Reclamation Guidelines
For Surface Mined Land in Southwest Virginia

POWELL RIVER PROJECT

Passive Treatment of Acid-Mine Drainage with Vertical-Flow Systems

*C. Zipper and C. Jage**

Introduction

The purpose of this publication is to present guidance for the design and construction of vertical-flow systems for the passive treatment of acid mine drainage (AMD). The term " passive treatment" refers to methods of treating AMD that rely on biological, geochemical, and gravitational processes. Passive systems do not require the constant input of chemical reagents that are characteristic of "active" AMD treatment.

This publication is intended to help potential users determine whether or not a vertical-flow passive treatment system should be considered for a specific AMD discharge. Should the reader decide to proceed, the reader is encouraged to engage the services of a professional with passive-system design and construction experience, especially if the system is intended to meet specific effluent criteria.

These guidelines reflect results of recent research and current practices. AMD treatment technology is developing rapidly as more is learned about how these systems function. Prior to engaging in a vertical-flow AMD-treatment project, readers are advised to access the on-line version of this publication, available through both Virginia Cooperative Extension http://www.ext.vt.edu/resources/ and the Powell River Project http://als.cses.vt.edu/prp/, for reference to updated design guidance as it becomes available.

Overview of Vertical Flow Systems

Vertical-flow systems have also been given a variety of names over the years such as: SAPS (for "successive alkalinity producing systems," Kepler and McCleary, 1994), RAPS (for "reducing and alkalinity producing systems," Watzlaf and others, 2000), and APS (for "alkalinity producing systems," Skousen and Ziemkiewicz, 1995). In 1987, A.C. Hendricks developed a vertical-flow system at Galax, Virginia, to treat the effluent from a long-abandoned pyrite mine (Hendricks, 1991). In 1990, Westmoreland Coal Company and A.C. Hendricks developed a vertical-flow system in Wise County, Virginia, working through Powell River Project (Duddleston and others, 1992). Kepler and McCleary (1994) developed similar systems in Pennsylvania. They are also largely responsible for the widespread use of vertical-flow systems in northern Appalachia, and the development of several design advances.

When properly designed, constructed, and maintained in appropriate situations, vertical-flow treatment offers advantages relative to other means of treating AMD. Unlike active treatment, vertical-flow systems do not require the purchase of chemical reagents or storage of chemical reagents on site. Although vertical-flow systems do require more area and volume than active systems sized with equivalent treatment capacity, they require far less area than other "wetland" systems. Vertical-flow systems are generally ineffective in removing Mn, but passive treatment methods for removing Mn from mine-discharge waters

* Extension Specialist, Crop and Soil Environmental Sciences, Virginia Tech; and Land Trust Representative, New Jersey Conservation Foundation, Far Hills, NJ, respectively

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are currently being developed (Kerrick and Horner, 1998; Brent and Ziemkiewicz, 1997; Sikora and others, 1996). These systems can, however, be very effective in pre-treating AMD prior to an active treatment finishing process, which may reduce the total costs of meeting regulatory standards.

Even where Mn is not a problem, vertical-flow treatment systems should not be considered as either a *stand-alone* or a *walk-away* AMD-treatment solution. This publication describes how vertical-flow treatment can be integrated with other passive-treatment elements to provide AMD treatment, and it presents guidelines for vertical-flow system design.

Although vertical-flow systems do require periodic attention and maintenance, they can be maintained on a week-to-week basis with less time and expense than conventional active systems. Operators should expect, however, that a vertical flow system in a long-term application will require renewal via replacement of major system elements. Current design practice assumes 20- to 25-year lifespans for these systems. As of this writing, at least two vertical-flow systems have operated successfully over periods approaching 10 years (Pine Branch in Virginia, and Howe Bridge in western Pennsylvania) without requiring renewal of major system elements. Many other systems have operated successfully over shorter periods, while still others have failed to meet treatment goals due to inadequate design.

Acid Mine Drainage

Acidic mine drainage (AMD) is an environmental pollutant of major concern in mining regions throughout the world. AMD occurs as a result of the oxidation of sulfide minerals when they are exposed to oxygen and water during the mining process. In coal-mining areas, the most common of these minerals is pyrite (FeS_2). The process for AMD formation is commonly represented by the following reactions:

$$FeS_2(s) + 3.5\ O_2 + H_2O \rightarrow Fe^{2+} + 2\ SO_4^{2-} + H^+ \quad (1)$$

$$Fe^{2+} + 0.25\ O_2 + H^+ \rightarrow Fe^{3+} + 0.5\ H_2O \quad (2)$$

$$Fe^{3+} + 2\ H_2O \rightarrow FeOOH\ (s) + 3\ H^+ \quad (3)$$

The process is initiated with the oxidation of pyrite and the release of ferrous iron (Fe^{2+}), sulfate, and acidity (Eq. 1). The sulfide-oxidation process is accelerated by the presence of Thiobacillus bacteria. Ferrous iron then undergoes oxidation forming ferric iron (Fe^{3+}) (Eq. 2). Finally, Fe^{3+} reacts with H_2O (is hydrolyzed), forming insoluble ferric hydroxide (FeOOH), an orange-colored precipitate, and releasing additional acidity (Eq. 3). The FeOOH formation process is pH-dependent, and occurs rapidly when pH is greater than 4.

Passive Treatment of AMD

Passive treatment systems are typically modeled after wetlands and other natural processes, with modifications directed toward meeting specific treatment goals. Early research included investigations of natural *Sphagnum sp*. peat wetlands that were receiving AMD (Weider, 1982). These systems were able to raise pH and lower iron concentrations without visible deterioration.

Aerobic Wetlands

One of the first designs put into use was a shallow (± 1 foot), surface flow wetland planted with cattails (*Typha sp*.) (Hedin and others, 1994a; Skousen and others, 1998; Skousen and others, 2000). Substrates for these wetlands varied from natural soils to composted organic matter. These "aerobic" wetlands aerated the mine waters flowing among the vegetation. This allowed for the oxidation of Fe^{2+} and its subsequent deposition as FeOOH. Aerobic wetlands are typically used to treat mildly acidic or net-alkaline waters containing elevated Fe concentrations. Published design criteria for Fe removal are up to 310 mg/day per square-foot on sites where the discharge is intended for regulatory compliance, and up to 620 mg/day per square-foot where regulatory compliance is not an issue (Hedin and others, 1994a). Where waters are net-alkaline and Fe is not a problem, aerobic wetlands have also proved capable of removing Mn, but very large areas are needed. Use of aerobic wetlands for Fe removal generally causes pH to decline due to the generation of proton acidity by Fe hydrolysis (Eq. 3) (Skousen and others, 1997).

Anaerobic Wetlands

Modifications of the aerobic wetland design were made to raise water pH and increase metal precipitation. These included the addition of a bed of limestone beneath an organic substrate (Hedin and others, 1994a). This design encouraged the generation of bicarbonate alkalinity (HCO_3^-) by both anaerobic microbial sulfate reduction (Eq. 4, with CH_2O representing biodegradable organic compounds) and limestone dissolution (Eq. 5).

$$2\ CH_2O + SO_4^{2-} \rightarrow H_2S + 2\ HCO_3^- \quad (4)$$

$$CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^- \quad (5)$$

The bicarbonate neutralizes the acidity of the AMD, thereby raising pH (Eq. 6) and increasing the precipitation of acid-soluble metals such as Fe.

$$HCO_3^- + H^+ \rightarrow H_2O + CO_2\ (aq) \quad (6)$$

Anaerobic wetlands have proved capable of removing Fe and producing alkalinity. Hedin and others (1994a) reported average Fe removal rates of up to 1300 mg/day per square-foot, but these systems are limited in capability to raise pH, especially where Fe is present. The primary factor limiting their effectiveness is the slow mixing of the alkaline substrate water with acidic waters near the surface. This slow mixing can be overcome by constructing very large wetlands to provide long retention times (Skousen and others, 1997). This demand on land area is a major impediment to the increased use of these systems by mine operators with limited space for wetland construction.

Current guidelines for the construction of anaerobic wetlands advocate use of a 1- to 2- foot layer of organic matter over a 0.5- to 1- foot bed of limestone with a surface water depth of 1 to 3 inches. At water levels deeper than 2 to 3 inches, growth of wetland vegetation is hindered. The organic matter must be permeable to water and biodegradable; spent mushroom compost has been used successfully at a number of sites in northern Appalachia. For greater effectiveness, limestone may be mixed in with the organic matter. Cattails (Typha sp.) may be planted throughout the wetland to supply additional organic matter for heterotrophic bacteria and to promote metal oxidation with the release of oxygen from their root system (Skousen and others, 1997). Available guidelines for system sizing recommend planning for acidity removal rates 100 mg/day per square-foot for systems designed to achieve regulatory compliance, and up to 200 mg/day per square-foot where regulatory compliance is not a concern. For a more thorough review of anaerobic wetlands, see either Hedin and others (1994a) or Skousen and others (2000).

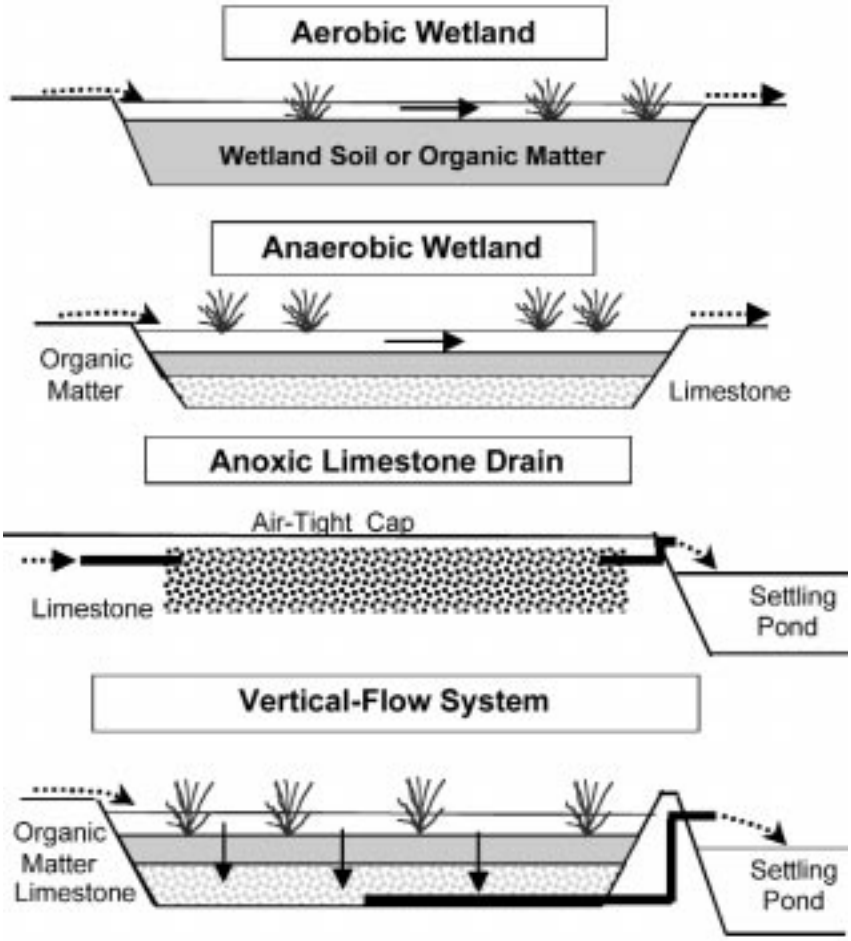

Figure 1. Simplified cross-sectional views of the four major passive treatment systems used in treating acidic mine drainage. Arrows represent perdominant flows.

Anoxic Limestone Drains

One method used to reduce wetland size is pre-treatment of the AMD using anoxic limestone drains (ALDs). ALDs are limestone-filled trenches that can rapidly produce bicarbonate alkalinity via limestone dissolution. They are installed at

the point of discharge to capture the AMD subterraneously. ALDs are capped with clay or compacted soil to prevent AMD contact with oxygen (Hedin and Watzlaf, 1994). The acidic water flowing through trench dissolves the limestone and releases bicarbonate alkalinity (Eq. 5). These systems have demonstrated capabilities to raise the alkalinity and/or neutralize acidity by as much as 300 mg/L ($CaCO_3$ equivalent) with retention times of only 14 - 23 hours (Hedin and Watzlaf, 1994, Hedin and others, 1994a), although net-alkalinity generation rates of 150 to 250 mg/L are more typical. The effluent is discharged into a settling pond to allow for acid neutralization, pH adjustment, and metal precipitation. ALD pretreatment of AMD allows for the construction of smaller, more effective treatment systems due to the decreased metal loadings and increased alkalinity of the ALD effluent discharged into them.

ALDs, however, are not capable of treating all discharges. Significant concentrations of Al or Fe^{+3} in the discharge can cause an ALD to clog with metal-hydroxides once a pH of 4.5 or above is reached (Hedin and others, 1994a). When excess Fe^{+3} is present in the AMD, or is allowed to form from Fe^{+2} due to the presence of O_2, formation of solid FeOOH can occur within the ALD (Eq. 3). Ideally, Fe^{+3}, Al, and dissolved O_2 concentrations of waters being treated by an ALD would all be below 1 mg/L. However, AMD is not always ideal. Skousen and others (2000) state that ALDs have been used successfully for AMD with dissolved oxygen concentrations of up to 2 mg/L and Al concentrations of up to 25 mg/L, when less than 10 percent of total Fe in the Fe^{+3} form. If Al is present at a concentration greater than 1 mg/L and waters in the ALD reach a pH of 4.5 or above, Al will precipitate as $Al(OH)_3$. Both FeOOH (eq. 3) and $Al(OH)_3$ precipitation generate acidity.

$$Al^{3+} + 3\ H_2O \rightarrow Al(OH)_3\ (s) + 3\ H^+ \qquad (7)$$

ALD systems will also fail if Fe^{3+} precipitates on the limestone surface, thus limiting its dissolution, a process known as "armoring." In low dissolved oxygen ("anoxic") environments, the Fe^{2+} form of iron predominates and does not form a coating on the limestone or interfere with limestone dissolution (Hedin and others, 1994a; Watzlaf, 1997). A thorough reference for the design and sizing for ALDs can be found in Hedin and Watzlaf (1994).

Vertical Flow Systems

Vertical flow systems combine the treatment mechanisms of anaerobic wetlands and ALDs in an attempt to compensate for the limitations of both (Kepler and McCleary, 1994). The basic elements of these systems are similar to the anaerobic wetland, but a drainage system is added within the limestone layer to force the AMD into direct contact with both the organic matter and the limestone.

The three major vertical-flow system elements are the drainage system, a limestone layer, and an organic layer. The system is constructed within a water-tight basin, and the drainage system is constructed with a standpipe to regulate water depths and ensure that the organic and limestone layers remain submerged. As the AMD waters flow downward through the organic layer, two essential functions are performed: dissolved oxygen in the AMD is removed by aerobic bacteria utilizing biodegradable organic compounds as energy sources, and sulfate-reducing bacteria in the anaerobic zone of the organic layer generate alkalinity (Eq. 4). Low DO concentrations, biodegradable carbon, and the presence of dissolved sulfate are necessary for sulfate-reduction to take place. An organic layer capable of removing DO to concentrations below 1 mg/L is essential to prevent limestone armoring. In the limestone layer, $CaCO_3$ is dissolved by the acidic, anoxic waters moving down to the drainage system, producing additional alkalinity. The final effluent is discharged from the drainage system standpipe into a settling pond to allow acid neutralization and metal precipitation prior to ultimate discharge.

In order to avoid clogging of the limestone layer with Fe^{+3} and Al precipitants (Eqs. 3 and 7), a valved flushing pipe is typically included as a part of the drainage system (Kepler and McCleary, 1997). When opened, this valved drain discharges at a lower elevation than the standpipe. Head pressure (usually, 6 to 10 feet) caused by the standing water in the system moves waters through the system rapidly, flushing the gel-like forms of Al and Fe ("floc") that accumulates in the drainage pipes and limestone pores. Opening this valve periodically removes the loose metal hydroxide floc and discharges it into the settling pond.

Current practices include a limestone layer of 2 to 3 feet in depth, an organic layer of 6 to 12 inches

in depth, and a standpipe and basin capable of maintaining a 3- to 5-feet deep body of water above the organic layer (Skovran and Clouser, 1998; Kepler and McCleary, 1994). Building systems with 3 feet or more of standing water over the mulch layer provides sufficient head-pressure and aids flushing.

For severe AMD discharges, several vertical-flow systems can be linked in series to generate alkalinity successively until the treatment goals are reached.

Open Limestone Channels

Where AMD must be conveyed over some distance prior to or during treatment, use of open channels lined with limestone has been shown to be an effective mechanism for removing Fe and generating small amounts of alkalinity (Ziemkiewicz and others, 1997). Even though the limestone in such channels typically becomes armored with Fe, research indicates that the armored limestone retains some treatment effectiveness. Open limestone channels are most effective when placed on slopes of greater than 20%, as the abrasive action of fast-moving water tends to dislodge the armoring Fe. Open limestone channels can be effective as one element of a passive treatment system, but typically are not relied upon for stand-alone AMD treatment.

Developing a Passive Treatment Strategy

AMD Characterization

The design of all passive treatment systems starts with characterization of influent AMD chemistry and flow. Prior to designing a passive treatment system, a complete characterization of influent AMD is needed to determine which type of system is appropriate and how to design that system to meet treatment goals.

Regular sampling over at least a 12-month period is recommended to account for the variations that may occur or in response to seasonal changes or storms. At a minimum, all water samples should be analyzed for pH, total Fe, Mn, Al, SO_4^{2-}, total alkalinity and total acidity. Additional analyses, including Fe^{+2}, Fe^{+3}, and dissolved oxygen, are necessary if an anoxic limestone drain is being considered as a treatment option. Dissolved oxygen and pH should be measured on-site. Dissolved oxygen measurements are sensitive, and experience by the sampling personnel is necessary to obtain an accurate reading. Samples designated for metals analysis should be filtered at the time of sampling to remove particulate matter and acidified to pH<2 (APHA, 1985). Acidity and alkalinity samples should be placed on ice immediately following sampling and analyzed within 24 hours. Flow measurements should also be taken on all sampling dates.

Based on water-sampling data, a "design" water quality condition should be established. This will generally be the worst-case condition, as defined relative to regulatory standards, if the AMD discharge is intended to achieve regulatory compliance. The water sampling procedures should assure that a variety of weather and climate conditions are represented, to ensure that the resultant data provide a realistic assessment of the design conditions. Average and maximum influent flow should also be estimated for use in the design process.

Passive Treatment System Selection

The selection of a passive treatment system is governed by influent water quality and site characteristics. The diagram in Figure 2 illustrates a decision process for selecting an appropriate system for a given discharge (Hedin and others, 1994a; Skousen and others, 1998). For net alkaline discharges containing elevated concentrations of Fe, no additional alkalinity additions are needed. The only conditions necessary to complete treatment are an oxidizing environment and sufficient residence time to allow for metal oxidation and precipitation. These conditions can be provided by a settling pond; if sufficient area is available, the settling pond may be followed by an aerobic wetland.

The treatment of net acidic drainage can be handled in a number of ways depending on influent chemistry. If the influent quality is suitable for an ALD, an ALD can be employed as a pretreatment method. A post-ALD settling pond or aerobic wetland is required to allow for the oxidation and precipitation of metals.

Acidic waters that are not suitable for ALDs can be treated with either an anaerobic wetland or a

vertical flow system. Due to the potentially large demands on land area of anaerobic wetlands, they are usually only practical for low-flow situations. For systems that receive water that has a pH greater than 4, settling ponds may precede an anaerobic wetland cell to remove significant quantities of Fe. The remaining discharges can be treated using a vertical-flow system.

Vertical-Flow System Design

Vertical-flow passive treatment systems are able to neutralize acidity and promote metal precipitation in difficult treatment situations. Due to the active mixing of the AMD with the limestone, acid neutralization is more rapid in vertical-flow systems than in anaerobic wetlands, and thus vertical-flow systems require shorter residence times

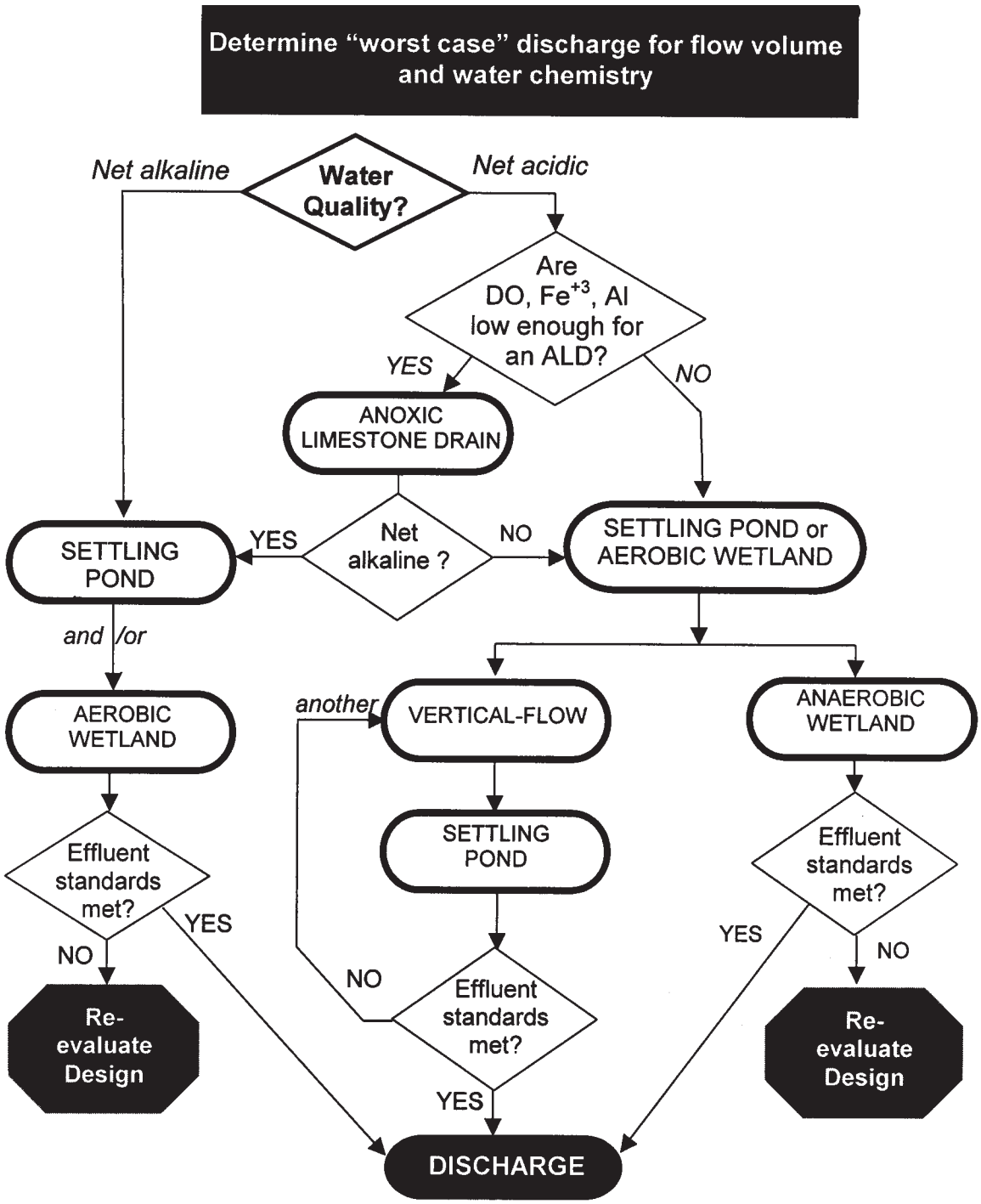

Figure 2. Flow chart for selecting a passive treatment system based on influent water quality. Additional treatment may be required for Mn if present at elevated concentration. (Adapted from Hedin and others 1994a; Skousen and others 1998; Skousen and others, 2000).

and smaller surface areas. These systems are not stand-alone, but require the addition of an oxidation/settling pond at the effluent point to allow for the precipitation and storage of the metals in solution. For discharges containing significant quantities of Fe^{+3}, vertical-flow systems should be preceded by either a settling pond or an aerobic wetland if sufficient land area is available. The removal of such metals prior to vertical-flow treatment will lengthen the system's useful life and reduce necessary maintenance by limiting accumulation of metal-hydroxide precipitants on the organic matter surface. A settling pond should also precede the system if incoming waters contain sediment.

Guidelines reported by Skovran and Clouser (1998), Skousen and others (1998) and Kepler and McCleary (1994) provide a general form for design of these systems.

Sizing the Limestone Layer

Although per-unit-area Fe removal-rates are typically applied in designing "wetland" treatment systems, per-unit-area rates of alkalinity generation by installed vertical-flow systems vary. Research has demonstrated the presence of relationships between influent water quality, AMD residence time in the limestone layer, and alkalinity generation (Jage and others, 2000). The primary factor governing alkalinity generation by most vertical-flow systems is the rate at which limestone dissolves relative to the rate at which AMD moves through the system. Residence-time of the AMD in the limestone layer is one factor governing alkalinity generation. Limestone dissolves most rapidly during the first few hours of AMD contact. As the waters in contact with the limestone become saturated with dissolved Ca^{2+} and HCO_3^-, the rate of limestone dissolution slows considerably. Another factor governing the rate at which limestone dissolves is pH; at lower pH, $CACO_3$ dissolves more rapidly.

Research has developed a model that can be used to estimate vertical flow systems' alkalinity generation rates as a function of AMD residence time within the limestone layer and AMD concentrations of Fe and non-Mn acidity (Jage and others, 2001; see Eq. 9 below). Given the volume and quality of the AMD to be treated, this model can be used to estimate the size of the limestone layer required to generate a given quantity of alkalinity. We recommend that the model be used to provide a design minimum, but that systems be constructed larger than indicated by the model whenever possible. Increasing the size of a vertical-flow system will increase the probability of successful treatment.

Calculating a Preliminary Limestone Volume

The first step in the system sizing process is to determine the size of the limestone layer and number of vertical-flow cells needed for adequate treatment. We recommend that the system be sized to generate alkalinity sufficient to offset incoming non-Mn acidity, plus additional alkalinity so as to achieve a factor of safety. We recommend sizing the system to generate at least 100 mg/L of alkalinity, over and above the amount needed to offset influent non-Mn acidity when sufficient land area is available, so as to provide a reasonable probability of successful treatment. Non-Mn acidity can be calculated as:

$$\text{Non-Mn Acidity} = \text{Acidity} - 1.818 * \text{Mn} \qquad (8)$$

where,

- Acidity = Total Acidity (mg/L as $CaCO_3$) of the design influent water quality
- Mn = Manganese concentration (mg/L) of the design influent water quality
- Non-Mn Acidity = acidity derived from Al, Fe, H^+ and other ions (mg/L as $CaCO_3$)

Once the design rate of alkalinity generation has been determined, the limestone residence time of a system can be estimated using the equation below:

$$Alk_{net} = 99.3 * \log_{10}(t_r) + 0.76 * Fe + 0.23 * \text{Non-Mn Acidity} - 58.02 \qquad (9)$$

where,

- Alk_{net} = net alkalinity to be generated (mg/L as $CaCO_3$)
- Fe = total iron concentration (mg/L) of the design influent water quality
- Non-Mn Acidity = non-manganese acidity (mg/L as $CaCO_3$ - see equation 8)
- t_r = average residence time in the limestone layer (hours).

Equation 9 ("the model") can be solved mathematically for t_r, if the reader is so inclined, or the reader may choose to estimate a residence time that may be achievable based on site conditions and use the model to determine whether or not a system built with such a residence time is likely to be adequate for treatment of the design AMD discharge. Figure 3 represents Equation 9's predictions for a sample influent water quality.

This model is intended for application to systems built with high-calcium limestone in the 4-to-6 inch size range. High-calcium limestone contains more than 90% $CaCO_3$ and is more soluble than limestone that contains appreciable quantities of Mn. The $CaCO_3$ residence time that results from solving Equation 9 should be adjusted to account for limestone dissolution as the system ages (see below). The model was developed by analyzing data from vertical flow systems receiving influent waters with Fe concentrations less than 300 mg/L and non-Mn acidity concentrations of less than 500 mg/L (Jage and others, 2001). The model has not been tested for drainages where Al concentrations exceed 60 mg/L.

Equation 9 is not expected or intended to give precise results. Figure 4 shows the relationship of predicted alkalinity generation to observed generation for 18 vertical flow cells. All values plotted are system averages over periods exceeding one year. The plots for Howe Bridge and the Oven

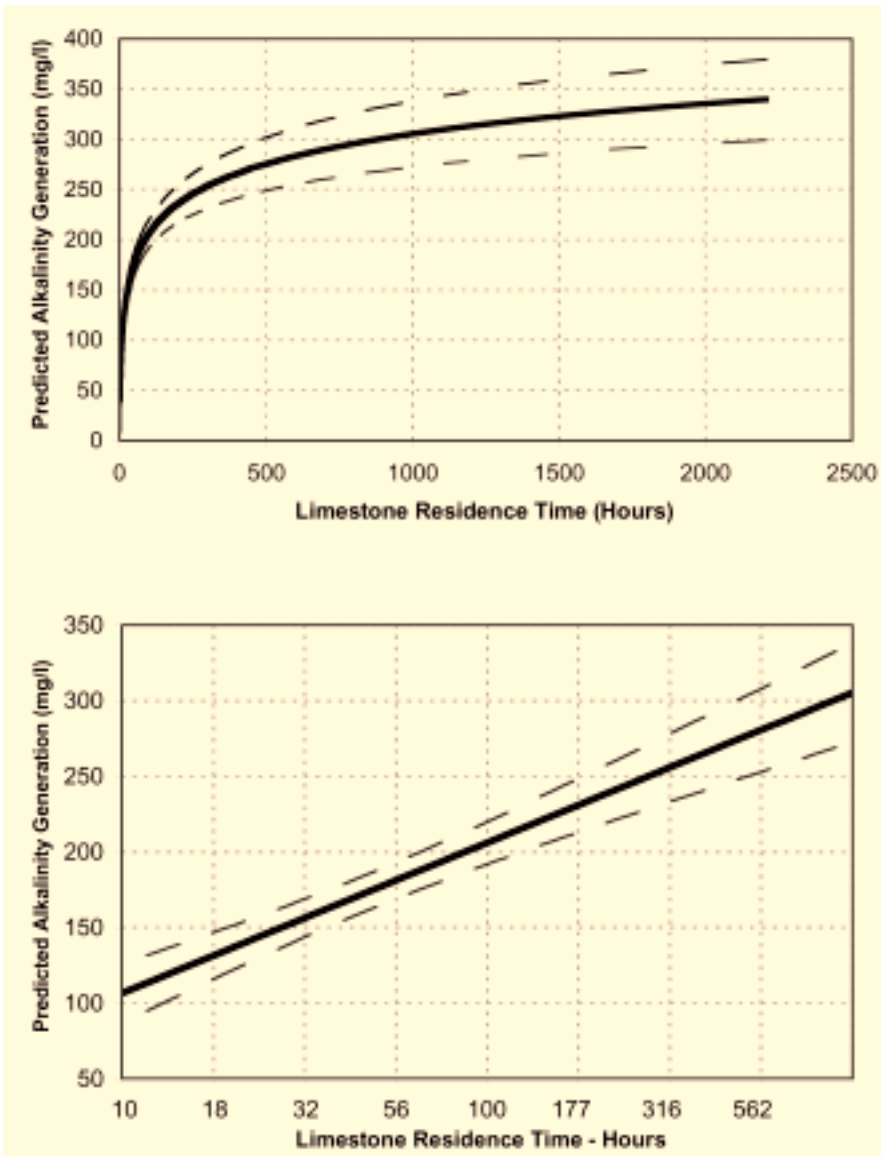

Figure 3. Alkalinity generation predicted by Equation 9 as a function of limestone residence time, with influent water-chemistry at values close to averages for the research data set. Both plots represent predicted response to influent water with Fe = 40 mg/l, acidity = 200 mg/l as $CaCO_3$, and Mn = 25 mg/l. The horizontal axis of the lower plot is on a $\log_{10}$ scale ($\log_{10}$ of 10 = 1; $\log_{10}$ of 100 = 2; $\log_{10}$ of 1000 = 3). The dashed lines represent a 95 percent confidence interval for 13 vertical flow cells providing data used to develop Equation 9.

Run systems were calculated from system averages published by Watzlaf and others (2000), while all other system averages were calculated from monthly observations.

For the data set of 179 observations used to derive the above predictive model (Jage and others, 2001), the standard deviation of the difference between observed and predicted values is about 50 mg/L. This deviation between predicted and observed values is the justification for suggesting sizing the system to generate alkalinity in excess of the anticipated need to offset incoming non-Mn acidity, especially if the system is intended to achieve regulatory compliance. Larger systems will provide an increased factor of safety, and are likely to operate successfully for a longer time prior to requiring major renovation.

Figure 5 demonstrates that alkalinity generation rates vary considerably between systems. Two of the systems exhibited average alkalinity generation rates in excess of 300 mg/L and less than 2500 mg/day per square foot. In both of these systems, average residence times exceeded 300 hours. One southern West Virginia system exhibited an average alkalinity generation rate of approximately 7000 mg/day per square foot; this system had a relatively short residence time, a rich organic layer more than one meter in thickness, and received AMD with pH's that are favorable to sulfate-reducing bacteria, in the 4-to-5 range. This system generated alkalinity most rapidly during the early years of its operation; during its third year, its performance declined considerably.

These data demonstrate Equation 9 may be used to provide design guidance, but does not provide precise predictions. Vertical-flow systems' performance exhibits considerable variation in the field, on a month-to-month basis as well as between locations (Figure 6). Building a system with a larger residence time will increase the probability of successful treatment.

For highly acidic AMD discharges, the above sizing method may generate an estimated residence time of several hundred hours. If area limitations prevent construction of such a large system, treatment may be provided as two or more successive vertical-flow cells separated by a settling pond. For example, considering the influent water chemistry represented by Figure 3: a limestone residence time on the order of 1000 hours would be required in a single cell to generate 300 mg/L acidity, whereas two cells in series, each with a 30-hour residence time and separated by an settling pond, may be capable of generating a comparable amount of alkalinity. As a conservative design principle, we recommend that residence times of less than 15 hours should be avoided and longer residence times should be preferred. At low residence times (that is, at rapid rates of AMD movement through the vertical-flow system), the organic matter layer within the vertical flow system may begin to limit system performance. At very rapid rates of water movement, the permeability of the organic layer may become limiting – especially if Fe is being precipitated on its surface. Also, as the organic layer ages, its capacity to remove oxygen from the AMD will decline. Therefore, with all other things being equal, larger systems with slower residence times can be expected to maintain performance for longer periods than smaller systems with short residence times.

The residence time calculated with Equation 9 is an estimate of the time that the AMD should reside in the limestone layer to achieve desired results. In order to size the system, the residence time must be converted into a limestone layer volume (V_{ls}, expressed in cubic feet):

$$V_{ls} = \frac{8.02\ Q\ t_r}{V_v} \qquad (10)$$

where,

Q = influent flow (gallons per minute)
t_r = residence time in limestone (hours)
V_v = bulk void volume of limestone expressed as a decimal (e.g., 50% = 0.5)

A reasonable estimate of the bulk-void volume of 4-to-6 inch limestone is about 50%. For common unit-conversion factors, see Table 1.

Adjusting Limestone Volume to Account for Loss over Time:

An additional volume of limestone should be added to compensate for limestone dissolution over the design life of the SAPS based on a method defined by Hedin and Watzlaf (1994) for ALDs. The additional volume of limestone needed (V_{ls+}, expressed as cubic feet) over the design size can be calculated as:

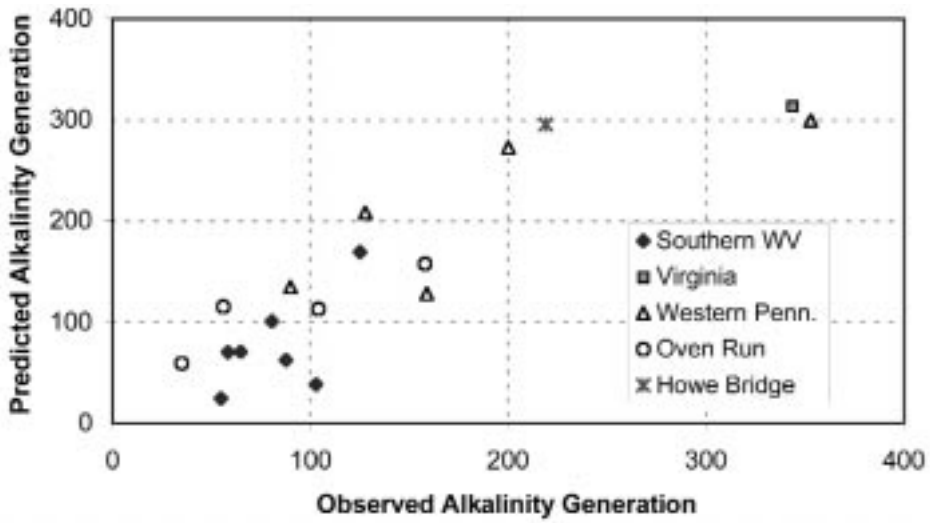

Figure 4. Observed net alkalinity generation, and net alkalinity generation predicted by Equation 9, (mg/l as $CaCO_3$ - system averages) for 18 vertical flow cells. Performance data for the Oven Run and Howe Bridge systems were obtained from published literature (Watzlaf and others, 2000).

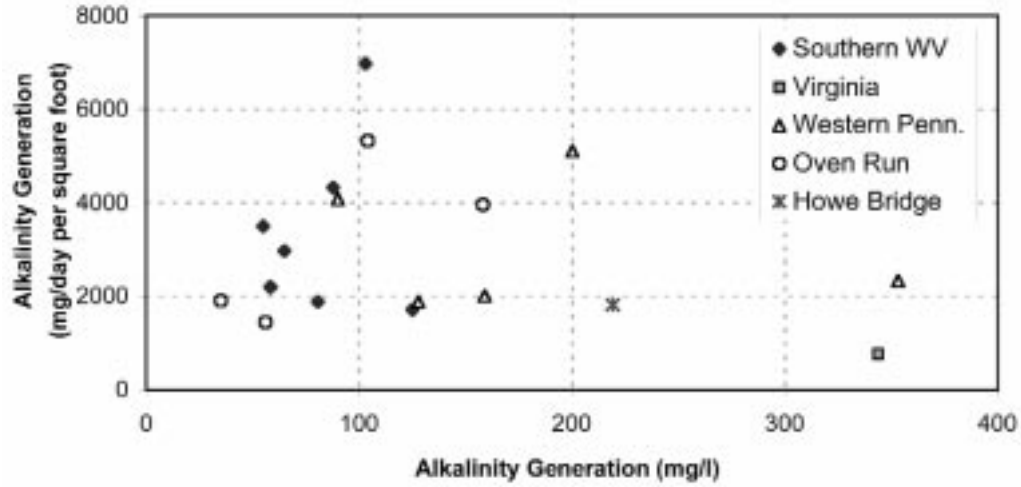

Figure 5. Observed alkalinity generation rates at 18 vertical flow cells (system averages over time), expressed as mg/l and per-square-foot of surface area. Performance variations occur due to differences in water chemistry, residence times, details of system design, and other factors. Performance data for the Oven Run and Howe Bridge systems were obtained from published literature (Watzlaf and others, 2000).

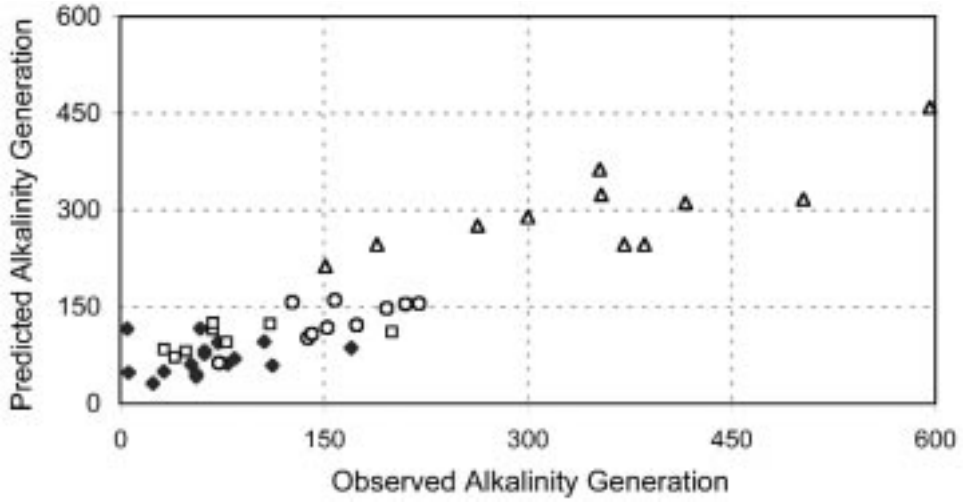

Figure 6. Observed alkalinity generation, and alkalinity generation predicted by equation 9, for 4 vertical flow cells, individual sampling events (mg/l as $CaCO_3$).

$$V_{ls+} = \frac{0.044\ Q\ C\ T}{x} \qquad (11)$$

where,

Q = influent flow (GPM)
C = predicted net alkalinity generation (mg/L)
T = design life (years)
x = $CaCO_3$ content of limestone, expressed as a decimal (e.g., 90% = 0.9)

This volume of limestone should be added to the amount needed to attain the design residence time (Table 2). By placing additional limestone in the vertical flow system, the design residence time will be maintained even as some limestone is dissolved by AMD moving through the system. Common practice is to design the limestone layer for 20- to 25-year lifetimes. High-calcium limestone should be used to construct the limestone layer; use of dolomitic limestones should be avoided. High-calcium limestone is more soluble than dolomitic limestone.

The Organic Layer

The organic layer is the most vulnerable of the major system elements and is critical to long-term performance. In addition to harboring sulfate-reducing bacteria, the organic layer removes dissolved oxygen and promotes reducing conditions necessary to prevent limestone armoring. The removal of dissolved oxygen, however, is directly related to water temperature and the AMD residence time in the organic matter. In order to ensure that the vertical-flow system performs well year-round and to prevent performance degradation due to limestone armoring, the organic layer must be sized adequately to ensure cold weather performance. Permeability is also a key property of the organic layer.

Well-weathered organic bark material has been used successfully in one high-residence-time Virginia system, but this system receives a relatively high-quality influent. Bark materials tend to be permeable, but they have a relatively low biochemical oxygen demand due to high proportions of large, woody debris that are not readily broken down by the bacteria. Other materials that are more easily processed by aerobic bacteria, such as composted manure or spent mushroom compost, should allow for shorter organic matter residence times given the greater bioavailability of the organic compounds in these materials. In practice, a variety of materials have been used successfully including well-decomposed wood mulch, spent mushroom compost, composted manure, and mixtures of composted materials with less-expensive organic sources such as rotting hay. Mixing organic-layer materials with limestone is not recommended, due to the potential for metal-hydroxide floc precipitation within the small pores of the mulch layer where flushing will not be effective.

For most systems, organic layer depths of 12 to 18 inches should be adequate. Deeper substrates can be problematic due to the low permeability of organic matter, especially as it begins to decompose. Shallower substrates should be avoided due to the risk of creating zones of preferential flow that would allow oxygenated water to reach the limestone layer. In designing systems with relatively rapid movement of water through the organic layer due to exceptionally short residence times and/or large limestone-layer depths, the permeability of the organic-layer material should be tested.

Care should be used in installing the organic layer to assure that the material is well mixed and to assure uniform distribution and depth of material across the limestone-layer surface. Once the organic layer is in place, any activity causing compaction, such as walking or driving equipment on the surface of the system, should be

Table 1. Common conversion factors for use in vertical-flow system design.

Units	Equivalent units
1 gallon	0.134 cubic feet
1 gallon per minute	8.02 cubic feet per hour
1 cubic foot of 4-to-6 inch limestone	100 pounds (approximate)
1 pound $CaCO_3$	454,000 mg of alkalinity (as $CaCO_3$)

avoided. Such activity may also result in the creation of zones of preferential flow. These areas will cause surface waters that are moving toward the drain to "short circuit" the system and decrease treatment effectiveness.

Drainage

The subsurface drainage system should be constructed from schedule 40 perforated PVC piping; piping diameter should be determined based on the design flow. Generally speaking, drainage diameters less than 6 inches should be avoided, due to the potential for metals precipitation and sediment accumulation within the drainage structure. Hole diameters should not be less than 1/2 inch, and 1 inch is preferred. The holes of tile drains, if used in vertical flow cells, should be enlarged. Adequately sized holes will help to ensure that plugging by floc precipitants does not occur. Typical layouts for the drain are 'T' or 'Y' shaped, and located in the lower 12 in of the limestone layer (Figure 7). Drains should be designed

Table 2. Example Calculation

1. Determine design water quality and flow from field measurements:

Fe concentration =	40 mg/l
Acidity =	200 mg/l as $CaCO_3$
Mn concentration =	25 mg /l
Flow =	10 gallons per minute

2. Calculate non-Mn acidity using Equation 8.	154.6 mg/l as $CaCO_3$
3. Determine design rate of alkalinity generation: Designer wishes to achieve a high probability of success, so the system is designed to generate excess alkalinity.	250 mg/l alkalinity, as $CaCO_3$
4. Determine residence time necessary to achieve 250 mg/l of alkalinity production, given the design water quality. Insert all parameters into equation 9; solve for residence time (Note that figure 3 was produced using influent data identical to this example).	270 hours
5. Determine preliminary volume of 4-to-6 inch high-calcium limestone necessary to achieve desired residence time, using equation 10. (This estimate assumes bulk void volume = 50%).	43,308 cubic feet
6. Determine design lifetime of system.	20 years
7. Determine additional limestone needed to offset amount dissolved over design life, using Equation 11. (This estimate assumes $CaCO_3$ content of limestone = 90%).	2,444 cubic feet
8. Determine total volume of limestone needed (add 7 + 8).	45,752 cubic feet

9. Determine if project is worth further investigation:
   - Assuming a limestone layer of 4 feet and sloping sides, this project will require an area on the order of 12,000 square feet for the vertical flow cell alone.
   - If this amount of flat area is not available but some smaller areas separated by elevation differences, are available: recalculate the required area as two cells, each designed to produce 125 mg/l alkalinity or more per day, separated by a settling pond.
   - If either option looks feasible, involve a party experienced in passive treatment.

and oriented so as to promote full utilization of the limestone volume. The drains are joined to an effluent standpipe that is elevated to maintain a constant head of water above the organic substrate. The effluent should cascade into the adjacent settling pond in order to oxygenate the waters and promote the precipitation of the metals in solution.

A flushing system should also be included to maintain maximum treatment efficiency. This consists of a valved discharge port connected to the drainage network located at a level below the height of the effluent standpipe (Figure 8). When the valve is opened, the head of water in the vertical-flow system causes a rapid drawdown of the system, which removes the metal-hydroxide floc that can accumulate in the limestone layer. The flushing system outlet should discharge the floc into the settling pond to allow for the collection and removal of the precipitants. This drawdown process can require 10 to15 minutes but should be continued until the discharge waters run clear.

A settling pond located after the vertical flow cell is crucial to effective treatment performance. For effective treatment prior to discharge, the settling pond is a necessity. The effluent of the vertical flow cell must undergo oxidation, pH adjustment, and subsequent precipitation of insoluble metal complexes before being discharged. The settling pond allows for these processes to take place in a controlled setting where the precipitates can be dredged and disposed of in a proper manner. Settling ponds should be large enough to allow for the accumulation of the precipitated metals with recommended residence times of at least 2.8 days (Skovran and Clouser, 1998).

Construction

Because Skovran and Clouser (1998) have produced a detailed guide to construction practice, only a small amount of construction guidance will be repeated here. Vertical-flow system construction requires the excavation of a basin, and a compacted clay or plastic liner to prevent seepage of untreated AMD into the groundwater. Side embankments may be constructed with 2:1 interior slopes and 3:1 exterior slopes with 8 – 10 ft top widths (Figure 8). Skovran and Clouser (1998) also recommend a minimum of 12 inches of freeboard above design high water to an emergency spillway in order to maintain system integrity.

Skovran and Clouser (1998) recommend considering public safety when designing the basin. Some developers have chosen to encircle vertical-flow systems with chain link fences and post warning signs, in an effort to discourage uninvited visitors that might be attracted by the open waters. Configuring the basin to include a shallow-water bench area adjacent to the bank can enhance safety. Such a shallow bench separates the deep-water pool from bankside walking areas; in the event of accidental entry into the pool (e.g., someone falls in), the shallow bench will aid a quick exit. Depending on the AMD's acidity, the shallow bench may also become populated with cattails and other wetland vegetation, making entry to the deeper pool appear more difficult.

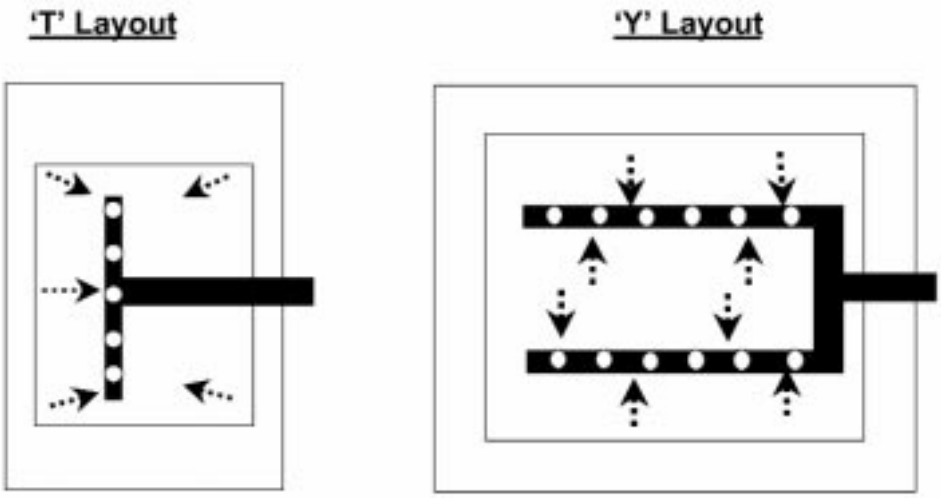

Figure 7. Typical layouts for vertical-flow system drainage (top view). Other patterns are possible.

In long-term applications, the system basin should be situated so as to allow access by mechanical equipment, such as a back hoe or a small loader, to aid eventual system renewal.

Operation, Maintenance, and Renewal

Once the installation is complete, influent and effluent water-chemistry and flow monitoring should continue to allow assessment of system performance. Availability of adequate background data will enable informed decisions regarding maintenance if water treatment performance begins to deteriorate. Drainage systems should be flushed periodically; common practice is about one flush per month, but the frequency should be determined based on the rate of Al and Fe accumulation.

Both organic matter and limestone are consumed by vertical-flow system operation, so degradation of performance over time should be expected. When the operator determines that the time for renewal is at hand, the first step would be to drain the system and excavate the organic layer. Depending upon the degree of limestone armoring, the system operator may wish to either remove and replace the limestone, or add some additional limestone prior to re-installation of the organic layer. If substantial quantities of Fe-precipitate are deposited in the limestone layer due to organic layer deterioration, then the drainage system may also require replacement.

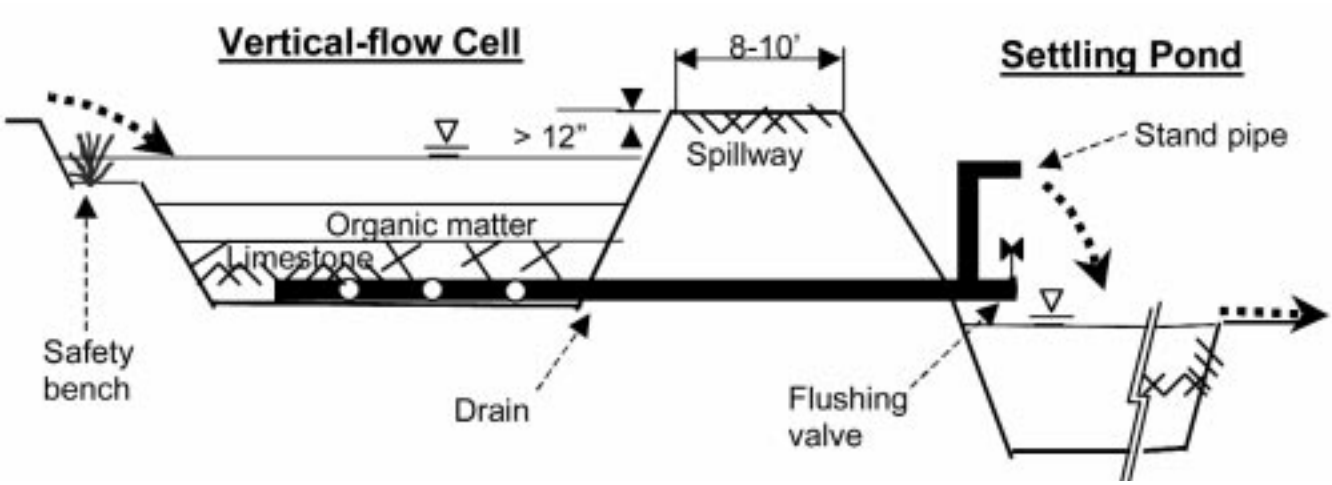

Figure 8. Simplified cross section schematic of vertical-flow system design. Not to scale. See text for further details (adapted from Skovran and Clouser (1998).

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Literature Cited

Brant, D.L., and P.F. Ziemkiewicz. 1997. Passive removal of manganese from acid mine drainage. P. 741-744, in: Proceedings of the 1997 Annual Meeting of the American Society for Surface Mining and Reclamation.

Duddleston, K. N., E. Fritz, A. C. Hendricks, K. Roddenberry. 1992. Anoxic Cattail Wetland for Treatment of Water Associated With Coal Mining Activities. p. 249-254. *In* Proceedings of the 1992 Annual Meeting of the American Society for Surface Mining and Reclamation, Duluth, MN. June 15-18, 1992.

Hedin, R. S., and G. R. Watzlaf. 1994. The Effects of Anoxic Limestone Drains on Mine Water Chemistry. p. 185-194. *In* Proceedings of the International Land Reclamation and Mine Drainage Conference, Pittsburgh, PA. April 24-29, 1994

Hedin, R. S., R. W. Nairn, and R. L. P. Kleinmann. 1994a. Passive Treatment of Coal Mine Drainage. Bureau of Mines Inf. Circ. IC9389. US. Dep. of the Int., Bureau of Mines, Washington, DC.

Hedin, R. S., G. R. Watzlaf, and R. W. Narin. 1994b. Passive Treatment of Acid Mine Drainage with Limestone. J. Environ. Qual. 23:1338-1345.

Hendricks, A. C. 1991. The use of an Artificial Wetland to Treat Acid Mine Drainage. *In* Proceedings of the International Conference on the Abatement of Acidic Drainage. Montreal, Canada. September 1991.

Jage, C., C.E. Zipper, and R. Noble. 2001. Factors affecting alkalinity generation by successive alkalinity producing systems: Regression analysis. Journal of Environmental Quality. *In Press*.

Jage, C., C.E. Zipper, and A.C. Hendricks. 2000. Factors affecting performance of successive alkalinity producing systems. P. 451-458, in: Proceedings, 2000 National Meeting of the American Society for Surface Mining and Reclamation. Tampa, FL.

Kepler, D. A., E. C. McCleary. 1997. Passive Aluminum Treatment Successes. *In* Proceedings of the National Association of Abandoned Mine Lands Programs. Davis, WV. August 17-20, 1997.

Kepler, D. A., and E. C. McCleary. 1994. Successive Alkalinity-Producing Systems (SAPS) for the Treatment of Acidic Mine Drainage. p. 195-204. *In* Proceedings of the International Land Reclamation and Mine Drainage Conference, Pittsburgh, PA. April 24-29, 1994.

Kerrick, K.H., and M. Horner. 1998. Retention of manganese by a constructed wetland treating drainage from a coal ash disposal site. P. 272-275, in: Proceedings of the 1998 Annual Meeting of the American Society for Surface Mining and Reclamation.

Sikora, F.J., L.L. Behrends, G. Brodie, and M.J. Bulls. 1996. Manganese and trace metal removal in successive anaerobic and aerobic wetlands. P. 560-579, in: Proceedings of the 1996 Annual Meeting of the American Society for Surface Mining and Reclamation.

Skousen, J. 1997. Overview of Passive Systems for Treating Acid Mine Drainage. Green Lands. 27(2)34-43.

Skousen J. , A. Rose, G. Geidel, J. Foreman, R. Evans, W. Heller. 1998. A Hand book of Technologies for Avoidance and Remediation of Acid Mine Drainage. National Mine Land Reclamation Center. Morgantown, WV. 131pp.

Skousen, J., A. Sexstone, and P. Ziemkiewicz. 2000. Acid mine drainage treatment and control. P. 131-168, in: R. Barnhisle, W. Daniels, and R. Darmody (eds). Reclamation of Drastically Disturbed Lands. American Society of Agronomy. Madison, WI.

Skousen, J. and P. F. Ziemkiewicz. (eds.) 1995. Acid Mine Drainage Control and Treatment. National Mine Land Reclamation Center. Morgantown, WV. 253pp.

Skovran G. A. and C. R. Clouser. 1998. Design Considerations and Construction Techniques for Successive Alkalinity Producing Systems. *In* Proceedings of the 1998 Annual Meeting of the American Society for Surface Mining and Reclamation, St. Louis, MO. May 16-21 1998.

Watzlaf, G. R. 1997. Passive Treatment of Acid Mine Drainage in Down-Flow Limestone Systems. p. 611-622. In Proceedings of the National Meeting of the American Society for Surface Mining and Reclamation (ASSMR), Austin, TX, May 10-15. 1997.

Watzlaf, G., K. Schroder, and C. Kairies. 2000. Long-term performance of passive systems for the treatment of acid mine drainage.

Wieder, R K., and G. E. Lang. 1982. Modification of Acid Mine Drainage in a Freshwater Wetland. pp. 43-53. *In* Proceedings of the Symposium on Wetlands of the Unglaciated Appalachian Region. Morgantown, WV.

Ziemkiewicz, Paul, J. Skousen, D. Brant, P. Sterner, and R.J. Lovett. 1997. Acid mine drainage treatment with armored limestone in open channels. Journal of Environmental Quality 26:1017-1024.

Powell River Project / Virginia Cooperative Extension Publications

Reclamation Guidelines

Creation and Management of Productive Mine Soils. W.L. Daniels and C.E. Zipper. VCE 460-121.
http://www.ext.vt.edu/pubs/mines/460-121/460-121.html

Revegetation Species and Practices. J. Skousen and C.E. Zipper. 1996. VCE 460-122.
http://www.ext.vt.edu/pubs/mines/460-122/460-122.html

Restoring Forests on Surface-Mined Land J.A. Burger and JL. Torbert. VCE 460-123.
http://www.ext.vt.edu/pubs/mines/460-123/460-123.html

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Constructing Wetlands During Reclamation to Improve Wildlife Habitat. R.B. Atkinson, C.E. Zipper, W.L. Daniels, and J. Cairns, Jr. VCE 460-129. http://www.ext.vt.edu/pubs/mines/460-129/460-129.html

Stabilizing Reclaimed Mines to Support Buildings and Development.C.E.Zipper and Steven Winter.
http://www.ext.vt.edu/pubs/mines/460-130/460-130.html

Reclamation of Coal Refuse Disposal Areas. Daniels, W.L., Barry Stewart, and Dennis Dove. VCE 460-131.
http://www.ext.vt.edu/pubs/mines/460-131/460-131.html

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http://www.ext.vt.edu/pubs/mines/460-138/460-138.html

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