Help Instruction File:

Limestone Bed Module Overview

Provided by the Office of Surface Mining Reclamation and Enforcement (OSMRE), the Pennsylvania Department of Protection (PADEP), the U.S. Geological Survey's (USGS) and the West Virginia Department of Environmental Protection (WVDEP).

Limestone Bed Module Overview

Table of Contents

1.0 Objective

A Limestone Bed (LB) is a passive treatment system (meaning that no machinery or daily chemical addition is required for its operation) that is typically used to treat net-acidic mine drainage of low to moderate flow with low to moderate acidity and dissolved metals.

The objectives of this overview are to: (1) Provide a basic understanding of the theory and application of LB and (2) Provide an overview of the LB module to guide users in developing an estimate of the cost to construct, operate, and maintain LBs for treating mine drainage. Therefore, this overview will be presented in two sections, **Treatment Component Overview** and **LB Module Overview**.

2.0 Treatment Component Overview

The following section is organized into three sections, (1) Physical and Hydraulic Description, (2) Application and Treatment Chemistry, and (3) Conceptual Treatment Module. The first section provides a physical description and hydraulic profile for a LB to provide context for users of AMDTreat. The second section describes the common application of the LB component. The third section describes a generalized conceptual model describing the treatment chemistry to help familiarize users with terms and concepts presented throughout the AMDTreat modules.

2.1 Physical and Hydraulic Description

The geometric shape of a Limestone Bed is an inverted trapezoidal prism consisting of two or three distinct "material layers" that always include a Limestone and Freeboard layer, along with an optional Water layer (Figures 1, 2, and 3). LBs are distinct from Vertical Flow Ponds (VFPs) because the LB lacks a compost layer. The bottom layer of a LB is filled with limestone ranging from 1.0 to 3.5 inches in size (AASHTO #1 or #3) and is commonly 3.0 to 4.0 feet (ft) thick. A water layer may or may not overlie the limestone layer. If a water layer is present, it is commonly 1.0 to 2.0 ft deep. The topmost layer is the freeboard layer, which is used to accommodate changes in the water depth from either a large surge in flow or from a gradual decrease in the permeability of the limestone layer due to the accumulation of metal precipitates on top of or within the limestone layer.

Water can flow vertically or horizontally in a LB. While either flow direction can be modeled in AMDTreat, the default method is the horizontal flow LB. For horizontal flow LBs, water flows into the top of the limestone layer, then both lengthwise and down through the limestone layer before entering a piping system for discharge. A single perforated header pipe at the base of the limestone layer along the downstream end is designed to uniformly draw water across the bottom width of the limestone layer (Figure 4), promoting both a vertical and horizontal flow path. The perforated header pipe converges to a single solid discharge pipe that extends through the embankment and either upwards via a pipe or through a water level control device that can regulate the water surface within the LB and facilitate drainage of the LB for maintenance. Treated water is then typically discharged to a rock-lined ditch that flows to a setting pond.

Most operators of LBs prefer for the beds to be periodically "flushed" to help remove precipitated solids before they become immobile and cause clogging and hydraulic issues. The three-common flushing configurations are:

1. Continuous plug flow through the LBs with periodic manual flushing. Operators open a valve or other water control structure to cause a high flow, aggressive drain of the system to mobilize and remove, or "flush," metal precipitates from the limestone layer. In plug flow, the velocity of flow is assumed to be uniform across the width of the bed. The drain piping network may be connected to the effluent piping network, or the flush piping network could be separate.

2. Continuous plug flow through the LBs with periodic automatic flushing. Flushing systems may use a battery or solar-driven timer and actuator to open and close a valve (e.g. Agri Drain Smart System). Typically, the valve actuators are set to flush on a weekly schedule, or at a user-prescribed duration.

3. Batch reactor flow with dosing siphon. Some LBs are equipped with dosing siphons installed in a concrete vault designed to automatically initiate the draining of a limestone bed once the water fills to a defined elevation within the limestone layer and concrete vault. The flush event is designed with larger diameter pipe to promote a rapid flush to remobilize precipitated solids in the limestone layer.

Figures 5 through 10 provide a perspective of the physical layout of a LB. Figure 5 shows a typical graded footprint of a LB and shows an empty LB. Figure 6 shows a newly-constructed, empty. Figure 7 shows a LB constructed with a focus on easy maintenance without continuous flushing, and Figure 8 shows a LB configured with a siphon to periodically flush the bed to a settling pond. Figure 9 shows an Agri Drain solar-powered water control structure that can be programmed to periodically drain the bed and remove precipitate and, lastly, Figure 10 shows Aluminum Hydroxide being discharged to a settling pond during a flushing event.

2.2 Application and Treatment Chemistry

A Limestone Bed is a type of "passive" treatment system used to treat net-acidic mine drainage. The term "passive" refers to the inability to exert operational control to adjust treatment in response to changing influent or effluent conditions. Net-acidic mine drainage describes solutions that contain more acid-producing than acid-consuming species when the water is "treated". Therefore, a net-acidic solution is one where the acidity of the solution is greater than the alkalinity (net acidity = acidity – alkalinity).

The primary objective of LBs is to impart alkalinity to mine drainage and turn the net-acidic water to net-alkaline (alkalinity > acidity) for the purpose of treatment. Once mine drainage is changed to a net alkaline condition, acid-producing reactions, such as the hydrolysis of dissolved metals, can occur and the pH will remain above 6.0.

The proper application of LBs is largely a matter of personal preference. However, an application strategy can be based on a geochemical conceptual model of treatment. Limestone beds are best poised to treat aluminum-rich mine water containing low concentrations of ferric or ferrous iron. Since aluminum solubility is largely dependent on pH, aluminum will precipitate in the limestone layer as pH increases due to limestone dissolution (Figure 10).

The accumulation of $Al(OH)_3$ in the limestone layer will eventually cause hydraulic failure through decreased porosity (void space) so many designers must choose whether to:

1. Incorporate an engineering solution into the design to periodically remove the aluminum precipitates from the limestone (e.g. flushing system), or

2. Use the money designated for the flushing system to create a larger LB, and instead focus the design on conducting periodic mechanical maintenance that includes stirring and cleaning the limestone with heavy equipment.

Both approaches have been successfully used. However, it is difficult to know exactly how effective the flushing systems are at removing solids and prolonging the operation of the system before rehabilitation is needed.

Extensive piping networks designed for flushing can make stone replacement or cleaning more difficult when rehabilitation is required. Limestone beds with a focus on maintenance generally have minimal piping and may lack a water level to allow for quick and easy maintenance by an excavator. In either case, LBs will eventually require maintenance, which includes periodic stone agitation by an excavator to break up small sections of bed that have become clogged with metal precipitates. Mechanically agitating the stone aims to restore permeability by redistributing the accumulated solids in certain areas of the bed to less-clogged areas. This helps to extend the use of the existing limestone, but eventually portions of clogged or severely armored limestone will have to be removed and replaced with new stone. Some operators prefer to periodically remove precipitate-coated stone from the bed and use a pressure washer to clean the stone as opposed to purchasing new stone, which has proven to be successful in improving the limestone dissolution.

2.3 Limestone Bed Conceptual Treatment Module

The following presents a conceptual treatment model for a LB treating low pH mine drainage containing elevated concentrations of aluminum and manganese, and low concentrations of iron.

2.3.1 Freeboard Layer: The freeboard is designed to accommodate fluctuations in flow or increasing water elevation due to decreased permeability over time. It doesn't perform a specific purpose pertaining to geochemical treatment of the mine drainage

2.3.2 Water Layer: Some LBs seek to maintain a water level just below the top of the limestone and will lack a "water layer" defined by AMDTreat. Users can model this scenario by setting the water depth to zero. In limestone beds containing a water layer, low pH drainage enters the water layer and gas exchange reactions occur with the atmosphere (O_2 in-gassing and CO_2 degassing).

2.3.4 Limestone Layer: As mine drainage flows from the water layer into the limestone layer, carbonic acid and pH acidity will react with limestone and cause the pH to increase ($CaCO3 + H_2CO_3 = Ca^{+2} + 2HCO^{-3}$). Any ferric iron ($Fe^{3+}$) will precipitate as the pH is increased to 4.0 or greater (the point at which $Fe(OH)_3$ solubility [Figure 11] is < 1.0 mg/L). Most of the aluminum will precipitate and release acidity as the pH approaches approximately 5.5 (Figure 11). The aluminum acidity will drive additional limestone dissolution, and the low water velocity will cause aluminum precipitates to settle within the pore spaces between individual pieces of limestone. The drainage flowing into the limestone layer will be oxic. Ferrous iron (Fe^{2+}) will oxidize and precipitate as the pH is increased to above 6.0, given enough retention time (Figure 12).

For a given pCO_2 (partial pressure), a VFP may generate more alkalinity than a LB if the compost layer increases pCO_2. However, the lack of a compost layer makes periodic maintenance (agitating or adding stone) of the bed easier and avoids some of the permeability issues caused by compost. While manganese removal does not occur in VFPs due to the anoxic conditions, some LBs experience significant manganese removal due to the combination of pH > 6.0 and oxic conditions. While the exact mechanism causing the manganese removal is not well understood (e.g., biotic, abiotic, adsorption followed by oxidation), the phenomenon is common but not a primary design objective due to the inability to predict performance. The amount of alkalinity that the LB can produce depends on the amount of metal acidity released in the limestone layer and the pCO_2 of the solution. Since aluminum hydrolysis and precipitation will occur within the limestone layer, a properly functioning LB will always achieve net alkaline conditions since the aluminum acidity will drive limestone dissolution. This is true for sites treating water with elevated pCO_2.

Sites that use dosing siphons to treat low pCO_2 drainage may discharge net acidic water since the water discharged by the siphon contains a wide range of retention times, and the alkalinity load of the water with long retention times may be insufficient to offset the acidity load of water with minimal retention time. After a siphoning cycle, water that first enters the dewatered LB will have a retention time equal to the time it takes for the discharge to fill the bed until the siphon is triggered again. The last water that entered the LB and tripped the siphon will have virtually no retention time, and the water flowing to the LB during the siphoning will have essentially no treatment with the limestone. Thus, the use of a siphon to flush solids and prolong maintenance may affect the effluent water quality during discharge events. Designers often prefer a constant plug flow reactor as opposed to the siphon batch reactor to preserve water quality. Many LBs that are configured as plug flow reactors use solar-powered flushing systems to periodically flush solids from the bed.

3.0 Limestone Bed Module Overview

3.1 Layout and Workflow

In general, inputs are on the left-hand side of the module and calculated outputs are on the right. The module inputs on the left-hand side are arranged into five sections: (1) Water Quality and Flow Input, (2) Sizing Methods, (3) System Properties, (4) Layer Materials, and (5) Other Items. The workflow for the module is for users to start at the top left-hand side. Enter the *Design Flow* and *Net Acidity*, then select a method to determine the amount of limestone contained in the limestone layer of the LB. Next, users specify design parameters such as the depth of the water and limestone layers, and unit costs for items affecting the capital cost to construct the LB. Finally, users can enter any capital cost not captured by the module into the *Other Items* section.

Module output is provided on the right-hand side of the module. Module outputs on the right-hand side are arranged into four sections: (1) Sizing Summary, (2) Capital Cost, (3) Annual Cost, and (4) Net Present Value. The sizing summary provides dimensional details for the system. The estimated cost to construct and operate the LB is provided under the *Capital Cost* and *Annual Cost* headings. Lastly, users can opt to conduct a Net Present Value (NPV) to obtain the total cost to operate and maintain a treatment system for a defined time period.

A general overview of the module input and output sections are presented below, however, users are directed to the numerous tool tips located in the module that provide additional detailed information, such as definitions of terminology. In most cases, the tool tips are accessed by clicking on the information icon (ℹ) in each of the subheadings in the module.

3.2 Module Inputs

3.2.1 Water Quality and Flow Input: The Water Quality and Flow Input section is where users specify the design flow and net acidity to size the passive treatment system component. The definitions for the required input can be found in the tool tip for this section. Click on the information icon (ℹ) on the right side of the Water Quality and Flow subheading.

3.2.2 Sizing Methods: Users can select from five different methods to size the Limestone Bed: Retention Time, Bureau of Mines, Alkalinity Generation Rate, User-specified Limestone Quantity, and User-specified Dimensions. The module offers two different approaches to sizing LBs. The first approach calculates the mass of limestone (tons) in the limestone layer before determining other dimensions. The Retention Time, Bureau of Mines, Alkalinity Generation Rate and User-Specified Limestone Quantity methods utilize this approach. The first approach is the most common as it relates the sizing of the treatment system based on flow and water quality characteristics. The second approach requires users to specify the length and width of the freeboard layer (User-specified Dimensions method) before calculating the remaining dimensions of the LB. The second approach is often used when the land area available for treatment is restricted, when reverse engineering, or when developing a cost estimate for an existing treatment system.

Calculate Mass of Limestone in Limestone Layer

3.2.2.1 Retention Time – The user enters the desired time to retain the water in the void spaces between the individual pieces of limestone. The mass of limestone required to achieve the user-specified retention time is calculated by multiplying the *Design Flow* rate by the *Retention Time* to determine the volume required to retain the water (Equation 1). The calculated volume is then divided by the porosity of the limestone layer to calculate the total volume of the limestone layer (Equation 2).

Volume Required for Water (yd^3) =

$$Design\ Flow\ (\text{gpm}) \times \frac{60\ \text{min}}{1\ \text{hr}} \times Retention\ Time\ (\text{hrs}) \times \frac{1\ \text{yd}^3}{201.974\ \text{gal}} \qquad \textbf{(1)}$$

$$\text{Limestone Layer Volume (yd}^3\text{)} = \frac{\text{Volume Required for Water (yd}^3\text{)}}{\text{Limestone Porosity (\%)}} \qquad \textbf{(2)}$$

The porosity represents the percent (%) of void space in the limestone layer (volume of the voids in between individual pieces of limestone/total volume of the voids and the limestone). Users can specify a value for porosity to match the gradation of limestone they plan to use in the limestone layer. Users can specify the porosity value under the *Limestone* section, which is located under the *Layer Materials* subheading. Based on the user-specified porosity value, AMDTreat calculates the *Bulk Density* of the limestone.

The mass of the limestone required in the limestone layer is calculated by multiplying the limestone layer volume by the *Bulk Density*.

Limestone Mass (tons) =

$$Limestone\ Volume\ (\text{yd}^3) \times \frac{27\ \text{ft}^3}{1\ \text{yd}^3} \times Limestone\ Bulk\ Density\ \left(\frac{\text{lbs}}{\text{ft}^3}\right) \times \frac{1\ \text{ton}}{2000\ \text{lbs}} \qquad \textbf{(3)}$$

Limestone Mass open parentheses tons close parentheses equals limestone volume open parentheses cubic yards close parentheses multiplied by twenty seven cubic feet

Results from bench-scale testing indicate that a retention time of 16 hours is a good balance between maximizing alkalinity production and the size of the treatment system (mass of limestone). Some professionals conduct "cubitainer" testing to determine the amount of time required to achieve net alkaline conditions. A cubitainer is filled with limestone and mine drainage and alkalinity is measured over time. Some professionals find it appropriate to add a safety factor to the retention time since the retention time and contact between limestone and mine drainage will change as soon as limestone starts to dissolve.

See Section 3.2.2.7 to 3.2.2.9 for volume calculations for the other layers.

3.2.2.2 Bureau of Mines - The Bureau of Mines was an agency in the U.S. Department of Interior that is now retired but was instrumental in conducting some of the early research in how to design passive treatment systems (Hedin and Watzlaf, 1994). A method they developed to determine the mass of limestone needed in passive treatment systems was to perform two calculations. The first calculation is to determine the mass of limestone required to retain the water for a given retention time. This calculation is the same as Equation 3, described above for the retention time sizing method.

A second calculation (Equation 4) is used to determine the mass of limestone required to neutralize the acid loading of the mine drainage for a specified time frame (*Neutralization Period*). The mass of limestone required to neutralize the acid loading is determined by multiplying the user-specified *Design Flow* by the *Net Acidity* and the *Neutralization Period*. The resultant value is divided by both the *Purity* and *Dissolution Efficiency* of the limestone to correct for the portion of limestone that will not dissolve to produce alkalinity and account for the fact that larger pieces of limestone are not likely to efficiently dissolve due to a loss of surface area from weathering and mineral precipitate coatings (i.e. iron hydroxide) that form on the surface and disrupt dissolution. A *Dissolution Efficiency* of less than 100% will increase the mass of limestone required in the LB to compensate for the mass of limestone that is unlikely to dissolve. Users can specify the *Purity* and *Dissolution Efficiency* of limestone under the *Limestone* section, which is located under the *Layer Materials* subheading.

Limestone Mass to Neutralize Acid (tons) =

$$\frac{Design\ Flow\ (\text{gpm}) \times \frac{1\ \text{ft}^3}{7.48\ \text{gal}} \times \frac{525600\ \text{min}}{1\ \text{year}} \times Net\ Acidity \times \frac{1\ \text{lb}}{453592\ \text{mg}} \times \frac{28.3168\ \text{L}}{1\ \text{ft}^3} \times Neut.Period\ (\text{yrs}) \times \frac{1\ \text{ton}}{2000\ \text{lbs}}}{Purity\ (\%\ \text{CaCO}_3\ \text{by weight}) \times Dissolution\ Efficiency\ (\%)} \quad \textbf{(4)}$$

The mass of limestone required to retain the water for a specified time (*Retention Time*) is added to the mass of limestone required to neutralize the acidity loading for the *Neutralization Period* to determine the total mass of limestone required for the LB limestone layer (Equation 5). This method ensures the user-specified *Retention Time* is preserved, to generate maximum alkalinity, at the end of the user-specified *Neutralization Period* when the limestone mass dedicated to neutralizing the acidity load is nearly depleted.

Total mass of limestone (Bureau of Mines method) =

$$\text{Retention Time Limestone mass (Eq. 3)} + \text{Limestone mass, neutralization (Eq. 4)} \quad \textbf{(5)}$$

See Section 3.2.2.7 to 3.2.2.9 for volume calculations for the other layers.

3.2.2.3 Alkalinity Generation Rate - This method calculates the mass of limestone required based on an expected rate of alkalinity production, or acidity neutralization, per area of limestone. Since the limestone depth in LB is commonly 3 feet, the alkalinity generation rate could be viewed as the alkalinity production per unit volume (ft^3). Penn State University professor emeritus Dr. Art Rose developed this method (Rose, 2004) by evaluating 29 operating VFPs and identifying a relationship between effluent net alkalinity and influent acidity (raw mine drainage) loading per unit area. Dr. Rose suggested a design guideline for the alkalinity generation rate (or acidity neutralization rate) of 25 grams of influent acidity/m^2 of limestone surface area/day.

The program calculates the mass of limestone by dividing the daily influent acidity load (gal/day) by the user-specified *Alkalinity Generation Rate* (g/m^2/day) to calculate the limestone surface area requirement (Equation 6). The surface area is multiplied by the user-specified limestone layer *Depth* to determine the volume required in the limestone layer (Equation 7). AMDTreat uses the user-specified porosity of the limestone material to determine the bulk density of loosely placed limestone. The limestone layer volume is multiplied by the bulk density to calculate the mass of limestone required, as shown in Equation 3.

Limestone Surface Area (ft^2) =

$$\frac{\text{Daily influent acidity load } (\frac{\text{g}}{\text{day}})}{\text{Alkalinity generation rate } (\frac{\text{g}}{\text{m}^2}/\text{d})} \times \frac{10.7639\ \text{ft}^2}{1\ \text{m}^2} \quad \textbf{(6)}$$

Limestone Volume (ft^3) = Limestone Surface Area (ft^2) x Limestone Layer Depth (ft) **(7)**

See Section 3.2.2.7 to 3.2.2.9 for volume calculations for the other layers.

3.2.2.5 User-Specified Limestone Quantity (tons) - If users have their own method for determining the mass of limestone, the user-specified limestone method can be used to calculate the dimensions of the limestone layer and remaining layers of the LB. The mass of limestone is entered, and the user-specified porosity value for the limestone layer is used to calculate the volume and retention time of the limestone layer. See Section 3.2.2.7 for volume calculations for the other layers.

3.2.2.6 User-Specified Dimensions – Mine drainage discharges often emerge at the base of hillsides. The available land area for constructing a treatment system between the point of emergence and the receiving stream can be limited. The use of other sizing methods may produce a LB that is larger than the available land area. A smaller LB can be designed for the site, but it will most likely require more maintenance and prematurely plug due to high metal loading per unit area/volume. Alternatively, a smaller LB could be designed to treat only a portion of the mine drainage while bypassing the rest. To use the freeboard sizing method, enter the top length and width of the freeboard. AMDTreat then uses the user-specified side slopes and depths to calculate the dimensions and volumes of the LB layers.

Volumetric Calculations

3.2.2.7 Volumetric Calculations –AMDTreat models all passive treatment systems, including LBs, as an “inverted” trapezoidal prism (Figure 1). AMDTreat calculates the overall dimensions of a passive treatment system by first breaking up the system into individual layers, such as the Freeboard Layer, Water Layer, Limestone Layer, etc. Each individual layer and the geometric shape of the overall system is modeled as an inverted trapezoidal prism. AMDTreat sizing methods fall into one of two categories: (1) users input information that is used to calculate a layer volume or surface area is calculated or Users specify the mass of limestone, or (2) users specify the Top Width and Length of the Freeboard. In either case, AMDTreat uses the information generated by the sizing method, along with user-specified depths, side slopes, and length-to-width ratios to determine the dimensions of a layer shaped as an inverted trapezoidal prism. What differs is the approached used to calculate the geometry. The two approaches are provided below

3.2.2.8 Calculations for Retention Time, Bureau of Mines, Alkalinity Generation Rate, and User-Specified Limestone Sizing Methods –

The equation for an inverted trapezoidal prism is:

$$V = \left(\frac{W_T L_T + W_B L_B}{2}\right) D \quad (\mathbf{8})$$

<u>*Where:*</u>
V = Volume of trapezoidal prism
$L_T W_T$ =Length & Width of top of prism
$L_B W_B$ =Length & Width of bottom of prism
D = Depth

These sizing methods determine the volume of the limestone layer. Therefore, AMDTreat calculates the volume of the limestone layer and users are required to specify the depth of the limestone layer, inside slope, and length-to-width ratio for the bottom of the limestone layer. The unknowns are the length and width of the top and bottom dimensions of the trapezoidal prism for the limestone layer. Since the depth and inside side slope of the LB is known, the top width and length of the limestone layer can be written in terms of the bottom length and width to reduce unknowns in the equation. Furthermore, since the bottom length-to-width ratio is known, the bottom width can be written in terms of the bottom length. Now Equation (8) is rearranged to solve for the bottom length of the limestone layer. The resultant equation is a quadratic:

$$L_{BLL} = \frac{-\left(\frac{2DR}{S} + \frac{2D}{S}\right) \pm \sqrt{\left(\frac{2DR}{S} + \frac{2D}{S}\right)^2 - 4(2R)\left(\frac{4D^2}{S^2} - \frac{2V}{D}\right)}}{2(2R)} \quad (\mathbf{9})$$

<u>Where:</u>
V = Volume of Limestone Layer
L_{BLL} = Bottom Length of Limestone Layer
D = Depth of Limestone Layer
S = Inside Side Slope of LB
R = Length to Width Ratio of Bottom of Limestone Layer

Once the bottom length is known, the bottom width of the limestone layer (W_{BWL}) is calculated by dividing the bottom length by the user-specified value for length-to-width ratio for bottom of the Limestone Bed:

$$W_{BWL} = \frac{L_{BLL}}{R} \quad (\mathbf{10})$$

The two remaining unknown dimensions of the limestone layer are the top length and width. The top length of the limestone layer is calculated by:

$$L_{TLL} = L_{BLL} + 2 * S * (D_{LL}) \quad \mathbf{(11)}$$

Where:
L_{TLL} =Top Length of Limestone Layer
L_{BLL} = Bottom Length of Limestone Layer
D_{LL} = Depth of Limestone Layer
S =Inside Side Slope of LB (rise/run)

The top width of the limestone layer is determined by the same approach. Now that all the dimensions of the limestone layer are known, the dimensions of the water and freeboard layers can be determined using a similar approach:

Water Layer
The bottom length of the water layer (L_{BWL}) is equal to the top length of the limestone layer (L_{TLL}).

$$L_{BWL} = L_{TLL} \quad \mathbf{(14)}$$

The top length of the water layer (L_{TWL}) is calculated by:

$$L_{TWL} = L_{BWL} + 2 * S * (D_{WL}) \quad \mathbf{(15)}$$

Where:
S =Inside Side Slope of LB (rise/run)
D_{WL} = Depth of Water Layer

The same approach used to calculate the bottom and top width of the water layer. Then Equation (8) is used to calculate volume of the water layer.

Freeboard Layer
The bottom length of the freeboard layer (L_{BFL}) is equal to the top length of the water layer (L_{TWL}).

$$L_{BFL} = L_{TWL} \quad \mathbf{(16)}$$

The top length of the freeboard layer (L_{TFL}) is calculated by:

$$L_{TFL} = L_{BFL} + 2 * S * (D_{FL}) \quad \mathbf{(17)}$$

Where:
S =Inside Side Slope of LB (rise/run)
D_{FL} = Depth of Freeboard Layer

Equation (8) is used to calculate the volume of the freeboard layer.

In addition to assuming all passive treatment systems are constructed as an inverted trapezoidal prism, an additional assumption is that the excavation volume is equal to the summation of all the individual layer volumes, except for the freeboard layer. It is assumed the freeboard layer is constructed with a portion of the excavated earth:

Limestone Bed Excavation Volume = Water Volume + Limestone Volume **(18)**

3.2.2.9 Calculations for User-Specified Dimensions Sizing Method – When users specify top width and length of the freeboard for a system, AMDTreat uses the user-specified values for inside side slope and the freeboard, water, and limestone layer depths to calculate the dimensions and volumes of the individual layers of the LB.

The bottom length of the freeboard layer (L_{BFL}) is calculated by:

$$L_{BFL} = L_{TFL} - 2 * S * (D_{FL}) \quad \mathbf{(19)}$$

Where:
L_{BFL} = Bottom Length of Freeboard Layer
L_{TFL} =User-Specified Top Length of Freeboard Layer
D_{FL} = Depth of Freeboard Layer
S =Inside Slope of LB (Run/Rise)

The bottom width of the freeboard layer is calculated using the same approach.

The volume of the freeboard layer is determined by:

$$V_{FL} = \left(\frac{W_{TFL}L_{TFL} + W_{BFL}L_{BFL}}{2}\right) D_{FL} \quad \mathbf{(20)}$$

Where:
V_{FL} = Volume of trapezoidal prism-shaped Freeboard Layer
W_{TFL} = Top Width Freeboard Layer
L_{TFL} = Top Length Freeboard Layer
W_{BFL} = Bottom Width Freeboard Layer
L_{BFL} = Bottom Length Freeboard Layer
D_{FL} = Depth of Freeboard Layer

Water Layer

The top length of the water layer (L_{TWL}) is equal to the bottom length of the freeboard layer (L_{BFL}).

$$L_{TWL} = L_{BFL} \quad \mathbf{(21)}$$

Now that the top width and length of the water layer is known, the user-specified values for inside slope and depth of water layer are used in Equation (19) to calculate the bottom width and length of the water layer. Equation (20) is used to calculate the volume of the water layer.

Limestone Layers

The same approach used to calculate the dimensions of the water layer are used to calculate these layers.

Lastly, the Excavation volume is determined by adding the volumes for the water and limestone layers (Equation 18). The model assumes that the excavated earth is used to construct the freeboard layer and any excess material is disposed of on-site.

3.2.3 System Properties: The Systems Properties section allows the user to specify the inside slope of the LB, the limestone layer bottom length-to-width ratio, and the excavation unit cost.

3.2.4 Layer Materials: Unlike active treatment systems which require the continuous addition of chemicals to maintain treatment of mine drainage, passive treatment systems typically consist of impoundments filled with enough reagent (e.g., limestone, compost) to provide treatment for many years. For some passive treatment system components, such as LBs, limestone is used within the impoundment to manipulate the geochemistry and control oxidation/reduction and solubility reactions as the mine drainage flows through the system. AMDTreat considers each reagent or material as a "layer" in the impoundment. Both "reagent" and "material" are used to describe layers because not all layers are comprised of reagents or materials meant to manipulate water chemistry. For example, the freeboard layer is designed to accommodate fluctuations in flow or increasing water elevation due to decreased permeability over time or plugging of layer materials from metal hydroxides or sediment. The pipe layer is located at the very bottom of the impoundment and is designed to transport water out of the LB or to flush the system in order to remove metal hydroxide precipitates that accumulate in the limestone layer. The *Layer Materials* section is where users can control the depth and other characteristics of the materials used in the various LB layers.

3.2.4.1 Freeboard Layer: Users specify the depth of the freeboard layer designed to produce enough storage to accommodate increases in the water layer due to increased flow events or clogging of the treatment media. In most passive systems, the influent to the LB is within or at the top of the freeboard layer. An emergency spillway is incorporated into the freeboard layer just below the influent elevation to prevent the restriction of water flowing into the LB and to prevent water from overtopping the embankment. The bottom of the freeboard layer is the top of the water layer for the LB. A typical freeboard layer depth is between 1.0 and 3.0 feet.

3.2.4.2 Water Layer: The water layer maintains the saturation of the treatment media and helps to disperse the water flow across the surface area of the LB. The depth of the water layer is often manipulated to maintain equilibrium as the treatment media clogs with sediment or metal hydroxide precipitates and to control gas exchange of the lower layers with the atmosphere. At times, the water elevation is manipulated to control the growth of aquatic plants that may occur in LBs. A typical water layer depth is between 1.0 and 2.0 feet. Some Limestone beds are designed without water layers (depth is zero), and AMDTreat can be used to cost model this configuration.

3.2.4.3 Limestone Layer: The limestone layer is the main source of alkalinity generation in a LB. Users can specify the depth, purity, dissolution efficiency, porosity and unit cost for both the material and placement of limestone in this section. A typical limestone layer depth is 3.0 feet and limestone used in passive treatment system components such as LBs typically have purity greater than 85% calcium carbonate ($CaCO_3$) by weight. The dissolution efficiency is used to compensate for limestone losing surface area and becoming less reactive as it dissolves/weathers and as a safety factor for additional limestone to compensate for potential plugging or coating (a.k.a. armoring) issues.

3.2.4.4 Pipe Layer: The pipe layer considers the piping required to convey the water into and/or out of the LB. The piping layer may be situated between the limestone and liner layers, or within or on top of the limestone layer (within the freeboard layer). The piping system is necessary to distribute the water and promote horizontal and vertical flow through the treatment media, and to collect the water and discharge it out of the LB. The LB module offers users two methods to estimate the cost to purchase and install the piping network, the **AMDTreat Piping Calculator** or user-specified Piping Layout.

The default design of the **AMDTreat Piping Calculator** for LBs is different than for VFPs, although it is very similar to Anoxic Limestone Drains (ALDs). The header pipes are attached to the influent/effluent pipes using a “Tee” or Elbow coupler depending upon the pipe orientation. The default design of the AMDTreat Piping Calculator for LBs is to have a perforated header pipe that extends along the upstream top width of the limestone layer on top of the limestone bed for the influent, and a second perforated header pipe along the downstream bottom width of the limestone layer (Figure 2) for the effluent. The perforated header pipes are intended to evenly distribute the raw mine water across the width of the limestone bed and to draw water both horizontally and vertically through the treatment media into the effluent pipe for discharge from the LB. The use of a larger-diameter header pipe for the influent may help with maintenance, while for the effluent it is intended to promote flow distribution and maximize flow velocity during flushing events to remove accumulated metal precipitates from the limestone layer.

Historically, designers have developed a wide variety of piping systems to accommodate the hydraulic functionality of LBs. In some instances, piping systems designed to flush the limestone layer are physically separated from the primary discharge flow pipe network. Additionally, some designers have incorporated zonal flush pipe systems which allow for flushing metal precipitates in areas of the limestone bed that are most susceptible to plugging, such as the area of the bed nearest the influent. Users that desire to customize their piping design can specify the size and length of header or other pipes, as well as adjust the labor rate cost.

3.2.4.5 Liner Layer: Many mine sites lack the soil characteristics required to prevent leaky passive treatment system components. AMDTreat offers three types of liner systems that prevent water from leaking from the impoundment(s): Clay, Synthetic (i.e. PVC), and Geosynthetic Clay (GCL). The volume of clay required is calculated from the entire inside sloped area of the pond, from the top of freeboard to the base of the limestone (bottom of pond), plus the bottom area of the LB and multiplying it by the user-specified compacted thickness (typically 0.5 to 1.0 foot) and unit cost to purchase and install the clay liner. The area required for Synthetic or Geosynthetic Clay liners is determined by calculating the inside sloped area and the bottom area of the LB similar to the clay liner and adding an additional 2.0 ft of length on all sides to accommodate the incorporation ("tie in") of the liner into the embankment near the top of the freeboard layer to secure the liner system. AMDTreat provides the option of adding Non-woven Geotextile as a separate material for all liner systems. Non-woven geotextile separation material is commonly used to protect the Synthetic or Geosynthetic Clay liner from the excavated inside surface of the pond and/or the limestone layer.

3.2.5 Other Items: The *Other Items* section allows users to consider the capital cost of inlet and outlet structures, valves, and flow distribution structures. **AMDTreat suggests default quantities and unit costs for construction of a single LB component.**

3.3 Module Outputs

3.3.1 Sizing Summary: The Sizing Summary section contains all the calculated module outputs, such as the dimensions, volumes, and plug flow retention times for the various layers. The mass of limestone required for the limestone layer is provided on the right-hand side of the Sizing Summary heading.

3.3.2 Capital Cost: This section provides the estimated costs for the various user-specified components and the total estimated cost to construct the entire LB component of the passive treatment system.

3.3.3 Annual Cost: Since a LB is a passive treatment system component, the only annual cost considered is the cost for maintenance. Annual costs, such as sampling, labor, and access road maintenance are "project-wide" costs since they apply to an entire treatment site, not each individual treatment component. Sampling, Labor, and Site Development (i.e. Clearing/Grubbing/Revegetation) modules are located under the "Project Modules" section of the main user interface and capture these types of annual costs.

Annual maintenance costs for LBs include periodic "flushing" of the limestone layer to evacuate accumulated metal hydroxide precipitates from the limestone void spaces, maintaining clear influent and effluent piping, and manipulating the water level control structure (e.g. Agri Drain) to change the water level in the LB as needed. It is assumed that some years will not require the full amount of funds set aside for annual maintenance, but funds will eventually be used over the system life. Users can estimate the annual maintenance costs by assuming a percentage of the capital cost (the more expensive the system, the more expensive the maintenance) or specify a known annual maintenance cost amount.

3.3.4 Net Present Value: The Net Present Value (NPV) section determines the cost to operate a treatment system component over a specified time frame. The NPV calculates the present-day financial investment required to generate the income to pay for future operation and equipment/materials replacement costs. Both **Financial Variables** and **Cost Categories** are required to calculate the NPV.

3.3.4.1 Financial Variables - The *Term of Analysis*, *Inflation Rate*, and *Rate of Return* are three variables used in the NPV calculations. The default values for these terms are shown under the

Net Present Value section of each module. Users must access the Net Present Value menu at the top of the main user interface to change the default values as they would apply to all modules used for an entire treatment system. While NPV is determined for each AMDTreat module activated by the user, the goal is to determine a total NPV for an entire mine drainage treatment system project (a collection of cost estimates for individual modules creates a treatment system project in AMDTreat). Therefore, a single value for *Term of Analysis*, *Rate of Return*, and *Inflation Rate* is applied to all modules and cannot vary between modules.

- Term of Analysis: The time period used for the NPV calculation is to determine the financial investment required to pay for all future costs of the treatment system components.

- Inflation Rate: Represents the average price increase of goods and services over time. AMDTreat uses the inflation rate to calculate the future cost of the annual operation and maintenance (O&M) and recapitalization items (e.g., limestone).

- Rate of Return: Describes the expected profit on an investment.

3.3.4.2 Cost Categories - For each treatment module, AMDTreat provides a list of recommended equipment and materials that require recapitalization. In addition, AMDTreat provides recommendations (default values) for life cycle and replacement percentage. Users can click on the default values for *Life Cycle* or *Replacement Percentage* and use the +/- buttons to change the default values. In addition, users can select *Custom Cost* and enter a new cost to represent the current cost of the equipment. Users can add new recapitalization items or deactivate/delete existing items for calculating the NPV.

An example of how the recapitalization variables are used to determine NPV is to consider the following hypothetical scenario. Assume a vertical turbine pump has a life cycle of 50 years but requires the motor component of the pump to be rebuilt every 20 years. Let's assume the present-day cost to purchase the pump is $500,000 and the cost to remove, rebuild, and reinstall the pump motor is only $20,000. Now assume we want to determine the amount of investment required today (NPV) to generate the income to pay for the future cost of rebuilding the pump motor over a 50-year Term of Analysis, which is also equal to the life cycle of the pump. In addition, let's assume an inflation rate of 5.0% and Rate of Return of 8.1%. The goal is to place the money in a relatively secure investment vehicle to generate 8.1% annually. The NPV will tell us the size of investment required to generate the income to pay for the future costs over 50 years.

There are several ways to model the replacement cost. One way is to replace 4% of the present day cost of the pump (4% of $500,000 = $20,000) with a life cycle of every 20 years. If the Term of Analysis is 50 years, then the entire pump would not require recapitalization since the life cycle of the pump is 50 years. However, the motor would require two replacements (50 years / 20 years = 2.5 rounded down to 2).

To determine the NPV to recapitalize rebuilding of the motor, AMDTreat calculates the future cost to rebuild the motor at each life cycle, 20 and 40 years. The program uses the Inflation Rate to inflate the present day default cost to rebuild the motor in 20 and 40 years from now. While the present day cost to rebuild the pump motor is $20,000, the future cost to rebuild the motor in 20 years at a 5.0% Inflation Rate is $53,065 and $140,799 in 40 years (Equation 8). Assuming an

8.1% Rate of Return, the 50-year NPV for the pump is $17,422. In other words, an initial investment of $17,422 is needed at an annual Rate of Return of 8.1% to generate the investment income required for the two motor rebuilds over the 50-year life cycle of the pump.

Cost to rebuild motor in 20 years =

$$Present\ Day\ Cost \times (100\% + Inflation\ Rate)^{20} = \$20{,}000 \times (100\% + 5\%)^{20} = \$53{,}065 \quad \textbf{(22)}$$

- Annual Operation and Maintenance Cost: By default, AMDTreat transcribes the annual O&M cost from the Annual Cost section to the Net Present Value section. The program assumes the module is being used to first estimate the annual cost for a treatment system component, so it automatically transcribes the annual cost to the NPV section. If this is not the case or the user wants to use some other annual cost, the “Use Custom” box can be selected to allow the user input of a different annual cost to utilize in the NPV calculation.

- Recapitalization Cost: Certain treatment system components, especially mechanical and water conveyance equipment, require periodic replacement. The recapitalization cost of an item is an estimate of the amount of money required to pay for future replacement costs for the item. In addition to the Financial Variables described above, three additional values are required to calculate the NPV of recapitalization costs, the Present-Day Equipment Cost, the Life Cycle, and the Replacement Percentage.

- Default Cost: This represents the current cost to purchase the equipment or material.

- Life Cycle: The time span between equipment or material replacement is termed as its Life Cycle. Some equipment manufacturers provide recommended life cycles for their equipment to provide consumers with an estimate of how long the equipment is expected to be operational. Some life cycles, such as those used for treatment media (limestone), are based on best professional judgement. Some operators prefer to periodically purchase and replace equipment before failure to preserve the continuity of operations, while others wait until failure to replace an item.

- Replacement Percentage: The Replacement Percentage is an adjustment factor to the Default Cost to accommodate situations where the entire piece of equipment or all of the material does not require recapitalization. For example, a passive treatment component may be designed to contain enough limestone to neutralize the acidity load for 20 years, however, the accumulation of metal hydroxide precipitates within the void space of the limestone layer may require that 25% of the limestone be replaced every 7 years to prevent hydraulic failure such as plugging or short-circuiting. For this scenario, the initial cost of the limestone making up the limestone layer is discounted by 75% and assigned a life cycle of 7 years to determine the amount of money required to cover the cost of replacing 25% of the limestone layer every 7 years over the Term of Analysis.

3.3.4.3 Rationale for Recapitalization Recommendations:

Recapitalization recommendations are based on professional experience of the AMDTreat Team and may not apply to all situations. Users are encouraged to customize the recapitalization assumptions to their treatment scenario. AMDTeat Team members are located in Pennsylvania and West Virginia and have collective experience in design, funding, and/or operation/maintenance for over 100 passive treatment systems. Most passive treatment systems constructed in Pennsylvania and West Virginia are less than 15 years old, thus the industry is still gaining experience in lifecycles for various components. However, the AMDTreat Team held discussions on personal experience to develop a list of recapitalization recommendations. Users may have different experience and opinions.

By default, AMDTreat includes a list of five recapitalization items for Limestone Bed. The items are listed even if they are not selected for the treatment system. The purpose of this is to inform the user of items they should think about recapitalizing or including in their treatment design. For example, Liner is listed as a recapitalization item even if no liner is selected in the cost estimation. In this case the recapitalization cost is set to $0.00 but the item is still shown as a reminder to the user that a Liner is a common item that should be considered. If a liner is included in the cost estimation, the estimated liner cost is used to calculate a recapitalization cost for liner. Users can delete or modify any of the default Recapitalization items by either deselecting the item or by setting the Replacement % to zero. If the item is deselected the Total Cost for the item will still be shown but the cost will be subtracted from the Net Present Value Cost, shown in the Net Present Value Heading.

Limestone: The limestone can require maintenance and periodic partial replacement, mostly due to clogging from metal precipitate. Therefore, the default recommendation in AMDTreat is to replace 50% of the limestone every 10 years.

Liner: Often liners are destroyed, especially synthetic, while conducting maintenance on passive treatment systems, if the equipment operator is inexperienced with passive systems. Thus, AMDTreat recommends planning to replace a portion of the liner while the Limestone is being replaced. The default assumption is to replace 50% of the Limestone every 10 years, so the same assumptions are recommended for Liner recapitalization.

Pipe: Piping is often exposed at the surface and can become damaged by vandalism, falling trees, and other factors. AMDTreat assumes 50% of the piping will require replacement after 25 years of service.

Other Items: The Other Items section in AMDTreat includes Flow Distribution Structures, Water Level Control Structures, and Outlet Protection Structures. These structures are often durable, and many treatment systems have never experienced replacement of these items, however, AMDTreat Team members have had at least one experience of each of these items requiring replacement, thus the Team wanted to include these items for replacement consideration.

3.4 Assumptions of Design Sizing and Costs

: AMDTreat is a cost estimation model that uses assumptions to provide treatment sizing and both capital and annual cost estimates. While there are many assumptions in the program, the ones provided below are important to consider for the LB module.

1. The Limestone bed is assumed to be constructed on a flat surface, where the water and limestone layers are excavated at or below the existing or original ground. A portion of the excavated material is then used to construct the freeboard embankments above the existing or original ground (see Figure 2). AMDTreat assumes an on-site balance of cut and fill material. However, if this is not the case, the user can modify excavation cost default values to reflect the anticipated conditions based on the site characteristics.

2. The geometric shape of a LB is an inverted trapezoidal prism (Figure 1). The volumetric equation for a trapezoidal prism is used to calculate the LB layer volumes.

3. None of the sizing methods provide a "design life" that properly accounts for both: a) the amount of limestone required to neutralize the acidity loading for a defined time frame, and b) hydraulic and treatment issues caused by the accumulation of metal hydroxide precipitates within the void spaces of the treatment media. Some sizing methods, such as the *Bureau of Mines*, account for reagent requirements. Others, like *Alkalinity Generation Rate*, indirectly attempt to address plugging issues by controlling the metal loading applied to a unit surface area.

4. In general, the goal of the LB sizing methods is to provide an estimate of the limestone mass required to generate net alkaline conditions. None of the sizing methods are based on achieving effluent water quality criteria or requirements. With that said, a properly sized LB treatment system should generate pH > 6.0 and net alkaline water, which in theory will decrease aluminum and ferric iron solubility to less than 1.0 mg/L.

4.0 References

Hedin, R.S. and Watzlaf, G.R., 1994. The effects of anoxic limestone drains on mine water chemistry. Proceedings of the 3rd International Conference of the Abatement of Acidic Drainage, Volume 1, Pittsburgh, PA. U.S. Bureau of Mines SP 06B-94, p. 185–194.

Rose, A. W., 2004. Vertical flow systems – Effects of time and acidity relations. Proceedings, American Society of Mining and Reclamation, Morgantown, WV, April 18-24, 2004, p. 1595-1615. https://www.asrs.us/Portals/0/Documents/Conference-Proceedings/2004/1595-Rose.pdf

5.0 Figures

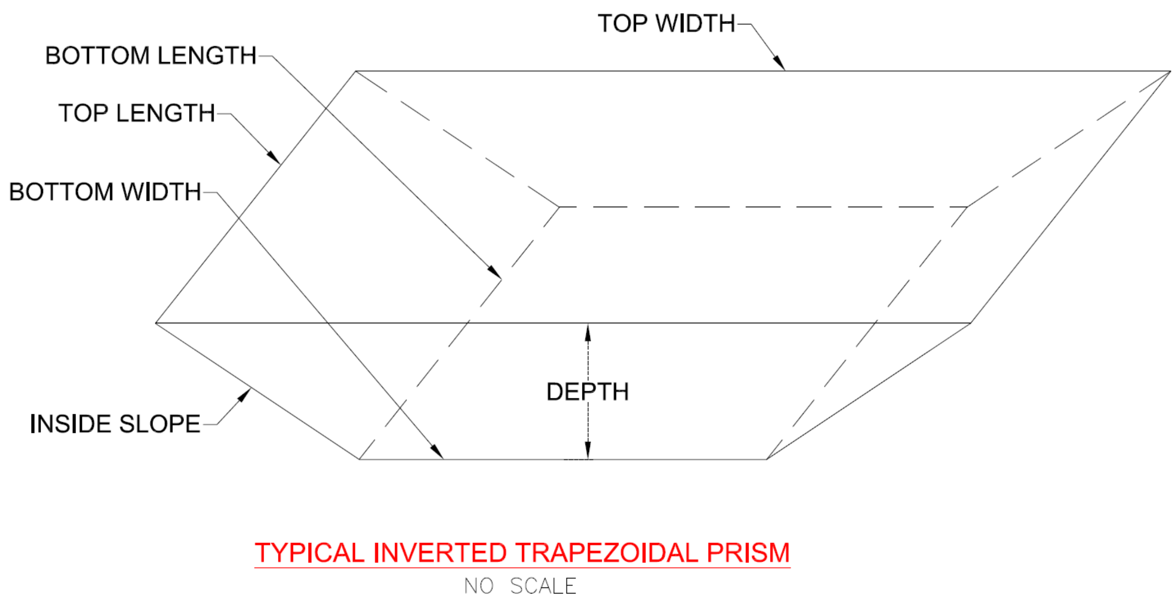


Figure 1: Typical Inverted Trapezoidal Prism

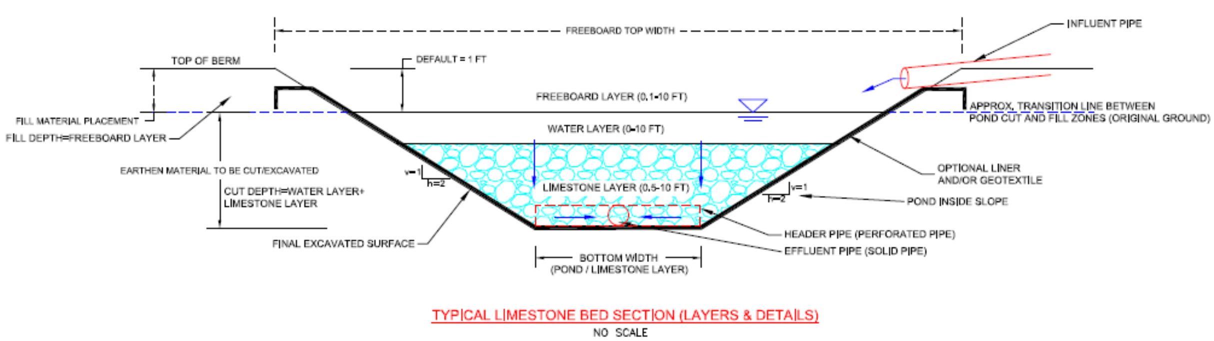
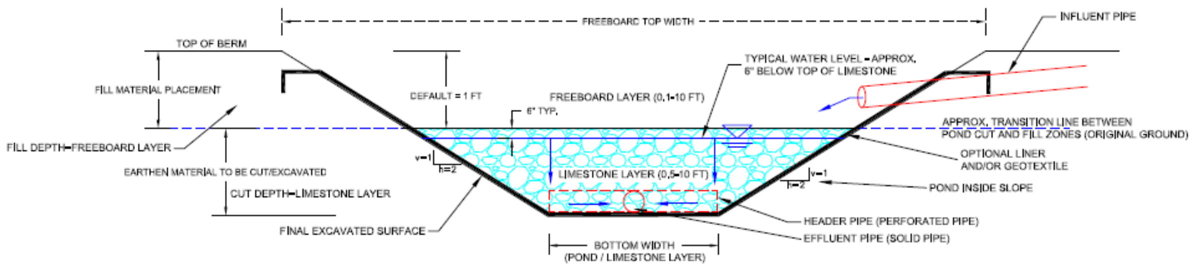
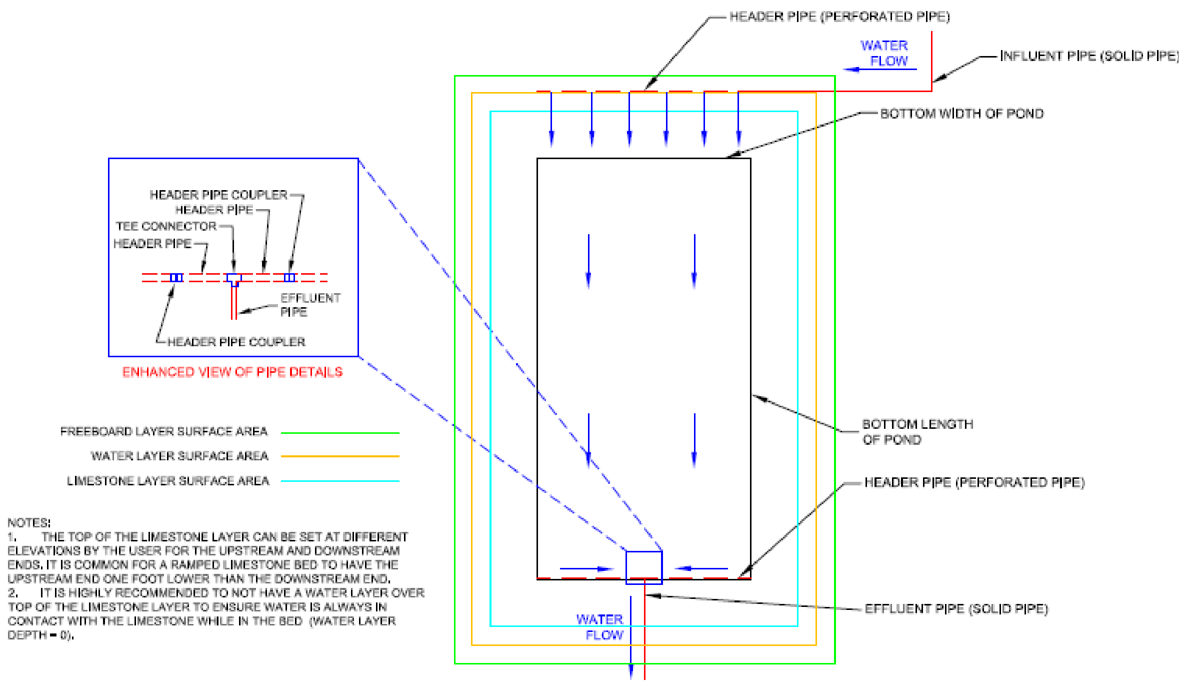


Figure 2: Typical Cross Section View of a Limestone Bed (LB) with a water layer.



TYPICAL LIMESTONE BED SECTION (NO WATER LAYER - LAYERS & DETAILS)
NO SCALE

Figure 3: Typical Cross Section View of a Limestone Bed (LB) without a water layer.



TYPICAL LIMESTONE BED AMDTREAT PIPING LAYOUT (BOTTOM OF POND)
NO SCALE

Figure 4: Plan View of the Limestone Bed (LB) to Illustrate Common Piping Layout and Components (Used in AMDTreat Piping Calculator) and the Layer Surface Areas

Figure 5: Graded footprint of limestone bed. Piles of limestone seen in the background.

Figure 6: Newly constructed Limestone bed before being filled with mine drainage.

Figure 7: A limestone bed constructed with a focus on easy maintenance and not using a piping network to continuously flush the system to remove precipitates. Water flows into the system from the piping manifold seen in the background and water exits in the foreground.

Figure 8: A newly constructed limestone bed (left) constructed with a dosing siphon. The system acts as a batch reactor that fills with mine drainage until a pre-determined elevation is achieved that triggers the dosing siphon to drain the system to a settling pond. The aquamarine color of the settling pond is caused by suspended aluminum flushing to the pond.

Figure 9: An “Agri Drain Smart” water control structure is shown enclosed by the black corrugated pipe. The solar-powered system can be set using the programmable logic controller (PLC) contained within the white box on the post to drain the limestone bed once a week and for a specified duration. The control box powers an actuator that opens and closes a gate valve to drain (flush) the system contained within the water level control structure in the embankment.

Figure 10:Aluminum Hydroxide being flushed from a Limestone Bed to a settling pond after the water level tripped the dosing siphon

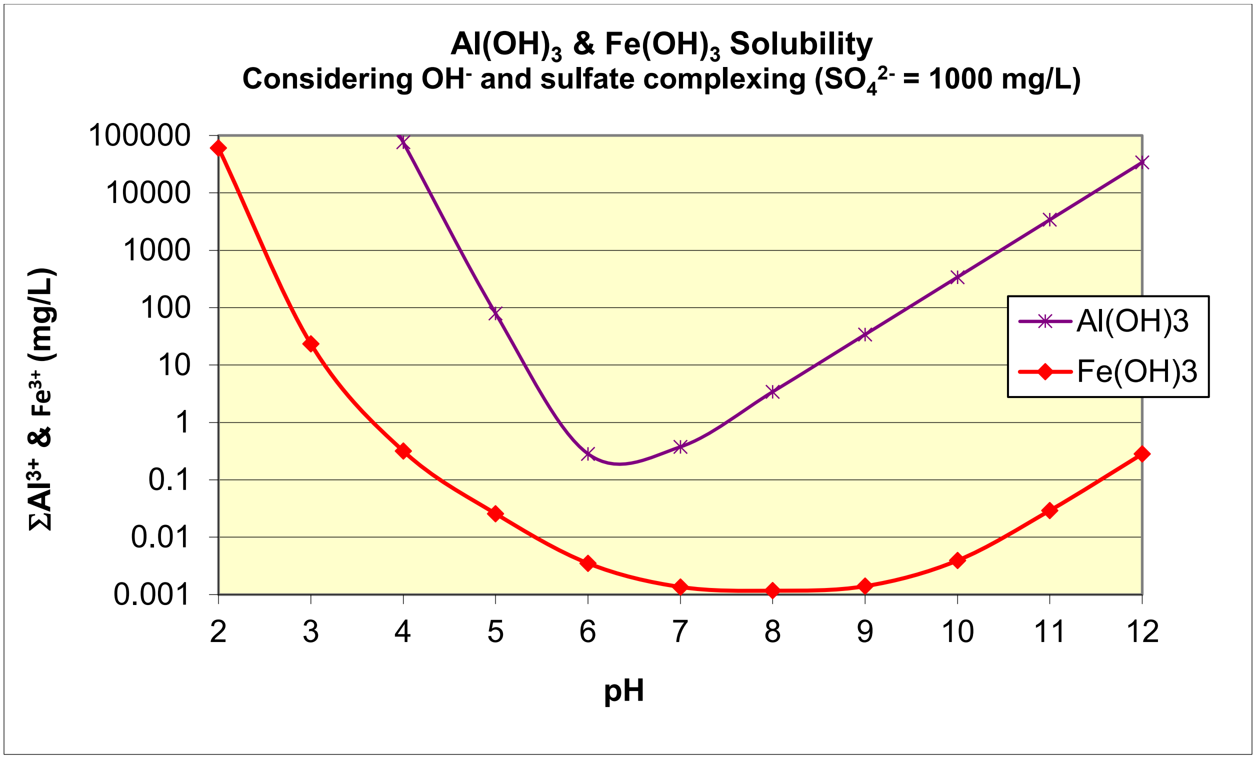


Figure 11: Aluminum becomes insoluble at pH > 5.5 and will precipitate and accumulate in the limestone. Ferric iron becomes insoluble at pH > 4.0.

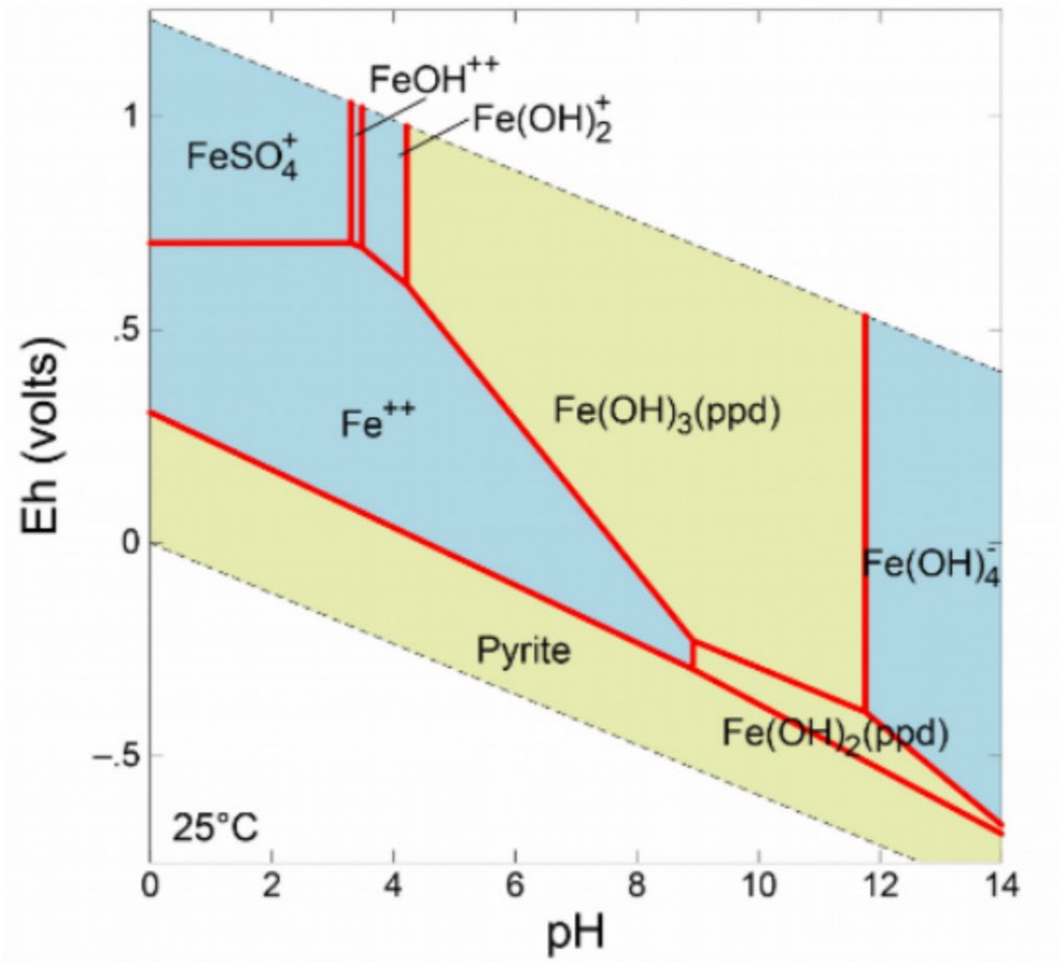


Figure 12. $Fe(OH)_3$ solubility diagram with pH versus Eh. If water in the limestone layer contains any oxygen, ferrous iron will oxidize and precipitate as the pH increases > 6.0.