PRELIMINARY DESIGN OF A TREATMENT SYSTEM TO REMEDIATE ACID ROCK DRAINAGE INTO JONATHAN RUN

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Jonathan Run is a tributary of Beech Creek that is impacted with fill material containing acid rock and clay during the construction of I-80 in Centre County, Pennsylvania. The acidic discharges into Jonathan Run contain white aluminum precipitates resulting in surface water quality degradation and loss of sustaining aquatic life. The purpose of this research is to identify sources of acid rock discharge and to conduct research aimed at identifying and developing methods to cost-effectively eliminate, mitigate, or treat acid rock discharge. Based on field research and subsurface investigations, preliminary suggestions are made involving flow elimination, by way of covering the acidic rock source or removing the groundwater, mitigation by injecting alkaline material into the source to neutralize the acid producing potential, and passive and/or active treatment systems to increase the pH of the water and allow metal precipitation. An active treatment system was selected for the major contaminated discharge into Jonathan Run while a passive treatment system was selected for a less contaminated discharge. A preliminary design is presented consisting of two vertical flow ponds, each designed to treat 100 gpm of flow. At this flow each pond will have a detention time of 24 hours and will each contain 2,050 tons of limestone, 19.5 inches in depth of organic compost consisting of mushroom compost and wood chips, and a ponded water layer of 4 ft. The ponds will discharge into a settling pond that will be 100’ x 24’ x 10’. The active system will consist of the chemical addition of sodium hydroxide at an average rate of 0.0298 gpm mixed through the contaminated water by stationary baffles or large rocks under turbulent conditions. The water will then discharge into a primary settling pond that is 79’ x 20’ x 6’ in dimension and then combine with the discharge from the vertical flow ponds in the second settling pond before entering back into Jonathan Run.

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PREFACE

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1.0 INTRODUCTION

Acid rock drainage (ARD), usually found relating to abandoned mines, is the leading pollution source in the Commonwealth of Pennsylvania that is killing streams and plant life. As of 1995 it was estimated that at least 5,000 km (3,100 miles) of streams in northern Appalachia are impacted by ARD (US EPA, 1995). Although ARD in Pennsylvania is attributed mostly to the coal mining industry where it is called acid mine drainage (AMD), a number of ARD sources can be traced to construction projects. Some of the most notable problems in North America include the Halifax International Airport, Sea to Sky Highway, and Interstate 99 here in Pennsylvania. Another ARD problem related to highway construction is the contributing pollution to a small perennial stream, Jonathan Run, by the constructed embankment of Interstate 80.

Jonathan Run is a tributary to the South Fork of Beech Creek, located near the intersection of State Route 144 and I-80 in Centre County, Pennsylvania. It was once a quality stream used as a trout fishery for the local public and was used to support breeding ponds for the Snow Shoe Summit Lodge Corporation. After the construction of I-80 in the 1960's by the Pennsylvania Department of Transportation (PennDOT), Jonathan Run was no longer able to support aquatic life. The interstate platform, which was built directly over the stream channel, as well as the construction staging areas and areas of excess rock storage, which were constructed in close proximity to the stream, were all constructed using outcrops from nearby road cuts that contained high amounts of sulfide in the form of pyrite. When these minerals are exposed to oxygen and water they oxidize and generate acidity. The acidic drainage, exiting the interstate platform, the construction staging areas, and the areas of excess fill storage, discharges into Jonathan Run.

What makes Jonathan Run different than many other ARD cases is the high amount of dissolved aluminum found in the discharges. When the acidic water runs over the alumino-silicate (clay) soil, the clay is dissolved and aluminum (Al^{3+}) is replaced by hydrogen ions (H^+).

The aluminum is also toxic to aquatic life, because of its ability to clog the gills of fish. In order to remediate the stream, the dissolved aluminum and the acidic discharges must be removed or treated.

There are many treatment techniques that can be explored, involving mitigation, elimination of the water sources, and passive and active treatment. No two ARD investigations are alike, so every one must be carefully researched and solutions must be designed that will effectively treat and restore the stream to quality standards.

The objective of this thesis is to present the basis of an effective treatment system design that will help to remediate the ARD that is contaminating Jonathan Run. The work presented includes a background of the work done on a PennDOT supported research project by the University of Pittsburgh and GAI Consultants Inc. encompassing field and groundwater investigations, evaluations of water sources and compositions, and presentation of passive and active treatment alternatives for the resolution of Jonathan Run contamination. The scope of this work is to support previously presented active treatment alternatives using NaOH and precipitation with a documented rational and scientific basis leading the detailed design to be done for PennDOT by others.

2.0 LITERATURE REVIEW

2.1 ACID ROCK DRAINAGE CHEMISTRY

Acid Rock Drainage (ARD) was around long before coal mining operations began, where it is commonly known as acid mine drainage (AMD). It is produced by atmospheric oxidation of the common iron-sulfur mineral pyrite (FeS_2) that is found throughout the Appalachian strata. Its presence is due to natural and anaerobic microbial processes that reduce dissolved sulfate in the earth to hydrogen sulfide. Some of the sulfide can escape to the atmosphere as a “rotten egg” odor, while some will accumulate in sediments as elemental sulfur and iron sulfide (FeS_2) minerals, commonly called pyrite. Pyrite is usually stable when it is in a natural anoxic (without oxygen) environment, but when exposed to oxygen and water, the pyrite is oxidized and acidity is generated.

$$FeS_2 + (7/2)O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad \textbf{(1)} \text{ (Stumm and Morgan, 1981)}$$

Smaller grain sizes, already low pH values and the presence of iron-oxidizing bacteria speed up the acid-forming reaction (Rose and Cravotta, 1998). The ultimate outcome of this process is water that has a low pH and high dissolved metal content, which impairs nearby water bodies, rendering them unsuitable for wildlife and human usage.

2.1.1 Iron Oxidation

The autoxidation of transition-metal ions generally is strongly dependent on the reaction medium. Typically the rate increases with pH and is first-order with respect to the metal ion to be oxidized. Most likely the reactive species is a hydrolyzed species $MOH^{(x-1)+}$. The scheme for oxidation is (Stumm and Morgan, 1981):

$$MOH^{(x-1)+} + O_2 + H^+ \longrightarrow MOH^{x+} + HO_2\cdot$$
$$M^{x+} + HO_2\cdot + H_2O \longrightarrow MOH^{x+} + H_2O_2$$
$$M^{x+} + H_2O_2 \longrightarrow MOH^{x+} + OH\cdot$$
$$M^{x+} + OH\cdot \longrightarrow MOH^{x+}$$

For iron:

$$Fe^{2+} + (1/4)O_2 + H^+ \rightarrow Fe^{3+} + (1/2)H_2O \quad \textbf{(2)}$$
$$FeS_2 + 14\ Fe^{3+} + 8\ H_2O \rightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+ \quad \textbf{(3)}$$
$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \quad \textbf{(4)}$$

When oxygen is absent from the water, ferrous iron (Fe^{2+}) is not oxidized to ferric iron (Fe^{3+}), but remains in a reduced state.

The oxidation of iron and sulfur in reactions 1 and 2, by dissolved oxygen, can also be produced by sulfur and iron oxidizing bacteria of the genus *Thiobacillus*. In some circumstances, the typical sequence of acid rock discharge generation begins with oxidation through reaction 1 to produce Fe^{2+}, which is then oxidized to Fe^{3+} by bacteria in place of the oxygen in reaction 2. The Fe^{3+} is then available for further oxidation through reaction 4 (Rose and Cravotta, 1998).

2.1.2 Aluminum Solubility and Precipitation

If the oxidation of pyrite takes place in a location where there is a high presence of alumino-silicate materials (clays) and the pH of the water becomes acidic enough, the ARD will solubilize the alumino-silicates into the water releasing Al^{3+} .

$$H^+ + \text{Al-silicate minerals} \rightarrow Al^{3+} + H^+\text{-silicates}$$

The precipitation of aluminum is important as well, because the gelatinous precipitate can coat the bottom of streams and also impair treatment systems designed to remediate a water source. The primary reaction of aluminum precipitate is the formation of gibbsite, a gelatinous solid (Guesek and Wildeman, 2002).

$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 \text{ (gibbsite)} + 3H^+\text{-silicates}$$

The most important factor in aluminum precipitation is the pH of the water. Aluminum will begin to precipitate at a pH >4, but precipitates closest to 100% at a pH of 6. If the water is raised to a pH above 10 the aluminum will resolubilize (Wei and others, 2005) (Guesek and Wildeman, 2002).

2.2 ACID ROCK DRAINAGE TREATMENT TECHNIQUES

2.2.1 Active Treatment

Active treatment, or treatment using an added chemical, is the most reliable and effective treatment technique. A system consists of an alkaline chemical added to an acidic discharge that flows into a series of settling ponds to allow for the precipitation of dissolved metals, mainly iron and aluminum, before the discharge is released into nature. The disadvantages that come with active treatment systems are the material costs and the maintenance and operational costs, along with the possibility of the environment exposed to dangerous chemicals (Figure 1).

There are six main chemicals that are used in ARD treatment. Limestone (calcium carbonate - $CaCO_3$), hydrated lime (calcium hydroxide - $Ca(OH)_2$), pebble quicklime (calcium oxide - CaO), soda ash (sodium carbonate - Na_2CO_3), caustic soda (sodium hydroxide - $NaOH$), and ammonia (anhydrous ammonia - NH_3). The amount of any chemical added will need to account for its efficiency; ammonia and caustic soda having the highest efficiency it would therefore be needed in the lowest amounts and limestone having the lowest efficiency would require a higher amount to be used (Skousen and others, 2000).

Figure 1. A 10,000 gallon tank holding sodium hydroxide

When designing active treatment systems there are several design parameters to consider. The amount of chemical added needs to be determined based on its ability to generate alkalinity to buffer the acidity already found in the water. The detention time needed to allow for sufficient settling of precipitates needs to be calculated based on the settling rate of the particles and the over flow rate of the water. This will also determine the size of the settling pond and the number of settling ponds. The design should take into consideration the fluctuation of flow levels, the extreme high flows, the control mechanism for adding the chemical, the mixing technique, the storage of precipitate sludge, and the final disposal of the sludge.

2.2.2 Passive Treatment

Passive treatment systems do not require continuous chemical inputs, instead they use naturally occurring chemical and biological processes and are powered by changes in elevation and not electrical sources. They do require more time and a larger amount of area and provide a less certain treatment efficiency. Passive treatment systems also have a finite life and will require rejuvenation or reconstruction after the materials have been completely used. However, they do have substantially reduced costs and need for maintenance, and are not as harsh to the environmental surroundings. There are several types of passive treatment systems, and are chosen based on the 1) water chemistry - what is the dissolved oxygen concentration in the water, the dissolved iron and aluminum concentrations, is the water net acidic or net alkaline, and the pH; 2) flow rate – accurate flow data is needed to properly size the system including readings of extreme high and low flow volumes; and 3) local topography of the area – is there enough area for the construction of the system and is there a sufficient gradient to create flow or pressure.

The types of passive treatments are:

- Constructed Wetlands (aerobic and anaerobic)
- Anoxic Limestone Drains (ALD)
- Successive Alkalinity Producing Systems (SAPS) or Vertical Flow Ponds (VFP)
- Open Limestone Channels

Anaerobic wetlands support reducing conditions that help to remove dissolved metals, mainly iron, in reduced forms. They contain an organic substrate that acts as an oxygen sink by creating anoxic conditions due to aerobic bacteria that decompose the organic matter. The lack of oxygen causes ferric iron to reduce to ferrous iron. Sulfate-reducing bacteria (e.g., *Desulfovibrio* and *Desulfomaculatum*) in the organic material, produce hydrogen sulfide (H_2S) and bicarbonate alkalinity (HCO_3^-) (McIntire and Edenborn, 1990). A layer of limestone on the bottom of the wetland or mixed throughout the organic matter will help to add alkalinity to a highly acidic water.

Vertical flow ponds are a combination of anoxic limestone drains and an organic substrate into one system typically used to treat water that has a net acidity and contains a DO concentration >1 mg/L and iron. VFPs consist of three layers; a bed of limestone at the bottom followed by a layer of organic matter and a ponded volume of water on the top of the system. As the acidic water flows downward through the pond, it is treated first by the organic layer. Two essential functions are performed: the dissolved oxygen (DO) is removed by aerobic bacteria and sulfate-reducing bacteria in the anaerobic zone of the organic layer generate alkalinity (Kepler and McCleary, 1994). It is also possible that iron and aluminum may be removed from the water through exchange and filtering with the organic matter. Once through the organic layer the water contacts the limestone and more bicarbonate alkalinity is produced and the pH of the water increases. The iron in its reduced form (Fe^{2+}) does not coat the limestone, which would cause the system to fail. At the bottom of the limestone layer, perforated piping allows the water to exit the pond and discharges it into a settling pond for further precipitate removal. These systems have been known to clog, but through necessary flushing of the system, iron and aluminum precipitates can be removed. VFPs are also known as vertical flow wetlands, due to the similar concepts, but VFPs have the ability to treat larger quantities of water using a smaller area than a wetland. If the water has not been exposed to the atmosphere to allow for the absorption of oxygen, it can be sent through an anoxic limestone drain, which is basically a VFP without the organic layer.

Open limestone channels are open ditches that contain a layer of limestone that acidic water runs over and acquires alkalinity. These channels have shown some success when operated at a 20° slope, but have been most successful when operated at a slope of 45 - 60° (Skousen, 1997). The slope of the channel allows for the precipitates to remain in suspension and keeps them from settling on and in the limestone bed.

The best treatment systems for waters high in aluminum are considered to be anaerobic wetlands, VFPs, and open limestone channels (Skousen, 1997).

2.2.3 Mitigation

Passive treatments are sometimes limited by the area available for the system construction or the chemistry of the water is not favorable to a particular system design. Therefore, other, sometimes relatively creative, treatment options are needed to treat an acidic discharge. One option for treatment is the injection of an alkaline material directly into the soil of acidic rock (Figure 2). The goal is to chemically affect the water by adding significant quantities of alkalinity that should neutralize the acidity, increase the pH, and allow any metal species to precipitate out of the water. Usually the alkaline material is a byproduct of coal combustion. These ashes contain large amounts of caustic alkalinity due to calcium compounds already found in the coal or to the addition of alkaline materials associated with air pollution control processes (Canty and Everett, 2006).

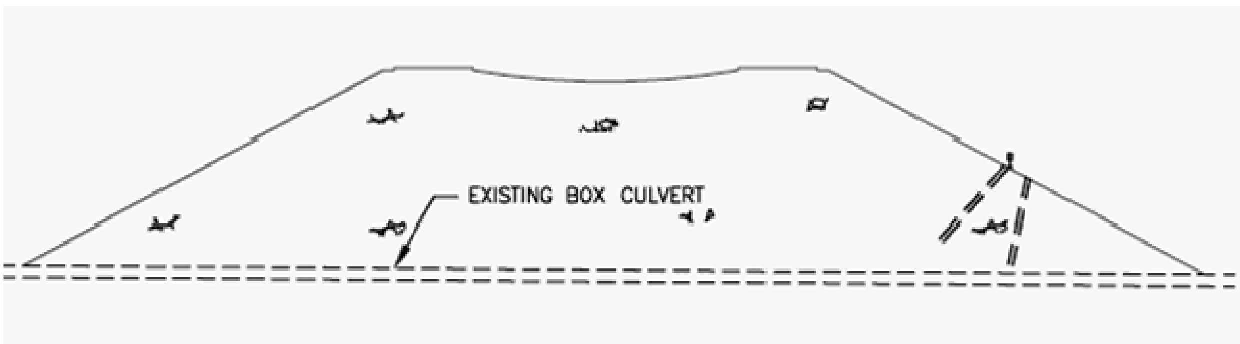

Figure 2. Injection of an alkaline substance into a series of boreholes to neutralize the acid producing potential

Another option for increasing alkalinity in an acidic fill area is to cover the surface with a layer of limestone. The goal is to allow water to generate enough alkalinity before infiltration through the acidic material. Due to the faster rate of acid production versus the rate of alkaline production, it is important to line the surface with enough limestone so that water flows more through the alkaline material than the acidic material (Caruccio and Geidel, 1996), which is difficult to do if there is a large quantity of acidic material.

2.2.4 Elimination

Both oxygen and water are necessary in order for the oxidation process to be initiated, and therefore, elimination of one or both of these components will also be effective in the prevention of acidic drainage. A method to achieve the goal of reducing oxygen or water influx are horizontal wells to remove groundwater and construction of some sort of cover system (Figure 3) over the waste material to prevent surface water infiltration. In this case, the final cover must be designed and constructed to 1) Provide long-term minimization of migration of liquids through the closed fill, 2) function with minimum maintenance, and 3) Promote drainage and minimize erosion or abrasion of the cover (Gagne and Choi, 2001). There are many different types and designs of caps that are used on landfills, hazardous wastes sites, and mining waste piles but emphasis should be on the selection of materials which are readily available, technologically feasible to construct, and have assurance of long-term stability. This review will briefly look at five types of covers: natural soil, compacted clay, geomembranes, geosynthetic clay liners, and capping with asphalt, concrete, or shotcrete.

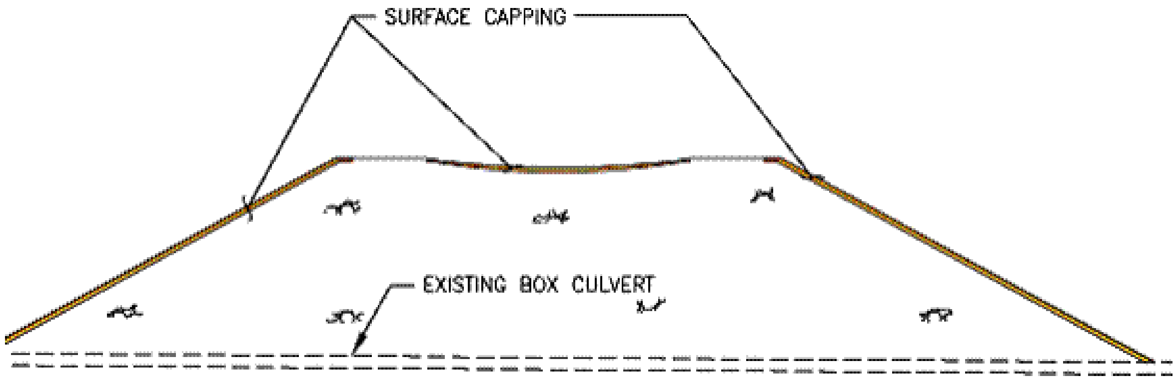

Figure 3. Covering of contaminated rock to keep water and oxygen from infiltrating

2.2.4.1 Natural Soils

In-situ soil liners refer to simple, excavated areas, without any additional engineering controls. The ability of natural soils to hinder transport and reduce the concentration of constituent levels through dilution and attenuation can provide sufficient protection when the initial constituent levels in the waste are very low (US EPA, 1999). Natural soils have the longest and most extensive history of use because the materials occur widely, are durable, require a low level of maintenance, are unlikely to suffer long-term degradation, and have been used extensively in liners and covers in landfill applications (WI DNR, 1995).

In layered natural systems, coarse and fine units are interlaid (WI DNR, 1995). Water infiltrating the system will be held by the fine-grained layers. The difference in moisture retention properties creates a capillary barrier at the interface of the fine-grained units with the coarse material, which helps to maintain near-saturated conditions in the fine-grained material. A fine-grained infiltration barrier is sandwiched between two coarse layers and overlain by a moisture retention zone, which is basically a soil cover used as a growth medium for vegetation.

2.2.4.2 Compacted Clay Liners

Compacted clay liners can be composed of natural minerals or bentonite-soil blends. This can be a cost effective method if the natural soils at the site contain a significant quantity of clay, then excavation can be done from onsite locations. Clay liners work very well as hydraulic barriers, controlling water infiltration. A liner with a thickness ranging from 2-5 ft will help ensure that the liner meets desired hydraulic conductivity values of around 1×10^{-7} cm/sec (US EPA, 1999).

However, it is not always possible to place compact natural clay. This is particularly true with steep slopes.

2.2.4.3 Geomembranes

Geomembranes or flexible membrane liners are primarily used to contain or prevent waste leachate from escaping a waste management unit (US EPA, 1999). When properly installed, they are essentially impermeable. They are made by combining one or more plastic polymers with ingredients such as carbon black, pigments, filler, plasticizers, processing aids, cross-linking chemicals, and biocides. The most common polymer resins used are HDPE and LLDPE. A good design should include a minimum thickness of 30 mm or for HDPE, a minimum thickness of 60 mm (US EPA, 1999). Geomembranes should be examined for tensile behavior, tear resistance, puncture resistance, susceptibility to environmental stress cracks, UV resistance, and carbon black content.

An alternative cap design for hazardous waste landfills was developed by the EPA Region I. The design consists of a drainage geocomposite, geomembrane, and soil. When designing a landfill cap, their primary objectives are to 1) limit the infiltration of rainwater to the waste so as to minimize generation of leachate that could possibly escape to ground-water sources, 2) ensure controlled removal of the landfill gas, and 3) provide the foundation for an aesthetic landscape and allow vegetation of the site (Gagne and Choi, 2001). The following will discuss the cap components:

1. Bottom Low-Permeability Soil Layer:

This provides a second layer of protection against infiltration in the event that the top low-permeability geomembrane has a leak. This layer should be at least 12 inches deep and should contain no stones larger than ½ inch that may damage the geomembrane.

2. Top Low-Permeability Geomembrane Layer:

The characteristics of this layer have already been discussed above, but a few notes should be mentioned. The German Federal Government has specified that the minimum thickness of high density polyethylene geomembranes should be 100 mm (Gagne and Choi, 2001). Thicker geomembranes are better able to resist chemical aggression, temperature changes and gradients, stress corrosion and cracking. It is also important to note that maintenance and remediation of the geomembrane is difficult once installed. On steep side slopes, the very low friction characteristics of the smooth geomembrane with adjacent layers may cause slope instability. Therefore, textured geomembranes may be needed to increase the cap side slope stability. There are some engineers who will only use a texture on the bottom surface and insist on the upper surface being smooth. This way, if the layer on top of the geomembrane does move it will slide on the geomembrane and not tear it. The soils on top of the geomembrane can be reinforced with a geogrid or a high strength geotextile.

3. Drainage Layer:

The purpose of the drainage layer is to remove excess rainwater, minimize infiltration through the low permeability layer and to enhance the stability of the cover soil on the side slopes. This layer should consist of 1 ft of granular material such as gravel or sandy gravel and must be designed to facilitate the area's maximum foreseeable rainfall. A thick non-woven geotextile layer may be needed at the bottom of the layer to protect the geomembrane from being punctured. Also, a geosynthetic filter should be placed directly over the drainage layer to minimize the mitigation of fines from the topsoil into the drainage layer. This layer should also be located below the maximum frost depth penetration.

4. Protective Soil Layer:

This layer should provide a soil that is capable of sustaining the vegetative cover through dry periods and protect the underlying drainage layer and low-permeability layers from frost damage and excessive loads. Drainage benches should be used to breakup steeply graded slopes of covered sites. For slopes great than 10% in steepness, the maximum distance between the drainage benches should be equal to or less than 100 ft.

There are questions that exist in terms of the long term durability of the material due to mechanical damage through loss of plasticity, cracking, or tearing under differential settling or naturally induced damage from variation in ambient temperature conditions, burrowing animals, and root penetration.

2.2.4.4 Geosynthetic Clay Liners

GCL's consist of a sandwich of bentonite and two geotextile layers. The function of the geotextile layers is to contain the bentonite in a restricted space and so facilitating their transport and their installation. The advantage of using this system of covering is that it is able, by swelling, to self seal any perforation that may occur. Also, by using at least one geotextile of a woven type, part of the bentonite is able to migrate through and seal the joints between adjacent layers (Recalcati and Rimoldi, 1997). GCL's must be covered with at least 0.3m of coarse soil in order to stay hydrated.

This type of cover was used, in addition to a geocomposite drainage layer, at the Cerro Maggiore Landfill in Italy (Recalcati and Rimoldi, 1997). The landfill was 30m high and had side slopes of 38° inclination and 35m long. The drainage layer was designed to discharge the maximum rainfall anticipated to fall in the area. If underestimated, the excess of water produces an uplifting pressure on the top soil, reducing the frictional behavior and causing top soil to slide.

On steep side slopes, the addition of a geogrid or a geomat can provide additional resistance and ensure stability.

2.2.4.5 Asphalt, Concrete and Shotcrete

Caps and seals, such as asphalt, shotcrete, and concrete mixes may provide stronger alternatives to membrane covers. However, these are not considered widely viable to due concerns mainly regarding their long-term durability (WI DNR, 1995).

In British Columbia, several organizations have been involved with the testing of a shotcrete cover on acid generating rock (CA Natural Resources, 1996). Initial laboratory results indicated that the mixture exhibited good mechanical strength and low permeability. In the second phase of research, fly ash and polypropylene were incorporated into the mixtures and the results showed good compressive strength, good ductility, and low permeability to water. In the third phase of research, a large-scale field application of shotcrete cover on a waste rock dump was conducted. Visual inspections over a three year period have indicated that the overall durability of the material was good. No frost damage was evident and no movement of the cap was detected. Some cracks were observed and appeared to be related to areas where the shotcrete was applied at less than the 75 mm thickness specified. Transport of the aggregate to the site was the largest cost component. The next study phase is to determine the effects on the shotcrete due to vegetation and a more detailed study on the effectiveness of the shotcrete cover in restricting acid generation in waste rock.

2.2.4.6 Horizontal Wells

Horizontal wells could be installed to remove a groundwater source that is entering the zone of contamination. The technology is similar to vertical wells, with a slotted screen intercepting the contained water, but is more effective because horizontal wells have a greater surface area in contact with the groundwater and also because horizontal aquifer transimissivity is usually greater than vertical transimissivity (Miller, 1996).

The well installation enters the ground on an angle to a certain depth where it is then changed to a horizontal direction (Figure 4). The boring process can be steered in three directions, allowing the well to be steered around subsurface obstructions. There is also a lesser chance of subsidence because directional drilling produces a small amount of drill cuttings, keeping less native material from being displaced.

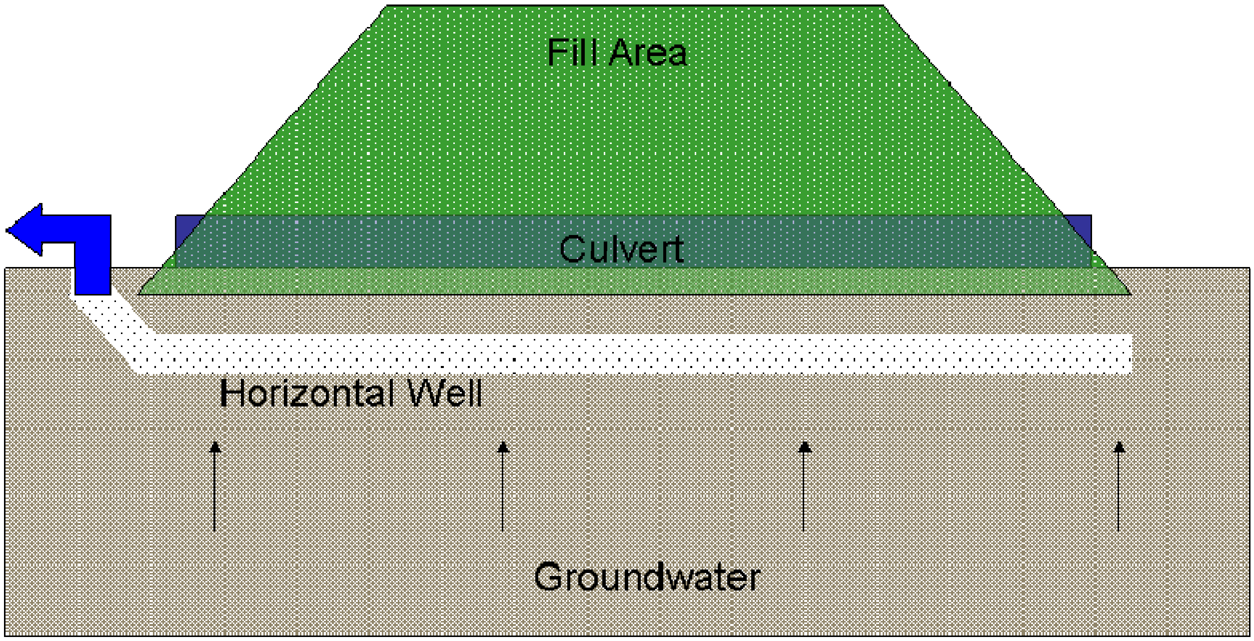

Figure 4. Horizontal wells intercept rising groundwater from infiltration

3.0 SITE INVESTIGATION

3.1 SITE DESCRIPTION

The Jonathan Run project area consists of the Jonathan Run watershed located in the Township of Snow Shoe, Centre County. As shown in Figure 5, the project is bisected by Interstate 80, which runs east/west across the site and sits on a platform that is raised 60' to 80' off the valley floor, and by Devil's Elbow Road, which runs parallel to and just north of I-80. Jonathan run flows northward through the project area, passing through a reinforced concrete 6'x 6' box culvert under I-80, and a 66 inch diameter corrugated metal pipe under Devil's Elbow Road. South of I-80, the Jonathan Run valley is characterized by piles of excess rock created during construction of I-80, and a construction staging area. On the northern side of I-80 and Devil's Elbow Road, the valley is characterized by a wetland area and steeply sloping ground to the west of Jonathan Run, and gradually sloping ground and a pond to the east. Much of the property within the project area is owned by Snow Shoe Summit Lodge Corporations. A map and photos of the project area can be seen in Appendix A.

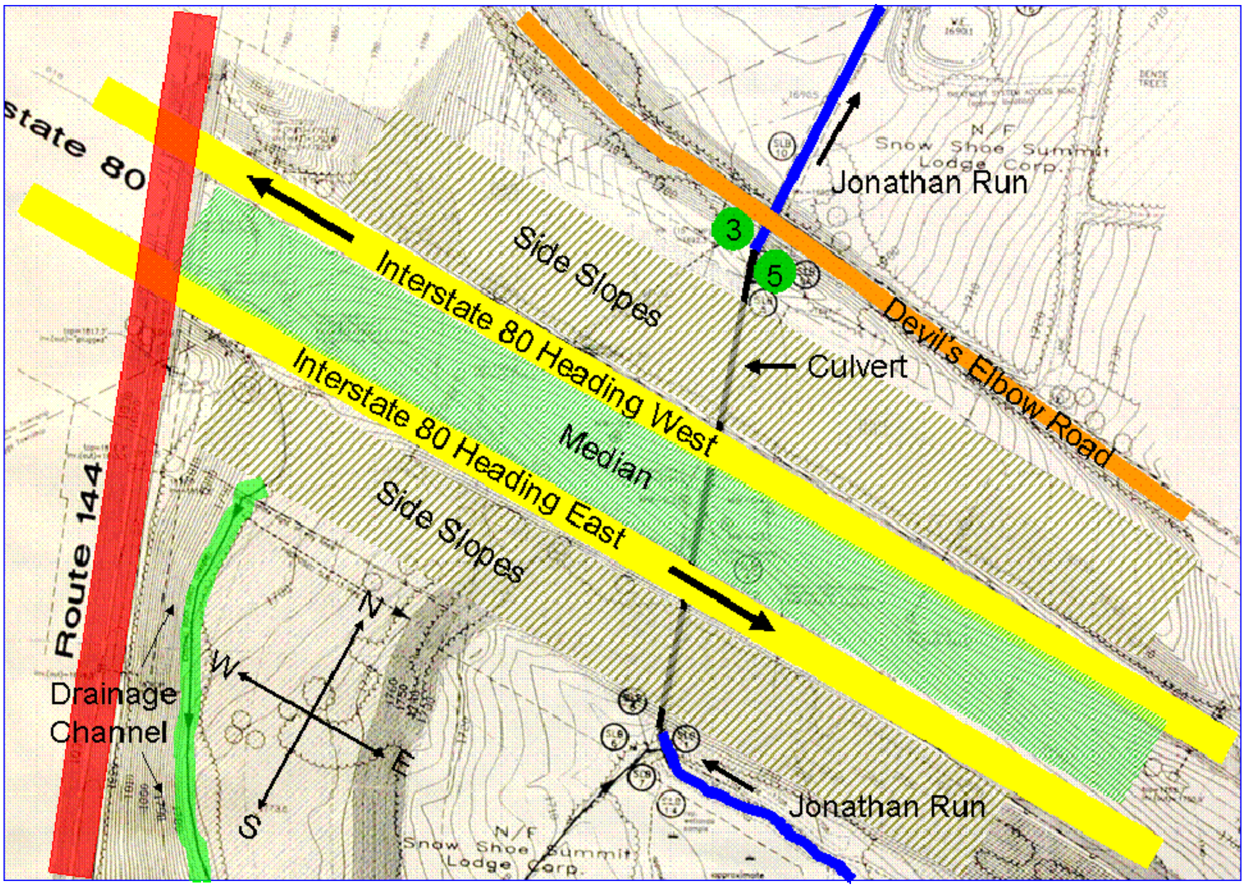

Figure 5. Map of the Jonathan Run Project Site

Large rock excavations were made to construct I-80 through the adjacent mountainsides, and the rock cuts were used to construct the embankment spanning the Jonathan Run valley. Excess rock from these excavations was also placed into fill areas on the southern side of I-80. The rock, and in particular a sandstone, contains pyritic material, which, upon weathering, does produce acidic water in a series of chemical processes identical to those in the formation of acid mine drainage. The act of excavation and fill has resulted in the acceleration of the natural weathering of the rock, thereby producing the acidic discharges observed in Jonathan Run.

There are a number of identified discharges around the Jonathan Run project area. A summary of those discharges are shown in Table 1. The discharges had been sampled and tested for water quality during previous site investigations of Jonathan Run (Parezik, 1980) (Hedin, 2003). The main discharges that were deemed important to the pollution to Jonathan Run were SLB3, and SLB5 (Hedin, 2003). SLB8 was not considered to be a high concern because it flows only during wet weather periods. The construction of a wetland to discharge SLB1 and SLB8 into should help to treat Jonathan Run during wet weather. SLB5 was the largest contributor of acidity and aluminum to Jonathan Run accounting for 62% of the total acidity and 56% of the total aluminum (Hedin, 2003). SLB3 is a discharge from a spring that was buried under the I-80 platform. It has a variable flow that ranges from <1 gpm during droughts to as high as 200 gpm in extended wet periods, which could be the result of two different sources of water. This spring contributes to 16% of the total acidity and 18% of the total aluminum in Jonathan Run. Therefore, the SLB3 and SLB5 discharges will be the primary focus of treatment. Their locations in regard to Jonathan Run and the North face of the culvert are roughly shown in Figure 6.

Table 1. Average Loading of Acidity and Aluminum into Jonathan Run
May 2000 - May 2001

			Lbs/day		mg/L		% of Total	
	Description	Flow (gpm)	Acidity	Al	Acidity	Al	Acidity	Al
SLB1	Large discharge just before culvert inlet	49	3.3	1.2	5.6	2.03	4	7
SLB8	Discharge from large extra fill area; only flows during wet weather	8	15.9	2.5	165.36	26.0	15	12
SLB4	Enters from cracks into culvert	1	0.9	0.2	74.9	16.6	1	1
SLB5	Discharge adjacent to culvert/east side	6	41.2	6.8	571.4	94.3	62	56
SLB3	Discharge of spring from spring box; west of culvert	53	13.4	2.8	21.04	4.4	16	18

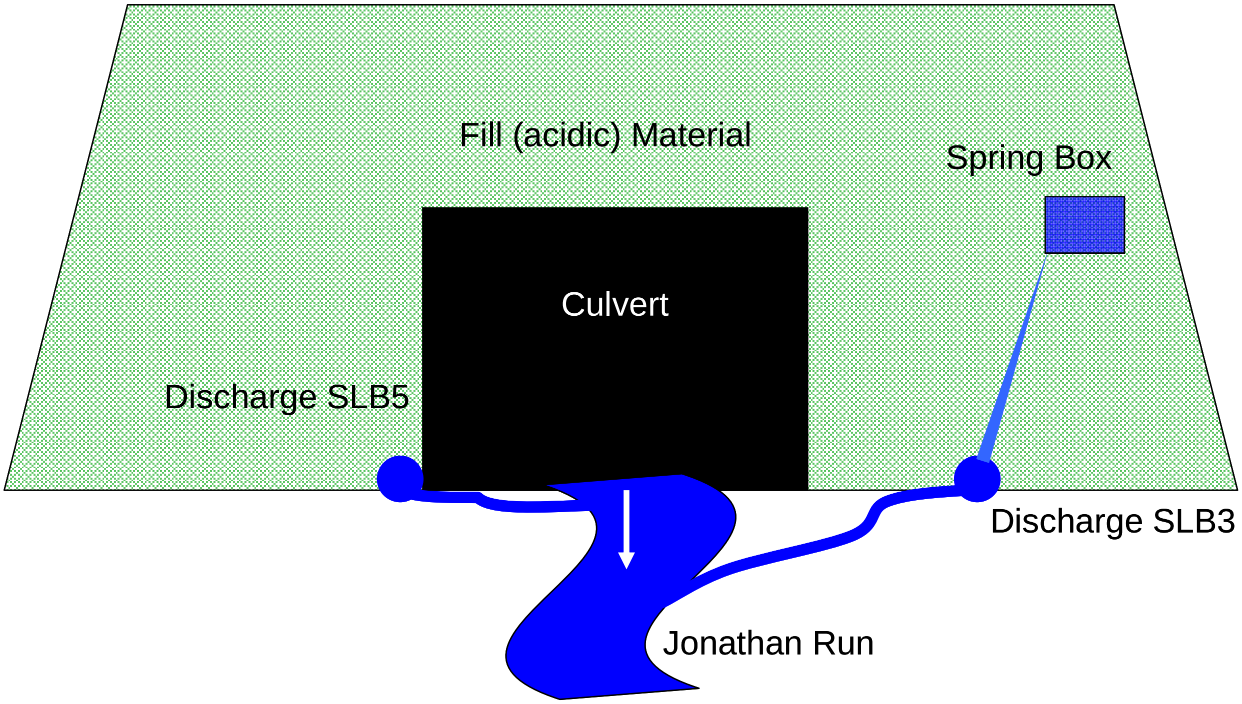

Figure 6. The locations of discharges SLB5 and SLB3, the two main sources of pollution into Jonathan Run

3.2 SITE INVESTIGATION

In order for the team of engineers from the University of Pittsburgh and GAI Consultants, Inc. to recommend a course of action to correct the condition of Jonathan Run it was necessary to determine the zone of contamination, which is the area the supplies the acidity and metal content to the water, and quantify the source(s) of water that moves through the zone of contamination. This site investigation was completed using a number of investigative techniques including: geophysical surveys, subsurface bore holes, soil sampling and analyses, acid/base accounting of the fill materials, monitoring well installations, ground water level monitoring, and groundwater sampling and analysis. These investigative techniques will help to determine the zone of contamination and the water source to that zone, the two prominent sources of water being groundwater or surface water (Figure 7).

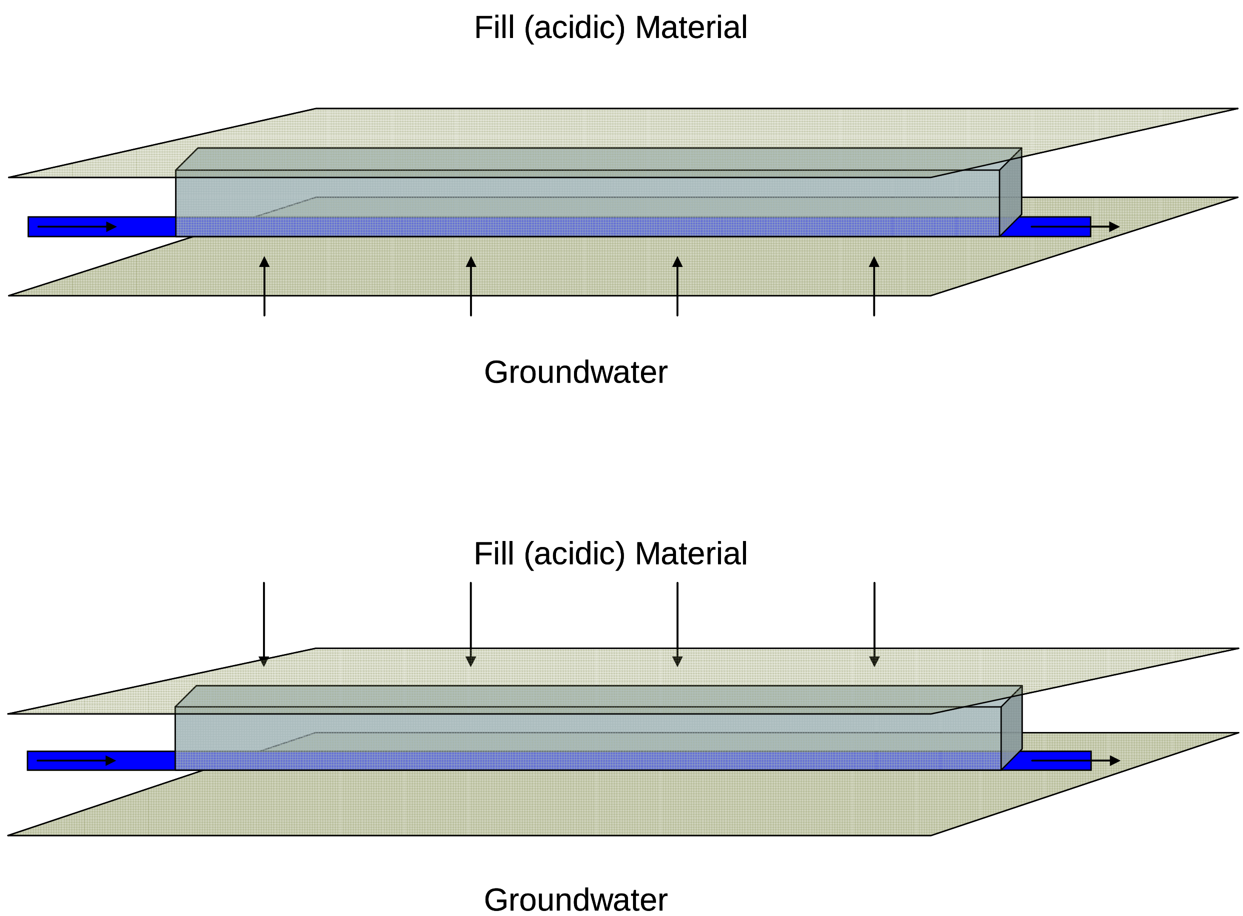

Figure 7. A sketch depicting the two possible water sources infiltrating the fill area

3.2.1 Geophysical Surveys

The Hutchison Group, hired by GAI, conducted a geophysical survey on the fill at the Jonathan Run Site on October 26-27, 2005 to locate any areas of elevated conductivities which could possibly be pools of water. The survey consisted of using a frequency domain electromagnetic (EM) meter, and a global positioning system (GPS). The EM meter has a transmitting antenna that emits an electromagnetic field to induce eddy currents in the earth. The currents generate a secondary electromagnetic field that is captured by the receiver in the form of an output voltage that is linearly related to subsurface conductivity. The GPS was used to locate the survey lines. Field observations indicated that 12 to 14 feet of highly conductive material was found on the southern side of the east-bound lane to I-80 (Appendix B, Figure 45). The area was recommended to be further investigated. There were, however, no pools of highly conductive fluids found to exist within the fill (Hutchison Group, 2005). Another investigation was conducted on February 4, 2006 using electrical imaging (Appendix B, Figure 46). Through this technology electric currents are carried through earth materials by the motion of the ions in connate water (water entrapped in sediments). Resistivity decreases in water-bearing rocks and water filled pores. Materials that lack pore space or water in the pore space will show high resistivity. Again, no areas were identified to be pools of water (Hutchison Group, 2006).

3.2.2 Exploratory Drilling

In addition to four boreholes (MW-1, MW-2, MW-3, and MW-4) that were previously drilled during an assessment of Jonathan Run by Hedin Environmental, 4 new boreholes (GAI-1, GAI-2, GAI-3, and GAI-4) were drilled between December 2005 and February 2006. From these boreholes, samples of the fill content were able to be recovered and analyzed (Figure 8). The information obtained from the boreholes indicated that there was little variation in the materials encountered throughout the width and depth of the fill. It consists of 60-80 feet of sandstone boulder with varying amounts of clay, silt, sand, and weathered sandstone and shale. The core recoveries also indicated that there are numerous soft spots or voids of one foot or less throughout the depth of the fill, with the voids at deeper depths filled with clay and silt. Shiny gold colored specs were seen on the core samples suggesting the existence of pyrite (Figure 9).

Figure 8. Section of fill recovered from boreholes

Figure 9. Close view of fill sample showing small gold colored specs

3.2.3 Groundwater

The groundwater levels and the water chemistry were monitored using the four existing monitoring wells drilled by Hedin and the three new wells installed by GAI (GAI-2, GAI-3, and GAI-4). There was no well installed in GAI-1 because the borehole collapsed before the well casing could be set. Based on the monitoring wells, the water table was found to be at or near the fill/natural soil interface. By separating the well water in GAI-3 from the water in the fill, the water level could be compared with the other nearby wells to determine if a main source of water entering the fill was groundwater. The water levels measured in GAI-3 were very close in elevation to the other wells and thus a conclusive determination of the existence of an upward gradient could not be made.

In addition to measuring the well water elevation, each of the three new wells and the four existing wells were sampled twice. The results are included on Table 13 in Appendix B. Well GAI-3 had significantly better water quality when compared to the rest of the wells that were sampled. Its high pH values indicate that it was monitoring the water below the acid rock fill, and is probably hydraulically separated from the fill by a clay layer at or near the original ground surface.

3.2.4 Acid-Base Accounting

Acid-Base Accounting (ABA), is an analytical process that helps to predict if the discharges from a certain overburden will be acidic. There are two procedures performed on overburden samples to help determine the discharge quality. The first procedure determines the maximum potential acidity (MPA), a measurement of the amount of acid that the overburden could produce from the oxidation of the sulfide sulfur. In the case of Jonathan Run it would be the Iron sulfide or pyrite. In many cases, however, using the total sulfur in the overburden is an adequate estimation of the sulfide sulfur and is an easier test to perform (PaDER, 1988).

The MPA is found by heating a portion of the rock samples with eschka mixture (a commercially available mixture or can be made by mixing anhydrous sodium carbonate with calcined magnesium oxide) to convert all sulfur to the sulfate form (PaDER, 1988). The sulfate is then leached with hot water and barium chloride solution is added to produce barium sulfate.

When cooled, the precipitated barium sulfate is filtered off and the total sulfur content is calculated from the weight of the barium sulfate (PaDER, 1988).

The second procedure determines the neutralization potential (NP) of the overburden by quantifying the neutralizing compounds, mainly carbonates. To determine the NP, portions of the rock samples are mixed with hydrochloric acid and heated to make sure that the HCl reacts completely with a given sample. After it has cooled, it is back titrated to a pH of 7 with a dilute solution of sodium hydroxide to determine the quantity of HCl that was neutralized by the sample (PaDER, 1988). This value is then used to calculate the neutralization potential of the sample and is expressed as $CaCO_3$.

After both procedures have been preformed the MPA value is subtracted from the NP value to find the net neutralizing potential (NNP) (Table 2). When the NNP is positive, there is less of a chance for acidic drainage to occur. When the NNP is negative, acid rock drainage is likely to occur. The more negative the NNP, the higher the likelihood of acid drainage.

Table 2. A Selection of Acid-Base Accounting results for Borehole GAI-1

Sample	Total Sulfur %	MPA	NP	NPP
0-3.8’	0.03	0.94	-8.82	-9.76
10.5-15.0’	0.11	3.44	-10.81	-14.25
32.0-37.0’	0.02	0.63	-9.52	-10.15
62.0-66.8’	0.01	0.31	-8.38	-8.69
77.0-82.0’	0.03	0.94	-8.67	-9.61
94.0-97.0’	0.02	0.63	4.00	3.37

The soil samples and rock cores collected from each of the boreholes were labeled appropriately and divided into sample intervals. The fill materials at the Jonathan Run project site were, however, fairly uniform in content so that in many cases sample sets of longer than three feet were grouped together for analyses. These samples were sent to Geochemical Laboratories of Somerset, Pennsylvania to be analyzed using ABA to determine the areas containing acid producing potential in the I-80 embankment fill.

Boreholes GAI-1, GAI-2, GAI-3, and GAI-4 were all subjected to ABA. Every column of material encountered (with the exception of the interval from 1.4 to 9 feet in GAI-4) showed all negative values in the deficiency column (also called the Net Neutralization Potential)

(Neufeld and others, 2007). Thus, the entire embankment area (as sampled in the four GAI boreholes) was acidic. The only area found not acidic was a small interval of GAI-4 (1.4 to 9 feet) which was determined to be concrete that had been deposited in the fill.

Utilizing the PaDEP developed assessment, GAI determined an estimated volume of the tons of neutralizing materials (limestone) that would be needed to neutralize the measured acidity. The input for the calculations includes the laboratory data from the core samples, the thickness of the stratigraphic units, and the estimated unit weight of each rock type. The calculation considers the areas of both the top and bottom of the pile. The Jonathan Run site is estimated to be 19 acres at its base, and 8.7 acres at the top. There is technically only one stratigraphic unit present in the fill at Jonathan Run; however this unit was divided into two layers to more accurately represent the volumes of the fill. The total overburden calculated by the spreadsheet was 5,492,926 tons. The deficiency in neutralizing materials required to treat that volume is 55,536 tons of limestone per acre. For a total of 19 acres approximately 1,060,000 tons of limestone would be needed to treat the entire fill (Neufeld and others, 2007).

3.2.5 Infiltration

After determining that most of the fill contained acid generating potential and groundwater did not seem to be much of a contributor of source water, an estimate of infiltration was completed in order to evaluate the contribution of surface water infiltration through the fill material as a source of some or all of the Jonathan Run contamination.

The following general parameters and assumptions were used (Neufeld and others, 2007): The site receives 38 inches of precipitation per year; the total project area is 18.6 acres. Of the project area, 10.1 acres are rocky side slopes, 5.1 acres are the grass median, and 3.4 acres are covered by the east and west bound lanes. Infiltration was assumed to be 0 percent for the road surface and 90 percent for the rocky side slopes. The runoff from the road was split between the grass median the slopes. The median between the lanes was modeled using the U.S. Environmental protection Agency Hydrologic Evaluation of Landfill Performance (HELP) Model (Schroeder, 1982). HELP is a widely accepted model that was designed as its name implies for seepage into landfills, but can be applied to most settings where there are multiple layers of varying permeabilities. The HELP modeling for the grass median resulted in an expected infiltration of 36 percent of the total precipitation.

The project team estimated that there are five contributing components to the average total of 16,150,000 gal/year of precipitation, including: 0 gal/yr from the road surface; 11,220,000 gal/yr from the rocky side slopes; 2,560,000 gal/yr from the grass median; 3,000 gal/yr runoff from the median that infiltrates currently through an erosion hole beside an inlet in the grass median; 2,375,000 gal/year from spring SLB-13 and < 500,000 gal/yr from the flat fill area on the south side of the embankment (Neufeld and others, 2007). Other contaminated flow comes from small discharges on the south side of I-80 and from discharge SLB3 (Figure 10).

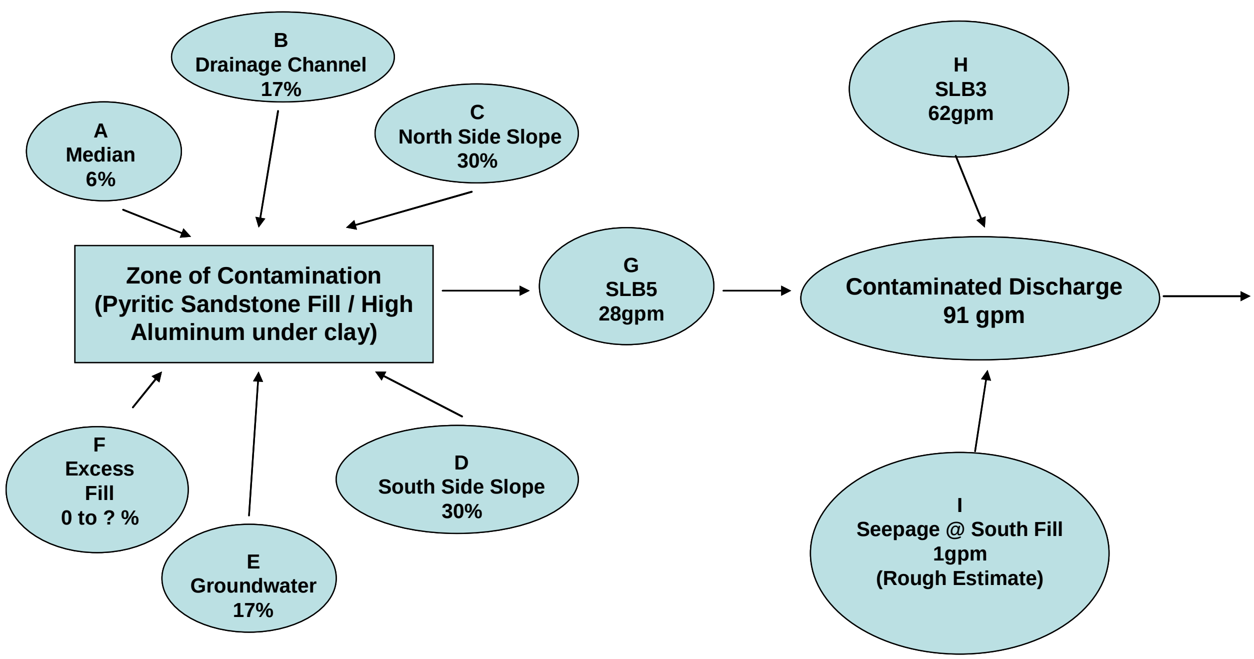

Figure 10. A diagram showing the contributing infiltration to the fill and the contributing polluted water into Jonathan Run

3.2.6 Discharged Water From the Fill

3.2.6.1 Natural Spring at Discharge SLB3

The SLB-3 discharge is located just west of the box culvert. This spring was of particular interest because of its location, quality, and flow volume. This spring was collected in a spring box, an engineered structure designed to collect and protect the spring from contamination and allow for settling, installed by PennDOT during construction of I-80 and piped out of the fill area in a 15-inch corrugated metal pipe, to a discharge point very close to Jonathon Run. The spring box is, however, approximately 220 feet up the discharge pipe, which is about 70 to 80 feet below I-80. It was generally believed that the water was “clean” and that the reason for its low pH was the contribution of contaminated water leaking into the pipe at its joints (Parizek and others, 1980).

GAI constructed a unique “sled-like” device (Figure 11) that enabled the successful insertion of a sampling tube a distance of 220 feet through the pipe directly to the spring box. The sampling tube was then subjected to a vacuum to start a siphon. Once the siphon was running, the sampling tube was allowed to flow for over 12 hours before water samples were collected. The two water samples were take in February, 2006, six days apart. The pipe outfall was also sampled at the same times as the spring box for comparison of the water quality. The water was analyzed for aluminum, iron, sulfate, pH, dissolved aluminum, alkalinity, acidity, total suspended solids, specific conductance, and manganese. The results are summarized in Table 14 in Appendix B. It was observed that the pH, iron, and TSS are similar in both locations, and the alkalinity values are also very close. The aluminum and manganese concentrations in the outfall samples were found to be twice as high as in the Spring Box, but there was not a significant increase in concentration.

Figure 11. Sled being inserted the SLB3 drain pipe to collect water samples from original spring discharge

Discharge flows (outfall) and water characteristics including pH, temperature, alkalinity, acidity, iron, aluminum, manganese, sulfate and TSS were measured by Hedin from May 1999 to June 2003 (Hedin, 2003). This report gives the most comprehensive data that conclusions can be drawn from. The averages are shown on Table 3 below and the complete data set is located in Table 15 in APPENDIX B.

Table 3. SLB3 Average Discharge Water Characteristics

pH	4.5	Iron	0.2 mg/L
Alkalinity	6.9 mg/L	Aluminum	6.1 mg/L
Acidity	39.2 mg/L	Manganese	1.7 mg/L
Temperature	9.5 °C	Sulfate	73.1 mg/L

The flows measurements are shown in Table 4 along with the percentile of the flow. The flows were then plotted on log-normal probability paper. The plot is show in Figure 12.

Table 4. SLB3 Flow Percentiles

Rank	*GPM*	*Percent*	*Rank*	*GPM*	*Percent*
1	300.00	0.983	31	65.00	0.483
2	250.00	0.967	32	63.70	0.467
2	250.00	0.967	33	60.00	0.450
4	182.00	0.933	34	56.40	0.433
5	175.00	0.917	35	50.00	0.417
5	175.00	0.917	35	50.00	0.417
7	130.00	0.883	37	38.00	0.383
7	130.00	0.883	38	37.40	0.367
9	115.00	0.850	39	35.00	0.350
9	115.00	0.850	40	29.00	0.333
11	112.00	0.817	41	28.90	0.317
12	110.00	0.800	42	24.00	0.300
13	104.00	0.783	43	20.60	0.283
14	103.60	0.767	44	20.00	0.267
15	100.00	0.750	44	20.00	0.267
15	100.00	0.750	46	18.60	0.233
15	100.00	0.750	47	15.00	0.217
18	92.80	0.700	48	10.00	0.200
19	90.00	0.683	49	8.60	0.183
20	85.00	0.667	50	6.80	0.167
21	82.10	0.650	51	6.10	0.150
22	80.60	0.633	52	5.00	0.133
22	80.60	0.633	52	5.00	0.133
24	78.00	0.600	52	5.00	0.133
25	75.60	0.583	52	5.00	0.133
26	75.00	0.567	52	5.00	0.133
26	75.00	0.567	57	2.50	0.050
28	73.30	0.533	58	2.00	0.033
29	70.00	0.517	59	0.30	0.017
30	69.00	0.500			

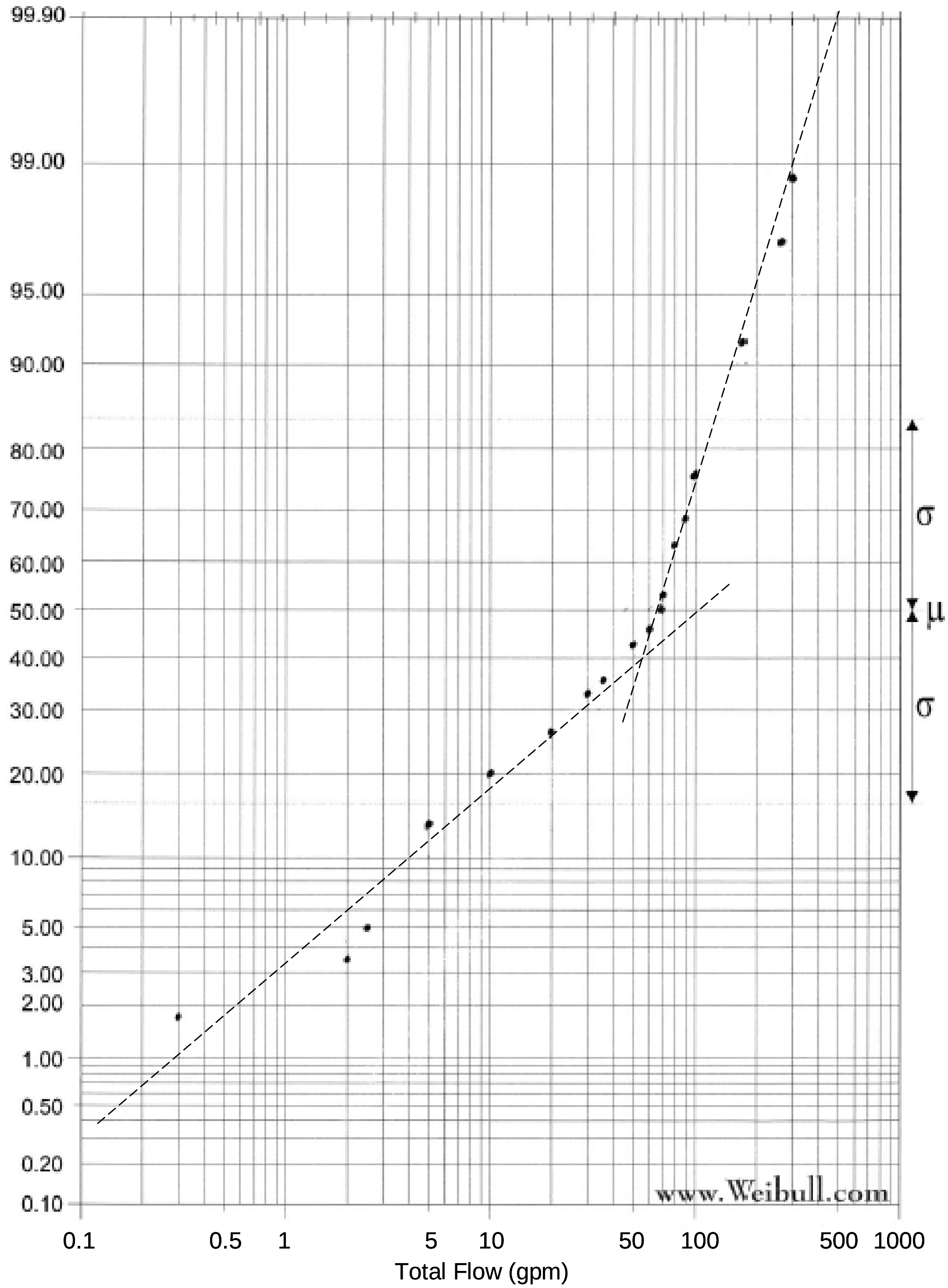

Figure 12. Probability plot showing the percentile of flows for the SLB3 discharge

The plot seems to show two different trends of flow. This could mean that during high precipitation events, a certain amount of the flow discharging into Jonathan Run through SLB3 is coming from a different source other than the spring and may contain a better water quality. While there is no substantial data to prove this, it should be better examined when detailed plans are prepared. If a large quantity of water has acceptable qualities then it would not need to be treated, which would decrease the land area needed and the construction costs.

The total mass of aluminum (in lbs/day) was plotted against the flow to determine how levels of aluminum in high flows compared to levels of aluminum in low flows (Figure 13). The plotted amounts of aluminum at a given flow show a fairly linear slope, meaning a constant concentration of aluminum. The slope is equal to 4.3 mg/L of aluminum.

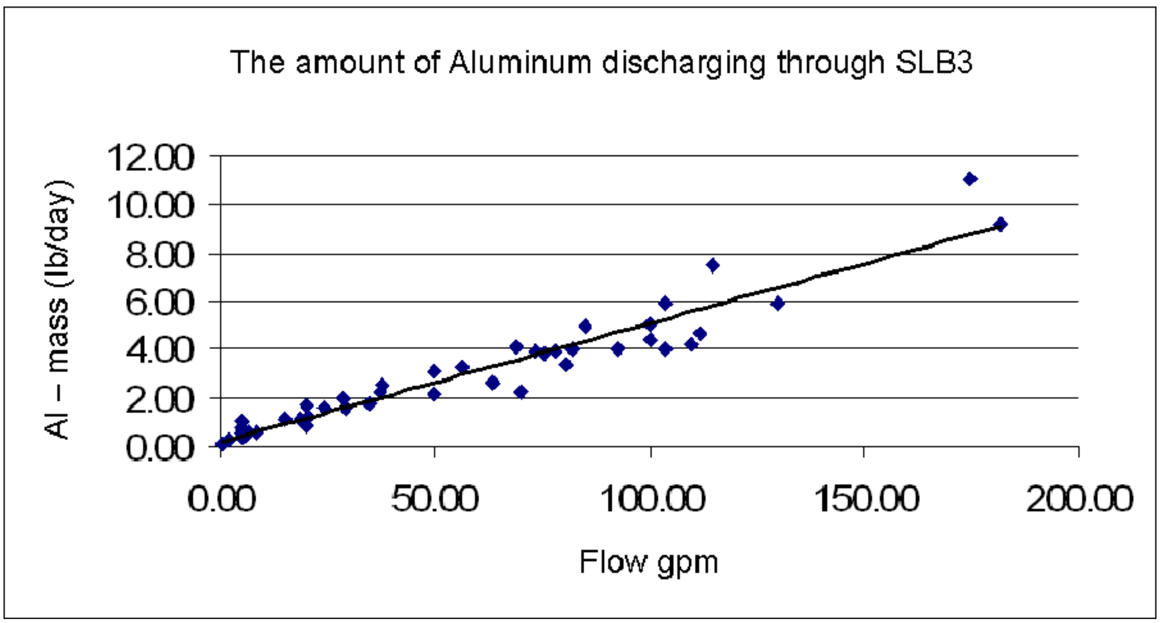

Figure 13. The amount of aluminum (lbs/day) plotted against the flow of SLB3 (gpm)

3.2.6.2 Discharge SLB5

The information that was gathered for discharge SLB5 is actually the sum of discharges originally labeled SLB5, SLB4, and an amount of uncontaminated flow directly from Jonathan Run. Hedin Environmental collected this flow to supply a pilot scale limestone drain (Hedin, 2003). This flow is considered to contain the majority of the contaminated flow that pollutes Jonathan Run. Flows were measured between May 2003 and September 2004 and are listed in

Table 5 along with the percentile of flow. They are plotted on log-normal probability paper shown in Figure 14.

Table 5. Culvert Collection
Flow Percentiles

Rank	*GPM*	*Percent*
1	75.4	0.96
2	59	0.92
3	50.65	0.88
4	42.8	0.84
5	41.3	0.8
6	41.05	0.76
7	35.8	0.72
8	33.5	0.68
9	32.2	0.64
10	30.7	0.6
11	29	0.56
12	28.1	0.52
13	27.45	0.48
13	27.45	0.48
15	26.8	0.4
16	23.45	0.36
17	22.5	0.32
18	21.75	0.28
19	16.7	0.24
20	14.2	0.2
21	11.9	0.16
22	10	0.12
23	9.9	0.08
24	9.4	0.04

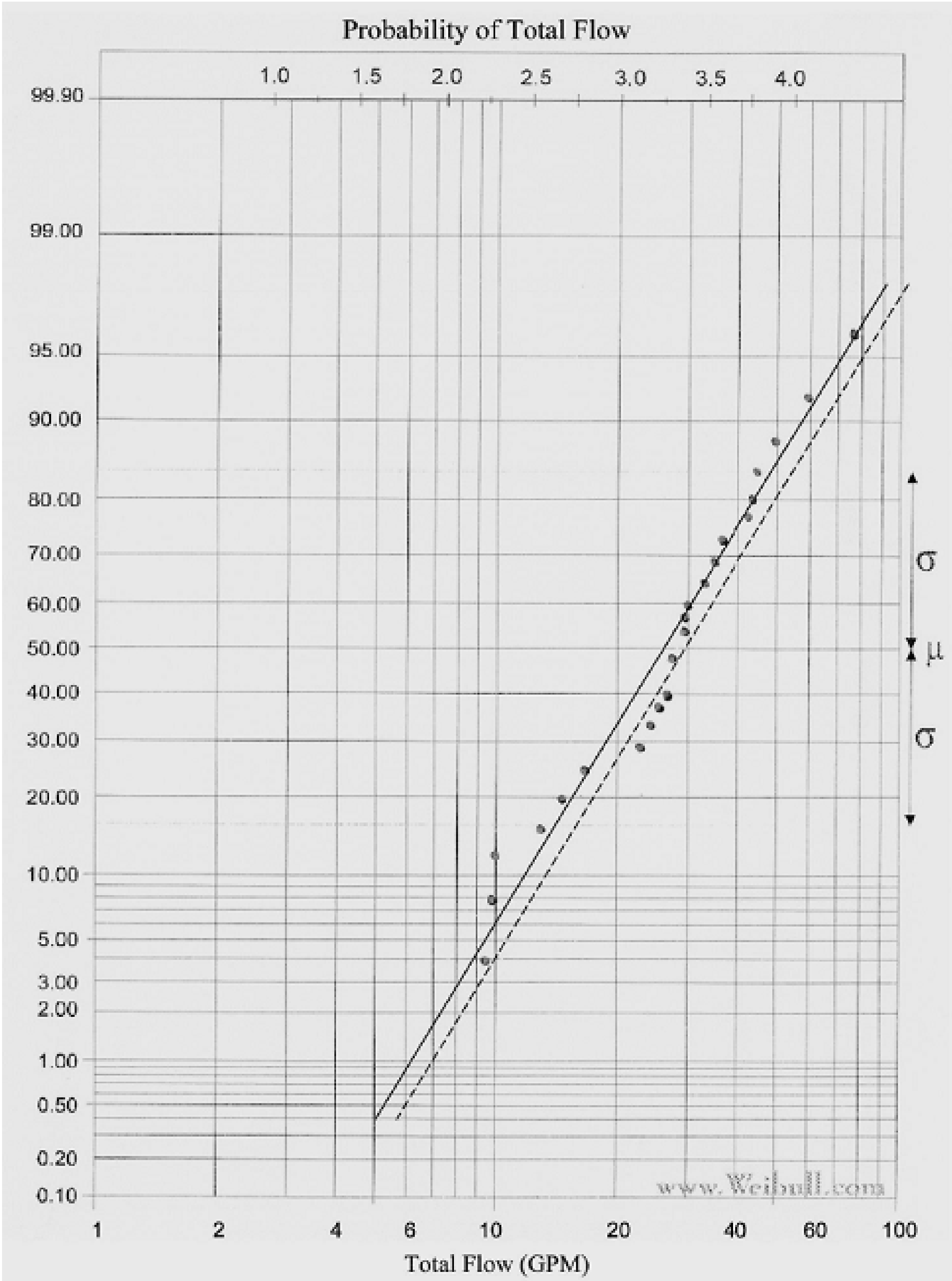

Figure 14. Probability plot showing the percentile of flows for Discharge SLB5

The plot shows that the average or 50 percent of flow is about 30 gpm, shown by the linear dotted line. Separate calculations by GAI based on theoretical evaluations estimate the average flow to be 28 gpm, surprisingly good agreement with statistical measured values. The linear solid line on Figure 13 was added with a slope parallel to the data set, but with the 50 percentile value set at 28 gpm. The 90th percentile flow is about 60 gpm. These flows will be used to construct a preliminary treatment design for Jonathan Run in this thesis. The chemistry of the water in the culvert collection system (Table 6) was determined by Hedin (Hedin, 2003) and will also be used in constructing a treatment design.

Table 6. Water Chemistry of the Discharge SLB5

Date	Field pH	Lab pH	Net Acid (mg/L)	Total Iron (mg/L)	Total Mn (mg/L)	Total Al (mg/L)	Dis Al (mg/L)	SO4 (mg/L)	TSS (mg/L)
5/20/03	3.5	3.5	305	1.5	9.1	51.7	47.9	447	7
6/5/03	3.4	3.4	300	1.4	9.5	46.7	43.8	453	6
6/6/03	3.5	3.4	317	1.4	9.7	50.8	48.4	372	4
6/12/03	3.5	3.5	292	1.3	10.1	46.7	44.0	365	6
6/14/03		3.5	301	1.2	6.6	46.3		346	2
6/19/03	3.4	3.5	300	1.2	9.4	49.1		395	1
6/23/03	3.0	3.5		1.1	9.8	52.4		389	5
6/24/03	3.5	3.5	304	1.2	9.5	48.3	43.8	370	7
6/25/03		3.5	298	1.2	9.3	47.3	43.4	435	4
6/27/03	3.4	3.6	321	1.1	9.0	49.1		728	1
Average	**3.4**	**3.5**	**304**	**1.3**	**9.2**	**48.8**	**45.2**	**430**	**4**

The large quantities of aluminum are of the most concern for the remediation of Jonathan Run, because of the toxicity of aluminum to aquatic life. Figure 15 shows the contribution of aluminum from each of the polluted water discharges.

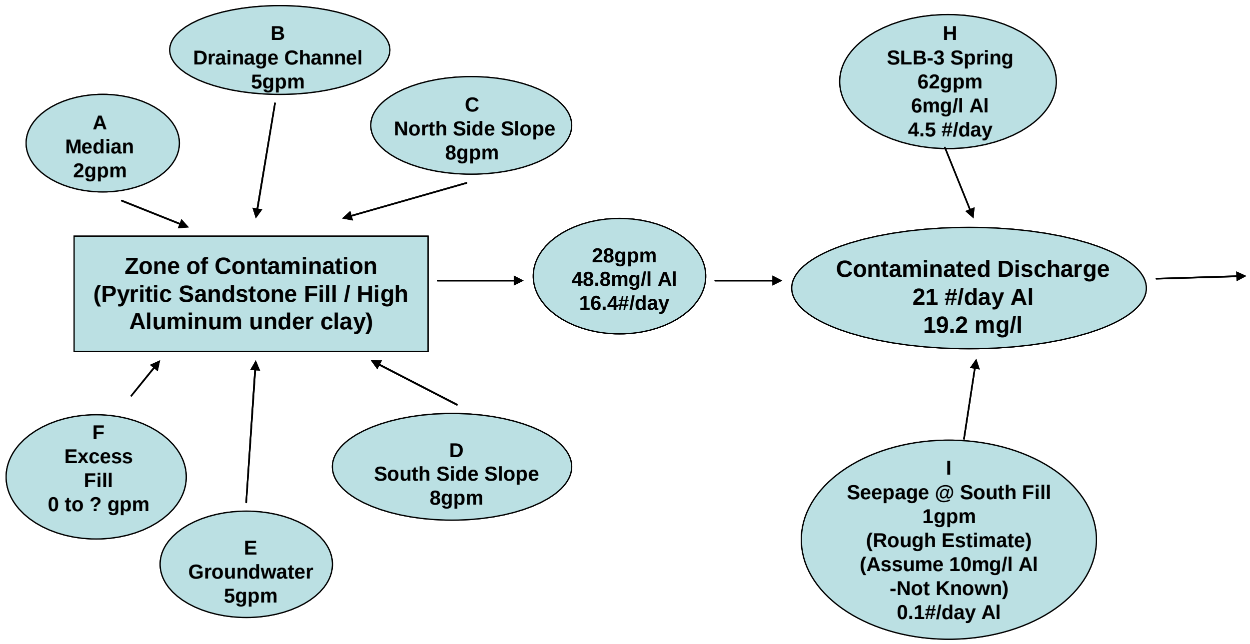

Figure 15. A diagram showing the contribution of aluminum from each water source and the total concentration of aluminum in Jonathan Run

3.3 PRELIMINARY DESIGN CONSIDERATIONS

As a result of the site investigation the most reasonable solutions based on possible effectiveness were determined and further examined. Eliminating the water source is one of the most ideal mitigation techniques, because of its low maintenance, friendliness to the environment, and long life span. Unfortunately, one of the major drawbacks in implementing an elimination technique is the efficiency in restoring Jonathan Run back into an inhabitable stream. In other words, will the technique be able to keep acidic aluminum and iron concentrated waters from entering into the stream. Although elimination techniques could remove a large portion of the infiltrating water, they will most likely not remove all of the infiltration water. Therefore, some type of treatment system would also need to be installed to ensure that water quality standards are met. It was suggested at a meeting between PennDOT and the Pitt research team that combining several of the technologies may produce the most cost effective “system approach.” For example, completing some infiltration-reduction projects coupled with polishing the reduced flow with a smaller active treatment facility could be the least cost approach since it is expected that infiltration reduction would reduce the quantity of polluted water coming from the embankment and would reduce the size and chemical requirement of the active treatment system.

3.3.1 Elimination

Since the interaction of oxygen and water with pyritic material results in a chemical reaction and acid discharge, taking steps to interfere with that interaction will eliminate acid generation. Eliminating the acidic water source is best accomplished by keeping water and oxygen from entering into the fill. The best method to achieve this goal is by constructing a cover system. Covers can range from soil to asphalt.

At the time of writing, PennDOT is currently working on another project that involves the need for a cover design. This cover system uses four layers (Figure 16). The bottom layer is a thick nonwoven geotextile that will help protect the HDPE layer above from the rough surfaces of the cut face. The second layer from the bottom is a 40 mil HDPE. It is the same material used as landfill liners. The splices require welding, and its surfaces are textured to increase friction between it and the layer of geotextile above and below. The third layer from the bottom is another nonwoven Class 4 geotextile to protect the top surface of the HDPE. The fourth and final top layer is called Geoweb or geocell (Figure 17). It resembles an empty honeycomb figure. It is used to hold soil or aggregate on the sloped surface and is also suppose to protect the geotextile/HDPE layers below from weather.

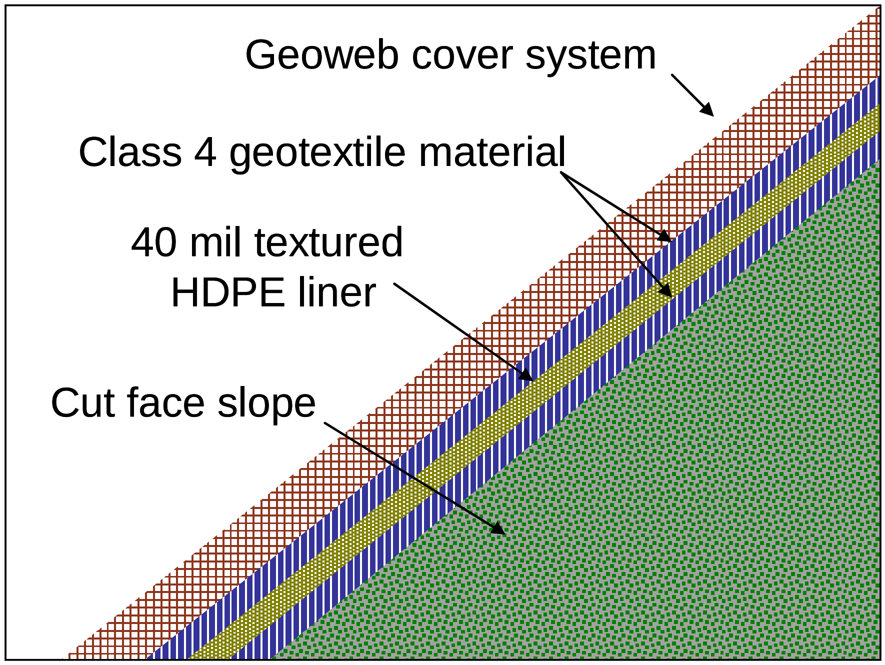

Figure 16. Diagram of cover system design used by PennDOT

Figure 17. Geoweb, the top and final layer to the cover system design at I-99

3.3.2 Elimination + Treatment

The remediation combination begins with the elimination of a portion of the infiltrating water into the embankment. Eliminating the water source would reduce the acidic water discharging into Jonathan Run. The amount of infiltration was estimated by GAI hydrologists to be approximately 23 gpm. Although it hasn't been thoroughly investigated, the groundwater was estimated to infiltrate at 5 gpm. The pollution from infiltration, ground water, spring SLB3 and the seepage from the fill south of I-80 has been determined to produce approximately 21 lbs/day of aluminum (0.92 mg/L) as shown in Figure 40 in Appendix B (Neufeld and others, 2007), the main pollutant in the water. Using the following elimination techniques, the infiltration quantity may decrease by about 87%:

- Covering/Capping the median,
- Replacing the leaking drainage channels with new pipe,
- Covering/Capping the North and South side slopes,
- Installing horizontal wells

The amount of aluminum produced will be reduced to about 6.8 lbs/day, or 8.5 mg/L of aluminum as shown in Figure 41 in Appendix B. Unfortunately, even this large of a reduction in aluminum production is not likely going to be enough to restore Jonathan Run to conditions suitable for sustaining aquatic life. Other steps must be taken after elimination to reduce the amount of aluminum entering Jonathan Run before restoration can be considered successful.

After elimination techniques are employed, additional remediation processes are needed. One technique would be to passively treat the remaining water discharging from the embankment and the flow from SLB3 by using a vertical flow pond. This system will cause the pH of the water to increase, allowing the dissolved aluminum to precipitate out of the water. The passive treatment system would also include a wetland containing a base of limestone to reduce the aluminum in the discharge from the fill on the South side of I-80. This process is estimated by GAI to reduce the aluminum discharge to 0.3 lbs/day (0.37 mg/L); see Figure 42 in Appendix B.

A third option includes an active treatment system to treat the water remaining after the elimination techniques are employed. This system consists of adding sodium hydroxide to the water to increase the pH and allowing the precipitates to settle out. It is a reliable approach to neutralize acidity and remove metal contaminants. There are many active treatment systems already in operation in central Pennsylvania that successfully remove dissolved solids from mine discharges. As in the elimination plus passive treatment system, a small wetland would be constructed on the South side of I-80 to catch the seepage from the excess rock fill. Using this system, GAI estimated that the amount of aluminum would decrease to 0.1 lbs/day or 0.12 mg/L, Figure 43 in Appendix B, making this process the most likely to succeed.

3.3.3 Active Treatment

A variation of the third option is to employ active treatment without any elimination techniques. This would utilize the addition of sodium hydroxide followed by sedimentation ponds. The system could be implemented relatively quickly and can be automated but will require continuous maintenance.

3.4 FINAL DESIGN DECISION

After meeting with PennDOT and PaDEP, a final decision was made on a design system to remediate Jonathan Run. The decision of th design was based on the need to develop a fast and efficient response to the problem The design includes the following three systems that will reduce the amount of aluminum to 1 lb/day or 0.91 mg/L as shown in Figure 44 in Appendix B.

- Active Treatment Sodium Hydroxide addition
- Passive Treatment Vertical Flow Ponds for the SLB3 Discharge
- Wetland on the South side of I-80

3.4.1 Active Treatment

The active treatment system will utilize sodium hydroxide to increase the pH and add alkalinity to the water that was discharged at SLB5. This water contains the largest amount of aluminum per day, 17.6 lb/day and the lowest pH of 3.4, and the best way to assure the highest reduction of the aluminum is by using an active treatment system. Passive treatment systems have been known to clog when treating water with high concentrations of aluminum, which reduces the limestone surface area, causing the system to fail.

3.4.2 Passive Treatment

A passive treatment system utilizing vertical flow ponds will be used to treat the flow from the SLB3 discharge. The flow rate is highly variable (see Figure 12), which makes it more difficult and costly to treat with sodium hydroxide, it contributes a lesser amount of aluminum per day, and it has a higher pH. All these characteristics make this flow a reasonable choice to treat with a passive treatment system. Passive treatment systems do require more area and time compared to active treatment systems, but will save on chemical and maintenance costs.

3.4.3 Wetlands

There is visual evidence, white and yellow precipitates, that acidic discharges are contaminating Jonathan Run on the South side of I-80 (see Figure 31), most likely being contributed because of the small excess rock piles located on the valley floor. At this time there has not be a significant study into this particular area of the Jonathan Run site, so exact conclusions can’t be drawn, but a small anaerobic wetland, possibly with limestone mixed throughout, should help to increase the pH of the groundwater and help to filter out metal precipitates by the wetland plant life. Due to the lack of information regarding this area of Jonathan Run, a detailed design will not be researched in this paper.

4.0 BASIS OF DESIGN FOR TREATMENT SYSTEMS

The goal of the treatment systems is ultimately to raise pH and precipitate out dissolved metals from contaminated water. The design characteristics will focus on the precipitation of aluminum, which happens most efficiently at pH values between 6 and 8 (Gusek and Wildeman, 2002). As of this writing there is not an effluent standard for aluminum covered by mining regulations. Systems that have high aluminum concentration effluents are assigned standards by contract, if those standards are not met the contract is violated. Jonathan Run has not currently been assigned effluent standards for aluminum. Through contact with the DEP (personal correspondence, Rosengrant, 2007), general limits applied are a concentration of no greater than 4.0 mg/L in a single sample, or 2.0 mg/L as a monthly average. To increase the likelihood for aquatic life restoration, the treatment systems will be designed to reach an effluent of less than 1 mg/L of aluminum.

4.1 ACTIVE TREATMENT SYSTEM USING SODIUM HYDROXIDE

To treat acidic discharge using a sodium hydroxide treatment system is a popular and largely successful method. There are several sodium hydroxide treatment systems already in operation in central Pennsylvania and all are currently having success in increasing pH and settling out dissolved metals. The main design characteristics that need to be determined for the treatment system are the amount of sodium hydroxide needed and the technique used to add it, the number of settling ponds, and the pond sizes (Figure 18).

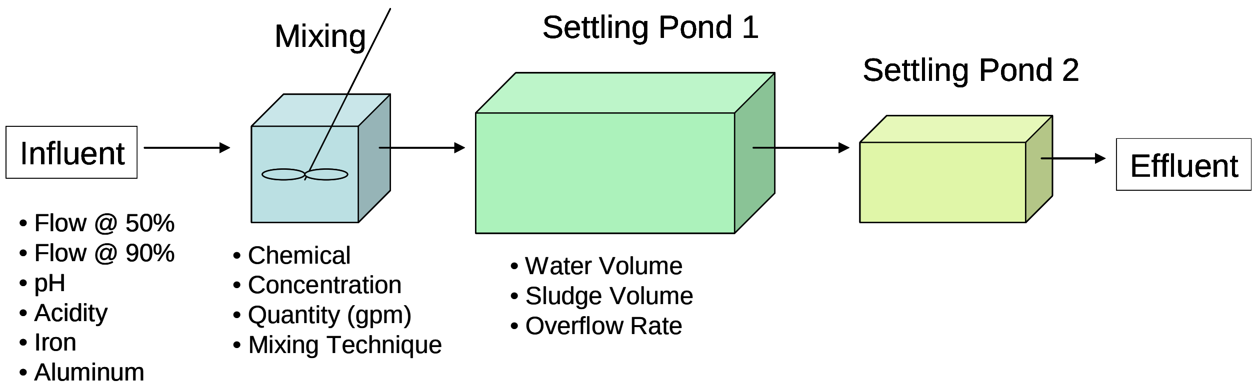

Figure 18. Schematic of active treatment process showing the issues that need to be addressed

4.1.1 Mixing/Addition of Sodium Hydroxide

Sodium Hydroxide (NaOH) is a common chemical choice for treating ARD and AMD because it is very soluble in water, it disperses rapidly and it raises the pH of the water quickly. The chemical can be gravity feed directly into the ARD so electricity is not needed; this makes caustic soda a common chemical choice for rural systems. Caustic Soda is usually contained in a 10,000 gallon tank located nearby the contaminated water. It can freeze over the winter, but if a 20% solution is used instead of 50% solution the freezing point drops from 0°C to -37°C (Skousen and others, 2000).

4.1.1.1 Quantity of Sodium Hydroxide

If the quantity and quality of the influent water is consistent, then the amount of caustic soda can be regulated by a gate valve located at the end of the discharge line. However, if the flow fluctuates and the quality of water changes during seasons or high and low flow periods, then to reduce labor costs an automatic monitoring system to control the amount of chemical being added could be employed.

The amount of caustic soda that is needed for the treatment of Jonathan Run can be estimated by using the amount of hot acidity in the water and the average flow. The hot acidity is the total acidity found in the water, which includes acidity from pH as well as from metal compounds (Kirby and Cravotta, 2005). We are given that the acidity is equal to 304 mg/L as $CaCO_3$, but to find the amount of caustic soda, the acidity needs to be given in terms of meq/L.

$$Acidity = \frac{304mg/L\ as\ CaCO_3}{50mg/meq} = 6.08meq/L\ of\ acidity$$

The amount of caustic soda to neutralize the acidity can be found by finding the meq/L of a 20% solution of NaOH.

$$NaOH\ @\ 20\% = \frac{20g\ NaOH}{20g + 80g\ water}$$

$$\text{Assume } \rho\ 20\%\ NaOH = 1.2219\ g/mL$$

$$\frac{\dfrac{20g\ NaOH}{40g/mol}}{\dfrac{100g\ 20\%\ NaOH}{1.2291\ mg/L}} = 6.11\ mol/L\ NaOH$$

$$\frac{6.11\ mol/L}{1eq/mol} = 6.11\ eq/L \cdot 1000 = 6110\ meq/L$$

Using a 1 L sample of water with a 6.08 meq/L concentration of acidity, the volume of NaOH needed to neutralize the acid is found (at the average flow rate) by the following calculations.

$$1\ L \cdot 6.08\ meq/L\ of\ acidity = 6110\ meq/L\ of\ NaOH \cdot xL$$

$$\frac{6.08\ meq}{6110\ meq} = 9.95 \times 10^{-4} L = 0.995\ mL\ of\ NaOH/L\ of\ acidic\ water$$

$$0.995\ mL/L \cdot 30\ gpm \cdot 3.785L/gal = 112.98\ mL/\min = 0.0298\ gpm$$

Or

$$112.98\ mL/\min \times 525600 \min/\ year \times 1L/1000mL \times 1gal/3.785L = 15689\ gal/\ year$$

4.1.1.2 Mixing Sodium Hydroxide

Adding caustic soda into polluted water is a simple procedure. Due to the high solubility and rapid dispersion of caustic in water, only short detention times and simple mixing techniques are necessary. Turbulent water flow by running the water through rocks or over a rocky streambed will provide enough mixing to evenly distribute the caustic throughout the water supply, as seen in Figures 19-22. The existing systems in operation in central PA only need seconds to effectively mix the chemical into the water. The mixing technique shown in pictures 18 and 19 is an appropriate technique to use for the Jonathan Run system. The mixing box consists of concrete sides and bottom, with a wooden hatch on top, and has dimensions around 3ft x 2ft x 3ft. This application is satisfactory for the Jonathan Run area.

Figure 19. Mixing technique found at a chemical treatment system for acid mine drainage in central Pennsylvania. A cement box filled with large rocks allows for turbulent mixing of water and caustic soda

Figure 20. The caustic soda is gravity feed into the mixing box and controlled by a manual valve

Figure 21. The caustic soda mixes into the water as it tumbles down the steps in the structure in the background and as it flows over the large rocks on its way to the first settling pond.

Figure 22. The water enters from the top through the PVC pipe and continues down the trough where caustic soda is added and mixes with the water

4.1.2 Settling Pond 1

This system greatly resembles a sedimentation basin that would be used in a water treatment plant to settle out the aluminum floc. In water treatment systems, the typical flocculent used is aluminum sulfate $Al_2(SO_4)_3$. When it is added to the water it reacts as follows:

$$Al_2(SO_4)_3 \cdot 14H_2O + 6(HCO_3^-) \rightarrow 2Al(OH)_3 + 3SO_4^{2-} + 14H_2O + 6CO_2$$

The aluminum hydroxide $Al(OH)_3$ is the primary precipitate that is used to help settle out the other contents of the water and is also the primary product created when dissolved aluminum precipitates out of acidic water as the pH increases. Therefore the characteristics of the alum floc found in water treatment plants will be used to estimate the settling ability of the gibbsite precipitation in the active treatment of acid rock discharges.

After exiting the mixing box, the water will enter the first of two settling ponds. The first pond will be capable of holding the 90 percentile of flow (60 gpm) for the needed amount of time to allow the precipitates to settle. The most important criteria are the surface loading rate and the settling velocity. For discrete particles in a controlled setting the settling rate is constant, but the aluminum and iron precipitates formed in the treatment system will not settle discretely. However, the settling velocity, determined by dividing the depth by the detention time of the pond, can be used to help determine the available surface area. If the settling velocity is faster than the overflow rate of the system, then the particles will settle out before exiting into the stream. In *Water Treatment: Principles and Design* (Crittenden and others, 2005) the average settling velocities for aluminum floc of different sizes at 15°C are listed in Table 7.

Table 7. Settling Velocity of Aluminum Floc at 15°C

Small	0.12 – 0.24 ft/min	1293-2585 gpd/ft^2
Medium	0.18 – 0.28 ft/min	1939-3016 gpd/ft^2
Large	0.22 – 0.30 ft/min	2370-3231 gpd/ft^2

Susumu Kawamura (2000), states that a slower settling rate for alum floc of 0.04 fpm (431 gpd/ft^2). Since this is the slowest settling rate published, this rate will be used in calculations for pond design considerations to better ensure an overflow rate that is less than the settling rate. Using this settling rate and the 90 percentile flow (60 gpm), the minimum needed surface area is calculated.

$$SA = \frac{Q}{V_s} = \frac{60\ gpm}{0.04\ fps} \times \frac{0.133681\ ft^3}{gal} = 200.5\ ft^2$$

Although the efficiency of a settling pond does not depend on the depth of the pond but on the settling velocity and loading rate, there is a minimum depth needed to decrease the effect that the sun, wind, and sludge volume could have on the settling. It is recommended that the depth should be 6 – 10 ft (Crittenden and others, 2005), especially in the first half of the pond where most of the precipitate settles out. There are several active treatment systems currently in operation in central Pennsylvania, and each of those systems have ponds that are 6 -10 ft in depth and appear to not be contributing any problems to the settling of the metals. This design will assume a depth of 6ft, the smallest accountable depth, because the difficulty of construction into the hillside near Jonathan Run.

This gives a detention time of $t_d = \frac{V}{Q} = \frac{200.5\ ft^2 \times 6\ ft}{60\ gpm \times 0.133681} = 150\text{ min} = 2.5\ hrs$, which will be needed to calculate the total volume of the pond. Most sedimentation systems in water treatment plants have detention times that fall between 1.5 – 4 hrs (Kawamura, 2000) (Crittenden and others, 2005).

To calculate the total volume of the pond, the volume provided for sludge storage along with the volume of water needed to hold the 90 percentile flow for at least the 2.5 hrs determined above will be added together.

The volume needed to store the settled precipitates depends on how often the ponds are cleaned and the sludge is moved to a waste pond. This design estimates sludge storage volume based on cleaning being performed twice a year, due to the high amount of dissolved aluminum. Other factors that are used in calculations are the concentration of aluminum since it is the primary dissolved solid precipitating out, the density of amorphous aluminum hydroxide, the precipitated floc most often observed, and the percent solids found in the precipitate. Aluminum hydroxide is a fragile gelatinous floc with poor compactability and therefore high water content

(Tambo and Watanabe, 1979) (AWWA and ASCE, 2005). It's density is difficult to determine because as the floc increases in diameter, the density decreases proportionally (Tambo and Watanabe, 1979), but an average density of 8.34 lbs/gal is used in calculations in *Water Treatment Plant Design 4th Ed.* (AWWA and ASCE, 2005) and this density will be used for calculations in this thesis. The percent solids also fluctuates depending on if the floc is more liquid, spongy, or clay like in consistency (AWWA and ASCE, 2005). Usually in settling basins the consistency is more liquid like which means the percent solids will be found between 0.5% - 2.0%. This thesis will assume a percent solids content of 1.25%, the median of the two values. Since the physical properties of the precipitate are difficult to estimate, it is suggested that a titration be preformed on the water to be treated, to get a better idea of the density of the sludge, the settling velocity and ultimately the amount of sludge that will be produced.

$$V_{sludge} = \frac{[Al] \times Q}{\%\ solids \times \rho} = \frac{48.8\ mg/L \times 60\ gpm \times 3.785\ gal/L \times 262800\ \text{min}/6\ months}{454000\ mg/lbs \times 0.0125\ \%\ solids \times 8.34\ lbs/gal \times 7.48\ gal/ft^3} = 8{,}226.76\ ft^3/6\ months$$

$$V_{sludge} = 61{,}540.4\ gal/6\ months$$

The volume needed for water can be found by the following calculation:

$$V_{water} = t_d \times Q = 2.5 hrs \times 60\ gpm \times 60\ \text{min}/hr = 9{,}000\ gal$$

By adding the water volume and sludge volume the total volume is determined.

$$V_{total} = 61{,}540.4 + 9{,}000 = 70{,}540.4\ gal = 9{,}430\ ft^3$$

To find the dimension of the pond, the new surface area is calculated and a length-to-width ratio of 4:1 is used (MWH, 2005). Also, the depth remains at 6ft.

$$SA = \frac{Volume}{depth} = \frac{9{,}430\ ft^3}{6\ ft} = 1{,}571.67\ ft^2 \approx 1{,}572\ ft^2$$

Table 8. Settling Pond 1
Dimensions

Length	79.0 ft
Width	20.0 ft
Depth	6.0 ft

The dimensions were rounded to the nearest half-foot which produces a surface area of 1,580 ft^2 and a total volume of 9,480 ft^3. The overflow rate of the new calculated surface area should still be slower than the settling rate for aluminum floc. If this is still true, then a pond of these dimensions should be effective and successful.

$$OFR = \frac{Q}{A} = \frac{60\ gpm \times 0.133681\ ft^3/gal}{1{,}580\ ft^2} = 0.005\ fpm\ \leq\ 0.04\ fpm\ (settling\ velocity)$$

$$OFR = \frac{Q}{A} = \frac{60\ gpm \times 1440\ \min/day}{1{,}580\ ft^2} = 54.7 gpd/ft^2 \leq 431 gpd/ft^2$$

4.1.2.1 Horizontal Flow Velocity

If the horizontal flow velocity is too high it will cause the water to be turbulent and not allow particles to settle efficiently. By calculating the Reynold's Number of the pond using the equation: $\mathrm{Re} = \frac{VR_h}{\nu}$, the turbulence can be evaluated (MWH 2005).

Where $R_h = \frac{A_x}{P_w} = \frac{cross-\sec tional\ area\ (m^2)}{wetted\ \ perimeter\ (m)}$

V = Average horizontal velocity (m/s)

v = kinematic viscosity (use 15°C) (m^2/s)

$$\mathrm{Re} = \frac{2.54 \times 10^{-5} \cdot \frac{146.787}{60.35}}{1.1457 \times 10^{-6}} = 53.93 < 20{,}000$$

If Re < 20,000 then the amount of turbulence is acceptable to allowing settling.

4.1.2.2 Settling Pond 1 Using Average Flow

At the average flow (30 gpm), when no precipitate has accumulated in the bottom of the pond, the detention time of the water is:

$$t_d = \frac{V}{Q} = \frac{70{,}915.3\ gal}{30\ gpm} = 2363.84 \text{ min} \approx 39.4\ hrs$$

The detention time when the sludge volume is half full:

$$t_d = \frac{V}{Q} = \frac{40{,}145.1\ gal}{30\ gpm} = 1{,}338.17 \text{ min} = 22.2\ hrs$$

When the sludge volume is near its desired capacity the detention time is:

$$t_d = \frac{V}{Q} = \frac{9{,}374\ gal}{30\ gpm} = 312.47 \text{ min} = 5.2\ hrs$$

4.1.2.3 Settling Pond 1 Using 90th Percentile Flow (60 gpm)

At the 90th percentile flow, when no precipitate has accumulated in the bottom of the pond, the detention time of the water is:

$$t_d = \frac{V}{Q} = \frac{70{,}915.3\ gal}{60\ gpm} = 1181.92 \text{ min} = 19.7\ hrs$$

The detention time when the sludge volume is half full:

$$t_d = \frac{V}{Q} = \frac{40{,}145.1\ gal}{60\ gpm} = 669.085 \text{ min} = 11.15\ hrs$$

When the sludge volume is near its desired capacity the detention time is:

$$t_d = \frac{V}{Q} = \frac{9{,}374\ gal}{60\ gpm} = 156.2\ \text{min} = 2.6\ hrs$$

4.1.3 Settling Pond 2

The second settling pond is used as a polishing pond and as a primary settling pond when Pond 1 is being cleaned. Pond 2 will be designed to treat the average flow of Jonathan Run. The same calculation techniques that were used to design Pond 1 will be employed again to design Pond 2.

Initial surface area: $SA = \frac{Q}{V_s} = \frac{30\ gpm}{0.04\ fps} \times \frac{0.133681\ ft^3}{gal} = 100.25\ ft^2$

Initial detention time: $t_d = \frac{V}{Q} = \frac{100.25\ ft^2 \times 6\ ft}{30\ gpm \times 0.133681} = 150\ \text{min} = 2.5\ hrs$

Volume needed for precipitated sludge:

$$V_{sludge} = \frac{[Al] \times Q}{\%\ solids \times \rho} = \frac{48.8\ mg/L \times 30\ gpm \times 3.785\ gal/L \times 262800\ \text{min}/6\ months}{454000\ mg/lbs \times 0.0125\ \%\ solids \times 8.34\ lbs/gal \times 7.48\ gal/ft^3} = 4{,}113.38\ ft^3/6\ months$$

$$V_{sludge} = 30{,}770.2\ gal/6\ months$$

The volume needed for water:

$$V_{water} = t_d \times Q = 2.5 hrs \times 30\ gpm \times 60\ \text{min}/hr = 4{,}500\ gal$$

By adding the water volume and sludge volume the total volume is determined.

$$V_{total} = 30{,}770.2 + 4{,}500 = 35{,}270.3\ gal = 4{,}714.95\ ft^3$$

To find the dimensions of the pond, the new surface area is calculated and a length-to-width ratio of 4:1 is used. Also, the depth remains at 6ft.

$$SA = \frac{Volume}{depth} = \frac{4{,}714.95\ ft^3}{6\ ft} = 785.825\ ft^2$$

Table 9. Settling Pond 2 Dimensions

Length	57 ft
Width	14 ft
Depth	6 ft

The dimensions were rounded to the nearest half-foot which produces a surface area of at least 785.825 ft^2. These dimensions give a surface area of 798 ft^2 and a total volume of 4,788 ft^3. The overflow rate is also calculate for Pond 2 and is found to be 0.005 fps.

$$OFR = \frac{Q}{A} = \frac{30\ gpm \times 0.133681\ ft^3/gal}{798\ ft^2} = 0.005\ fps \le 0.04\ fps$$

$$OFR = \frac{Q}{A} = \frac{30\ gpm \times 1440\ \text{min}/day}{798\ ft^2} = 54.13\ gpd/ft^2 \le 431 gpd/ft^2$$

The Reynold's Number of the water in settling pond 2:

$$\mathrm{Re} = \frac{2.54 \times 10^{-5} \cdot \frac{74.14}{43.28}}{1.1457 \times 10^{-6}} = 38 < 20{,}000$$

Table 10. Summary of Settling Pond Dimensions

	Settling Pond 1	Settling Pond 2
Length	79.0 ft	57.0 ft
Width	20.0 ft	14.0 ft
Depth	6.0 ft	6.0 ft

4.2 PASSIVE TREATMENT SYSTEM – VERTICAL FLOW WETLANDS

Vertical flow ponds (VFPs), also called vertical flow wetlands or successive alkalinity producing systems, are a combination of anoxic limestone drains and an organic substrate into one system typically used to treat water that has a net acidity and contains a DO concentration >1 mg/L and iron (Kepler and McCleary, 1994). A diagram of a VFP is shown in Figure 23. The issues that need to be addressed when design a system are described in Figure 24. Each vertical flow pond will be designed for a life span of 20 years.

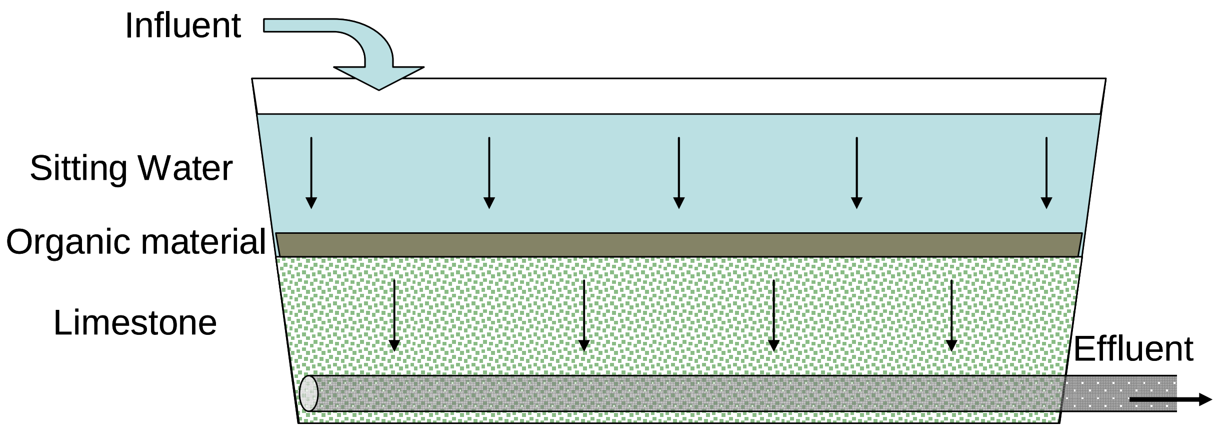

Figure 23. Diagram of a Vertical Flow Pond showing the four components; the ponded water, organic material, limestone, and drainage system

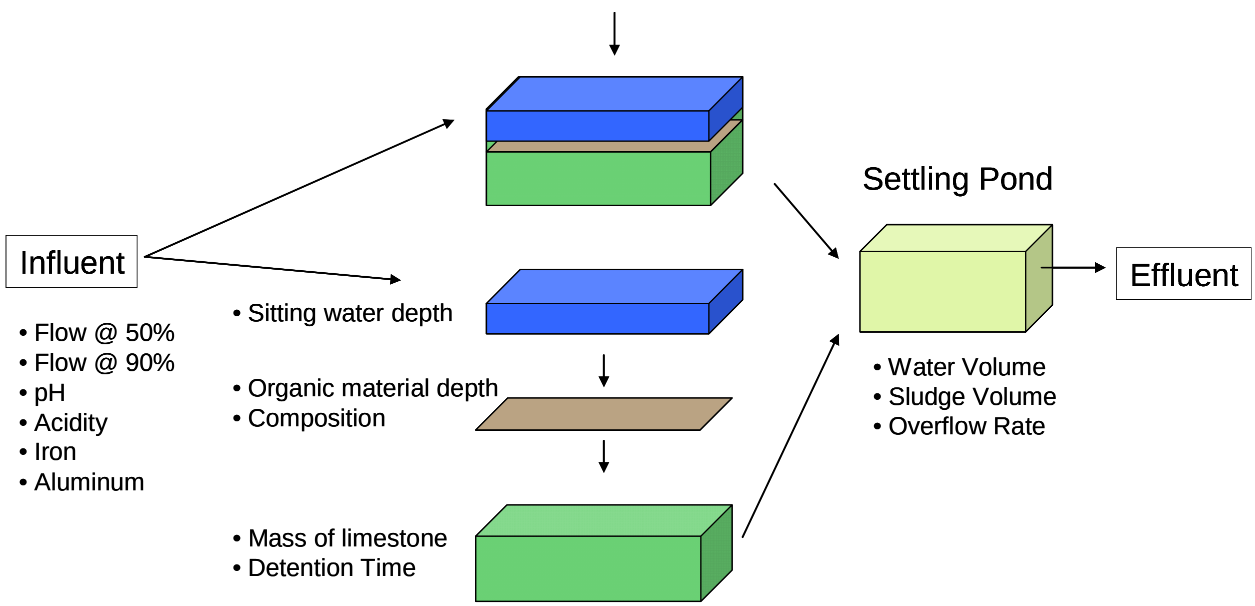

Figure 24. Issues to be address when designing a Vertical Flow Pond System

4.2.1 Limestone Layer

The four main components of the VFP is the ponded water layer that sits on the top of the system, the organic substrate layer, the limestone, and the drainage system (Figure 23). The most important aspect of the system that determines the construction design is the amount of limestone required to neutralize the acidic waters by its alkalinity production. A study conducted on determining the factors that affect the alkalinity generation by VFPs believe that the residence time in the limestone layer, and the water quality are the two main factors (Kepler and McCleary, 1994) (Jage and others, 2001). Jage (2001) developed an empirical equation (Equation 1) that will calculate a detention time using the desired amount of alkalinity needed to equal the amount of acidity in the water, and the concentrations of iron and manganese. The equation was based on VFPs that used high-calcium limestone aggregate ranging from 4-6 inches in diameter. This equation also assumes that the relationship of alkalinity generation to limestone-layer residence time is logarithmic, since the rate of alkalinity generation is rapid at first but decreases over time.

$$\text{Net alkalinity (mg/L as } CaCO_3) = 34.82 \ln(t_r) + 0.61\text{Fe} + 0.56\text{non-Mn acidity} - 49.27 \quad (1)$$

$$\text{Where, non-Mn acidity} = \text{acidity} - 1.82 \text{ Mn}$$

This equation was changed slightly in a more recent publication for reasons unmentioned (Zipper and Jage, 2001). The equation (Equation 2) will be used to help estimate the needed detention time in the limestone layer to provide the required alkalinity. The calculated detention time will only be used as an estimated time, and not as a precise prediction (Zipper and Jage, 2001).

$$\text{Net alkalinity (mg/L as } CaCO_3) = 99.3 \log(t_r) + 0.76\text{Fe} + 0.23\text{non-Mn acidity} - 58.02 \quad (2)$$

$$\text{Where, non-Mn acidity} = \text{acidity} - 1.818 \text{ Mn}$$

The water characteristics of the SLB3 Spring that feeds into Jonathan Run are listed Table 11.

Table 11. SLB3 Discharge Water Characteristics

pH	4.5	Iron	0.2 mg/L
Alkalinity	6.9 mg/L	Aluminum	6.1 mg/L
Acidity	39.2 mg/L	Manganese	1.7 mg/L
Temperature	9.5 °C	Sulfate	73.1 mg/L
50% Flow	62 gpm	90% Flow	200 gpm

The net alkalinity that needs to be generated is 39.2 mg/L to equal the amount of acidity in the water. Using this amount of net alkalinity the detention time can be calculated.

$$t_r = 10^{\frac{Alk+58.02-0.23non-Mn\ acidity-0.76Fe}{99.3}} = 10^{\frac{39.2+58.02-.23(36.1094)-0.76(0.2)}{99.3}} = 7.83\ hours$$

However, the 179 observations that were used to derive the equation had a standard deviation of 50 mg/L for the difference between the observed and predicted values. Therefore, to be on the conservative side, 50 mg/L of additional alkalinity should be considered when using the equation. This gives a detention time of 24.97 hours.

This is an estimated amount of time that is necessary to increase the pH and reduce the amount of acidity given the alkalinity generation rate. It is important to remember that alkalinity generation rates vary considerably between systems. Researchers have given assumptions to average alkalinity generation rates between 30 to 40 g/m^2/day, but actual rates have been found between 11 to 52 g/m^2/day (Demchak and Skousen, 2001). If alkalinity generation rates differ so widely, then the needed detention times will vary as widely as well. Researchers have concluded minimum detention times to be around 12 to 15 hours, with actual detention times in operational VFP ranging from hours to weeks (Zipper and Jage, 2001) (Kepler and McCleary, 1994) (Hedin and Watzlaf, 1994).

It is safer to construct VFPs with larger amounts of limestone and longer detention times than smaller systems with short detention times, and since recent research has not suggest many system to have detention times over 23 hours, this design will use a conservative detention time of 24 hours, calculated above, and base further calculations off that decision.

The amount of limestone needed to reach the desired detention time can now be calculated. The density of the limestone, 1722.5 kg/m^3 or 107.53 lbs/ft^3, and the bulk void volume, which can be estimated to be 50% or 0.5 (Hedin and Watzlaf, 1994) (Zipper and Jage, 2001), are both needed for the calculation.

$$M_{\lim estone} = \frac{t_d \cdot Q \cdot \rho}{V_{bulk}}$$

The mass of limestone in tons is found:

$$M_{\lim estone} = \frac{24\ hrs \cdot 100\ gpm \cdot 107.53\ lbs/ft^3 \cdot 60\ \mathrm{min}/hr}{0.5 \cdot 7.48\ gal/ft^3 \cdot 2000\ lbs/ton} = 2{,}070\ tons$$

It is suggested that additional limestone be included into the VFP to compensate for the limestone dissolution over the design life (20 years) of the system (Hedin and Watzlaf, 1994).This amount of limestone is calculated using the equation:

$$M_{\lim estone} = \frac{Q \cdot C \cdot T}{x}$$

Where Q is the flow of the water into the VFP, C is the predicted concentration of alkalinity that needs to be produced, T is the design life of the system, and x is the calcium carbonate content of the limestone, which is assumed to be 0.9 (Hedin and Watzlaf, 1994). The additional amount of limestone needed, in terms of tons, is calculated:

$$M = \frac{100\ \frac{gal}{\mathrm{min}} \cdot 89.2 \frac{mg}{L} \cdot 20\ yrs \cdot 3.785 \frac{L}{gal} \cdot 525949 \frac{\mathrm{min}}{yr} \cdot 10^{-3} \frac{g}{mg} \cdot 0.002205 \frac{lbs}{g}}{2000 \frac{lbs}{ton} \cdot 0.9} = 435\ tons$$

The total amount of limestone that will be included into the design of the VFPs for Jonathan Run is 2,505 tons, which gives a volume of 46,591.6 ft^3. The depth of the limestone bed will be 4 ft, this would give a surface area of 11,647.9 ft^2.

4.2.2 Organic Substrate Layer

What makes a VFP different than an anoxic limestone drain (ALD), is the layer of organic material. Usually, ALDs are used when water does not have the ability to come into contact with the outside air and absorb oxygen, so it already has a low DO concentration. The reason for the desired low DO in water is due to the settling characteristics of the dissolved iron found in the acidic drainage. Ferric iron (Fe^{3+}), the usual form of iron found in high acidic waters, will precipitate as iron hydroxide, $Fe(OH)_2$, when the pH increases which will lead to the coating or armoring of the limestone. When DO concentrations are low, ferric iron will transform into ferrous iron (Fe^{2+}). The ferrous iron will not readily precipitate from solution when the pH is raised, but once the water exits the drain and is exposed to oxygen the dissolved iron will rapidly oxidize and precipitate out. This makes the organic layer critical to long term performance of the VFP.

The removal of DO depends on the water temperature and the residence time of the water in the organic material. A deeper organic layer is preferred to lessen the possibility that oxygenated water might reach the limestone layer, but if the layer is too deep it will cause low permeability (Zipper and Jage, 2001). A study was performed to evaluate the redox conditions of the organic layer in VFP, by placing equilibrators throughout the layer of system (Demchak and Skousen, 2001). They found that oxidation conditions occurred at 30 cm and reduction conditions were found at 60 cm. They suggest that the organic substrate layer be at least 50 cm in depth. This design will incorporate an organic layer that is 19.5 inches in depth.

It is also important that the organic layer be evenly distributed and well mixed, so as not to cause uneven water flows and compaction that could lead to poor performance of the system (Zipper and Jage, 2001) (Demchak and Skousen, 2001).

The type of material is also important. It needs to have the ability to decompose slowly and contain the necessary carbon for the microbial community. Mushroom compost has been widely used in many situations requiring an organic layer and will be used in the vertical flow ponds. Demchak (2001) suggests using a combination of larger material, such as wood chips, and mushroom compost. This would help with the longevity of the layer by the slower decomposition of the wood chips, and with hindering compaction and varying water flow.

4.2.3 Ponded Water Layer

This pool of water that sits above the organic substrate layer and the limestone layer provides a cushion from flow surges, allows for even distribution of water throughout the entire treatment area and provides a positive head to force the water through the layers below (Kepler and McCleary, 1997). This pressure is especially important during flushing of the system to get rid of the aluminum and iron precipitates that accumulate in the limestone and drainage pipes. Studies have shown the pools of water to be from 0.5 to 2 meters (1.64 to 6.56 ft) in depth (Kepler and McCleary, 1994 and 1997) (Demchak and Skousen, 2001). One study suggests depths between 6 to 10 ft to successfully flush the system (Zipper and Jage, 2001). It is hard to determine a definite depth of water for any system, so a free-board depth of a couple extra feet could be helpful if more water is needed. The VFPs at Jonathan Run will have a standing pool of water 4 ft deep, with a free-board depth of 2 ft.

4.2.4 Draining and Flushing System

Draining layouts for VFPs are typically 'T' or 'Y' shaped and located in the last 12 inches of the limestone layer (Zipper and Jage, 2001), but increasing the number of drainage pipes was suggested as an improved construction technique (Demchak and Skousen, 2001). The drain pipe layout for the Jonathan Run VFPs will be designed as in Figure 25.

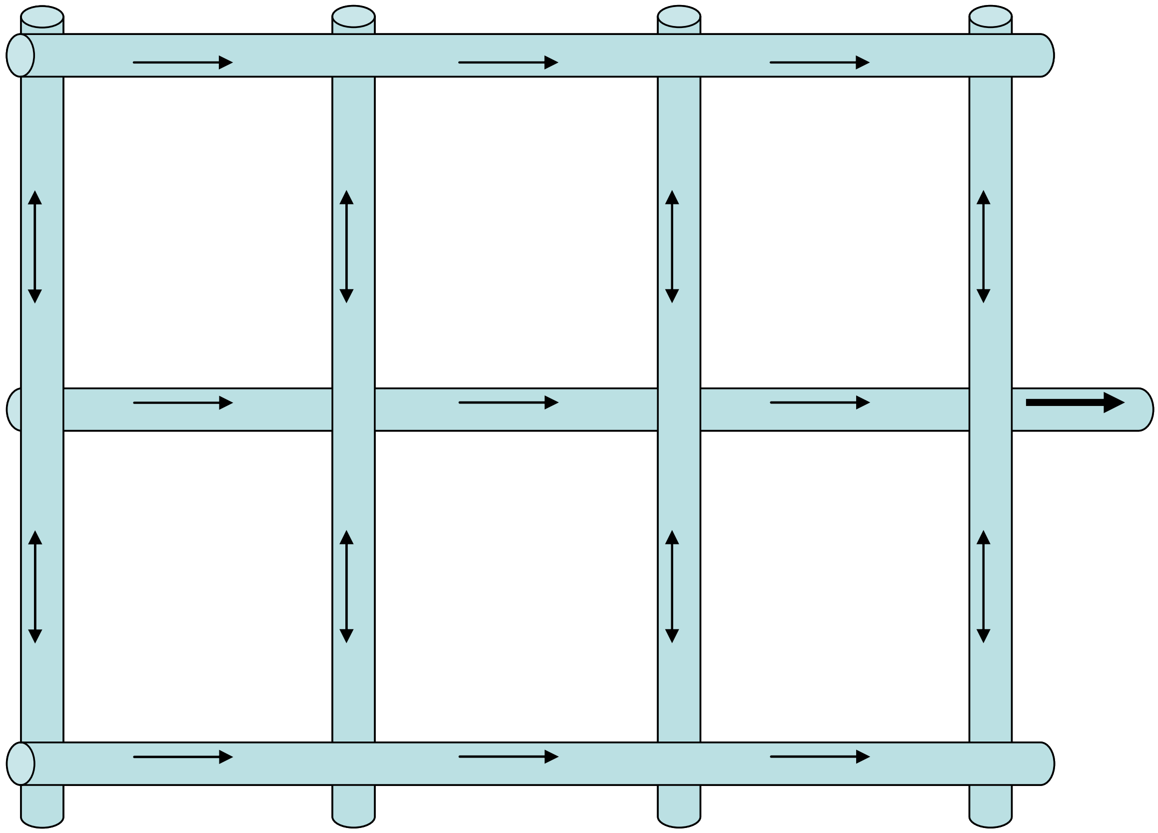

Figure 25. Drain pipe layout for Jonathan Run VFP

It is suggested that the drainage system be constructed of schedule 40 perforated PVC piping with the pipe diameter being larger than 6 inches and the hole diameters being larger than ½ inch, preferably 1 inch (Zipper and Jage, 2001). The drain pipes will be connected to an effluent standpipe that is elevated to maintain a constant head of water above the organic substrate.

The SLB3 discharge has a 6.1 mg/L concentration of aluminum, equivalent to 4.5 lb/day during the average flow. This amount of aluminum will precipitate and be retained in the limestone layer. Aluminum hydroxide is not known to armor the limestone as ferric hydroxide does, but it will fill the available void space throughout the limestone, prohibiting the amount of alkalinity that can be generated. To continue effective treatment for the life span of the system, periodical flushing of the system using the natural head of the pooled water needs to be done. A flushing system has been developed that has shown to work and continued to have success, removing greater than 80% of the accumulated aluminum in a single flush (Kepler and

McCleary, 1997). The flushing pipe is included as part of the drainage system as a valved discharge located at a level below the height of the standpipe. When the valve is opened the head pressure moves water rapidly down through the system flushing the aluminum and iron precipitates that have accumulated in the limestone and drain pipes (Kepler and McCleary, 1994 and 1997) (Zipper and Jage, 2001).

4.2.5 Settling Pond

The size of the settling pond needs to be large enough to hold the amount of water necessary to flush the iron and aluminum precipitates from the limestone layer of the treatment system and to retain them for a period long enough to allow the precipitates to settle out of the water.

There has not been a lot of research completed to determine how often the VFP should be flushed out, but would probably depend most on how fast the limestone layer is filling up with aluminum precipitate. Enough aluminum hydroxide in this layer will cause the limestone to not function as efficiently. There has been no evidence found indicating what percentage of the void space can be filled and still produce an efficient limestone response. Concerning this preliminary design, it will be assumed that the bulk void volume in the limestone can be filled by 35% and still allow the limestone to function properly.

The limestone layer was calculated to be 46,591.1 ft^3 in volume and since limestone has an estimated bulk void volume of 50% or 0.5 (Hedin and Watzlaf, 1994) (Zipper and Jage, 2001), the most water that could be retained in the limestone layer is 23, 295.8 ft^3 or 174,265 gallons. Allowing 35% of the bulk voids volume to fill with aluminum sludge would allow 16,307.1 ft^3 of sludge. By using sludge volume equation in the previous section, the amount of time until each flush is necessary can be found.

$$V_{sludge} = \frac{[Al] \times Q}{\%\ solids \times \rho} = \frac{6.1\ mg/L \times 100\ gpm \times 3.785\ L/gal \times t\ (years)}{454000\ mg/lbs \times 0.0125\ \%\ solids \times 8.34\ lbs/gal \times 7.48\ gal/ft^3} = 16{,}307.1\ ft^3$$

$$t\ (years) = \frac{16{,}307.1 ft^3 \times 454000 mg/lbs \times 0.0125\ \%\ solids \times 8.34\ lbs/gal \times 7.48\ gal/ft^3}{6.1\ mg/L \times 100\ gpm \times 3.785\ gal/L \times 525600\ \min/year} \approx 5 years$$

It is also not clear how to determine how much water needs to be flushed to remove a majority of the precipitates. This will, most often, not be able to be determined until completion of the VFP construction and could possibly fluctuate with each flush of the system.

In all likely hoods, the maximum amount of water used to flush will probably not be equal to the bulk void volume of the limestone layer (174,265 gallons). However, it is always safer to design a larger system rather than too small. In order to decrease the size of the settling pond, the depth will be estimated to be 10 ft. This then results in a surface area of 2,329.58 ft^2. Using a 4:1 length to width ratio, the dimensions of the settling pond are calculated and listed in Table 12.

Table 12. Settling Pond Dimensions for VFP Discharge

Length	100.0 ft
Width	24.0 ft
Depth	10.0 ft

This results in a final calculated surface area of 2,400 ft^2 and a total volume of 24,000 ft^3. Since this settling pond is much greater in size to that of the 2nd settling pond for the active treatment system, this pond will be used in its place.

During regular operation of the two treatment system (not during a flush) the total inflow of water into the 2nd settling pond is 260 gpm (calculated using the 90th percentile flow for each system). Just as in determining if the settling ponds in the active treatment system will promote settling of precipitates, the over flow rate and the Reynold's Number will be calculated for this settling pond. The OFR of the pond is equal to:

$$OFR = \frac{Q}{A} = \frac{260\ gpm \times 0.133681\ ft^3/gal}{2{,}400\ ft^2} = 0.0144\ fpm\ \leq\ 0.04\ fpm\ (settling\ velocity)$$

$$OFR = \frac{Q}{A} = \frac{260\ gpm \times 1440\ \min/day}{2{,}400\ ft^2} = 156\ gpd/ft^2 \leq 431 gpd/ft^2$$

And Reynold's Number is found to be:

$$\mathrm{Re} = \frac{7.315\times10^{-5}\cdot\dfrac{222.97}{75.6}}{1.1457\times10^{-6}} = 188.3 < 20{,}000$$

Therefore, this pond will allow for precipitates to settle.

5.0 SUMMARY AND CONCLUSIONS

Jonathan Run is a perennial stream located in Centre County in central Pennsylvania, near the intersection of Interstate 80 and State Route 144. In the 1960's I-80 was constructed near the headwaters of Jonathan Run. The platform construction for I-80 used the rock cuttings from nearby hill sides, which contained acid producing rock, most commonly known as Pyrite. When pyrite is exposed to oxygen and water from its natural compacted state, it oxidizes producing acidity; shown by the reactions below. The acidic drainage exiting the interstate platform discharges into Jonathan Run.

$$FeS_2 + (7/2)O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$
$$Fe^{2+} + (1/4)O_2 + H^+ \rightarrow Fe^{3+} + (1/2)H_2O$$

If these acidic conditions are found near alumino-silicate (clay) materials, the ARD will solubilize the alumino-silicates into the water releasing Al^{3+}.

$$H^+ + \text{Al-silicate minerals} \rightarrow Al^{3+} + H^+\text{-silicates}$$

Even relatively low concentrations of dissolved Al can be toxic to aquatic organisms. Jonathan Run used to be a quality stream, capable of supporting aquatic life and trout ponds, however since the construction of I-80, the acidic discharge and high levels of dissolved aluminum have rendered Jonathan Run uninhabitable by aquatic life.

A series of tasks were performed to accurately identify the source of the acidic discharge. These tasks consisted of geophysical surveys, exploratory drilling, groundwater measurements, acid/base accounting of soil/rock samples collected during drilling, examining the quality of discharges SLB3 and SLB5, and infiltration estimation using the Hydrologic Evaluation of Landfill Performance (HELP) Model.

The exploratory drilling indicated that the majority of the interstate embankment contained large sandstone boulders filled in some places with varying amounts of clay, silt, sand, and weathered sandstone and shale. And from the acid/base accounting results, the entire area is considered to be acid producing, which was thought to be true before the investigation began.

What was unknown previously was the source of the water that was discharging from the fill. It was thought that most of the water was probably groundwater. However, the elevation of the water table in the fill turned out to be coincident with the fill/natural material interface. There was not enough variation in the water levels of the well pairs to definitively determine that an upward gradient exists, but there is the possibility that small contributions of the acidic discharge come from the underlying soils. The geophysical surveys also indicated the absence of water in the fill by the negative findings of highly conductive fluid, or abnormalities of resistivity.

An estimate of infiltration was performed in order to evaluate the contribution of surface water infiltration through the fill material as a source of some or all of the Jonathan Run contamination. A total of 16,150,000 gallons per year of water was estimated to infiltrate through the acidic material, most of which, 11,220,000 gal/yr enters through the rocky side slopes. It was also stated that a small contribution of water could be entering from groundwater sources.

Discharge points SLB3 and SLB5 were measured for flow volumes and tested for quality. Both discharges were found to have high metal concentrations, mostly high levels of aluminum, most likely due to the clay materials found in the voids and at the bottom of the I-80 platform. SLB3 discharged over 200 gpm of water during wet weather periods, but showed smaller concentrations of metals during high flows. SLB5 discharge contained extremely high amounts of aluminum and an average pH value of 3.4.

Possible remediation techniques were discussed and researched based on the observations from the site investigation. Injecting an alkaline material into the fill to neutralize the acidic potential was ruled out first, because of the largeness of the area that would need to be treated. It was determined by GAI that over 1 million tons of limestone would be needed to treat the entire fill. Elimination and/or a passive treatment technique seemed to be the best available method to choose. By covering the acidic rock most of the infiltration could be reduced, but another treatment option, either passive or active treatment system would need to be constructed to treat the water that does manage to infiltrate the fill.

It was decided, based on success rates and construction costs that using a passive treatment system (vertical flow pond) to treat the discharge from SLB3 would be best because of its high flow volume during wet weather periods and lower aluminum concentrations. An active treatment system (sodium hydroxide) would be constructed to treat the discharge from SLB5 because of its high aluminum concentrations. A wetland would also be constructed on the south side of I-80 to help control acidic drainage from the additional smaller rock piles.

This thesis performed a preliminary design for the active and passive treatment systems proposed for Jonathan Run. There will be two vertical flow ponds designed to treat the discharge from SLB3. Each one would be constructed to treat 100 gpm of flow, splitting the 90th percentile of flow in half. At this flow each pond will have a detention time of 24 hours. Each will contain 2,505 tons of limestone and 19.5 inches of organic compost consisting of mushroom compost and wood chips. The ponded water depth will be 4 ft with a 2ft free-board depth to allow space for extreme flow conditions. The ponds will discharge into one settling pond that will be 100 ft x 24 ft x 10 ft.

The active treatment system for SLB5 discharge will use sodium hydroxide to increase the pH of the water. It is estimated that 0.0298 gpm of chemical flow will be needed, resulting in 15,689 gallons being used per year. This water will be mixed using stationary objects, such as large rocks and wooden baffles, and turbulent water conditions. The water will discharge into a primary settling pond that is 79 ft x 20 ft x 6 ft in dimension and then will discharge into the secondary settling pond, which is the same pond used for the passive treatment system.

6.0 FURTHER INVESTIGATIONS

There are several other considerations and further investigations that should be performed before making a final design for the treatment of Jonathan Run. The first investigation that should be performed is the water quality measuring of Jonathan Run particularly on the south side of I-80. This water has been given poor attention in past reports and not much is known about its present quality conditions. Through recent site visits it has been determined that water quality is good enough to support some aquatic life as a pool of tadpoles was seen swimming in Jonathan Run.

For the passive treatment system, the most important design characteristic is the rate of dissolution of the limestone. This will help to determine the detention time needed and the total amount of limestone needed to neutralize the acidity in the water. This thesis assumed an average dissolution rate, but rates will vary depending on the type, quality, and size of limestone used in the actual construction. When designing the active treatment system, it is recommended that a titration be performed on the water that is to be treated to help determine the amount of sludge that will be precipitated from the water. This will help most in determining the size of the primary settling pond that is important for removing the majority of precipitates from the water. Sludge is different for every treatment system in its density, consistency, which determines the volume and settling rate of the sludge.

It is also recommend that further investigations be made in determining if a wetland should be constructed to discharge the final effluent of treated water into. Through observations and experimental studies it has been concluded that chemically treated ARD ponds have a distinct lack in aquatic productivity, even though these effluent waters may meet state and federal water quality standards (Simmons and others, 2004). The research states that the lack in phytoplankton productivity stems from a lack of phosphate availability, not necessarily metal toxicity. However, water treated using a biological treatment system (wetland), maintained productivity rates similar to unpolluted ponds. If construction is completed and aquatic productivity in the water is low and not showing life sustaining qualities, the construction of a wetland to discharge the water into should be investigated.

APPENDIX A

PICTURES OF JONATHAN RUN

These pictures are shown to give a better understanding of the site description to Jonathan Run. Please click on the titles of the pictures in Appendix A to view them.

Figure 26. Map of the Jonathan Run Site

Figure 27. Taken during the construction of I-80; the construction of the culvert is shown in the picture.

Figure 28. The headwaters of Jonathan Run.

Figure 29. Jonathan Run flowing past an excess rock pile downstream from the headwaters. The rock pile is of the same material that the I-80 embankment was made from.

Figure 30. Jonathan Run flowing through the valley South of I-80.

Figure 31. Jonathan Run flowing towards I-80 (top of picture). Inside the yellow oval, orange colored precipitate covered the limestone.

Figure 32. Another picture of Jonathan Run flowing towards the culvert taken further downstream

Figure 33. Jonathan Run flowing into the culvert

Figure 34. Jonathan Run exiting the culvert on the North side of I-80. Notice the whiteness to the water; flocs of aluminum precipitate can be seen gathered in the water.

Figure 35. Aluminum floc in Jonathan Run.

Figure 36. The flow from discharge SLB3.

Figure 37. The discharge flow from SLB3 combining with Jonathan Run.

Figure 38. Jonathan Run flowing away from the culvert and I-80**.**

Figure 39. Jonathan Run a few hundred feet downstream from exiting the culvert.

APPENDIX B

SUPPLEMENTARY TABLES AND FIGURES

Table 13. Ground Water and Spring Monitoring
Jonathan Run Acid Rock Drainage Study

Monitoring Point	Date	Top of Casing Elevation	Total Depth of Well	Bottom of Well Elevation	Depth to Water	Water Table Elevation	pH	Conductivity	Flow
MW-1									
	2/16/2006	1780.36	88	1692.38	84	1696.36	4.23	2050	NA
	2/22/2006	1780.38	88	1692.38	80.67	1699.71	4.32	1250	NA
	3/10/2006	1780.38	88	1692.38	81.2	1699.18	4.1	840	NA
MW-2									
	2/16/2006	1776.34	84	1692.34	78	1698.34	3.34	1630	NA
	2/22/2006	1776.34	84	1692.34	77.9	1698.44	3.57	1490	NA
	3/10/2006	1776.34	84	1692.34	78.3	1698.04	3.44	370	NA
MW-3									
	2/16/2006	1775.34	85	1700.34	78.5	1696.84	4.78	360	NA
	2/22/2006	1775.34	85	1690.34	76.42	1698.92	5.87	280	NA
	3/10/2006	1775.34	85	1700.34	77.2	1698.14	4.69	360	NA
MW-4									
	2/16/2006	1776.64	101.8	1674.84	77	1699.64	3.17	920	NA
	2/22/2006	1776.64	101.8	1674.84	77.32	1699.32	3.98	810	NA
	3/10/2006	1776.64	101.8	1674.84	78.2	1698.44	4.05	920	NA
GAI-2									
	2/16/2006	1781.43	101	1680.43	80.50	1700.93	4.73	300	NA
	2/22/2006	1781.43	101	1680.43	82.00	1699.43	4.82	230	NA
	3/10/2006	1781.43	101	1680.43	84.2	1697.23	4.73	320	NA
GAI-3									
	2/16/2006	1772.00	110.00	1662.00	72.00	1700.00	6.50	420	NA
	2/22/2006	1772.00	110.00	1662.00	72.55	1699.45	6.49	380	NA
	3/10/2006	1772.00	110.00	1662.00	73.65	1698.35	6.26	260	NA
GAI-4	2/22/2006	1788.65	76	1712.65	64.51	1724.14	4.92	420	NA
	3/10/2006	1788.65	76	1712.65	65.05	1723.6	4.6	300	NA
SLB-3-SB	2/9/2006	NA	NA	NA	NA	NA	5.18	NA	NA
Spring Box	2/10/2006	NA	NA	NA	NA	NA	5.04	NA	NA
	2/13/2006	NA	NA	NA	NA	NA	5.2	NA	NA
(see note below)	2/16/2006	NA	NA	NA	NA	NA	4.94	180	NA
	2/9/2006	NA	NA	NA	NA	NA	4.91	NA	100
	2/10/2006	NA	NA	NA	NA	NA	5.08	NA	150
	2/13/2006	NA	NA	NA	NA	NA	4.90	NA	NA
SLB-3-OF	2/16/2006	NA	NA	NA	NA	NA	4.79	180	100
Outfall	2/22/2006	NA	NA	NA	NA	NA	4.60	150	50
	3/10/2006	NA	NA	NA	NA	NA	4.87	130	25
SLB-13									
	2/10/2005	NA	NA	NA	NA	NA	4.85	NA	20
	2/16/2006	NA	NA	NA	NA	NA	4.72	210	20
	2/22/2006	NA	NA	NA	NA	NA	5.37	150	5
	3/10/2006	NA	NA	NA	NA	NA	NA	NA	Dry

Note The spring box sample was collected through a sample tube the was advanced up inside the 15-inch cmp 220 feet using a specially designed sled and ten foot sections of metal electrical conduit. The sampling apparatus was removed but could be employed again at any time.

Table 14. Spring SLB-3 Water Quality

		SLB-3-SB-A[1]	SLB-3-SB-B[1]	SLB-3-OF-A[2]	SLB-3-OF-B[2]	SLB-3-OF-C
		02/16/06	02/22/06	02/16/06	02/22/06	03/10/05
Specific Conductance	ohms/cm	143	124	203	180	158
Total suspended solids	mg/L	< 5	< 5	< 5	< 5	19
Aluminum	mg/L	1.5	1.2	3	2.6	2.1
Iron	mg/L	< 0.05	< 0.05	0.05	< 0.05	<0.05
Manganese	mg/L	0.26	0.22	0.56	0.5	0.44
Sulfate	mg/L	27	23	43	38	35
Aluminum, dissolved	mg/L	1.4	1.3	2.8	2.5	1.9
Acidity to pH 8.2	mg/L CaCO3	16	16	25	25	16
Alkalinity to pH 4.5	mg/L CaCO3	6	8	6	< 5	14
pH	su	4.9	4.93	4.7	4.71	4.8

[1] SLB-3-SB-A and SLB-3-SB-B represents the samples collected by GAI through a tube that was temporarily inserted into the discharge point near Jonathan Run and advanced up the pipe 220 feet to the spring box that was constructed when the fill was placed. Previous camera work by PennDOT indicated that the spring box was about 220 feet from the outfall.

[2] The OF in the label refers to Out Fall.

Table 15. Jonathan Run SLB3 Discharge Water Quality Measurements

Date	Flow	pH field	pH lab	Temp	Alk mg/L	Acid mg/L	Iron mg/L	Mn mg/L	Al mg/L	Sulfate mg/L	TSS mg/L
11/21/00	0.30		4.4		14	204	2.4	13.3	38.5	337	4
10/9/00	2.00		4.5	9.5	10	46	0.4	2.9	10.6	77	8
9/23/99	5.00	4.7	4.5	10.4	9	50	0.2	2.2	8.7	71	1
8/29/01	5.00	4.0	4.3	10	3	37	0.4	1.9	6.4	93	1
9/21/01	5.00	4.0	3.8	11	-	72	1.8	3.5	11.8	161	22
10/27/01	5.00	4.5	4.2		5	96	0.9	4.4	17.8	228	1
9/9/00	6.10	4.5	4.4	10	8	46	0.2	1.8	6.7	96	
1/24/01	6.80		4.5		9	46	0.2	1.6	6.8	44	1
10/6/99	8.60	4.7	4.5		7	34	0.2	1.5	5.2		22
12/21/00	15.00		4.5	7	9	40	0.2	1.3	6.1	87	22
8/4/00	18.60	4.6	4.4	10	7	34	0.1	1.2	5.0	72	1
7/17/01	20.00		4.3		6	49	0.1	1.5	6.8	84	1
7/24/02	20.00	4.5	4.5	10	0	23	0.1	0.8	3.5	58	1
8/11/00	20.60	4.6	4.5	10	10	30	0.2	1.1	4.8	60	6
7/28/00	24.00	4.7	4.4	10	8	44	0.1	1.3	5.7	68	1
7/20/00	28.90	4.6	4.4	9	7	36	0.1	1.3	5.6	60	1
6/22/01	29.00	4.8	4.6		10	61	0.1	1.2	4.7	39	14
1/8/02	35.00		4.6		1	38	0.1	0.8	4.1	80	5
7/14/00	37.40	4.5	4.3	9	7	72	0.1	1.1	5.0	232	1
12/2/99	38.00	4.6	4.4	8.5	7	34	0.0	1.1	5.6	71	6
7/8/99	50.00		4.5		8	24	0.1	0.9	3.7	70	1
5/23/01	50.00		4.5		8	30	0.1	1.2	5.2	45	1
7/7/00	56.40	4.8	4.4	10	7	32	0.1	10.4	4.8	47	1
6/9/00	63.70		4.5		9	24	0.1	0.7	3.4	44	1
5/19/00	69.00		4.7		10	32	0.1	1.1	4.9	44	1
3/13/02	70.00		4.6		2	21	0.1	0.6	2.7	50	1
5/22/00	73.30	4.8	4.5	9	8	28	0.1	1.0	4.5	62	1
6/30/00	75.60		4.4	9	6	30	0.1	0.9	4.2	48	1
3/15/01	78.00		4.4		6	26	0.1	0.8	4.2	38	1
6/2/00	80.60	5.0	4.5	9	8	24	0.1	0.7	3.5	37	1
6/2/00	80.60	5.0	4.5	9	8	24	0.1	0.7	3.5	37	1
5/26/00	82.10		4.5		8	24	0.1	0.9	4.1	50	1
5/16/00	85.00	4.8	4.5	10	8	32	0.1	1.1	4.9	55	10
6/16/00	92.80	5.0	4.6	16	10	26	0.1	0.8	3.6	46	20
5/3/99	100.00	4.5	4.6		8	22	0.0	0.9	4.2	47	4
4/29/02	100.00	4.0	4.7	8	2	19	0.1	0.7	3.6	51	2
6/23/00	103.60		4.5		9	24	0.0	0.7	3.3	44	1
12/22/99	104.00	4.6	4.5	8	8	26	0.1	0.8	4.7	52	4
4/11/02	110.00	4.1	4.6	7.6	1	23	0.0	0.6	3.2	51	2
2/22/01	112.00		4.5		7	22	0.0	0.6	3.5	45	40
5/9/00	115.00		4.4		8	32	0.1	1.1	5.4	46	1
2/8/02	130.00	4.5	4.7		2	27	0.1	0.7	3.8	58	4
5/2/00	175.00	4.5	4.5	9	8	34	0.1	1.0	5.2	52	10
4/12/01	182.00		4.5		8	28	0.1	0.8	4.2	10	6
3/27/02	250.00										
6/12/02	250.00										
6/10/02	300.00										
Averages:	**66.72**	**4.6**	**4.5**	**9.5**	**6.9**	**39.2**	**0.2**	**1.7**	**6.1**	**73.1**	**5.5**

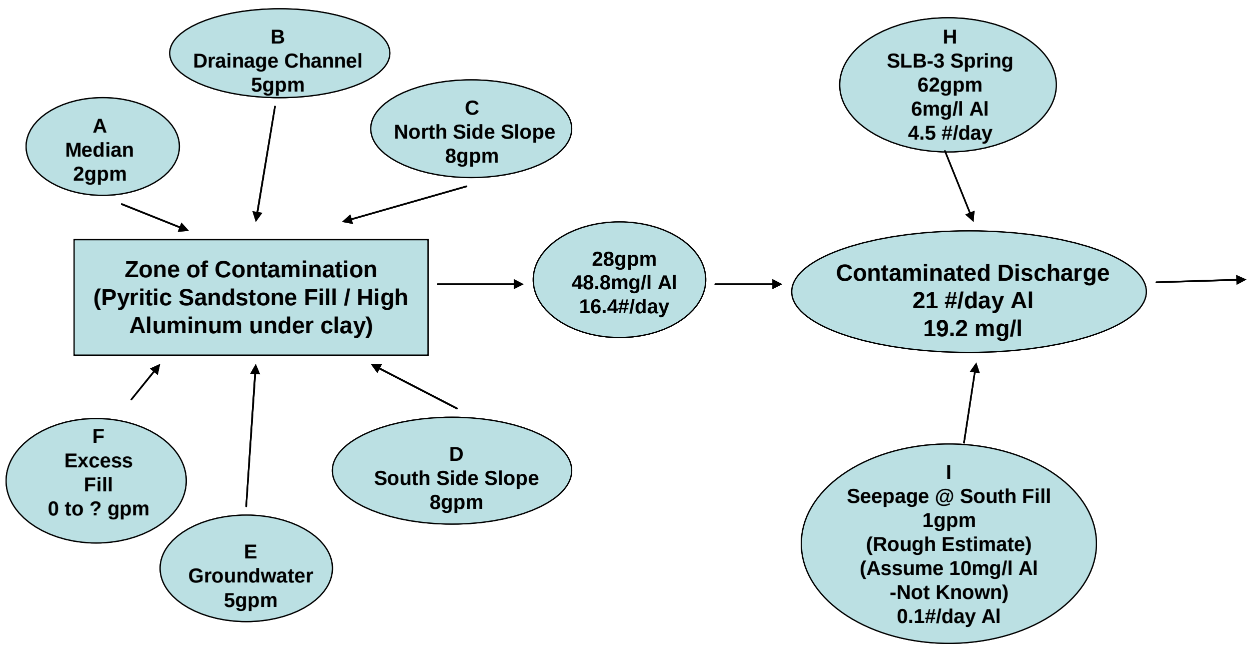

Figure 40. Existing flow conditions that contribute to the aluminum acquired in Jonathan Run.

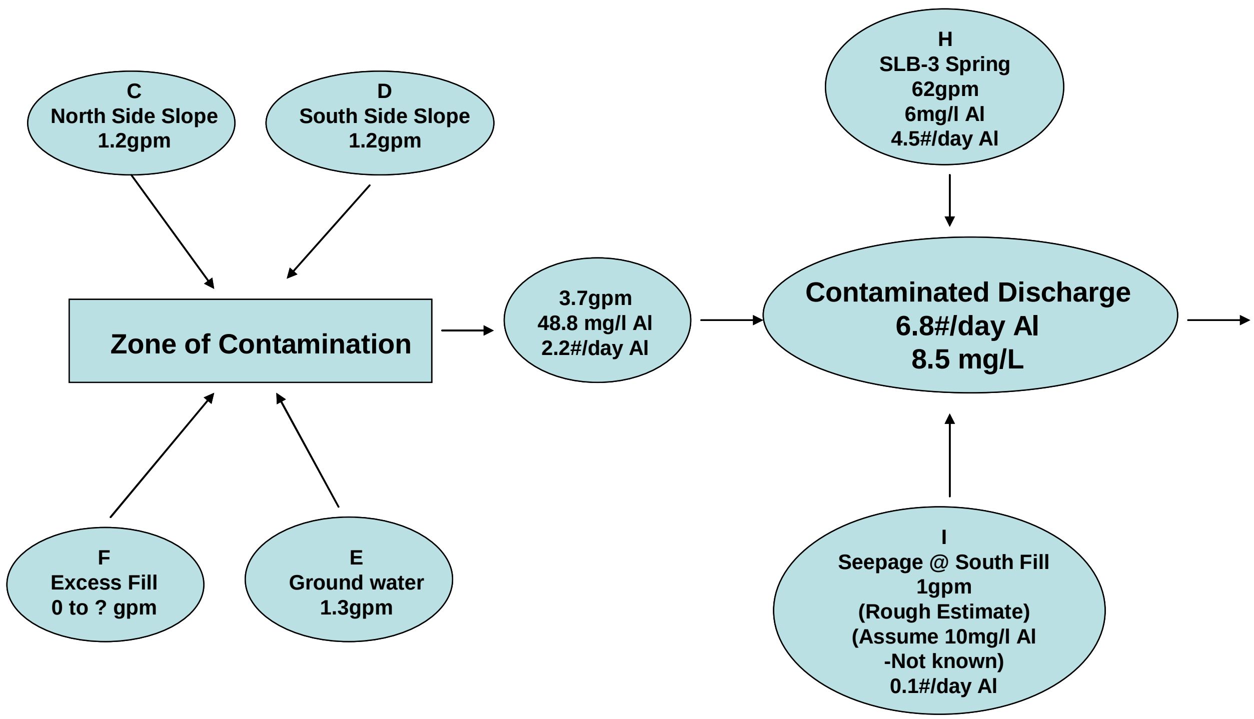

Figure 41. Estimated flows after elimination

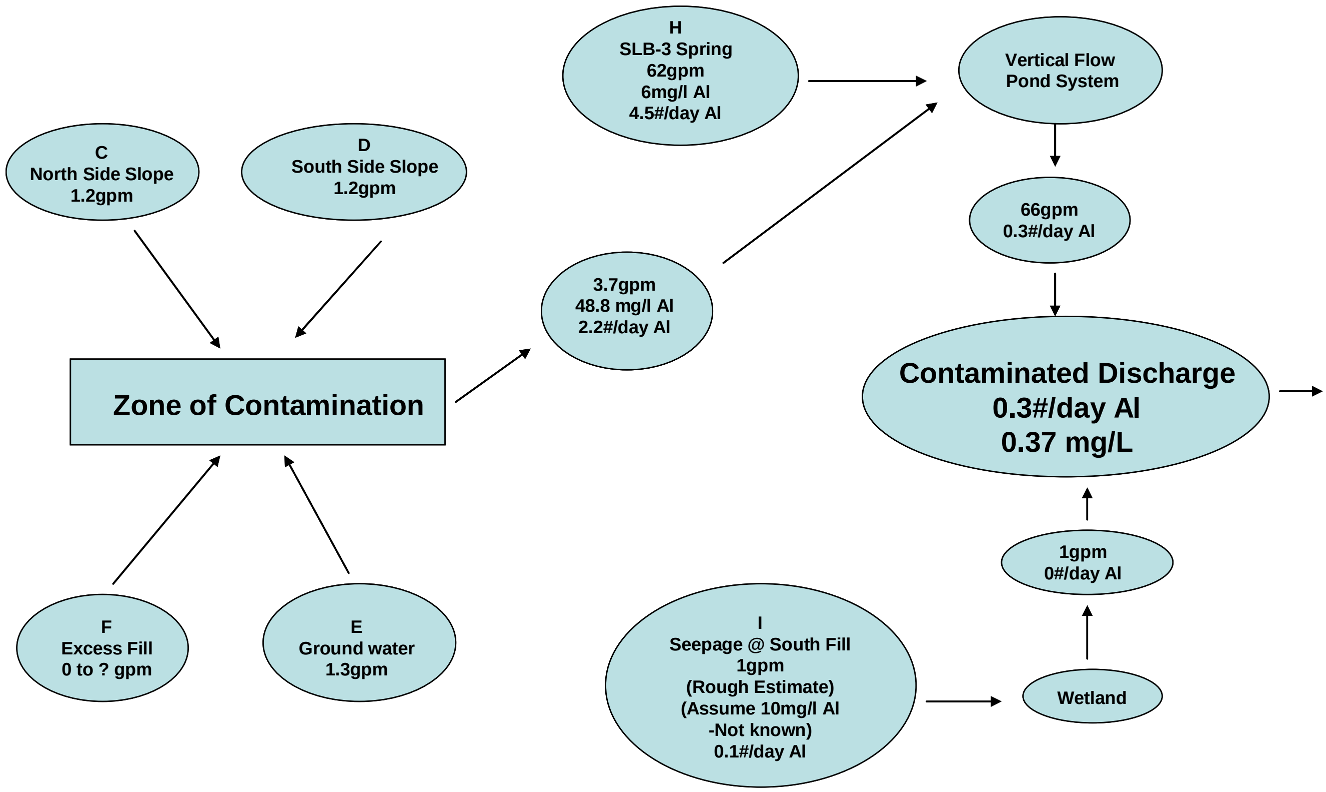

Figure 42. Estimated flows after elimination and passive treatment

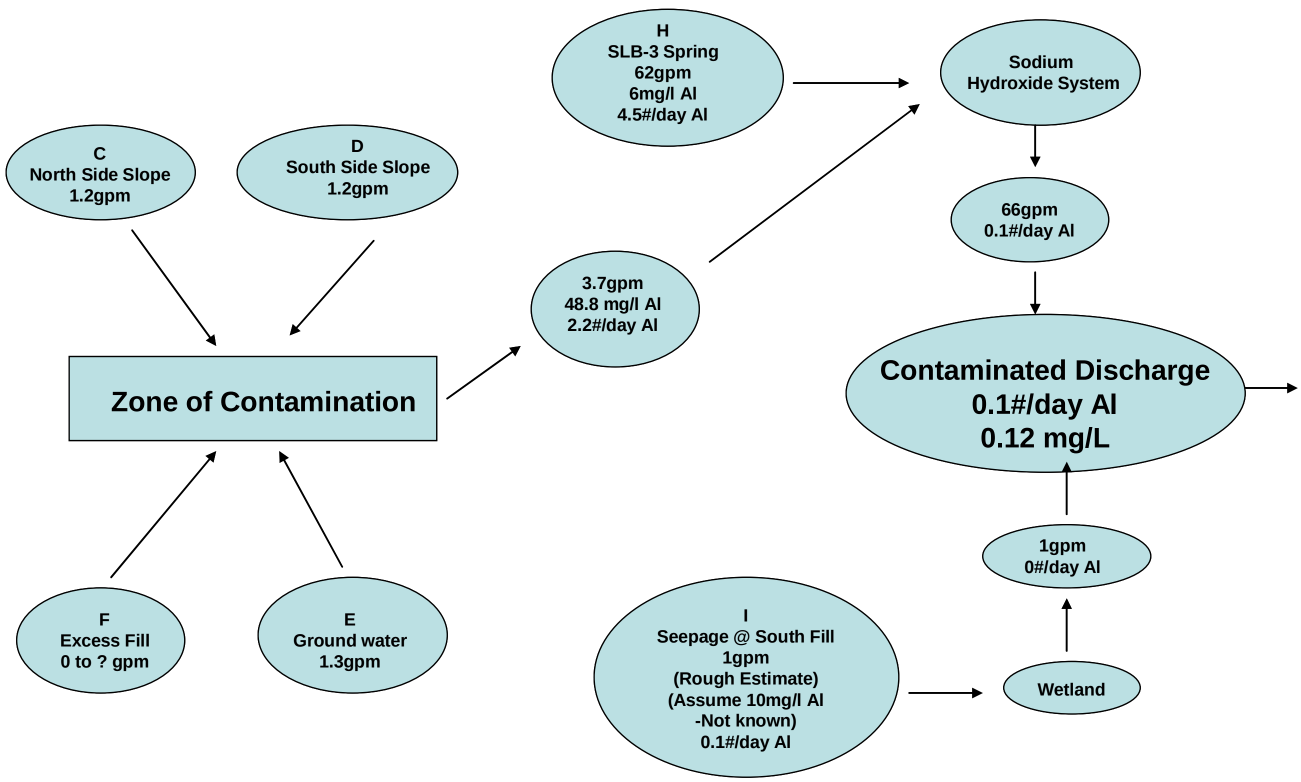

Figure 43. Estimated flows after elimination and active treatment

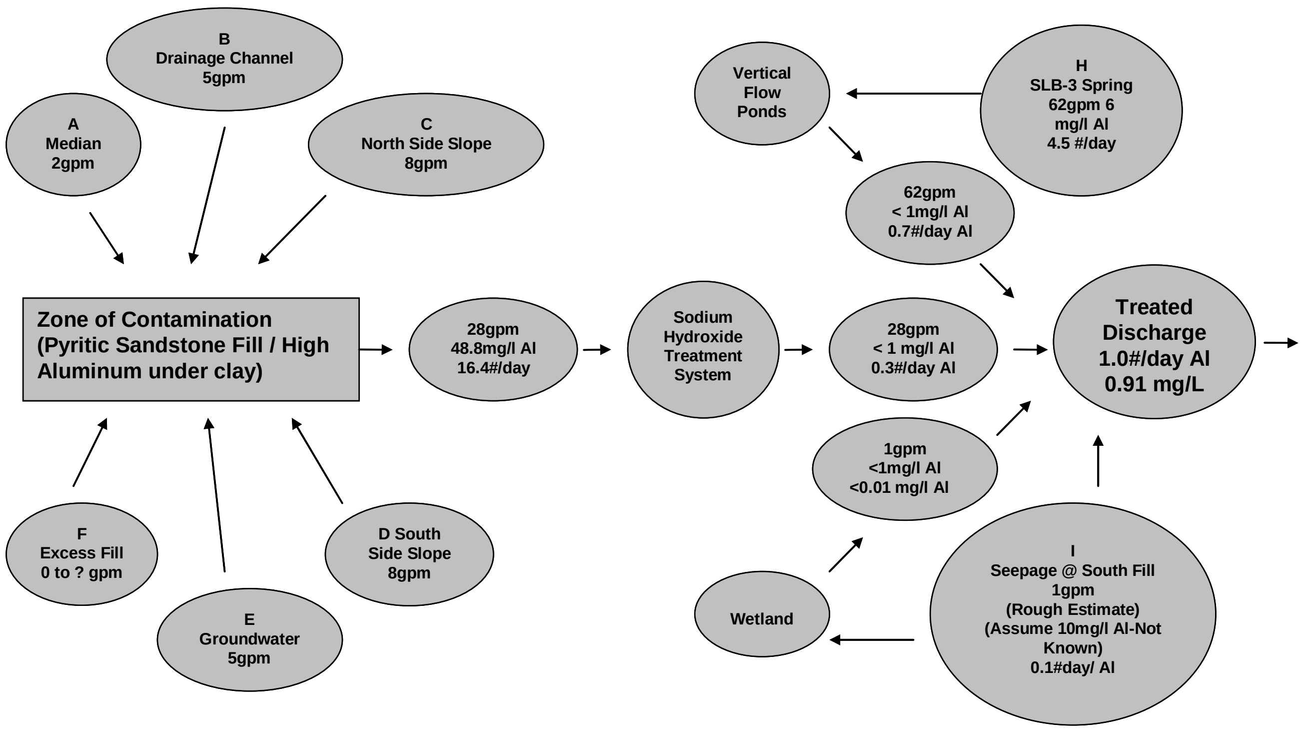

Figure 44. Estimated flows after final design decisions were made using active treatment and passive treatment systems, as well as a wetland on the south side of I-80

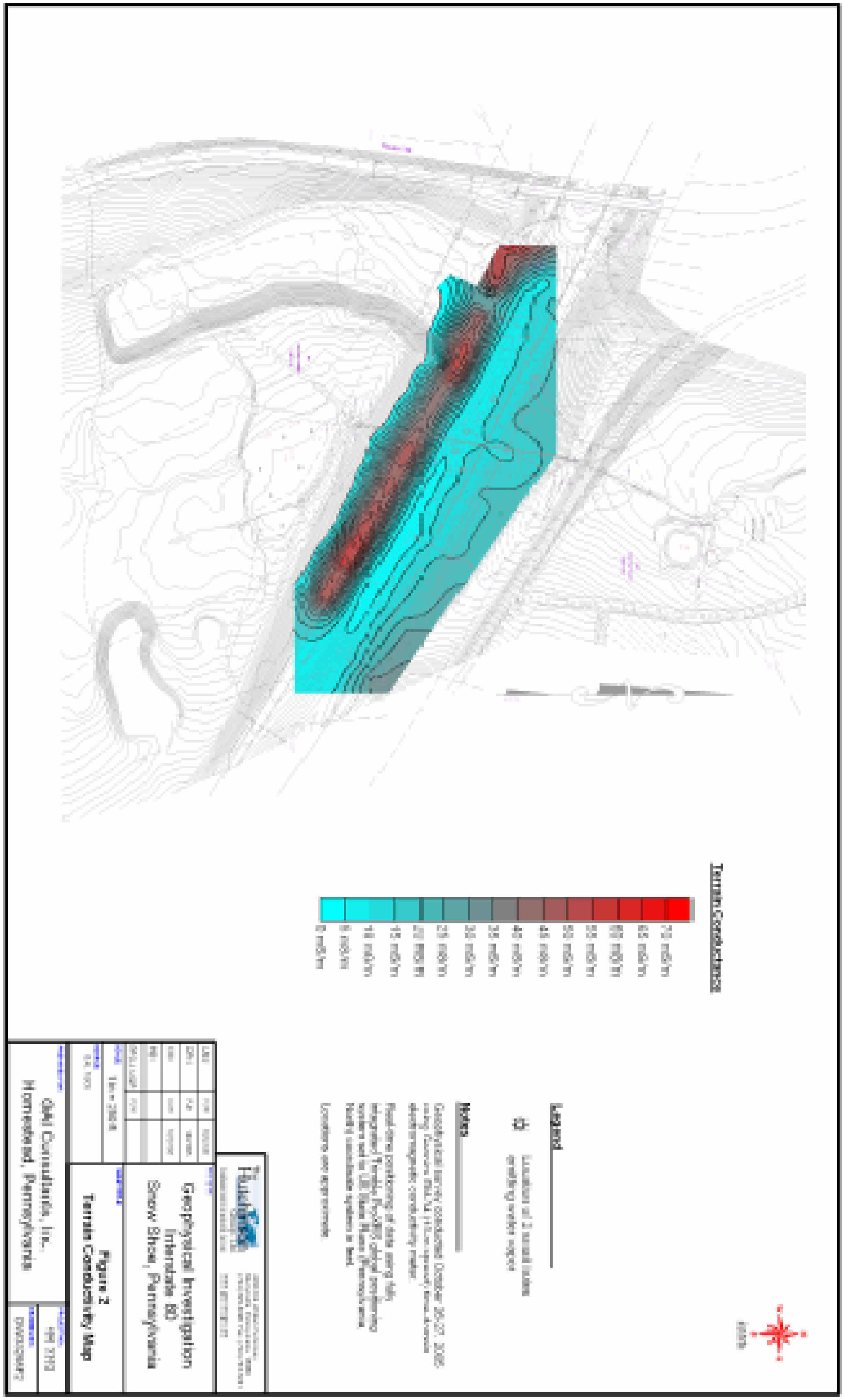

Figure 45. Hutchison Group, Electromagnetic meter survey results

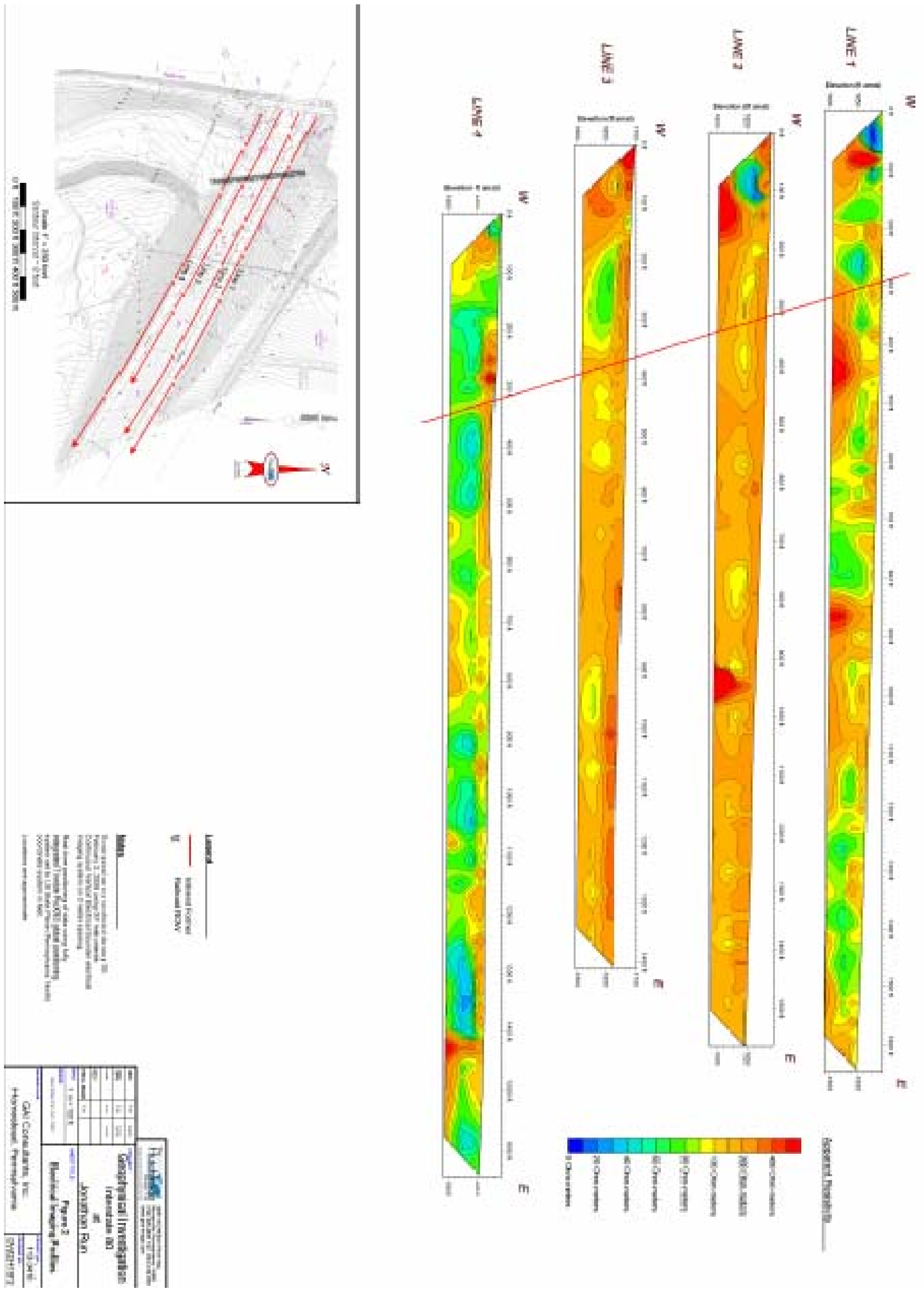

Figure 46. Hutchison Group, Electrical imaging survey results

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