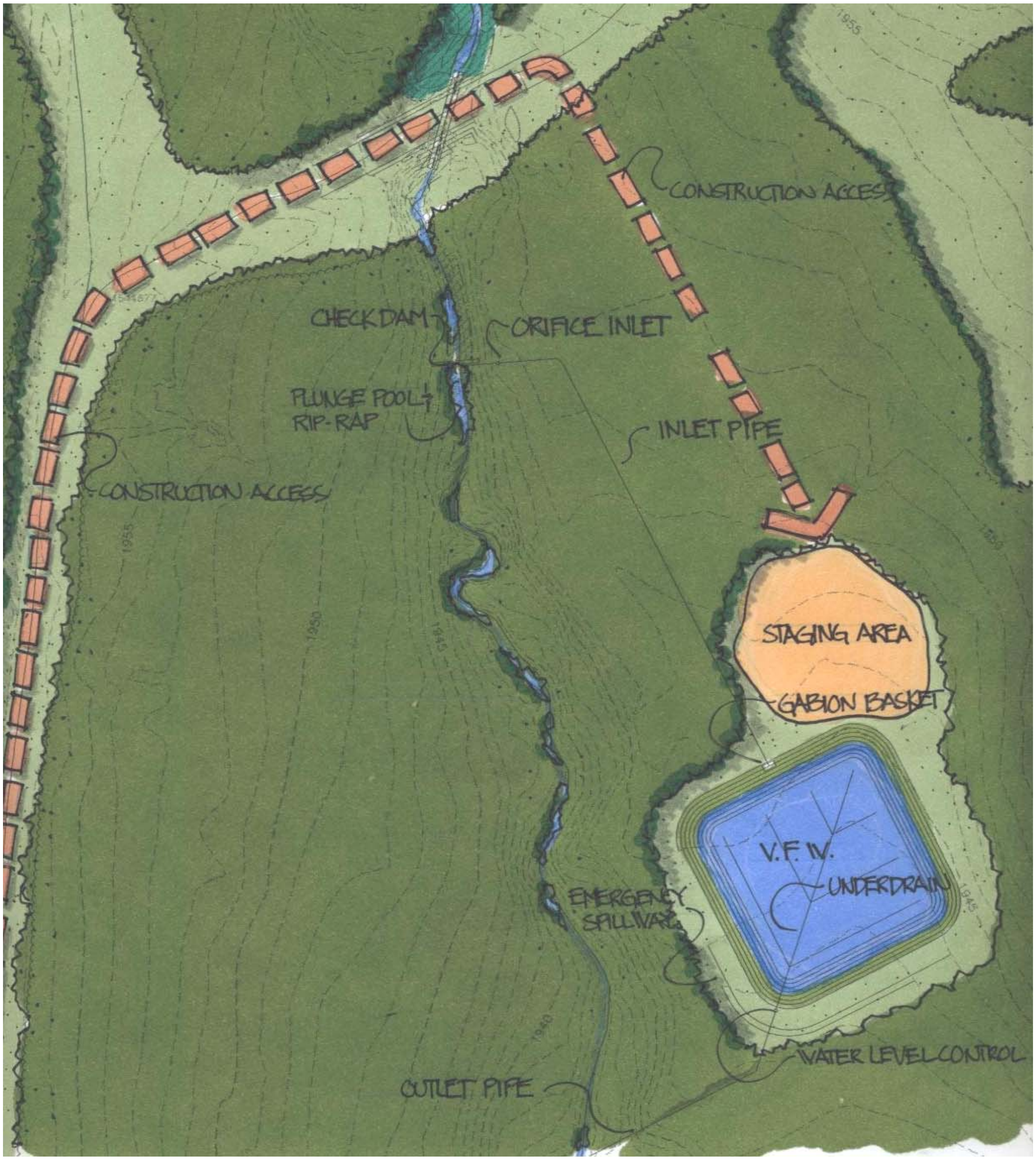


Figure 4-9: Deserter Run Vertical Flow Limestone Bed Construction Plan



## 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 to be effective over a broad range of flows because higher flows tend to mobilize the sand and increase its rate of dissolution by entrainment contact and surface abrasion. Figure 4-10 provides an example of a recent limestone sand dosing project on Gifford Run in the Mosquito Creek watershed.

Several generic formulae have been developed for determining the required limestone sand dosing rate for a given stream using the variables of watershed area and pH. Table 4-3 provides a summary of three published methods based on Schmidt & Sharpe (2002). Where used as a factor, pH is normally taken as the spring (high) flow measurement to represent worst-case conditions. For each of these methods, the annual application rate has been predicted for Gifford Run at M-20 and M-9 using the pre-addition high flow pH estimated in Section 3. Watershed areas upstream of these points are 7,134 acres and 9,850 acres, respectively. All three methods recommend doubling the predicted addition rate in the first year of treatment. The actual annual upstream addition rates and observed alkaline excesses for M-20 and M-9 are shown for comparison at the bottom of Table 4-3.

Figure 4-10 – Example of Limestone Sand Dosing – Merrill Road Bridge below M-14

An Empirical Method developed for this project is also presented in Table 4-3 based on ANC and flow, and assuming that direct pre-treatment stream measurement data are available. The alkaline addition requirement in this case is the difference between the average target restoration ANC and the existing average measured ANC, multiplied by the measured average flow and a conversion factor. For the Gifford Run example, the actual average ANC measurements for M-20 and M-9 are used as the target ANC, with the pre-addition ANC from Table 3-1 used as the assumed existing ANC. The Empirical Method is presumably not affected by regional rainfall variations because it uses measured flow instead of watershed area, and it also allows a scalability of restoration goals by changes to the target ANC value.

The results of existing limestone sand dosing in Gifford Run are an average ANC of 40 meq/L at M-20 and 80 meq/L at M-9. As indicated by the annualized alkalinity excesses in Table 4-3, these values equate to higher alkalinity exports than are explainable by limestone sand addition alone. It is speculated that some inherent alkalinity is present in the older bedrock units incised by Gifford Run in its lower reaches. As would be expected from the use of actual data, the Empirical Method best describes the alkaline export observed at M-20 and M-9. It is believed that if ANC data were available for the period prior to alkaline addition, this method would also best describe the actual limestone sand addition rates. In the absence of measured data, the Virginia Method appears to provide the most reasonable estimate of the minimum dosing requirements.

Table 4-3: Common Calculations for In-Stream Limestone Sand Dosing

| Method | Calculation | Addition Rates |
|---|---|---|
| West Virginia | Annual Application (tons/yr) = 0.05 x Watershed Area (acres) | 357 Tons – M-20<br>448 Tons – M-9 |
| Clayton | Annual Application (tons/yr) = 0.4 x Watershed Area (acres) x 10.3 $e^{-1.15pH}$ | 110 Tons – M-20<br>164 Tons – M-9 |
| Virginia (Downey) | Annual Application (tons/yr) = Watershed Area (acres) x [0.028 - 0.015 Ln(pH)] | 31 Tons – M-20<br>42 Tons – M-9 |
| Empirical | Annual Application (tons/yr) = 0.00012 x (Target ANC – Existing ANC) x Flow (gpm) | 53 Tons – M-20<br>122 Tons – M-9 |
| | Actual Annual Addition Rate by MCSA Upstream of Sample Point | 36 Tons – M-20<br>72 Tons – M-9 |
| | Annualized Alkaline Excess Observed at Sample Point | 43 Tons – M-20<br>105 Tons – M-9 |

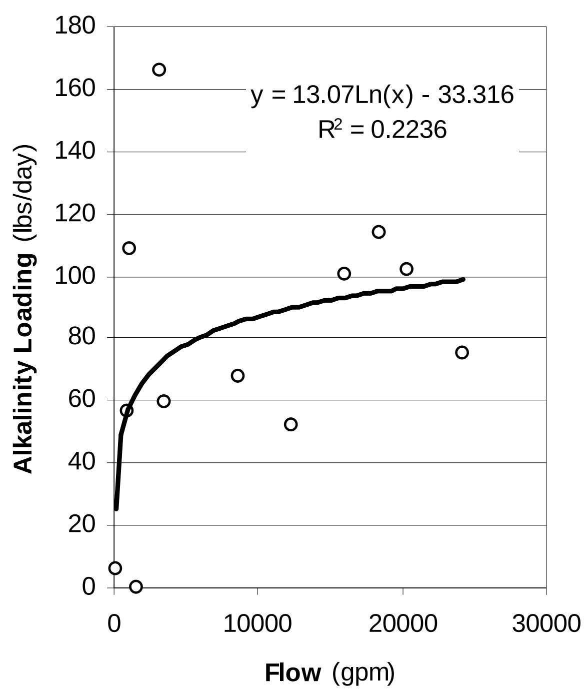
Figure 4-11 shows a comparison of alkalinity loading to flow for sample point M-20. As expected for a direct addition method, the alkalinity generated by limestone sand dosing is rather poorly correlated to flow. However, there is sufficient consistency to the trend to indicate that alkalinity export increases at higher flows. This analysis suggests that limestone sand dosing is capable of providing a measure of protection during high flow acidification events, but that it would be prudent to err on the high side of dosing requirements to assure desired results during these events.

Limestone sand dosing is best suited to small to moderately-sized streams with low to moderate acidification impacts. A sufficient flow velocity is required to cause migration and abrasion of the sand under average and higher flow conditions (a minimum thalwag velocity of 2 ft/s is recommended under average conditions). Dosing requires a dumping access point, such as a bridge abutment, but no other appreciable capital investment. Depending on 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 (about 1/8' to 3/8" dia.) which was available for this project at about $20 per ton delivered. On an annualized basis, this equates to about $0.01 per pound of alkaline addition.

There are concerns that long-term sand dosing can degrade streambeds by clogging cobble bottoms with the finer-grained sand, reducing the quality of habitat for benthic macroinvertebrates. A buildup of aluminum precipitates has also been noted downstream of dosing sites in some cases, where increased pH renders aluminum less mobile in solution. During high flow events, reduced pH can re-dissolve these deposits, potentially causing aluminum concentrations locally in excess of those existing prior to treatment. As discussed later in this section, HFBCs were developed as "off-line" addition methods using limestone sand outside of the natural stream channel, potentially limiting these types of impacts.

Because limestone sand dosing involves placement of material within a stream channel, this activity may be regulated by state and federal agencies. The MCSA receives authorization for their dosing program through the Pennsylvania Fish & Boat Commission.

Figure 4-11: Alkalinity Loading vs. Flow at M-20



## LAKE LIMING

Lake liming and other forms of riparian lime addition 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 on open water bodies, creating a large reservoir of alkaline water that is progressively flushed out to neutralize downstream reaches. Figure 4-12 shows an aerial liming operation on the headwaters lake on Beaver Run that was conducted as a cooperative research project between the MCSA and the PA DCNR Bureau of Forestry, Moshannon State Forest. An example study plan for this type of work is included for reference as Appendix B.

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 or 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. The rule-of-thumb approach is to start with 2 tons of limestone per acre. This rate was used for the Beaver Run lake, with 50 tons of lime spread over the 25 acre impoundment in early May 2004.

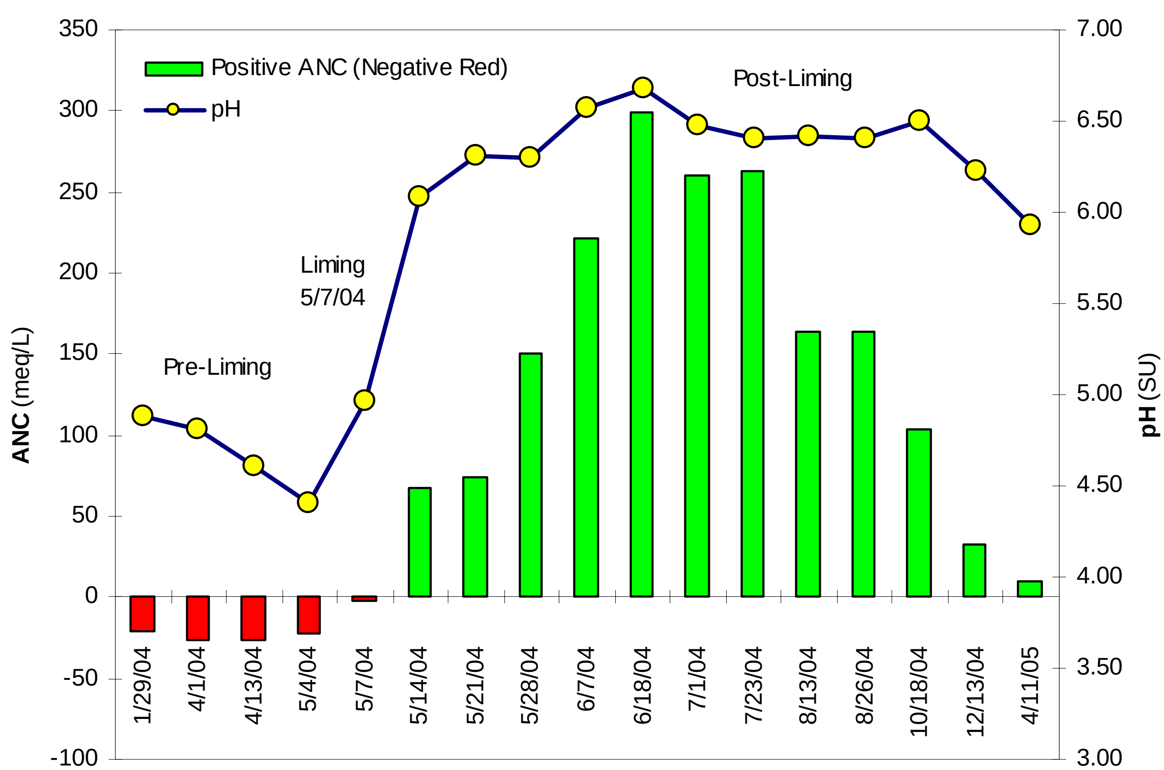
As shown by Figure 4-13, alkaline conditions were maintained at the lake discharge (sample point BRP-1) for approximately one year, and the effect would likely have been longer if not for several excessively large storm events during this period. Beaver Run was sampled downstream at M-18 approximately five months after lake liming. The pre-addition ANC for the measured flow on that date is predicted to be about -41 meq/L, while the actual sampled ANC was -17 meq/L, an increase of nearly 60% and the highest ANC recorded to date for the stream.

Aerial liming requires a specially equipped airplane or helicopter, but can reach water bodies that are otherwise inaccessible by land. 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. At 2 tons/acre, this equates to about $0.30 per pound of alkaline addition.

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 overall application cost equals about $0.10 per pound of alkaline addition.

Figure 4-12: Example of Aerial Lake Liming – Beaver Run Lake

Figure 4-13: Water Quality Results at Beaver Run Lake Discharge (BRP-1)



## HIGH FLOW BUFFER CHANNELS

HFBCs are an innovative concept intended to address two concerns involved with in-stream limestone sand dosing: the placing of fine materials in natural stream channels, and the wasting of limestone by dissolution during low flow periods in episodically acidified streams. The concept is to create a “stream beside a stream” in which limestone sand can be placed and retained in a controlled flow regime outside of the natural channel.

An in-stream structure, such as a cross vane, is designed to direct a portion of high flow events into the HFBC. A smaller portion diffuses into the HFBC through inlet rocks during low flow events 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 at the end of the HFBC traps the undissolved 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 were designed and permitted for Gifford Run at the Lost Run Road bridge (Figure 4-14) and the Merrill Road bridge (Figure 4-15). The Lost Run Road HFBC was funded under a Round 7 Grant, with construction expected to begin in 2007. Pending performance results from the systems after construction, the current design approach for HFBCs is to size the inlet structure to begin diversion at or below the predicted neutrality threshold flow for negative ANC. As flows increase, a progressively greater percentage of the total flow passes through the HFBC for return to neutralize the main stream flow. For the Lost Run Road HFBC, the diversion level was predicted to correspond to near bank full flow. The HFBC sizing requirement is established through channel hydraulics based on the maximum intended diversion flow. A construction site is necessary on a floodplain or other low-lying area capable of receiving flows diverted from a stream.

With future construction of VFLBs on Lost Run and Deserter Run, and other conceptual projects in the headwaters, it is anticipated that the Gifford Run HFBCs will allow eventual discontinuation of sand dosing in the stream. Implementation costs for the two HFBCs are estimated at about $90,000 per unit, with annual maintenance costs being equivalent to that of limestone sand dosing thereafter. The per-pound cost of alkalinity generation will be determined by future monitoring of the constructed projects.

Figure 4-14: High Flow Buffer Channel Construction Plan – Lost Run Road

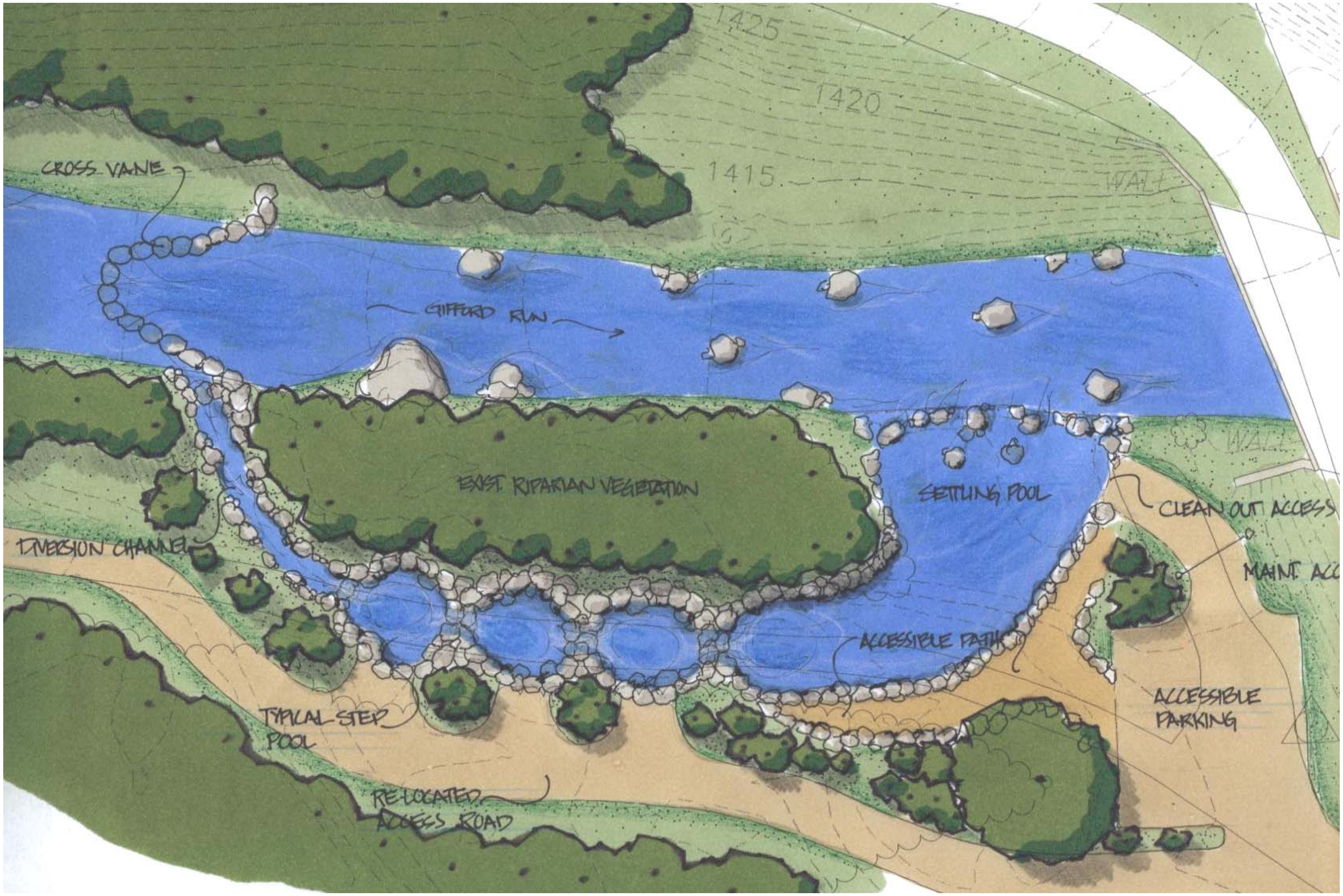
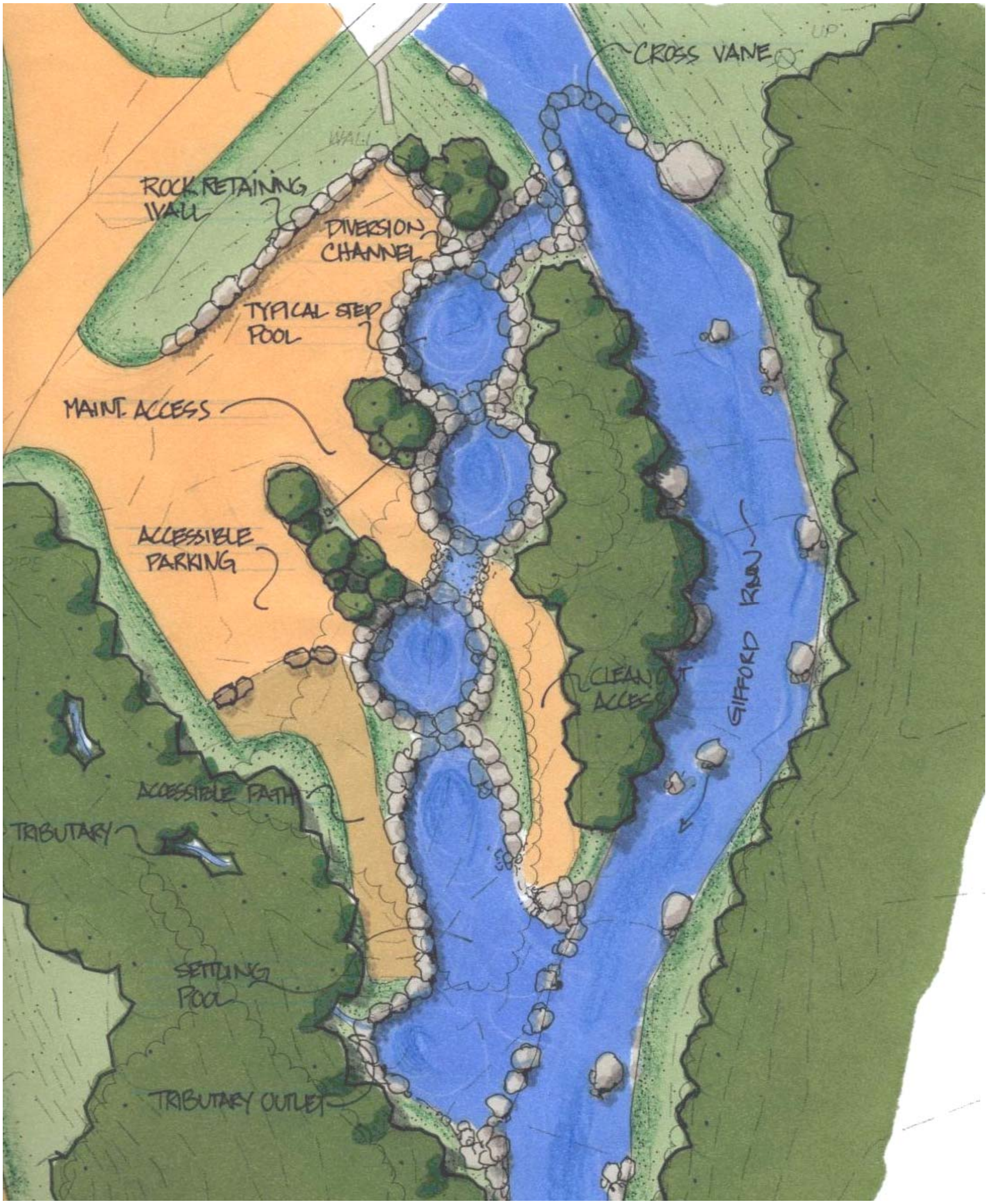


Figure 4-15: High Flow Buffer Channel Construction Plan – Merrill Road



## LIMESTONE ROAD ADDITION

Use of limestone for unpaved road surfacing and runoff ditch stabilization may provide an alkaline benefit to acidified watersheds during precipitation events. Vehicle travel and grading operations on such roads provide abrasive action to keep the reactive surfaces of the limestone particles fresh, and during drier periods the limestone dust can also 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 runoff volume. While studies to document this effect are in the early stages, preliminary observations indicate that this could be a worthwhile practice to pursue, especially in cases where surfacing and stabilization are required in any case.

Over the course of the Mosquito Creek projects, a number of field measurements were taken during storm events along limestone-lined forest roads already maintained by the Moshannon State Forest and Pennsylvania Game Commission. The cumulative field observation was that overland flows from untreated forest areas would gain about one full unit of pH on contact with limestone-surfaced roads and ditches. This ANC generation could make the difference between episodic and sustainable conditions for a receiving stream with a significant watershed portion affected by roads.

As a cooperative research project between the Moshannon State Forest and the MCSA, an alkaline road runoff channel (ARRC) was constructed along Lost Run Road on its descent into the Mosquito Creek valley below Meeker Run. As shown by Figures 4-16 and 4-17, the ARRC consisted of a bed of coarse limestone riprap, with the interstitial voids filled with limestone sand. The slope of the channel was sufficient that limestone sand alone would have been inadequate for stabilization; however, the R-4 riprap core prevents erosion while allowing sand transport to generate alkalinity. This work was conducted using residual construction funds from the Phase 3 VFW projects.

Figure 4-16: Typical ARRC Section

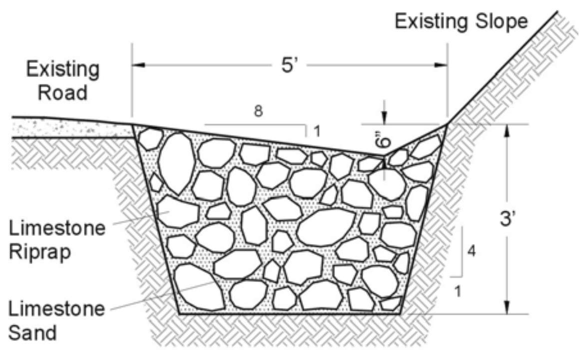



Figure 4-17: Finished ARRC

The total limestone quantities emplaced for the ARRC were 500 tons of R-4 riprap and 150 tons of No. 10 sand, with an additional 450 tons of 2RC crushed limestone for surfacing of the adjacent road. The Moshannon State Forest provided in-kind labor for the construction, which totaled about $15,000 for materials. Assuming that about one quarter of this limestone will eventually contribute to alkalinity generation, the cost for this type of ARRC with normal equipment and labor rates would be approximately $0.05 per pound of alkalinity output.

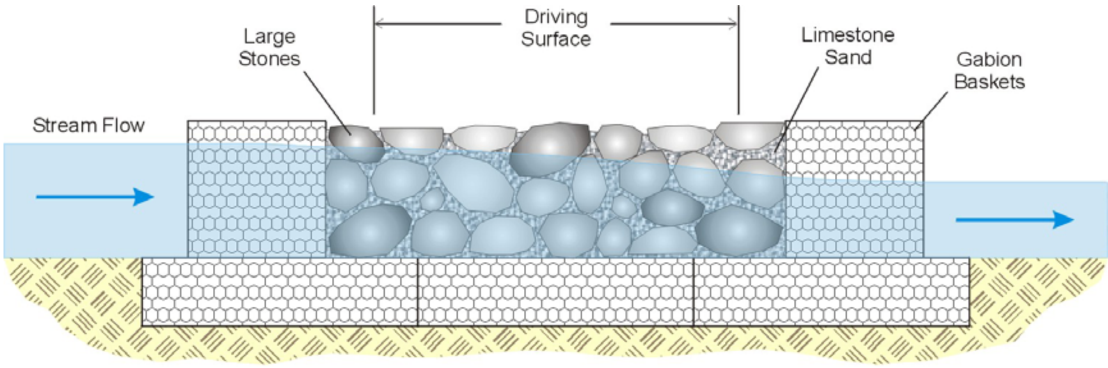
Measurement of the results from the ARRC proved difficult because of the necessity to have a sampler on site in the period after a storm event during which the channel would flow. This sampling was only achieved on April 1st, 2004, with the results included in Appendix A as sample point ARRC-1. As this sample shows, the ARRC had a discharge alkalinity of 19.8 mg/L and ANC of 459 meq/L, with a pH of 7.63 SU.

Costs of other types of limestone road surfacing depend greatly on the nature of the road, including width, thickness of cover, and coarseness of the aggregate applied. Basic crushed 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.

A variation on limestone road surfacing is to use limestone in construction of in-stream road structures. To demonstrate this concept, the Pennsylvania Game Commission designed a limestone sand dosing ford for the crossing of Ardell Dam Road on Mosquito Creek. The basic design, shown by Figure 4-18, was to enclose coarse limestone riprap between two gabion retaining walls, then pour limestone sand into the riprap void spaces. The sand would be in contact with water flowing through the structure, and some of it would presumably be flushed out during high flow events in a dosing action. More sand could be added as needed by a dump truck crossing the ford.

The ford (Figure 4-19) was constructed in 2001 concurrent with the Ardell tributary VFW system. Subsequent monitoring proved inconclusive as to what influence the ford has on alkalinity in the stream, largely because the effects are masked by the greater upstream alkalinity input of the VFW at Ardell and later from the Duck Marshes. It was observed that the ford was subject to high flow overtopping that quickly depleted the sand. An algal growth also soon formed on the upstream side, limiting flow-through in the structure. Algae extend downstream as well, suggesting that this is a result of a more alkaline microenvironment around the ford. Despite these problems, the ford was an inexpensive crossing solution for this setting compared to a bridge, with a construction cost of about $20,000. Application of similar structures may be of more benefit on smaller, higher gradient streams where currents can better scour algal growths.

Figure 4-18: Construction Plan for a Limestone Sand Dosing Ford




Cross-Section Parallel to Stream Flow

Figure 4-19: Completed Dosing Ford at Ardell Dam Road on Mosquito Creek

## FOREST LIMING

Liming of forest floors and other catchment areas has been used as an alkaline addition strategy in the Scandinavian countries for many years. The concept is to both neutralize acid deposition in the runoff stage and to restore acidified soils in the hydrologic source areas. Although the effects may not be immediately observed in receiving streams, forest liming can produce long-term improvements lasting for decades.

There are as yet no established criteria for land application liming rates to treat acid deposition, although the 2 tons per acre rule-of-thumb is generally used as a starting point. 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 by 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. Scrubland and forests require more specialized equipment to navigate between obstacles. The type of lime product applied depends on the nature of the spreading equipment used. Pelletized lime is available for about $25 per ton, and agricultural limestone can be obtained for about $30 per ton.

In 2003, PSU conducted forest surface liming in the headwaters of two unnamed tributaries to Gifford Run in the vicinity of Merrill Road (samples LRL and 90 on Figure 4-20), with two adjacent tributaries serving as untreated controls (samples Tick and MRL). AASHTO No. 10 dolomitic lime sand was applied at a rate of 2 tons per acre on one-half of one subwatershed and three-quarters of the other test area. Water quality and aquatic habitat monitoring were then conducted in 2004 and 2005 at downstream points on the treated and control tributaries.

As expected, little effect on water quality in the receiving streams was observed for the liming operation in the relatively short period since application. The downstream pH increased in both years, and the ANC increased in 2005, although flows were lower in 2005 and could have affected the results. The abundance of more acid-sensitive *Ephemeroptera* increased in the treated streams in 2005, but no change in overall macroinvertebrate diversity was discernable, possibly due to slow recolonization rates. It is anticipated, however, that long-term improvements will occur and supplement other alkaline addition efforts on Gifford Run.

Figure 4-20: PSU Forest Liming Project Locations and Controls

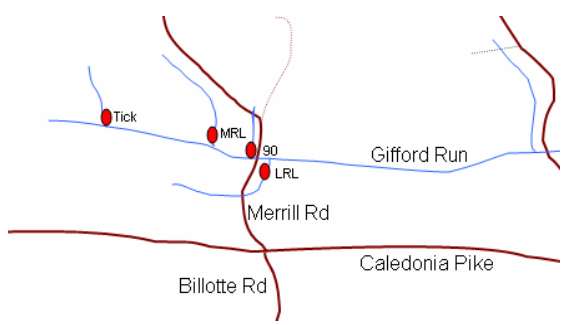



Figure by PSU

For their forest liming projects, PSU purchased and outfitted a log skidder with a liming hopper, the “Regenerator” shown by Figure 4-21. 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 amounts to cost on the order of $150 for 2 tons per acre of application, or about $0.05 per pound of potential alkalinity. The “Regenerator” is currently a unique piece of equipment, and has been used for other restoration projects in the central Pennsylvania region. For more information on using the “Regenerator,” the reader is referred to contact Dr. William Sharpe at the Penn State Institutes of the Environment at University Park, PA.

Problems with forest liming include difficulty of application in wooded areas, slow dissolution of applied material under the forest canopy, and potentially long periods until effects appear in receiving streams. It has also been noted that liming may have adverse effects on existing plant communities adapted to acidic conditions, especially bryophytes and lichens.

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 4-21: The Penn State “Regenerator”

# OTHER ALKALINE ADDITION TECHNOLOGIES

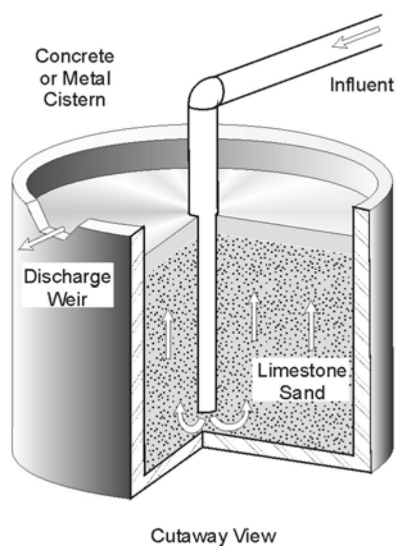
There are numerous alkaline addition technologies and variations that have been applied to acid deposition, and it was not possible to test and assess all these technologies within the Mosquito Creek watershed. However, three of these other technologies have been successfully applied in the past and are worth consideration: limestone diversion wells, limestone rotary drums and basket wheels, and pebble quicklime addition.

## LIMESTONE DIVERSION WELLS

Limestone diversion wells originated in Norway and Sweden as methods for treating acid deposition, and they were adopted for mine drainage treatment in the United States during the 1990s. As shown by Figure 4-22, a diversion well 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").

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 alkalinity 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 or mildly episodic streams where an unspecified alkaline addition would be beneficial.

Figure 4-22 Typical Diversion Well



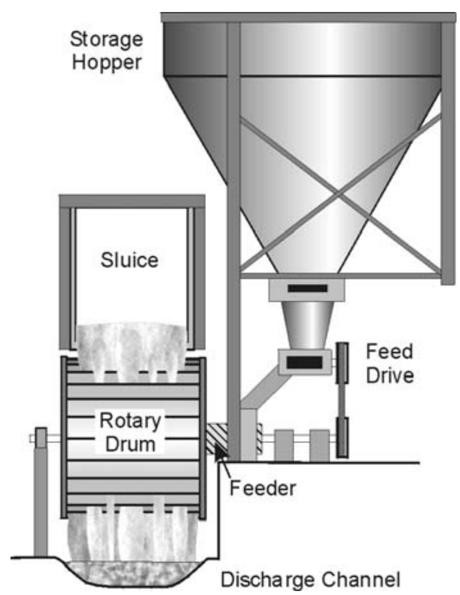

Diversion wells also require frequent replenishment of limestone lost to dissolution and washout, sometimes on a weekly basis. One project on Swatara Creek in Pennsylvania reported two diversion wells consuming approximately one ton of limestone per week, although the flow and influent acidity loading 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.

## ROTARY DRUMS & BASKET WHEELS

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 4-23). 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 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 4-23 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.

## PEBBLE QUICKLIME ADDITION

In recent years, an effective alkaline addition system has been developed using pelletized pebble quicklime (CaO), which has approximately twice the alkalinity generation rate per pound as limestone. 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 4-24 provides a schematic of the Aquafix mechanism.

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.

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.

Figure 4-24: Aquafix Pebble Quicklime Unit


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 very little 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.

Pebble quicklime 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). A 25 ton silo system (Figure 4-25) costs about $100,000 to construct, while a hopper system (Figure 4-26) up to 1 ton capacity is about $20,000. Over a 15-year operational life, these equate to a range of about $0.05 to $0.10 per pound of alkalinity generated, respectively.

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, and professional assistance is recommended. 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.

Figure 4-25: Silo-Type Aquafix Unit

Figure 4-26: Hopper-Type Aquafix System

# 5

# ECONOMIC ANALYSIS

Assigning a dollar value on stream restoration can be complicated. At the low end of the scale, it might be argued that the value equates to the direct expenditures by new recreational users visiting the community. At the high end is a collection of intangible assets that community members are willing to pay through a combination of taxes, donations, and volunteer efforts to maintain the perceived benefits of a healthy stream. Somewhere in this range is a point of reasonable expectation of returns on restoration investments.

Since 2000, the Growing Greener program has invested about $1 million in the Mosquito Creek watershed. In addition to local stream improvements, this work has led to the development of assessment methods and alkaline addition technology design standards that can benefit the remainder of Mosquito Creek and other Pennsylvania watersheds impacted by acid deposition. Standardized assessment and design approaches represent a further return on investment beyond the local community.

This section presents an estimate of the costs and benefits anticipated for the existing alkaline addition projects and future efforts specific to Mosquito Creek as part of a progressive restoration plan for the full watershed. The valuation approach is to provide a comparison of predicted implementation and maintenance costs to a range of anticipated returns based on estimated direct recreational benefits and community willingness to pay. Dollar values are given at approximately the 2000 level to correspond to the beginning of the Grant work.

## WILLINGNESS-TO-PAY ANALYSIS

One approach for quantifying stream restoration values is the willingness-to-pay (WTP) analysis. As the name implies, this is measure of the willingness of individuals or groups to pay for a perceived benefit, such as having fishable streams in close proximity to home. A WTP survey is conducted by presenting participants with choice sets of alternatives, such as water quality level (boatable, fishable, drinkable, etc.), travel time, and extent of restoration, along with a choice of acceptable costs for these attributes. A statistical reduction then estimates the typical willingness-to-pay for specific sets of conditions.

In 2000, a WTP survey was conducted for Clearfield Creek as part of a study to determine the socioeconomic value of restoring streams impacted by acid mine drainage in rural Pennsylvania (see Brooks et al., 2001 for detailed documentation of this study). The survey consisted of questionnaires mailed to 387 random residential households in Clearfield County (64% return). Analyses included annual WTP per household based on travel time from home to a restored stream (fishable or drinkable conditions) and total length of restored stream. The relationship developed for these factors is given by Equation 5-1:

Eq. 5-1:

$$\text{Annual Household WTP} = \$41.65 + \$2.24 \times \text{Miles Restored} - \$1.92 \times \text{Travel Time (min.)}$$

The 2000 study included a second WTP survey for the Broadtop area of south-central Pennsylvania that produced comparable values for fishable restoration. Both surveys fall within the general WTP ranges reported by similar studies elsewhere in the Appalachian region. It is assumed that the WTP value of restoration on Mosquito Creek is at least equal to that of Clearfield Creek given the greater percentage of accessible public lands and absence of mining impacts, and that Equation 5-1 will also yield meaningful values for that watershed.

To estimate potential WTP values specific to Mosquito Creek, it is first necessary to determine the number of households within a reasonable travel time from the watershed. Figure 5-1 shows approximate travel time from home envelopes of 5, 10, 20, and 30 minutes around the study area assuming an average speed of about 45 miles per hour (a range of 3.75 to 22.5 miles). The outer envelope includes large portions of Cameron, Centre, Clearfield, Clinton, and Elk Counties, and small portions of Jefferson and Potter Counties.

Figure 5-1: Approximate Time from Home to Mosquito Creek Watershed

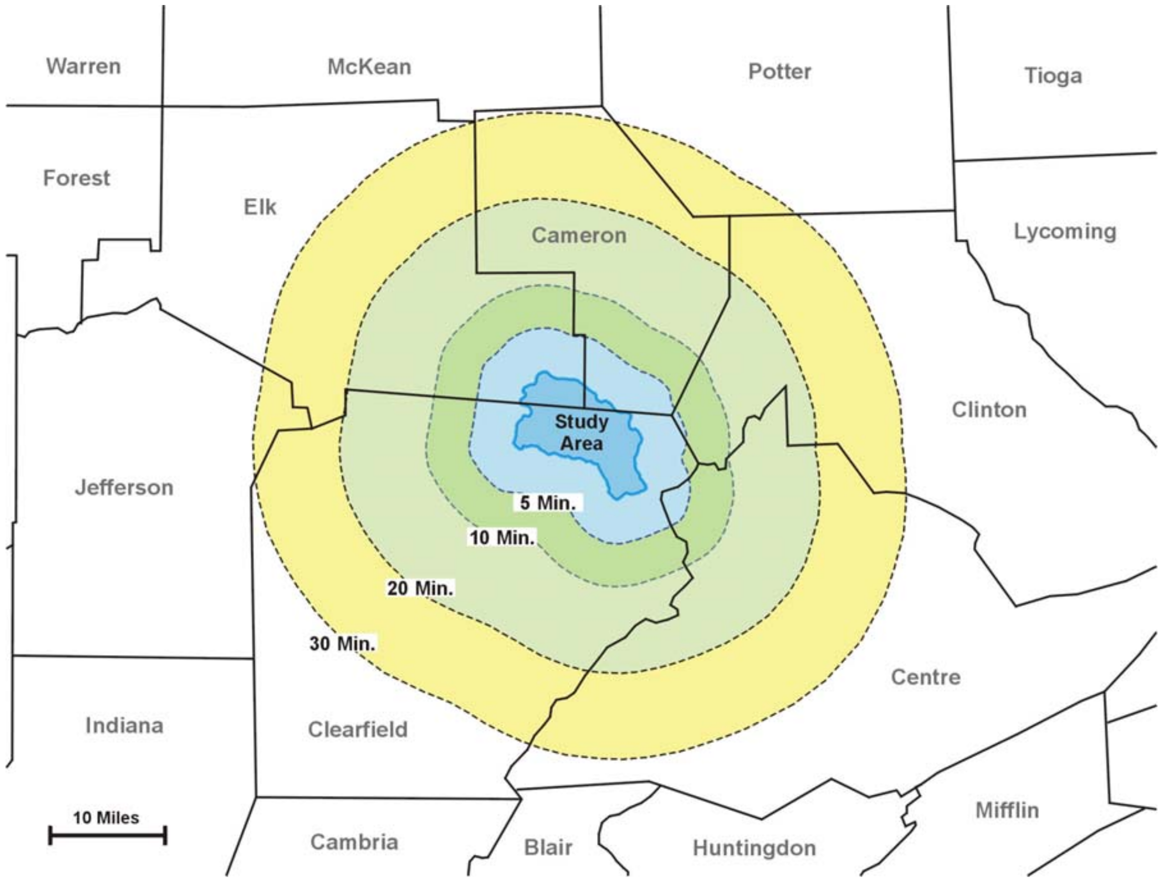



Table 5-1 provides a summary of estimated numbers of households per county by travel time from home. Household densities are based on the 2000 Census, with travel time areas determined from mapping overlays. The total estimate is that over 70,000 households are present within a 30 minute drive of Mosquito Creek, with the greatest number of affected residents located in Clearfield and Centre Counties.

In Table 5-2, Equation 5-1 has been applied to predict annual household WTP values for the time from home categories and for stream restoration lengths of 1, 5, 10, and 20 miles. The numbers of households from Table 5-1 have then been multiplied by the WTP values in each category to arrive at an aggregate value representing the community willingness to pay for different lengths of stream restoration. For example, it is estimated that the surrounding communities would be willing to support about $900,000 per year to restore and maintain 5 miles of fishable streams in the Mosquito Creek watershed. The influence of distance on WTP is also apparent in Table 5-2, with households more than 20 minutes away not predicted to perceive benefit from restoration projects of less than 20 miles in length.

Table 5-1: Estimated Households in the Vicinity of Mosquito Creek

| County | Household Density (#/mi2) | Area (mi2) | Time from Home (minutes) | | | |
|---|---|---|---|---|---|---|
| | | | 5 | 10 | 20 | 30 |
| Cameron | 11.6 | 399 | ($33\ mi^2$) 380 | ($45\ mi^2$) 521 | ($159\ mi^2$) 1,844 | ($162\ mi^2$) 1,878 |
| Centre | 48.0 | 1,112 | ($6\ mi^2$) 307 | ($29\ mi^2$) 1406 | ($178\ mi^2$) 8,534 | ($294\ mi^2$) 14,112 |
| Clearfield | 33.0 | 1,154 | ($164\ mi^2$) 5,412 | ($112\ mi^2$) 3,683 | ($265\ mi^2$) 8,758 | ($266\ mi^2$) 8,785 |
| Clinton | 20.4 | 898 | 0 | ($29\ mi^2$) 581 | ($82\ mi^2$) 1,665 | ($183\ mi^2$) 3,731 |
| Elk | 21.9 | 832 | ($52\ mi^2$) 1,143 | ($56\ mi^2$) 1,229 | ($123\ mi^2$) 2,683 | ($204\ mi^2$) 4,457 |
| Jefferson | 33.7 | 657 | 0 | 0 | 0 | ($22\ mi^2$) 741 |
| Potter | 11.2 | 1,081 | 0 | 0 | 0 | ($49\ mi^2$) 547 |
| **Total Households by Category:** | | | **7,243** | **7,420** | **23,484** | **34,250** |

Table 5-2: Estimated Willingness-to-Pay for Mosquito Creek Restoration

| Miles Restored | Time from Home (minutes) | | | | Total Annual Value |
|---|---|---|---|---|---|
| | 5 | 10 | 20 | 30 | |
| #Households | 7,243 | 7,420 | 23,484 | 34,250 | 2000 Dollars |
| 1 | ($34.29) $248,358 | ($24.69) $183,201 | ($5.49) $128,929 | 0 | $560,488 |
| 5 | ($43.25) $313,254 | ($33.65) $249,684 | ($14.45) $339,349 | 0 | $902,287 |
| 10 | ($54.45) $394,374 | ($44.85) $332,788 | ($25.65) $602,375 | 0 | $1,329,537 |
| 20 | ($76.85) $556,614 | ($67.25) $498,997 | ($48.05) $1,128,425 | ($28.85) $988,124 | $3,172,160 |

($X.XX) – WTP Value per Household per Year

$XXX,XXX – Annual Value for Distance Category

# BENEFIT/COST ANALYSIS

Full remediation of acid deposition impacts to Mosquito Creek will require a prolonged effort and significant funding. Because acidification impacts are cumulative moving downstream through the watershed, it may be necessary add alkalinity in headwaters reaches for some time before significant benefits are observed in the main stem, or until improvements are sufficient to make direct treatment of the main stem economically feasible. On Figure 5-2, this progressive restoration plan has been broken down into four implementation phases that produce mutually supportive alkaline addition and cumulative, contiguous improvements.

Tables 5-3 through 5-6 provide a benefit/cost analysis of the progressive restoration plan, with the predicted direct stream restoration lengths for each project, and the cumulative restoration lengths produced by mutually supportive alkaline addition. Implementation costs have been estimated primarily assuming the use of VFWs because their construction costs and alkalinity output can be predicted reasonably well. The number of required units is based on the alkaline deficiencies determined in Section 3, with a single VFW assumed to generate about 9 tons of alkalinity per year. Project costs have been annualized over a 15-year period to equal the typical anticipated operational life of a VFW before major maintenance.

Cumulative costs are provided for each phase and on an annual basis per stream mile restored. For the later phases in Tables 5-5 and 5-6, the costs of previous upstream alkaline addition are included in the totals assuming that main stem improvements will result from these additions. The cumulative restoration mileage totals include the main stem reach improvements anticipated to result from each project based on this assumption.

Annual public benefits resulting from stream restoration have been assessed using two comparative estimates. In 1995, the Pennsylvania Fish & Boat Commission valued the losses to recreational fishing on wild trout streams from acid mine drainage impacts at $23,400 per mile per year (about $28,000 in 2000 dollars). Although an average figure, this is probably a reasonable value for acid deposition impacts to Mosquito Creek given its overall amenities versus its remoteness. As a direct loss value for the community, this is assumed to be the minimum justifiable restoration benefit. The results from the 2000 WTP survey by PSU are the assumed maximum value to the community in terms of what local residents would be willing to pay out of pocket for restoration. The following provides summaries of each phase and a comparison of the projected costs to this range.

Figure 5-2: Existing, Designed, and Conceptual Locations of Progressive Restoration Plan Projects

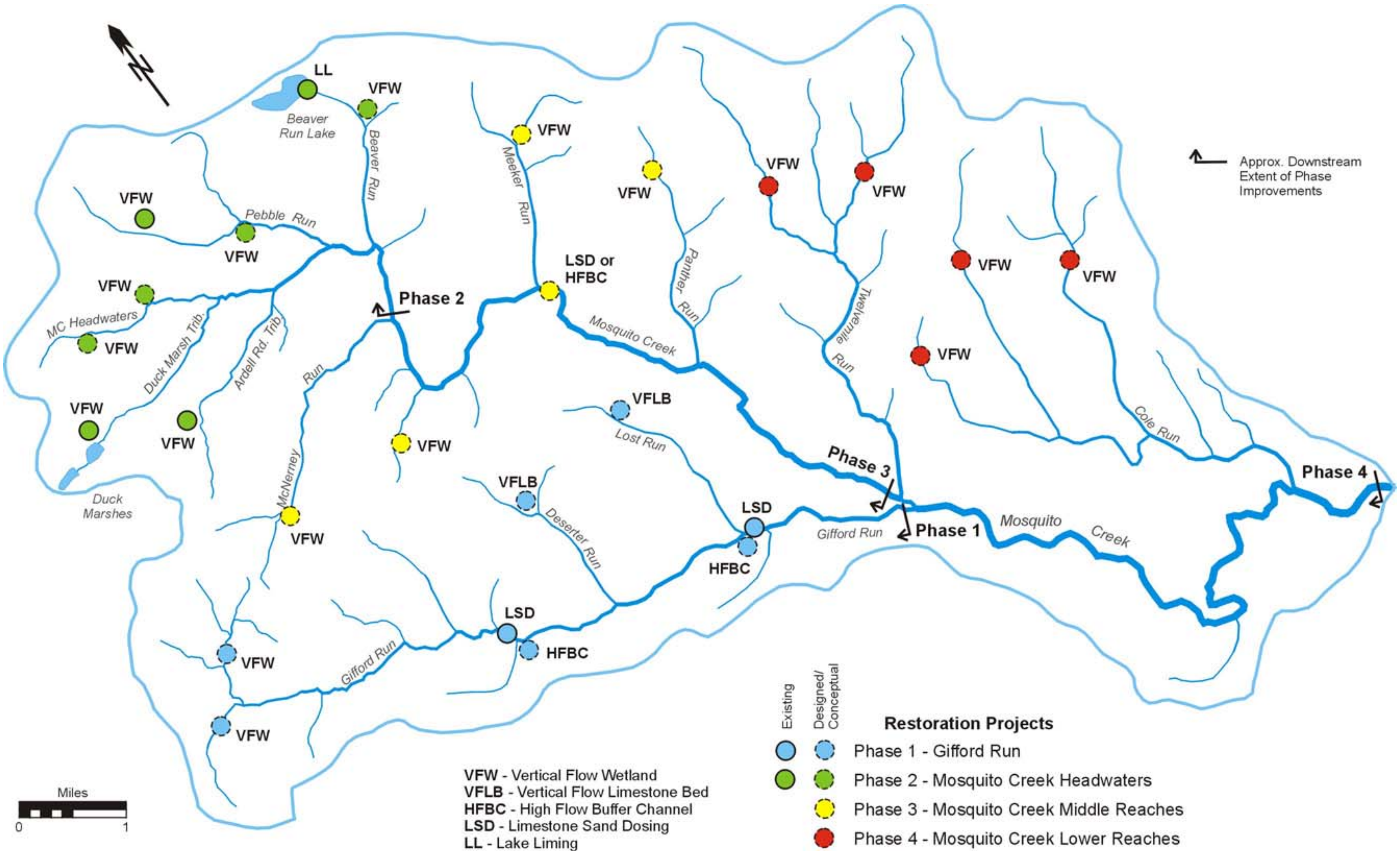


Table 5-3: Phase 1 Restoration Benefit/Cost Analysis, Gifford Run

| Projects | Stream Miles Restored | | Project Costs | | 15-Year Annualized Costs | | | Annual Public Benefit | |
|---|---|---|---|---|---|---|---|---|---|
| | Direct | Cumulative | Capital Construct. | Annual O&M | Project | Cumulative | Proj. $/Mile | Recreation Use | Willingness to Pay |
| *Existing Projects* | | | | | | | | | |
| Limestone Sand Dosing<br>Sand dosing at Lost Run Road and Merrill Road bridges, restoration extending to Mosquito Creek | 4.5 | 4.5 | $0 | $3,000 | $3,000 | $3,000 | $700 | $130,000 | $860,000 |
| | | Existing Totals: | $0 | $3,000 | | | | | |
| | | 15-Year Existing Total Cost: | | $45,000 | | | | Minimum | Maximum |
| | | **15-Year Annualized Existing Cost:** | | **$3,000** | | | **Annual Benefit Return Range:** | **$130,000** | **$860,000** |
| *Designed/Conceptual Projects* | | | | | | | | | |
| Lost Run HFBC<br>Replaces limestone sand dosing at Lost Run Road Bridge downstream to Mosquito Creek | 1.8 | 1.8 | $90,000 | $3,000 | $9,000 | $9,000 | $5,000 | $50,000 | $630,000 |
| Merrill Road HFBC<br>Replaces limestone sand dosing at Merrill Road Bridge downstream to Lost Run | 2.7 | 4.5 | $90,000 | $3,000 | $9,000 | $18,000 | $3,300 | $130,000 | $860,000 |
| Lost Run VFLB<br>Restores Lost Run downstream from power line, adds to cumulative alkalinity at M-9 | 1.8 | 6.3 | $175,000 | $0 | $11,667 | $29,667 | $6,500 | $180,000 | $1,010,000 |
| Deserter Run VFLB<br>Restores main trunk of Deserter Run, adds to cumulative alkalinity at M-20 | 1.6 | 7.9 | $175,000 | $0 | $11,667 | $41,333 | $7,300 | $220,000 | $1,150,000 |
| Two Headwaters VFWs<br>Restores remainder of Gifford Run main trunk, may be augmented by additional forest liming in headwaters | 2.8 | 10.7 | $400,000 | $0 | $26,667 | $68,000 | $9,500 | $300,000 | $1,390,000 |
| | | Phase Totals: | $930,000 | $6,000 | | | $6,400 | Phase Cost/Mile/Yr | |
| | | 15-Year Phase Total Cost: | | $1,020,000 | | | | Minimum | Maximum |
| | | **15-Year Annualized Phase Cost:** | | **$68,000** | | | **Annual Benefit Return Range:** | **$300,000** | **$1,390,000** |

## Table 5-4: Phase 2 Restoration Benefit/Cost Analysis, Mosquito Creek Headwaters

| Projects | Stream Miles Restored | | Project Costs | | 15-Year Annualized Costs | | | Annual Public Benefit | |
|---|---|---|---|---|---|---|---|---|---|
| | Direct | Cumulative | Capital Construct. | Annual O&M | Project | Cumulative | Proj. $/Mile | Recr. Use | Willingness to Pay |
| *Existing Projects* | | | | | | | | | |
| Ardell VFW*<br>Isolated restoration of the Ardell tributary to Mosquito Creek | 1.6 | 1.6 | $200,000 | | $13,333 | $13,333 | $8,300 | $40,000 | $610,000 |
| Duck Marsh VFW<br>Isolated reestoration of the Duck Marshl tributary to Mosquito Creek | 1.7 | 1.7 | $200,000 | | $13,333 | $26,667 | $7,800 | $50,000 | $620,000 |
| Pebble Run VFW<br>Isolated restoration of the upper reaches of Pebble Run | 0.6 | 0.6 | $200,000 | | $13,333 | $40,000 | $22,200 | $20,000 | $530,000 |
| Beaver Run Lake Liming<br>Isolated restoration of the lacustrine fisheries at the headwaters of Beaver Run | 1 | 1 | | $10,000 | $10,000 | $50,000 | $10,000 | $30,000 | $560,000 |
| *Actual construction cost was approx. $250,000, but included research and development components not used in later designs. | | Existing Totals: | $600,000 | $10,000 | | | | | |
| | | 15-Year Existing Total Cost: | | $750,000 | | | | Minimum | Maximum |
| | | **15-Year Annualized Existing Cost:** | | **$50,000** | | | **Annual Benefit Return Range:** | **$50,000** | **$620,000** |
| *Conceptual Projects* | | | | | | | | | |
| Two Headwaters VFWs<br>Restoration of the Moquito Creek headwaters, with effects exrtending downstream to Pebble Run | 2.6 | 5.9 | $400,000 | | $26,667 | $76,667 | $10,300 | $170,000 | $980,000 |
| 2nd Pebble Run VFW<br>Restoration of the remainder of Pebble Run and downstream to the confluence with Beaver Run | 0.9 | 7.4 | $200,000 | | $13,333 | $90,000 | $14,800 | $210,000 | $1,110,000 |
| Beaver Run VFW<br>Restoration of the remainder of Beaver Run and downstream to the confluence with McNernry Run | 2.1 | 10.5 | $200,000 | | $13,333 | $103,333 | $6,300 | $290,000 | $1,370,000 |
| | | Phase Totals: | $1,400,000 | $10,000 | | | $9,800 | Phase Cost/Mile/Yr | |
| | | 15-Year Phase Total Cost: | | $1,550,000 | | | | Minimum | Maximum |
| | | **15-Year Annualized Cost:** | | **$103,333** | | | **Annual Benefit Return Range:** | **$290,000** | **$1,370,000** |

Table 5-5: Phase 3 Restoration Benefit/Cost Analysis, Mosquito Creek Middle Reaches

| Projects | Stream Miles Restored | | Project Costs | | 15-Year Annualized Costs | | | Annual Public Benefit | |
|---|---|---|---|---|---|---|---|---|---|
| | Direct | Cumulative | Capital Construct. | Annual O&M | Project | Cumulative | Proj. $/Mile | Recr. Use | Willingness to Pay |
| *Conceptual Projects* | | | | | | | | | |
| McNerney Run VFW<br>Restoration starting above headwaters wetlands in McNernery Run | 2.9 | 13.4 | $200,000 | | $13,333 | $13,333 | $4,600 | $380,000 | $1,620,000 |
| Midstem VFW<br>System on old forest road between McNerney Run and Meeker Run to Improve mian stem | 1.6 | 15.0 | $200,000 | | $13,333 | $26,667 | $8,300 | $420,000 | $1,760,000 |
| Meeker Run VFW<br>Restoration of Meeker Run affecting main stem downstream to M-6 at Lost Run Road | 1.4 | 16.4 | $200,000 | | $13,333 | $40,000 | $9,500 | $460,000 | $1,930,000 |
| Lost Run Road Limestone Sand Dosing<br>Supplemental dosing to account for excess acidity observed at M-6 | 1.9 | 18.3 | | $6,000 | $6,000 | $46,000 | $3,200 | $510,000 | $2,240,000 |
| Panther Run VFW<br>Restoration of Panther Run downstream from Reactor Road | 4.3 | 22.6 | $200,000 | | $13,333 | $59,333 | $3,100 | $630,000 | $2,940,000 |

| | | | | |
|---|---|---|---|---|
| Phase Totals: | $800,000 | $6,000 | | |
| Upstream Improvement Costs (Phase 2): | $1,400,000 | $10,000 | $7,200 | Cumulative Cost/Mile/Yr including Phase 2 |
| Cumulative Improvement Cost: | $2,200,000 | $16,000 | | |
| 15-Year Phase Total Cost: | | $2,440,000 | | Minimum / Maximum |
| **15-Year Annualized Cost:** | | **$162,667** | **Annual Benefit Return Range:** | **$630,000** / **$2,940,000** |

Table 5-6: Phase 4 Restoration Benefit/Cost Analysis, Mosquito Creek Lower Reaches

| Projects | Stream Miles Restored | | Project Costs | | 15-Year Annualized Costs | | | Annual Public Benefit | |
|---|---|---|---|---|---|---|---|---|---|
| | Direct | Cumulative | Capital Construct. | Annual O&M | Project | Cumulative | Proj. $/Mile | Recr. Use | Willingness to Pay |
| *Conceptual Projects* | | | | | | | | | |
| Twelvemile Run - 2 VFWs<br>Restoration of Twelvemile Run with improvements extending downstream to Cole Run | 12.1 | 33.3 | $400,000 | | $26,667 | $26,667 | $2,200 | $930,000 | $4,670,000 |
| Cole Run - 3 VFWs<br>Restoration of three branches of Cole Run, completing restoration of Mosquito Creek in Study Area | 8.9 | 42.2 | $600,000 | | $40,000 | $66,667 | $4,500 | $1,180,000 | $6,110,000 |

| | | | | | |
|---|---|---|---|---|---|
| Phase Totals: | $1,000,000 | $0 | | | |
| Upstream Improvement Costs (Phases 1-3): | $2,200,000 | $16,000 | $5,400 | Cumulative Cost/Mile/Yr including Phases 1 - 3 | |
| Cumulative Improvement Cost: | $3,200,000 | $16,000 | | | |
| 15-Year Phase Total Cost: | | $3,440,000 | | Minimum | Maximum |
| **15-Year Annualized Cost:** | | **$229,333** | **Annual Benefit Return Range:** | **$1,180,000** | **$6,110,000** |

### PHASE 1 – GIFFORD RUN

As shown by Table 5-3, the existing limestone sand dosing on Gifford Run has proven to be very economical. The main concern is that this activity may also damage the streambed through the accumulation of sand fines. The new alkaline addition projects designed and permitted for Gifford Run (HFBCs and VFLBs) are intended to provide long-term restoration benefits without streambed degradation. These projects should be able to eventually replace sand dosing and maintain water quality downstream from Merrill Road to Mosquito Creek, about 8 miles of reach including Lost Run and Deserter Run.

Acidification will remain in the areas upstream from Merrill Road, and it is anticipated that the equivalent of two more VFWs will be needed in the headwaters. Location of these projects near the upper fork of the stream would improve about 2.8 miles in a reach that is reasonably accessible to anglers on foot.

Gifford Run already has significant value as a stocked fishery and represents the best immediate investment for the watershed. The predicted phase cost of $1 million has a 15-year annualized value of $68,000. This is well below the range of expectations on return between $300,000 for recreation and $1.4 million for WTP. The total restoration of 11 miles equates to about $6,400 per mile per year. The MCSA is committed to maintaining the fisheries in this stream, and implementation of these projects would reduce the annual maintenance burden on the association while greatly extending the fishable reaches.

### PHASE 2 – MOSQUITO CREEK HEADWATERS

The Mosquito Creek headwaters show the worst acidification conditions in the watershed, and worthwhile improvements to the Phase 3 middle reaches may not be realized until this area is addressed. The majority of alkaline addition efforts to date have been directed at this area through the VFWs on the Ardell tributary, Duck Marshes, and Pebble Run, and the lake liming on Beaver Run. These improved reaches, however, are currently isolated by remaining poor quality segments of Mosquito Creek. On Table 5-4, their existing benefits are thus predicted for the individual projects rather than as a cumulative restoration length.

It is expected that the equivalent of two more standard VFWs or one larger VFW will be needed in the upper Mosquito Creek headwaters area north of the Duck Marshes, extending improvements on the Mosquito Creek main stem downstream to Pebble Run. Lake liming may be considered as well on the Duck Marshes to boost the alkalinity output of that tributary to the main stem. A second VFW-equivalent will also be required for the lower half of Pebble Run to extend benefits for that tributary to its mouth and downstream to Beaver Run.

Continuation of lake liming in the Beaver Run headwaters should allow the remainder of the stream to be restored with a single VFW. This is complicated somewhat by the Quehanna Wild Area, where construction and motorized equipment are not permitted, and it may be necessary to explore other non-constructed technologies in this area, such as sand dosing or forest liming. Lake liming is considered to be worthwhile for continuation because of the potential to reestablish a large area of open waters fishery, very little of which currently exists in the Mosquito Creek watershed.

Because contiguous stream reaches have not yet been created in the headwaters, the cost total of $750,000 for the existing Phase 2 activities is not directly comparable to a total of the individual returns from recreational losses or WTP, but the 15-year annualized cost of $50,000 is within the range of positive benefits for the individual projects. Creation of stream connectivity through the proposed new projects will result in a phase total cost of $1.6 million, with 15-year annualized cost of $100,000. This is below the estimated annual return range of $290,000 for recreation to $1.4 million for WTP. The final cost for Phase 2 equates to about $9,800 per mile per year.

### PHASE 3 – MOSQUITO CREEK MIDDLE REACHES

As discussed in Section 3, the reaches between Beaver Run and Meeker Run are interpreted to contain the greatest acidity *loading* in the watershed. It is predicted that the equivalent of as many as three VFWs would be necessary to account for the alkaline deficiency in this reach in addition to those to provide treatment for McNerney Run and Meeker Run.

The proposed approach is to install VFWs or equivalents on McNerney Run and Meeker Run, and on an unnamed tributary to Mosquito Creek on Moshannon State Forest land between these streams. No other accessible flowing tributaries have been identified within this reach. Although it is desirable to eventually end the practice, sand dosing at Lost Run Road may be the only practical alternative to overcome excess acidity below Meeker Run. On Table 5-5, this is estimated to require approximately twice the annual cost as currently applied for Gifford Run. Pending the results of upstream addition, it may be possible to replace dosing with one or more HFBCs in this vicinity.

The final component of Phase 3 is a VFW or equivalent on Panther Run. Although the stream is remote, its headwaters appear to be accessible for construction from Lost Run Road. On completion of this project, improvements should extend downstream in Mosquito Creek to the confluence with Twelvemile Run and possibly to Gifford Run.

Including the Phase 2 costs for headwaters improvements, the overall cost of achieving Phase 3 benefits would be approximately $2.4 million, with a 15-year annualized value of $163,000. The cumulative stream restoration from Phases 2 and 3 above Twelvemile Run is predicted to be about 23 miles at this stage, with an annual return range between $630,000 for recreation and $2.9 million for WTP. At $7,200 per year, the cost per mile is also lower than the upstream Phase 2 owing to the increase in connected improvements.

### PHASE 4 – MOSQUITO CREEK LOWER REACHES

Twelvemile Run and Cole Run are fairly large streams with moderate acidification levels, and work on them may be worthwhile concurrent with the previous phases. Because of their size and associated alkaline loading deficiencies, however, they will require a comparably greater investment before improvements are realized. Twelvemile Run and Cole Run are fairly remote from convenient public access compared to most other streams in the watershed. It is also probable that the previous phases will result in significant improvements, if not full restoration, in the lower Mosquito Creek main stem before they are addressed. As such, Twelvemile Run and Cole Run are included as the last phase of the progressive restoration plan.

It is estimated that Twelvemile Run will require the equivalent of two VFW systems, most likely located on two of its headwaters forks as best accessible from the Quehanna Highway. In conjunction with the proposed alkaline addition on Gifford Run, this should finalize improvements in Mosquito Creek downstream to Cole Run. In Cole Run, up to three VFW-equivalents will be needed in the headwaters forks. This work should complete restoration of Mosquito Creek downstream to Grimes Run at Route 879. Improvements beyond this point would require a separate study and remediation plan for acid mine drainage impacting Grimes Run. These final lower reaches extending to the Susquehanna River are mostly on private land and would not provide as immediate a public benefit.

As shown by Table 5-6, substantial stream mileage gains will be realized by completion of Phases 1 – 4, with the ultimate restorable connected reach length estimated at about 42 miles. The 15-year total cost for Phases 1 – 4 is predicted to be about $3.4 million, or $229,000 per year. This is considerably lower than the expected returns of $1.2 million for recreation and $6.1 million for community WTP. The cost per mile is further reduced by connectivity to $5,400 per year. Using the total alkaline addition requirement for the watershed of about 150 tons per year estimated in Section 3, the net cost of alkaline addition equates to about $0.76 per pound over 15 years.

### ALTERNATIVE PROJECTS

Although VFWs are the most predictable of the passive technologies discussed in Section 4, they are a relatively high cost source of alkalinity. Much of the watershed assessment in this study was limited to determination of the gross alkaline deficiencies of the major tributaries. It is anticipated that site-specific characterization for future projects may allow use of more economical technologies, such as VFLBs, HFBCs, and forest and road liming, to augment or replace some of the VFWs. As such, it is believed that the cost estimates presented in Tables 5-3 through 5-6 represent the high end of the total potential restoration cost. Despite this, all phase cost estimates are below the expected returns for both recreational use and community willingness to pay, resulting in a positive benefit/cost evaluation for restoration in the Mosquito Creek watershed.

# 6

# CONCLUSIONS AND RECOMMENDATIONS

The detailed Growing Greener Goals and Accomplishments Worksheets for this project are included with this report as Appendix C. The overall conclusion of this study is that restoration of acid deposition impacts to Mosquito Creek is technically feasible and economically beneficial. The Growing Greener Program has already made a substantial investment in this watershed, and it is believed that the results warrant continuation of this work to its conclusion and full realization of socioeconomic returns from restoration. The following are the specific conclusions in support of this finding:

- Mosquito Creek is fairly unique in Pennsylvania as far as its accessibility and recreational value as an undeveloped watershed.

- Acidification impacts to Mosquito Creek are long-term and will not be immediately remedied by upwind acid source reductions.

- The local watershed association (MCSA) has undertaken substantial efforts as a “grass-roots” organization to maintain the values of their watershed, and wishes to continue this work until quality fisheries are restored.

- A variety of viable passive alkaline addition technologies have been demonstrated capable of addressing alkaline deficiencies with relatively little ongoing effort.

- Standardized design criteria and performance expectations have been developed for many of these technologies through the course of these projects, and results are applicable to other watersheds impacted by acid deposition.

- The total estimated restoration cost for the watershed of $3.4 million is a reasonable level of investment for a potential return of up to 42 connected stream miles.

- The 15-year annualized restoration cost of $229,000 is well below the expected annual returns of $1.2 million for recreational use and $6.1 million for community willingness-to-pay.

- The 15-year annualized cost per restored mile of $5,400 is very reasonable compared to the costs of acid mine drainage remediation in adjacent watersheds.

Implementation of the progressive restoration plan will likely take a number of years, and it is expected that further monitoring of the watershed and improvements in the understanding of the alkaline addition technologies will result in revisions to the plan. As discussed in Section 5, the most immediate benefits would be realized by implementing the planned projects for Gifford Run, and then adding to the existing alkaline addition efforts in the Mosquito Creek headwaters areas. Specific recommendations for these initial phases are as follows:

- The remaining HFBC at Merrill Road and VLFBs on Lost Run and Deserter Run should be funded for construction using the existing designs before the secured permits expire in 2010.

- A design and permitting phase should be funded to develop remaining required alkaline addition projects in the headwaters of Gifford Run above Merrill Road.

- A design and permitting phase should be funded to develop remaining required alkaline addition projects for the upper Mosquito Creek headwaters, lower Pebble Run, and Beaver Run.

- A means of perpetual funding should be secured for lake liming in the Beaver Run headwaters to allow reestablishment of fisheries in that water body; a combined effort for the Duck Marshes could be considered.

- Alkaline addition requirements and conceptual project approaches for the Phase 3 area should be reevaluated after completion of Phase 2 to account for actual water quality improvements in the middle reaches; and likewise Phase 4 should be reevaluated after completion of Phase 3.

- Sampling budgets should be included in future funding efforts to continue the in-stream monitoring program (April and October rounds at minimum) to develop long-term trends and document the effects of alkaline addition activities. Sampling and assessment budgets should also be included with each new alkaline addition project to improve the data records and efficiencies of the technologies over time.

# Sample Point Data Analysis

**Project Name:** Mosquito Creek Acid Abatement Project **Sample Point:** M-1 Ardell Tributary above Ardell Road

| | | | Field Parameters | | | | Laboratory Analyses | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | Sample Date | Sampler | Flow (GPM) | pH (SU) | Temp. (°C) | Cond. uomhs | pH (SU) | ANC (meq/L) | Al (mg/L) | Ca (mg/L) | Fe (mg/L) | Mg (mg/L) | Na (mg/L) | K (mg/L) | Cl (mg/L) | DOC (mg/L) | $NO_3$ (mg/L) | Orth-P (mg/L) | $SO_4$ (mg/L) |
| 1 | 11/16/00 | PSU | | | | | 5.15 | -7.78 | 0.036 | | | | | | | | | | |
| 2 | 12/13/00 | PSU | | | | | 5.68 | | 0.670 | | | | | | | | | | |
| 3 | 1/12/01 | PSU | | | | | 5.25 | | 0.066 | | | | | | | | | | |
| 4 | 2/16/01 | PSU | 1669 | | | 26.9 | 4.78 | -25.97 | 0.073 | 0.296 | 0.003 | 0.725 | 0.361 | 0.458 | 0.937 | 1.972 | 0.065 | 0.003 | 8.181 |
| 5 | 2/27/01 | PSU | | | | 24.1 | 5.08 | -14.92 | 0.042 | | | | | | | | | | |
| 6 | 3/15/01 | PSU | | | | 25.0 | 4.89 | -0.84 | 0.070 | | 0.003 | | | | | | | | |
| 7 | 3/29/01 | PSU | 472 | | | 24.6 | 5.03 | -11.31 | 0.066 | 0.720 | 0.003 | 0.789 | 0.342 | 0.335 | 0.706 | 0.772 | 0.008 | 0.003 | 6.829 |
| 8 | 4/17/01 | PSU | 1006 | | | 25.0 | 4.84 | -21.52 | 0.414 | | | | | | | | | | |
| 9 | 5/3/01 | PSU | 269 | | | 21.5 | 4.72 | -5.90 | 0.089 | | | | | | | | | | |
| 10 | 11/29/01 | PSU | | | | 31.2 | 4.67 | -23.08 | 0.115 | 0.282 | | | | | | | | | |
| 11 | 12/13/01 | PSU | | | | 24.5 | 5.04 | -8.52 | 0.100 | | | | | | | | | | |
| 12 | 12/28/01 | PSU | | | | 27.3 | 4.92 | -10.13 | 0.108 | 0.564 | | | | | | | | | |
| 13 | 1/10/02 | PSU | | | | 20.5 | 5.27 | -2.27 | 0.096 | 0.746 | 0.024 | 0.766 | 0.752 | 0.570 | 0.879 | 0.746 | 0.047 | 0.003 | 6.513 |
| 14 | 1/23/02 | PSU | 403 | | | 21.8 | 5.48 | 0.09 | 0.088 | 0.652 | | | | | | | | | |
| 15 | 2/8/02 | PSU | 380 | | | 23.7 | 5.04 | -14.35 | 0.130 | 0.519 | 0.038 | 0.770 | 0.683 | 0.503 | 0.770 | 0.941 | 0.049 | 0.019 | 6.998 |
| 16 | 2/20/02 | PSU | 206 | | | 21.8 | 5.07 | -5.22 | 0.092 | 0.619 | | | | | | | | | |
| 17 | 3/7/02 | PSU | 380 | | | 23.0 | 5.05 | -8.47 | 0.139 | 0.533 | | | | | | | | | |
| 18 | 3/22/02 | PSU | | | | 25.4 | 5.43 | -10.15 | 0.085 | 0.646 | 0.032 | 0.683 | 0.382 | 0.510 | 0.810 | 0.585 | 0.050 | 0.011 | 7.12 |
| 19 | 4/4/02 | PSU | 403 | | | 24.9 | 4.90 | -11.89 | 0.146 | 0.506 | | | | | | | | | |
| 20 | 4/18/02 | PSU | 634 | | | 28.0 | 4.37 | -15.60 | 0.162 | 0.478 | | | | | | | | | |
| 21 | 5/23/03 | PSU | | | | 24.7 | 4.96 | -12.00 | 0.155 | 0.960 | | | | | | | | | |
| 22 | 6/19/03 | PSU | | | | 22.9 | 5.15 | -10.70 | 0.135 | 1.050 | | | | | | | | | |
| 23 | 7/16/03 | PSU | | | | 16.9 | 5.11 | -7.24 | 0.145 | 0.980 | | | | | | | | | |
| 24 | 8/12/03 | PSU | | | | 24.1 | 4.76 | -18.80 | 0.110 | 1.350 | | | | | | | | | |
| 25 | 9/13/03 | PSU | | | | 19.8 | 5.05 | -8.32 | 0.062 | 1.120 | | | | | | | | | |
| 26 | 10/16/03 | PSU | | | | 27.8 | 4.95 | -21.30 | 0.155 | 1.120 | | | | | | | | | |
| 27 | 11/6/03 | PSU | | | | 23.9 | 5.15 | -9.20 | 0.115 | 1.450 | | | | | | | | | |
| 28 | 12/4/03 | PSU | | | | 19.1 | 5.06 | -10.90 | 0.115 | 1.120 | | | | | | | | | |
| 29 | 1/6/04 | PSU | | | | 25.1 | 5.52 | -26.30 | 0.160 | 1.140 | | | | | | | | | |
| 30 | 3/9/04 | PSU | | | | 23.0 | 4.81 | -16.50 | 0.145 | 1.100 | | | | | | | | | |
| 31 | 4/2/04 | PSU | | | | 24.2 | 4.93 | -15.40 | 0.115 | 1.050 | | | | | | | | | |
| 32 | 5/10/04 | PSU | | | | 23.6 | 4.72 | -16.10 | 0.115 | 1.150 | | | | | | | | | |
| | | **Averages:** | 582 | | | 23.9 | 5.03 | -12.35 | 0.135 | 0.840 | 0.017 | 0.747 | 0.504 | 0.475 | 0.820 | 1.003 | 0.044 | 0.007 | 7.128 |
| | | **Maximums:** | 1669 | | | 31.2 | 5.68 | 0.09 | 0.670 | 1.450 | 0.038 | 0.789 | 0.752 | 0.570 | 0.937 | 1.972 | 0.065 | 0.019 | 8.181 |
| | | **Minimums:** | 206 | | | 16.9 | 4.37 | -26.30 | 0.036 | 0.282 | 0.003 | 0.683 | 0.342 | 0.335 | 0.706 | 0.585 | 0.008 | 0.003 | 6.513 |
| | | **St. Deviations:** | 442 | | | 2.9 | 0.27 | 6.86 | 0.117 | 0.330 | 0.016 | 0.043 | 0.197 | 0.088 | 0.091 | 0.556 | 0.021 | 0.007 | 0.631 |
| | | **95% Values:** | 1393 | | | 28.9 | 4.57 | -24.12 | 0.335 | 1.417 | 0.050 | 0.837 | 0.924 | 0.663 | 1.013 | 2.189 | 0.089 | 0.023 | 8.474 |
| | | **95% Predictions:** | 1393 | | | | | | | | | | | | | | | | |