Bowman’s Creek Acidic Deposition Remediation Plan

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Approval

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Abstract

Bowman's Creek, a tributary of the Susquehanna River in Northeastern Pennsylvania, has potential as a freshwater wild trout fishery. However, due to chronic atmospheric deposition and low natural alkalinity, the upper portions of the watershed are periodically acidified, limiting trout populations. The purpose of this report is to design a remediation plan for the Upper Bowman's Creek Watershed that can sustain healthy fish populations. Limestone dosage requirements were calculated based on a mass balance approach, factoring in stream flow and net acid neutralization capacities of the existing watershed. Acid neutralization capacity contributing technologies were chosen based on proven effectiveness after a review of relevant literature and planned for locations in the watershed based on needs and land availability. A total of five vertical flow wetlands are recommended for the watershed, along with two high flow buffer channels. This will contribute approximately 30 tons of buffering as calcium carbonate per year to the watershed. The estimated capital cost for this design is $1.5 million including direct construction and permitting costs along with needed access.

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Introduction

Bowman's Creek is classified as a High-Quality Cold-Water Fishery (HQ-CWF) for its entire 26-mile length. The headwaters of the creek originate in Pennsylvania State Game Lands 57, within Luzerne County, Pennsylvania near Ricketts Glen State Park (Figure 1). At its source, it is a small headwater stream. Bowman's Creek first flows through Pennsylvania State Game Lands 57. It is fed by fourteen separate tributaries, increasing in size and volume until it reaches the town of Noxen, where it has an average width of 50-70 feet. Here the land use transitions from primarily forested to largely agricultural, which is maintained until its confluence with the Susquehanna River in Tunkhannock.

Upper Bowman's Creek is managed by the Pennsylvanian Fish and Boat Commission as a Coldwater fishery (Figure 2). Many small tributaries and the headwaters are managed as class A wild trout fisheries (Moase, Wnuk, Chavez, & Vitale, 2003) (Figure 2). These are streams that support the highest biomass of wild trout that a stream can achieve within the commonwealth. The biomass of wild trout in class A tributaries shows that these streams are unaffected by pollution and can sustain a sporting population of wild trout. Most of the upper watershed is managed by natural trout reproduction regulations (Moase, Wnuk, Chavez, & Vitale, 2003) (Figure 2). This means that these sections of stream do not contain Class A populations of wild trout. They do contain wild trout to an extent less than sporting populations, and therefore are managed as wild trout streams without stocking.

The Pennsylvania Fish and Boat Commission (PFABC) will not add hatchery origin fish to streams that they have found to have significant wild trout (Frey 2023). This designation constitutes most of the area of interest. The last section of the stream is managed as a stocked trout fishery (Moase, Wnuk, Chavez, & Vitale, 2003) (Figure 2). This means that the waters cannot support wild trout populations to a sporting level, but water quality does support addition of hatchery origin fish for sporting purposes, finding that acidic water quality was the limiting factor (Moase, Wnuk, Chavez, & Vitale, 2003).

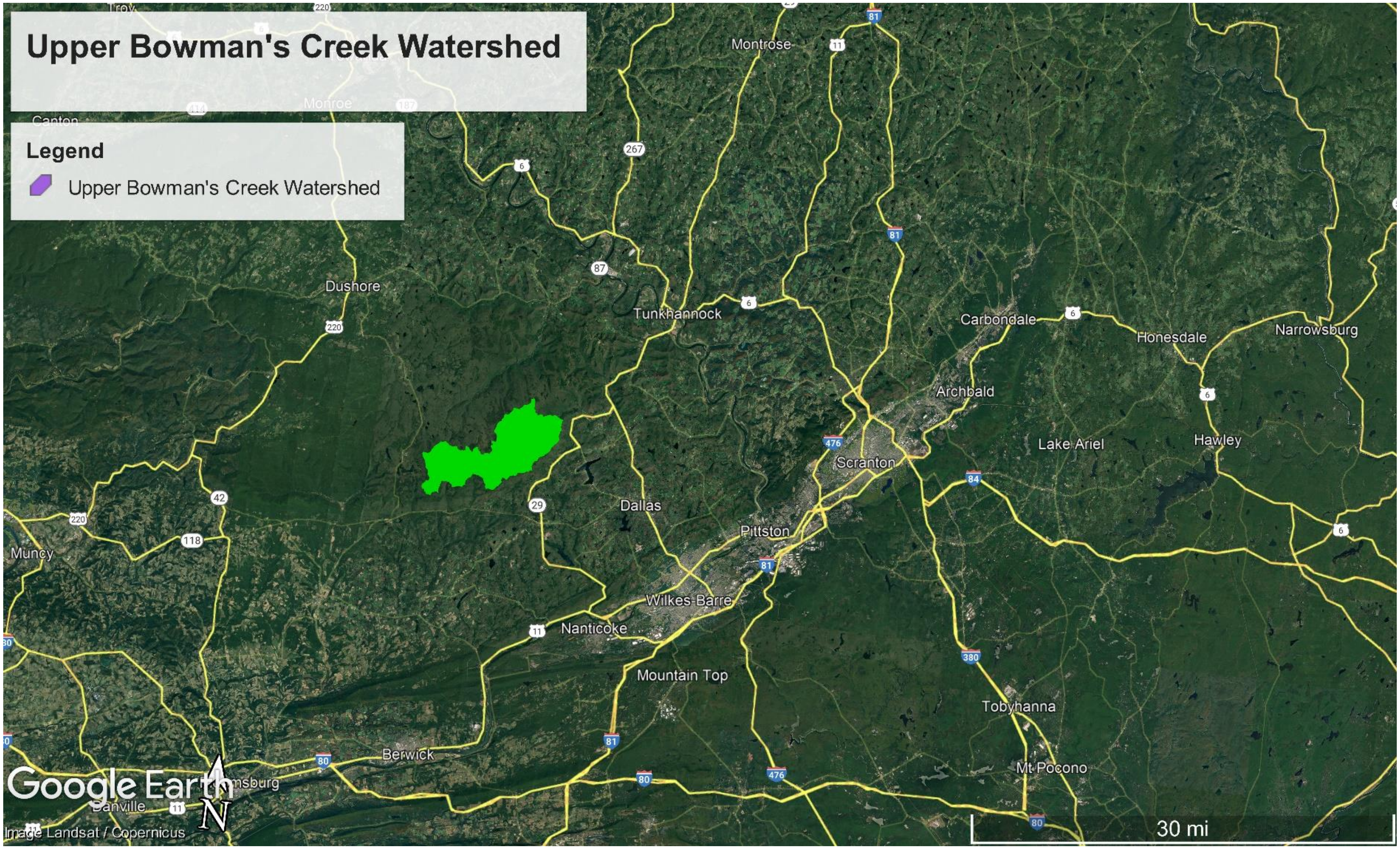


Figure 1: Upper Bowman's Creek Watershed Map

Pennsylvania Fish and Boat Stream Designations

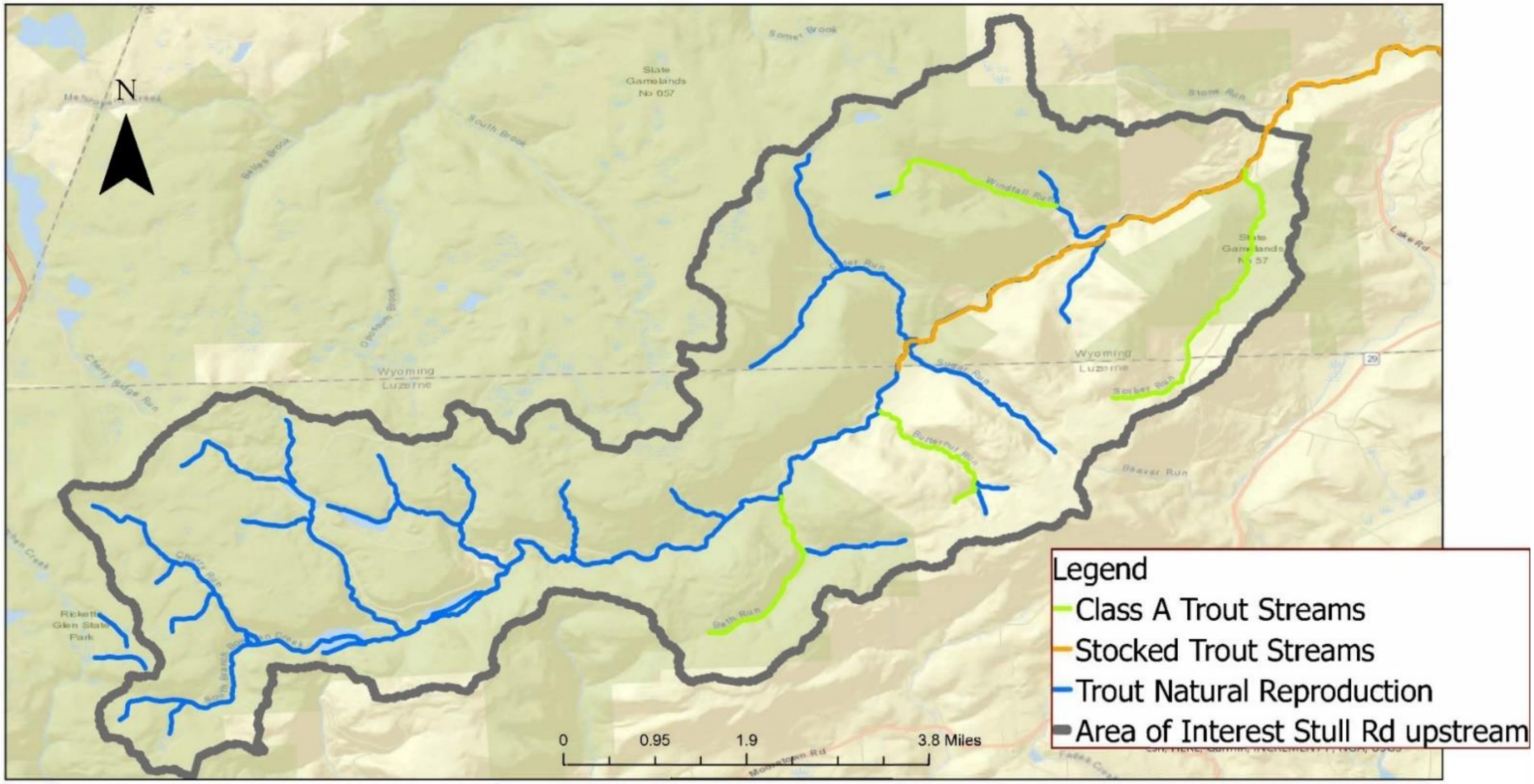


Figure 2: Upper Bowman's Creek Stream Designations

Purpose and Scope

Upper Bowman's Creek has a pH lower than typical ranges in the region, (Moase, Wnuk, Chavez, & Vitale, 2003), (Levitsky, 2002), (Hnat, B., *et al*. 1985). These papers noted the acidity in several of the tributary streams including Baker Run (Rush, K *et al*., 2002), and Mountain Springs Lake (Ragni, B., *et al.*, 1995). Rush noted that the region is "hampered with acidic conditions" causing decreased macroinvertebrate populations both in Bowman's Creek and the previous Mountain Springs Lake.

The low pH values were first noted in the mid-1990s by local Trout Unlimited members in Eaton Township, Pennsylvania. The Stanley Cooper Chapter of Trout Unlimited, along with the Bowman's Creek Watershed Organization, commissioned Borton-Lawson Engineering to create and implement the Bowman's Creek Watershed Acidic Deposition Mitigation Monitoring Pre/Post Lime Application Report (Levitsky, 2002) from 2000 to 2002.

Rush *et al*. 2002 found Baker Run (a tributary to Bowman's Creek) has a lowered pH due to acid rain in the region. Attempts were made by Rush to remediate with the addition of limestone by gabion baskets within stream channels. They found through measurements that the restoration of acidified streams by addition of limestone in temporary gabion baskets was not feasible, and that other avenues should be examined.

Levitsky *et al.* (2002) noted the primary cause of lowered pH values in the watershed was due to increased acidic deposition, both wet and dry. This acidic material originated from NOx and SOx emissions from burning of coal for power generation (Figure 3). Natural alkalinity can often buffer acid input, but in cases of severe acid rain or limited geologic alkalinity,

alkalinity must be added to the stream to maintain fish populations (Hoover, K. L., & Rightnour, T. A. 2006).

It is worth noting that the entirety of The Bowman's Creek Watershed is not seriously impacted by acidification (Levistky et al. 2002). Instead, the stream begins to approach a nearly neutral pH at approximately the confluence of Sorber Run. This occurs due to several reasons, most prominently agricultural liming (Levistky et al. 2002). This is also approximately where ownership passes from public to private hands. As a result, this confluence is used as a cutoff point for this study. See Figure 4 for a depiction of the area of study.

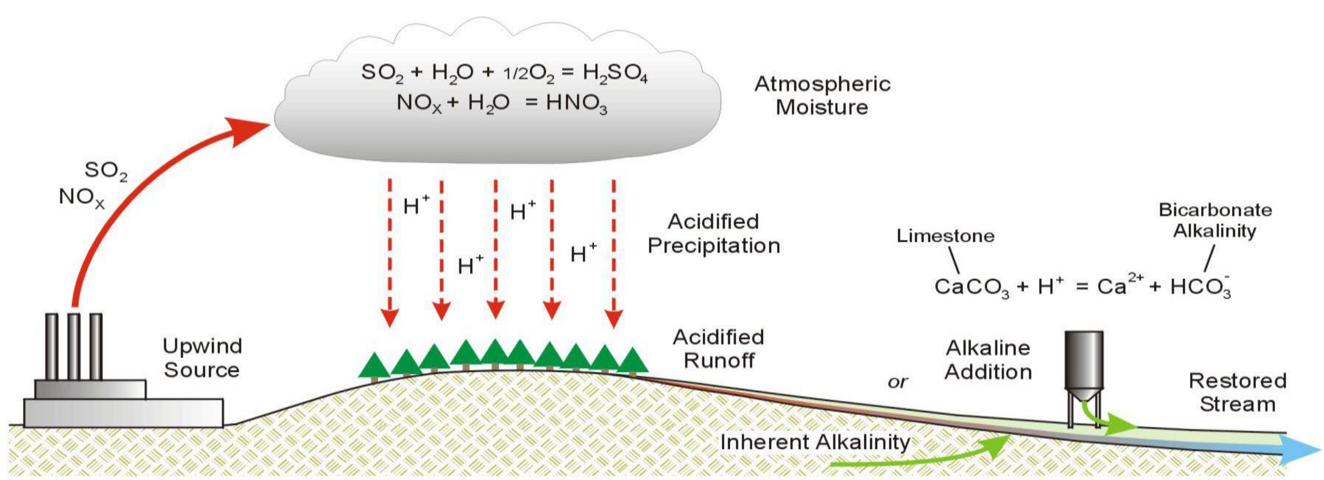


Figure 3 : Acid Rain Production (Hoover & Rightnour, 2006)

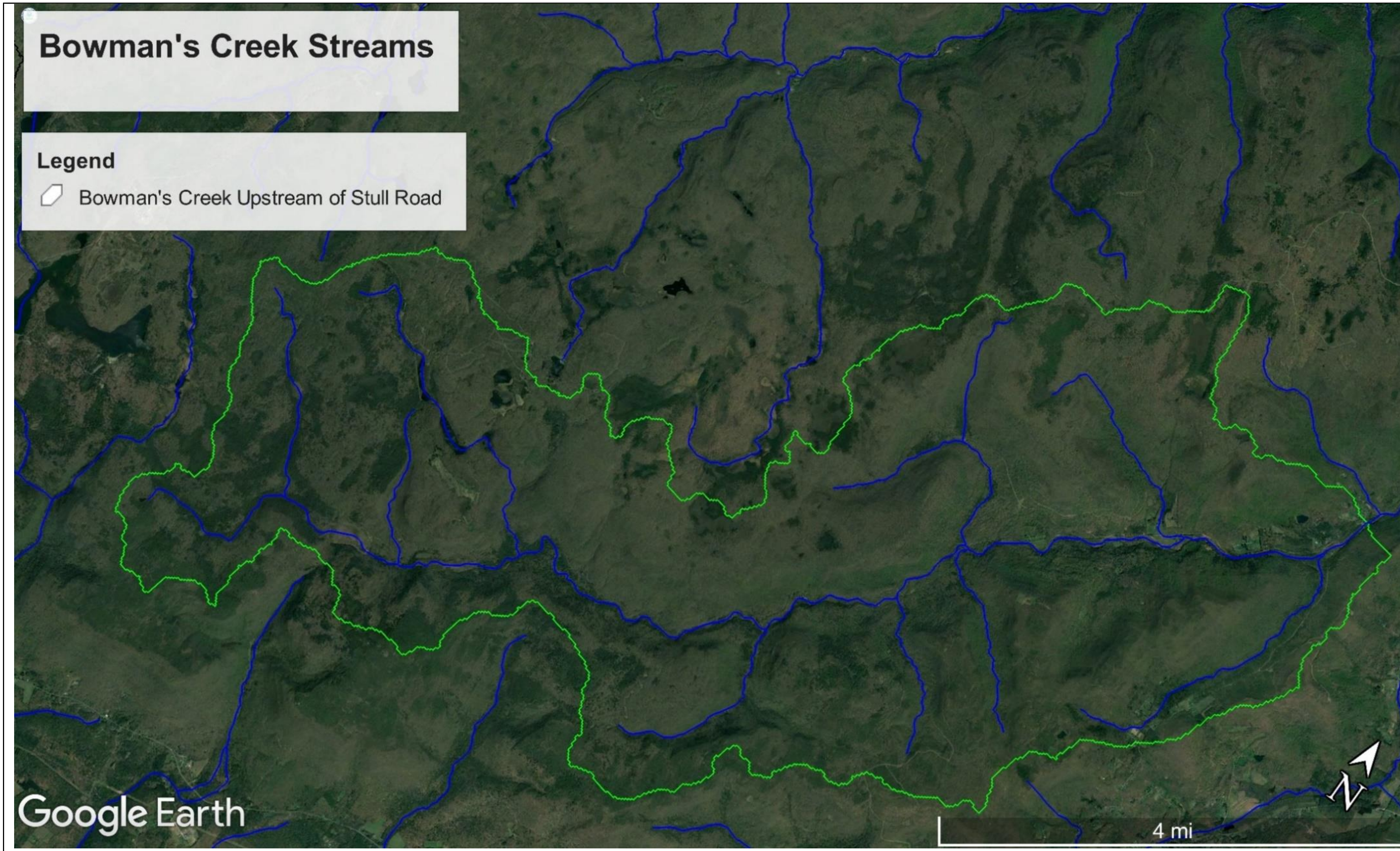


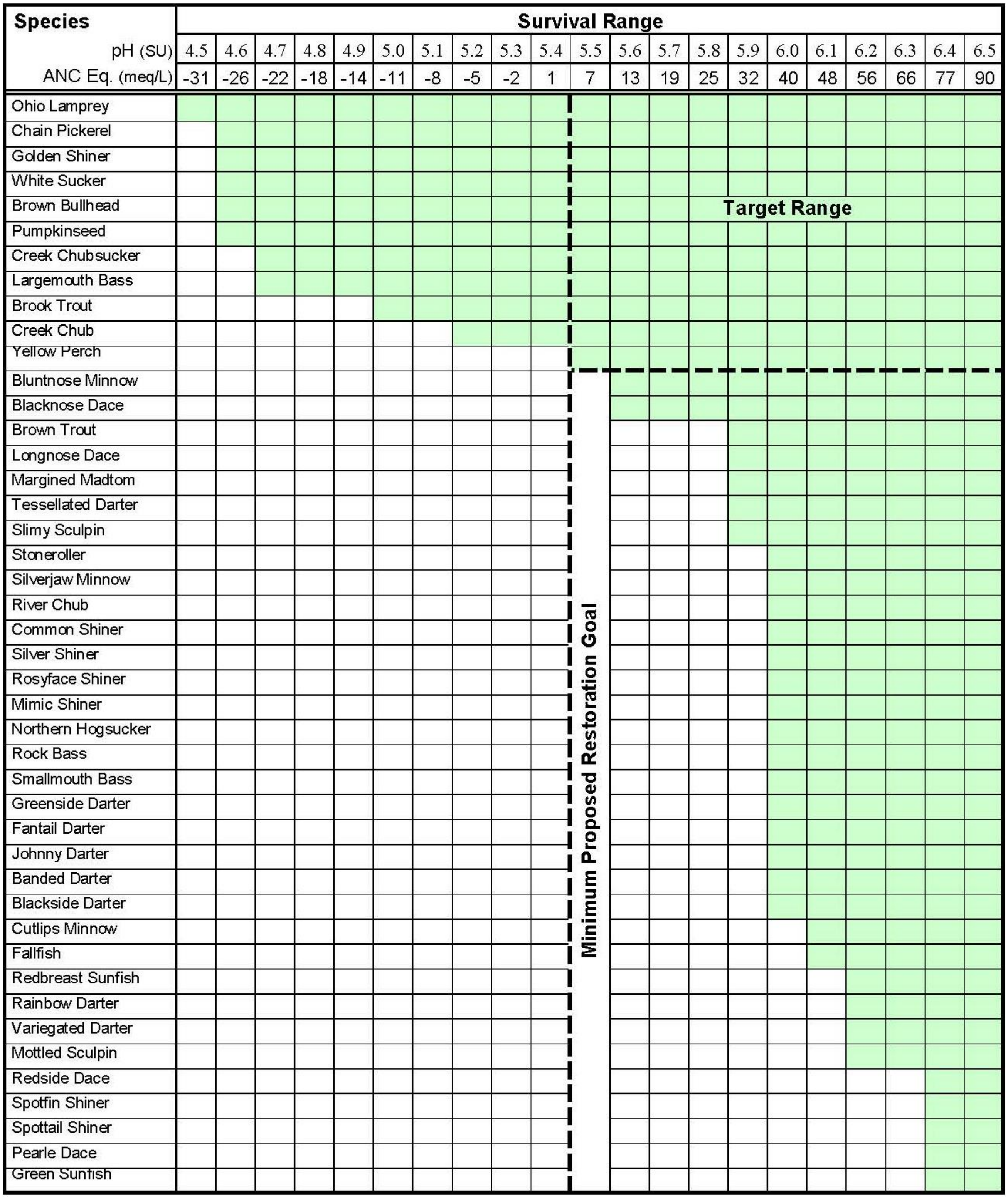
Figure 4: Entire Bowman's Creek Watershed

Acidification in Upper Bowman's Creek is caused by a combination of two main sources: high acidic loading due to wet and dry atmospheric deposition, and a low natural alkalinity. The low alkalinity is due to natural geology, a predominantly forested land use, and historical deposition. Long periods of acidic deposition, as present in Bowman's Creek from testing of soil samples, can deplete the natural buffering capacities in the region (Lawrence *et al*. 2016). It is important to note that geologic formations are the primary driver of acidification in streams.

Fish survivability can also be attributed to the acid neutralization capacity (ANC). Acid neutralization capacity is a measurement of buffering, like alkalinity. A higher ANC resists drops in pH, and thus allows fish to survive in water bodies despite acidic loading. It is important to note that pH and ANC are not directly proportional, but they are highly correlated in natural water systems. A more comprehensive explanation of how pH and ANC interact in water systems can be found later in this report.

Table 1 shows the pH and ANC (acid neutralization capacity) survivability of different aquatic species to survive in waters. Most aquatic species require a pH between six and nine, along with an ANC measurement that is higher than mineral acidity in the system (Hoover, K. L., & Rightnour, T. A. 2006). While fish can survive small periods of reduced pH, which is often during high flow events, by taking shelter in alkaline tributaries, acidification during normal flows is detrimental to fish (Hoover, K. L., & Rightnour, T. A. 2006).

Table 1: Fish Survivability (Hoover & Rightnour, 2006) *note that the ANC unit included (meq/L) refers to microequivlants per liter*



The negative effects of low pH on trout are multifaceted. Low pH can lead to high aluminum ion concentrations in streams, which in turn cause sodium deficiencies in fish (Gagen & Sharp, 1987). The main cause of these deficiencies occurs due to aluminum and hydrogen ions blocking the sodium pumps used by trout to maintain a sodium and chloride gradient. Death occurs within hours if sodium or chloride ion levels drop below 30% of healthy levels (Bulgur *et al*., 1998). Low pH can also decrease trout egg survivability (Menendez, 1976) and impede cardiovascular function (Smith *et al*., 2006).

In 2001, the Bowman's Creek Watershed Association (BCWA) began to deposit limestone sand within the watershed at multiple locations (Levitsky, 2002). BCWA saw an increase in both macroinvertebrate and trout populations throughout the watershed (Levitsky, 2002). They recorded an average 2,322% increase in wild brook trout biomass within the treated sections, compared to an 11% increase in wild brook trout populations within untreated sections (Moase et al., 2003).

Since liming in the region first began, lime has been distributed intermittently by interested parties. Due to the lack of an overall plan, not all locations or dates are known, but those known are identified (Figure 5). Moreover, no comprehensive study on how much limestone is needed to maintain healthy native fish populations has been conducted for the watershed. Instead, past parties have noted that alkalinity additions are beneficial to the stream ecosystem. This report will layout the total alkaline deficiencies in the upper Bowman's Creek watershed and provide tested methods of addition to the watershed.

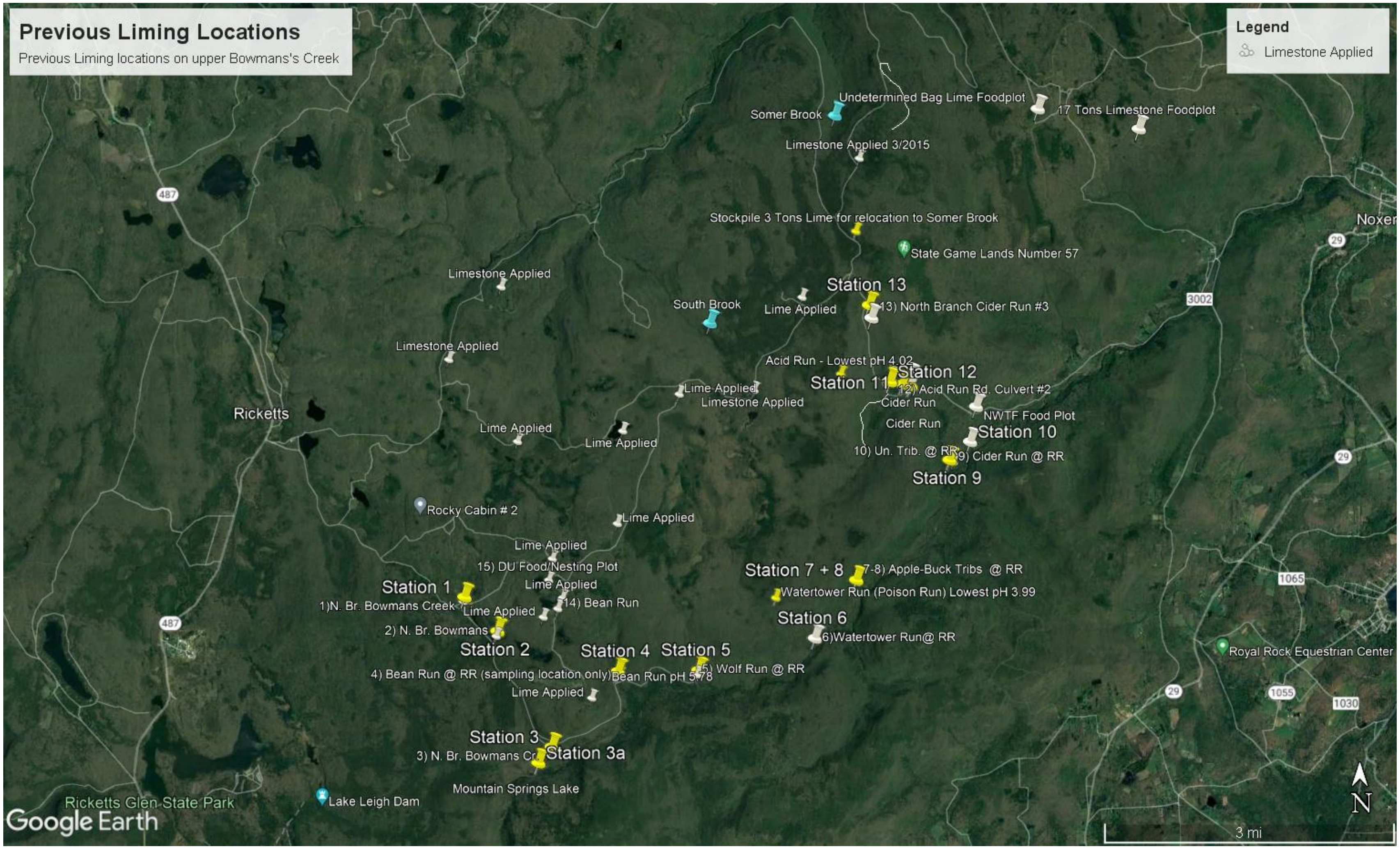


Figure 5: Area of Study Past Liming Locations

Literature Review:

Acidic Deposition

Due to the common nature of acidic deposition across the Commonwealth of Pennsylvania and the country, there is a large database of reports and previous data of effects of acidic deposition and the impacts they have on streams. An extensive collection of data was gathered from several sources including watershed groups that have completed projects both in Bowman's Creek, and around the state. A review of this information was used to understand what causes acidic deposition and how to mitigate the harmful effects.

Evaluation of the previous Bowman's Creek Acidic Deposition Report (Levitsky, 2002) gave insight into both the elevated acidification issue and what has been done to correct it in the past. The report discusses how liming has been completed since 2001, often funded by Growing Greener Grants or by Trout Unlimited. Several similar projects have been completed throughout Pennsylvania and have seen varying successes and implementation. It is worth noting that projects with a more reasonable price, minimal excavation, and limited site development often resulted in the highest implementation rate.

Upper Bowman's Creek is not consistently acidic. As demonstrated in Figure 6, using data compiled within Bowman's Creek Watershed Association acid deposition mitigation monitoring pre/post lime application report, Bowman's Creek's pH varies significantly, with periods of significant acidification and periods that are more neutral. This is a trend consistent across multiple monitoring locations along Bowman's Creek, and several contributing tributaries.

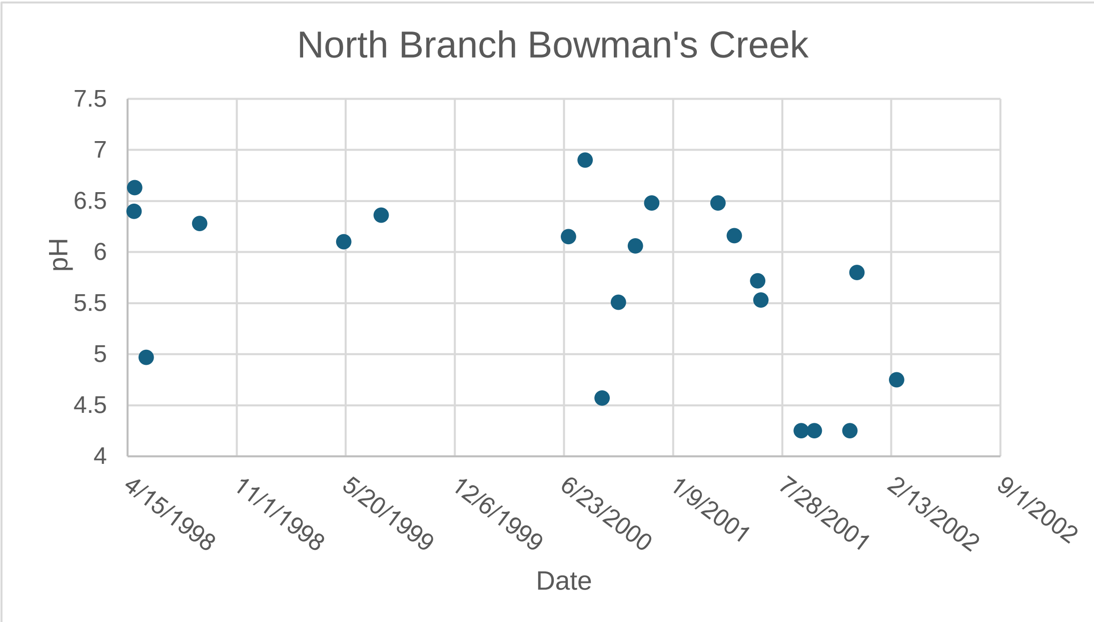


Figure 6: Measured pH in North Branch Bowman's Creek, April 1998-September 2002

However, short periods of low pH are known to kill trout when they last at least one full day (Gagen & Sharp, 1987). Since pH is difficult to predict, it is not practical to focus on pH exclusively. Instead, it's preferred to raise the available buffering capacity. A stream with a higher buffering capacity, commonly reported as alkalinity, can resist sudden increases in acidic loading, as the buffering resists changes to the overall pH (DeWalle *et al*., 1987). As such, the goal for this project is to raise the buffering capacity of Bowman's Creek, thus reducing the potential for periods of low pH which are harmful to fish. It also can be noted that repeated exposures to low pH can stress fish significantly and reduce reproduction rates and decrease populations even if fish are not killed directly (Hoover and Rightnour 2006).

Hydrology

Dosage for remediation in acid impaired watersheds can be calculated through a net acid neutralization capacity mass balance, as conducted for the Mosquito Creek Watershed

(Hoover and Rightnour 2006). This requires stream flow data, current net acid neutralization capacity, and a target acid neutralization capacity. Stream flow is ideally measured periodically with installed weirs, to gather a complete hydrologic assessment of the target stream flow year-round (Hoover and Rightnour 2002). However, this is well beyond the budget and time frame allocated for the completion of this project. An alternative method, hydrologic modeling, is instead necessary.

The hydrologic model that will be used to estimate stream flow along Bowman's Creek and its tributaries comes from the National Hydrography Dataset Plus (NHDPlus). NHDPlus is a program developed by the U.S. Environmental Protection Agency and the U.S. Geologic Survey to support the estimation of streamflow and stream velocity with the intended application in chemical fate and transport modeling. Streamflow is calculated using an enhanced unit runoff method (EROM) for a given drainage basin. Runoff is calculated using the Thornthwaite water balance model. This model was developed to examine the various components of the hydrologic cycle for the contiguous United States. Inputs to the model are mean monthly temperature, monthly total precipitation, and the latitude of the location, which is used in the computation for potential evapotranspiration. A diagram of the water-balance model can be seen in Figure 7.

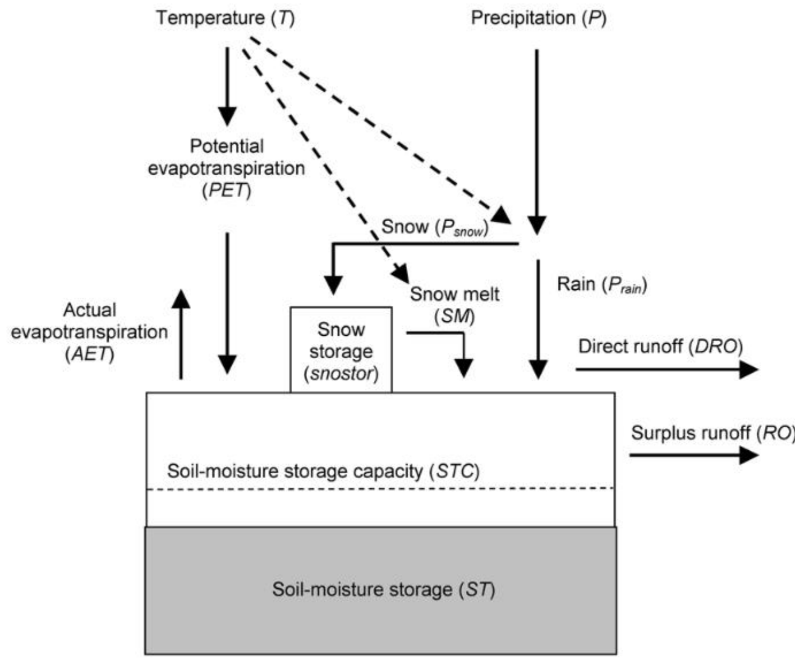


Figure 7: Diagram of the Thornthwaite Water Balance Model

The first computation of the water-balance model is the estimation of the amount of monthly precipitation that is rain or snow. When the mean monthly temperature is below a certain threshold, all precipitation is considered to be snow (P_{snow}). This value is set to -1 °C. If the temperature is greater than a specific threshold, all precipitation is considered to be rain (P_{rain}). This value is set to 3.3 °C. If the mean monthly temperature falls between these thresholds, a linear relationship is used to calculate P_{snow}, and the remainder is P_{rain}. Direct runoff, which results from impervious surfaces or from infiltration-excess, is calculated with Equation 1.

$$DRO = P_{rain\ \times drofrac}$$

Equation 1

Drofrac is the fraction of P_{rain} that becomes direct runoff. 5% is the typical value used. Direct runoff is subtracted from P_{Rain} to calculate the amount of remaining precipitation P_{remain}. The fraction of snow storage that melts in a month (SMF) is computed from mean monthly temperature and a maximum melt rate, which is set to 0.5. The fraction of snow storage that melts in a month is calculated using Equation 2.

$$SMF = \frac{T - T_{snow}}{T_{rain} - T_{snow}} \times meltmax$$

Equation 2

If the SMF is greater than *meltmax*, then SMF is set to *meltmax*. The amount of snow that melts in a month (SM), is then computed as $SM = P_{snow} \times SMF$. SM is added to P_{remain} to calculate the total liquid water input to the soil (P_{total}). Actual evapotranspiration (AET) is derived from potential evapotranspiration (PET), P_{total}, soil moisture storage (ST), and soil moisture storage withdrawal (STW). Monthly PET is estimated from mean monthly temperature using the Hamon Equation 4.

$$PET_{Hamon} = 13.97 \times d \times D^2 \times W_t$$

Equation 4

Where d is the number of days in a month, D is the mean monthly hours of daylight, and W_t is a saturated water vapor density term which is a function of mean monthly temperature.

When P_{total} for a month is less than PET, then AET is equal to P_{total} plus the amount of soil moisture than can be withdrawn from storage in the soil. Soil-moisture storage withdrawal linearly decreases with decreasing ST, because as the soil becomes drier, water becomes more difficult to remove. STW is calculated using Equation 5.

$$STW = ST_{i-1}\left[abs(P_{total} - PET) \times (\frac{ST_{i-1}}{STC})\right]$$

Equation 5

ST_{i-1} is the soil moisture storage for the previous month and STC is the soil-moisture storage capacity, which is assumed to be 150 mm. If the sum of P_{total} and STW is less than PET, then a water deficit is calculated to be PET-AET. If P_{total} exceeds PET, then AET is equal to PET and the water in excess of PET replenishes ST. When ST is greater then the STC, the excess water becomes surplus and is eventually available for runoff. Runoff is generated from the surplus at a specified rate (rfactor), which is commonly used as 0.5. This parameter determines the fraction of surplus that becomes runoff in a month. Direct runoff is added directly to the runoff generated from surplus to compute total monthly runoff in millimeters (McCabe 2007). This value in mm/month can be used to average the flow in a stream in ft^3/s (cfs).

Buffering

Acid neutralization capacity, abbreviated ANC, is a measurement of pH buffering, similar to the concept of alkalinity (USGS, 2012). It is a measurement of resistance to lowering pH, as acids are added to solution (Kirby & Cravotta, 2005). ANC is commonly reported as either microequivalents per liter, or as milligrams per liter as calcium carbonate (mg/L as $CaCO_3$) (USGS 2012). This does not mean that all the buffering is provided by calcium carbonate, but rather indicates that the buffering present equals the buffering that would theoretically be provided by an equivalent mass of pure calcium carbonate. ANC differs from alkalinity in that ANC samples are unfiltered, whereas alkalinity samples are filtered (USGS, 2012). As a result, ANC includes buffering provided by undissolved suspended solids in a field environment, while alkalinity is more commonly reported.

Buffering occurs due to the presence of dissolved chemicals that can become one or more different species, as pH changes. The pH of a water body is essentially a measurement of Hydrogen (H^{+}) ions present in solution. Greater concentrations of H^{+}ions are reported as a lower pH (Kutty, 1987). As this ion concentration changes, certain chemicals will form different associated species. For instance, in a basic solution carbonate will remain as carbonate. However, if the system becomes more acidic, it will become bicarbonate, and then eventually carbonic acid. This transformation will take up H^{+} ions that would otherwise contribute to a lower pH (Kirby and Cravotta, 2005). As such, the pH of a water body with a high ANC will decrease much slower than a waterbody without ANC, when facing the same acidic loading (USGS, 2012). Figure 8 below depicts this process specific to carbonate, and it unfolds in a similar way for other contributing chemicals.

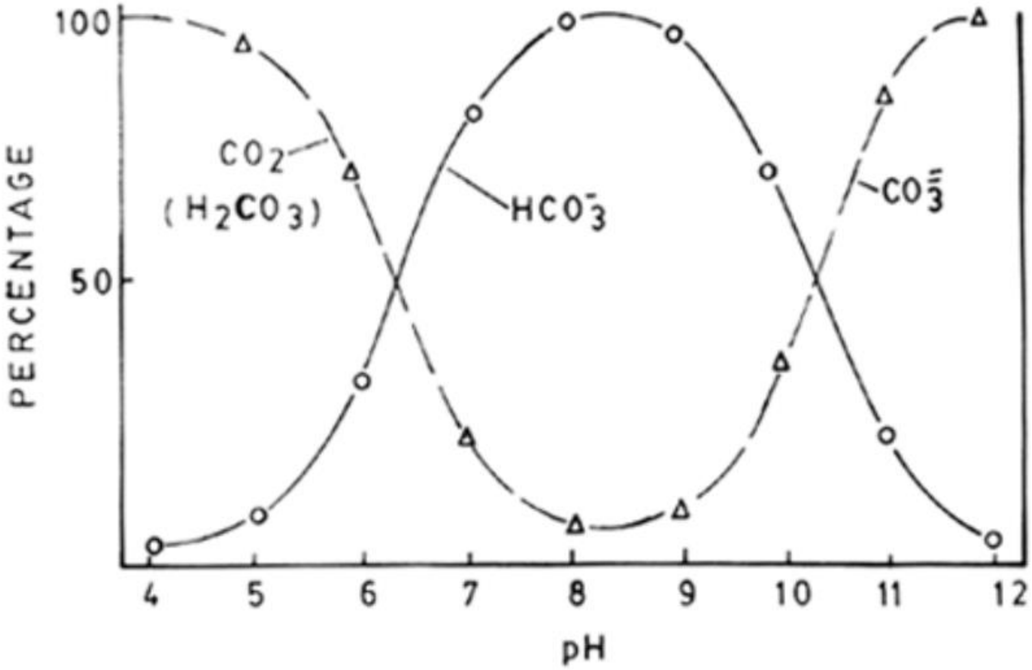


Figure 8: Depicting the Carbonate Species Present in Changing pH. (Kutty, 1987)

Mineral acidity, sometimes just referred to as acidity or metal acidity, is the resistance to raising pH in an acidic solution as alkaline materials are added. It can be reasonably thought of as the inverse of alkalinity and is commonly reported as negative alkalinity (Kirby & Cravotta, 2005). Mineral acidity occurs due to the presence of inorganic acids like sulfuric acid, as well as metal ions. As bases are contributed to the system, thus making it more basic, metal ions will occupy hydroxide ions to oxidize the metals, thus slowing the rise in pH. (Kirby & Cravotta, 2005). The difference of mineral acidity from alkalinity is sometimes referred to as net alkalinity (Kirby & Cravotta, 2005).

A similar measurement, substituting ANC for alkalinity, can be called net ANC, as it summarizes all pH buffering present in the system. Net ANC can be calculated in several ways. One such method is the Gran Function Titration (USGS, 2012). Unlike a typical inflection point titration, often used to measure alkalinity, a Gran Function Titration can report a “negative” ANC, which indicates a water body has more mineral acidity than acid neutralization capacity. Gran Function Titrations are used by industry professionals for calculating ANC for stream acid remediation, such as in the Mosquito Creek Report (Rightnour, 2024).

Lime Dosing

The addition of limestone, or lime, is the commonly accepted method for introducing buffering to natural water bodies (Hoover, K. L., & Rightnour, T. A. 2006). This is because lime is predominantly composed of calcium carbonate, which occupies hydrogen ions as it transitions into bicarbonate and carbonic acid, as depicted below. Note that this is a simplified depiction and does not include all relevant species.

$$CaCO_3(s) + H_2O(l) \rightarrow Ca^{+2}(aq) + CO_3^{-2}(aq) + H_2O(l)$$

$$CO_3^{-2}(aq) + H^+(aq) \rightarrow HCO_3^{-1}(aq)$$

$$HCO_3^{-1}(aq) + H^+(aq) \rightarrow H_2CO_3(aq)$$

Equation 6

Lime is safe to transport and relatively inexpensive. The carbonate species and calcium ions it contributes to water bodies when dissolved can all be found in natural water systems and are not harmful to the environment (Hoover, K. L., & Rightnour, T. A. 2006). Sudden changes to hardness, which would occur due to the addition of calcium carbonate, are not harmful to trout even in concentrations significantly higher than present in this remediation (Huysman *et al*., 2022).

ANC Goal

To make design recommendations, a target ANC level is required. The required ANC level for trout survival in a specific stream is difficult to determine, as every stream is subject to different acidic loading, natural alkalinity, and a variety of other relevant environmental and biological factors (Bulgur *et al*., 1998). As per the Mosquito Creek Report, Gifford Run, a tributary of Mosquito Creek, was able to maintain sporting populations of wild trout with an ANC of 20 μeq/L. As a result, this level was chosen as a target for the remainder of remediation at Mosquito Creek (Hoover and Rightnour, 2006). A similar trend was observed in Beth Run, and Bean Run, both notable Bowman's Creek tributaries known to maintain trout populations. Both also had an ANC above the 20 μeq/L threshold. Generally, an ANC of 20 μeq/L is considered transitional for buffering in freshwater trout streams, indicating survival is possible in certain contexts (Bulgur *et al*., 1998). A higher target would likely lead to greater trout populations, but a net ANC at 20 μeq/L is economically feasible to implement.

Buffering Addition Techniques

To address the widespread prevalence of acid rain in the Continental United States, multiple liming techniques have been developed. The practicality of these methods varies depending on site constraints and the magnitude of alkalinity addition needed. These techniques have been summarized in the Lime Addition Technology Table 2, which outlines the different types of liming technology and the advantages and disadvantages of each technique. Similar watersheds throughout the state have comparable issues with acidic deposition, including the Mosquito Creek Watershed (Hoover & Rightnour, 2002) and the Upper Fishing Creek Watershed (Hoover *et al*. 2007). We chose these watersheds as they share many of the same characteristics as the Upper Bowman's Creek watershed including geology, and watershed size.

Designs in this project will work to use technologies that do not require large construction as these are more cost effective per pound of lime added to the system. These technologies often cost between $0.02 and $0.05 per pound of lime added to the stream, depending on the spreading cost of the material (Hoover *et al*. 2007). Construction of the limestone addition structures can crest $250,000, alongside the cost of lime, making techniques that do not require construction considerably cheaper, while these methods are often much less expensive, they have been found to not provide long term remediation to a system. (Hoover and Rightnour, 2002).

Table 2: Alkalinity Addition Techniques, Adapted from Rightnour (2006)

Technology	Pro	Con
Road Surface Liming	Can be incorporated. with existing surfacing programs, no earth disturbance required.	Limited intercept area for runoff, net alkaline output relatively small.
Roadside cast liming	Lower cost than forest liming due to easier equipment access.	Limited area affected, requires specialized equipment.
Roadside Ditch lime addition	Lower cost than forest liming due to easier equipment access.	Requires channels be maintained and cleaned.
Direct Stream application	Very simple, low cost, little or no capital investment.	May degrade streambed, effectiveness variable, dosage difficult to estimate, often not legal to institute locally.
Limestone Diversion Wells	Simple to construct, proven in existing applications, unskilled maintenance.	High frequency of maintenance, no current information on alkalinity output.
Pebble Quicklime	Rapid neutralization and controllable dosage, small construction footprint	Frequent maintenance and skill in quicklime handling required, higher material cost.
Rotary Drum	Allows a degree of dosage control and response to flow changes.	High frequency of maintenance, mechanical system malfunction.
Lake Liming	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	Saves limestone for when needed in episodic events, prevents streambed degradation.	Performance untested, requires suitable floodplain construction site, downcutting of streams can leave channels useless.
Forest Liming	Long-term improvements to soil condition, runoff neutralization, and vegetative cover, stream macroinvertebrates were improved.	Can be difficult to apply with high initial cost, improvements not immediate.
Vertical Flow Wetlands	Large alkalinity reservoir, very low maintenance, one-time cost, known alkalinity input, known parameters for permitting.	Relatively high capital cost, long-term performance not studied extensively, without addition of buffer wetlands discolored water can be discharged.

Vertical Flow Wetland Analysis

Vertical flow wetlands (VFW) were first introduced to treat abandoned mine discharges across the country. They include a large reservoir for ANC and require minimal long-term maintenance. These systems are particularly useful in situations where a one-time funding source such as a government grant is available, as they do not require the replacement of limestone for many years (Hoover, K. L., & Rightnour, T. A. 2006). Figure 9 shows the layout of a VFW that was constructed in the Mosquito Creek project utilizing Growing Greener grant money. These systems utilize a check dam to bring water to the system (Figure 10). This diverts water from the affected stream at a metered flow rate to avoid overloading the stream system during high-flow events.

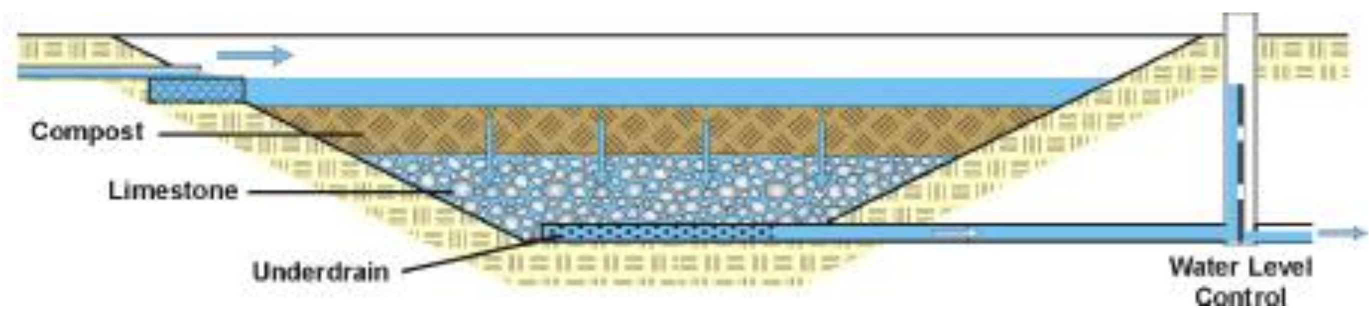


Figure 9: Vertical Flow Wetland Cross Section (Hoover, K. L., & Rightnour, T. A. 2006)

Figure 10 shows an overall layout of the pebble run system that was installed on the Mosquito Creek Project. A constructed VFW consists of a check dam intake structure on the stream (Figure 11) and piping to the constructed wetland cell. The wetland cell is lined with an HDPE liner (Figure 12), while six-inch underdrain piping is installed above the liner. Washed limestone aggregate is then introduced (Figure 13), and a compost layer is added on top (Figure 14) to remove oxygen from the influent. This anoxic environment prevents metal deposition on the limestone surface, that would otherwise prevent calcium carbonate from dissolving (Hoover, K. L., & Rightnour, T. A. 2006). An artistic depiction of this layout can be found in Figure 15.

Figure 10: Pebble Run VFW Constructed on Mosquito Creek (Hoover, K. L., & Rightnour, T. A. (2006))

Influent Water is diverted to the VFW through a staged check dam to maintain a maximum flow rate and allow the stream to convey material as it naturally would.

Figure 11: VFW Check Dam (Hoover, K. L., & Rightnour, T. A. 2006)

Poly Liner is laid out in the proposed VFW size to limit water lost to the ground. This helps to maintain pre-treatment stream flows. Perforated pipe is laid out in a rectangular pattern, as done in mine water treatment systems. This was later altered in subsequent systems to improve water spreading.

Figure 12: VFW Underdrain and Liner (Hoover, K. L., & Rightnour, T. A. 2006)

Washed Limestone aggregate is used to limit clogging in the system. ¾ minus material is primarily used. Larger material may be used around the underdrains to reduce clogging in VFLB and to help with the flushing of precipitated metals. The alkalinity addition depends on the limestone purity, therefore high-quality limestone is used.

Figure 13: VFW Limestone Spreading (Hoover, K. L., & Rightnour, T. A. 2006)

Mushroom compost was used in the original systems to strip out metals and create an anoxic state. This prevents metals in the influent from precipitating onto the limestone structure. Later the compost was blended with limestone sand to add extra alkalinity addition capacity. When influent water does not include metal ions, compost is not needed.

Figure 14: VFW Compost Spreading (Hoover, K. L., & Rightnour, T. A. 2006)

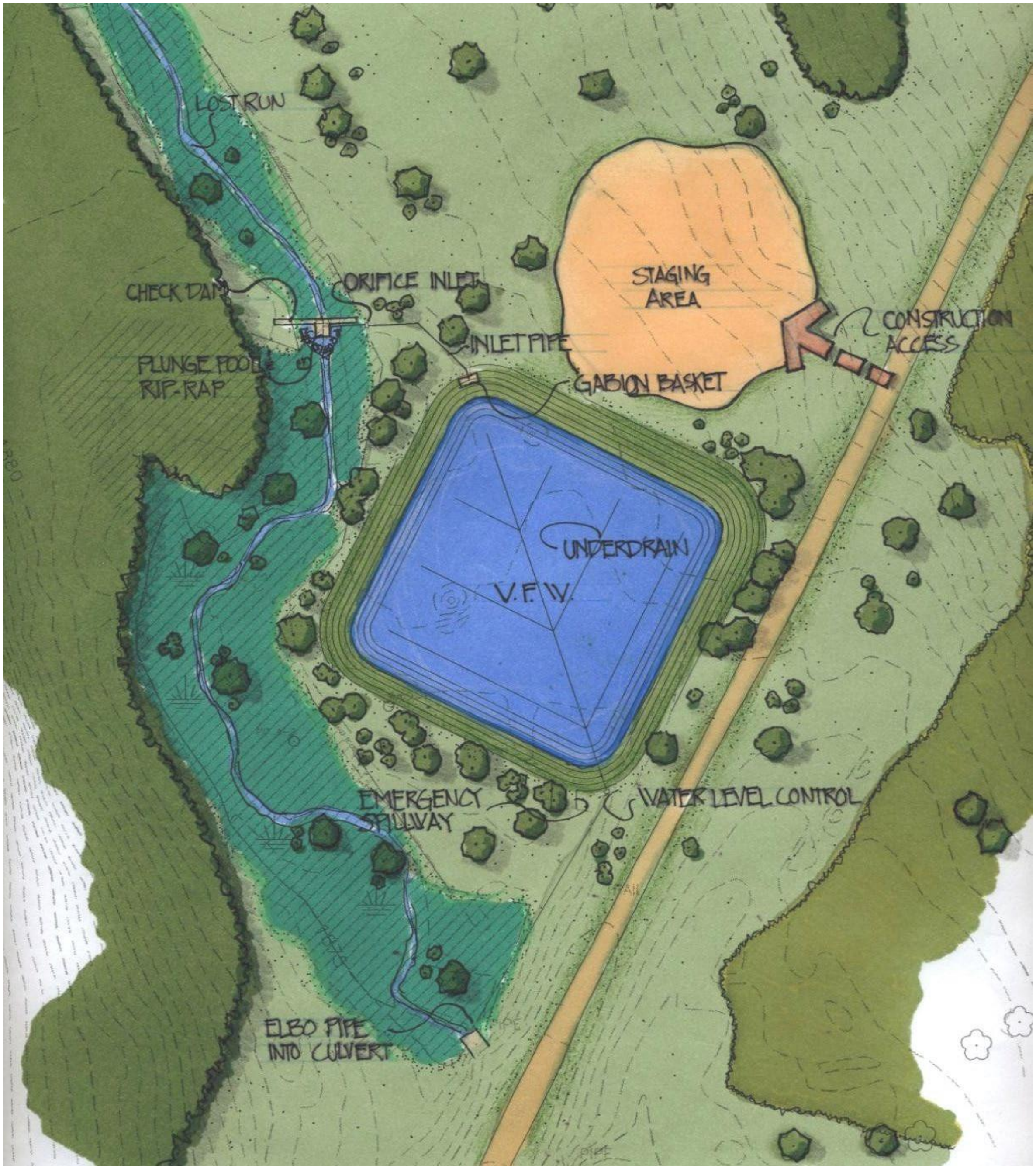


Figure 15: Proposed Vertical Flow Limestone Bed (Hoover, K. L., & Rightnour, T. A. 2006)

During The Mosquito Creek Remediation Project, ideal design parameters for vertical flow wetlands handling atmospheric deposition were evaluated extensively. A summary of these findings can be found in Appendix A (pg. 57). The project also evaluated the performance of vertical flow wetlands on Mosquito Creek. (Rightnour, 2006). A summary of the results can be found below in Table 3. This data can be used to estimate the performance of VFW system designs for Bowman's Creek.

Table 3: Mosquito Creek Vertical Flow Wetland Performance (Hoover, K. L., & Rightnour, T. A. 2006)

VFW System	**Discharge Performance Parameters**			
	Flow (gpm)	pH	Alkalinity (mg/L) as $CaCO_3$	ANC (μeq/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

High Flow Buffer Channels

High flow events were when the Mosquito Creek watershed experienced the worst acid loading conditions, caused by first flush events. This occurs after a longer period of dry acid loading, followed by a sudden influx of acidic rain, causing a drop in pH and the need for additional buffering capacity (Hoover, K. L., & Rightnour, T. A. 2006).

By designing for high flow events, the size of requisite vertical flow wetlands far exceeds desired costs and land use. Within the Mosquito Creek project, multiple high flow buffer channels (HFBC) were added to the mainstem of Mosquito Creek along with several tributaries in the watershed. These structures are only flooded, and therefore operational, during high flow events and are designed to treat water with limestone sand. Figure 16 shows the proposed drawings for a high flow buffer channel that was constructed off Merill Road as part of Growing Greener grants at Mosquito Creek. Sites with easy access to the stream floodplain are chosen to reduce large construction costs increasing project feasibility.

Step pools are designed to break up the sand particles by causing them to tumble. This increases the amount of alkalinity added to the stream. The large settling pool is used to capture material that can be transported back to the top of the structure. While these devices add direct alkalinity to the stream during a high flow event, they can also act as alkaline refuge during acidic events for trout to shelter in (Hoover, K. L., & Rightnour, T. A. 2006).

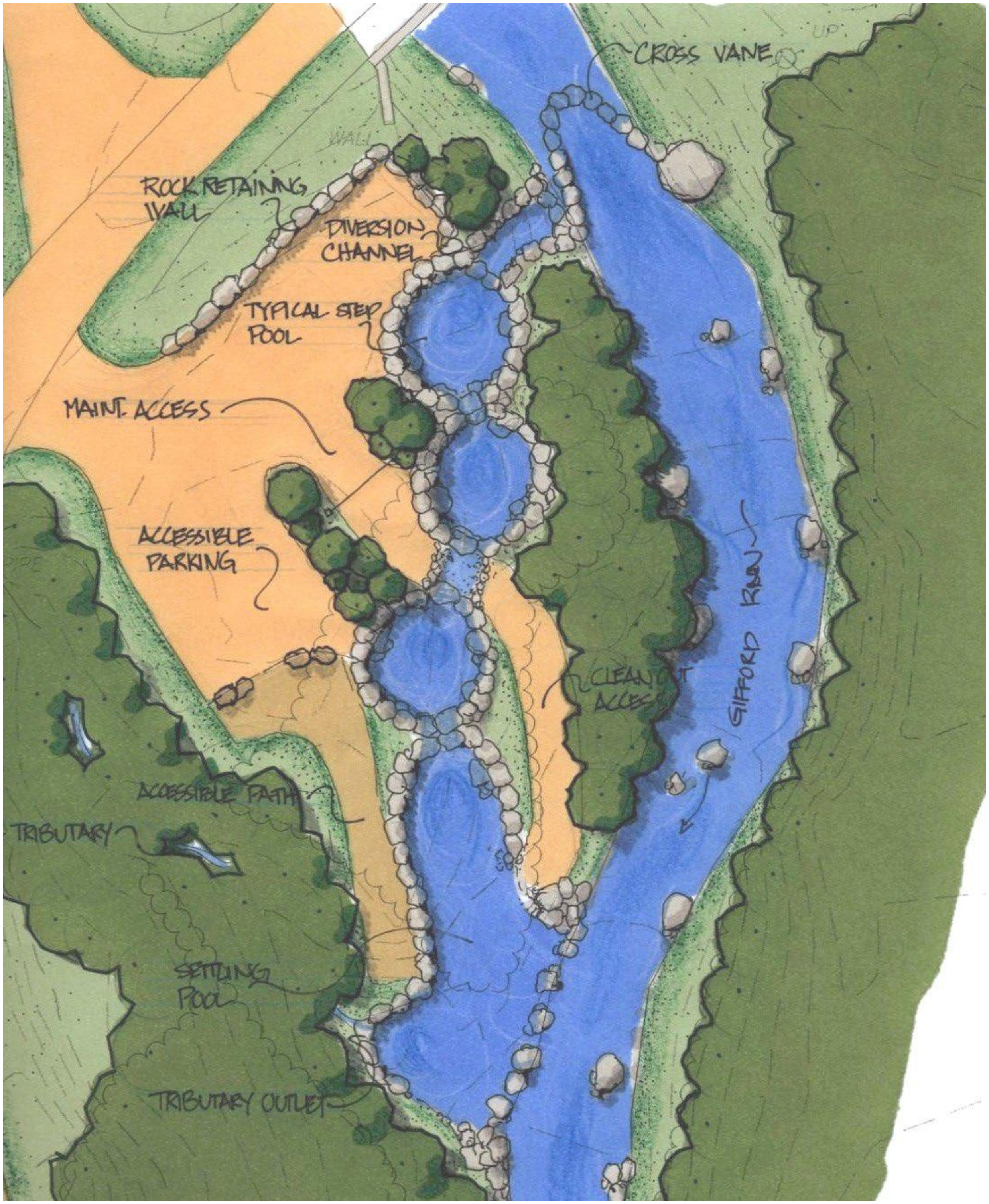


Figure 16: Merrill Road High Flow Buffer Channel Design (Hoover, K. L., & Rightnour, T. A. 2006)

Methodology

Field data monitoring and sample collection is a principal part of this project. This includes measurements for pH. These pH measurements were not used directly for calculations, but instead provide helpful information regarding overall trends, and identifying the tributaries which are in most need of remediation. A complete mass balance for the stream system is needed to know ANC addition requirements. The primary components of this balance are stream volumetric flow estimates and current pH buffering data.

Surface water samples for the ANC titrations were gathered by hand, in sealed, washed containers, and refrigerated. Sampling was conducted along the entire watershed, specifically positioned near accessible tributaries with high flows or periodically low pH. Existing stream buffering capacities were sampled several times over multiple months to find average buffering capacities over a yearly cycle, as these devices are to work year-round. Acid neutralization capacity was used as the main parameter to be corrected in this project as it shows how the entire system reacts to added acid.

This allows for a new mass balance to be constructed at each major change in water chemistry. The monitoring locations used in the mass balance used are depicted in Figure 17.

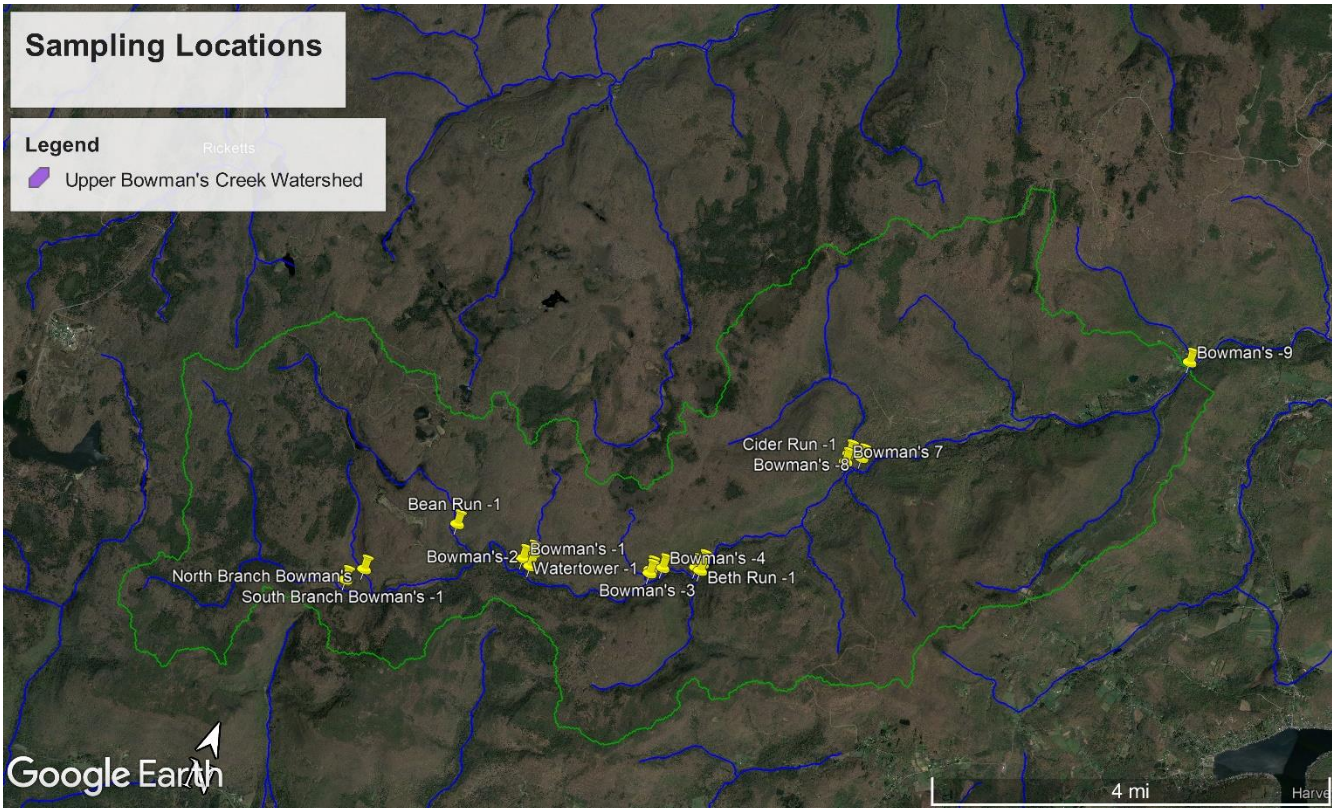


Figure 17: Monitoring Locations Used for the Mass Balance.

ANC was measured from an acid titration in a lab setting. ANC testing methods were all derived from the National Field Manual for the Collection of Water-Quality Data (NFM), which is published by USGS (2012). Sulfuric acid was added in gradual amounts to a surface water sample. Corresponding changes in pH were then measured. The alkalinity is then evaluated using the Gran Function Method. Since the Gran Function Method is rather complex, the USGS web alkalinity calculator was used to complete ANC calculations.

ANC measurements were conducted without using a digital titrator, with relatively large sample volumes (100 mL) and relatively dilute acid (0.02 N). This was due to the low alkalinity levels in the stream currently. Acid normality was confirmed through the titration of a sodium carbonate standard solution with known buffering. The titrations were continued below the typical inflection point, to a pH of about 3.2, which is needed for the gran function method for evaluating ANC. As this method is complex, the USGS web alkalinity calculator was used on titration data to avoid mathematical errors.

A mass balance was used to evaluate lime dosage. Multiplying volumetric stream flow by the present ANC can be used to find the equivalent annual tonnage of calcium carbonate buffering currently in stream at a specific monitoring location, Equation 7 shows the setup of the equations. An example calculation, for monitoring location BC-2, is also provided as Equation 8.

$$\frac{mg\ as\ CaCO_3}{L}(ANC\ current) * \frac{Liters\ of\ Stream\ Flow}{Year} * \frac{Ton}{mg} = \frac{Tons\ as\ CaCO_3}{Year}(current)$$

Equation 7

$$\frac{0.8\ mg\ as\ CaCO_3}{L} * \frac{27\ cubic\ feet}{second} * \frac{28.3168\ L}{cubic\ foot} * \frac{31536000\ seconds}{year} * \frac{ton}{907200000\ mg} = \frac{21.26\ tons}{year}$$

Equation 8

A similar calculation is used to find the equivalent tons of calcium carbonate needed in the stream to hit the target (equation 9), with associated sample calculations for BC-2 Equation 10.

$$\frac{mg\ as\ CaCO_3}{L}(ANC\ Target) * \frac{Liters\ of\ Stream\ Flow}{Year} * \frac{Ton}{mg} = \frac{Tons\ as\ CaCO_3}{Year}$$

Equation 9

$$\frac{1\ mg\ as\ CaCO_3}{L} * \frac{27\ cubic\ feet}{second} * \frac{28.3168\ L}{cubic\ foot} * \frac{31536000\ seconds}{year} * \frac{ton}{907200000\ mg} = \frac{26.58\ tons}{year}$$

Equation 10

Note that 20 micro equivalents/L, which is the target ANC level, is equal to 1 mg/L as $CaCO_3$. Subtracting the current equivalent ANC tonnage from the target ANC yields the needed additions for each sampling location. Equation 11 is how the calculation was set up, and Equation 12 is a sample calculation.

$$\frac{Target\ Tons\ ANC\ as\ CaCO_3}{Year} - \frac{Current\ Tons\ ANC\ as\ CaCO_3}{Year} = \frac{Tons\ of\ CaCO_3\ Required}{Year}$$

Equation 11

$$\frac{21.26\ tons}{year} Current - \frac{26.58\ tons}{year}\ Target\ = -\frac{5.32\ tons}{year}\ Balance$$

Equation 12

A negative value for ANC balance indicates an equivalent mass of calcium carbonate that must be dissolved into the stream by each location per year. These balances are arranged on flow charts (Figure 19), which are subsequently used to determine design locations. In a stream system, ANC additions upstream are assumed to also contribute to all subsequent downstream monitoring locations. Generally, the further upstream an addition technology is implemented, the more miles of stream is affected by the device, and therefore is most recommended. Design constraints such as terrain, access, and limestone solubility cause a distributed layout of buffering addition technologies.

While each watershed is distinctive, including differences in land use, geology, and topography, Mosquito Creek and Bowman's Creek are similar in many regards, making the work at Mosquito Creek a reasonable model for remediation on Bowman's Creek. To our knowledge, Mosquito Creek is the only watershed within Pennsylvania where acidic deposition restoration of this scale has been attempted. As a result, many of the design concepts and ideas that were implemented in the Mosquito Creek Watershed will be included into the plan for the Bowmans's Creek Watershed.

Although the primary goal of this project is to improve the water quality in Bowman's Creek, it remains advantageous to restore as many miles of stream as possible within watershed, not just the main branch of Bowman's Creek. This will be accomplished by working to add alkalinity in the tributaries of Bowman's Creek, not just the main stem. Not only will this work to restore more miles of stream for recreational benefit, but it has also been found that wild trout, and especially brook trout, need more than just the main stem habitat to thrive. Smaller headwaters and tributaries with a healthy pH are needed to create a more robust ecosystem that is better suited to adapting to a changing climate and other environmental factors (Mulhollem, 2020).

The methodology used to determine designs was multifaceted. A variety of constraints had to be considered. All liming technologies are real, physical objects and thus are limited by the surrounding terrain. First, it's preferred to choose structure locations that minimize environmental destruction, by relying on pre-existing roads and infrastructure wherever possible, as well as avoiding wetlands and endangered species. Specific liming devices also rely on a variety of factors, such as ground slope and proximity to water. Computer software, including GIS, Google Earth, and Lidar, was used to assess potential locations, based on the above factors. This concluded, potential sites were evaluated on the ground, to determine if each location is practical.

Estimations of vertical flow wetland performance were calculated based on real world data from the Mosquito Creek Report (see Table 3, pg. 30). Annual tonnage of equivalent buffering was estimated with Equation (13), based on average flow and buffering outputs. And example calculation for the Ardel Tributary VFW is provided in Equation 14.

$$Average\ Flow\ \left(\frac{gal}{minute}\right) * \frac{3.7854\ L}{gal} * \frac{mg\ as\ CaCO_3}{L} * \frac{525600\ minutes}{year} * \frac{ton}{907200000\ mg} = \frac{tons\ buffering}{year}$$

Equation 13

$$\frac{67\ gal}{minute} * \frac{3.7854\ L}{gal} * \frac{51.71\ mg}{L} * \frac{525600\ minutes}{year} * \frac{ton}{907200000\ mg} = \frac{7.6\ tons}{year}$$

Equation 14

This calculation yielded values of 7.6, 5.96, and 6.26 tons per year of buffering as calcium carbonate. For design purposes, 6 tons per year was used, as it is a reasonable, conservative estimate of buffering output for VFWs in conditions similar to Bowman's Creek.

Results:

Table 4 depicts data gathered on each monitoring location for both flow and net ANC. Figure 18 displays that information in a chart representing the watershed. Table 5 shows the calculated present, desired, and ANC balances for each monitoring location. Figure 19 shows those values on the stream layout as well.

Table 4: Bowman's Creek ANC Measurements and Flow Data

Bowman's Creek ANC data					
Station	Cordinates		2/11/2024	2/24/2024	3/20/2024
SBC-1	41°20'21.14"N	ANC (mg/l)	-0.02	0.8	0.3
	76°13'34.72"W	Flow (CFS)	9	9	9
NBC-1	41°20'29.93"N	ANC (mg/l)	-0.7	2.3	0.1
	76°13'25.52"W	Flow (CFS)	3	3	3
BC-1	41°21'6.79"N	ANC (mg/l)			0.5
	76°11'45.99"W	Flow (CFS)	12	12	12
BC-2	41°21'4.49"N	ANC (mg/l)			0.8
	76°11'39.18"W	Flow (CFS)			27
BC-3	41°21'24.98"N	ANC (mg/l)			0.6
	76°10'20.29"W	Flow (CFS)			27
BC-4	41°21'30.25"N	ANC (mg/l)			0
	76°10'13.40"W	Flow (CFS)			27
BC-5	41°21'37.00"N	ANC (mg/l)			0
	76° 9'51.78"W	Flow (CFS)			27
BC-6	41°21'40.10"N	ANC (mg/l)			-0.1
	76° 9'49.04"W	Flow (CFS)			27
BC-7	41°22'58.18"N	ANC (mg/l)			1.2
	76° 8'43.32"W	Flow (CFS)			34
BC-8	41°23'3.19"N	ANC (mg/l)	5.55		
	76° 8'34.05"W	Flow (CFS)	38		
BC-9	41°24'55.19"N	ANC (mg/l)		2.5	
	76° 5'26.90"W	Flow (CFS)		65	
BR-1	41°21'10.36"N	ANC (mg/l)	1.8	1.9	
	76°12'37.54"W	Flow (CFS)	5	5	
WR-1	41°21'10.59"N	ANC (mg/l)	-0.7	-3	
	76°11'41.85"W	Flow (CFS)	NA	NA	
BER-1	41°21'36.34"N	ANC (mg/l)		2.3	
	76° 9'48.34"W	Flow (CFS)			
CR-1	41°23'2.63"N	ANC (mg/l)	-1	0	-2.9
	76° 8'43.06"W	Flow (CFS)			
WTR-1	41°21'26.83"N	ANC (mg/l)	-8.4		
	76°10'20.73"W	Flow (CFS)	NA		

Bowman’s Creek Raw Data

Station Name

Volumetric Flow
Net ANC Concentration

Volumetric flow in cubic feet per second

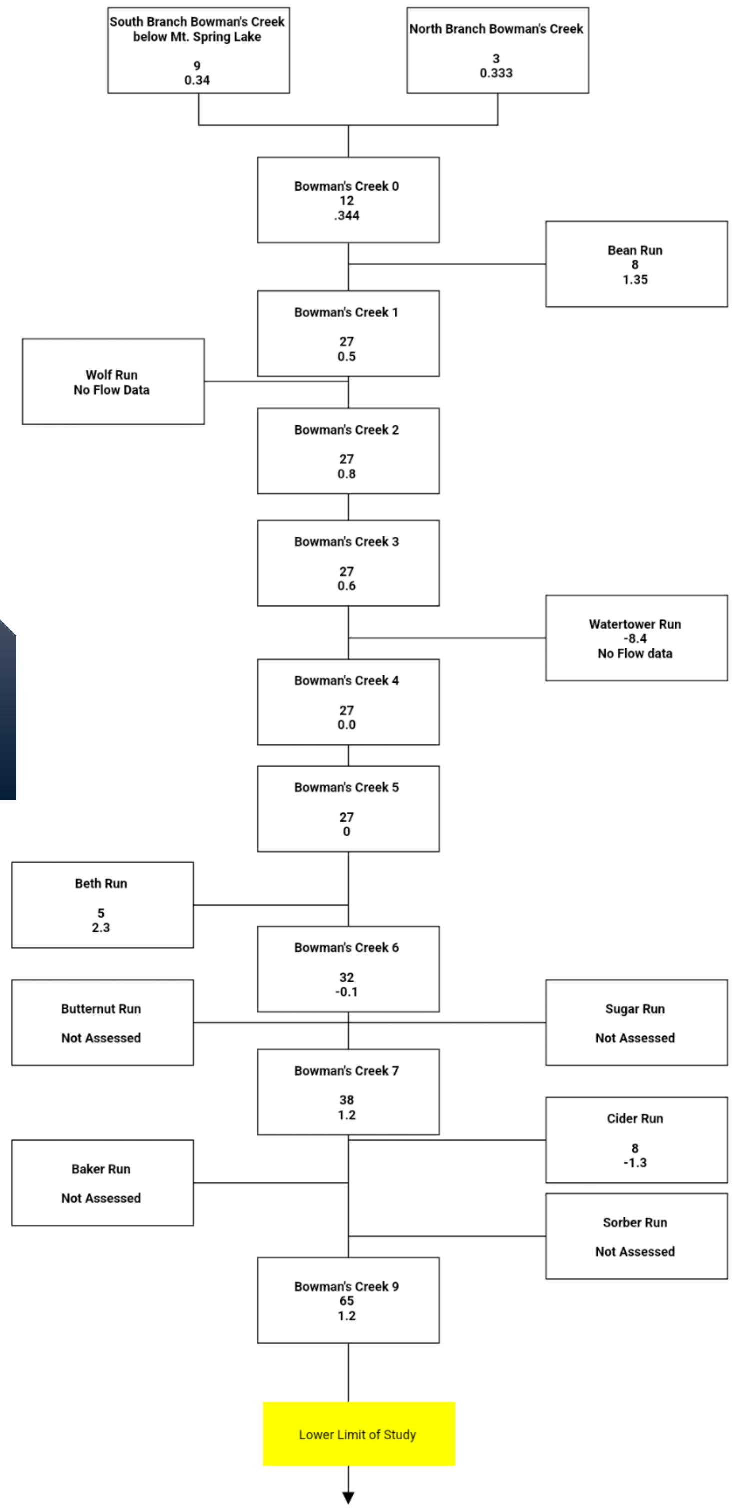


Figure 18: Current Flow and ANC Values

Table 5: Data and Calculated Results

Station Description	NB Bowmans above Bowmans marsh	NB at MTN spring Bridge (NBC-1)	sB above MTN spring Lake	SB Bowmans at MTN spring lake (SBC-1)	Bowman's Creek Above Wolf Run (BC-1)	Bowman's Creek Below Wolf Run (BC-2)	Bowman's Creek Above Water Tower Run (BC-4)	Cider Run (CR-1)
AVG Yearly Flow Rate (cfs)	3.00	3.00	7.00	9.00	27.00	27.00	27.00	8.00
Avg Yearly Flow Rate (Million L/Year)	2679.0	2679.0	6251.0	8037.0	24111.0	24111.0	24111.0	7144.0
Average Lab tested ANC values (mg/L as Calcium Carbonate) (Gran Method)	1.00	0.33	0.30	0.34	0.50	0.80	0.60	-1.30
Desired ANC (mg/L as CaCO3)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Current Tonnage per Year as CaCO3	2.95	0.98	2.07	3.01	13.29	21.26	15.95	-10.24
Desired Tonnage per Year as CaCO3	2.95	2.95	6.89	8.86	26.58	26.58	26.58	7.87
Calcium Carbonate Deficit (tons per year)	0.00	1.97	4.82	5.85	13.29	5.32	10.63	18.11
Station Description	Bowman's Creek Below Water Tower Run (BC-4)	Bowman's Creek Above Beth Run (BC-5)	Bowman's Creek Below Beth Run (BC-6)	Bowman's Creek Above Cider Run (BC-7)	Bowman's Creek At Sorber Mountain Bridge (BC-9)	Bean Run (BR-1)	Beth Run (BER-1)	
AVG Yearly Flow Rate (cfs)	27.00	27.00	34.00	38.00	65.00	8.00	5.00	
Avg Yearly Flow Rate (Million L/Year)	24111.0	24111.0	30362.0	33933.9	58044.9	7144.0	4465.0	
Average Lab tested ANC values (mg/L as Calcium Carbonate) (Gran Method)	0.00	0.00	-0.10	1.20	2.50	1.35	2.30	
Desired ANC (mg/L as CaCO3)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	
Current Tonnage per Year as CaCO3	0.00	0.00	-3.35	44.89	159.96	10.63	11.32	
Desired Tonnage per Year as CaCO3	26.58	26.58	33.47	37.41	63.98	7.87	4.92	
Calcium Carbonate Deficit (tons per year)	26.58	26.58	36.81	-7.48	-95.97	-2.76	-6.40	

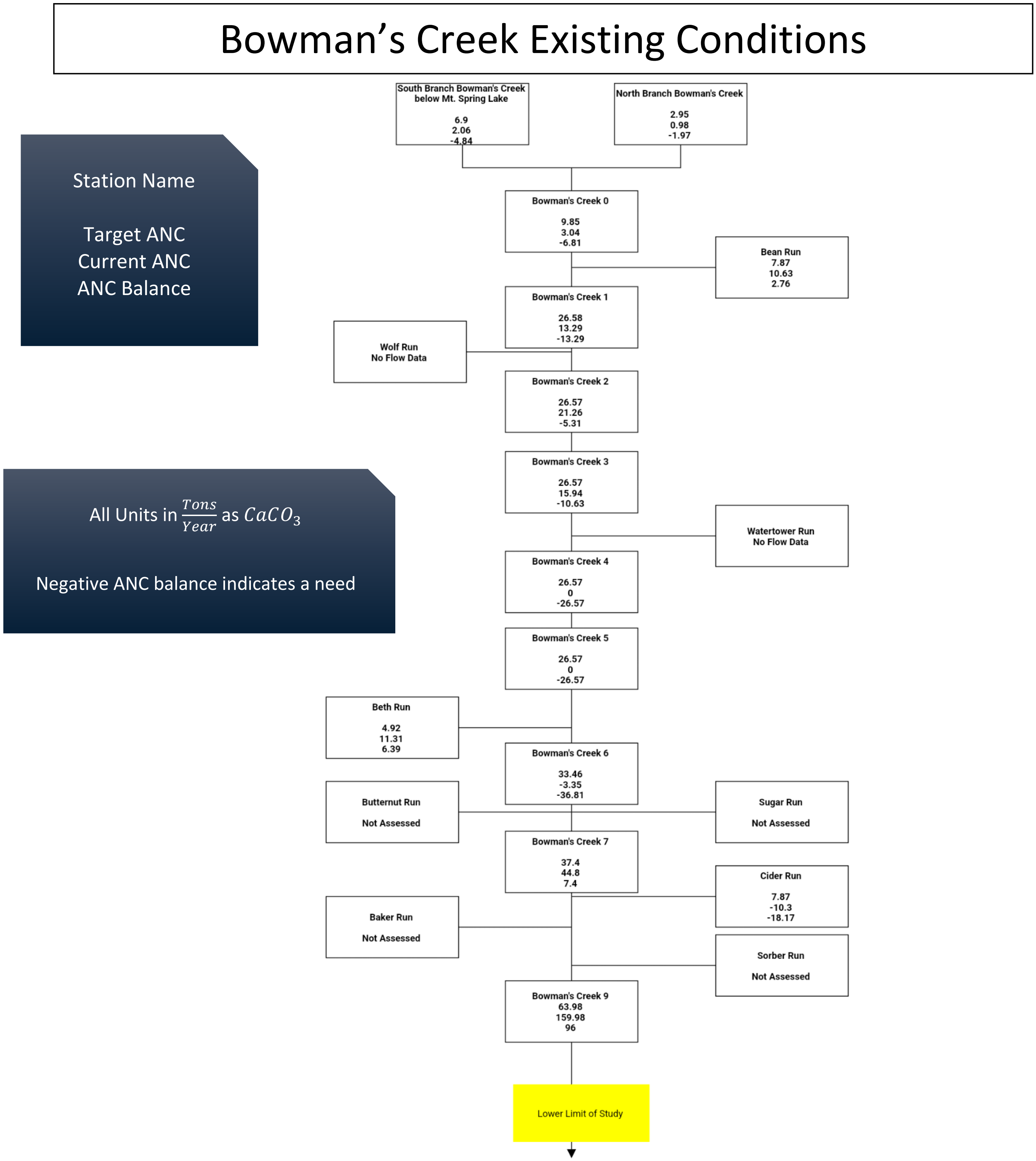


Figure 19: Existing Conditions

Recommendations

In comparison, alkalinity-generating devices with known outputs and efficiencies were considered over devices with unknown long term performance. While other technologies may work (including VFLB) these were not selected for the design as the long-term effectiveness of the devices is not known and this is something that should be considered if this report were to be implemented.

Once the existing conditions were determined, knowing the performance of an alkalinity addition technology helps in proposing where these structures can be implemented. While the alkalinity requirements were one part of where and how many devices were to be added, the physical characteristics of the stream, and the land around the stream are limiting factors to where devices can be added. The last item that was considered when choosing locations was if it was to be located on state-owned land. While most of the area of study is state-owned, several small privately owned parcels of land are to be avoided for long-term access to the projects.

Based on the mass balance, several systems would need to be installed in the headwaters of Bowman's Creek to reach the target ANC. Vertical flow wetlands would need to be constructed on both the North Branch of Bowman's Creek and South Branch Bowman's Creek to improve the upper portions of the stream from the confluence of the North and South branches down to just above the confluence of Wolf Run. Considering the constraints for vertical flow wetlands, and based on lidar mapping of the region, placing these structures near the remnants of the abandoned town of Mountain Springs makes the most sense.

In this area, there is an existing dry stream channel on North Branch Bowman's Creek that could be converted into a high-flow buffer channel with minimal excavation and construction required (Figure 20). The largest part of construction would be to create a grade control (Figure 21) at the intake of the channel to allow water to enter the channel at high flow rates. This would also have the added benefit of diverting water at high flow events away from the currently undersized bridge over the active channel of North Branch Bowman's Creek. During high flows, the flow overtops the existing bridge and causes excess erosion on the bridge abutments.

The next sizable tributary that enters Bowman's Creek is Bean Run. While this tributary has a higher ANC value than other streams, it is still below the restoration value and will need alkalinity addition to meet the goal. A single vertical flow wetland would bring Bean Run close to the targeted value. There are several reservoirs in the headwaters of Bean Run, making access for construction, along with providing the possibility for the existing reservoir to be used as the intake structure.

Traveling downstream the next large tributary that enters is Wolf Run. While no flow data was available for the stream, ANC data was collected that was below the target level. One single Vertical flow wetland would bring the stream to attainment. Likely placement of the treatment device would be in the large parking lot off the game lands main road.

Figure 20: Existing Channel to be Converted to High Flow Buffer Channel

Figure 21: Existing Channel Grade Control to be Excavated

Watertower Run had the lowest ANC value tested in the project and is a great candidate for restoration. We were unable to find a suitable location for any alkalinity addition device nearby and recommend continuing the addition of limestone sand near the confluence with Bowman's Creek. Additional surveys could be completed to determine the feasibility of an alkalinity device.

Beth Run has a deficit of 5.1 tons per year and is perfectly suited for the addition of alkalinity in the headwaters with a vertical flow wetland. Due to the state game land road along the watershed, additional grants should be pursued for the addition of limestone road materials in areas within proximity to the stream.

The addition of a high-flow buffer channel on mainstem Bowman's Creek could help maintain alkalinity during high-flow events. The necessary landform needed to construct a HFBC are not common in the Bowman's Creek watershed making it hard to quantify the number of needed devices. There are several locations around the confluence of Beth Run that could be utilized to create a buffer channel.

The lowest level stream needing remediation was Cider Run, which is currently being treated with riparian liming. A vertical flow wetland around the confluence of North Branch Cider Run and South Branch Cider Run would allow adequate flow to a wetland complex. Acid run was not sampled (tributary to South Branch Cider Run) but past data has shown the lowest pH values in the entire watershed. Due to the steep gradient and limited access, not much can be done other than riparian liming. An overall graphical depiction of these recommendations can be found in Figure 22, while exact locations can be found in Table 6.

Design Implementation

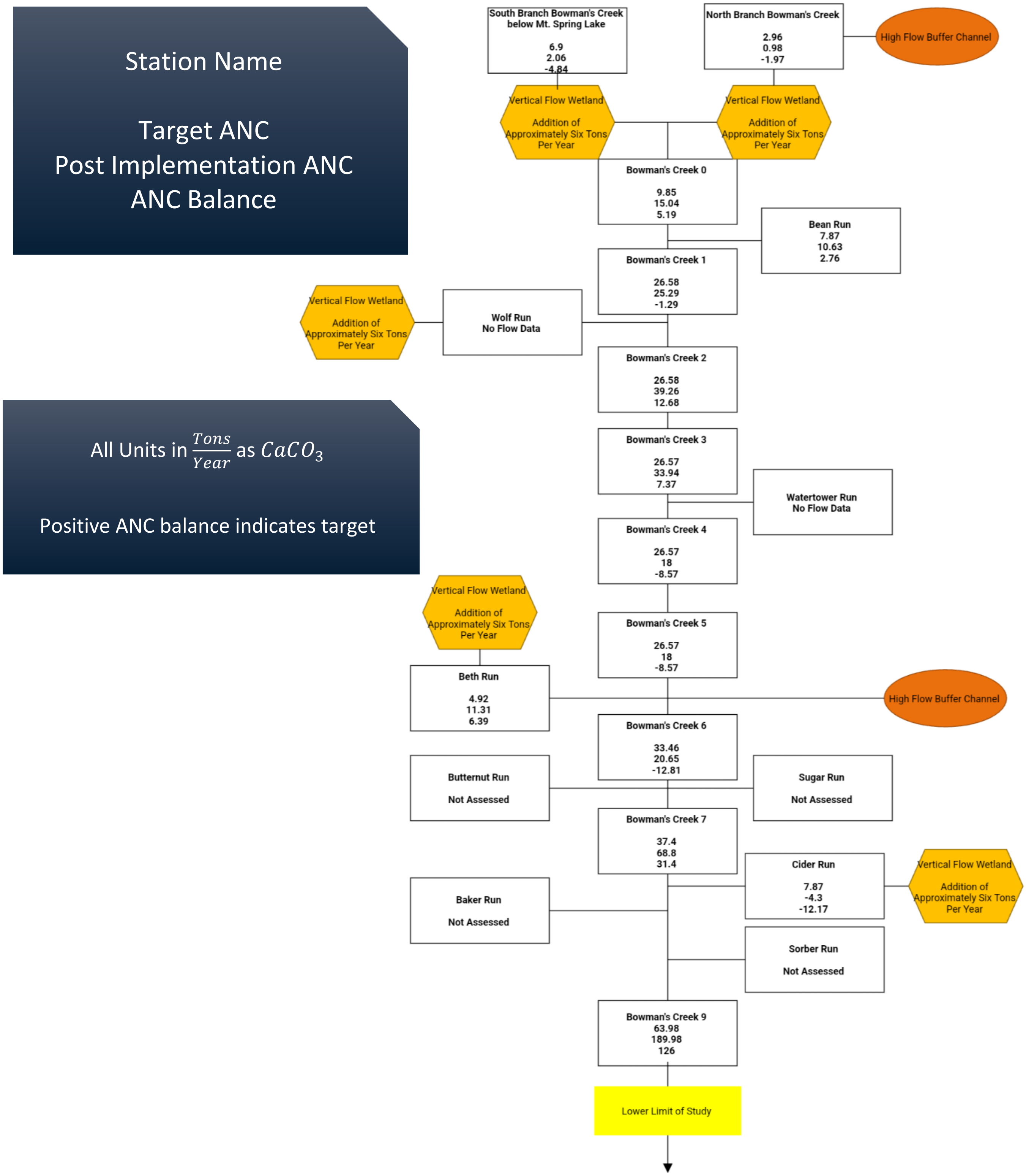


Figure 22: Design Flow Chart

Table 6: Buffering Addition Locations

ANC Addition Technology	Description	Coordinates
Vertical Flow Wetland	Bowman's South Branch	41°20'25''N, 76°13'29''W
Vertical Flow Wetland	Bowman's North Branch	41°20'30''N, 76°13'20''W
High Flow Buffer Channel	Bowman's North Branch	41°20'29''N, 76°13'16''W
Vertical Flow Wetland	Bean Run	41°21'47''N, 76°13'17''W
Verrical Flow Wetland	Beth Run	41°21'10''N, 76°9'33''W
High Flow Buffer Channel	Bowman's Main Stem	41°21'58''N, 76°9'40''W
Vertical Flow Wetland	Cider Run	41°23'43''N, 76°9'25'' W

Budget

AMDTreat was used to estimate the cost of constructing and maintaining the proposed alkalinity addition technologies. AMDTreat is a cost estimation tool developed by USGS and the Office of Surface Mining Reclamation and Enforcement that assists users in estimating costs and sizing facilities to abate water pollution using passive or chemical treatment technologies (OSMRE n.d.).

Based on similar implementation projects, it should be noted that people are more likely to pay for technology that has been proven effective in other regions of the state.

The proposed plan for remediation includes five vertical flow wetlands and two high flow buffer channels. Using AMDTreat, the cost associated with constructing a vertical flow wetland is determined based on the size of the wetland and the cost of material. The size of the wetland is calculated from the design flow into the wetland and the desired retention time through the limestone layer. The design flow into the wetland was evaluated at 80 gpm and the desired retention time is 18 hours. These values come from the previous implementation of vertical flow wetland technologies. AMDTreat is then able to calculate the size of the wetland, and any associated costs for excavation. Additionally, the costs associated with design, permitting, limestone material, and compost material are added to the total capital cost. It was determined from the program that the capital cost for each vertical flow wetland would be approximately $210,000. The capital cost for the implementation of five vertical flow wetlands and two high flow buffer channels was determined to be approximately $1.5 million.

Working on any restoration project for publicly owned assets can be quite difficult. Different people and groups have radically varying measures of success and value within a publicly owned tract of land. Also, in the case of streams impacted by atmospheric deposition like Bowman's Creek, tracking contaminant origin is nearly impossible. Funding for such projects is almost entirely handled by government agencies instead of private citizens and landowners. As a result, this report only suggests the funding required to build and maintain a collection of treatment systems and technology on the publicly owned upper reaches of Bowman's Creek.

While completion of this project requires some initial capital investment, the long-term benefits, while hard to quantify, are significant. Restoration of trout populations in Upper Bowman's Creek would not only benefit anglers, but many other relevant stakeholders as well. Local businesses will benefit from increased tourist traffic. Restored, nearby trout populations will inspire more fishing license purchases, benefiting the PA Fish and Boat Commission. Moreover, with the completion of this report, concrete goals have been established, an excellent first step in applying for grant money.

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Appendix A

Mosquito Creek Performance data

Within the Mosquito Creek project, a 18-24 hour detention time was targeted as longer residence times yielded diminishing ANC returns due to the dissolution rate decreasing as concentration increases.

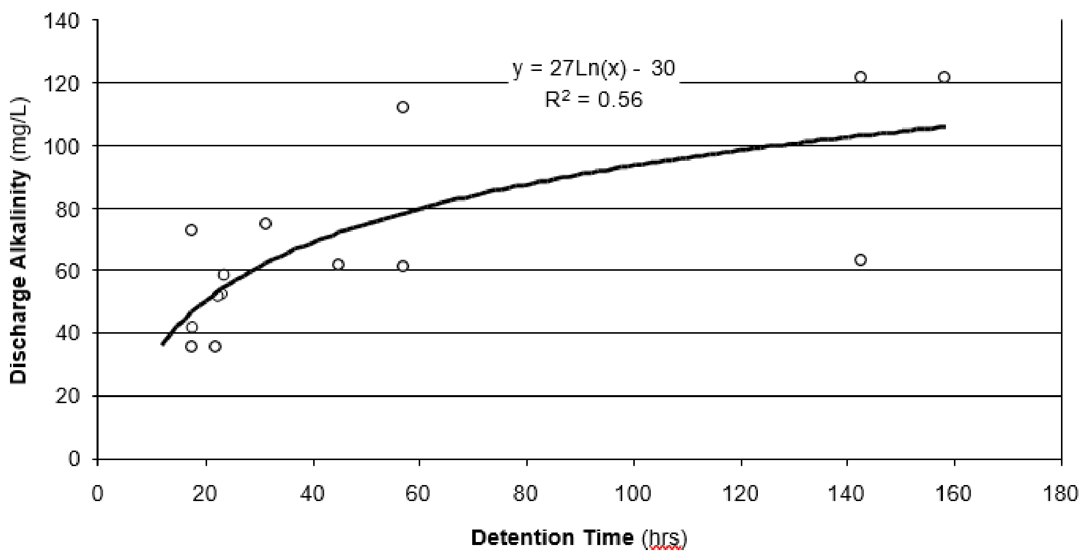
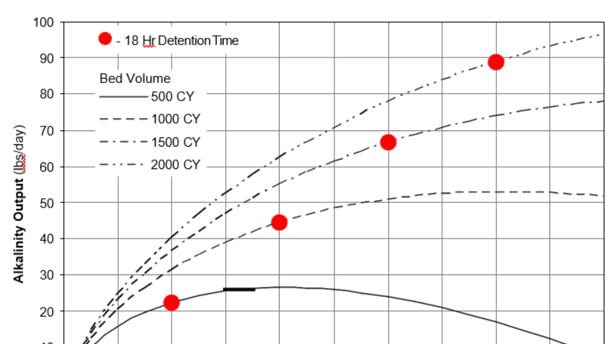


Figure A.1: Detention Time VS Discharge Alkalinity (Hoover, K. L., & Rightnour, T. A. 2006)

As a result, a flow rate of 90 gallons per minute is ideal as the designed flow rate for a 100 by 100-foot system. Shows the alkalinity discharged vs bed size with an 18-hour detention time. Detention time is based on the bed volume and the treated flow rate. If a larger flow rate is needed the bed volume should be increased to maintain maximum efficiency.



Flow Rate Vs Detention Time **Hoover, K. L., & Rightnour, T. A. (2006)**