

PASSIVE TREATMENT METHODS FOR ACID WATER IN PENNSYLVANIA



PENNSTATE



COLLEGE OF AGRICULTURAL SCIENCES
AGRICULTURAL RESEARCH AND COOPERATIVE EXTENSION

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INTRODUCTION

Acid rain and acid mine drainage have polluted thousands of miles of Pennsylvania streams with acid water. Many different types of acid water treatment systems have been developed over the past 30 years to combat this problem. These include both active and passive systems. Passive treatment systems rely on chemical and biological processes to treat acidity with little or no mechanical assistance or continuous maintenance. Active treatment systems are more costly to build and usually require daily manipulation by trained operators and frequent maintenance. Passive systems are more commonly used in smaller restoration projects by community organizations and watershed groups. The recent growth in community watershed organizations and available restoration funds through the Pennsylvania Growing Greener program serve to highlight the need for clear and concise information regarding passive acid water treatment systems.

The high incidence of acid rain and abandoned acid mine drainage areas in Pennsylvania has left many streams polluted and in need of restoration. Over 2,400 miles of Pennsylvania streams do not meet water quality standards due to acid mine drainage (AMD), and the Commonwealth has 135 miles of chronically acidified streams due to acid rain. However, many more miles of streams are degraded to some extent by acid runoff episodes. Acid runoff episodes degrade stream water quality and often result in the elimination of fish and other aquatic life.

THE CHEMISTRY OF ACIDIC STREAMS

The following are five basic chemical measurements that can help determine which acid water treatment to use:

pH—Measures the amount of free hydrogen ions (H⁺) in water. The pH ranges from 0 to 14, with a pH of 7 being neutral and indicating water that is neither acidic nor basic. Water with a pH below 7 is acidic; water with a pH greater than 7 is basic. (See Figure 1.) The most common natural control of the pH of water is the bicarbonate buffering system, which depends on the amount of calcium carbonate dissolved in the water. pH is an important water quality variable because aquatic animals are sensitive to changes in pH, especially when these changes are sudden or large.

Alkalinity—Often defined as the capacity of a solution to neutralize acidity. The important property of alkalinity is that it acts as a buffer.

One aim of treatment for acid-impacted water is to increase alkalinity by dissolving substances with calcium carbonate (CaCO₃), such as limestone, into the water. While many different substances can add alkalinity, calcium carbonate is most often the major contributor in natural waters. For this reason, alkalinity is usually shown as an equivalent amount of CaCO₃. One confusing aspect of alkalinity is that a solution can be mildly acidic but also contain some alkalinity. In fact, this can often happen as a result of treatment of acidic water. Having water with high alkalinity, particularly when there is a likelihood of this water mixing with more acidic water at some point downstream, is usually desirable.

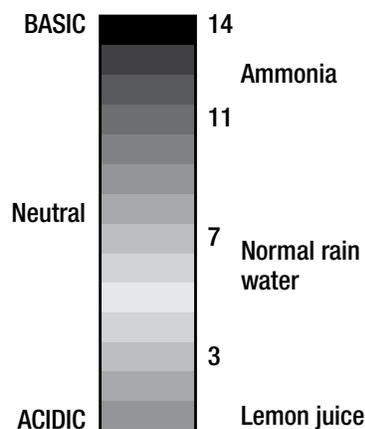
Acidity—Measures the capacity of water to neutralize alkalinity. An acid mine drainage stream that has an acidity of 100 mg/L CaCO₃ would require that much carbonate to neutralize the acid. For work on streams affected by acid mine drainage, knowing both the alkalinity and acidity before and after treatment is important.

Acid Neutralizing Capacity (ANC)—Another measurement similar to alkalinity. The difference between ANC and alkalinity is that ANC measures the net condition of the water. For example, an ANC below 0 means the water is acidic and has no buffering capacity. If the ANC is above 0, the water has some buffering ability.

Metals—Iron (Fe), manganese (Mn), and aluminum (Al) are common in acid mine drainage. Aluminum (Al) is the most common toxic metal in streams affected by acid rain. During treatment, pH and alkalinity must be high enough so that when metals precipitate, sufficient alkalinity remains to buffer any additional acid inputs.

In AMD treatment, iron and manganese precipitate at different pHs.

Figure 1. Range of pH.



Manganese requires a higher pH—generally around 8.0—compared to the 6.5 needed for iron to precipitate. Often, many passive treatments are unsuccessful at removing manganese due to this high pH requirement.

Metals are an important factor to consider because they are toxic to aquatic life and harm their habitats. For example, metal precipitate on the bottom of streams covers and destroys habitat for many types of aquatic insects. Dissolved aluminum is toxic to fish and can cause fish kills. These side effects must be considered in any plan to treat acid streams.

TREATMENT OBJECTIVES AND GUIDELINES

Acid water treatment methods can be divided into two categories: Category I passive treatment methods and Category II passive treatment methods. The division is based on differences in treatment objectives. Category I methods aim to increase pH and alkalinity; Category II methods attempt to increase pH and alkalinity and remove metals.

CATEGORY I: RAISE PH AND ALKALINITY

Category I methods neutralize acidity by raising pH and alkalinity. Category I methods differ mainly in the delivery of acid neutralizing compounds. None of the methods are 100 percent effective, and varying site-specific characteristics can alter success rates even within the same method. For instance, acid rain has affected some areas in Pennsylvania more severely because of higher aluminum inputs from forest soils to streams. Limestone sand may be less successful in these areas than in others because aluminum will precipitate in large amounts and remain in the stream.

CATEGORY II: REMOVE METALS

Category II systems remove metals in addition to raising pH and alkalinity. Metals are removed by one of four processes. The first two processes are metal uptake by plants or metal adsorption to the substrate. These processes do not occur at rates sufficient to provide much benefit in standard treatment systems. The third process is called oxidation and occurs when water is close to a pH of 7 and

contains oxygen. The fourth method is bacterially mediated sulfate reduction. Bacteria, which are sustained by organic-rich substrates, reduce sulfate in the mine drainage. This reaction produces bicarbonate alkalinity and reduces the sulfate to sulfide. The sulfide then reacts with the toxic metals present in the water, which precipitate or settle out of the water. Some sulfide will combine with hydrogen to form the gas hydrogen sulfide, which escapes into the air. Bacterial sulfate reduction can occur in both aerobic (with oxygen) and anaerobic (without oxygen) wetland designs, but is promoted in anaerobic wetlands.

The chemical nature of the mine drainage may dictate the metals-removal process. Oxidation reactions are appropriate for net alkaline mine drainage, because oxidation reactions lower pH. Therefore, alkalinity levels in mine drainage must be high enough to counteract the acidity produced by the oxidation of metals.

In contrast, alkalinity is added to net acidic drainage by the reduction of sulfate and by addition of an acid neutralizing compound such as limestone.

MANAGEMENT STEPS

The Category I and Category II divisions are used to understand the treatment processes that are most important to these methods. Category I passive treatment methods include watershed liming, wetland liming, in-stream limestone sand, alkaline groundwater addition wells, limestone diversion wells, and anoxic limestone drains (ALD). Category II methods include aerobic wetlands, anaerobic wetlands, and successive alkalinity producing systems (SAPS). Selection of a particular method depends on the chemistry of the water to be treated and treatment objectives, which may vary from restoring fisheries to simply improving downstream habitat conditions for aquatic insects. Before selecting a treatment method, the following should be considered:

First, determine the physical and chemical characteristics of the stream to be treated; second, review treatment goals; third, examine the advantages and limitations of different treatment systems as they relate to your project objectives; and fourth, ensure that a program is in place for the operation and maintenance of whatever system is selected.

PASSIVE TREATMENT METHODS

CATEGORY I

The following Category I methods are most often used to treat streams affected by acid rain. They can be used alone or in combination with each other. In fact, it has been recommended that treatment be done on a watershed basis using a combination of methods, including watershed liming, in-stream limestone sand, and wetland liming.

A watershed is the area of land that contributes water to a certain point in a stream or another body of water. You can use a topographic map to determine watershed boundaries and to look at the physical characteristics of the landscape surrounding the stream of interest. Acid rain affects the entire watershed, not just the streams draining the watershed. In all instances, streams should be monitored throughout treatment and during high and low water flows to determine if application amount and frequency are adequate.

WATERSHED LIMING

Basic Design Principles and Operation

Watershed liming consists of spreading ground agricultural limestone over all or part of a watershed to neutralize the acidity of water draining that watershed. The added limestone reacts with rain and snowmelt water moving through the soil to make it less acidic. The less-acidic water will not leach aluminum from the soil into nearby streams and will not result in episodes of acidic runoff. A side benefit from

whole-watershed liming is increased forest productivity and better forest health.

No specific guidelines are available for watershed liming for streams in the United States. High-quality agricultural lime with high concentrations of CaCO_3 works best for acid water treatment, but high magnesium lime is best for the forest. A compromise between the two may be desirable for most applications. If helicopter application is planned, pelletized lime must be used. Smaller amounts can be specified because of the higher purity of this material. We recommend using 1 ton per acre of pelletized lime with high magnesium content. Ground application with specially constructed spreading equipment is possible on flatter terrain, provided that the tree cover allows sufficient spreader movement.

Most studies have shown watershed liming to be an appropriate mitigation approach for lakes. Watershed liming may also be used for streams, although the effects may not last as long.

Advantages of Watershed Liming

- Effective duration longer compared to in-stream liming methods; in some cases effects last 10 to 20 years.
- Lower amount of aluminum is exported to streams. May have less aluminum precipitate on stream bottom compared to other stream liming methods.
- Forest growth, health, and overall productivity potentially improved.

Limitations of Watershed Liming

- Much higher short-term cost than in-stream limestone sand method. However, long-term cost benefits are most likely equivalent or lower than other methods.
- Limited control of short-term acid runoff events. May need to be combined with other methods.

IN-STREAM LIMESTONE SAND

Basic Design Principles and Operation

Limestone sand is placed directly into the streambed of high-gradient headwater streams. The sand dissolves into the water column as it spreads downstream during high stream flow periods (see Figure 2). Dissolved limestone sand adds CaCO_3 , which in turn results in higher pH and ANC and lowered aluminum concentrations.

Where to add the limestone depends on treatment objectives and road access. For example, a dump truck delivering limestone sand may weigh as much as 30 tons and require bridges rated for such heavy loads. Smaller trucks may be used to ferry limestone sand into less accessible areas, and helicopters could be used to reach more remote areas. Wherever the limestone is placed, the site should have sufficient flow and stream gradient to carry sand downstream. Sand placed in fish spawning areas may temporarily destroy the spawning habitat.

Roads, weather, and water quality dictate the timing of limestone sand addition. For example, having greater availability of limestone during spring high flows can help control the acid runoff episodes associated with streams affected by acid deposition. Since access to remote sites may be especially difficult in the spring, sand may be stockpiled at sites in the fall for addition in early spring. The frequency and timing of limestone sand addition may vary with stream conditions.

The type of limestone sand added should be Grade A agricultural limestone, with high CaCO_3 content and of sand size (average diameter of about 0.02 inches). Most research on limestone sand effectiveness has used limestone with calcium carbonate content higher than 97 percent. Use limestone with calcium content of at least 90 to 100 percent.

Figure 2. Limestone sand piles just after addition to the headwaters of an acidified stream (note water in the foreground). The piles will be washed downstream at high stream flow.



S. R. LeFevre photo

The amount of limestone sand added should, theoretically, be sufficient to neutralize the acid load in the stream. The amount of the acid load varies based on flow and concentration of hydrogen ions in stream water. Total annual flows at a given point in a watershed are dependent on the watershed area draining to that point and annual precipitation amounts. Three formulas have been proposed to calculate the amount of limestone sand needed to neutralize annual acid load. These are the West Virginia, Clayton, and Virginia formulas.

The West Virginia Formula is the simplest method of the three, and requires only that the surface area of the watershed in acres be known. This method assumes that acid loading is a consequence of acidic deposition and accounts for flow by relating the amount of lime used to watershed area. Implicit in this formula is that stream water acidity is low and relatively constant throughout the year.

West Virginia Formula

Limestone Sand Applied (tons) = Watershed Surface Area (acres) x 0.05 tons/acre

This amount should be doubled for the first year.

Clayton Formula

Limestone Sand Applied (metric tons) = Watershed Surface Area in hectares (1 hectare = 2.4 acres) x dosage factor

This amount should be doubled for the first year.

Virginia Formula (Downey Formula)

Limestone Sand Applied (tons) = Watershed Surface Area (acres) x D_1 (dosage factor)

This amount should be doubled for the first year.

The Clayton Formula attempts to account for different stream water acidity by using pH to calculate a dosing factor. Stream water acidity and pH for many different watersheds were compared and used to obtain the relationship shown in Figure 3. The amount of limestone is calculated as follows:

- Determine the watershed surface area in hectares.
- Obtain annual mean pH of stream. This requires monitoring the stream for at least a year prior to adding limestone sand, and should include pH at both high and low stream flows.
- Determine dosing factor. First, locate annual mean stream pH at the bottom of the graph and draw a vertical line perpendicular to the pH line as shown by the dotted line labeled 1 in Figure 3. At the point where line 1 crosses the curved line draw a horizontal line (line 2) parallel to the horizontal pH scale line until it intersects the vertical dosage factor scale line. Read the dosage factor nearest to this intersection point, always selecting the higher value (0.04 in the example shown).
- Calculate amount of limestone using the Clayton Formula by multiplying the watershed area in hectares by the dosage factor (0.04) from Figure 3 as shown.

Example: Assume a watershed area of 100 hectares:

Limestone sand required = 100 (watershed area in hectares) x 0.04 (dosage factor). The answer for this example is 4 metric tons or 4.4 U.S. tons (1 metric tonne = 1.102 U.S. tons).

The Virginia Formula, also known as the Downey Limestone Sand Dose Model, also varies the amount of limestone sand added based on pH. However, it uses mean spring pH instead of annual pH,

Figure 3. Clayton Method dosing factor graph.

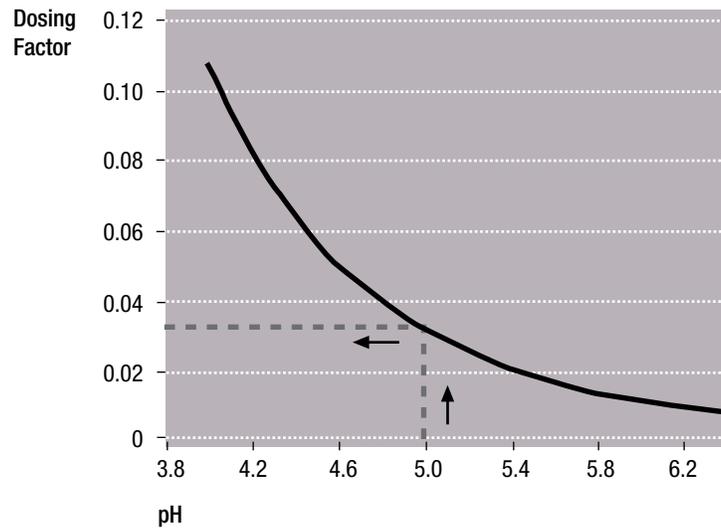
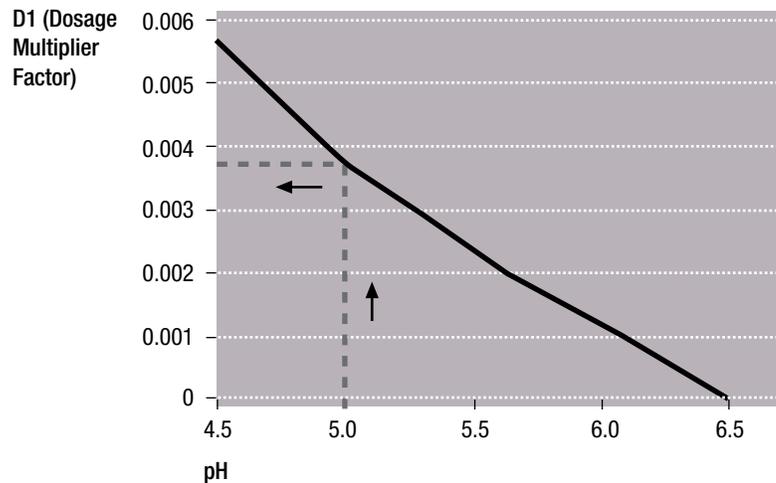


Figure 4. Virginia Method dosing factor graph.



which is more conservative because stream acidity as a consequence of acid deposition is always highest (lowest pH) at high flows.

- Determine watershed size in acres.
- Determine mean stream pH under normal flow conditions in spring by monitoring.
- Estimate D₁ (dose factor) using Figure 4 in exactly the same manner as explained for using Figure 3 in the Clayton Formula. Example shown is for a mean spring pH of 5.0.

- Calculate the amount of limestone sand required by multiplying the surface area of the watershed upstream of the application point by the dosage factor.

Example: Assume watershed area of 240 acres (100 hectares):
Limestone sand required = 240 acres x 0.004 = 0.96 U.S. tons

All methods require that the first application be double the recommended amounts.

Advantages of Limestone Sand

- No maintenance, simple, and relatively inexpensive.

Limitations of Limestone Sand

- Water quality improvement may be inconsistent.
- The three formulas are contradictory in their recommendation for limestone sand amounts. However, the pH of the water to be treated is an important variable that should be accounted for. A more conservative approach would involve using the lowest pH measured to calculate the dosage factor. This may enhance fish survival. Not enough information is available to allow for a clear-cut recommendation regarding the best method to use.
- Effectiveness diminishes with time. Limestone sand must be applied repeatedly, usually at least once per year.
- In the case of moderate to high aluminum loads, increasing the pH will cause aluminum to precipitate onto the streambed. This may change the community makeup of bottom-dwelling insects in downstream areas near sand introduction points, and it could result in the remobilization of large amounts of aluminum under future acidic conditions.
- Access to remote sites could limit use.

WETLAND LIMING

Basic Design Principles and Operation

Wetland liming involves the direct application of finely ground limestone to wetlands, where it mixes with the top soil layer. This method is very successful when wetlands make up a significant portion of the watershed, especially in riparian (streamside) areas.

Again, no guidelines exist for wetland liming. Amounts used range from the minimum of 3.3 tons per acre upward. The limestone should be finely ground or pulverized and high in CaCO_3 , or Grade A agricultural limestone. Where aerial application is required, pelletized lime must be used at considerably higher cost (up to \$100 per ton more). Limestone with magnesium should be avoided. Wetland liming does not have to be repeated as often as in-stream limestone sand, although times can vary. A monitoring program can help determine if more limestone should be added.

Advantages of Wetland Liming

- Less area to lime than an entire watershed, with reported greater effectiveness.
- Effective duration longer than instream limestone sand.

Limitations of Wetland Liming

- Not as effective at low flow on chronically acidified watersheds.
- Pelletized lime may be required at higher costs.
- Application by air or by boat may be required at increased costs.

PUMPING ALKALINE GROUNDWATER

Basic Design Principles and Operation

Groundwater previously stored in limestone or calcareous shale bedrock is the main source of alkalinity for many headwater streams in Pennsylvania. We can exploit this natural condition by pumping alkaline groundwater directly into streams from underlying aquifers. To date, groundwater pumping has only been used in Pennsylvania on an episodically acidified stream to restore a seasonal put-and-take trout fishery.

This method requires a groundwater source able to yield significant amounts of alkaline water, a well and pump, and a power source to operate the pump. A hydrogeologist skilled in fracture trace water well location should be used to locate the wells for maximum yields, and as much information as possible should be obtained about the ANC of local groundwater and volume and acidity of the stream to be treated. Installation costs where power is available at the well site are about \$5,000 to \$7,000 per well. Operating costs, assuming full-time pumping, are about \$300 per month for a pump capable of delivering 125 gallons of water per minute (gpm).

Advantages of Pumped Groundwater

- Lifetime of system equal to sustainability of groundwater source.
- Relatively simple.
- Modest operating costs.
- Operation can be fully automated.

Limitations of Pumped Groundwater

- Requires reliable alkaline groundwater source.
- Requires power supply and maintenance of power lines.
- Aluminum precipitation may be an issue downstream of the well discharge point.
- Requires site accessible to drilling rigs.
- Wells should be sited by a hydrogeologist who has fracture trace mapping experience.

LIMESTONE DIVERSION WELLS

Basic Design Principles and Operation

Diversion wells are used to raise alkalinity and pH in streams affected by acid deposition and by acid mine drainage. The diversion well is a

concrete circular casing that resembles a large diameter, shallow well sunk into the ground next to the stream. To force water through the well, a small intake dam is constructed upstream from the well to create an elevation difference between the well and the intake of 8 feet to 13 feet (2.5 m to 4 m). Water enters through an 8- to 12-inch (20 to 30 cm) intake pipe at the dam and is piped downstream to the well. Water exits the pipe a few inches from the bottom of the well and flows upward, fluidizing or suspending the limestone, before it exits through an overflow pipe back into the stream. The fluidized bed of limestone dissolves and is slowly added to the stream. The suspended gravel-sized particles grind against one another improving their solubility by maintaining fresh reaction surfaces. (See Figure 5.)

The limestone gravel should be about 0.8 to 1.2 inches in diameter and have calcium content greater than 85 percent. The wells should be filled

to about 2/3 their depth with limestone. Generally the well can hold enough limestone to last 1 to 2 weeks.

Limestone diversion wells can treat streams with relatively small flows. During low flow periods, all the water will be diverted through the well to maintain a fluid bed, while at higher flows the well receives only part of the total stream flow. For this reason, the greatest pH rise occurs when flow is at the minimum level. When necessary, more than one diversion well may be constructed on a stream system to provide adequate acid neutralization. Well construction specifications can be found in Arnold and Gray (1998). Estimated costs to a typical citizen organization using free labor are \$5,000 to \$6,000 for installation and \$1,000 yearly thereafter for supplies and maintenance.

Advantages of Limestone Diversion Wells

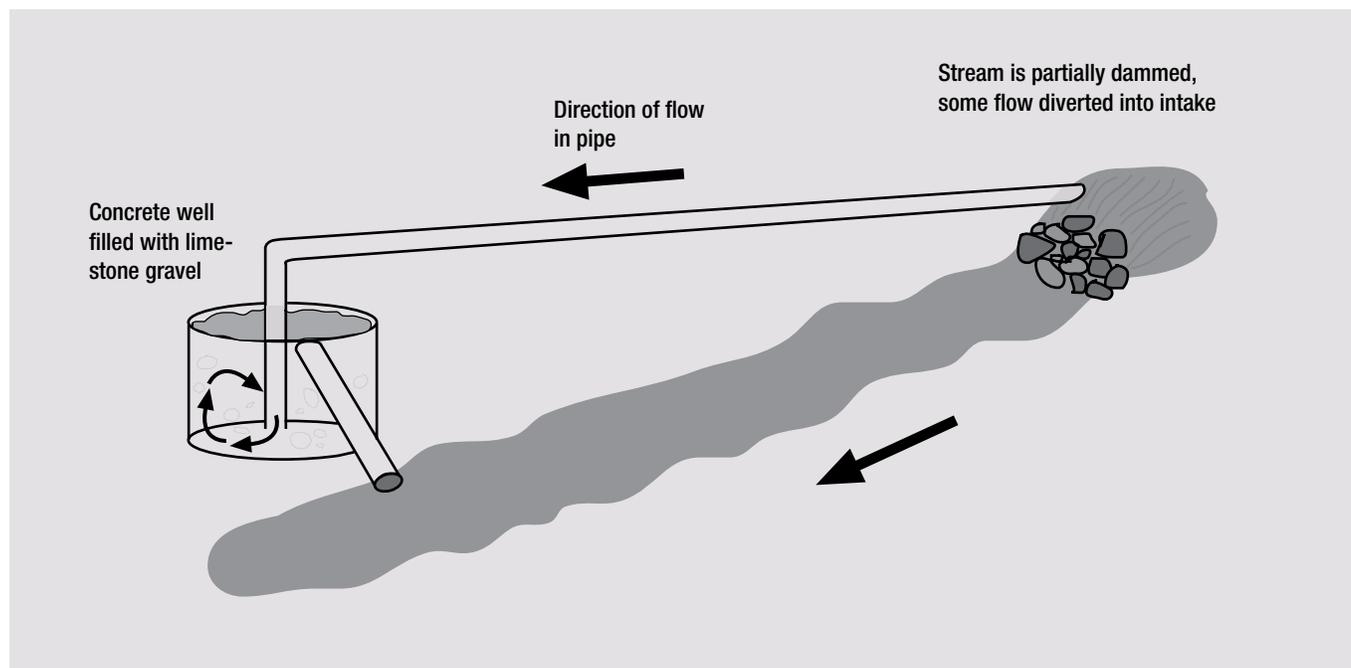
- Typical pH increases are about ½ to 2 units during average flows.

- Increased ANC and decreased metals concentrations. A quick glance at results from 13 diversion wells in Pennsylvania revealed ANC increases ranged from 0 to 75 milligrams per liter, with an average around 4 milligrams per liter. Both aluminum and iron decreased from 2 percent to 56 percent.
- Multiple diversion wells can be installed to increase effectiveness.

Limitations of Limestone Diversion Wells

- Aluminum and other metals may precipitate in receiving stream.
- Treats small flows. More likely to fail on streams where the flow regime varies widely.
- Maintenance required is weekly to biweekly; refilling well with limestone and clearing intake of debris.
- Intake repairs due to high flows may be required periodically.
- Need good access to deliver limestone.

Figure 5. Cross-sectional diagram of limestone diversion well.



ANOXIC LIMESTONE DRAINS (ALD)

Basic Design Principles and Operation

Anoxic limestone drains (ALDs) are buried trenches of limestone that receive acid mine drainage and convert net acidic water to net alkaline water under anoxic (without oxygen) conditions. The anoxic environment prevents limestone from becoming coated or armored with metals, which normally occurs when oxygen is present. Limestone that is coated with metals will not dissolve; consequently it will not neutralize acidity. The net alkaline drainage can then exit the ALD and enter a constructed wetland or settling pond where metals will oxidize and settle to the bottom of the pond.

An ALD consists of a trench lined with plastic, filled with chunks of limestone about the size of a baseball, and buried under several feet of clay (see Figure 6). The trench should be inundated with water at all times and intercept mine water low in dissolved oxygen. Typically, water intercepted right out of the mine is low in dissolved oxygen. However, some deep mine discharges may

be high in dissolved oxygen due to conditions within the mine. An ALD would not be suitable for treating such discharges.

The maximum amount of alkalinity produced by an ALD is about 275 to 300 mg/L CaCO_3 . The size of the drain is determined using this theoretical maximum alkalinity in combination with the projected flow rate through the ALD and the acid load of the drainage.

The life of this system depends on the dissolution rate of the limestone, but may be much less due to limestone armoring or other operational difficulties.

Experience has shown that ALDs are most effective at treating water with the following qualities:

- Net acidic: less than 300 mg/L
- pH less than 6
- Very low concentrations of aluminum (Al) and ferric iron (Fe^{3+}): Al less than 1mg/L, Fe^{3+} less than 1 mg/L
- Moderate concentrations of iron if in the ferrous form: Fe^{2+} may be greater than 20 mg/L
- Very low Dissolved Oxygen: D.O. less than 1 mg/L

Advantages of Anoxic Limestone Drains

- Effective method to neutralize acidic AMD.
- Increases efficiency of other treatment types. For example, anoxic limestone drains are used to pre-treat AMD prior to entering a wetland system. ALDs can also be used as a post-treatment system to add additional alkalinity.
- Significantly reduce the size of the treatment area.

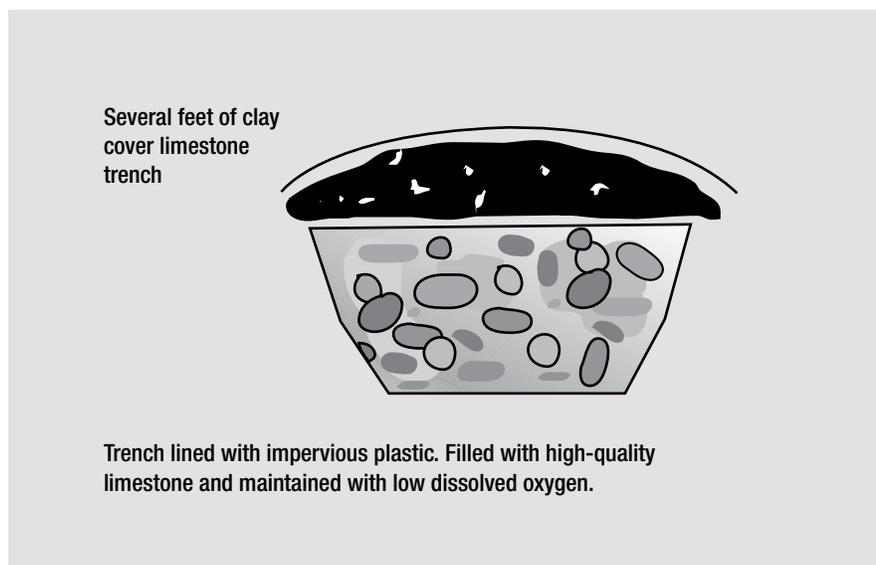
Limitations of Anoxic Limestone Drains

- Variable alkalinity output.
- Effluent pH difficult to maintain over time.
- Treatable effluent limited to low oxidized metal concentrations (aluminum and ferrous iron) and low dissolved oxygen.

CATEGORY II

The following methods have mainly been used for treating acid mine drainage. Some of these systems could be appropriate for streams affected by acid rain, depending on the cost-benefit ratio as compared to the previous methods. The main difference among the following systems is that they are each designed to be most efficient given a different set of water quality parameters. Determining cost for any one of these systems, given differences in site characteristics and the fact that many projects are a combination of different methods, is difficult. However, a list of recent projects (see Appendix C) supported by the Pennsylvania DEP Bureau of Abandoned Mine Reclamation revealed a total cost range of \$166,000 up to \$1 million.

Figure 6. Cross-section of an anoxic limestone drain.



AEROBIC WETLANDS

Basic Design Principles and Operation

Aerobic wetlands are used to treat mine drainage that is net alkaline and contains low to moderate concentrations of metals (iron, aluminum, and manganese). The purpose of an aerobic wetland is to aerate the water, and remove iron, aluminum, and manganese through oxidation and hydrolysis. Although dimensions may vary, an aerobic wetland design consists of about 1 to 3 inches of standing water on top of 1 to 3 feet of an impermeable substrate such as clay. Wetlands are measured in acres or square meters, and the overall size is dependent on the concentration of iron, aluminum, and manganese in the influent water (see Figure 7).

Wetland plants help provide more uniform flow and introduce organic material. Plants should be native to the region and selected based on their ability to tolerate the quality of incoming water. Commonly used

species include cattails (*Typha*) and rushes (*Juncus*). However, a more diverse species composition generally enhances wetland health.

Aerobic wetlands treat acid mine drainage influent that meets the following criteria:

- pH greater than 5.5
- Net alkaline. May treat water with acidity less than 100 mg/L, but generally have lower iron removal rate and no manganese removal.
- Low to medium metal concentrations. Up to 50 mg/L iron and 15 mg/L manganese.
- Low to moderate flow rates if the area available for the wetland limits wetland size.

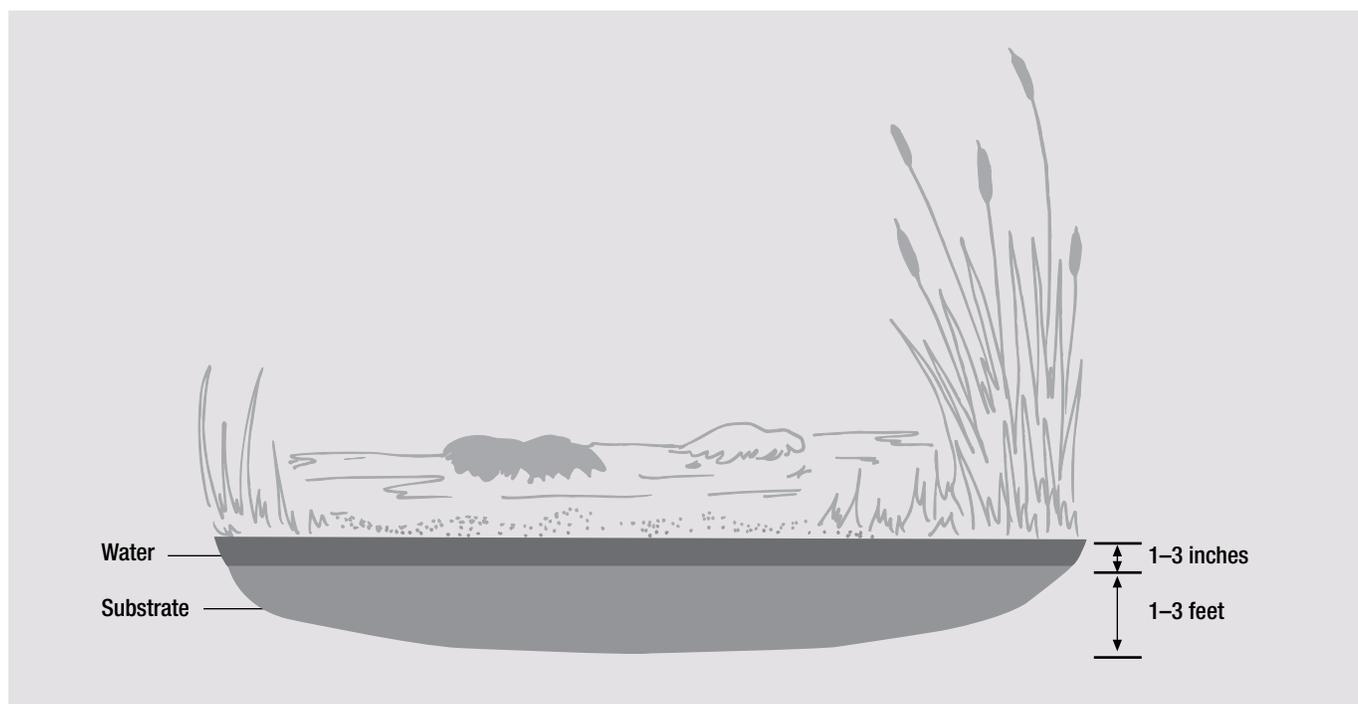
Advantages of Aerobic Wetlands

- Relatively inexpensive—estimated costs from about \$10 per square yard without plants up to \$30 per square yard with plants.
- Lower maintenance than active treatment systems.

Limitations of Aerobic Wetlands

- Metal load limitations of 0.00042 to 0.00084 pounds per square foot per day (10–20 grams per square meter per day) for iron and 0.000084 pounds per square foot per day (2 grams per square meter per day) for manganese. These metal removal rates are for the concentrations listed previously at pH greater than 8.0. Metal removal efficiencies vary because pH is seldom constant.
- pH decreases as metals are removed.
- Land area required must be quite large.
- Limited useful life. Substrate becomes saturated with metals and must be replenished or replaced. Most are constructed within a 15- to 25-year lifetime.

Figure 7. Cross-section of an aerobic wetland.



ANAEROBIC WETLANDS

Basic Design Principles and Operation

Anaerobic (or anoxic) wetlands add alkalinity, raise pH, and promote removal of metals. They appear similar to aerobic wetlands but have a thick, permeable, organic substrate that is either mixed with limestone or placed over a limestone bed. The combination of the organic substrate and limestone removes metals and adds alkalinity. The organic substrate keeps the water moving through the system free of oxygen so that the metal ions in the acid mine drainage remain in a reduced state. This prevents the coating or armoring of limestone.

Anaerobic wetlands consist of 1 to 3 inches of water on top of a substrate that is 2- to 3-feet thick. The mine water moves horizontally through the substrate layers from an inlet point to an outlet point. The

organic substrate is approximately 1 to 2 feet thick with a limestone layer 0.5 to 1 foot in thickness (see Figure 8). The most common type of substrate is spent-mushroom compost combined with limestone, although any high organic content compost will work. Wetland plants can be used since they stimulate microbial processes; however, they may not survive in highly acidic environments.

Wetland size depends on the influent water acidity and metal concentrations. The U.S. Bureau of Mines standard wetland size is based on removing 0.01 pounds (5 grams) of acidity, 0.02 pounds (10 grams) of iron, and 0.001 pounds (0.5 grams) of manganese per square yard per day. However, if an anaerobic wetland is used in combination with other methods such as an anoxic limestone drain, 0.044 pounds (20 grams) of iron removal per square yard may be possible. Anaerobic wetlands treat

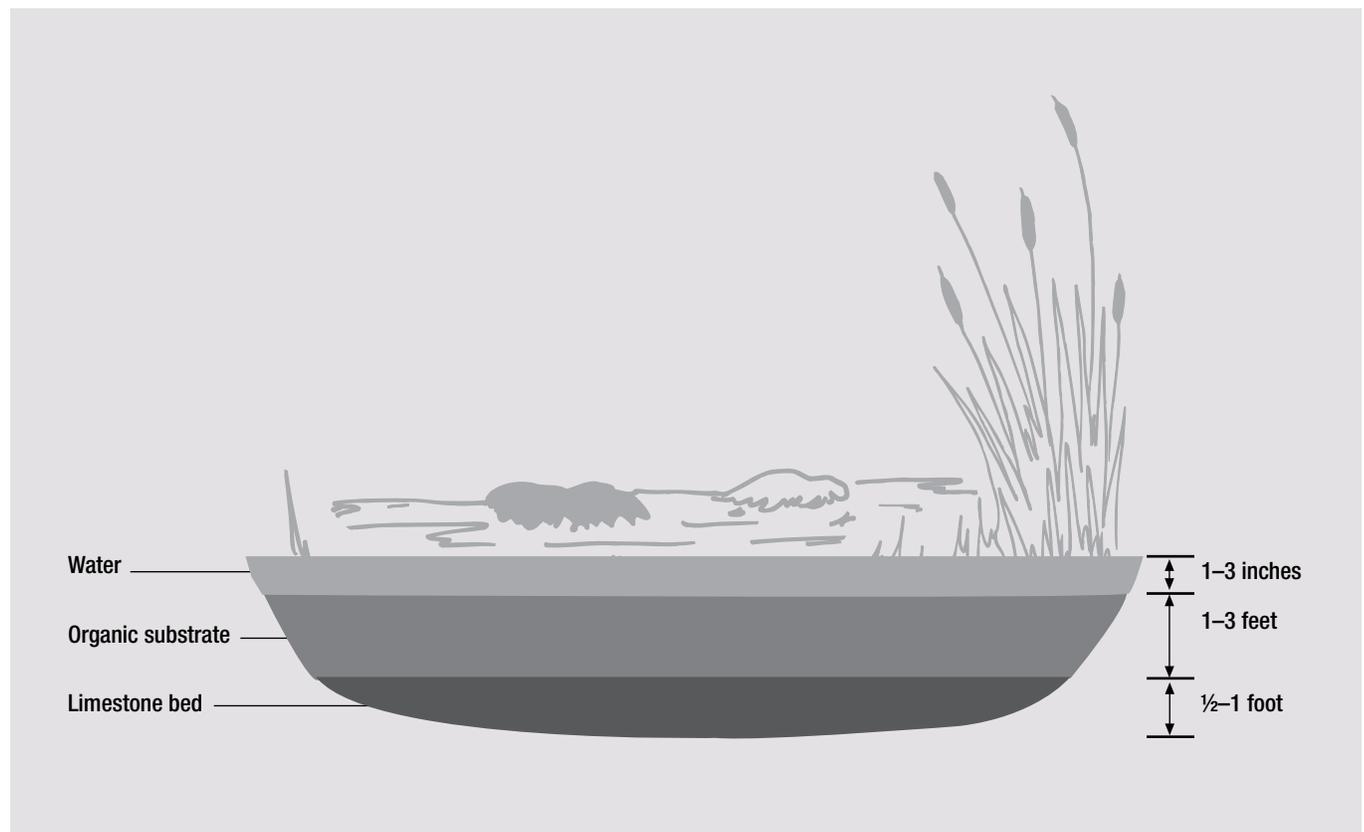
acid mine drainage influent that meets the following criteria:

- Net acidic. Can generally treat acidity levels in the range of 300–500 mg/L.
- Moderate to high levels of ferric and ferrous iron ($\text{Fe}^{3+}/\text{Fe}^{2+}$ greater than 0.25 mg/L), aluminum, dissolved oxygen (greater than 5 mg/L)
- Low to moderate flow rate.
- Lower pH limit around 4.0.

Advantages of Anaerobic Wetlands

- Will neutralize most acidity if within given parameters and decrease concentrations of heavy metals.
- Anaerobic wetlands may be used in succession or combined with other treatment system types to increase efficiency.

Figure 8. Cross-section of an anaerobic wetland.



Limitations of Anaerobic Wetlands

- Inconsistent metal removal rates, especially at higher metals concentrations.
- Larger size required than aerobic wetlands.
- Limited useful life. Substrate becomes saturated with metals and must be replenished or replaced. Most are constructed with a 15- to 20-year planned lifetime.

SUCCESSIVE ALKALINITY PRODUCING SYSTEMS (SAPS)

Basic Design Principles and Operation

The principle behind Successive Alkalinity Producing Systems (SAPS) is to combine the benefits of anoxic limestone drains and anaerobic wetlands. At one point in time, SAPS represented one type of system. Today, the term

is more generic and can reference many similar types of systems, such as vertical-flow wetlands, vertical-flow ponds and vertical-flow reactors. Basic SAPS look like anaerobic wetlands that are constructed on top of limestone drainage beds. Water flows vertically through the wetland and an anoxic limestone bed into a bed of underlying drainage pipes that convey it into a settling pond or an aerobic wetland (see Figure 9).

SAPS overcome the limitations that anaerobic wetlands and ALDs have when used alone. SAPS are designed to treat water with dissolved oxygen content between 2 and 5 mg/L, and medium to high metal concentrations. The vertical flow-through increases contact time between the influent and the compost substrate, which creates anoxic conditions. Upon entering the limestone, the water has lower dissolved oxygen, metals primarily in reduced form,

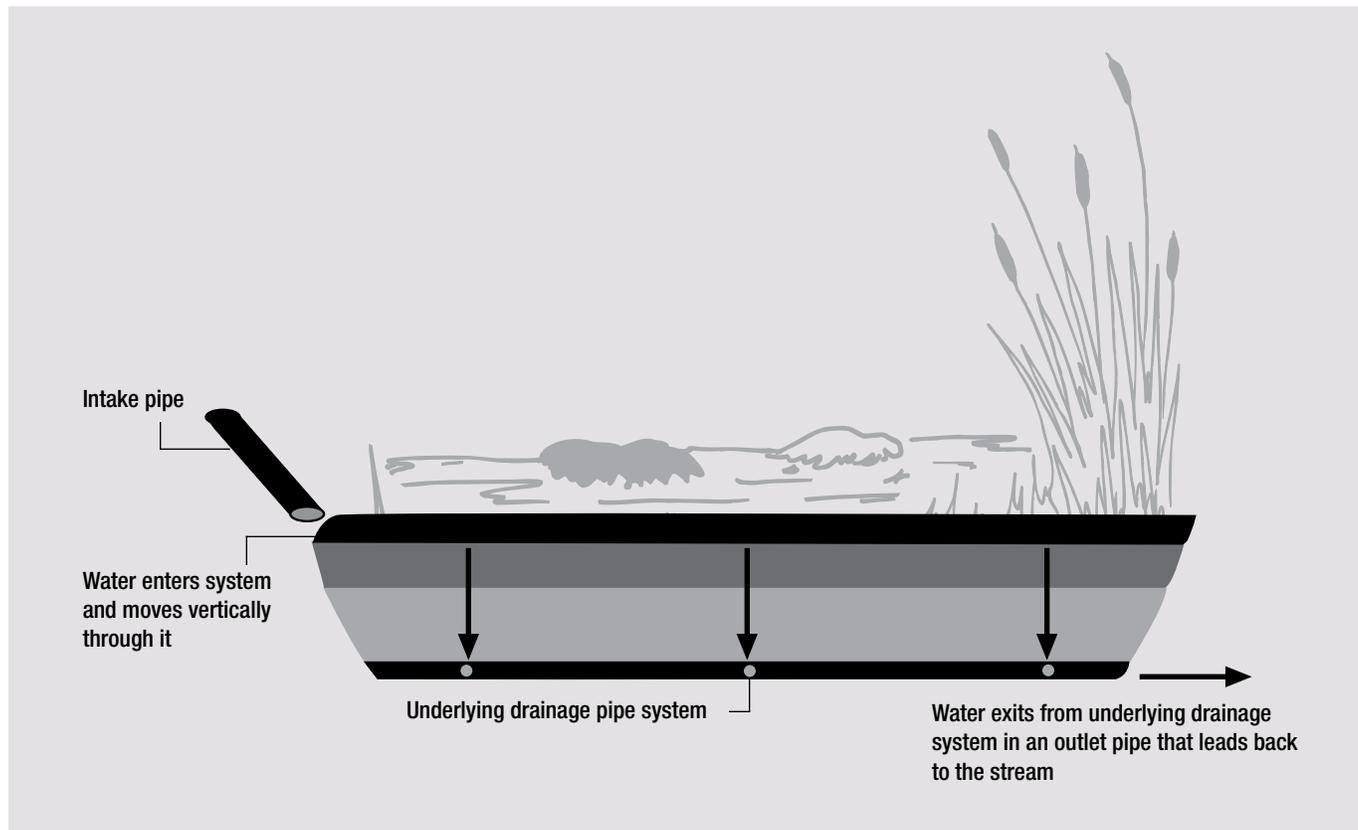
and higher alkalinity. At this point, limestone dissolves and further increases alkalinity. A frequently noted limitation of this design is that ferric iron may adhere to the limestone or clog drainage pipes. Aluminum is also flushed from the system if the effluent has high aluminum concentrations. Most designs incorporate a flushing system to remove metal accumulations from the pipes and limestone.

Size is based on water retention times and acid removal rates. Studies have found that approximately 0.066 pounds (30 grams) of acid can be removed for every square yard per day, which is about 270 pounds of acidity per acre per year.

SAPS can treat water quality that meets the following criteria:

- Net acidic. Can generally treat maximum acidity levels ranging from 300 to 500 milligrams per liter.

Figure 9. Cross-section of a vertical-flow wetland.



- Moderate to high levels of ferric and ferrous iron ($\text{Fe}^{3+}/\text{Fe}^{2+}$ greater than 0.25 mg/L), aluminum, dissolved oxygen (greater than 5 mg/L)
- Flow rates low to moderate (less than 0.12 cubic feet per second), where space limits SAPS size.

Advantages of Vertical-Flow Wetlands

- Area required for SAPS is relatively small.
- Treat poorer quality water compared to other systems.

Limitations of Vertical-Flow Wetlands

- Drainage system limited by high concentrations of aluminum and ferric iron.
- Noxious odor (hydrogen sulfide) produced in vicinity of the system.

CONCLUSION

The methods included in this publication may mitigate the effects of acid deposition and acid mine drainage, but prevention of these types of water quality problems remains the highest priority. Combinations of multiple applications of these systems may be required before any watershed-level benefits are achieved. Little information is available on the success of these systems in restoring fish and other aquatic organisms to acid waters. Greater attention to objectively monitoring the biological benefits of these systems would help in assessing the value of passive acid water treatment systems. Other sources of assistance are available at Pennsylvania DEP Bureau of Abandoned Mine Reclamation, Eastern Pennsylvania Coalition for Abandoned Mine Reclamation, Western Pennsylvania Coalition for Abandoned Mine Reclamation, and Pennsylvania Cooperative Extension and Conservation District offices located in every county in the Commonwealth.

GLOSSARY

Acid Runoff Episode

Chemically expressed as ANC less than or equal to 0 $\mu\text{eq/L}$. Occurs when the acid neutralizing capacity is equal to or less than zero following an increase in stream flow. For natural streams, an acid runoff episode means the stream is net acidic and cannot neutralize additional acidity.

Acidity

Measures the capacity of water to consume alkalinity, usually expressed as equivalents of CaCO_3 in mg/L .

Aerobic

In the presence of oxygen.

Alkalinity

Measures the capacity of water to neutralize acidity, usually expressed as equivalents of CaCO_3 in mg/L .

Anaerobic

In the absence of oxygen.

Acid Neutralizing Capacity (ANC)

Chemically expressed as: $\text{ANC} = [\text{HCO}_3^-] + 2[\text{CO}_3^{2-}] + [\text{other proton acceptors}] - [\text{proton donors}]$ ($\mu\text{eq/L}$). Accounts for all major cations and anions that can act as buffers and is useful in streams where there are no major sources of mineral acidity such as the iron in acid mine drainage.

Bacterially Mediated Sulfate Reduction

Process that produces alkalinity. Certain kinds of bacteria—*Desulfovibrio* and *Desulfotomaculum*—use the organic substrate in anaerobic wetlands as an energy source and

convert sulfate to hydrogen sulfide. A by-product of that reaction is bicarbonate alkalinity.

Buffer

Type of substance that is capable of neutralizing both acids and bases, but usually thought of as preventing pH decreases by neutralizing acids introduced into water.

Hydrolysis

A reaction that splits a molecule of water to form new compounds.

Ion

A charged particle. Water naturally contains dissolved ions. Cations have positive charges (+) and anions have negative charges (-). The relative combinations of these ions can change pH.

Oxidation

Process where an ion, like iron, reacts with oxygen and gains electrons, as in ferrous iron (Fe^{2+}) being oxidized to ferric iron (Fe^{3+})

pH

Chemically expressed as $\text{pH} = -\log_{\text{base}10}(\text{H}^+)$ and is a scale from zero to fourteen that measures the concentration of hydrogen ions in water and other liquid substances. pH 7 is neutral, pH 6 is ten times more acidic than pH 7, and pH 8 is 10 times more basic than pH 7.

Successive Alkalinity Producing System (SAPS)

Type of passive treatment system for acid mine drainage, also known as Vertical-Flow Wetlands (VFW), Vertical-Flow Reactors (VFR), and Vertical-Flow Ponds (VFP).

Soluble

Describes the extent to which a substance will dissolve in water. When the solubility of a substance increases more of that substance will dissolve in water. At lower pH, metal solubility is increased, resulting in a potential increase in the concentration of metals in water.

APPENDIX B

TREATMENT SYSTEM DETERMINATION GUIDE

The flow chart on page 17 was developed by Hedin and Nairn (1994) to help you select the appropriate treatment system depending on stream water chemistry and physical parameters.

Use the worksheet on this page as a rough guide in conjunction with the flow chart to review the possible treatment systems that may be appropriate for your stream. Keep in mind that selecting the appropriate system is highly dependent on a wide range of data collected over long periods of time. Monitoring over time will reveal how widely stream chemistry may vary—an important consideration depending on your treatment objectives.

IDENTIFY ACID SOURCE: _____

MEASURE STREAM CHEMISTRY

pH

Period of record: _____

Frequency of measures: _____

Average: _____

Minimum: _____

Maximum: _____

Acidity

_____ (mg/L)

Alkalinity

_____ (mg/L)

Aluminum

Period of record: _____

Frequency of measures: _____

Average: _____ (mg/L)

Minimum: _____ (mg/L)

Maximum: _____ (mg/L)

Iron

Period of record: _____

Frequency of measures: _____

Fe²⁺ (mg/L)

Average: _____ (mg/L)

Minimum: _____ (mg/L)

Maximum: _____ (mg/L)

Fe³⁺ (mg/L)

Average: _____ (mg/L)

Minimum: _____ (mg/L)

Maximum: _____ (mg/L)

Ratio of Fe³⁺/ Fe²⁺: _____

Dissolved oxygen (D.O.)

_____ (mg/L)

*Flow**

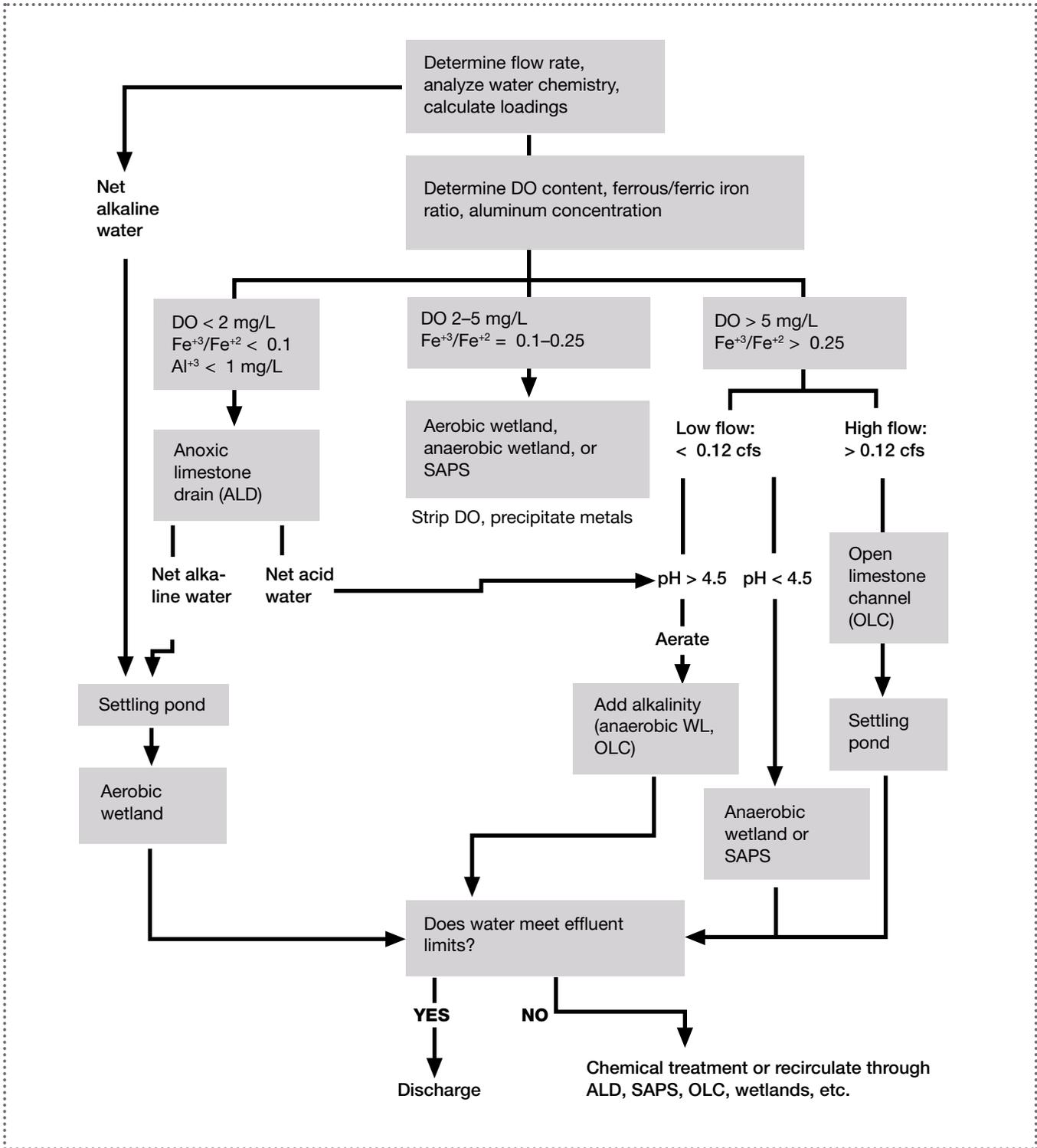
Average: _____ (cubic feet per second)

Peak storm flows: _____ (cubic feet per second)

Low base flow: _____ (cubic feet per second)

Base flow occurs during the summer month when most to all of the flow in streams is due to groundwater input and not precipitation.

*Most acid water treatment systems cannot be designed adequately without water quality information at both very high and very low flows.



Key

Aerobic	With oxygen
Al	Aluminum
Anaerobic	Without oxygen
Cfs	Cubic feet per second
DO	Dissolved oxygen
Fe	Iron
mg/L	Milligram per liter
OLC	Open limestone channel
SAPS	Successive Alkalinity Producing Systems
WL	Wetland

APPENDIX C

COST COMPARISON

Costs are difficult to determine, given the high variability in site characteristics, lack of data, and other factors. The following tables provide a range of expected costs and are meant for comparison only.

Table 1. Comparison of costs for Category I treatment methods.

<i>Method</i>	<i>Approximate Cost</i>
Watershed Liming	*
In-Stream Limestone Sand	*
Wetland Liming	*
Groundwater Addition Well	\$5,000–\$7,000 installation; \$300/month operation costs (No labor costs required)
Limestone Diversion Well	\$5,000–\$6,000 installation; \$1,000 yearly operation costs
Anoxic Limestone Drain	See below

*Costs are dependent on amount of limestone required and transport method. Average costs of limestone delivered to sites in Pennsylvania vary from \$25 to \$75 per ton.

Table 2. Comparison of costs of acid mine drainage treatment projects using passive treatment methods.

<i>Site</i>	<i>System Type</i>	<i>Final Cost</i>	<i>Iron or Acid Influent Load (tons/yr)</i>	<i>Approximate cost/ton of acid or iron treated</i>
ALKALINE DISCHARGE				
Monastery Run	Aerobic Wetland	\$539,000	109 (iron)	\$198.53
Tanoma South	Aerobic Wetland	\$359,000	65.8 (iron)	\$218.23
ACID LOAD < 100 TONS/YR				
Loyalsock	ALD + SAPS	\$575,000	81 (acid)	\$283.60
Middle Branch	SAPS	na	82 (acid)	\$142.25
Roaring Run	SAPS	\$609,750	66 (acid)	\$369.54
Bellwood	ALD + SAPS	na	29 (acid)	\$386.46
Glen White	ALD + (2) SAPS	na	69 (acid)	\$329.68
Cucumber Run	ALD	\$166,000	40 (acid)	\$210.20
ACID LOAD >100 TONS/YR				
Cold Stream	(2) SAPS	na	110 (acid)	\$125.81
Oven Run	SAPS	\$1,102,000	422 (acid)	\$130.56
Schrader Creek	(2) SAPS	\$1,266,000	253 (acid)	\$199.87

Source: Pamela Milavec, Pennsylvania Department of Environmental Protection, Bureau of Abandoned Mine Reclamation.

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